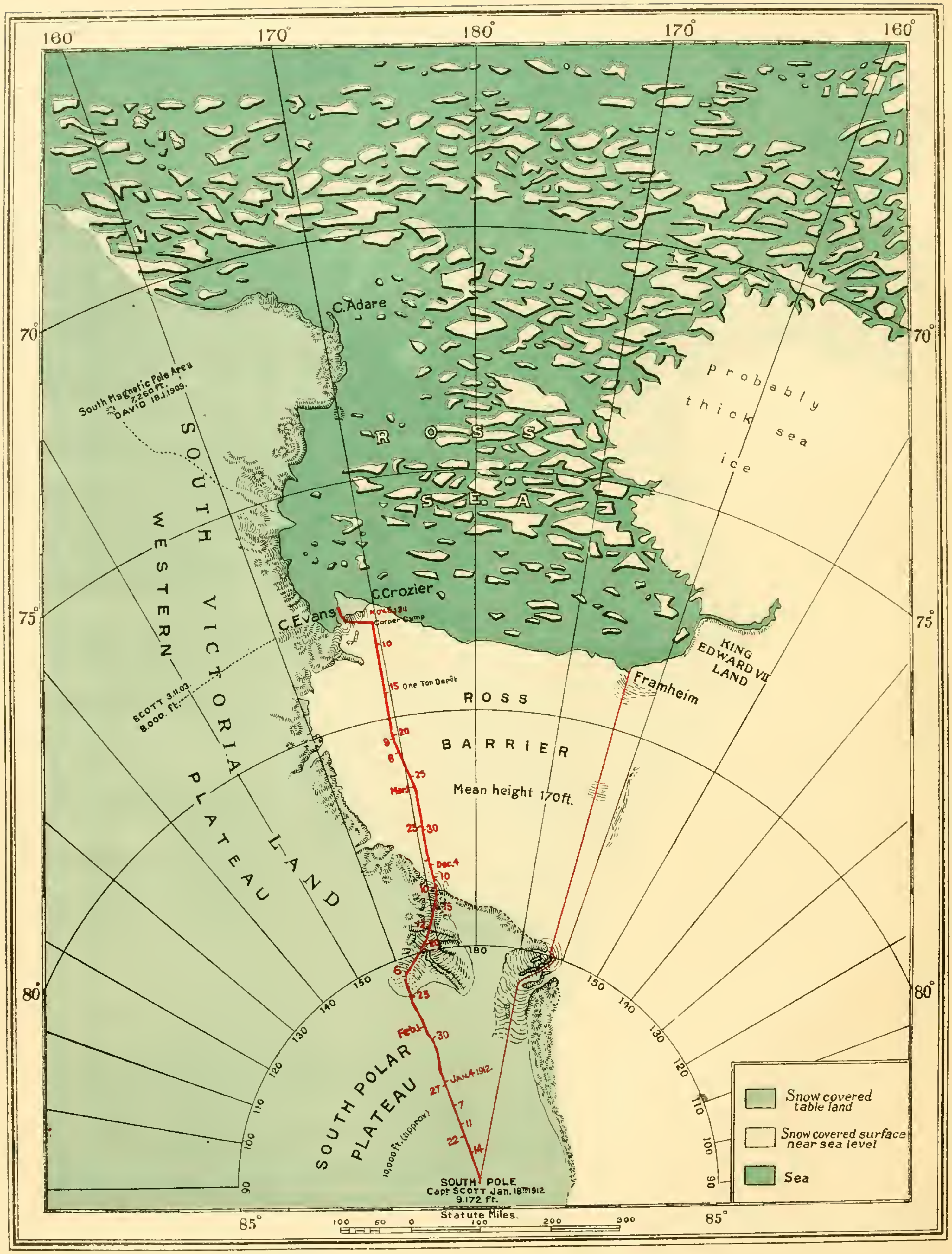

Scott's track ———— Amundsen's track - - - - -

BRITISH ANTARCTIC EXPEDITION

1910-1913

METEOROLOGY

Vol. I

DISCUSSION

BY

G. C. SIMPSON, D.Sc., F.R.S

Prepared under the directions of the
Committee for the Publication of the Scientific Results
Chairman: Col. H. G. Lyons, F.R.S

CALCUTTA
PRINTED BY THACKER, SPINK & CO
1919

Sketch map of part of Europe drawn to the same scale as the map of the Ross Sea area to which it is attached.

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TO MY WIFE

THIS WORK
Which has stolen from her many hours
of companionship

IS DEDICATED

PREFACE.

In November 1909 I received in India a cable from Captain Scott asking me to join his expedition as meteorologist. Arrangements were quickly made with the Government of India who granted me three years' 'leave without pay' and by the end of the month I was on my way to England. On January 1st I commenced five months of strenuous work during which instruments had to be begged, bought, designed, manufactured and tested and journeys made to Scotland, Germany, Norway and Denmark in order to discuss with the scientists in those countries the problems which we intended to investigate.

I soon realized that my work would be seriously handicapped if I had to depend on the general funds of the expedition for the cost of my instruments. After discussing my difficulties with Captain Scott and numerous friends in my native town, Derby, it was decided to issue an appeal to the inhabitants of Derbyshire to subscribe sufficient funds to give me a free hand in obtaining all the instruments necessary for my work. I cannot be too grateful to the late Mr. W. Crowther and to his daughter Miss Ethel Crowther who acted as honorary secretaries to this appeal, for in consequence of their indefatigable efforts £500 was collected which relieved me of further financial anxieties. Subscriptions were received from all classes of town and county and I trust that these public-spirited givers will accept this work as some tangible return for their generous gifts.

In addition to the instruments bought by the Derbyshire fund we received the loan of many special instruments particularly from the London Meteorological Office, the National Physical Laboratory, Mr. Munro, The Gutta Percha Company, the Australian Meteorological Office and the New Zealand Meteorological Office, to all of whom I wish to express the thanks both of the expedition and of myself. In consequence of this generosity all the instruments required by the expedition were ultimately obtained.

I doubt whether any expedition sailed with a more complete outfit of meteorological and magnetic instruments, but it is possible that other expeditions have come back with more recorded observations, for I find in the reports of other expeditions accounts of many observations which we never attempted. One of the chief reasons for this was the want of trained help. Captain Scott's ship did not stay during the winter in the Antarctic, but after landing the shore parties returned to New Zealand. Thus we were deprived of the scientific help which nearly all previous expeditions have received from the navigating officers of the ship when their own work was in abeyance during the sojourn of the ship in its winter quarters. There were probably more trained scientists at Cape Evans than have ever been together in any previous expedition, but each and every one had his own work to attend to and had little or no time to spare for the most hard pressed of his colleagues. As will be seen later I did receive considerable help, but this could not be depended upon and the programme of magnetic and meteorological work had to be planned for one man. Even then it was found impossible to carry out this limited programme, for difficulties with the instruments were unending and new problems connected with the effects of the cold and the blizzards on the self-recording instruments cropped up almost daily. Some of these had been anticipated and precautions taken, but frequently experience proved them unavailing. From the first the whole of my time was taken up in keeping the record of the most important elements complete and there was no opportunity for making elaborate investigations of special problems. What is more, the whole conditions are so different from those with which one is familiar that it takes at least a year to adjust one's ideas to them. At the end of the first year I could see many interesting problems calling for investigation and had planned to follow them up during the second year's work, but this could not be done for I was recalled to my work in India, when the *Terra Nova* returned to the Antarctic in January 1912.

The most obvious omission in the meteorological record is that of atmospheric humidity. There are two methods of measuring humidity: first by means of wet and dry bulb thermometers and secondly by means of hair hygrometers. The first however is very unsatisfactory at low temperatures and Mr. Dines in reviewing the two-hourly readings of the wet and dry bulb thermometers made on the Discovery Expedition wrote :—

> 'The general opinion of meteorologists seems to be that the tables by which the relative humidity is obtained from the wet and dry bulb readings are open to doubt at very low temperatures and very low values of the humidity and hence it hardly seems worth while calculating the values of the humidity from these readings.'
>
> 'One cannot help feeling regret that the opportunity to revise the humidity tables at low temperatures could not have been utilised.'

With the whole of the wet bulb readings taken on the Discovery Expedition unused I did not feel inclined to add to the accumulation. Also there was much more important work to be done in the Antarctic than revising the humidity tables, for this can be done in more accessible regions of the globe. I therefore decided to take no more wet bulb readings.

The use of the hair hygrometer at low temperatures has been studied by Professor Mohn and his students in Norway, and a hygrometer designed which is said to be reliable in use. In the short time available for preparation before the expedition sailed I had no opportunity to obtain and familiarise myself with this instrument. The consequence was I removed direct observations of the humidity of the atmosphere from my programme hoping that I should be able to devise some indirect method of observation when in the Antarctic. The opportunity for this however never arose, so humidity is not discussed in the present work.

Another omission is any account of meteorological optics. This is a subject in which I am particularly interested and I gave it constant study when in the South. With the exception however of iridescent clouds I came across no phenomenon which appeared to me to involve any new physical principles. All the halos I saw appeared to conform to the physical explanation given in such great detail by Pernter in his Meteorologische Optik, and I had not the time or instruments accurately to measure the halos to find small departures from the theory. My study of iridescent clouds led to the formation of a new theory to account for this beautiful natural phenomenon. As this has already been published in the Quarterly Journal of the Royal Meteorological Society it has not been included in this work.

The measurement of precipitation is another omission, but this is discussed in its proper place in the book.

Even with all these omissions of observations and the strictly limited programme it would have been impossible to keep the record complete if I had not received help from other members of the expedition. Captain Scott therefore arranged that during the winter the night watchman should record hourly observations of the aurora and take the midnight and 4 A.M. meteorological observations. But in addition to this I needed help in work which required co-operation and I always found the members of the expedition, from Captain Scott to the cook, willing and ready to accord this help if their own duties would allow. For all this help I am sincerely grateful and to each and all my thanks are due, but naturally I received more help from certain members of the expedition and to them I would like to express my thanks in particular.

First and foremost I must record my gratitude to Lieutenant H. Bowers of the Royal Indian Marine. Bowers was one of the hardest worked men with the expedition, yet he was always ready to help those who needed help. He could not be idle for a moment, and the whole of his recreation was taken in doing something for someone else. When he needed exercise he would take with him a pony for a walk or go up on to the foothills of Erebus to read the thermometer in one of the outlying screens. His greatest help to me was in connection with the balloon ascents, for he undertook the filling of the balloons while I prepared the instruments to be attached to them. Then, as it was dangerous for one man to go alone in search of the fallen instrument, we went together on many a long tramp over the rocks and sea ice surrounding Cape Evans following the trail of the long silk thread which had been attached to the instrument and should have led us to it. Bowers loved the Antarctic and he was the only man with us who was never heard to anathematize the weather or the discomforts of Polar life. One of the gleams of comfort accompanying the shock of the news of his death with the Polar Party was the knowledge that he would have considered the object worthy of the sacrifice.

Another busy man always ready to help was Griffith Taylor, and it was only through his willingness to take over the meteorological work for a fortnight that I was able to experience the joys and trials of sledging. But this was not the only occasions on which he showed his interest in meteorology by undertaking part of the drudgery of making observations, for he was always ready to take a set of observations if I was away from the hut at observation time.

C. S. Wright was my right-hand man in regard to the magnetic work and during the first year in addition to his own work of chemistry and ice study he was always ready to relieve me of a set of absolute magnetic observations or to take the routine meteorological observations. On my return at the end of the first year he took over as much of my work as possible and with the help of T. Gran continued the chief magnetic and meteorological observations, so making the record of these complete for two years. Gran's meteorological work during the second year was remarkable as he was faced by difficulties with which we did not have to contend during the first year and in working up the results I have frequently had cause to be grateful to him for the trouble he took to make the record complete.

During the summer when nearly everyone was away from the hut and there was no night watchman E. Nelson volunteered to relieve me of the midnight observations and this made it possible for me to get a tolerable night's rest in spite of having to turn out at 4 A.M. to read the meteorological instruments.

Turning now from the work in the field to the work in the study I find that this part of my undertaking also requires explanation and the acknowledgment of help ungrudgingly given. The whole of the data was not in my hands until near the end of 1913 and before the discussion was half completed the war broke out. These were strenuous times and as the work had to be done in my spare time it was not until April 1916 that the discussion was completed. It then seemed best not to print the work until the end of the war, but as the war dragged on its weary way it was decided in June 1918 to make the experiment of publishing the book in India. I was then engaged on war work and had little time to give to work of this nature, which seemed of little account in view of the great issues then being fought out on the battlefields of Europe. The publishing house was also hard pressed and the printing of the work has been long drawn out, but at last in happier times the book is ready for issue.

One of the effects of the preparation of such a work in such circumstances has been the impossibility of consulting original works, copies of which were not available in India. Frequently I have had to rely on extracts and reviews of previous work where I should have preferred to obtain the original papers, but the disorganized state of the world and the uncertainty of mails made this impossible.

Many meteorologists will look in vain in this book for statistical results with which they have become familiar in similar works. I am no statistician and statistical meteorology has no attraction for me, therefore I have not loaded my discussion with statistical tables. These have all been banished to Volume III which will consist of tables only and will, I hope, prove a happy hunting ground for the statistical meteorologist. On the other hand no statistical investigation has been too laborious when it has been undertaken to unravel some physical problem.

The keynote of my work has been physics and I have attempted to find the physical explanation of each of the meteorological phenomena observed. It will probably be found that many of my physical explanations are not sound and will not bear critical examination, still to me an imperfect physical explanation is better than none, for it acts as a thread to bind the facts together and being an object for attack may lead ultimately to a correct explanation while the mere statement of the facts might have been passed unheeded. Those who have the patience to read through this book will find many fascinating unsolved problems and these, I hope, will be incentatives to further investigation both in the study and in the field.

A word must now be said about the units used in this work. I had to take with me the instruments available and as most of the ordinary meteorological instruments were provided by the London Meteorological Office they were graduated in English units: the thermometers in degrees fahrenheit and the barometers in inches. Thus if I had not used these units in my discussion every reading would have had to be converted into another set of units. But what units should these be? On my return I found the meteorological world vehemently discussing the relative values of the fahrenheit, the centigrade and the absolute scales of temperature, and the inch, the centimetre and the millibar units of pressure. The controversy still rages and we now have all these units in actual use by official meteorologists. In such an atmosphere of unrest it would have been difficult to justify the immense labour of converting my observations from the units in which they were taken into any other set of units. Therefore in the ordinary meteorological and climatological observations I have used the old English units of fahrenheit degrees in temperature and inches in barometric pressure. On the other hand, in special problems I have used the units which are most frequently met with in previous works. My upper air observations have been given in centigrade degrees and metric units, and when I have been discussing the work of continental writers I have followed these units even in ordinary climatological elements. Thus I lay myself open to criticisms of inconsistency, but if my inconsistency helps to facilitate discussion I am quite content. The book has been written in a transitional age and it bears the marks of the transition.

I have received much help in writing this book, and in every case in which I have asked for data it has been willingly and promptly supplied. I cannot record all the help which I have received in this way but I must acknowledge that which I received from the directors of the meteorological services of Australia and New Zealand. Mr. Hunt in Melbourne and the Rev. D. C. Bates in Wellington extended to me personal hospitality and placed the resources of their departments at my disposal. The data sent to me by Mr. R. C. Mossman have been of the utmost value and I am grateful to him for the help he has given. Dr. Gilbert

Walker and Mr. C. Normand of the India Meteorological Department have always been ready to discuss my problems with me and to these discussions I owe many clear views of problems which at first appeared dark and hazy.

The greater part of the reduction of the observations has been done by Babu Mohammad Bakhsh of the Simla Meteorological Office and his reliable work has been a great relief to me, for it is good to be able to trust your chief computer.

The diagrams have all been prepared by Mr. R. M. Batt of Simla and as the excellency of his work is obvious to all readers, it is only necessary for me to record my thanks.

The work, begun ten years ago, is now finished and about to be submitted to those who are interested in problems of Polar meteorology, but it leaves me with a sense of sadness for the two men to whom it would have made the strongest appeal and whose opinion I should have valued above all others are no longer with us to receive it.

Over and over again as point after point was cleared up I have longed to be able to show the result to Captain Scott, for there was hardly a problem of Antarctic meteorology which we had not discussed together. His interest in every scientific problem with which the expedition was concerned was intense and I do not think that I have ever met a man who had the true scientific spirit so utterly unalloyed. To most of us who have given our lives to science our investigations are frequently tinged with an unscientific desire to increase our scientific reputations, but with him it was the added knowledge alone which gave pleasure. He was constantly looking forward to the successful completion of the journey to the Pole, the exact value of which was perfectly clear to him, in order that he might spend his remaining time in the Antarctic in opening up new country and making new discoveries.

And Professor H. Mohn has also passed away. Every meteorologist knows how much Polar meteorology owes to Professor Mohn for his discussion of the results obtained by Nansen in the Arctic, and only a few months before his death he discussed the meteorological data brought back from the Antarctic by Captain Amundsen. He gave to me liberally of his great experience on my visits to Christiania, and after my return from the Antarctic he placed the whole of Amundsen's data at my disposal, before even he himself had discussed them. He was keenly looking forward to the publication of the results of Captain Scott's expedition, and I feel confident that no one would have been able so well as he to separate the sound from the unsound in this work.

SIMLA:
March 1919.

G. C. S.

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ERRATA.

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Figure 53, page 158,	,,	Fraimheim	,,	Framdrift.
Page 268, line 11,	,,	contract	,,	contact.
Page 268, line 37,	,,	above	,,	about.

CHAPTER I.

INTRODUCTION.

THE GEOGRAPHICAL FEATURES OF THE ROSS SEA AREA.

AS the greater part of this work deals with the meteorology of the Ross Sea area of the Antarctic, it is essential to have a clear idea of the general geographical features of this region. This is particularly necessary as the several characters of the Sea, Barrier, and Plateau exert their own influences on the air overlying them, and their boundaries determine to a large extent the direction of the air motion.

In figure 1 (frontispiece) an attempt has been made to indicate diagrammatically the physical features of the Ross Sea area during January.

The region is divided naturally into three main divisions: (*a*) the extensive plateau on the west, (*b*) the Ross Sea, and (*c*) the Barrier.

The Plateau.—Geological evidence points to a great seismic catastrophe having at some time taken place in this region. The high land which once probably extended over the whole region appears to have split along a line running almost due south from near Cape Adare, and the eastern portion to have sunk below sea-level. The line of fracture is now shown by a narrow belt of broken land, which forms a fringe along the whole eastern edge of the plateau, and through which it is necessary to pass to reach the high land from the Barrier or the Ross Sea on the east. The fringe is very narrow in most places, being less than twenty miles in width, so that the descent from the plateau to sea-level is very rapid. It is intersected at right angles by numerous valleys, through which the accumulated ice on the plateau flows down to sea-level in the form of gigantic glaciers.

The plateau has been reached from the Ross Sea side in three places. In 1903 Captain Scott made the ascent almost due west of Ross Island, and travelled on the summit to the position 78° S., 147° E. He found the height of the plateau in this region to be about 8,000 feet. In 1909 David reached the south magnetic pole (72° 25′ S., 155° 16′ E.), where the height of the plateau was determined to be 7,300 feet. The plateau near the South Pole has been visited by Shackleton, Amundsen, and Scott and the height found to be just under 10,000 feet. The character of the plateau is the same at each of these positions. As soon as the mountains and valleys which form the fringe are left behind, the plateau becomes a level, unbroken plain, the snow surface being unrelieved by any feature to break the dull monotony of the outlook.

The Ross Sea.—In 1841 Ross discovered the open sea which now bears his name. After forcing his way through a thick belt of pack ice he emerged into open water near to Cape Adare. He then sailed south along the coast of the plateau which he called South Victoria Land, until he sighted an active and an extinct volcano side by side, to which he gave the names of his ships, Erebus and Terror. As these mountains barred his way to the south he was forced to turn to the east, and after sailing a short distance he discovered the great ice-cliff which forms the southern limit of the open Ross Sea. Ross sailed eastwards along this great cliff of ice hoping to find a way to the south, but as the ice-cliff made this quite impossible he gave to it the very suitable name of the 'Great Ice Barrier.' Scott, in the *Discovery*, thirty-nine years later, was able to explore this ice barrier more thoroughly than had been done by any other explorer. He found that the ice-cliff extended from Cape Crozier almost due east to the new land which he discovered and named King Edward VII Land. The height of the Barrier varies between a few feet and 240 feet, but the general height is between 50 and 100 feet. Scott was unable to proceed to the east of King Edward VII Land owing to thick ice. With Scott's first expedition what may be called the permanent extent of the Ross Sea on its western and southern sides was fixed.

The extent of the Ross Sea on the east is not known. Every explorer has had his progress in this direction stopped by thick, impassable sea ice. It is obvious that the edge of this ice varies from year to year. In 1842 Ross sailed up the east of the Ross Sea along a course almost due north-west from near King Edward VII Land, and he found 'compact hummocky ice' to the east of him.

In 1912 Evans in the *Terra Nova* sailed somewhat to the east of Ross's track, and he had the greatest difficulty in forcing his way through the pack ice. There can be little doubt that the sea to the east of 165° W. longitude is permanently covered with ice, and that this meridian may be considered to limit the open water of the Ross Sea on the east.

Looking now at the map we see that the Ross Sea on the north opens into the Antarctic Ocean in about latitude 70° S., and is bounded on the west by the coast of the high tableland, on the south by the Great Ice Barrier, and on the east by an undefined mass of ice or land which is probably at or very near sea-level, in any case the probabilities are against its being high land similar to that on the west.

For our discussion of the meteorology of the region it is essential to have some knowledge of the varying ice conditions of the Ross Sea. Unfortunately the data available are very few, and they chiefly refer to the three summer months, December, January, and February.

During January the Ross Sea is nearly free from ice between the coast of South Victoria Land and the heavy sea ice near longitude 165° W. There are, however, isolated patches of pack ice and floating bergs to be met with in all parts, and probably these occur more frequently in the eastern than in the western half. These floating masses of ice are indicated by lozenge-shaped areas in figure 1. North of the Ross Sea there is an almost constant stream of pack ice which has broken off from the coast of the Antarctic Continent and is slowly drifting from east to west. The *Terra Nova*, in 1910, entered this stream in latitude 65½° S. and took nearly three weeks to force her way through, which she did not do until she was in latitude 71½° S.

In March the sea commences to freeze, but the wind is a great obstacle to the formation of a permanent coat of ice. During March 1910 the sea in McMurdo Sound froze over as far as the eye could see several times, only to have every bit of ice removed by a subsequent blizzard. In April the ice along the coast gradually became sufficiently thick not to be removed by the wind, and afterwards daily increased in thickness and so became more and more able to withstand subsequent gales. It was not until the end of May that the Sound was completely frozen over. During the winter of 1912 the gales were so frequent that the Sound never became properly frozen over, and open water extended right up to Cape Evans for the greater part of the winter.

The wind must play a similar part in the freezing of the Ross Sea, and as there is very much more wind over the western half of the sea than over the eastern half it is almost certain that the ice will form earlier and grow much thicker in the east than in the west.

By the middle of the winter it is probable that the ice conditions over the Ross Sea are somewhat as follows. The greater part of the eastern half of the sea is firmly frozen over with ice which in the course of the winter attains a thickness of between ten and fifteen feet. Also along the western coast all the bays and inlets are frozen and the fixed ice probably extends several miles out from the coast. Between the fixed ice on the two sides there is an area which is sometimes frozen over and sometimes free from ice, even in the middle of the winter. That such a region of thin variable ice does exist was made certain by the observations of the party which visited Cape Crozier in July 1911. From Cape Crozier the Ross Sea can be seen, and the party made a record of the changes in the ice-covering of the sea during the time they spent there.

When they arrived on the 15th July they found that the Ross Sea was completely frozen as far north as they could see, 'but much of the ice appeared to be young and thin, with little snow on it.' The next day they saw in the distance a cloud of frost smoke, which is a sure sign of open water. On the 17th they report 'two open leads of water, like broad irregular streets extending from the Cape Crozier cliffs away to the north-east and lying more or less parallel to one another.' These leads had disappeared the next day, but more open water was seen on the 19th. When this party descended to the sea ice they came to the conclusion that the ice had shortly before been blown out and only recently formed again, and they note 'some support is lent to this possibility by the absence of all snow-drifts on to the sea ice from the ice foot.'

A day or two after the party reached Cape Crozier a very severe gale occurred. For several days winds of hurricane force blew. When the wind dropped and the Ross Sea could again be seen it was found that the ice had all been blown north. Cherry-Garrard says 'in the gale the ice went right out from the Barrier as far as we could see. But we could see the ice on the horizon from 900 feet up: just a line of blink, but it was there I feel sure. Otherwise open sea.'

Everything therefore points to the centre of the Ross Sea being a region in which the ice is constantly forming and being blown away so that it can never become thick, and in which open water is constantly present either in leads or large open expanses.

Very little is known about the winter ice conditions in the north of the Ross Sea. The only information is that obtained from observations made at Cape Adare. At Cape Adare the station was on the west of a lofty promontory and only the sea to the north-west was visible from the station. Young ice commenced to form during the first week of April, but here again it was constantly removed by high winds. It was not until the end of May that the ice was sufficiently firm to allow of journeys being made across it. After this large leads were opened by every gale and the presence of Antarctic petrels in July indicated that the open water was not very far away to the north. At the end of October the sea ice became too rotten for safe sledge travelling and in December the ice both east and west of the Cape broke out with great rapidity.

These observations point to the ice conditions at the north of the Ross Sea being very similar to those seen from Cape Crozier, and probably the ice here never becomes more than four or five feet thick, and is constantly, during the whole winter, opening up to produce long and wide leads of open water. These conditions probably exist to two or three hundred miles to the north of Cape Adare, where the northern boundary of the frozen area is very likely composed of pack sometimes free and sometimes firmly bound together by thin new ice.

The ice conditions in the Ross Sea are therefore in the main something as follows :—

In the summer the open water is bounded on the west by the coast of South Victoria Land, on the south by the vertical face of the Great Ice Barrier, and on the east by a variable mass of sea ice the extent of which is not known, but which in all probability extends in a north-north-westerly direction from King Edward VII Land. A certain amount of detached ice floats on the open sea and this is most abundant in the east and in a belt across the entrance to the sea in approximately latitude 67° S. In March new ice commences to form and by the end of the month the ice is permanently fixed in sheltered bays and during April and May this fringe of ice extends outwards from the coast. During the winter the east of the sea and a belt along the coast of South Victoria Land are permanently frozen over, between these two regions of fixed ice there is an area extending from the Barrier northwards to the open ocean some hundred miles or so north of Cape Adare in which the sea is sometimes frozen over and sometimes cleared of ice by the wind and in which the ice never attains any great thickness.

The Barrier.—It has been stated that Ross gave the name 'Barrier' to the ice-cliff which barred his way to the south. Ross was not able to mount to the top of the cliff, but when subsequent explorers did so they found it to be the seaward edge of a great almost level plain of ice and snow. The name originally given by Ross to the cliff has been extended to this great snow plain, and now the original significance has been lost and the word 'Barrier' is used almost exclusively as a place name for the level low-lying area of snow and ice which is terminated on the north by the ice-cliff to which Ross gave the name originally.

On the west the Barrier is bounded by a continuation of the escarpment which further north has formed the western coast of the Ross Sea. Starting near Ross Island and proceeding due south along the level surface of the Barrier, one has on the right the lofty mountains of the escarpment between which large glaciers flow down from the surface of the plateau 8,000 to 10,000 feet above the level of the Barrier. The high land continues on the right until latitude 82° S. is reached, where the escarpment turns slowly to the east and cuts across the direct way to the Pole. From 82° S., 160° E., the escarpment of the plateau runs almost south-east to near 85° S., 160° W., where according to Amundsen's observations it turns sharply to the right and continues in a more southerly direction, passing within about 120 geographical miles of the Pole.

The eastern boundary of the Barrier is unknown. There are indications of land in a line to the south of King Edward VII Land, but it is almost certain that if land does exist here it is low land or a series of low islands. For meteorological purposes we may consider that the whole of the area beyond the escarpment of the plateau is low, and if it is not actual Barrier it is snow-covered low land which is similar in most respects. Neglecting for the present the character of the region to the east of longitude 160° W., we may say that the area bounded on the north by the great ice-cliff joining Ross Island and King Edward VII Land, on the west and south by the escarpment to the plateau and on the east by longitude 160° W., is occupied by the Barrier. The area of this region is approximately 200,000 square miles, *i.e.*, nearly the same as France. The distance from Ross Island to the Beardmore Glacier is almost exactly the same as from Paris to Marseilles. The whole of this huge area is practically a level plain. Barometric determinations indicate that its surface is on the average 170 feet above sea-level and this is only slightly higher than the ice-cliffs on its northern edge. The question of the origin and the formation of the Barrier is discussed elsewhere; it is sufficient to give here the conclusions arrived at. There is little doubt that for the greater part, if not for the whole, of its extent the Barrier is a floating sheet of ice. If this is so and assuming that there is seven times as much ice below the level of the sea as floats above, the average thickness of the sheet of ice is something like 1,400 feet. The Barrier surface is snow, often soft, but sometimes hardened by the wind, so that the feet sink in only a fraction of an inch. The Barrier surface is nowhere composed of hard ice, and it is probably only at considerable depths that the snow loses its porous texture and becomes solid ice. This fact will be shown to have an important bearing on the temperatures measured on the Barrier.

The Stations.

Cape Evans.—The winter quarters of Captain Scott's second expedition were situated on a small cape jutting out from Ross Island into McMurdo Sound (see figure 2). Ross Island is almost entirely occupied by two volcanoes, Mount Erebus and Mount Terror, the former of which is still active. It is separated from the mainland by McMurdo Sound. The western coast of the island runs almost due south for fifty miles from Cape Bird to Hut Point and is roughly parallel with the opposite coast of the Sound which is forty miles away.

Fig. 2. Map of the Surroundings of Cape Evans.

McMurdo Sound is therefore approximately rectangular in shape, the long and the short sides being fifty and forty miles respectively; it is open to the Ross Sea on the north and closed by the Barrier to the south. The Sound has open water during January and February, but freezes over during the winter. The winter conditions of the ice are however very varied from year to year. During some winters the whole Sound is frozen over from April to the end of December, while during other winters frequent gales remove the ice as soon as it is formed and only the southern half becomes firmly frozen over.

The summit of Mount Erebus is about fifteen miles to the north-east of Cape Evans, and is over 13,000 feet high. The side of the mountain in this region rises rapidly from the coast and is covered with one huge glacier. Cape Evans is a small triangular piece of land at the foot of the mountain. One side of the triangle is against the slopes of Erebus while the other two are washed by the waters of the Sound. During the summer a large proportion of the black volcanic debris of the Cape is exposed, but in the winter it is all covered by snow except in a few places where the wind sweeps the surface clear. The slopes of Erebus to the south of Cape Evans are quite impassable, hence when the sea is not frozen over Cape Evans is entirely cut off from the south. When the Sound is frozen over the sea ice forms a splendid surface over which the coast of Victoria Land can be reached or journeys made to the south.

It was mentioned above that McMurdo Sound is closed to the south by the Great Ice Barrier. As a comparison of the conditions at Cape Evans with those on the Barrier will form an important part of this work, it is essential that the geographical features to the south of Cape Evans should be thoroughly understood. We have already become familiar with the great surface of the Barrier extending southwards from the ice-cliffs which form the southern limit of the Ross Sea. The edge which the Barrier presents to McMurdo Sound is much less imposing than that to the Ross Sea, for the latter is a cliff of ice approximately 100 feet high, while the end of McMurdo Sound is closed by a cliff only a few feet high and this is in many places, especially at the end of the winter, almost obliterated by snow-drifts which form inclined planes from the Barrier surface to the sea ice. The edge of the Barrier ice is shown in figure 2. It will be seen that it extends from near Hut Point in a zigzag line to the coast of South Victoria Land just to the north of the Koettlitz Glacier. The position of Hut Point is also of considerable importance as it was here that the Discovery Expedition had its headquarters in 1902–04. The hut itself was situated on a small cape around which open water extends during most summers. It is possible however to reach the Barrier from Hut Point even when the sea is not frozen, for a way leads over land from the hut to the position where the Barrier permanently joins the land.

Details of the exposure of the instruments and the lie of the land at both Cape Evans and Hut Point will be considered as occasion arises in the discussion of the observations.

Cape Evans to the Pole.—A great number of meteorological observations were made on the sledging journeys undertaken in connection with the attempt to reach the Pole; it is therefore desirable that the route taken on those journeys should be described here. The first part of the journey was from Cape Evans to Hut Point. This could only be undertaken when McMurdo Sound was frozen over. The hut erected at Hut Point by the Discovery Expedition was used as a base for all journeys further south and here it was possible for various parties to wait while the Sound froze over or until the time arrived for continuing their journey. From Hut Point the Barrier was reached either over the sea ice to Safety Camp, or through 'the Gap'; then, in order to miss crevasses formed in the Barrier ice by the Bluff, the course was laid east-south-east to Corner Camp in 77° 54′ S., 167° 17′ E. From Corner Camp the journey to the Beardmore Glacier was made along or near to the 170° E. meridian. Ninety-six geographical miles south of Corner Camp, at 79° 30′ S., 169° 22′ E., was the main depôt on the Barrier called One Ton Camp. There was considerable passing to and fro between Cape Evans and One Ton Camp, but beyond this point journeys were made only during the summer of 1911-12 in connection with the main Polar journey.

Framheim.—As far as one can gather from the published account of Captain Amundsen's Expedition, the situation at Framheim was ideal from a meteorological point of view. The house itself was erected on the surface of the Barrier about one and a half miles from the sea ice in Whale Bay, and there were no hills anywhere near which could affect the force or direction of the wind.

The general conditions at Framheim are entirely different from those at either of the two other stations in the Ross Sea area. To the south the Barrier extends as an unbroken level plain and to the north exists the Ross Sea, the ice conditions of which have already been considered. The ice conditions in the immediate neighbourhood of Framheim are of importance, but Amundsen has given no information of the state of the sea ice at different times of the year. Looking at the map (frontispiece), however, we see that the permanent ice which bounds the Ross Sea on the east leaves a bay on the south of which Framheim lies. It is very probable that this bay freezes over very early in the winter and that the ice attains a considerable thickness.

Cape Adare.—Cape Adare is the northern point of a promontory twenty miles long which forms a kind of horn to the extreme north-easterly point of South Victoria Land. The promontory

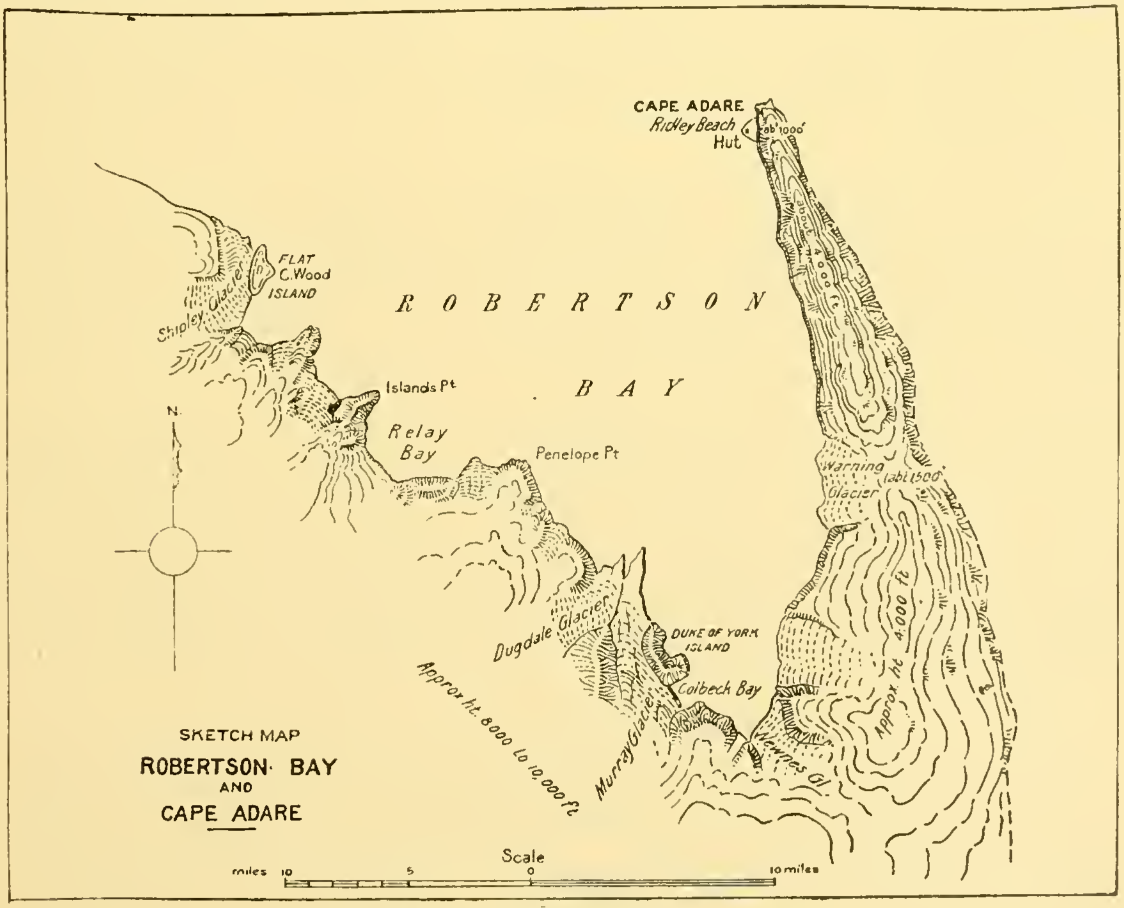

Fig. 3. Map of the Surroundings of Cape Adare.

is a long narrow high ridge running approximately north and south (see figure 3). The camp was formed on a beach on the west side of the promontory and the land rose very rapidly behind the station to the ridge some 1,000 feet above sea-level. Thus the station was shut out from all winds between south-east and north-west and its open horizon only extended over Robertson Bay to the west and over the Antarctic Ocean to the north-west. The situation was far from ideal from a meteorological point of view.

HISTORY OF THE STATIONS.

Cape Evans.—The *Terra Nova* with the whole expedition on board arrived in McMurdo Sound on January 4, 1911, and the discharge of stores commenced at Cape Evans the same day. As soon as the general work of unloading allowed, the Stevenson screen for the thermometers was erected and the first set of meteorological observations was taken on shore on January 13. During the next few weeks the various meteorological and magnetic instruments were set up and put into working order. With few exceptions they were all in use on the 1st March, 1911, from which date the full meteorological programme may be considered to commence. While the *Terra Nova* was unloading at Cape Evans the meteorological log was kept more or less completely on the ship and these observations have been found of much use in supplementing the shore observations during the first few weeks of preparation. Until the end of February 1912 the writer remained in charge of the meteorological work at Cape Evans and the record of all the chief meteorological factors is nearly unbroken. After the first year's work the ship returned to Cape Evans, to take off the expedition, but owing to the non-return of Captain Scott from the South Pole, it was found necessary to leave a party of men for another year. I had hoped to stay with this party, but letters brought by the ship necessitated my early return to India. I therefore left Cape Evans on the 4th March, 1912, and C. S. Wright, assisted by T. Gran, took over the meteorological work.

The large meteorological and magnetic programme which had needed all my time in addition to considerable help from other members of the expedition was no longer possible. Also as soon as the second winter was over all available strength was devoted to the search for the Polar Party. In consequence the meteorological work was less complete during the second year, and there is an unbroken record for two years of only a few of the most important meteorological elements.

Sledging Journeys from Cape Evans.—Soon after the landing at Cape Evans a party was sent to lay a depôt as far south on the Barrier as possible. This party left Cape Evans on January 24, 1911, and reached 79° 30′ S. on February 17th where they left one ton of stores, giving the depôt the name One Ton Camp. The party returned to Hut Point and found the sea ice, which formed the road to Cape Evans, all gone out so they were compelled to remain at Hut Point until the new ice had formed to a sufficient thickness to allow of the journey back being completed. A valuable set of observations was made on this journey.

During the winter Wilson, Cherry-Garrard and Bowers made a wonderful sledge journey to Cape Crozier. They encountered such weather as no other party of men has ever experienced when sledging. They left Cape Evans on June 27, 1911, and returned on August 1, 1911, thus being away during 36 days. Bowers kept a most complete meteorological journal, which is of the greatest value as showing for the first time the conditions on the Barrier at midwinter. On this journey the record low temperature for the Antarctic, −76°F., was observed.

In September 1911 Evans took a party to Corner Camp on the Barrier. The journey was short but it gave important information about the early spring conditions on the Barrier.

In the same month Captain Scott made a sledge journey across McMurdo Sound to the Western Mountains. The most important result from a meteorological point of view was a series of observations the writer was able to make on fog bows and iridescent clouds, which led to the explanation of these phenomena published in the Quar. Journal Roy. Met. Soc., Vol. 38, page 291, 1912.

The various parties which traversed the Barrier during the summer of 1911-12, in connection with the journey to the Pole, kept meteorological journals which have been of the greatest use in the investigation of the meteorology of the Barrier. The journal of the Polar Party was kept by Bowers, and during the last few weeks affords remarkable evidence of his devotion to the scientific work of the expedition. The records of three observations a day are practically complete until March 4; they then became irregular, but one set of observations was made each day until March 11 when they ceased. The final camp was made on March 21 so that observations were carried on to within ten days of the setting in of the blizzard which proved fatal.

It is convenient to tabulate here the chief meteorological journals kept by the various parties on the Barrier.

TABLE 1.

Name of Party.	Observer.	Dates.	Position.
One Ton Depôt Party	Bowers	January 26, 1911 March 10, 1911	Hut Point to One Ton Depôt and back.
Corner Camp Party	Evans	September 9, 1911 September 15, 1911	Hut Point to Corner Camp and back.
Main Polar Party	Bowers	November 3, 1911 March 12, 1912	Cape Evans to Pole and back to 80° S.
Motor Party out	Evans	October 27, 1911 November 21, 1911	Hut Point to 80° 32′ S., 169° 23′ E.
Motor Party return	Day	November 25, 1911 December 20, 1911	81° 10′ S., 169° 30′ E. to Hut Point.
Dog Party	Meares	November 5, 1911 January 4, 1912	Hut Point to Mount Hope and back.
1st Return Party	Wright	December 22, 1911 January 26, 1912	Upper Glacier Depôt to Hut Point.
2nd Return Party	Evans	January 4, 1912 February 9, 1912	Plateau 87° 19′ S., 160° 40′ E. to Barrier 79° 33′ S., 169° 22′ E.
Depôt Party	Day	December 26, 1911 January 21, 1912	Hut Point to One Ton Camp and back.
1st Relief Party	Cherry-Garrard	February 26, 1912 March 16, 1912	Hut Point to One Ton Camp and back.
2nd Relief Party	Atkinson	March 27, 1912 April 1, 1912	Hut Point to seven miles beyond Corner Camp and back.

During 1911 and 1912 Taylor led two parties to investigate the geology of the Western Mountains. A full meteorological journal was kept on each journey, and these have been found particularly useful in plotting weather maps.

During the second year meteorological observations were made on several journeys, but as the simultaneous observations at Cape Evans were far from complete, these records are not so valuable as those made during the first year.

Cape Adare.—The party landed on February 18, 1911, and the meteorological record was commenced by R. E. Priestly on the 27th. It was kept with great regularity until the party left Cape Adare on 3rd January, 1912. During one or two short periods when all the men were away on sledge journeys the observations are wanting, but the observations made by the sledge parties have been of great help in filling in the record.

Framheim.—Meteorological observations were made at Framheim by Captain Amundsen's Expedition three times a day from 1st April, 1911, until 29th January, 1912. In addition a valuable set of observations was made on the Barrier between 8th September and 26th January during Captain Amundsen's journey to and from the Pole. The results have been published by the Fridtjof Nansen's Fund.*

The Terra Nova.—Three voyages were made between New Zealand and the Antarctic by the *Terra Nova* and throughout a full meteorological log was kept. The voyages were as follows :—

1st Voyage.

Left New Zealand (Port Chalmers)	November	30, 1910.
Arrived McMurdo Sound	January	3, 1911.
Left McMurdo Sound	,,	28, 1911.
Arrived off King Edward VII Land	February	2, 1911.
Visited Bay of Whales	,,	4, 1911.
Returned to McMurdo Sound	,,	8, 1911.
Left McMurdo Sound	,,	9, 1911.
Arrived Cape Adare	,,	18, 1911.
Left Cape Adare	,,	20, 1911.
Discovered Oates Land	,,	22, 1911.
Arrived New Zealand (Stewart Island)	March	27, 1911.

2nd Voyage.

Left New Zealand (Port Lyttelton)	December	15, 1911.
Arrived Cape Adare	January	4, 1912.
Left Cape Adare	,,	5, 1912.
Arrived Cape Evans	February	5, 1912.
Left Cape Evans	March	4, 1912.
Arrived New Zealand (Akaroa)	April	1, 1912.

3rd Voyage.

Left New Zealand (Port Lyttelton)	December	14, 1912.
Arrived Cape Evans	January	18, 1913.
Left Cape Evans	,,	22, 1913.
Arrived New Zealand (Oamaru)	February	10, 1913.

TIME.

Cape Evans.—Owing to the great convenience of using Greenwich time in the scientific work of the expedition, it was decided to keep our watches and clocks set to the time of the 180th meridian instead of to local time. In the following whenever times at Cape Evans or on journeys undertaken from Cape Evans are given without qualification they will be

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* Roald Amundsen's Antarctic Expedition, Scientific Results, Meteorology by H. Mohn.

times according to this practice. Local time at Cape Evans is fifty-four minutes behind that of the 180th meridian, hence for most meteorological purposes, when local time is required, it is sufficient to deduct one hour from the times given. As four minutes is imperceptible on most of the meteorological self-recording instruments used, the clocks were set to station time and hourly values tabulated. Conversion to local time was then obtained by deducting one from the denominator of the hours at the head of each column.

Cape Adare and Framheim.—Local time only was used at these stations.

WEATHER.

It will probably be useful to conclude this introductory chapter with a short general description of the weather conditions which we are about to discuss in detail.

Weather at Cape Evans.—McMurdo Sound is situated between two masses of high land: Ross Island on the east and the Western Mountains on the west. The air motion in the Sound is therefore limited, and all the winds can be classed according to whether the air motion is through the Sound from the north or through the Sound from the south. The former includes at Cape Evans all winds between E.N.E. and W., and the latter all winds between W.S.W. and E., and these two classes will throughout be specified as northerly winds and southerly winds respectively. There is a close relationship between the wind direction and weather, and it is convenient to consider the weather at Cape Evans under three headings:—

(*a*) The weather associated with northerly winds.

(*b*) The weather associated with calms and light winds.

(*c*) The weather associated with southerly winds.

The period during which the wind blows with a greater velocity than 10 miles an hour from the north and the south is 8 per cent. and 49 per cent. respectively; while during the remaining 43 per cent. of the time the air is calm or the wind velocity less than 10 miles an hour.

Weather associated with Northerly Winds.—The chief characteristics of the type of weather associated with northerly winds are relatively high temperatures and an almost total absence of cloud. The air is nearly always clear during a northerly wind; but the wind sometimes raises a little surface drift from the ground if there happens to be newly-fallen snow lying. Northerly winds interfere very little with the outdoor work of the expedition and therefore they receive very scant notice in the popular descriptions of Antarctic life, but we shall see that they are very important from the meteorological point of view.

Weather associated with Calms and Light Winds.—One of the interesting features of the air motion in McMurdo Sound and on the Barrier is the tendency of the wind to be either entirely absent or to be blowing a gale. The records for twenty months show that the wind was blowing at 30 miles an hour or over during 30 per cent. of the total period, while during 22 per cent. the velocity was 4 miles an hour or less. As far as I have been able to find there is no other place in the world at which such a large proportion of high winds is associated with such a large proportion of calms. In the summer the temperature during calm weather is little different from the average of the month, but during the winter it is very much lower. Except for its low temperature during the winter, calm weather has no outstanding peculiarities: the sky may be completely overcast or completely clear, and also occasionally snow falls.

Weather associated with Southerly Winds.—During practically half the whole time the wind blows from the south with a greater velocity than 10 miles an hour, and of this period a half is occupied by winds of a greater velocity than 30 miles an hour. The majority of winds from the south are typical blizzards. As in every section of this work reference will be made to the blizzard, it is desirable that a short account of this phenomenon should be given here.

The origin of the word blizzard is unknown, but it is now used in meteorological literature for any high wind accompanied by unusual cold and snowfall. In the Antarctic the members of our expedition used the term rather loosely and any high wind was called a blizzard almost independently of its direction and of the weather conditions accompanying it. There is, however, no doubt about the description of a typical blizzard which would be given by anyone who has spent a year in McMurdo Sound.

In the most typical case light cirrus cloud first spreads over the sky and gradually gets thicker and lower, until finally the whole sky is covered with a uniform dark gray layer of cloud. For a longer or shorter period there may be a complete calm and then the wind rises. We shall see later that over the Barrier the blizzard wind blows from the south parallel to the Western Mountains, but Ross Island stands up as a great obstruction in its path and the southerly wind is deflected into two streams, one of which passes the Island on the east, and the other passes into and blows through McMurdo Sound on the west. The actual direction of the air motion in a blizzard at different parts of the Sound depends on the surrounding land masses. At Cape Evans the blizzards are deflected by the shoulder of Mount Erebus into easterly to south-easterly winds. The arrival of the wind is frequently very sudden and within a few minutes, a calm may be replaced by a wind of 30 or 40 miles an hour. Figure 46, page 128, shows three typical examples of the sudden setting in of a blizzard. This however is by no means a general rule, and on many occasions a gentle southerly wind will get stronger and stronger until it develops into full blizzard force.

In a true blizzard the wind is accompanied by clouds of driven snow. The snow is in the form of exceedingly fine grains which penetrate through the smallest chink or hole in a house or tent. The whole air appears to be full of drift, so that it is impossible to see any great distance, and when it is at its worst even a tent cannot be seen for more than a few yards. Not only does the drift make it difficult to see, but anyone exposed to it seems to become bewildered and to lose all power of thinking clearly. For these reasons it is sheer folly to attempt to travel in a blizzard even when the temperature is relatively high and the wind at one's back.

There can be no doubt that the large amount of drift in a blizzard is due to the high wind sweeping along with it all the snow which has been precipitated, for none can settle out of the air except in a few sheltered places where large snow-drifts accumulate. Thus with only a moderate rate of precipitation the lower atmosphere in time contains a great deal of snow. Opinions differed as to the relative importance of old snow blown up from the surface and new snow which is falling. My own experience led to the conclusion that there can never be really bad drift unless new snow is actually falling. I have certainly seen a high wind convert newly-fallen snow from the surface into drift, but this drift was never so thick and bewildering as the drift which accompanies heavily overcast skies from which new snow is falling. If no new snow has fallen for several days the highest wind produces only a low surface drift, for the surface of the snow becomes compact in a comparatively short time. For a really bad blizzard both high wind velocity and actual precipitation are necessary. The wind during blizzards is often squally and generally gusty, and on some occasions the gustiness is very marked, see figure 38A. There is a tendency for a blizzard to become more gusty towards its end; but this is by no means a general rule.

From beginning to end of a blizzard the wind is extremely constant in direction. Neither at Cape Evans nor on the Barrier is there any evidence of a regular change of wind direction during a blizzard. When the blizzard comes to an end, the air motion stops entirely, or there may be a sudden change in wind direction of 180°, and the wind, sometimes of a high velocity, then blows from the north.

For a typical blizzard snowfall and drift are necessary, but from a meteorological point of view there is no essential difference between a southerly wind with little or no cloud and a blizzard with drift so thick that one cannot see more than a couple of yards ahead, for every grade between these two extremes occurs. In all our statistical work, therefore, and generally in our descriptions, a blizzard will really mean a high southerly wind, which may or may not be accompanied by snow and drift.

The duration of a blizzard can be anything from an hour or two to several days. There are many examples of a southerly wind rising in a few minutes from a calm to 30 or 40 miles an hour and then dying away again within the hour; on the other hand the longest blizzard occurred in June 1912 when from 20 hours on the 7th until 11 hours on the 14th, *i.e.*, for 6 days and 14 hours, the anemometer recorded more than 20 miles in every hour and the mean velocity during the period was 48 miles an hour.

The temperature during southerly winds in the winter is always much higher than during calm weather. This has given rise to the idea that the temperature during blizzards is abnormally high, and often in Antarctic literature one's attention is called to 'the unexpected warmth of southerly, *i.e.*, Polar, winds.' We shall show that the southerly wind is not a warm wind, but as would be expected it is always colder than a corresponding wind from the north.

The sequence of weather changes is remarkable. It was a popular opinion amongst the members of the expedition that a blizzard was usually preceded by a northerly wind. As a matter of fact the records do not support this opinion. It frequently happens that a period of northerly wind precedes a blizzard, but it as frequently happens that a blizzard commences without a previous northerly wind. On the other hand many blizzards end by the wind changing completely round and blowing from the north. We shall show in the section on Pressure, Wind and Weather that the theoretical sequence of weather is a cycle in which northerly and southerly winds alternate, with the period of the southerly winds longer than that of the northerly winds. In reality this is what happens, but the cycle is constantly broken up by periods of calms. Blizzards are therefore associated with northerly winds, but they as frequently occur after as before.

Weather at Framheim.—The weather at Framheim is totally different from that at Cape Evans. The true Antarctic blizzard does not occur at Framheim and during Amundsen's stay only 2 per cent. of the wind observations recorded velocities over 30 miles an hour—this compares with 30 per cent. at Cape Evans. The frequency of calms at Framheim is nearly twice as great as at Cape Evans and during 42 per cent. of the whole time the wind is 4 miles an hour or less. The direction of the prevailing wind at Framheim is due east, while there is practically no air motion from W.N.W. to N.N.E.

Although Framheim is only 60 miles further south than Cape Evans its temperature is very much lower. The mean temperature at Framheim during the period April to September 1911 was 19°F. lower than at Cape Evans, and the observations during 1911 and 1912 indicate that in all probability the mean annual temperature at Framheim is 15°F. lower than at Cape Evans.

Weather at Cape Adare.—Cape Adare is situated on the coast of the Antarctic Ocean which is the most boisterous ocean in the world. In a similar situation about 700 miles further west Mawson found the highest average wind velocity of any place in the world, the average velocity for a whole year being 50 miles an hour. It is therefore amazing to find that the mean wind velocity at Cape Adare is less than 10 miles an hour, and that for 72 per cent. of the whole time the wind velocity is less than 5 miles an hour. Thus the frequency of calms is nearly twice as great as at Framheim and nearly four times as great as at Cape Evans, and at each of these places the frequency of calms has been considered remarkable. (At Yarmouth in England the frequency of calms—0 to 4 miles an hour—is only 5 per cent.)

On the other hand Cape Adare is visited by violent hurricanes: during 10 months 14 storms occurred in each of which the wind was recorded as 11 or 12 on the Beaufort Scale. These high winds, as a rule, lasted only a few hours; but while they blew the members of the Cape Adare Party were in deadly fear that their hut and all their belongings would be blown into the sea. Although the wind direction in the hurricanes is from the south-east or south they are in no way connected with the blizzards of Cape Evans.

Thus the outstanding features of the weather at Cape Adare are the remarkable frequency of calms and the abnormally high winds.

CHAPTER II.

TEMPERATURE.

INSTRUMENTS AND METHODS.

Instruments and their Exposure.—The exposure of the thermometer screen at Cape Evans could not have been better. Immediately behind the hut the land rose rapidly to a small hill, 64 feet above sea-level. The top of the hill, called Windvane Hill, was so exposed to the wind that it was always quite free from snow even after the severest blizzards. Here the screen was mounted on four stout posts well bound together and secured firmly into the kenyte rock. The thermometers were about five feet above the ground, but the latter sloped away on all sides so that the temperatures measured were practically free-air temperatures. In the screen were (*a*) a mercury dry bulb thermometer, (*b*) a mercury maximum thermometer, (*c*) a spirit minimum thermometer; and (*d*) a bimetallic thermograph.

The thermograph in the screen was an ordinary commercial instrument made by Messrs. Short and Mason. The pen was actuated by means of a bimetallic coil and marked in the ordinary way on a graduated paper. The usual troubles with thermographs in polar climates were met. When the temperature fell below about −30°F. the clock stopped in spite of all the oil having been cleaned out of the bearings; also the whole instrument became choked up with driven snow during blizzards. These were not faults of the thermograph, which was a splendid instrument to work with. The bimetallic control was very strong, the sensitiveness of the instrument was very uniform over the whole scale and remained constant throughout. The heat capacity was small so that rapid changes of temperature were registered.

It was realised in England that we should have difficulty with the thermograph in the screen. A thermograph was therefore designed which would register inside the hut, where the clock and other moving parts would not be subject to the severe outside conditions. This instrument consisted of a copper tube, filled with spirit, which was coiled within a large brass tube through which air could be drawn by an electric fan. This was fixed on to the north-east side of the hut, and a very narrow lead tube, passing through the wall of the hut, connected the spirit in the copper tube (bulb) with a spirit reservoir contained within a movable iron piston floating on mercury inside the hut. To the piston the pen arm was pivoted, and the pen recorded on a moving drum. A thermometer near to the bulb was read every four hours, so that the record did little more than register the change between these eye observations. At first the electric fan was used to draw air past the bulb coil; but it was found that it made practically no difference whether the fan was in action or not, so after the first month the fan was no longer used. The instrument was sluggish and not so well exposed as the thermograph in the screen.

For convenience these two thermographs are described as the 'screen thermograph' and the 'hut thermograph.' The record of the former was used whenever available, but it frequently failed in the winter of 1911 and almost completely after the middle of April, 1912, but from the two instruments a complete hourly temperature record is available from February, 1911, to August, 1912.

Method of taking Temperature Observations.—The screen was visited each morning between 8 and 8-30 A.M. As soon as the door had been opened the pen of the thermograph was depressed, the time noted, and the dry bulb thermometer read. Thus the time and temperature recorded by the thermograph were controlled. The maximum and minimum thermometers were then read and reset, immediately afterwards all three thermometers were read again and their readings recorded.

Method of Reducing the Thermograph Records.—The mean temperature at Cape Evans for nineteen months was obtained from hourly values of the thermograph records, hence it is important that these records should be correctly reduced. The method employed was different for the two instruments.

(*a*) *The Screen Thermograph.*—The papers supplied by the makers on which temperature and time lines are engraved were used. If these lines had been correctly drawn and the rate of the clock and the setting of the pen adjusted once for all it would only have been necessary to read off the temperature at the correct time intervals. It is well known, however, that these instruments can never be set with the required accuracy, hence the necessity for some method of reduction which will allow for the errors of time and pen setting. It has been stated above that every day the pen was depressed at a recorded time. Hence on every sheet there were seven time checks. Taking these checks into account it was easy to mark the trace by a series of dots, each one of which corresponded to the exact hour. At the instant the time mark was made each morning the temperature of the dry bulb thermometer was read and recorded. A comparison of the reading of the trace and these recorded temperatures gave the error of the thermograph. The mean error for the week was calculated from the seven observations and applied to the trace throughout the week. It will be seen that by this method the thermograph record was reduced to the scale of the dry bulb thermometer.

(*b*) *The Hut Thermograph.*—This was a daily instrument, a new paper being put on to the drum each morning at 8 o'clock. These papers were blank. The pen of the thermograph was depressed every hour by an electric current controlled by the standard clock so that accurate time was shown on the record itself. The thermometer fixed near the bulb of the thermograph was read every four hours and these readings were entered on to the trace at the corresponding times. The deflection of the thermograph for a given change of temperature had been previously determined and a glass scale constructed. This scale was used for marking the position of 0°F. on the sheet at each of the eight points determined by the eye-readings and through these marks a line was drawn from which the trace at each hour was measured with the glass scale. Thus the recorded temperatures were reduced to the scale of the thermometer attached to the bulb of the thermograph.

The Accuracy of the Temperatures Observed.—It has just been pointed out that the two thermograph records depended on the scales of the two thermometers. Both these thermometers, when tested at Kew before the expedition sailed, had no errors over the range of temperatures to which they were exposed in the Antarctic. Unfortunately they were left in the Antarctic so they could not be compared on the return. Still they were compared in the Antarctic with other thermometers and there were no indications of any change having taken place. Thus the hourly values of temperature may be considered to be quite correct.

The accuracy of the maximum and minimum thermometers must be considered in two periods—(*a*) up to the end of February, 1912, and (*b*) after this date.

During the former of these two periods the maximum and minimum thermometers were read immediately after setting each morning and compared with the simultaneous reading of the dry bulb thermometer as already described. These daily comparisons gave a good check on the behaviour of the thermometers and the results are shown in the following table, in which the mean values found by the daily comparisons from February, 1911, to February, 1912, are collected, the numbers in brackets giving the number of comparisons involved.

TABLE 2.

Thermometer Comparisons.

	Difference between Mercury Thermometer No. 8474 and Mercury Maximum Thermometer No. 3436.		Difference between Mercury Thermometer No. 8474 and Spirit Minimum Thermometer No. 3450.	
Temperatures	At Kew	In Antarctic	At Kew	In Antarctic
> +15° F. .	0·0	0·0 (89)	0·0	+0·3 (89)
+15° to −15° . .	+0·2	+0·1 (151)	0·0	+0·4 (155)
< −15° F . .	..	+0·2 (66)	−0·1	+0·4 (73)

The mercury dry bulb thermometer No. 8474 was in use throughout the expedition and was the standard for the reduction of the screen thermograph. The above comparison shows that it and the maximum thermometer No. 3436 had retained their Kew corrections. On the other hand the spirit minimum thermometer had changed its correction by + 0·3.

In practice the method of correcting the maximum and minimum thermometers was to consider the dry bulb thermometer No. 8474 to be correct, then at the end of each month the mean corrections of the other two thermometers were determined from the daily comparisons during the month and applied to the individual readings.

After February, 1911, the daily comparisons were not made and there were several changes in the maximum and minimum thermometers used. The dates of the changes were not always recorded, and there are other small uncertainties. After a careful study of the records the appropriate corrections to apply throughout have been determined, I believe, with a fair degree of certainty, but as some doubt still remains the maximum and minimum temperatures during the second year may be in error by ± ·5° F.

Method of Measuring Temperatures on Sledging Journeys.—Experience on previous expeditions had taught that there are considerable practical difficulties when the air temperature has to be measured on sledge journeys. As it is quite impossible to transport a suitable screen some form of artificially ventilated thermometer becomes a necessity. An Assman's ventilated psychrometer would appear at first sight to meet the case, but these instruments were tried on Captain Scott's first expedition and found to be quite unsatisfactory. The actual difficulties will be found described in 'The Voyage of the Discovery,' Vol. I, page 276; it is sufficient here to mention the impossibility of getting clockwork mechanism to work in low temperatures, and the appreciable weight of any but the smallest pattern, which are too small for accurate reading under the difficult conditions met with in the Antarctic. Some form of the sling thermometer was the only alternative. The simple method of swinging a thermometer on the end of a string becomes practically impossible when one has to work in thick fur mitts, and in bulky clothes nearly as stiff as thin sheet metal owing to the frost. After considerable thought and experiment a form of sling thermometer based on a very old principle was designed, which proved to be admirable in every way when put to the severe test of continued use on sledging journeys.

The instrument is shown in figure 4. The thermometer T is attached rigidly to an aluminium back 2·5 cm. wide and 22·5 cm. long. The latter is pivoted at F to a solid aluminium handle 22·5 cm. long in such a way that by gripping the handle near the end the thermometer can be made to revolve rapidly around F by a slight circular motion of the wrist.

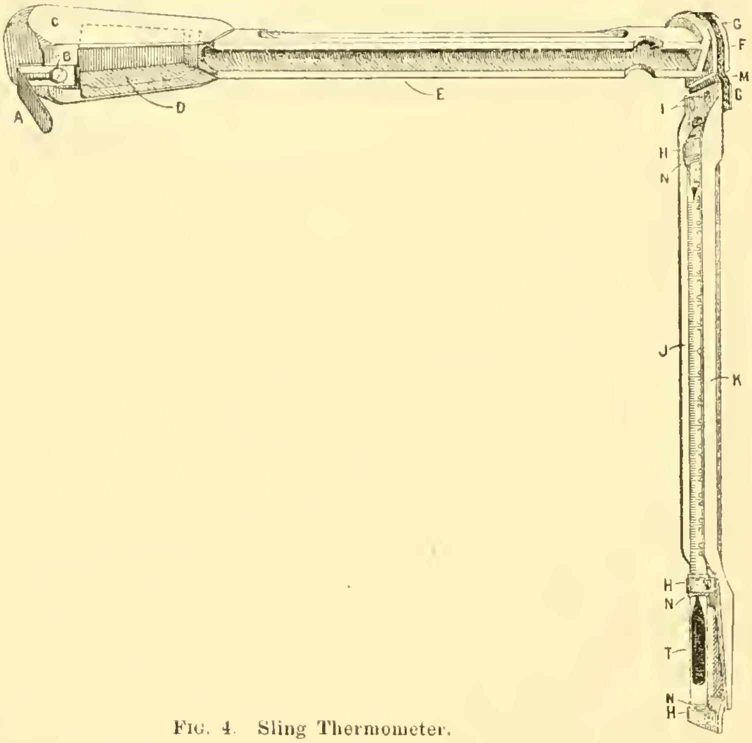

Fig. 4. Sling Thermometer.

The back K is hinged by means of a piece of raw hide at M so that after use the back folds over the handle, in which a groove E, D has been cut to take the thermometer. When closed and the back secured by the sliding catch A (made very large so that it can be opened and closed with the hand in mitts), the thermometer is enclosed in a strong metal box and it is practically impossible to break no matter how roughly the instrument is handled.

It was the original intention to have the handles made of wood, but as it was found that these would be very expensive and aluminium handles could be cast at a very small cost, all the instruments we took, with one exception, were made of metal. These were quite satisfactory in all except the lowest temperatures, but when the temperature was below −40°F. it became painful to hold the instrument for the time necessary to swing it to obtain a correct reading, even when wearing the thickest mitts. The one instrument having a wooden handle was perfect and was used by Bowers throughout the Polar journey, until, when very near the end, it was broken, probably as a consequence of the weak state in which Bowers then was.

It was usual during sledging to take meteorological observations each time camp was made and broken. Thus normally observations were taken three times a day:

(*a*) In the morning just before the march for the day commenced.
(*b*) Near midday, during the lunch halt.
(*c*) In the evening after the tent had been erected and while the evening meal was being prepared.

Nearly all the sledging thermometers (spirit) were provided with minimum indices, and after the sledge had been straightened for the night the open thermometer was carefully placed under the sledge in such a position that it was shielded from radiation. There is little doubt that a thermometer so placed gave minimum temperatures too low by a degree or two, but it will be shown that the minimum temperatures are of great value and cannot be neglected in obtaining the mean temperature for the day. The daily range of the temperature on the Barrier is so great that the mean temperatures cannot be obtained rom simple temperature observations taken two or three times a day, for the time at which the observations are taken makes a very large difference in the temperatures recorded. The following example will illustrate this and will serve to show how the mean temperatures on the Barrier were obtained.

During the main southern journey temperature observations were taken by Bowers and Meares. The former marched with the ponies and the latter travelled with the dogs. During the greater part of the journey, the ponies marched at night and rested during the day. In consequence the observations were generally taken by Bowers as follows:—

(*a*) When the march started at about 9 P.M.
(*b*) At the mid-march halt at about 3 A.M.
(*c*) When the march ended at about 10 A.M.

Owing to the fact that the dogs did the same march as the ponies in a very short time and without any break, the times for observing used by Bowers were not convenient to Meares. The latter, therefore, made his observations at (*a*) 4 A.M., (*b*) 8 A.M., and (*c*) 4 P.M. approximately.

The following table gives the two sets of observations for a short period of four days:—

TABLE 3.

Bowers.			Meares.		
	Hours.	°F		Hours.	°F
November 17 . .	3	−19	November 17 . .	4	−14
	8½	−12		9	− 4
	21	−12		15	− 2
,, 18 . .	2½	−20	,, 18 . .	5	−10
	9½	− 4		9	+ 1
	20¼	− 9		16	+ 4
,, 19 . .	3	−15	,, 19 . .	4	− 6
	10	− 2		8	0
	21¾	− 9		12	+ 8
,, 20 . .	3¼	−11	,, 20 . .	4	− 4
	10½	+ 2		8	+ 6
	21¼	− 1		..	..
	Mean	−9·3 F		Mean	− 1·5 F

Each of the observers took observations three times a day and yet the mean temperatures shown by the observations differs by nearly 8 degrees. The reason is at once apparent as soon the observations are plotted. This has been done in the upper curve in figure 5, Bowers' observations being shown by a dot in a circle and those of Meares by a circle.

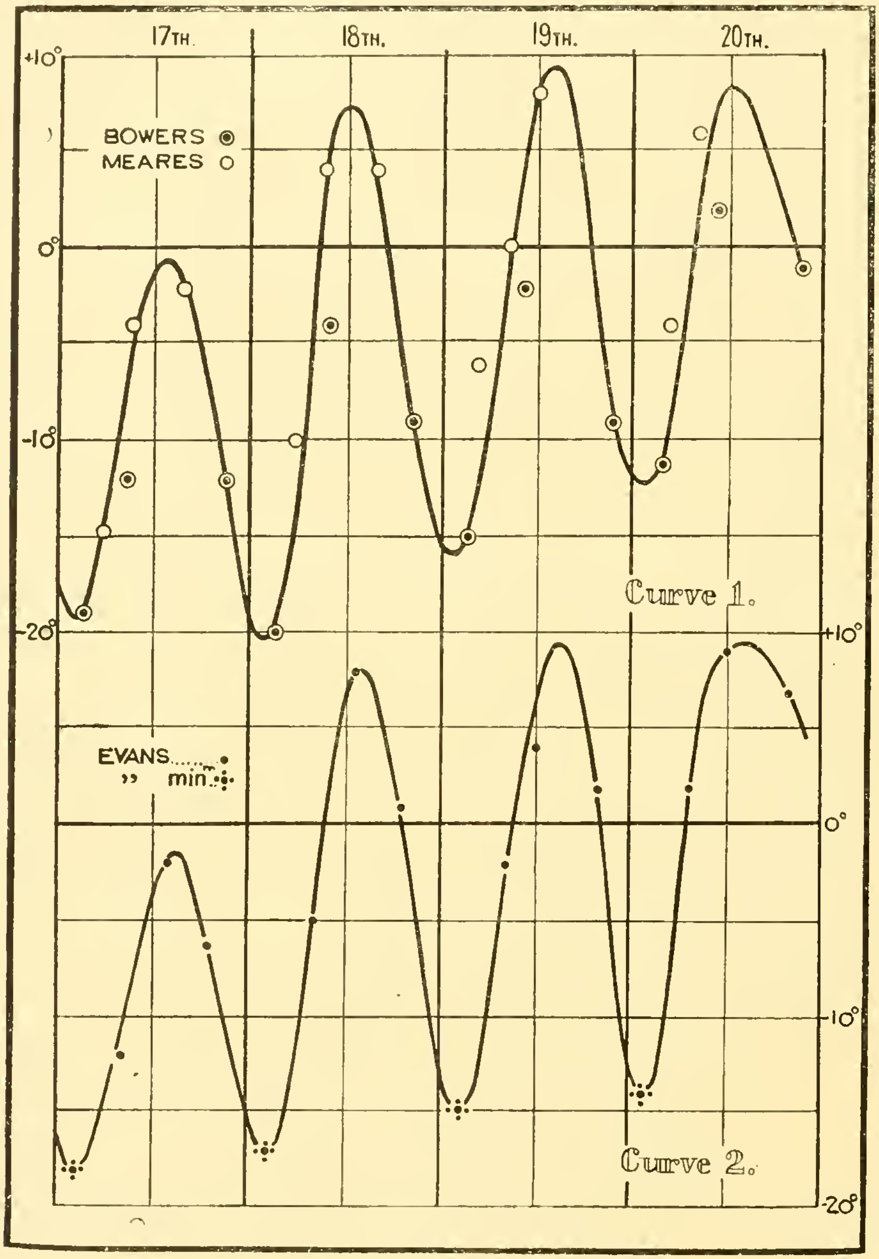

Fig. 5. Temperatures on Barrier.

It will be seen that with one or two exceptions the observations lie on a regular curve.

Another set of observations made in the same region at the same time proves the correctness of the temperature curve arrived at by combining these two sets of observations and shows also the imperative necessity of taking the minimum temperature into account in calculating the mean temperature on the Barrier. A small party had gone ahead of the main party to a pre-arranged position where they waited until the main party came up. The junction was effected on the 21st November when, unfortunately, the detached party ceased to record temperatures. This party had been taking observations three times a day and had used a minimum thermometer under a sledge to obtain a night temperature. The results are plotted in the lower curve of figure 5, and it will at once be seen that the second curve is almost exactly a replica of the first. It will also be noticed that if the temperatures recorded during the day (shown by the dots on the diagram) only had been considered the mean temperature of the period would have been much too high. Without the independent evidence of the low night temperatures shown in the upper curve which were obtained with a sling thermometer, one would have been in doubt as to the accuracy of the minimum temperatures shown in the lower diagram found by exposing the minimum thermometer under the sledge.

These two curves show clearly that the daily variations of temperature are much too great to be neglected, and that true mean temperature cannot be obtained without taking this variation into account. Nearly all the temperature observations made on sledge journeys have, therefore, been plotted and the mean daily temperatures determined by reading the curve at four-hourly intervals.

The only exceptions are the temperatures of the first Return Party and of Cherry-Garrard's Relief Party. In these two cases minimum temperatures were not recorded while observations were taken in the morning, in the evening and near to midday. If the midday temperatures had been taken without counterbalancing night temperatures the means would have been too high, hence in these two cases the morning and evening temperatures only have been used in obtaining the mean daily temperatures.

GEOGRAPHICAL DISTRIBUTION OF TEMPERATURE.

Sea-level Temperatures.

Winter Temperature on the Barrier.—When the *Discovery* was in the Antarctic, 1902–04, the regular temperature observations were made in a Stevenson screen erected on the sea ice near to Hut Point, and other temperature observations were made at a position a little to the south of Cape Armitage (marked A on figure 2). The distance between the two positions was only one and a half miles, yet the temperatures recorded at Cape Armitage during the winter were very much lower than those observed at the same time at Hut Point. Differences of from 10° to 20° F. in the recorded minimum temperatures were quite common, and differences of even 25°F. between the two places occurred at times. These large differences could not be understood and Mr. Dines, who discussed the *Discovery* temperature observations, was inclined to believe that 'the thermometer screen at the *Discovery* was placed too near the tide crack, and that the temperatures are unduly high on account of the influence of the sea-water in the crack.' Captain Scott strongly repudiated this explanation, and those who are familiar with ice conditions will agree with him that even if there had been a tide crack near the screen, which there was not, it could not have affected the temperatures to anything like the extent shown by the observations.

The explanation will be apparent at once when we have considered the temperature observations made on the journey now to be described.

A party led by Wilson left Cape Evans on 27th January, 1911, to visit the emperor penguin rookery at Cape Crozier. The path they took is shown on figure 2. They went first over the sea ice to Hut Point, and while on this part of their journey the temperatures they measured were similar but slightly higher than those measured simultaneously at Cape Evans. At 1-30 P.M. on the 28th, when they were just off Hut Point, they measured −26°F. which was the temperature at the same time at Cape Evans. They then rounded Cape Armitage and approached the edge of the Barrier, which at this point was only 12 feet above the sea ice. Wilson in his report states: 'Coming down the snow slope off the Barrier was a stream of very cold air which we felt first when we were only a few yards from the foot, and lost very soon after reaching the top.' At 7 P.M. they camped on the Barrier, and at 8 P.M., when meteorological observations were taken, the temperature was found to be −44°F., which was 18°F. colder than the temperature they had measured off Hut Point only six and a half hours previously. That there had been no general fall of temperature was shown by the Cape Evans temperature having risen by two degrees in the same period. Assuming, therefore, that there had been little or no change at Hut Point, the temperature on the Barrier must have been nearly 20 degrees lower than the simultaneous temperature at Hut Point only five miles away. The stream of cold air encountered at the edge of the Barrier must have been the direct consequence of this large difference of temperature. On the return journey the experience was repeated. At 9 hours on the morning of the 31st July, seven miles from the edge of the Barrier, the temperature was −57°F., which was 24 degrees below the corresponding temperature at Cape Evans. The party reached the Barrier edge and descended to the sea ice just before 3 P.M., and Wilson wrote: 'Here again we felt the flow of cold air pouring from the Barrier on to the sea ice, so we camped about 100 yards away to be out of it and had lunch. The temperature here was −43°F.' They were then three miles from Hut Point and therefore not far from the position where the Cape Armitage thermometer had been exposed in the *Discovery* days. They arrived at Hut Point at about six o'clock and here the temperature was −27°. Thus the temperature rose 14° on leaving the Barrier and another 16° in the three miles between the Barrier edge and Hut Point, while the temperature at Cape Evans had only varied from −33° to −28° F. during the whole period.

From these observations we see that the temperature at Hut Point was the same, or nearly the same, as at Cape Evans and that the temperature on the Barrier was between 20 and 25 degrees lower.

This explains the low temperatures recorded in 1902–04 at Cape Armitage: they were the direct consequence of the cold air flowing off the Barrier from which the small bay in which the *Discovery* lay was entirely screened.

The remaining observations of the Cape Crozier party will now be considered to illustrate the temperature conditions on the Barrier in the depth of winter.

The position of the party at the evening camp of each day is shown in figure 2. The following table gives the mean daily temperatures recorded with the corresponding temperatures at Cape Evans, and general weather notes are added:—*

TABLE 4.

Date.	Temperature			Weather.
	Barrier.	Cape Evans.	Difference.	
	°F	°F	°F	
June 29 .	−50·9	−25·7	−25·2	Clear and calm at Cape Evans and on Barrier.
,, 30 .	−59·7	−31·7	−28·0	Do. do. do.
July 1 .	−64·2	−36·4	−27·8	Do. do. do.
,, 2 .	−62·0	−34·4	−27·6	Do. do. do.

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* As stated on page 21, the individual observations on the Barrier were used to plot the course of the temperature throughout the day, and by measuring up this curve at four-hourly intervals a much truer value of the mean temperature for each day was obtained than would have been the case if the observations alone had been considered. In the following discussion, unless otherwise stated, mean temperatures have always been obtained in this way

TABLE 4—*contd.*

Date.	Temperature.			Weather.
	Barrier.	Cape Evans.	Difference.	
	°F	°F	°F	
July 3 . .	−56·7	−35·7	−21·0	Calm with little cirrus at Cape Evans and on Barrier.
" 4 . .	−36·9	−25·2	−11·7	High wind with snow at Cape Evans and on Barrier.
" 5 . .	−55·4	−32·4	−23·0	Calm with cirrus at Cape Evans and on Barrier.
" 6 . .	−72·9	−43·7	−29·2	Calm and nearly clear at Cape Evans and on Barrier.
" 7 . .	−64·9	−40·2	−24·7	In morning calm and clear; in evening blizzard started at Cape Evans but not on Barrier.
" 8 . .	−48·9	−34·7	−14·2	Blizzard with very high wind at Cape Evans, calm on Barrier with light cloud.
" 9 . .	−26·7	−19·4	− 7·3	Do. do. do.
" 10 . .	−19·0	+ 1·6	−20·6	Blizzard at Cape Evans and on Barrier.
" 11 . .	+ 5·3	+ 6·0	− 0·7	Do do.
" 12 . .	− 2·0	+ 3·3	− 5·3	Very strong blizzard at Cape Evans and on Barrier.
" 13 . .	−23·7	− 4·0	−19·7	Blizzard ceased on Barrier at 3 A.M. and at Cape Evans at 2 P.M. Sky partly cleared.
" 14 . .	−23·5	− 7·7	−15·8	Light variable winds with cloudy sky at Cape Evans and on Barrier. Some light snow.
" 15 . .	−20·5	−11·4	− 9·1	Moderate wind and partly overcast sky at Cape Evans and Cape Crozier. Party at Cape Crozier.
" 16 . .	−23·9	−16·2	− 7·7	Sky nearly clear but moderate variable wind at Cape Evans and Cape Crozier.
" 17 . .	−22·2	−18·0	− 4·2	Sky nearly overcast and light to moderate wind
" 18 . .	−27·0	−17·8	− 9·2	Little cloud, more wind at Cape Crozier than at Cape Evans.
" 19 . .	−30·9	−34·3	+ 3·4	Calm and clear at Cape Evans and at Cape Crozier.
" 20 . .	−25·5	−27·5	+ 2·0	Light wind in morning and high wind in evening at both places.
" 21 . .	−22·2	−30·0	+ 7·8	Clear at Cape Evans; overcast at Cape Crozier, light wind.
" 22 . .	..	−15·4	..	Heavy blizzard commenced at Cape Crozier at 3 A.M. and at Cape Evans at 7 A.M.
" 23 . .	..	− 2·3	..	Blizzard of hurricane force at Cape Crozier and gusts over 60 miles per hour at Cape Evans.
" 24 . .	..	− 6·1	..	Blizzard stopped early in the morning, afterwards dull day with light wind.
" 25 . .	−16·5	− 9·1	− 7·4	Wind rose again at about midday. Overcast sky on Barrier again.

TABLE 4—*concld.*

Date.	Temperature.			Weather.
	Barrier.	Cape Evans	Difference.	
	°F	°F	°F	
July 26 .	−29·4	−15·1	−14·3	Wind continued until near midday, then fell calm.
,, 27 .	−46·7	−26·2	−20·5	Clear and calm at Cape Evans and on Barrier.
,, 28 . .	−43·4	−28·6	−14·8	Clear and calm on Barrier. Clear with light wind in afternoon at Cape Evans.
,, 29 . .	−45·5	−18·0	−27·5	Calm on Barrier, high wind at Cape Evans until the evening.
,, 30 . .	−63·4	−33·4	−30·0	Clear and calm at Cape Evans and on Barrier.

During the first few days that the party was on the Barrier calm weather with little or no cloud prevailed over the whole region. In consequence low temperatures occurred, but while the mean temperature did not fall below −36·4°F. at Cape Evans it fell to −64·2°F. on the Barrier. During these five days the mean temperature on the Barrier averaged 26°F. below the corresponding temperature at Cape Evans.

On the next day a high wind accompanied by overcast sky and snow set in. The temperature at once rose by 10 degrees at Cape Evans and 20 degrees on the Barrier, but the Barrier temperature remained on the average of the day 11 degrees below that of Cape Evans, although at 9-30 A.M. the difference was only 6 degrees.

After the wind had died away a period of extreme cold set in on the Barrier. On July 6th (for position see figure 2) the temperatures measured on the Barrier were the following :—

TABLE 5.

On Barrier.		Cape Evans.	Difference.
	°F.	°F.	F.
Minimum during night between 5th and 6th	−74	−44	−30
Temperature with sling thermometer at 9 h. 30 m.	−69	−45	−24
Do. do. do. 12 h. 00 m.	−76	−44	−32
Do. do. do. 17 h. 15 m.	−76	−43	−33
Do. do. do. 24 h. 00 m.	−68	−48	−20

The Barrier temperatures were taken with extreme care. Against the entry in the meteorological log at 17 hours 15 minutes, Bowers has noted 'Carefully checked by Wilson'; he also measured the temperatures with a spare thermometer and found the two agreed within half a degree. This is the lowest temperature recorded on the Barrier—or anywhere in the Antarctic—and it is satisfactory to know that it was so carefully checked. The mean temperature on this day was −72·9°F. on the Barrier and −43·7°F. at Cape Evans. This was the coldest day at Cape Evans during our stay in the Antarctic and no doubt it was the coldest day on the Barrier.* Although the temperature was so low at Cape Evans the difference between the Barrier and Cape Evans has only been exceeded on a few occasions, most of which occurred in March, 1912, during the abnormally low temperatures which proved fatal to the Polar Party (see page 29). This cold period was succeeded at Cape Evans by the most severe weather of which I have been able to obtain a record. During the morning of the 9th, while the temperature was still −35°F., the wind rose to 43 miles in the hour. Between 7 and 8 P.M. the wind velocity was 63 miles per hour with a temperature of −31°F. As the blizzard continued the temperature slowly rose until it reached +8°F. at 2 P.M. on the 11th, *i.e.*, a little over three days after the starting of the blizzard. The blizzard was not felt by the party on the Barrier near Terror Point until the early morning of July 10th—twenty hours after it had commenced at Cape Evans; but during this period the temperature had been rising rapidly and steadily with an overcast sky from which snow was falling. When the blizzard set in on the Barrier the wind was very high and accompanied by much snow and the temperature rose more rapidly until on the morning of the 11th it became the same as that at Cape Evans. The blizzard ceased on the 13th when the temperature at once fell, but more rapidly on the Barrier than at Cape Evans, and in consequence large temperature differences again became established.

On the 15th the party reached Cape Crozier and camped on the shoulder of Mount Terror at an elevation of over 700 feet above the Ross Sea which lay completely frozen over below them. For six days they measured the temperature at this place, during three of which it was lower than at Cape Evans (average difference −7·0) while on the remaining three it was higher (average difference +4·4). On some of these days there was a moderate amount of wind and on others the weather was calm, but no blizzard occurred to equalise the temperature over a large area. It therefore appears that the temperature at Cape Crozier is very similar to that at Cape Evans.

After being six days at Cape Crozier a terrific blizzard arose and lasted for three days: 22nd–24th July. During this blizzard the party was nearly lost owing to the blowing away of their tent and the unroofing of the temporary hut which they had built. During this period the weather was too bad to allow of temperature observations being taken.

When the blizzard was over the party was forced to return to headquarters with all haste. They spent the 25th and 26th in getting to the true Barrier surface which they traversed on the next four days, finding again the low temperatures which they had encountered there on their way out. The mean temperature for the four days was −49·8°F. with a corresponding temperature of −26·6°F. at Cape Evans, a difference of −23·2°F.

The remainder of the journey back to winter quarters, how the temperature rose on leaving the Barrier and how the temperature at Hut Point was found to be the same as that at Cape Evans, has already been described.

This journey which Scott has described as 'the hardest which has ever been done' has revealed conditions on the Barrier in winter which had previously been suspected but never proved. They are the same as subsequent observations showed to hold throughout the whole year, but much accentuated. To act as a guide in our future study they will be summarised here.

(*a*) Temperatures on the Barrier during the winter are much lower than those found in McMurdo Sound and at Cape Crozier near to the frozen Ross Sea.

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* A minimum thermometer left at One Ton Camp throughout the winter recorded −73·0°F. and the lowest temperature measured at Framheim was −73·3°F.

(*b*) The greatest difference is found on clear, calm days.

(*c*) High winds not only raise the temperature in McMurdo Sound and on the Barrier, but also reduce the difference and occasionally remove it altogether.

Spring Temperature on the Barrier.—After the return of the Cape Crozier Party the Barrier was not visited again until September when the sun had returned and spring conditions were becoming established.

On September 9 a small party led by Evans left Cape Evans to visit Corner Camp (for position see figure 2). At Hut Point they again had temperatures similar to those at Cape Evans, and on reaching the Barrier low temperatures were immediately experienced. The following table gives the mean daily temperatures met with during a stay of four days on the Barrier :—

TABLE 6.

MEAN TEMPERATURE.				WEATHER.	
Date.	Barrier.	Cape Evans.	Difference.	Barrier.	Cape Evans.
	F.	F.	F.		
September 10 .	−41·5	−24·0	−17·5	Light air, Ci. S. .	Calm or light wind, overcast some snow.
" 11 .	−45·5	−30·4	−15·1	Blizzard in evening.	Calm, overcast.
" 12 .	−35·2	−21·7	−13·5	Blizzard . .	Calm or light wind, overcast.
" 13 .	−44·2	−23·1	−21·1	Light to moderate southerly winds with low S. clouds.	Calm. Sky cleared during day.
Mean . .	−41·6	−24·8	−16·8		

On the journey a minimum temperature of −72°F. was registered.

Although much wind was met with on the Barrier and the sky was overcast, low temperatures prevailed on the Barrier, where the mean temperature for the period was 16·8°F. below the simultaneous temperature at Cape Evans.

Summer Temperatures on the Barrier.—During the summer (from 1st November, 1911), there was a great deal of travelling backwards and forwards on the Barrier. Each party was provided with meteorological instruments and in consequence a great many data are available. It would take up too much space to discuss the results of each party in detail and therefore the actual observations have been printed in Vol. III, and here we will confine ourselves to a general discussion of the results. The curves on figure 6 show the temperature observations in a very comprehensive manner. In this figure the mean daily temperatures at Cape Evans are shown by the upper thick line. The observations on the Barrier have been divided into two sets, one comprising those made to the north of One Ton Camp and the other those to the south. The former are shown by a thin continuous line and the latter by a thin broken line. The observations made on the plateau are shown

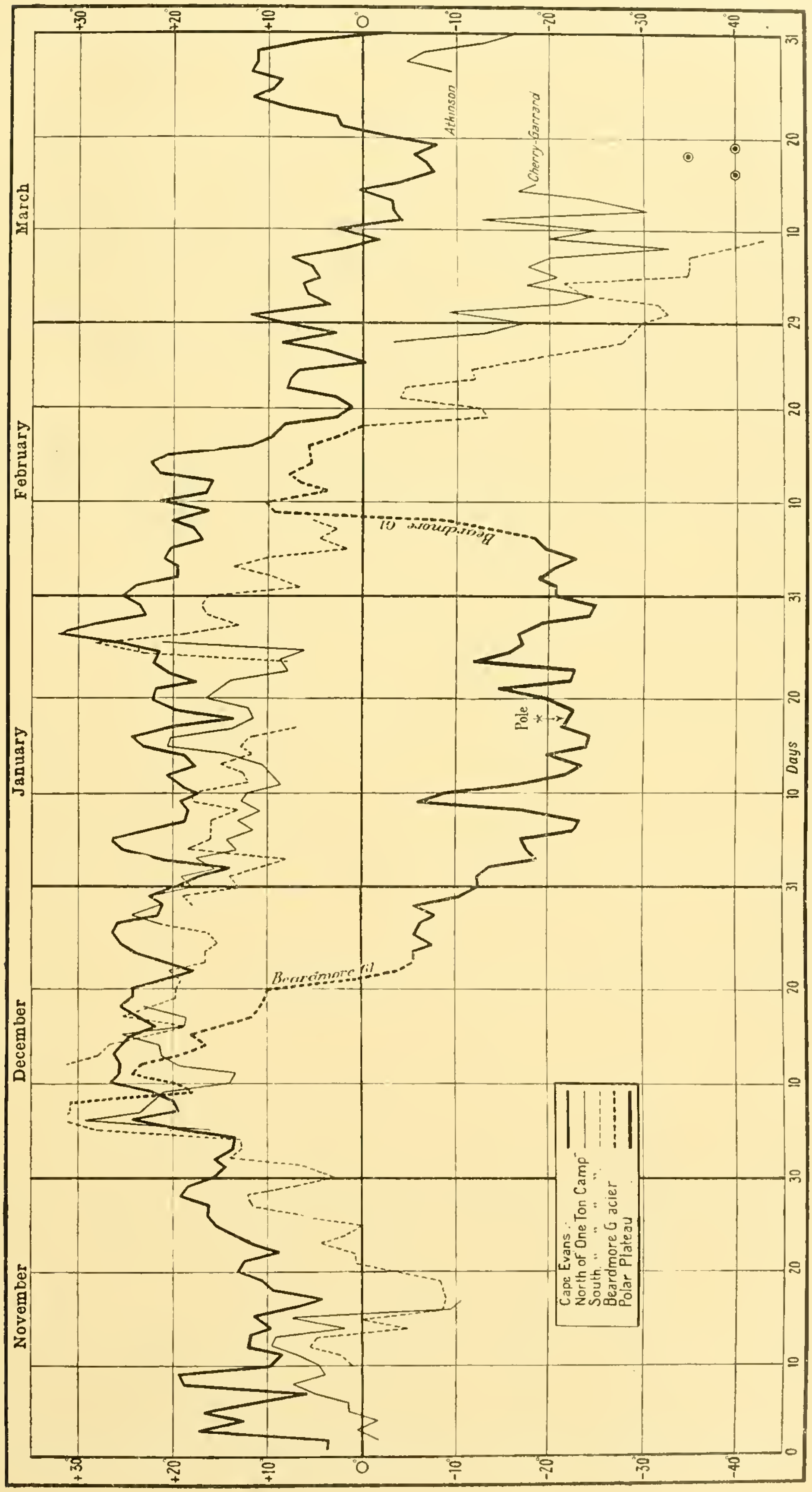

Fig. 6. Cape Evans, Barrier and Plateau temperatures.

by the lower thick line, while the observations made on the Beardmore Glacier are shown by the thick dotted line which joins the plateau curve to a Barrier curve at each end.

At present we are not concerned with the temperatures measured on the Beardmore Glacier and the plateau.

It will be noticed that between the 1st November and 4th December all the Barrier temperatures are below those of Cape Evans, and that during the few days in November, when there were parties to the north and south of One Ton Camp, the southern temperatures were the lowest except on two days. During this period the Barrier to the south of One Ton Camp was on the average 10 degrees colder than Cape Evans. On December 5 the Barrier was affected by a deep depression which appears to have caused a great inflow of moist warm air from the Ross Sea into the south of the Barrier. The main southern party was at the time near the southern limit of the Barrier 12 miles from the foot of the Beardmore Glacier.

Readers of Captain Scott's book will remember how serious this storm was to the Southern Party, causing four days' delay and covering the surface with three feet of soft wet snow. The general conditions which accompanied this storm will be considered later; at present it is important to us as showing that high temperatures occur sometimes on the Barrier as far south as 83½° S. A very remarkable circumstance was that during this period the temperature was higher in the extreme south than at Cape Evans.

TABLE 7.

To show the Increase of Temperature towards the South.

Date.	CAPE EVANS. Latitude 77½°.	MOTOR PARTY. Latitude 79½°.	SOUTHERN PARTY. Latitude 83½°.
	F.	F.	F.
December 5 . . .	19·2	16·0	28·2
,, 6 . . .	24·3	29·9	32·0
,, 7 . . .	19·4	23·7	31·0
,, 8 . . .	19·8	22·9	31·0

The probable cause of this inversion of the geographical distribution of temperature was that the air from the Ross Sea passed first into the south of the Barrier far to the east and then travelled northwards along the western edge, and had become cooled by the time it reached Cape Evans. Support is given to this explanation by the fact that the snowfall was much greater in the south than in the north.

The weather was disturbed throughout December on the Barrier, and as will be seen from the curve it was not until the 4th January that the Barrier temperatures became again consistently below those of Cape Evans. Throughout January this was so, but it will be noticed that sometimes the Barrier was coldest to the north and sometimes to the south of One Ton Camp. During December the Barrier temperatures had varied on the whole very little from those of Cape Evans; but in January the difference steadily increased, except during a few disturbed periods. As February advanced the Barrier cooled very rapidly and by February 8 the Barrier was 15°F. colder than Cape Evans. On February 18 the Polar Party reached the Barrier on their return from the Pole, they found lower temperature than they had expected but after two days on the Barrier the temperatures rose to a mean daily temperature of −4·0°F. This recovery was, however, very short-lived and from February 22 the temperature fell at an amazing rate from −4·5°F. on February 22 to −43°F. on March 9. As everyone knows this low temperature, so entirely unexpected, was one of the chief causes of the great tragedy. After March 9 regular temperature observations ceased, but from a few entries in Captain Scott's diary it appears that the temperature remained in the neighbourhood of −40° until March 20. During these last few days the difference between the Cape Evans and the Barrier temperatures was over 40° and exceeded the largest difference found by the Cape Crozier Party by more than 10 degrees.

During the latter part of this period a second series of temperature observations was made on the Barrier. Cherry-Garrard had left Hut Point on February 26 to meet the returning party with the dogs. He reached One Ton Camp on March 3 and remained there until the 10th. The following table gives the temperatures during these days:—

TABLE 8.

Date.	Cape Evans.	Latitude 79½° One Ton Camp.		Latitude 81° Polar Party.	
			Difference		Difference
	F.	F.	F.	F	F
March 3	5·7	−24·5	−30·2	−23·7	−29·4
,, 4	6·5	−17·5	−24·0	−21·4	−27·9
,, 5	4·6	−26·0	−30·6	(−35·0)	−39·6
,, 6	5·4	−17·5	−22·9	(−35·0)	−40·4
,, 7	7·7	−20·0	−27·7	−35·0	−42·7
,, 8	2·1	−33·0	−35·1	−39·0	−41·1
Mean	5·3	−23·1	−28·4	−31·5	−36·8

These low temperatures on the Barrier so early in the year were entirely unexpected and have no parallel in either north or south polar regions. It is therefore of importance that we should know whether they are the normal conditions in that region.

Some light is thrown on the question by a short journey made by Atkinson between 27th and 31st March, 1912, when he made an unsuccessful attempt to reach the Polar Party whose non-appearance had given grave cause for anxiety. Atkinson was only able to go from Hut Point to Corner Camp, but this was the same tract which Cherry-Garrard had crossed in his return from One Ton Camp a few days previously. The temperatures are shown in figure 6 and the following table gives the data:—

Table 9.

To show Rise in Temperature over the North of the Barrier during March, 1912.

	Date.	Cape Evans.	Hut Point to Corner Camp.	Difference.
		F.	F.	F.
Cherry-Garrard	March 14	+0·5	−16·5	−17·0
	,, 15	−3·6	−18·5	−14·9
	,, 16	−7·7	−18·0	−10·3
Atkinson	March 27	+11·9	−10·2	−22·1
	,, 28	+11·2	− 5·0	−16·2
	,, 29	+11·1	− 7·0	−18·1
	,, 30	+ 6·4	−13·7	−20·1
	,, 31	− 2·8	−17·2	−14·4

Atkinson's temperatures show a great rise on those experienced by Cherry-Garrard nearly a fortnight before, and this is more easily realised by examining figure 6 in which the rise between Cherry-Garrard's last observations and those of Atkinson is clearly shown. These observations and the general trend of the curves in figure 6 can leave little doubt that the temperatures experienced by the Polar Party were abnormally low. Captain Scott was well aware of the rapid fall in Barrier temperature during February, but his statement in his wonderful *Message to the Public* that 'no one in the world would have expected the temperatures and surfaces which we encountered at this time of year' was certainly justified. It is difficult to discuss the records of this period mingled as they are with such tragedy, but they clearly bring to light the possibility of great cold at an extremely early period in the year within a comparatively few miles of an open sea where the temperatures were over 40 degrees higher. The cause of these low temperatures will be considered later, after other temperature conditions have been discussed.

Monthly Values of Barrier Temperature.—The actual observations of temperature on the Barrier are far too few to determine directly the mean monthly Barrier temperatures, but an indirect method allows us to form some idea of this important factor. It is well known that variations in meteorological conditions are generally similar over fairly large areas. Thus the differences in a meteorological element between two stations undergo much smaller changes than the actual element itself, and while many years may be necessary to find the mean value of the element at either station, a much shorter time is necessary to obtain a reliable value of the difference. If, then, we know the mean value of the element from a long series of observations at one station and the difference between that and another station from a short series, the mean values at the latter can be obtained by applying the known differences to the mean values at the former. We now have temperature data for McMurdo Sound for five years, from which the mean monthly temperature can be obtained with some fair degree of accuracy, and these values are given on page 81 below. We have now to see if it is possible to determine from the few available data the difference between McMurdo Sound and the Barrier.

The temperatures measured on the Barrier have been divided geographically into the regions north and south of One Ton Camp, 79½° S. This geographical division is not all that could be desired, because it sometimes happened that observations which fall in the two divisions were made only a few miles apart, for example when two parties were near to One Ton Camp, one to the north, and the other to the south; while at other times the whole expanse of the Barrier separated the parties taking the observations. Still this is the best that can be done with the data.

The mean daily temperatures for the Barrier have been obtained from the observations made by the sledging parties in the way already described. These have been collected according to months and the geographical positions, and the results entered in the following table:—

TABLE 10.

Mean Temperature Difference, Barrier–Cape Evans.

Month.	BARRIER NORTH OF ONE TON CAMP.					BARRIER SOUTH OF ONE TON CAMP.				
	Number of days.	Mean day of period.	MEAN TEMPERATURE.			Number of days.	Mean day of period.	MEAN TEMPERATURE.		
			Cape Evans.	Barrier.	Difference.			Cape Evans.	Barrier.	Difference.
			°F.	°F.	°F.			°F.	°F.	°F.
January	26	13th	+20·4	+13·6	− 6·8	17	8th	+20·3	+13·6	− 6·7
February	28	14th	+18·9	+ 3·9	−15·0	11	24th	+ 4·8	−16·9	−21·7
March	27	16th	+ 4·4	−17·0	−21·4	9	4th	+ 5·2	−32·9	−38·1
July	20	10th	−23·4	−43·1	−19·7	..	..	..	..	..
September	4	12th	−24·8	−41·6	−16·8	..	..	..	..	..
October	4	29th	+ 3·0	− 4·0	− 7·0	..	..	..	..	..
November	17	8th	+10·8	+ 2·1	− 8·7	21	20th	+12·2	+ 1·1	−11·1
December	18	15th	+23·1	+20·9	− 2·2	28	17th	+21·7	+20·9	− 0·8

The temperature differences between Cape Evans and the Barrier north of One Ton Camp are shown in figure 7 by dots enclosed in circles, while the differences between Cape Evans

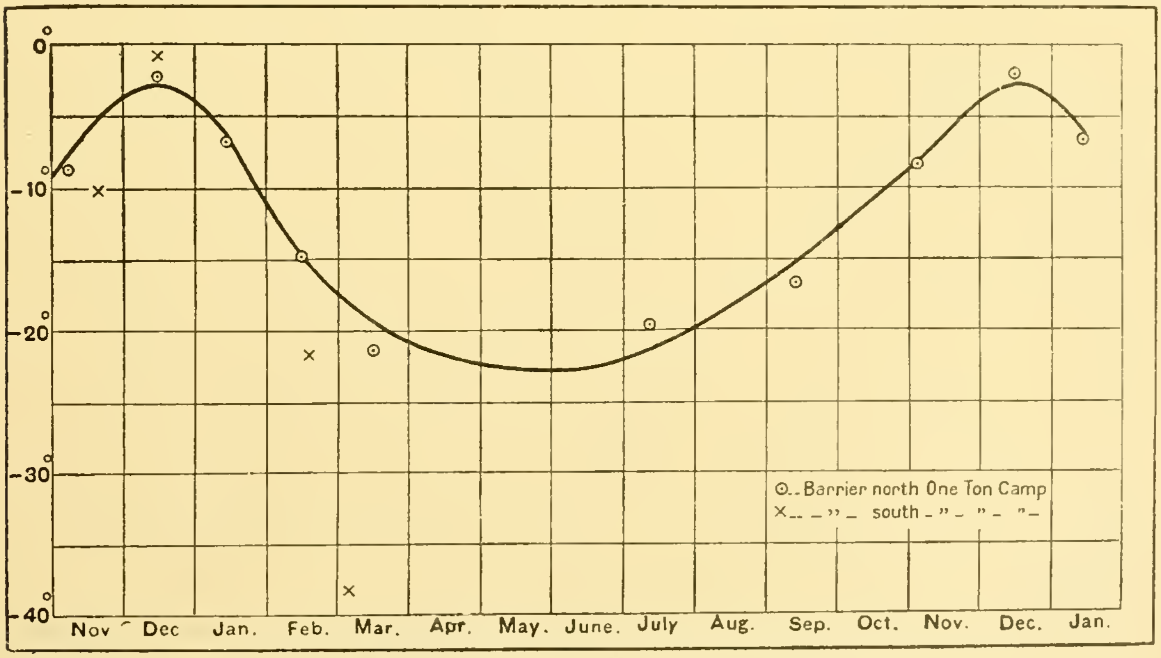

FIG. 7. Temperature difference between Cape Evans and Barrier.

and the Barrier south of One Ton Camp are shown by small crosses. At first we will disregard the latter and fix our attention on the former. It will be seen at once that the circles lie fairly regularly about a curve having a maximum in December and a minimum in May or June, and there can be little doubt that this curve gives approximately the mean difference in temperature between Cape Evans and the Barrier north of One Ton Camp throughout the year. By taking the mean values of this curve for each month and applying them to the mean temperature of McMurdo Sound we obtain the mean temperature of the Barrier.

TABLE 11.

Mean Temperature of McMurdo Sound and of the Barrier north of One Ton Camp

Month.	McMurdo Sound 5 years.	Difference from curve.	Barrier north of One Ton Camp.
	F.	F.	°F.
January	+24	− 7	+17
February	+16	−15	+ 1
March	+ 4	−19	−15
April	− 9	−21	−30
May	−10	−23	−33
June	−12	−23	−35
July	−15	−21	−36
August	−15	−19	−34
September	−12	−15	−27
October	− 2	−11	−13
November	+14	− 6	+ 8
December	+25	− 3	+22
Year	+ 0·7	−15	−15

Turning now to the temperatures on the Barrier south of One Ton Camp we see from the crosses in figure 7 that it is impossible to construct a similar curve giving the annual variations of temperature for this region. It has already been explained that the high temperature over the south of the Barrier in December was mainly due to a period of very unsettled weather which may or may not be usual at this time of year. The only safe conclusion to be drawn from the summer observations is that during November, December, and January, there is no large consistent difference in temperature between the north and south of the Barrier. After January, however, the temperature appears to fall much more rapidly over the south than over the north of the Barrier, but for reasons already given it is more than probable that 1912 was an abnormal year. It is quite impossible to believe that normally there is a difference of nearly 40 degrees in March between McMurdo Sound and the south of the Barrier. In fact the position of the cross for March in figure 7 is further support for the contention that Captain Scott experienced unusually low temperatures on his return from the Pole. We are therefore left with the conclusion that the temperatures after the summer are lower over the south than over the north of the Barrier, but that the amount of the normal difference is unknown.

Framheim.—For our study of the geographical distribution of temperature the observations made at Framheim are of the greatest importance. Although Framheim was so near the

Ross Sea it was actually on the Barrier and appears to have experienced in consequence true Barrier temperatures as will be seen from the following table:—

TABLE 12.

Temperature at Framheim 1911–12.

Month.	Temperature at Framheim.	Difference Framheim—Cape Evans.	Month.	Temperature at Framheim.	Difference Framheim—Cape Evans.
	°F.	°F.		°F.	°F.
April . .	−17·7	−16·6	September .	−35·5	−19·7
May . .	−31·7	−20·9	October .	−11·6	− 8·2
June . .	−29·9	−16·4	November .	+ 4·1	− 8·2
July . .	−33·7	−12·6	December .	+19·9	− 2·1
August . .	−48·6	−27·5	January . .	+14·5	− 6·8

It will be shown later that Framheim shares with other parts of the Barrier a large daily range of temperature. Now at Framheim temperature observations were made three times a day at 8 hours, 14 hours and 20 hours. The 14 hours' observations fell at the time of the daily maximum temperature and as there were no corresponding observations taken at or near the minimum, the mean of the observations spaced as these are must be too high. Hence in calculating the mean temperatures given in the above table the 14 hours' observations have been rejected and the observations at 8 hours and 20 hours only considered. There can be no doubt that the mean temperatures calculated in this way are nearer the true values than if all three observations had been taken into account.

Temperatures at Cape Adare.—The observations available for determining the mean temperatures at Cape Adare will be discussed later (page 83), we will use here the mean values which will be then derived.

TABLE 13.

Temperature at Cape Adare.

Month.	Temperature.		Month.	Temperature.	
	Cape Adare.	Difference Cape Adare—McMurdo Sound.		Cape Adare.	Difference Cape Adare—McMurdo Sound.
	°F.	°F.		°F.	°F.
January . .	+31·6	+ 7·9	July . .	−11·9	+2·7
February . .	+27·0	+11·2	August . .	−13·6	+1·0
March . .	+18·7	+14·3	September .	− 7·5	+4·2
April . .	+ 9·4	+18·2	October . .	− 0·6	+1·5
May . .	− 2·2	+ 8·3	November .	+18·5	+4·3
June . .	−14·5	− 2·6	December .	+29·5	+4·6
			Year .	+ 7·0	+6·3

The most interesting and important conclusion to be drawn from this table is that during the winter from June to August there is practically no difference between the mean temperature at Cape Adare and at Cape Evans although they are separated by more than six degrees of latitude. The difference is greatest during the three months February, March, and April, being then about 15°F.

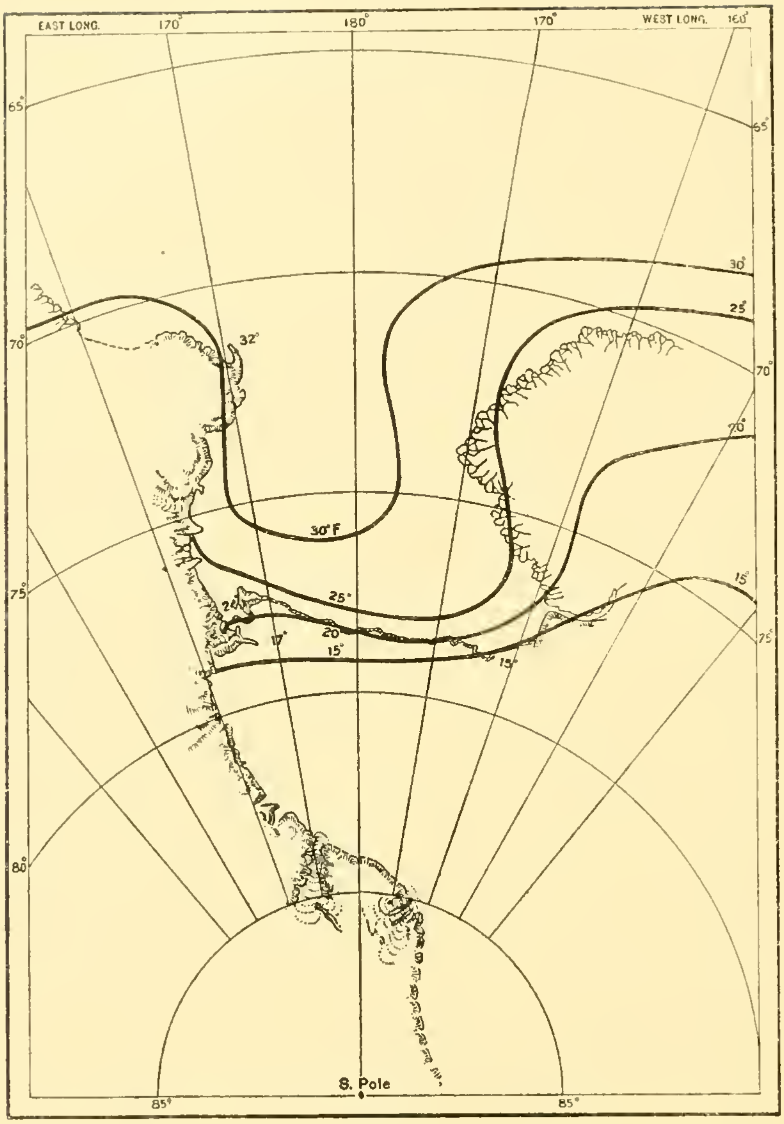

FIG. 8. Isotherms for January.

We are now in a position to discuss the probable geographical distribution of temperature in the Ross Sea area. As typical months January and July will be taken.

The temperatures used are the mean temperatures obtained from all available observations.

TABLE 14.

Normal Temperatures.

	January.	July.
	°F.	°F.
Cape Adare	+32	−12
McMurdo Sound	+24	−15
Framheim	+15	−34
Barrier North of One Ton Camp	+17	−36

These data have been entered on maps and an attempt made to construct isotherms from them. The results are shown in figures 8 and 9. The considerations which have led to the form of the isotherms are the following.

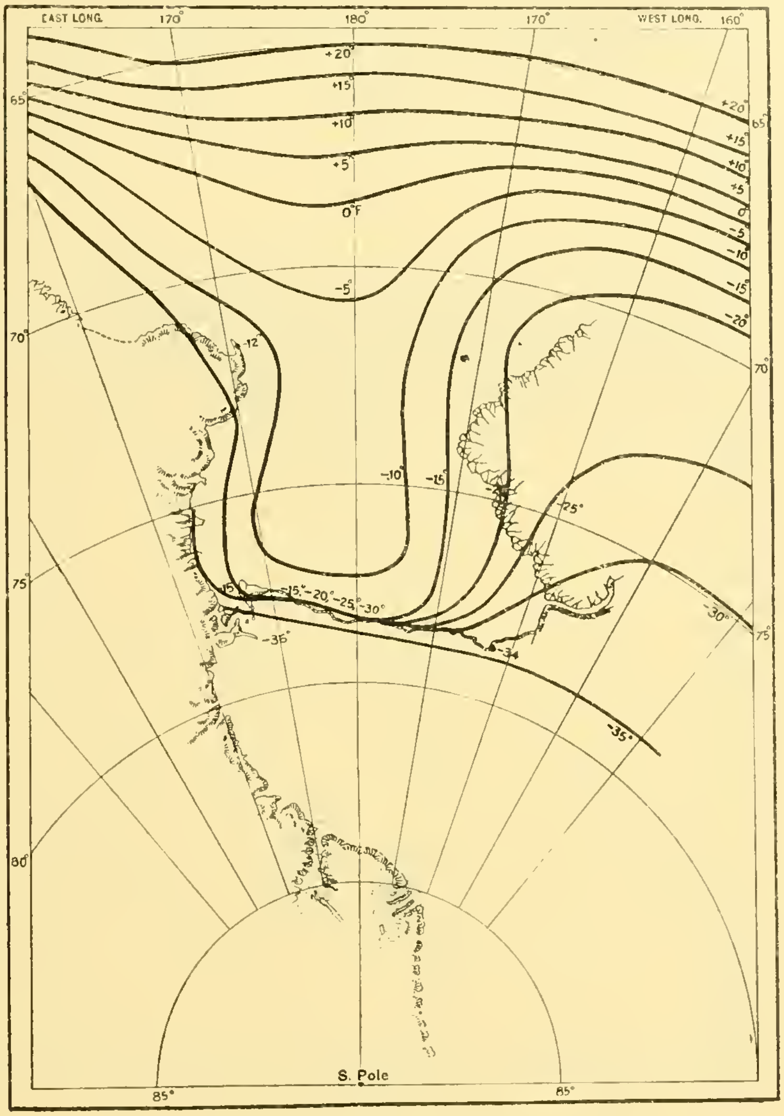

FIG. 9. Isotherms for July.

Isotherms for January.—The temperature in McMurdo Sound is 24° F. and at Cape Adare 32°F., it is therefore probable that the temperature over the open water of the Ross Sea is approximately 30°F. The floating ice and ice-covered land will probably reduce the temperature to 25°F. near the south and east of the sea. The 25°F. isotherm has therefore been shown to encircle the sea near to the Barrier and to the permanent ice in the east, with the 30°F. isotherm surrounding a warmer central area. The temperature of the whole of the Barrier is within a degree or so of 15°F., which fixes the position of the 15°F. isotherm. The 20°F. isotherm has been drawn between those for 15°F. and 25°F., and we see that the closeness of the isotherms near to the edge of the Barrier indicates the large temperature gradient which must exist between the cold Barrier surface and the relatively warm open sea.

Isotherms for July.—The temperatures at Cape Evans and at Cape Adare are practically the same during June, July, and August and they are more than 20° above those of the Barrier. We shall show later (see page 90) that during the winter the temperature of the sea ice decides the temperature of the air above it and one knows that the sea ice is much thinner over the centre of the Ross Sea than either in McMurdo Sound or at Cape Adare. We also know that during the winter open leads often form in the sea to the north of Cape Crozier.

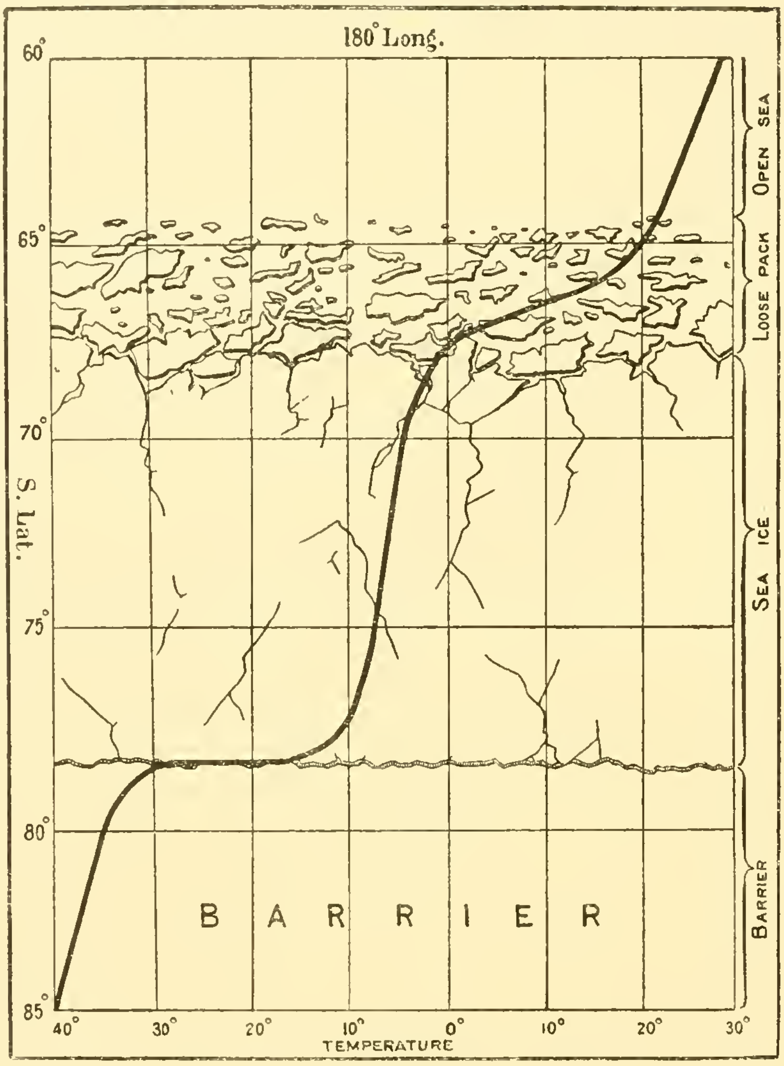

FIG. 10. Temperature distribution along 180° E. longitude.

We are therefore quite safe in assuming that the mean temperature over the centre of the Ross Sea is somewhat higher than at Cape Evans and at Cape Adare. The centre of the Ross Sea has therefore been encircled by the −10°F. isotherm. The discontinuity of temperature at the edge of the Barrier found to exist in McMurdo Sound by the Cape Crozier Party is much more likely to exist along the main edge of the Barrier; hence we have here a temperature discontinuity with several isotherms following the edge of the Barrier too close to be separated. The sea ice is probably very thick near Framheim during the winter as it forms early, and the atmosphere is still and cold in this region. Hence it is probable that the isotherms open out near Framheim in the manner shown in the map.

The physical meaning of the temperature distribution which is shown by the isotherms for July will probably be made more clear and convincing by setting out the temperature distribution in another way. The character of the ice along the meridians 180° E. and 150° W. is shown diagrammatically in figures 10 and 11. The former meridian runs down the centre of the Ross Sea and the diagram, figure 10, shows open sea north of about latitude 64° S., then a belt of loose pack gradually getting more dense until in about latitude 67° S. the sea is completely frozen over, but the ice is broken up by a few cracks. South of latitude 78° S. we have the Barrier surface.

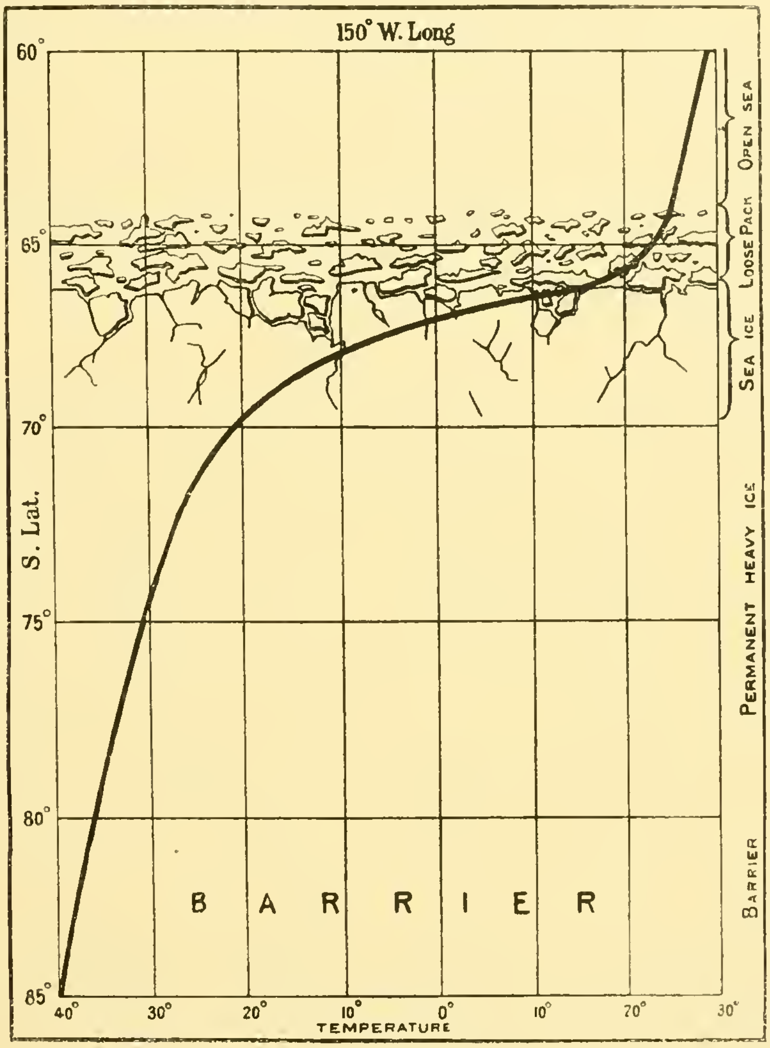

FIG. 11. Temperature distribution along 150° W. longitude.

In figure 11 the character of the ice along 150° W. is shown. Here again we have open water north of about latitude 64° S. Then the belt of loose pack followed by sea ice intersected by opening and closing leads. It is almost certain that south of 70° S. on this meridian there is permanent heavy ice either in the form of a Barrier or of a snow-covered land. Therefore south of this latitude the surface conditions will be similar to those on the Barrier.

On each of these diagrams there has been superposed a curve of temperature, the ordinates being latitude and the abscissæ temperature. Examining figure 10 we see that north of latitude 65° S. the temperature falls slowly with increase of latitude. In latitude 65° S. the loose pack is entered and the ice causes a rapid fall of temperature which continues as we proceed south until the more or less completely frozen centre of the Ross Sea is reached in latitude 67° S. From here onwards towards the south the temperature decreases very slowly until the Barrier is reached in latitude 78° S. The discontinuity of temperature at the Barrier edge is shown by the temperature running horizontally for 15°F. From the edge of the Barrier towards the south the temperature again falls slowly.

Turning now to figure 11 we again see the slow fall of temperature over the open sea and a rapid fall as the pack is reached. The rate of decrease of temperature falls off over the sea ice and when the heavy permanent ice is reached in latitude 70° S. the decrease of temperature as we proceed towards the south becomes slow and finally reaches the same rate as over the Barrier.

It must be borne in mind that a great deal of what has just been written is based only on conjecture; it would no doubt have been more accurate to have used the word 'probably' before many of the statements, but for clearness that has not been done. As further actual observations are not likely to be obtained in the near future the above description of the probable temperature conditions in the Ross Sea area must stand as best representing our present knowledge.

Plateau Temperatures.

Captain Amundsen reached the South Polar Plateau on 21st November, 1911, and left it on January 5, 1912, while Captain Scott reached it on 22nd December, 1911, and left it on February 6, 1912. Thus observations were made on the plateau continuously from 21st November, 1911 to February 6, 1912. As the plateau is not level the temperature varies on account of changes in height, hence it is necessary to reduce all the temperatures measured to a constant height before they can be compared. It has become an international convention to reduce the temperature to sea-level by applying a constant temperature correction of +·5°C. per 100 metres of ascent (·274°F. per 100 feet).* In his discussion of the observations made on the plateau by Amundsen, Professor Mohn did not follow this convention, but from the observations concluded that the actual temperature gradient was ·53° C. per 100 metres. He therefore reduced the temperature to sea-level by applying this correction. For the reasons given by Hann it is more satisfactory to retain in all parts of the world the same value of the temperature gradient and this has been done in the following discussion

In reducing the plateau temperatures to sea-level it is necessary to know the height at which each observation was made. Mohn has calculated the height of each place where Amundsen's temperatures were measured and the same has been done for Scott's journey (see Chapter IX). Unfortunately the two determinations of the height of the South Pole do not agree, Mohn making it 2,454 metres while I make it 2,765 metres. As the observations must be reduced to the same standard it is necessary to take one or other of the above values. I have therefore increased all the plateau heights given by Mohn by 311 metres in order to make the height of the only common station agree in the two sets of observations. Amundsen's temperature observations were taken at irregular times, on some days only two observations were made and on others three, four or six. I have taken as the mean temperature of the day the mean of two observations taken as far as possible at the same hour in the morning and evening. Thus on December 1st observations were made at 8-30 A.M., 1 P.M. and 5-30 P.M., the mean of the observations at 8-30 A.M. and 5-30 P.M. after reduction to sea-level has been taken as the mean temperature of the day.

Scott's observations have been treated somewhat differently. All the temperature observations were plotted and a curve drawn through the points as already described for the Barrier. This curve was measured at four-hourly intervals and the mean temperature for the 24 hours calculated for each day. The height at the lunch camp was taken as the height for the day.

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* See Hann Lehrbuch d. Meteorologie, 3rd edition, page 138.

During the period that Amundsen and Scott were on the plateau there were parties on the Barrier south of One Ton Camp (latitude 79½° S.) except during the last 17 days so that observations are available for a comparison between the temperatures on the plateau and over the south of the Barrier. The observations on the plateau were made between 86° S. and the Pole, we may therefore take the mean latitude of the plateau as being 88° S. The mean latitude of the south of the Barrier may be taken as 82° S.

In figure 12 the thick curve shows the mean daily temperature on the plateau reduced to sea-level, while the thin curve shows the mean daily temperature over the south of the Barrier. It will be seen that except at the end of November the reduced plateau temperatures were generally lower than the simultaneous temperatures over the south of the Barrier. It is interesting to notice the large correlation between the temperatures on the plateau and on the Barrier, all the larger changes affecting both regions. The high temperature on the plateau recorded by Amundsen at the end of November occurred during a blizzard, which kept him confined to his camp for four days. The wind during this blizzard was very unusual, being from the N.E. At the same time the weather was nearly calm and cloudless on the Barrier. The high temperature both on the Barrier and plateau at the beginning of December was associated with the storm which held up Captain Scott at the foot of the Beardmore Glacier for several days.

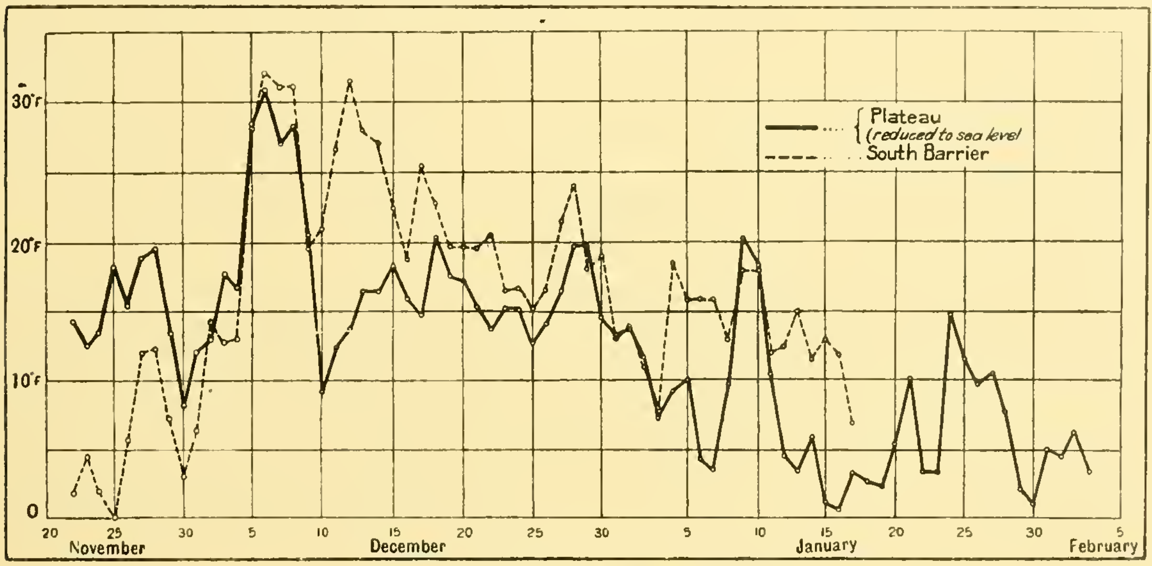

FIG. 12. **Plateau and Barrier temperatures.**

Table 15 contains the mean values of the reduced plateau temperatures, and the corresponding temperature on the south of the Barrier and at the base stations.

TABLE 15.

Mean Temperature.

	Cape Evans.	Framheim.	South Barrier.	Plateau reduced to sea-level.
Latitude . . .	77½°	78½°	82°	88°
	°F	°F	°F	°F
December	22·0	19·9	21·0	17·3
January	21·3	14·5	..	7·4

During December, as we have already pointed out, the temperature over the Barrier is practically uniform, the temperature over the south of the Barrier being the same as the mean temperature at Cape Evans and Framheim. It seems reasonable to assume that if the Barrier had extended right up to the Pole the temperature there would have been the same as that over the rest of the Barrier, *viz.*, 21°F. The reduced plateau temperature is however only 17·3°F., which indicates that during December the plateau is between 2 and 3°F. colder than its geographical position warrants. During January we have not sufficient observations from the south of the Barrier to determine the change of temperature with latitude on the Barrier. Plateau observations are however available for the whole of the month. From table 15 we see that during January the reduced plateau temperature was 10·3°F. lower than the mean of Cape Evans and Framheim. How much of this difference is due to change of latitude it is impossible to say, but if it were all due to latitude it would indicate a fall of temperature at the rate of 1·0°F. per degree of latitude. This amount seems impossibly large for this time of the year, therefore it is almost certain that the low relative temperature on the plateau both in December and January is not due to its geographical position, but is mainly due to its high elevation.

From this discussion it appears clear

(*a*) that the temperature on the plateau is lower than its geographical position warrants;

(*b*) that this relative deficiency of temperature is greater in January than in December;

(*c*) that the observations made on the plateau cannot therefore be used in determining the change of temperature with change of latitude.

It is instructive to compare the reduced plateau temperatures with the sea-level temperatures at the corresponding latitude and time in the northern hemisphere. According to Mohn's * determinations the mean temperatures at 88° N. during June and July are 28·6°F. and 31·1°F. respectively. Thus we have

TABLE 16.

North and South Polar Temperatures.

	Sea-level temperatures.			
		°F		°F
88° S.	December .	17·3	January .	7·4
88° N.	June . .	28·6	July . .	31·1
Difference . . .	. . .	−11·3	. . .	−23·7

Thus during the midsummer month the temperature in the neighbourhood of the South Pole, when reduced to sea-level at the rate of ·5°C. per 100 metres, is 11·3°F. (6·3°C.) lower than the corresponding temperature in the neighbourhood of the North Pole. The difference is still greater in the next month, for whereas in the north the temperature continues to rise for a month after the solstice it commences to fall in the south immediately after midsummer day.† In consequence the temperature is 23·7°F. (13·2°C.) lower in January near the South Pole than near the North Pole in July.

We have so far considered only the plateau temperatures after they have been reduced to sea-level, but it is of considerable interest to know the actual temperatures which were

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* The Norwegian North Polar Expedition, 1893–1896, Vol. VI, Meteorology, by H. Mohn, page 575.

† See page 88.

experienced on the plateau by the two parties; the following table has therefore been prepared (see also figure 6):—

Table 17.

Actual Temperatures on the South Polar Plateau.

Month.	Observer.	Mean observed temperature.	Maximum observed temperature.	Minimum observed temperature.
December	Amundsen .	− 8·6°F = −22·6°C	+5·5°F = −14·7°C	−19·3°F = −28·5°C
January	Scott . .	−18·7°F = −28·2°C	−3·2°F = −19·6°C	−29·7°F = −34·3°C

Thus the mean actual temperature in December was −8·6°F. It must be accounted as one of the wonders of the Antarctic that it contains a vast area of the earth's surface where the mean temperature during the warmest month is more than 8° below the Fahrenheit zero, and where throughout the month the highest temperature was only +5·5°F. It should also be noticed that the actual temperature on the plateau was 10°F. lower in January than in December, indicating a very rapid lowering of the temperature immediately the solar radiation commences to decrease. If this fall was not abnormal it indicates that the temperature on the South Polar Plateau is influenced by changes in insolation much more than any other place for which we have records.

Vertical Distribution of Temperature

Having now used all the available data for discussing the geographical distribution of temperature at ground level, we will turn to the question of its distribution in the upper atmosphere.*

In figure 13 are plotted all the observations made by the aid of balloons of the temperature of the upper air over the frozen McMurdo Sound. In this diagram heights are shown in metres and temperatures in centigrade degrees.

It will be noticed that all the ascents made in November and December, summer months (Nos. 5 to 10), show temperature decreasing with height and the mean gradient for the first 2½ kilometres is 6·8°C. per 1,000 metres. It is of great interest to notice that this is practically the same gradient as that found in summer months in Europe and America although the actual temperatures in the Antarctic summer are similar to those of winter in those regions.

The conditions are entirely different during the winter. On account of darkness upper air observations could not be made before August. In this month, however, four successful balloon ascents were made and the instruments recovered. The difficulties of the balloon work in cold weather were so great that only moderate heights could then be reached. The ascent on August 13, No. 1, was made on one of the coldest days of the year, the temperature on the ground being −39°C. at the time of the ascent. The temperature record on this and on all other occasions in the winter revealed the temperature inversion which is often met with on calm winter days in Europe and America. The inversion extended higher on August 13 than on any of the other days, but it was not so pronounced as on August 16. The curve for August 30, No. 4, is interesting as it was

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* The upper air observations are discussed in detail in Chapter VIII.

obtained within a few hours of the cessation of a fairly strong blow from the north-west. In this case the inversion is very small, if it exists at all, but the tendency to the formation of an inversion is shown by a practically constant temperature from the ground to a height of 1,000 metres. No doubt if the ascent had been made a few hours later a more marked inversion would have been found.

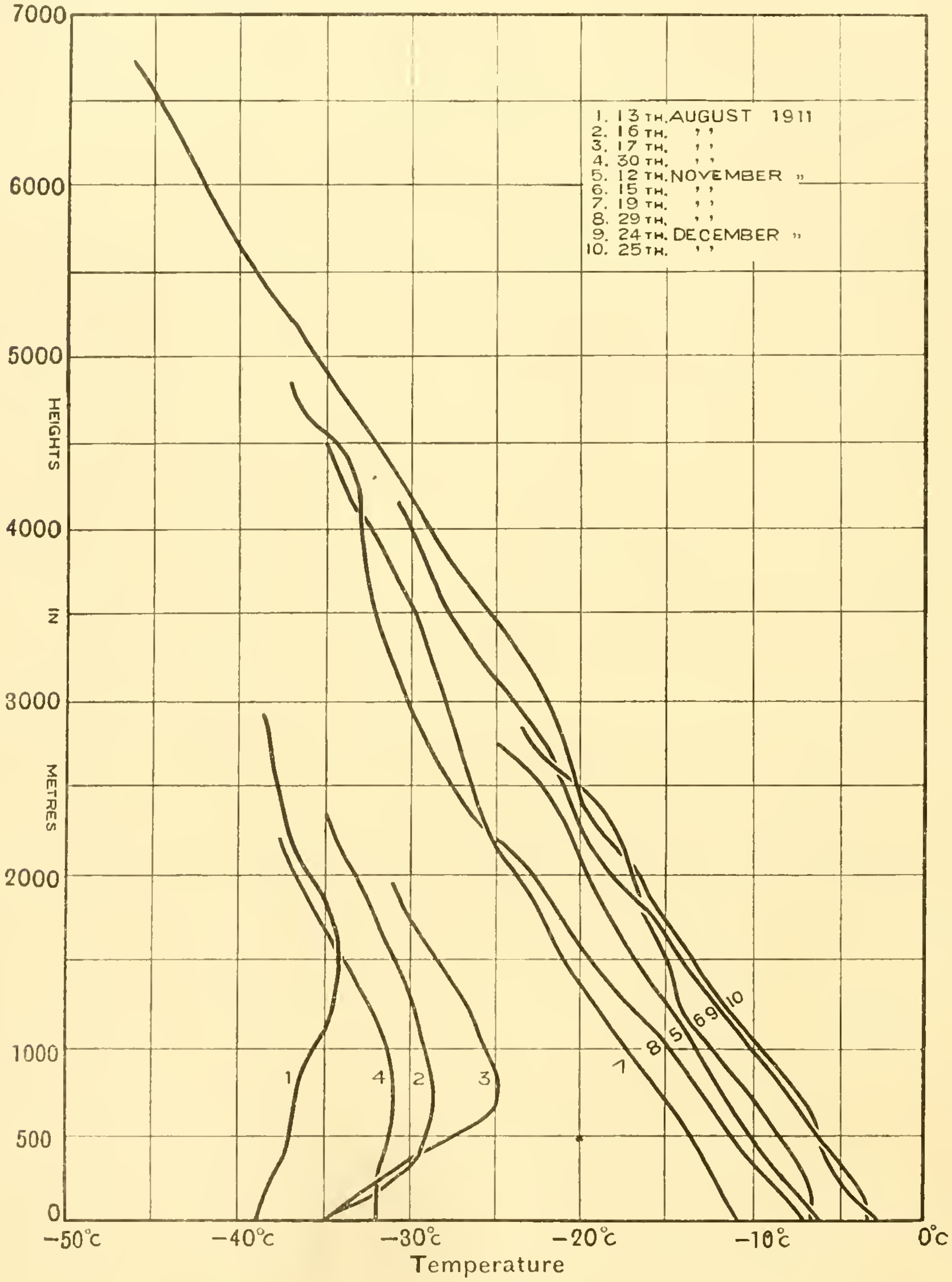

Fig. 13. Upper air temperatures.

The physical meaning of these observations is very simple. When a vessel containing gas is heated at the base, convexion currents are produced and a thorough mixing of the air takes place. A temperature gradient is thus set up which approaches the adiabatic gradient if the mixing is sufficiently rapid. On the other hand, if the base is cooled, a layer of cold air forms there which has no tendency to rise and warmer layers rest upon it. In this case a temperature inversion results. In the Antarctic summer the snow surface is warmed relative to the overlying air by the almost continuous solar radiation and convexion currents produce a normal temperature gradient. In the winter there is little or no sunshine, while rapid radiation takes place from the snow surface which cools the air in its immediate neighbourhood. A cold layer of air is thus formed, which, under favourable circumstances, may be many degrees colder than the air a few hundred metres above.

These conditions obviously can only obtain during the absence of wind. If there is a wind it produces vertical mixing of the air without the aid of convexion currents. The effect of a wind is different in summer and in winter. In the summer there is already a large temperature gradient which is little affected by the wind. In the winter the wind removes the cold surface layer and produces a normal temperature gradient. This process will be considered more fully later; it is mentioned here to point out that the temperature gradient shown by the curves on figure 13 during the summer probably exists during all kinds of weather, while that shown for the winter exists only during calm weather.

The different vertical temperature gradients in summer and winter have two very important consequences when we consider the temperature of the upper air. The first can be seen at once from the curves in figure 13. The balloon ascents made on August 13 and December 25, Nos. 1 and 10, were made on one of the coldest and one of the warmest days of the year. The temperature difference at the ground on these two days was 36°C. The curves show, however, that the temperature difference at 3,000 metres was only 18°C. The four winter curves are probably typical of the conditions during the coldest days of the winter, while the curves 9 and 10 are typical of the warmest summer conditions. It is very probable, therefore, that the temperature difference between the warmest and coldest days at two to three thousand metres altitude is only about half of the corresponding difference at the ground.

What has just been shown to hold for different times of the year is true also for different geographical positions during the winter. That is, during the winter the temperature differences between different geographical positions are less in the upper air than on the ground.

According to the isotherms for July shown in figure 9 the temperature over the Ross Sea just to the north of the Barrier edge is −10°F. (−23°C.) while over the Barrier itself it is −35°F. (−37°C.) Thus there is a temperature difference near the ground of 14°C. The temperature gradients over the two regions are, however, quite different. The high temperature over the Ross Sea is due to the warming of the air by the warm water which is never separated from the overlying air by more than a thin coating of ice. Hence during the winter the air over the Ross Sea is warmed from below and convexion currents are produced which give a normal temperature gradient. Over the Barrier there are often much greater temperature inversions than those found during August in McMurdo Sound, but as there are also periods during winds when the gradient is normal we probably shall not be far wrong in assuming that the *average* conditions over the Barrier in July are similar to those shown by curves 1 to 4 of figure 13. Based on these considerations the average temperatures up to 4,000 metres during July have been shown on the left of figure 14 for the Ross Sea and the Barrier. The gradient over the Ross Sea has been taken as 5°C. per 1,000 metres for the first kilometre and above this height slightly less. Over the Barrier an inversion of 4°C. is shown for the first 500 metres above which there is a gradient of 4°C. per 1,000 metres. It will be seen that with these assumptions the temperature over the Barrier at 4,000 metres is only 2°C. lower than at the same height over the Ross Sea. Thus in 4,000 metres ascent the temperature difference between the Barrier and the Ross Sea has been reduced from 14°C. to 2°C.

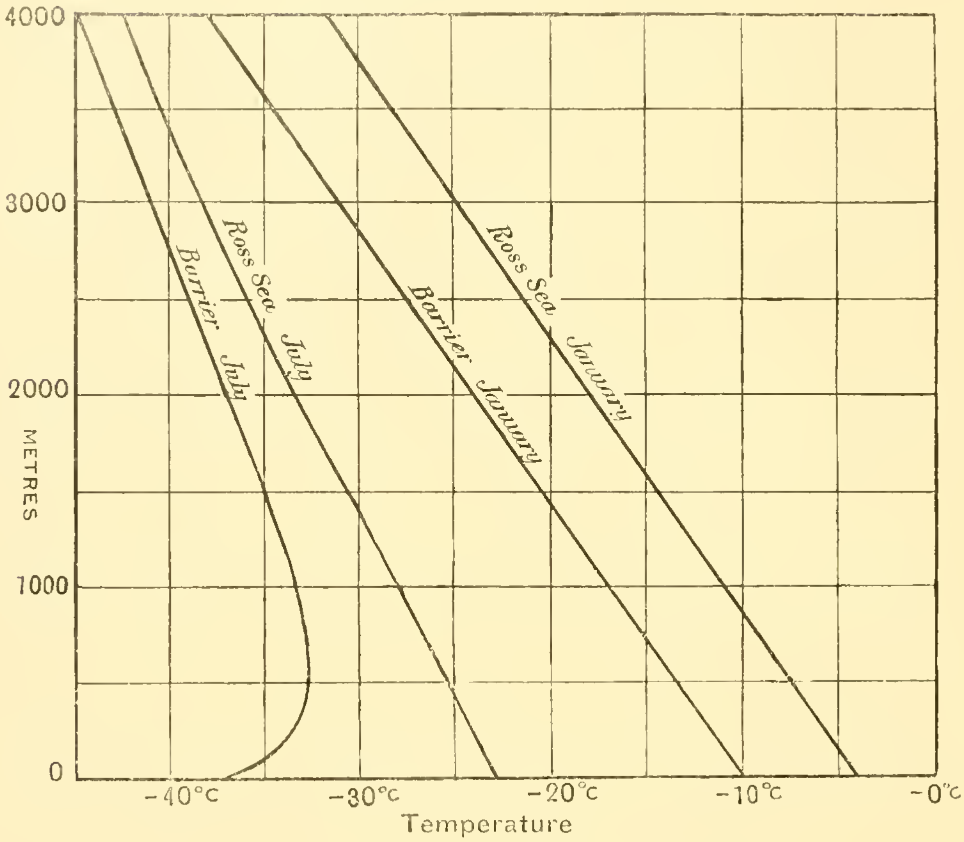

Fig. 14. Upper air temperatures over Ross Sea and Barrier.

An interesting and important consequence of this relationship is found when the temperature differences between the Barrier and the Ross Sea in July and January are compared. On the right hand side of the diagram similar curves for January are shown. In this month normal temperature gradients of about 7°C. per 1,000 metres probably exist always over both the Barrier and the Sea. In consequence the full temperature difference which exists near the ground exists also at 4,000 metres. If the assumptions on which these curves are based are true, the remarkable consequence results that the temperature difference between the Barrier and the Ross Sea is less at 4,000 metres in July than in January. In the next section we shall see that this conclusion is supported by the temperature observations during winds.

Temperature and Winds.

The effect of the wind on temperature is twofold—

(*a*) the wind causes a mechanical mixing of the upper and lower strata which may appreciably affect the temperature near the ground ;

(*b*) the wind brings air from different geographical positions, which may be warmer or colder according to the direction from which it comes.

With the vertical temperature distribution which we have seen exists over the Antarctic during cold calm weather, the former of these two effects must then play a large part.

During a high wind there is so much forced vertical mixing of the air that the temperature gradient becomes roughly adiabatic in the air layers affected. We have no upper air temperature observations during high winds in the Antarctic, but from general considerations we know that the gradient must then be between 6°C. and 7°C. per 1,000 metres. In figure 15 the thick curve represents the vertical temperature distribution during cold calm weather as found by the balloon observations. The inversion up to 1,000 metres is shown, and from there upwards the temperature falls 4°C. per 1,000 metres. If now a wind springs up the lower cold layers are swept away, and if it disturbs the air up to 2,000 metres a temperature gradient of about 6·5°C. is set up in this region. The temperature of the air above 2,000 metres will not be materially affected but from this point downwards the temperature rises 6·5°C. for each 1,000 metres. The new temperature conditions are shown by the line (*a*) in the diagram.

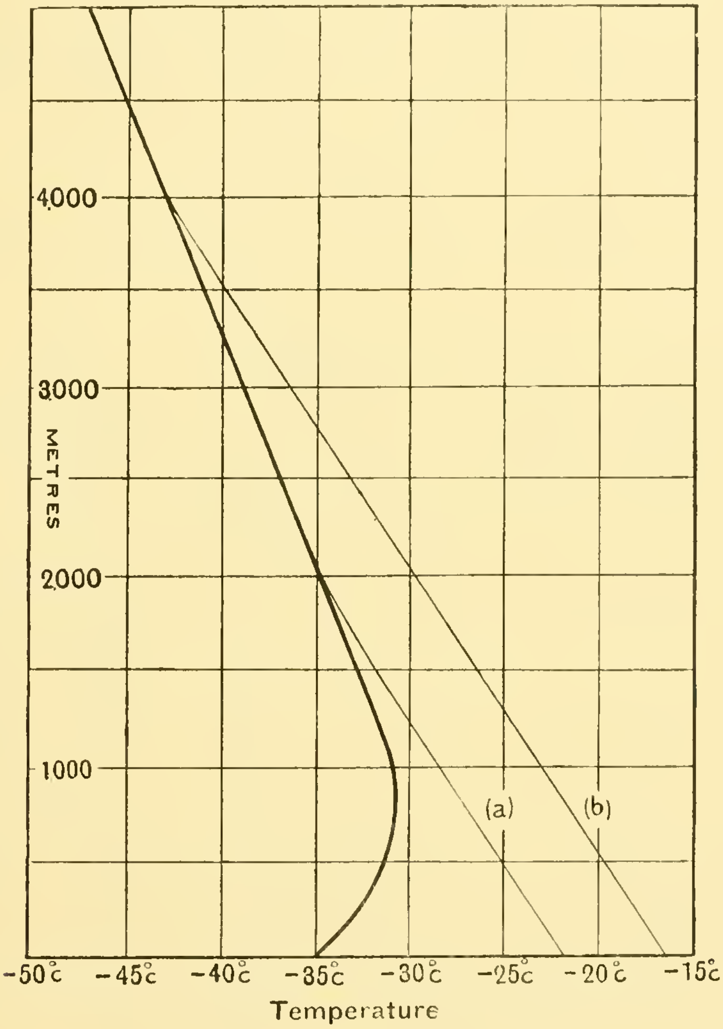

FIG. 15. Effect of removing inversion layer.

Before the wind sprang up the ground temperature was −35°C. and by the time the wind has produced the gradient the temperature has risen to −22°C., *i.e.*, the wind has produced a rise of 13°C. = 23°F. If the wind had disturbed the air to 4 kilometres the temperature would be indicated by the line (*b*) which represents a rise of the ground temperature of 18°C. = 32°F.

From these considerations we should expect the temperature in winter during winds to be considerably higher than during the calms.

The first effect of a wind under such conditions is to raise the temperature quite independently of the direction from which it comes. But when the wind has removed the cold surface layers the temperature it produces will depend on the direction from which it comes. Thus we should expect both southerly and northerly winds to be warmer than calms, but the former to be themselves colder than the latter. This is clearly shown to be the case during the months from June to September by the mean temperatures entered in the first four lines of the following table:—

TABLE 18.

Temperature and Wind at Cape Evans.

I	II	III	IV	V	VI	VII	VIII
			SOUTHERLY WINDS HAVING VELOCITIES				
Month.	Calm, wind velocities 0 to 5 miles per hour.	Northerly winds having velocities 11 to 30 miles per hour.	11 to 30 miles per hour.	Greater than 30 miles per hour.	Difference III—II.	Difference IV—II.	Difference IV—III.
	°F.	F.	F.	F.	°F.	F.	°F.
June	−20·6	−10·3	− 8·2	− 3·7	+10·3	+12·4	+2·1
July . . .	−24·7	− 8·9	−12·4	− 4·3	+15·8	+12·3	−3·5
August . .	−25·8	− 5·0	− 9·1	− 1·4	+20·8	+16·7	−4·1
September . .	−22·4	−10·0	−12·0	− 4·6	+12·4	+10·4	−2·0
October .	− 5·7	− 2·3	− 4·0	− 0·2	+ 3·4	+ 1·7	−1·7
November	+14·7	+17·0	+10·4	+ 8·7	+ 2·3	− 4·3	−6·6
December	+21·8	+23·4	+21·8	+21·8	+ 1·6	0·0	−1·6
January .	+21·9	+24·4	+19·7	+25·1	+ 2·5	− 2·2	−4·7
February .	+20·3	+23·4	+15·6	+ 9·6	+ 3·1	− 4·7	−7·8
March . . .	+ 6·3	+ 7·5	+ 5·1	+ 3·4	+ 1·2	− 1·2	−2·4
April . . .	− 3·9	− 2·2	− 3·8	− 2·6	+ 1·7	+ 0·1	−1·6
May . .	−12·0	− 9·3	− 9·6	− 3·4	+ 2·7	+ 2·4	−0·3

During these four months the temperature during calms (column II) was considerably lower than during either northerly or southerly winds (columns III, IV and V). The difference in temperature between northerly winds having velocities between 11 and 30 miles per hour and calms is shown in column VI and for similar southerly winds in column VII. It will be seen that both northerly and southerly winds raise the temperature by over 10°F. It was stated above that the more violent winds as they disturb the atmosphere to a greater height should be warmer than the less violent winds [curves (*b*) and (*a*) in figure 15]. This is clearly seen to be the case by comparing columns IV and V, which give data for winds from the south having velocities of 11 to 30 and greater than 30 miles an hour. The higher winds, although from the same direction, are nearly 8°F. warmer than the less violent winds. The same was found to hold for northerly winds, but they occurred too seldom to show the effect so clearly, and have therefore not been included in the table. In column VIII the differences in temperature between northerly and southerly winds of velocity between 11 and 30 miles an hour are shown. With the exception of June the southerly winds were the colder by two to four degrees. The June observations were taken in 1911 and 1912; in the latter year the southerly winds obeyed the rule and were 4·6°F. colder than the northerly winds; it is therefore probable that the June discrepancy would disappear if more observations were available. It is to be noted that although in the winter the Barrier is probably on the average nearly 30°F. colder than the Ross Sea, the southerly winds which blow from the Barrier are not quite 5°F. colder than the northerly winds which blow from the Ross Sea. This is entirely due to the fact that the temperature of the winds is governed by the temperature of the upper atmosphere, which has been shown to be only slightly colder over the Barrier than over the Ross Sea during the winter (see page 44). This result confirms, therefore, the assumptions used in determining the probable temperature of the upper atmosphere.

The layer of cold air near the ground, on the removal of which depends the sudden rise of temperature when a wind commences, cannot come into existence if sufficient solar radiation is received to keep the temperature of the ground above that of the air in contact with it. This appears to take place in October and from then on to the corresponding month in the autumn, February, the solar radiation is sufficient to cause convexion currents which maintain a sensible temperature gradient, and prevent the formation of a cold ground layer. In the absence of solar radiation in March, April, and May the same effect is produced by the relatively warm water of McMurdo Sound, for it is not until the end of May that the ice is sufficiently thick to prevent an appreciable warming of the air by the underlying water. From October to May, then, the cold layer cannot form over McMurdo Sound and the figures in columns VI and VII for these months show only a small difference of temperature between calm weather and windy weather. It will be noticed, however, that the northerly winds are two or three degrees warmer than calms, while the southerly winds are colder than calms except in the extreme months of the period.

This is exactly what would be expected from geographical considerations when there is no cold surface layer to be removed; for southerly winds are cold and northerly winds are warm. It will also be noticed that with the exception of December the difference in temperature between northerly and southerly winds (column VIII) is greater in the summer months, November to February, than in the winter, May to August, although the actual temperatures of the Ross Sea and Barrier have the reverse relationship. This again confirms our conclusion that the temperature of the upper air determines the temperature of the winds, for we have already shown that the difference in temperature in the upper air over the Ross Sea and Barrier is greater in summer than in winter. The small difference of only 1·6°F. in December is a direct consequence of the uniformity of temperature found over the whole Ross Sea area in this month.

Examples of the Effect of the Wind on Temperature.—In the foregoing we have discussed the influence of the wind on the temperature by taking the observations in the bulk, and have found that the average conditions are explained by taking into consideration the vertical as well as the horizontal distribution of temperature. We will now examine a few typical examples which will show the process in action in individual cases. For this purpose figures 16 to 19 have been prepared from the records of the thermograph and the Dines' anemometer. The thin continuous curve shows the temperature according to the scale on the left of the diagram, and the lower ragged curve the wind velocity according to the scale on the right of the diagram. The wind direction is entered along the bottom of the diagrams.

Typical Case of a Southerly Blizzard on September 16 and 17, 1911 (figure 16).—The forenoon of September 15 was cold after a clear, calm night, and therefore we may expect that a layer of cold air had formed near the ground with an appreciable temperature inversion above. The temperature of this layer is shown by the temperature curve to have been about −35°F. At 8 A.M. the sky commenced to cloud over, at first with cirrus clouds but later with heavy low clouds. When such conditions precede a blizzard it indicates that the upper air has commenced to move from the south, but is moving over the lower layers without disturbing them. The condensation of water vapour indicated by the cloud has warmed up still further the upper air, and as radiation to the clear sky has been cut off by the clouds, the temperature of the cold air near the ground commenced to rise. This rise is shown in the temperature curve to have taken place steadily until midnight of the 15th. By this time the lower layers had become disturbed and little puffs of wind from the south commenced to be shown on the wind trace, and the temperature curve became irregular as the cold layer was invaded by warmer air from above. Between 8 hours and 18 hours on the 16th the surface layer became more and more disturbed as shown both by greater temperature irregularities and the increasing frequency of the fitful light wind gusts; it is obvious that the moving layer was now coming lower in the atmosphere. At 18 hours the blizzard commenced, the wind suddenly appeared at the ground and swept away the remainder of the surface layer, as is shown by the sudden rise in wind velocity and the almost instantaneous rise of temperature of 15 degrees.

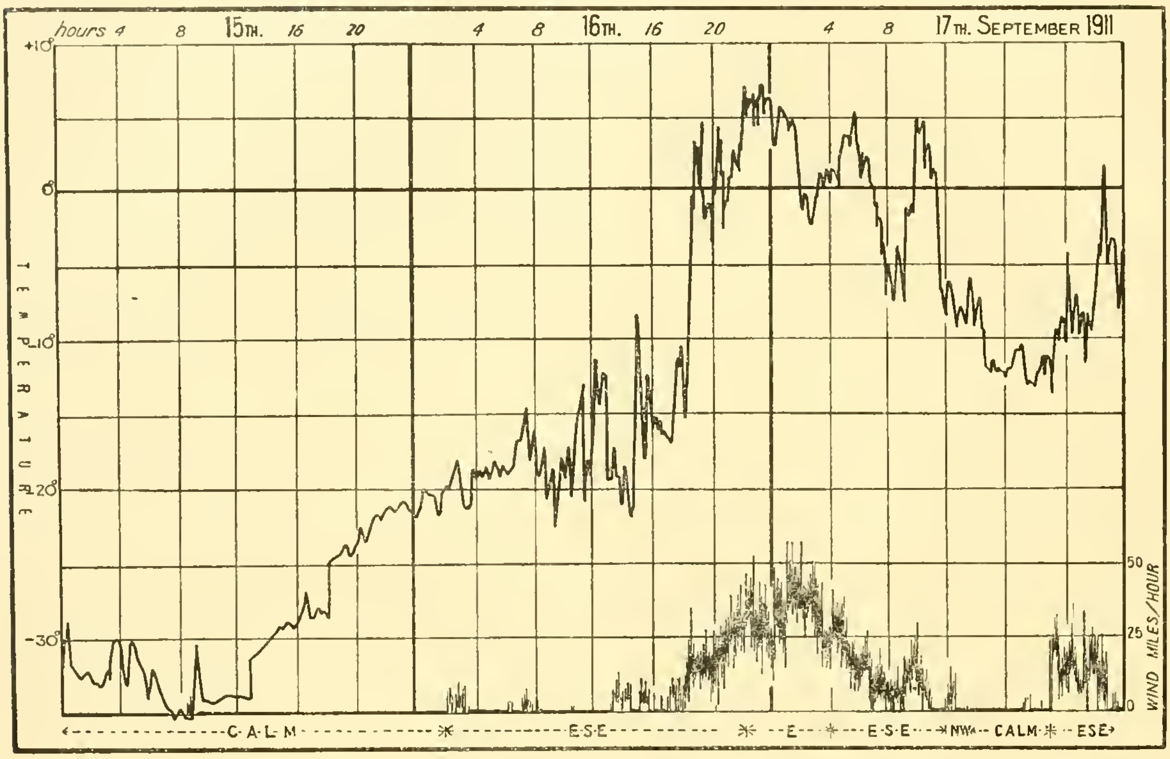

FIG. 16. Wind and Temperature.

The wind continued to increase in velocity until after midnight, and it was accompanied by an increase of temperature. The wind then decreased and disappeared completely at midday on the 17th. It will be noticed that as soon as the wind had reached its maximum the temperature commenced to fall—this is a most characteristic feature of southerly blizzards. In practically all cases the temperature decreased towards the end of the blizzard.

In this case we have a cold surface layer of $-35°$F., being replaced by a warm current of air of $+5°$F., a change of 40°F. Thus, if the conditions previous to the blizzard had been something like those shown in figure 15, the observed change would have necessitated the thorough mixing of the lower 5,000 metres of the atmosphere. The cirrus clouds with which the disturbance commenced were well above this height, so that the explanation given is well able to account for the observed effect.

Southerly Blizzard preceded by a Northerly Wind—May 15, 16, *and* 17 (*figure* 17).—After midnight on the 14th the sky was clear and the temperature was unusually low, showing the formation of a cold layer in spite of the thin ice. Just before 8 hours on the 15th, when the temperature was $-25°$F., a northerly wind sprang up which removed this layer and caused the temperature to rise by 10 degrees. An interesting feature of this northerly wind was that above it there were alto-cumulus clouds moving from the south. The northerly wind continued until about midday on the 16th, when, after a calm hour, a southerly blizzard sprang up accompanied by much cloud and drift. During this blizzard the temperature rose slowly until near the end, when it started as usual to decrease before the blizzard came to an end. Three things are interesting in this case—(1) the sudden rise of temperature when the northerly wind swept away the cold surface layer; (2) there was no sudden rise of temperature when the southerly wind commenced, for the layer had already been cleared away; (3) the fact that the temperature rose much higher with the southerly than the northerly wind. The explanation of the latter fact is clear and supports the explanation already given of the cause of temperature changes under the influence of the wind. It has been stated that over the northerly wind there was a wind from the south; thus the air must have been moving in sharply marked layers and therefore there could have been little or no vertical mixing, hence as soon as the northerly wind had removed the cold surface layer it could produce no further increase in temperature. On the other hand, the southerly wind must have extended much higher and the production of snow shows that there was considerable ascensional motion, thus a normal temperature gradient must have been established to a considerable height, raising the ground temperature to nearly 0°F. This explanation is further supported by the fact that after the blizzard stopped the wind returned to the north and the temperature of the northerly wind was then not what it had been previously, but what it was during the southerly blow.

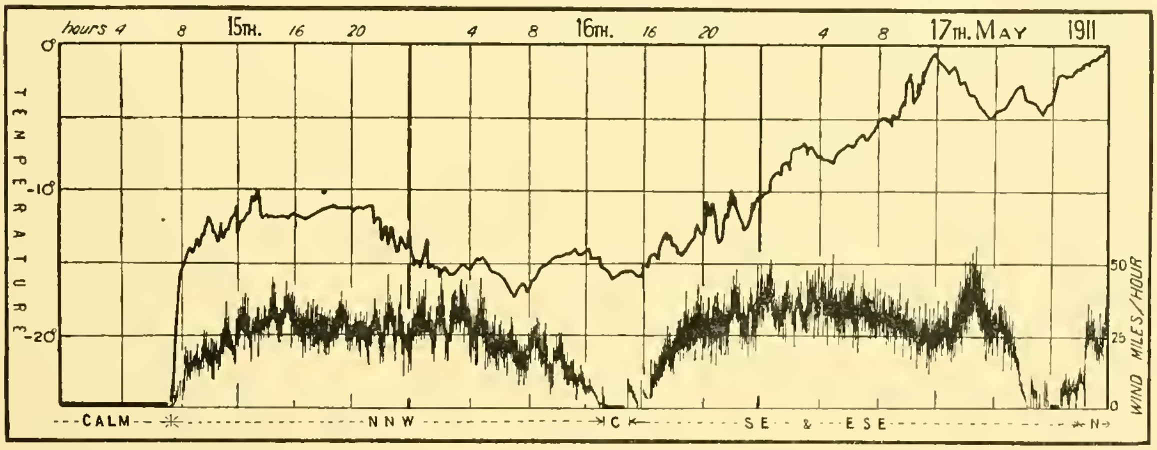

FIG. 17. Wind and Temperature.

Removal of the Cold Surface Layers by a Light Local Wind—September 22 *to* 25 (*figure* 18).—The thermograph trace shows many interesting examples of a sudden puff of wind causing an instantaneous rise of temperature of many degrees. These sudden rises prove conclusively that there must be warm air very near to the cold air which is so suddenly removed. There is no reason to believe that there was warm air anywhere near in a horizontal direction, hence the warm air could only have been part of a warm layer lying above the cold surface layer. The period September 22 to 25 contains several good examples, and the thermograph trace for this period is reproduced here. A detailed discussion is unnecessary, the relationship between the wind and the temperature is obvious.

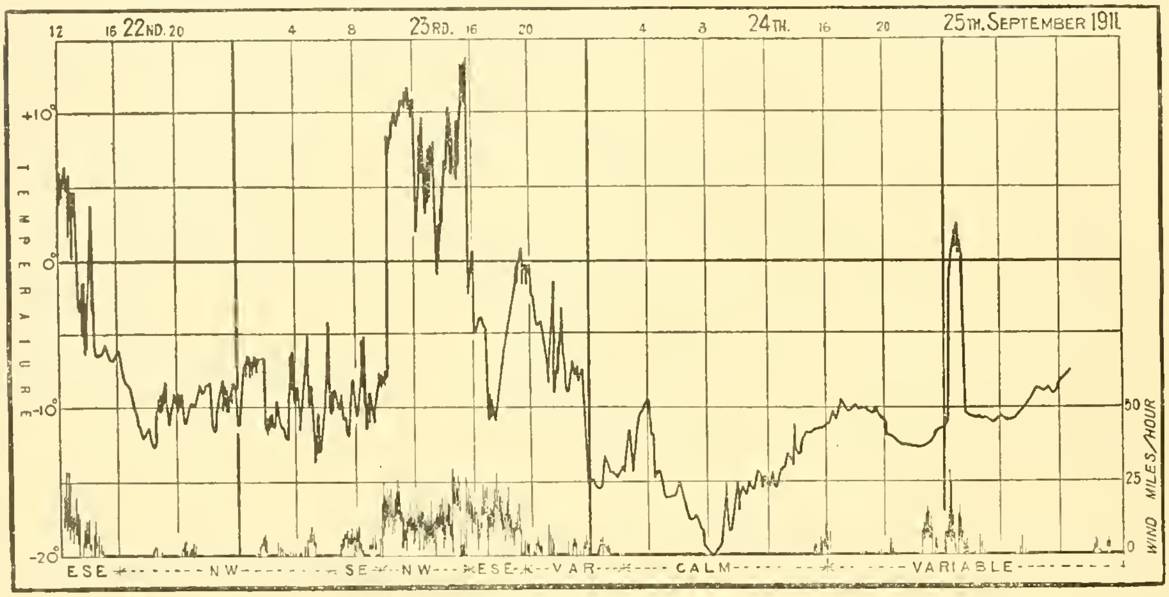

Fig. 18. Wind and Temperature.

Cold Blizzard during the Summer—February 14, 15, *and* 16, 1912 (*figure* 19).—In this diagram also the relationship between the wind and the temperature is obvious. But we have a different effect from those previously considered. Here we see that the direction of the wind plays the chief part in deciding the temperature. The two short periods of northerly

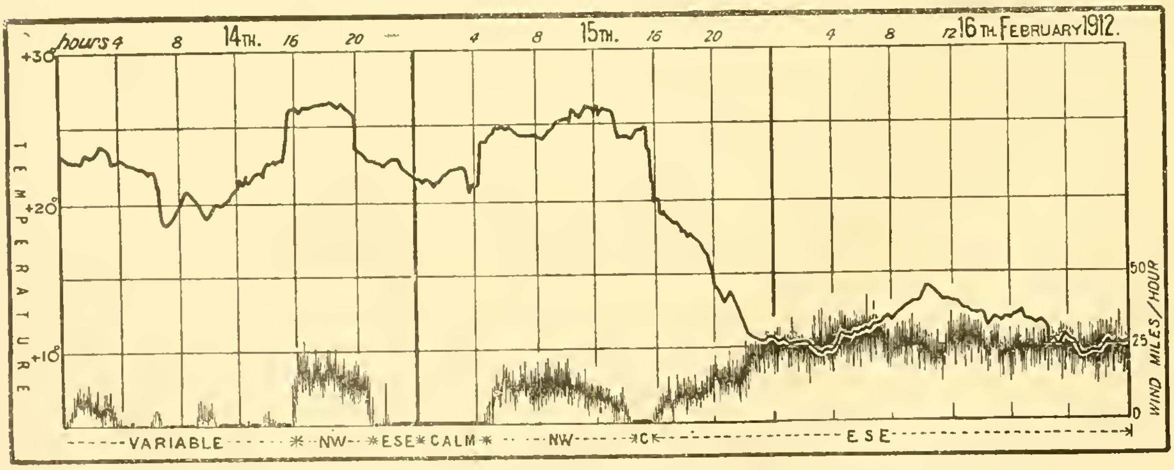

Fig. 19. Wind and Temperature.

wind brought with them comparatively high temperatures, while, when the southerly wind set in, the temperature dropped rapidly and remained low so long as the wind continued.

The examples given above have had to be restricted in number, and therefore only typical cases have been chosen from the large number available. It goes without saying that the direct relationship between wind and temperature was not always so clearly shown as in the cases illustrated; but the relationship is more or less discernible throughout. The raising of the temperature by all winds in the winter and the dependence of the temperature on the wind direction in the summer are the two outstanding features of the relationship between wind and temperature at Cape Evans.

The large rise in temperature caused by southerly blizzards during the winter was first observed on the Discovery Expedition. The true cause was not realised, and the explanations then given have led to two very erroneous ideas becoming firmly fixed in meteorological literature. They are both included in the following paragraph taken from page 424 of the discussion of the meteorological results of the Discovery Expedition.

> 'The rise of temperature in these gales from south-east and east-south-east, doubtless, is in some measure due to the föhn effect produced dynamically by the descent of air from the mountain tops, and also to the check given, by wind in motion, to cooling by radiation. But may it not, to some extent at least, be attributed to the conveyance of warmer air drawn from lower latitudes, circulating about a low pressure system and conveying to the locality the higher temperatures of the region whence it originated?'

These explanations have been generally accepted and quoted in nearly every paper dealing with the meteorology of the Ross Sea area; it is important, therefore, that they should be criticised in the light of our fuller knowledge.

Föhn.—The föhn effect has been introduced to account for the high temperature of the winds. Air is supposed to start from the plateau surrounding the Barrier and to be dynamically warmed by its forced descent to sea-level. If such forced descent does take place, for which however there is no evidence, the air might be warmed, but at the same time there would be a corresponding fall in the relative humidity of the air. Now one of the chief characteristics of an Antarctic blizzard is the heavily overcast sky and large precipitation, which would be quite impossible with descending air. Even if a satisfactory explanation had not been already given this consideration alone would be sufficient to show that the high temperatures in blizzards are not due to a föhn effect.

Air Circulation about a Low Pressure System.—It has been usually assumed that blizzards are due to the passage eastwards of low pressure systems having their centres over the southern ocean. It will be shown later that such cyclones do not affect the Ross Sea area and that blizzards are due to entirely different causes. Even if this were not the case it is easy to show that the high temperatures in blizzards are not due to 'the conveyance of warmer air drawn from lower latitudes, circulating about a low pressure system and conveying to the locality the higher temperature of the region whence it originated.' In such a circulation air which reached McMurdo Sound as a south-easterly wind, would have previously passed over Framheim as a northerly wind when it was nearer its place of origin. It would therefore be warmer at Framheim than when it reached McMurdo Sound after passing over the cold Barrier. To test this hypothesis the temperature at Cape Evans and Framheim during blizzards at the former station have been compared, with the result shown in the following table:—

Table 19.

Difference in Temperature Framheim-Cape Evans during Blizzards at Cape Evans.

Month.	WIND AT CAPE EVANS.		Month.	WIND AT CAPE EVANS.	
	11 TO 30 MILES PER HOUR FROM SOUTH.	GREATER THAN 30 MILES PER HOUR FROM SOUTH.		11 TO 30 MILES PER HOUR FROM SOUTH.	GREATER THAN 30 MILES PER HOUR FROM SOUTH.
	Difference of temperature.	Difference of temperature.		Difference of temperature.	Difference of temperature.
1911.	°F.	°F.	1911.	°F.	°F.
April . .	−14·0	− 6·1	September .	−28·6	−4·4
May . .	−23·7	− 9·4	October . .	− 7·1	−0·3
June . .	−15·4	− 6·7	November .	− 7·8	−5·6
July . .	−14·6	− 8·9	December .	− 0·9	+5·2
			1912.		
August . .	−42·1	−31·8	January . .	− 4·3	−8·6

Except with high winds in December 1911 the temperature was lower at Framheim than at Cape Evans during blizzards, hence the air in the blizzards at Cape Evans cannot have passed over Framheim as warm northerly winds.

Because of the relatively high temperature of blizzards during the winter the explanations discussed above have been formulated, but it was forgotten that if the explanations were true for the winter they would be true for the summer also. Thus we should expect high temperatures in summer blizzards as well as in winter blizzards. But we have already shown that this is not the case‘ for summer blizzards are cold.

We have now shown that the föhn effect and the circulation of air around low pressure systems do not explain the relationship found between the temperature and wind; on the other hand an explanation has been given depending on the vertical distribution of temperature which explains all the observed conditions; it is therefore reasonable to conclude that the latter is the true and sufficient explanation.

Daily Variation of Temperature.

In this and the following section use will be made of three terms which have often been used by writers as being almost interchangeable, but to which a special significance will be attached throughout this work, therefore it is desirable that they should be carefully defined:—

(*a*) The expression *daily variation of temperature* will be used to express the daily march of the temperature when all temperature changes other than those due to true daily periodic causes have been eliminated as far as possible. The irregular and non-periodic changes due to wind, cloud, etc., are eliminated by combining a large number of days having a similar periodic temperature variation; for then the irregular changes more or less completely cancel one another while the true daily variation remains. In addition a correction has to be applied to remove the effect of the yearly variation of temperature. During certain seasons of the year this may be large, for example during September 1911 each midnight was on the average ·9°F. warmer than the previous midnight owing to the large change of temperature which occurred between the beginning and end of the month. The correction applied for this purpose is the usual one $+\frac{1}{24}(r_0 - r_{24})(n-12)$ in which r_0 and r_{24} are the mean readings answering to the first and second midnights of the day and n the hour interval since the first midnight.

(*b*) When the true daily variation of temperature has been obtained in this way, the difference between the highest and lowest hourly values gives *the daily amplitude of temperature.*

(*c*) The expression *daily range of temperature* is strictly confined to the difference between the maximum and minimum temperatures recorded during each day. The average value of the daily range is much larger than the corresponding amplitude.

In the Antarctic the unperiodic temperature changes are so large in comparison with those due to true period causes that a long series of years would be necessary to eliminate them completely. By combining the results of the observations at Cape Evans and Hut Point we have four years' observations for all the months from February to August and three years' observations for the remaining months. In the following discussions the results of all the years combined have been used and only where it is necessary in order to investigate particular points will the results for individual years be separately considered. In the volume of tables, however, the data for each year are given in such a way that they are easily available for further investigation.

The daily variation for each month is shown in table 20 and the results are plotted in the left half of figure 20. As the data for Hut Point have been given only for two-hourly intervals, it was only possible to combine alternate values of the Cape Evans' temperatures with them. Hence two-hourly intervals are used in the curves and tables.

TABLE 20.

Daily Variation of Temperature as determined from all the Observations of Captain Scott's first and second Expeditions.

Local time.	January. 1903 1904 1912	February 1902 1903 1911 1912	March. 1902 1903 1911 1912	April 1902 1903 1911 1912	May. 1902 1903 1911 1912	June. 1902 1903 1911 1912	July. 1902 1903 1911 1912	August. 1902 1903 1911 1912	September. 1902 1903 1911	October. 1902 1903 1911	November. 1902 1903 1911	December. 1902 1903 1911	Year.
0	−1·72	−0·89	+0·12	+0·21	−0·13	−0·46	−0·25	+0·32	−0·44	−1·15	−1·79	−0·63	−0·57
2	−2·47	−1·68	−0·23	+0·06	−0·60	−0·73	+0·03	+0·08	−0·18	−0·82	−1·26	−1·57	−0·79
4	−2·82	−1·54	−0·79	+0·52	−0·40	−0·23	+0·80	+0·59	+0·19	−1·18	−1·61	−1·30	−0·56
6	−1·33	−0·91	−0·75	+0·25	−0·50	+0·07	−0·03	+0·53	−0·71	−1·41	−1·22	−0·98	−0·58
8	−0·48	−0·18	−0·21	−0·06	−0·28	−0·14	−0·07	+0·16	−0·89	−0·58	−0·35	−0·72	−0·32
10	+0·58	+0·34	+0·48	+0·09	+0·26	−0·08	+0·10	−0·31	−0·08	+1·13	+0·68	+0·46	+0·37
12	+1·26	+0·95	+0·64	−0·34	+0·64	+0·24	−0·31	−0·70	+0·43	+1·33	+1·39	+0·95	+0·54
14	+1·78	+1·21	+0·62	−0·06	+0·70	+0·02	+0·15	−0·39	+0·87	+1·50	+2·12	+1·51	+0·84
16	+2·17	+1·27	+0·36	−0·11	+0·69	+0·20	−0·04	−0·40	+0·75	+1·35	+1·66	+1·47	+0·78
18	+1·78	+0·89	+0·03	−0·33	+0·13	+0·61	−0·42	+0·13	+0·49	+0·52	+1·08	+1·09	+0·50
20	+0·90	+0·63	−0·15	−0·31	−0·34	+0·30	−0·14	+0·02	−0·23	+0·05	+0·14	+0·37	+0·10
22	+0·28	−0·11	−0·03	+0·08	−0·43	−0·10	+0·08	−0·15	+0·14	−0·84	−1·00	−0·63	−0·23
Mean .	+23·2	+14·6	+4·2	−8·3	−11·9	−13·1	−14·1	−14·3	−15·5	−6·2	+13·1	+23·8	−0·4
Amplitude	5·0	3·1	1·5	0·9	1·3	1·3	1·2	1·3	1·8	2·9	3·9	3·2	1·6
Time of maximum	16	16	12	4	15	18	4	4	14	14	14	14	14
Time of minimum	4	2	4	12	2	2	18	12	8	6	4	2	2

From figure 20 it will be seen that the observations are not sufficient to give smooth curves, especially in the winter months, when the daily amplitude is small and non-periodic changes large.

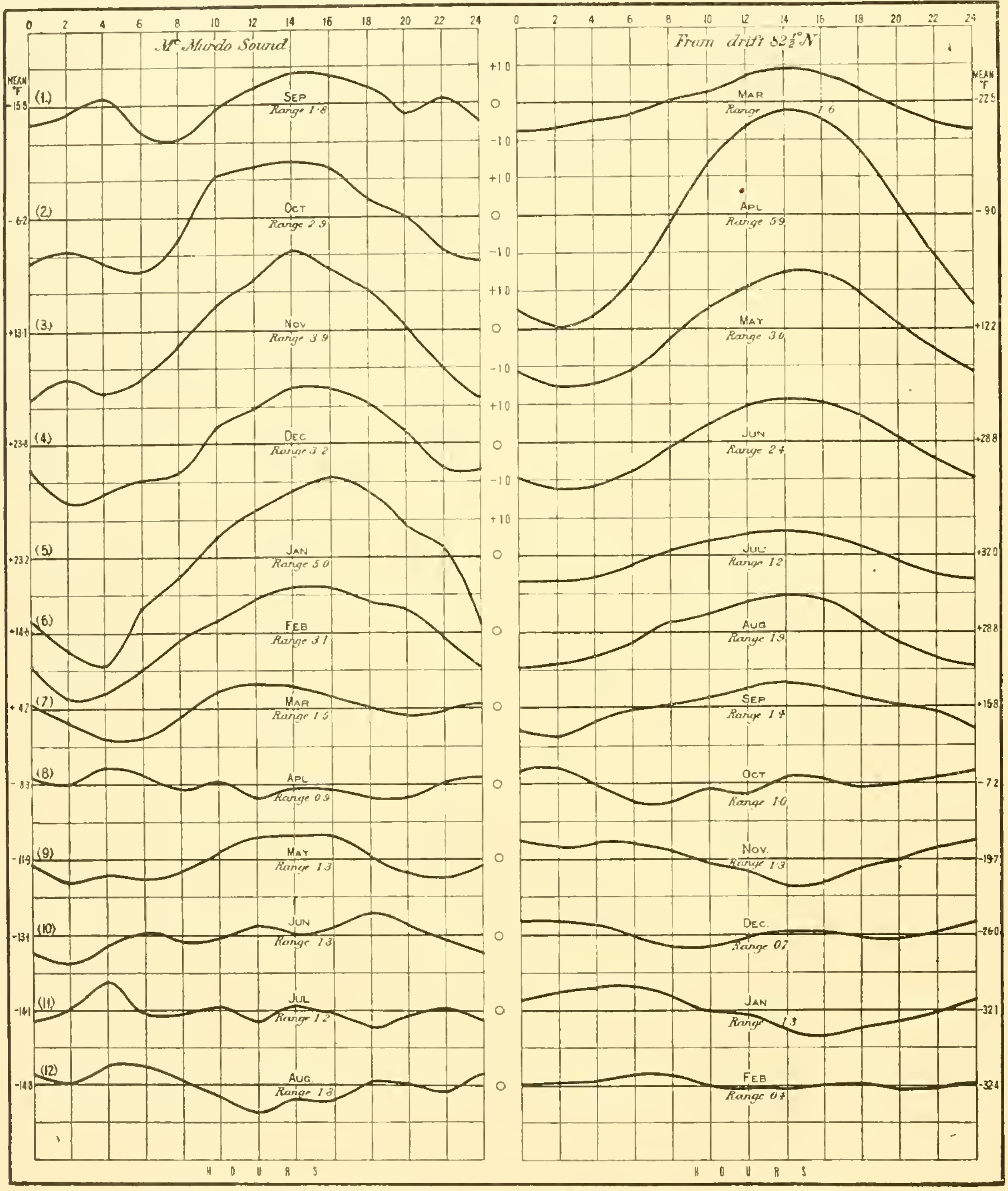

FIG. 20. Daily variation of temperature. McMurdo Sound and Fram Drift.

The sun returns after the winter on August 21, so that September is the first month of the year in which the sun is above the horizon every day. The days lengthen at a rapid rate, and on October 26 the sun does not set again until February 17, after which the days shorten rapidly until on April 24 the sun rises for the last time.

September to March—Period with direct Solar Radiation.

From September to March the daily variation of temperature is well marked and is obviously the result of the daily variations in the intensity of solar radiation.

The amplitude of the daily oscillation increases steadily from September to January and decreases from January to March, with the single exception of the month of December in which it is somewhat smaller than in November and January. As December showed this peculiarity each year it is probably a real effect.

Before discussing the physical meaning of the curves for this period in McMurdo Sound, it is desirable that we should compare the daily variation of temperature over the Barrier, and also at other places of high latitudes.

Daily Variation of Temperature on the Barrier.—The method of obtaining the daily variation from temperature observations made during sledging journeys on the Barrier has been described on page 21.

By combining the observations made on the Barrier by different parties and dividing the observations into months irrespective of the latitude in which they were made, the following results have been obtained, from which it will be seen that the temperature amplitude on the Barrier is much larger than in McMurdo Sound (table 20) :—

TABLE 21.

Daily Variation of Temperature on the Barrier.

	Party.	Date.	Latitude.	No. of days.	Mean temperature. °F.	Variation.						Amplitude.
						4	8	12	16	20	24	
November.	Motor. Polar .	Nov. 1 to Nov. 30. Nov. 7 to Nov. 30.	78° to 80½° 78° to 82½°	25 24 } 49	+2·4	−7·2	+0·8	+5·9	+5·9	+0·5	−6·2	15°
December.	Motor. Day's Depôt.	Dec. 1 to Dec. 18 . Dec. 27 to Dec. 31	80° to 78° 78° to 78°	18 5 } 23	+18·4	−6·0	−0·5	+3·5	+4·1	+2·0	−3·3	1°
January.	Day's Depôt.	Jan. 1 to Jan. 21 .	78° to 79½°	21	+14·0	−6·3	+0·7	+5·5	+5·4	+0·1	−5·6	13°
February.	Polar .	Feb. 19 to Mar. 4 .	83½° to 81°	15	−19·5	−5·7	+1·7	+6·4	+5·1	−0·1	−7·3	15°
	All .	Nov., Dec., Jan. .	..	..	+11·6	−6·5	+0·3	+5·0	+5·1	+0·9	−5·0	11½°

The variations for each month have been plotted in figure 21, but the scale has had to be reduced considerably from that used for figure 20, therefore the mean summer daily variation for Cape Evans has been plotted on the same figure for comparison.

For the three months November, December and January combined, the amplitude on the Barrier was 11·5°F., while for the same months in McMurdo Sound it was only 4·0°F. A comparison of the simultaneous temperatures measured on the Barrier and at Cape Evans is very instructive and gives a real insight into the cause of the large difference in the daily amplitudes. For this purpose the observations made during the southern march of the Polar Party have been plotted in figures 22a and 22b. The results of this party have been chosen, because, as already stated (page 19), the observations made with sling thermometers are well spaced over the day, and as minimum thermometers were not used there can be no question as to the reality of the low night temperatures.

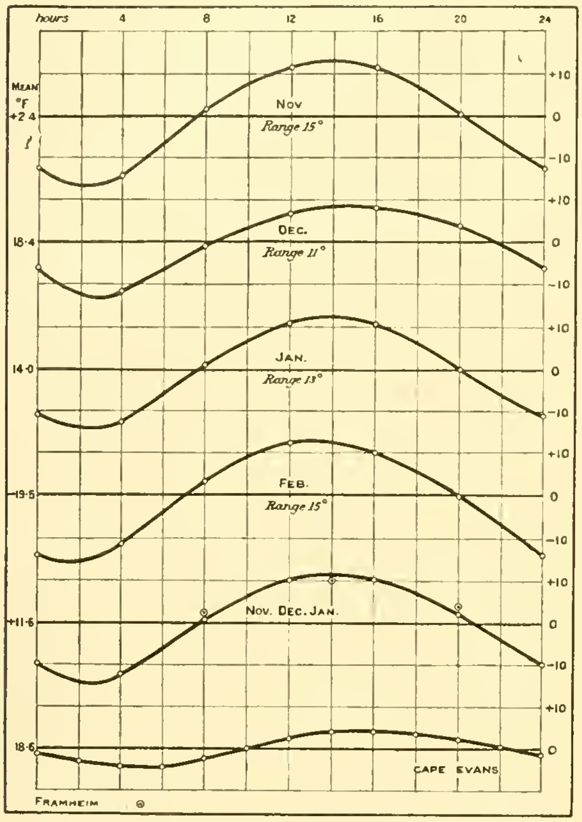

Fig. 21. Daily variation of temperature. Barrier.

The temperature at Cape Evans is shown in figure 22 by a thick line, and that of the Barrier by a thin line. On the latter curve the observations of the two observers (see page 20) are indicated by the use of dots and circles. As the observers were often separated by ten or more miles, and as the temperature changes were so rapid it is not surprising that on some occasions the observations vary by a few degrees, but whenever the temperature became fairly constant it will be found that the observations agree very well.

Between the 17th and 22nd November there was only a slight south-westerly breeze on the Barrier and from the figure it will be seen that the daily variation of temperature during this period was enormous, the average amplitude being 20°F. For comparison it may be stated that the mean daily amplitude over India is 19·2°F., while it is only in the desert areas when the sun is nearly in the zenith at midday that the amplitude goes above 30°F. Thus the Barrier with its relatively small change in daily insolation, the sun only oscillating between 10° and 35° above the horizon, has occasionally a temperature amplitude comparable with that of tropical India.

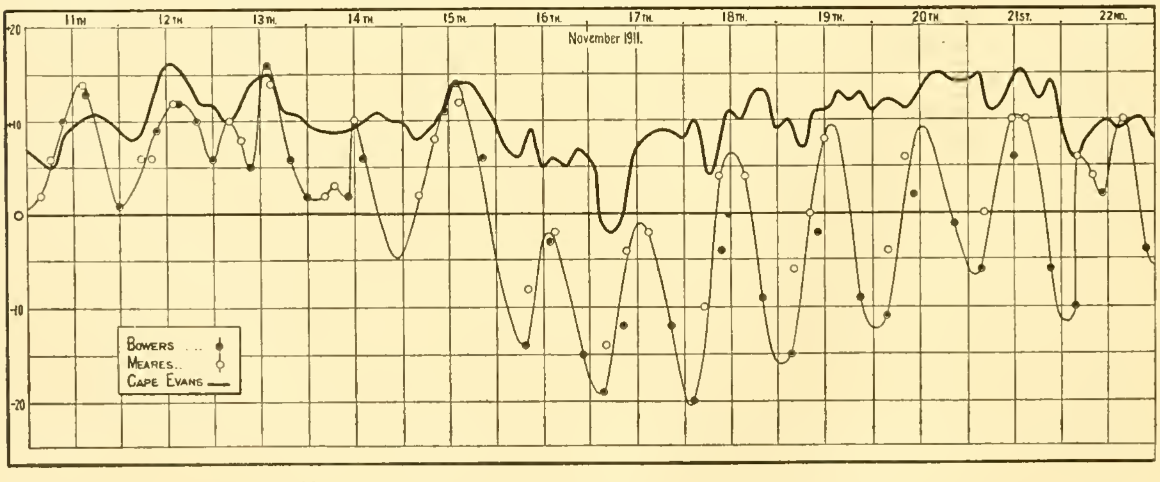

Fig. 22a. Simultaneous temperature on Barrier and at Cape Evans.

A comparison of the curves for the Barrier and Cape Evans reveals a most important relationship: the maximum temperatures on the Barrier are only a few degrees below the simultaneous temperatures at Cape Evans, while the minimum temperatures are very much lower. It is therefore not abnormally high temperatures, but abnormally low temperatures which cause the large temperature amplitude.

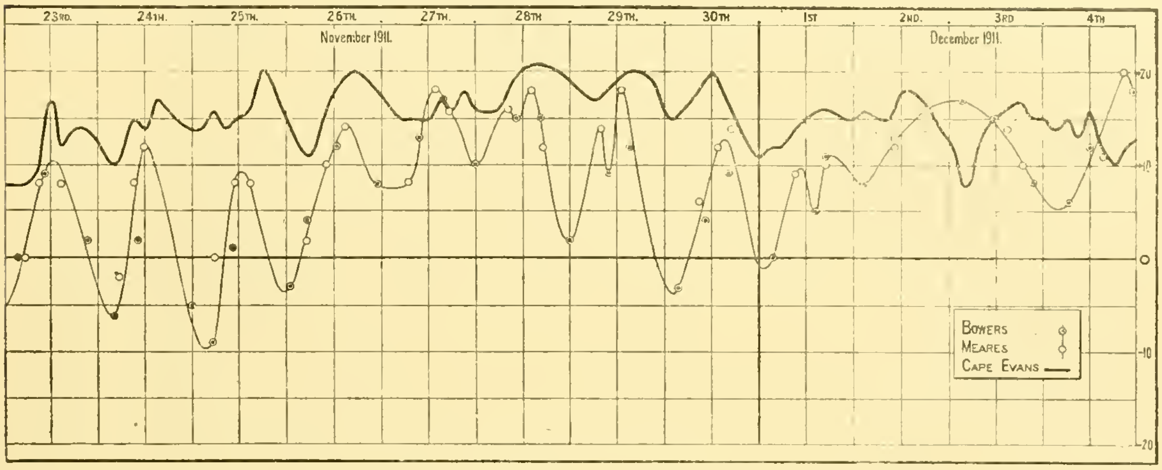

Fig. 22b. Simultaneous temperature on Barrier and at Cape Evans.

Daily Temperature Variation at Framheim.—It has been stated that the temperatures at Framheim were similar to those of the Barrier. It would therefore have been interesting to compare the daily variations at that station with the observations made on sledging journeys. Unfortunately temperature observations are only available at Framheim for the three hours of observations, 8 A.M., 2 P.M. and 8 P.M. These observations, however, show that the amplitude at Framheim was very nearly that measured on the open Barrier.

The relationship is clearly shown in the following table in which the same days have been used in each case for calculating the means:—

TABLE 22.

Month.	No. of Days used.	CHANGE FROM 8 A.M TO 2 P.M.			CHANGE FROM 2 P.M. TO 8 P.M.		
		Barrior.	Framheim.	Cape Evans	Barrier.	Framheim.	Cape Evans
		°F.	°F.	F.	F.	F.	F.
November . .	30	+5·8	+4·8	+2·0	−6·1	−3·7	−1·1
December . .	23	+5·0	+3·4	+2·6	−2·5	−1·8	−1·7
January . .	21	+5·3	+5·0	+2·3	−5·9	−3·6	−0·8
Nov., Dec., Jan. .	..	+5·4	+4·4	+2·3	−4·8	−3·0	−1·2

The large daily amplitude on the Barrier is therefore supported by the observations made at Framheim, and it is the largest amplitude yet measured in any polar region.

That the daily amplitude of temperature on the Barrier should be between two and three times greater than in McMurdo Sound points to some essential difference in the thermal conditions of the two places. The effect of solar radiation will be considered later, but it may be stated here that the variations of solar energy during the day were less on the Barrier than at Cape Evans, and therefore they are unable to account for the large difference in temperature variations. Under the same conditions of solar radiation the temperature of the air will depend entirely on the nature of the ground upon which the radiation falls, for the radiation does not warm the air directly, but only by first warming up the ground on which it falls. Now the Barrier is composed entirely of snow, which is never closely packed, the low temperature and entire absence of melting preventing the snow crystals combining into anything approaching solid ice. Unfortunately no actual measurements of the density of the Barrier snow are available, but it is almost certain that it was only ·2 or ·3 of that of ice. In McMurdo Sound on the other hand the surface is sea ice, which at the end of the winter has a very thin coating of snow. On account of the high wind which blows through the Sound there are then large patches of ice with no snow at all and the snow which does exist is large grained and very compact.

The thermal conductivity of ice is very much greater than that of snow, and the conductivity of snow is greater the greater its density.

Let us now consider the temperature of the surface of the Barrier during a bright sunny day and the following night. During the day time the sun shines on the snow and although a large proportion is reflected, some is absorbed. As the conductivity of snow is very small this heat is not conducted downwards to any considerable depth, but is all retained near the surface ; also on account of its small density the thermal capacity of snow is small. Thus a very little heat, being retained near the surface and acting on a substance of small heat capacity, raises the temperature of the snow near the surface appreciably. During the night the snow surface radiates heat to the clear sky and its temperature falls, but those conditions which caused its temperature to rise while the sun was shining now act in the opposite direction. On account of the small heat capacity of the snow a small loss of heat by radiation lowers the temperature considerably, and as the low conductivity prevents heat being conducted from below, the temperature of the surface may fall very greatly during a clear night.

Let us now consider that the Barrier is changed into ice with just sufficient snow on the surface to give it the same absorbing power. The amount of heat absorbed will be the same as before, but owing to the much greater conductivity of ice—at least a hundred times as great as that of snow—changes of temperature at the surface are accompanied by a greater transference of heat into the mass of the ice. This keeps the surface temperature lower during the day, but during the night when the air temperature falls this same amount of heat can again reach the surface, and if the radiation is particularly great still more heat which was stored up in the ice will be conducted outwards and so prevent the temperature of the surface falling so low as it would have done had the mass been snow through which heat can only pass slowly to the surface. If now instead of the Barrier we consider a sheet of ice floating on the sea, the temperature of which cannot fall much below freezing point, we have a still greater protection against an excessive fall of temperature during the night ; for the ice with its high conductivity is always conducting heat from the warm sea below and is therefore always a little warmer than the mean temperature of the air above it. Thus as soon as the surface temperature falls owing to radiation, the heat from the sea stored up in the ice becomes available to counteract any large fall of temperature of the surface due to radiation.

Thus we see that the chief difference between a snow and an ice surface is that the latter prevents low radiation temperatures, while excessive radiation always produces low temperatures over the snow.

We have now the explanation of the different daily variations of temperature over the Barrier and over McMurdo Sound. Very low night temperatures are possible over the former owing to the bad conductivity of the snow, while over the latter the high conductivity of the ice and the store of heat retained in it from the warm sea below prevent low temperatures during the night. It will be remembered that the observations showed that the day temperatures of the Barrier were nearly the same as those at Cape Evans, while the night temperatures on the former were many degrees lower than those at the latter.

Comparison of the Daily Temperature Variation during September to March at McMurdo Sound and at other Stations in High Latitudes.

So far as I am aware there is only one other set of temperature observations in high latitudes so complete as these at McMurdo Sound with which to make comparison. The observations made during the drift of the *Fram* in a mean latitude of between 82° and 83° N. give the daily temperature variation for each month from a homogeneous series of observations extending over three years. For comparison the curves given in Professor Mohn's masterly discussion of the meteorology of that expedition have been added to figure 20 as they show marked and important differences from those for McMurdo Sound. For purposes of comparison the northern observations have been plotted against those of the corresponding months in the south ; thus January in the north is plotted against July in the south and so on.

The first striking difference is in the time of year at which the daily variation has its greatest amplitude. In McMurdo Sound the amplitude increased slowly from the return of the sun on August 24th until January (neglecting for the moment the decrease in December), while in the north the amplitude increased more rapidly and the greatest amplitude was reached as early as the second month after the return of the sun. From this month, April (corresponding to October in the south), the amplitude in the north decreased rapidly to a very small value at midsummer, after which there was a temporary rise during the last two months, August and September, before the sun set for the winter.

The contrast in this respect shown between the McMurdo Sound and *Fram* data is found to be present when other stations are investigated. There appear to be two types of polar climate. In one, of which the *Fram* conditions are typical, the daily amplitude of temperature has its maximum in one of the spring months, while in the other the maximum daily amplitude is found in a summer month. The following two tables give examples of the two types :—

TABLE 23.

'Fram' Type.

Month.	*Fram* 82½° N.		*Gauss* 66° S.	
	Amplitude.	Mean temperature.	Amplitude.	Mean temperature.
	°F.	°F.	°F.	°F.
S. September N. March . .	1·6	−22·5	6·6	+ 0·1
S. October N. April . .	5·9	− 9·0	9·3	+ 8·8
S. November N. May . .	3·0	+12·2	7·5	+19·6
S. December N. June . .	2·4	+28·8	6·2	+29·7
S. January N. July . .	1·2	+32·0	5·6	+30·4
S. February N. August . .	1·9	+28·8	4·3	+26·4
S. March N. September . .	1·4	+15·8	*	+17·1

* The *Gauss* daily amplitude for March is given as 3·82°C.=6·9°F. in Deut. Sudpolar Expedition, Meteorology, Vol. 1, part 1, page 55 This, however, is much too large. During the first sixteen days of March the temperature observations were taken on board the *Gauss*, and during twelve of the remaining days in a Stevenson screen on the ice near the ship. Calculating the amplitude for the 16 days on which the observations were made on the ship and for the 12 on the ice we obtain the following: Ship 4·71°C., Ice 2·00°C. As the ship's observations obviously give too large an amplitude and twelve days are not sufficient to give a reliable value, I have not included this month in my discussion.

TABLE 24.

'McMurdo' Type.

Month.	McMurdo Sound 77½° S.		Snow Hill 64½° S.		Framheim * 78½° S.	
	Amplitude.	Mean temperature.	Amplitude.	Mean temperature.	Amplitude.	Mean temperature.
	°F.	°F.	°F.	°F.	°F.	°F.
September . .	1·8	−15·5	4·6	+ 3·9	6·4	−35·7
October . . .	2·9	− 6·2	5·0	+14·9	5·4	−11·6
November . .	3·9	+13·1	5·6	+17·4	8·6	+ 4·1
December . .	3·2	+23·8	6·1	+28·4	5·0	+20·1
January . . .	5·0	+23·2	4·3	+30·4	7·2	+14·9
February . .	3·4	+14·6	4·9	+25·6	..	..
March . . .	1·5	+ 4·2	4·0	+13·5	..	..

The two examples under the *Fram* type show the maximum amplitude early in the spring after which the amplitude decreases until midsummer. In the case of the *Fram* there is a temporary rise during August before the amplitude begins to decrease to its winter value.

The amplitude in the second type increases until the summer is reached, and it is interesting to notice that in each case the warmest of the three summer months shows a slight decrease in the amplitude as compared with the months on either side.

Both Professor Mohn and Professor Meinardus have given explanations of the *Fram* type, both are different and both appear not to be the full explanations. A discussion of these two explanations will be fruitful in showing some important factors connected with the temperature of polar regions and therefore I propose to give their explanations, point out where they fail, and then attempt to give a true explanation.

Professor Mohn's Explanation of the 'Fram' Type of Daily Temperature Variation.—Mohn first examines the effect of cloud and wind on the daily variation of temperature and finds that both these factors reduce the amplitude. The effect of the cloud is to reduce the variations in solar radiation and radiation from the surface, while the wind stirs up the lower atmosphere and distributes the effect of the varying temperature of the ground through a large mass of the atmosphere. He also calculates the difference in the amount of solar energy received on each square centimetre of surface at midday and midnight, on which the temperature variation must ultimately depend.

We will now quote from page 605 of Mohn's discussion:—

> 'In the following table I have put together the mean monthly values of (1) the diurnal amplitude † of the radiation of the sun and sky, a; (2) the amount of cloud, c;

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[*] The data for Framheim are only approximate. At this station temperature observations were taken only at 8 A.M., 2 P.M. and 8 P.M. Assuming as a rough approximation that the mean of the 8 A.M. and 8 P.M. observations gives the mean of the day and that the 2 P.M. observation is near the maximum, the approximate amplitude has been taken as twice the excess of the 2 P.M. mean above the mean of the 8 A.M. and 2 P.M. observations.

[†] I have taken the liberty of altering the word 'range' used by Mohn into 'amplitude' in order to keep the use of these two words consistent throughout this work.

(3) the velocity of the wind in metres per second, v; and (4) the diurnal amplitude of the temperature of the air, A, for the months March to September.

Table 25.

Month.	a	c	v	A
	Cal.	0—10	m.p.s.	°C.
March	0·168	5·62	4·25	0·89
April	0·515	4·84	4·05	3·29
May	0·625	7·57	4·97	1·69
June	0·633	8·67	4·56	1·32
July	0·639	9·06	4·40	0·69
August	0·681	8·45	4·31	1·07
September	0·273	9·10	4·74	0·78

'The radiation varies regularly from month to month, and is nearly constant from May to August.

The amount of cloud varies considerably, and is highest from May to September.

The velocity of the wind does not vary much.

The diurnal amplitude of the temperature shows the largest variation during the months from March to September.

From March to April the amplitude of radiation increases rapidly, the amount of cloud decreases to a minimum, as does also the velocity of the wind; and all three factors are working to raise the diurnal amplitude of the temperature. From April to May the amplitude of radiation rises a little, but the amount of cloud is rapidly increasing, and also the velocity of the wind. The two last-named factors bring the amplitude of the temperature down notwithstanding the effect of the radiation.

From May to June the amplitude of radiation increases very little, but the amount of cloud increases one degree, and the temperature amplitude is lowered by the cloudiness in spite of the increasing radiation and decreasing wind velocity.

From June to July the same process goes on.

From July to August the amplitude of radiation rises (the mean latitude of the *Fram* being relatively lowered), and the amount of cloud and the velocity of the wind decreases. The temperature amplitude rises, all three factors working together.

From August to September the amplitude of radiation is going down rapidly, the amount of cloud and the velocity of the wind are increasing, and all three factors cause the amplitude of the temperature to decrease.

We see that the maxima of the diurnal amplitude of the temperature in both April and August, correspond with a higher amplitude of the radiation, and minima of cloud and wind velocity.

The low amplitude of the temperature in summer, particularly in July, corresponds to a high degree of cloudiness during a season which has hardly one clear day.'

There can be little doubt that Professor Mohn's explanation contains part of the truth; but if the observations are examined in another way it will be seen that it is not the whole.

Professor Mohn attributes most of the irregularities in the temperature amplitude from month to month to the changes in the cloud and wind. That this cannot be so will be seen from the table given on page 604 of Mohn's work, part of which is reproduced here.

TABLE 26.

Month.	a.	CLOUD.				WIND.			
		Cloud.	A.	Cloud	A.	Wind	A.	Wind	A.
April	0·515	0·0	3·56	10	2·63	3·0	3·52	6·0	2·16
May . .	0·625	0·0	1·89	10	1·44	3·0	2·28	6·3	1·72
June . . .	0 633	4·5	2·36	10	1·08	3·2	1·39	6·5	1·03
July	0·639	4·4	0·77	10	0·74	3·6	0·69	5·9	0·64

This table has been computed by taking the mean daily temperature amplitude on days with 0 cloud and 10 cloud (in June and July there were no clear days, so days less than half overcast were used), and on days with mean wind velocity greater and less than 4·5 miles per second. The values entered in the columns headed Cloud and Wind are the mean values of these factors during the days considered.

Now it will be noticed that with one exception in spite of the increase of the amplitude of the solar radiation from April to July the daily amplitude of temperature decreases in the same period *in every type of weather.*

This gives good reason to believe that if there had been no change in the type of weather the temperature amplitude would still have decreased. Therefore we cannot ascribe the decrease in temperature amplitude to changes in wind and cloud.

Further the fact that the temperature amplitude was greater during April and May with completely overcast skies than it was during June and July with skies less than half overcast, gives further support to the conclusion that cloud was not the chief cause of the decrease in the amplitude. On the other hand as the wind decreased every month from May to August (see table 25), wind cannot have been the cause.

Professor Meinardus's Explanation of the 'Fram' Type of Daily Temperature Variation.—In his discussion of the meteorological results of the Gauss Expedition, Meinardus says :—

> 'The amplitude of the daily period of temperature is greatest during the spring months and in March ;* in the summer it is considerably less, probably because the midday temperature during this time is approximately that of the freezing point which cannot be passed on account of the heat during the process of melting. Also during the summer the effect of radiation on the air temperature is reduced owing to the shortening of the night and lengthening of the period of sunshine. Similar changes of the temperature amplitude were found during the drift of the *Belgica* and the drift of the *Fram.* Also there the regular variations were greatest in the spring. On the contrary the greatest values occurred in January at the *Discovery* station where the freezing point was seldom reached.'

Two probable explanations are given in this paragraph, neither of which was considered by Mohn : (*a*) a curtailing of the amplitude in the warmer months due to the temperature of the surface being unable to rise above the freezing point, and (*b*) a decrease in the amplitude due to the shortening of the night and the lengthening of the period of sunshine.

The latter of these two is obviously based on a misconception ; the daily amplitude of temperature does not depend on the amount of energy received from the sun, but on the difference between the amount of energy received at midday and at midnight. In any one latitude the difference of energy received on a square centimetre of ground at midday and midnight increases right up to the summer solstice. There is therefore no decrease in the

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* See footnote to page 95.

amplitude of solar energy between the spring and summer to account for the decrease of temperature amplitude.

As the temperature of an ice surface cannot rise above the freezing point, it is obvious that the temperature amplitude will be decreased as soon as the mean temperature closely approaches that point. This is in all probability the reason why the warmest months of the McMurdo type of daily temperature variation have a smaller amplitude than those on either side. Even when the mean temperature of the month is low, as at Framheim and McMurdo Sound, there are a few days in the month when the maximum temperature might have gone higher if the melting of the ice had not prevented the complete warming up of the surface. It must be remembered that the temperature amplitude of the surface itself is many degrees greater than that of the air, and therefore the surface might reach and strive to pass the freezing point on many days with air temperature well below that point.

But this explanation does not account for the rapid decrease in amplitude which takes place in the *Fram* type a long time before the mean temperature gets near to the freezing point. Thus in the case of the *Fram* the amplitude falls from 5·9°F. in April to half its value in the following month, yet in the latter month the mean temperature was practically twenty degrees below the freezing point. The same was the case, but to a lesser extent, with the *Gauss*. In November the maximum air temperature only once reached the freezing point and throughout the month the mean maximum temperature was 7·5°F. below the freezing point, yet in spite of this the temperature amplitude decreased from 9·3°F. in October to 7·5°F. in November.

Suggested Explanation of the Variation in the Amplitude During the Period September to March.—There can be no doubt that the prime factor in determining the daily temperature amplitude is the solar energy amplitude. The first step in the investigation should, therefore, be to plot the observed temperature amplitudes against the calculated energy amplitudes to see if there is any close relationship. This has been done for two stations of the *Fram* type and two of the McMurdo type, namely, (*a*) *Fram* and *Gauss* : (*b*) McMurdo Sound and Snow Hill, and the observations made on the Barrier have been included for reference. Mr. Normand, of the India Meteorological Department, has very kindly made the calculations of the solar energy amplitude by the method described by Mohn on page 588 of his discussion of the meteorological results of the Fram Expedition. This method takes into account both the energy received directly from the sun and also that diffused from the illuminated atmosphere. The following table contains the results of the radiation calculations :—

TABLE 27.

Solar Radiation (*gram. cals. per min. per sq. cm. of horizontal surface*).

MONTH.		SNOW HILL 64° 21′ S.			GAUSS W. Q. 66° 02′ S.			MCMURDO SOUND 77° 35′ S.			FRAM DRIFT 81° 41′N.–83° 12′.		
South.	North.	Midday.	Midnight.	Difference.	Midday.	Midnight.	Difference.	Midday.	Midnight.	Difference.	Midday.	Midnight.	Difference.
September	March	0·92	0·00	0·92	0·86	0·00	0·86	0·30	0·00	0·30	0·19	0·02	0·17
October	April	1·48	0·00	1·48	1·40	0·00	1·40	0·83	0·05	0·78	0·64	0·12	0·52
November	May	1·88	0·02	1·86	1·80	0·03	1·77	1·31	0·19	1·12	1·03	0·41	0·62
December	June	2·04	0·05	1·99	2·01	0·07	1·94	1·52	0·34	1·18	1·22	0·59	0·63
January	July	1·96	0·04	1·92	1·90	0·05	1·85	1·37	0·26	1·11	1·14	0·50	0·64
February	August	1·64	0·00	1·64	1·58	0·01	1·57	1·02	0·08	0·94	0·85	0·17	0·68
March	September	1·13	0·00	1·13	1·05	0·00	1·05	0·48	0·00	0·48	0·32	0·05	0·27

In figure 23 the temperature amplitudes given in tables 23 and 24 (pages 59 and 60) have been plotted against the solar energy amplitudes given above, the points for the different stations being indicated by various signs, and the months to which they refer by entering against each the initial letters of the months. For the sake of comparison the months for the *Fram* have been marked both by their own initials and by the initial letters of the corresponding months in the south.

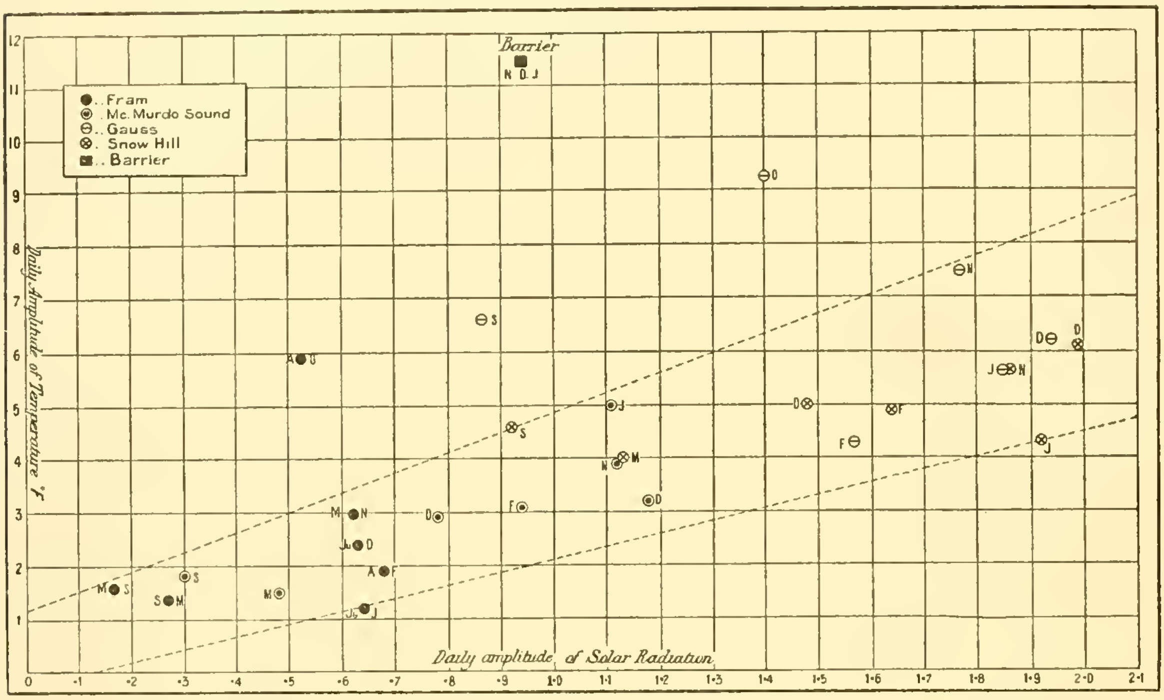

FIG. 23. Amplitude of temperature plotted against amplitude of solar radiation.

The first striking feature of this diagram is the relatively small variations from a linear relationship shown by most of the points. Neglecting for the moment the point for the Barrier, twenty-four of the twenty-seven points lie within the two dotted lines. This leads to the conclusion that except for small differences the relationship between temperature amplitude and energy amplitude is linear.

The three points which do not lie within the dotted lines are the most important for our present discussion. It will be noticed that they are the spring months of the *Fram* type, being the *Fram's* observations for April and the *Gauss's* observations for September and October. Both Mohn and Meinardus in their discussion of the temperature amplitude tried to explain the low values of the amplitude in the summer, we now see that it was the high amplitude in the spring which needs explanation.

The abnormal temperature amplitude on the Barrier is clearly shown by the position of the point for the Barrier near the top of the diagram, and it is the position of this point which supplies the solution of the whole problem.

We have already shown that the difference in temperature amplitude over the Barrier and McMurdo Sound is due to the sea ice preventing low nocturnal radiation temperatures. This action of the sea ice could not exist if there were a thick layer of loose snow upon it. Now both the *Fram* and *Gauss* were surrounded by sea ice, it is therefore important to examine the varying character of the snow covering of the ice during the year. Unfortunately I cannot find in Mohn's discussion of the *Fram's* observations any remarks on the character of the snow accumulations on the sea ice during the voyage, but in Meinardus's account of the *Gauss* observations there are a few important remarks. We will therefore consider the latter and then see how far similar considerations can be applied to the *Fram* conditions.

The *Gauss* was frozen in on February 22. As soon as the sea was completely frozen over snow commenced to accumulate on the surface, and the depth of the snow increased throughout the winter and first months of spring.

The exact depth of the snow is not given, but we are told that the snow surface rose about 60 c.m. from June to October (page 157 *). With the increasing intensity of solar energy the surface however quickly underwent an important change, to quote Meinardus (page 154).

> 'The advent of warm weather and strengthened solar radiation produced a gradual lowering of the snow surface on account of the melting together of the snow-crystals, a process, however, which was often retarded through fresh snow accumulations. Still the consequence of the progressive concentration of the snow was that the old snow gauges which had been snowed up in the middle of October appeared one after the other.'

We see from these remarks an important change in the character of the snow-covering to the sea ice. At the end of the winter and until the end of October there was an appreciable depth of snow which on account of low temperatures and the absence of melting would be in a comparatively loose condition, the surface only being compacted by the wind. Such a snow layer would have a low conductivity which together with its depth would make it an effective protection against a supply of heat from the underlying sea ice. The surface during September and October would therefore approach the condition of the Barrier, with a consequent large daily amplitude of temperature.

After October the snow, as we are informed, became more compact and its thickness decreased. This process probably continued at first rapidly and then more slowly until midsummer, when what little snow was left would oppose only a small impediment to the transfer of heat from the sea ice to the air. Thus we should expect at the *Gauss* station the daily amplitude of temperature to decrease, relatively to the amplitude of solar radiation, from October to midsummer. An examination of figure 23 will show that this occurred: in spite of increasing amplitude of radiation from October to December the temperature amplitude greatly decreased and in December the point for the *Gauss* station is exactly in the middle between the two dotted lines. After December the points for the *Gauss* station do not depart largely from the linear relationship between temperature amplitude and solar radiation amplitude.

Returning now to a consideration of the *Fram* observations, there is no reason to suppose that the sea ice in the north would not also be covered by a blanket of dry loose snow at the end of the winter. Also as the snowfall is known to be heavier in the north than the south the depth of snow was probably greater around the *Fram* than around the *Gauss.* It is interesting to notice that the two points for March and April for the *Fram* lie on the line joining the point for the Barrier with the origin. This is what would be expected if the surface were similar in the two regions and the temperature amplitude depended only on the radiation amplitude.

By midsummer in the north as in the south the snow-covering would have become a very poor insulator and we find a rapid decrease in the temperature amplitude. The *Fram* point for June is in the middle between the two dotted lines, showing therefore a normal relationship between the temperature and insolation amplitudes. The only difficulty is the low

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* Meinardus. Deut. Sudpolar-Exped. Meteorologie, Band I.

position of the point for May; for one would have expected this to be about half way between the points for April and June, as was the case at the *Gauss* station. Here I think Mohn's explanation has weight. Compared with April, May was a cloudy and windy month and these together would have reduced the temperature amplitude if there had been no change of surface.

Therefore the effect of the cloud and wind must be added to the change of surface, thus accounting for the low position of May relatively to April, but it is interesting to notice that in spite of the cloud and wind the point for May is higher than the mean position of the other points, showing that the surface had not got into the normal state for sea ice. The low position of the *Fram* point for July is in all probability due to the explanation given by Meinardus; for the mean temperature of this month was the freezing point, and the daily amplitude of temperature could not be great above a wet snow surface.

From this discussion we see that the variation of the temperature amplitude in the *Fram* type is mainly accounted for by changes in the surface and solar radiation, these are the chief factors, small variations may be due to other causes such as cloud, wind or local conditions.

We must now examine why the McMurdo type differs from that of the *Fram* type. The explanation is that owing to the local conditions there was no large change at any of the stations of this type in the surface conditions between the spring and summer. At Framheim the surface was that of the Barrier which can undergo no change. At McMurdo Sound and Snow Hill the observations were on the coast between a snow-covered land and a frozen sea. In McMurdo Sound there was little change of the snow-covering of the land throughout the year and the sea ice was almost swept clear of snow by the blizzards during the winter. In fact there was more snow on the sea ice in January than in October, and the effect is seen by the relatively high position of the point for the former month in the diagram. Similar conditions probably held at Snow Hill which was subject to very high dry winds which must have prevented any large accumulation of snow on the sea ice.

Summary and Conclusions: Temperature Variation in the Period of Solar Activity, September to March.—(*a*) The daily temperature amplitude during this period over sea ice nearly free from snow is a linear function of the daily amplitude of solar energy.

(*b*) In consequence the temperature amplitude increases from the return of the sun to midsummer and then decreases, except that the warmest month has generally a lower amplitude due to the inability of the surface to warm up above the freezing point. This gives rise to the McMurdo type of daily temperature variation.

(*c*) A layer of loose snow increases the temperature amplitude.

(*d*) In consequence, in situations where there is a layer of loose snow covering the sea ice in the early spring months the temperature amplitude is relatively high. As the solar energy increases the snow-covering becomes more dense and thinner, in consequence the temperature amplitude generally decreases from spring to midsummer in spite of the increasing amplitude of solar energy. This gives rise to the *Fram* type of daily temperature variation.

(*e*) In places where the surface consists of a very deep layer of snow—for example the Barrier—the temperature amplitude is very large.

Daily Variation of Temperature during May, June and July. Period with No Direct Solar Radiation.

During May, June and July the sun does not rise above the horizon in McMurdo Sound and the amount of indirect radiation from the sky is so small that it may be entirely neglected.

In these circumstances one would not expect any consistent daily variation of the temperature, and a first glance at the curves for these months given in figure 20, page 54, seems to confirm this opinion.

A closer investigation, however, shows that the curves are not entirely irregular. By taking the mean of the three months, May, June and July together, we obtain curve 1 in figure 24. This curve has been derived from observations extending over four years, it is therefore the mean curve of 368 days; hence it should be free from accidental irregularities. This curve shows two remarkable features :

(*a*) The temperature is above the average from 9 A.M. to 7 P.M. and below for the remainder of the day except for

(*b*) a sudden and pronounced rise at 4 A.M.

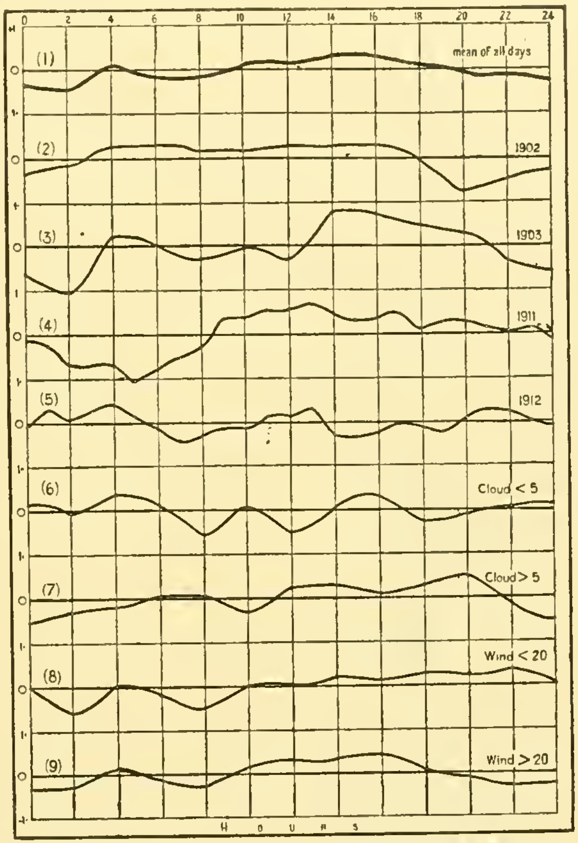

FIG. 24. Daily variation of temperature. McMurdo Sound. May, June and July.

The question at once arises—are these features real ?

The usual method for testing the reality of a feature which is shown in the average of a large number of separate events, is to divide the data up into different blocks and investigate each one separately. In the present case our data are taken from three months' observations, May, June and July, in each of four separate years. A convenient method of dividing them up is to combine the three months together for each year giving four separate blocks; again the data for May from the four years may be combined, and similarly those for June and July giving another three separate blocks. By this method we can see whether the feature looked for is shown in each year and also whether it appears separately in each of the three months. The number of observations which falls in each sub-division is small, therefore the irregularities will not neutralise one another so well as when all the observations are included in one block. We must therefore expect the curves for each sub-division to be more irregular than that for the whole data shown in curve 1. But if the features are real they should show up against the irregularities.

We are looking for two features : if (*a*) is present, *i.e.*, if the temperature is above the average from 9 A.M. to 7 P.M., then in each of the divisions the sum of the departures from the mean between these times should be positive; if (*b*) is present and there is a sudden and pronounced rise at 4 A.M., the departure at 4 A.M. should be greater than the average departure at 2 A.M. and 6 A.M.; in other words,

$$\text{departure at 4 A.M.} - \frac{\text{departure at 2 A.M.} + \text{departure at 6 A.M.}}{2}$$

should be positive. Thus we have two numerical relationships to look for.

The data have been divided as described above and the resulting departures for every two hours from the mean of the day calculated. The curves for the mean of each month, *i.e.*, the means for May, June and July during the four years, have already been seen on figure 20, page 54. The means for each year taken separately are shown as curves 2 to 5 on figure 24. The results of the numerical tests for (*a*) and (*b*) are entered in the following table, where a plus sign indicates that the feature is present and a negative sign that it is absent :—

TABLE 28.

Data arranged according to		TEST FOR (*a*) MEAN DEPARTURE FOR HOURS 10 TO 18 INCLUSIVE	TEST FOR (*b*) EXCESS OF THE DEPARTURE FOR 4 A.M. OVER THE MEAN DEPARTURE FOR 2 A.M. AND 6 A.M.
		A positive sign indicates the presence of the effect	A positive sign indicates the presence of the effect
		°F.	°F.
All Days	Curve 1, Fig. 24	+0·19	+0·35
Years May, June, July, 1902	Curve 2, Fig. 24	+0·18	+0·18
,, ,, ,, 1903	,, 3 ,, 24	+0·34	+0·75
,, ,, ,, 1911	,, 4 ,, 24	+0·42	−0·02
,, ,, ,, 1912	,, 5 ,, 24	−0·12	+0·44
Months May of all years .	Curve 9, Fig. 20	+0·98	+0·15
June ,, ,, .	,, 10 ,, 20	+0·20	+0·10
July ,, ,, .	,, 11 ,, 20	−0·10	+0·80
Cloud < 5 throughout the day	Curve 8, Fig. 24	−0·09	+0·32
Cloud > 5 ,, ,,	,, 9 ,, 24	+0·12	−0·05
Wind < 20 miles in every hour during the day.	Curve 6, Fig. 24	+0·13	+0·39
Wind > 20 miles in one or more hours during the day.	,, 7 ,, 24	+0·28	+0·27

The Reality of the Feature : Excess of Temperature During the Hours 9 *a.m. to* 7 *p.m. during May, June and July.*—From column 2 of table 28 we see that taking all the observations together the mean excess of temperature during these hours is positive. It is also positive in each of the years 1902, 1903 and 1911, each considered separately ; it is absent, however, in 1912. When the months are taken separately the feature is seen to be present in May and June but not in July. Thus out of the seven separate sub-divisions of the data five show the effect while only two do not. This must be taken as very good evidence of the reality of the effect. We can therefore conclude that in McMurdo Sound during the three winter months when there is no direct solar radiation the day is warmer than the night. In other words in spite of the absence of a varying solar radiation the variations of temperature are in the same direction, but much less in intensity, than when the sun shines.

It would be of great interest to know if this were a feature of the whole of the Antarctic in high latitudes, but unfortunately all the other stations in the Antarctic from which we have data are either very near or just outside the polar circle, hence they received some radiation during these months. They each have warmer days than nights, but this may be due to the sun and therefore cannot be taken as proof of the presence of the feature found in McMurdo Sound.

The Reality of the Feature : Marked Excess of Temperature at 4 a.m.—The results of the test for this feature are shown in column 3 of table 28. Four A.M. is warmer than the mean of 2 A.M. and 6 A.M. in six out of the seven sub-divisions into which the data have been divided. It was absent only in the year 1911. There is thus even better evidence for the reality of this feature than was found for the days being warmer than the nights.

A glance at the curves for McMurdo Sound in figure 20, page 54, will show that this excess of temperature at 4 A.M., which is present throughout the winter months, becomes more marked at other periods. While it is feebly marked during May and June it becomes so large in July and August that it then forms the main maximum temperature of the day. It is still well marked in September, but now the returning sun has produced a larger maximum later in the day. From October to March the 4 A.M. temperature shows no maximum, but it is noteworthy that of these months October, November and March show a similar effect at 2 A.M. ; may not this be the same effect but displaced by the minimum due to the solar radiation falling very near to 4 A.M. ? After March the effect reappears and is very marked in April.

We now see that in McMurdo Sound there is an excess of temperature at 4 A.M. compared with 2 A.M. and 6 A.M. in every month from April to September inclusive, and the same effect is possibly present in October, November and March although during these months the minimum of the solar temperature amplitude is a disturbing factor.

The same effect is clearly seen in the temperature observations at the *Gauss* station although data for one year only are available.

The *Gauss* wintered just outside the Antarctic Circle and therefore direct solar insolation was never entirely absent ; yet during four months, July to October, the maximum at 4 A.M. is clearly distinguishable. As the curves given in Plate V of Meinardus's work have been smoothed the effect we are discussing is not clearly shown. I have therefore plotted the actual data from midnight to 8 A.M., and reproduce them here in figure 25. In July and August the maximum is clearly visible as an actual peak on the curves. It is visible in September and October as an interruption in the smooth course of the curve at 4 A.M.

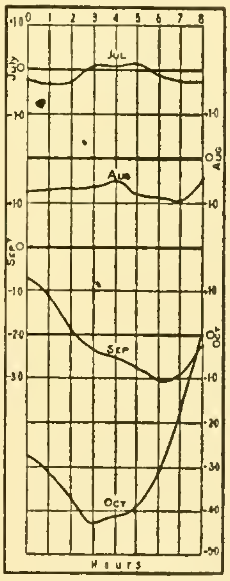

FIG. 25. Daily variation of temperature. *Gauss* station. Midnight to 8 A.M.

The Snow Hill observations also show the same effect in July and August as will be seen from the following table :—

TABLE 29.

Departures from Mean Temperature at Snow Hill.

Month	0	1	2	3	4	5	6	7	8 A.M
July . .	–0·18	–0·34	–0·47	–0·34	–0·17	–0·52	–0·37	–0·61	–0·31
August . .	–0·10	+0·16	+0·15	–0·22	–0·08	–0·08	–0·20	–0·38	–0·25

The Cause of Warm Days in the Absence of Insolation and of the Excess of Temperature at 4 a.m.—We have now shown that the former of these effects is real in McMurdo Sound, which is the only station at a sufficiently high latitude to allow of the effect being visible, while the latter effect has been shown by all tests to be a real factor in McMurdo Sound and to have been present at the *Gauss* station and Snow Hill. It is not shown in the only observations that we have from Cape Adare (see page 73 below). I am not at present able to offer any explanation of either of the effects. The only glimmer of light comes from the observations made on the *Fram* voyage in north polar regions, which will now be discussed, but up to the present this has not led towards a physical explanation.

Daily Temperature Variation in North Polar Regions from the Records of the 'Fram.'—During the voyage of the *Fram* which lasted from July 1893 to August 1896, the sun was below the horizon during 12 months. From the observations Mohn deduces the daily variation of temperature during these dark months shown in curve 1 of figure 26. It will be seen that it is totally different from the corresponding curve for McMurdo Sound shown as curve 1 of figure 24, page 67.

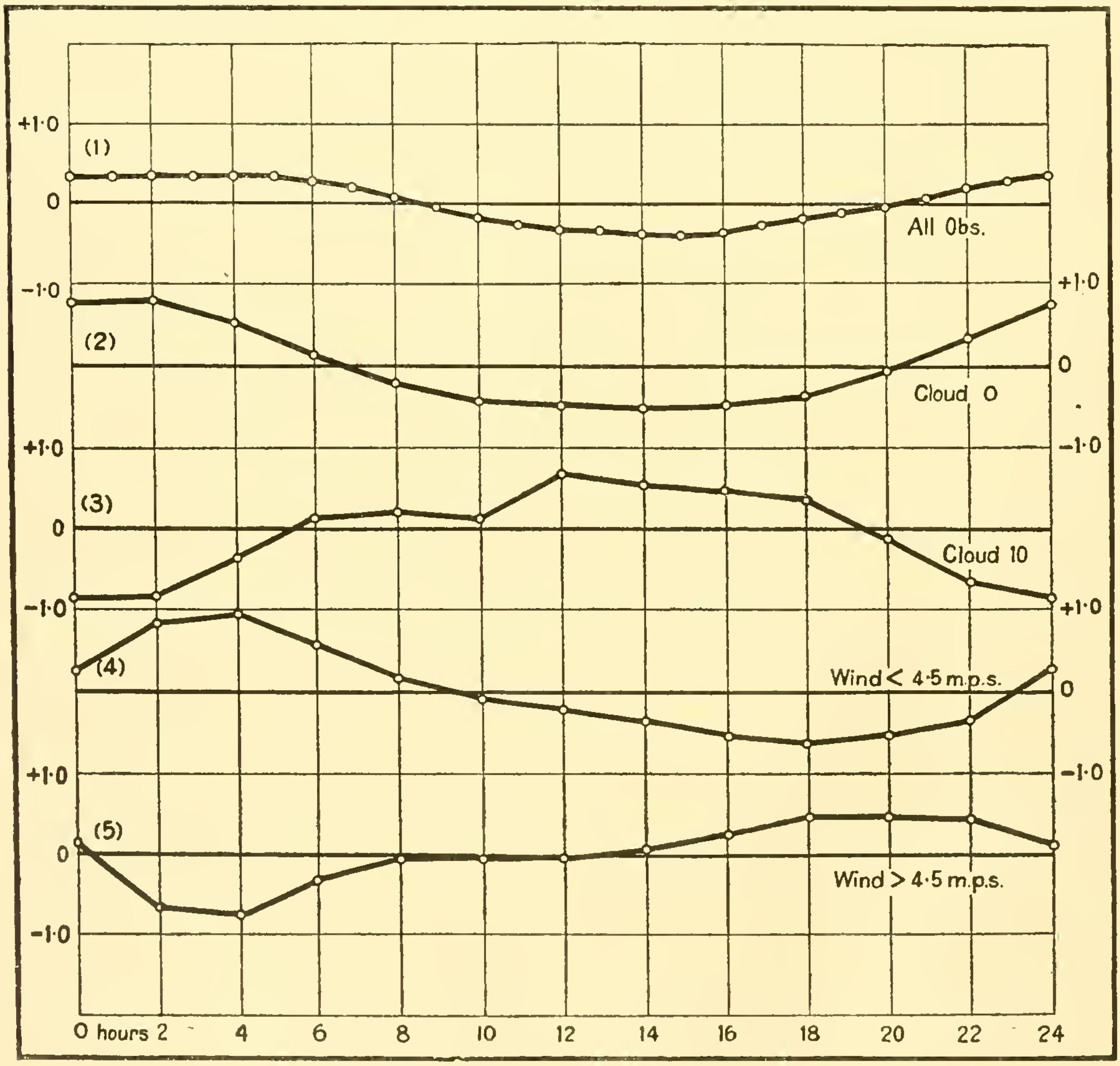

FIG. 26. Daily variation of temperature during the dark months. *Fram* Drift.

The temperature is above the mean of the day from 9 P.M. to 8 A.M. and below during the rest of the day. No excess of temperature is shown at 4 A.M. and the day is colder than the night; thus neither of our effects is present. Mohn concludes that the daily variation is fully accounted for by the daily variation of the wind: 'In the dark season the north component of the wind's frequency exceeds the south component uninterruptedly from 7 A.M. to 8 P.M. and the northerly winds are colder than the southerly winds. It seems reasonable to ascribe the diurnal period of the temperature found in the dark season to the effect of the wind.'

But Mohn has gone further; he has determined the daily march of temperature for the dark months (*a*) during cloudless days; (*b*) during overcast days; (*c*) during days with an average wind velocity less than 4·5 metres per second; and (*d*) during days with an average wind velocity greater than 4·5 metres per second. The results for each of these for the three winter months, November, December and January, are shown as curves 2, 3, 4 and 5 of figure 26. It will at once be seen that the temperature variations on cloudless and on windless days are almost mirror images of the variations on overcast and windy days. The warm period found in the Antarctic between 9 A.M. and 7 P.M. is certainly present in the north on overcast days, and the excess of temperature at 4 A.M. is very marked in the north on days with little wind. This leads us to investigate the effect of cloud and temperature on the Antarctic temperature variations. The variation was therefore calculated for cloudless days and overcast days, but it was found that the number of days was too small to give smooth curves, therefore all days were considered in which the cloud amount was less than 5 at all observations, and all days in which the cloud amount was more than 5 at all observations. These curves were still irregular but smoother than the former, they were however the same in general run. They have been plotted as curves 6 and 7 of figure 24, page 67. The days of May, June and July of the four years were then divided according to wind by first taking out those days in which the hourly wind velocity did not rise to 20 miles an hour in any one hour throughout the day, these formed the first class; the remaining days on which the wind rose above 20 miles per hour during at least one hour in the day formed the second class. The temperature variations for each class were determined and plotted as curves 8 and 9 of the same figure.

Examining the two latter curves we see that they are so similar to one another and to the mean of all days, curve 1, that wind can have little direct influence in McMurdo Sound on either of the features under discussion.

The influence of cloud, however, although small, is quite marked. It will be seen that curves 6 and 7 in their general run are similar to those found for the north; days with cloudy skies are warmer during the day time than during the night, while days with clear skies are on the whole warmer during the night hours than during the day hours. But a still more important relationship is shown. The excess of temperature at 4 A.M. is clearly marked with clear skies, 4 A.M. being the warmest hour of the day; while there is no indication of the excess at 4 A.M. on cloudy days.

It therefore appears that our first effect, the day warmer than the night, is associated with cloudy days, while the second effect, excess of temperature at 4 A.M., is associated with cloudless or slightly clouded days. Except that the maximum is at 2 A.M. instead of 4 A.M. in the north the same relationship holds there.

Mohn has given an explanation of the average conditions in the north, but he gives no suggestions for the remarkable difference in daily variation according to cloud and wind.*

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* It should be remarked that in the north cloud is so intimately related to wind, windy days being nearly always overcast, that it is impossible to separate the two effects. The curves for no cloud and little wind on figure 26 are practically from the same data; similarly with the curves for overcast skies and windy days.

This is obviously the key to the whole problem, the solution of which would be an important addition to our knowledge of the physics of the atmosphere. Already I have spent more time over this problem than over any other discussed in this work. As the investigation has led only to negative results, this is not the place to go into details. It is to be hoped that the problem will be taken up again when more data become available in the future.

Fourier Coefficients.

The Fourier Coefficients for the daily variation of temperature are given in the following table. The coefficients lead to no new results. The value of a—the amplitude of the whole-day period—is greatest in January and it is slightly less in December than in the two neighbouring months. The phase of the whole-day period does not vary to any large extent from September to March, when the daily variation is governed by the sun. During the period April to August, when the solar energy is weak, both the amplitude and phase of the whole-day period are extremely irregular, this is to be expected from the curves for this period given in figure 20, page 54. The amplitude of the half-day period is small throughout, and the irregularity of the phases for the different months shows that this period has no real physical basis.

TABLE 30.

Fourier Coefficients of the Daily Variation of Temperature.

	No. of months	a	A	b	B
		°F.	°	°F.	°
January	2	2·22	219	0·26	191
February	4	1·41	223	0·21	195
March	4	0·52	229	0·36	95
April	4	0·24	35	0·05	338
May	4	0·61	238	0·30	45
June	4	0·34	215	0·24	245
July	4	0·21	31	0·10	345
August	4	0·40	54	0·27	276
September	3	0·54	219	0·29	9
October	3	1·37	235	0·30	57
November	2	2·61	229	0·12	30
December	2	1·56	224	0·10	156
Summer Nov. Dec. Jan.	6	1·90	225	0·04	159
Equinox Mar., April, Sept., Oct.	14	0·57	227	0·20	53
Winter May June July	12	0·27	238	0·06	359
Year	40	0·81	228	0·03	32

Daily Variation of Temperature at Cape Adare.—Observations of temperature were taken at Cape Adare every two hours in June and July; during other months observations were not taken during the night hours. As it is impossible to correct the latter for non-periodic change they will not be discussed here, but the data will be found in the book of tables.

TABLE 31.

Daily Variation of Temperature at Cape Adare.

Month.	2	4	6	8	10	12	14	16	18	20	22	24	Mean
June 1911 . .	−0·5	0·0	0·0	+0·5	+0·6	+0·3	+0·2	−0·2	+0·1	−0·7	+0·1	−0·7	−16·1°F.
July „ . .	−0·1	−0·9	+0·5	+0·1	−0·3	−0·6	0·0	+0·3	+0·5	+0·4	+0·3	+0·4	−14·9°F.

No excess of temperatures at 4 A.M. is shown in either of these months. The day hours were warmer than the night hours in June, but in July the period 16 hours to 24 hours was above the average.

NON-PERIODIC CHANGES OF TEMPERATURE.

In the previous section the object was to determine the true daily variation of temperature unaffected by irregular changes. With this end in view, data from as large a number of days as possible, having a similar periodic variation, were combined in order that irregular changes which are independent of the time of day would cancel one another, the residual variation was assumed to be mainly due to true periodic causes. The irregular variations which were removed in this process are, however, of considerable meteorological importance and will be studied in this section. We have now therefore to employ a process which will eliminate the true daily variation and leave the non-periodic changes.

Many methods have been used by other writers for this purpose, but most of them lead only to statistical results. As the essential purpose of the investigation is to find the physical laws underlying the meteorological observations, I have chosen two methods which appear to me to be the most suitable for the available data. The first method which depends on daily maximum and minimum temperatures will be used in discussing the non-periodic temperature variations in McMurdo Sound, because maximum and minimum temperatures are available for a longer period than temperatures recorded in any other way. On the other hand, no maximum and minimum temperatures were recorded at Cape Adare and Framheim, hence to compare the irregular temperature changes at these stations with those at McMurdo Sound another method will be adopted.

Maximum and Minimum Temperatures in Relation to Non-periodic Temperature Changes.—If there were no irregular temperature changes the maximum and minimum temperature of the day would be determined by the daily periodic temperature variations. In this case the daily temperature range would be the same as the daily temperature amplitude.* This is practically the case in tropical countries. When, however, there are irregular temperature changes, these increase the difference between the range and the amplitude. In the Antarctic where irregular changes are very large compared with the regular changes, the mean range is considerably greater than the amplitude, and the difference, range − amplitude, affords a qualitative measure of the non-periodic changes. The difference between the range and the amplitude which we shall now study will for convenience be called the 'reduced range.'

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* See the definition of these terms, page 53.

In the following table are given the mean temperature, the mean range, the amplitude, and the reduced range for each month. The values for the amplitude are those given in table 20, page 53, and the temperatures have been obtained from data for each month from four years.

TABLE 32.

Unperiodic Temperature Variations in McMurdo Sound.

Month.	Mean temperature.	Mean max.	Mean min.	Mean range.	Amplitude.	Reduced range.
	°F	°F	°F	°F	°F	°F
January	+23	+28·7	+16·9	11·8	5·0	6·8
February	+15	+20·0	+ 8·7	11·3	3·1	8·2
March	+ 4	+ 9·4	− 2·2	11·6	1·5	10·1
April	− 8	− 2·0	−15·5	13·5	0·9	12·6
May	−12	− 5·2	−20·7	15·5	1·3	14·2
June	−13	− 4·9	−22·4	17·5	1·3	16·2
July	−14	− 6·1	−23·6	17·5	1·2	16·3
August	−14	− 6·5	−23·8	17·3	1·3	16·0
September	−15	− 5·2	−22·7	17·5	1·8	15·7
October	− 6	+ 2·2	−12·1	14·3	2·9	11·4
November	+13	+18·5	+ 7·4	11·1	3·9	7·2
December	+24	+28·6	+18·3	10·3	3·2	7·1

From the column for reduced range we see that non-periodic temperature changes are smallest in January and largest in July. Also by comparing the first and last columns we see that the reduced range has almost the same yearly variation as the mean temperature.

This close relationship between the non-periodic temperature changes and the mean temperature, leads at once to the conclusion that cold weather is favourable to unsteady temperatures while warm weather is unfavourable. If, however, we examine the reduced range for any one month in different years, we do not find that it follows very closely the mean temperature. Thus, in the month of June the years arranged in order of increasing mean temperature were 1902, 1903, 1911 and 1912, but in order of decreasing reduced range they are 1903, 1902, 1912, 1911, the data are as follows:—

TABLE 33.

June.	1902.	1903.	1911.	1912.
Mean temperature . . .	−16·0	−13·8	−13·5	−9·2 °F
Reduced range	17·4	21·3	11·6	14·5

If, however, we had used the average minimum temperature instead of the mean temperature for the comparison, the years would have been arranged thus :—

TABLE 34.

June.	1903.	1902.	1911.	1912.
Mean minimum	−27·0	−26·3	−18·2	−18·0°F
Reduced range	21·3	17·4	11·6	14·5

in which only one month of the four is out of the sequence.

The investigation has been carried further by plotting the reduced range for the cold months against the average maximum and average minimum temperature of the month. The points for the months May to August are plotted in figure 27. A glance shows at once that whereas there is only a small tendency for the points to lie on a straight line in the upper diagram, there is a considerable tendency in the lower diagram. This means that during the period May to August the reduced range, *i.e.*, the unperiodic temperature changes, depends much more on the minimum than on the maximum temperatures. The relationship, expressed in statistical terms, is represented by the correlation coefficients −·7 and −·2 respectively.

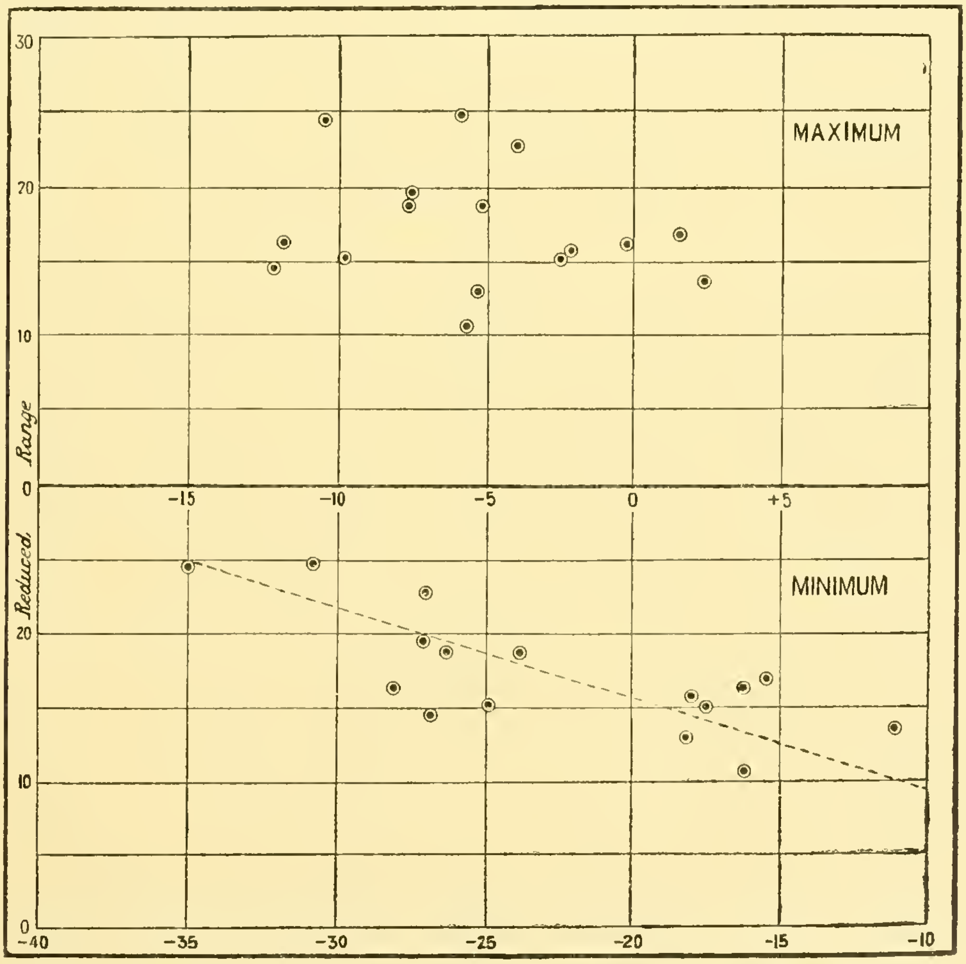

FIG. 27. Reduced temperature range plotted against maximum and minimum temperatures.

During the warm months of the year there is a similar tendency, but much less marked. For the months November to February the correlation coefficients between the reduced range and the minimum and maximum temperatures are −·4 and ·0 respectively. Thus we see that during the warm months neither the maximum nor the minimum temperature plays a large part in determining the unperiodic temperature changes.

In order to understand these results, the temperature conditions in McMurdo Sound must be kept in mind. We will first confine our attention to the cold months May to August. There is little difference in mean temperature during this period, hence they may all be considered together as having similar general temperature conditions. We have already shown that during the cold weather the direction from which the wind blows has little effect on the temperature, both northerly and southerly winds having higher temperatures than hold during calm weather. We have also shown that low temperatures are associated with a cold layer of air just above the surface, while high temperatures during the winter are caused by the removal of this cold layer and the establishment of a normal temperature gradient throughout the lower atmosphere. A little consideration will show that minimum temperatures are much more largely governed by the cold layer than maximum temperatures, while maximum temperatures are more affected than minimum temperatures by the relative warmth produced by the winds. For every time a cold layer forms even for a few hours it is recorded by the minimum thermometer, but it must exist undisturbed throughout the whole 24 hours if it is to affect the maximum temperature. Similarly a wind which only lasts a few minutes may raise the temperature and give a high maximum temperature, but if it does not last 24 hours it may not affect the minimum temperature.

A month during which cold layers frequently form will have a low average minimum temperature. But the cold layer is very unstable, for at a comparatively small distance above it, there is warm air; hence during a period when the minimum temperature every day is low, there may be a large proportion of days with a relatively high maximum temperature. On the other hand when windy conditions exist both the maximum and minimum temperatures are high for the cessation of the wind for a few minutes does not at once lead to a cold surface layer which takes time to form. Thus frequently when maximum temperatures are high, minimum temperatures are high, but much less frequently are maximum temperatures low when minimum temperatures are low. In other words where the temperature is largely governed by the formation and removal of cold layers, average maximum temperatures cannot undergo such large variations as average minimum temperatures. That these conditions are fulfilled in McMurdo Sound during the winter is clearly seen from figure 27 in which the points for the minimum temperatures are spread over a much larger range than those for the maximum temperatures. In fact the average deviation of the maximum temperatures from their common mean is only a little more than half that of the minimum temperatures, being 3·8°F. and 6·2°F. respectively.

The tendency then during this period is for temperature changes to take place between two limits, the lower being the temperature of the cold layers, which vary largely from month to month both in intensity and duration, and the upper being the approximately uniform temperature which exists when the normal temperature gradient has been established in the lower atmosphere. It is now clear why the non-periodic changes during the winter are much more nearly related to the average minimum than the average maximum temperature, for the latter is an indication of the prevalence and intensity of the cold layer, the formation and sweeping away of which give rise to the majority of the temperature changes.

In the summer months the cold surface layers do not form, while the temperature is now affected by the wind direction. Hence we see that not only are the temperature variations much smaller than in the winter, but they depend now much less on the minimum temperature; the correlation factor between reduced range and minimum temperature in the summer being only half what it was in the winter.

Comparison of Non-periodic Temperature Changes at Cape Evans, Cape Adare and Framheim.—Unfortunately no maximum and minimum observations are available at Cape Adare and Framheim. Hence it is impossible to compare the aperiodic changes of temperature at these stations with Cape Evans by the method just used.

The comparison may be made, however, by the second method mentioned above. The change in temperature from day to day depends almost entirely on aperiodic changes. The difference has therefore been taken between the temperature at the same hour on consecutive days. At Framheim temperature observations were taken at 8 A.M., 2 P.M. and 8 P.M., the mean difference between the readings at each of these observations and the corresponding one on the following day have been used. This gives 90 determinations of the change in a month of thirty days. The changes have been grouped according to whether the temperature rose or fell during the interval and the mean for the former entered in table 35 in the column headed + and the latter in the column headed −. (The occasions when the changes were zero have been divided equally between the positive and negative groups.) In the right hand half of the table the number of times the changes were positive and negative have been entered. In order to make the comparison complete the same procedure, using the same hours, have been applied to the observations made at Cape Evans and Cape Adare, the results being entered in the same table.

Unfortunately no observations are available at Cape Adare for January or February or at Framheim for February and March.

TABLE 35.

Month.	INTERDIURNAL VARIABILITY.						NUMBER OF OCCURRENCES.					
	Cape Adare.		Cape Evans.		Framheim.		Cape Adare.		Cape Evans.		Framheim.	
1911	+	−	+	−	+	−	+	−	+	−	+	−
February	..	..	2·8	3·6	..	..	..	..	40	41	..	..
March	2·2	2·5	4·3	3·9	..	..	39	54	47	46	..	..
April	5·3	3·9	4·3	4·5	10·7	11·6	36	54	40	50	43	44
May	4·5	4·4	7·0	5·3	11·2	11·2	39	54	46	47	49	44
June	7·3	6·5	7·7	10·0	13·4	14·3	44	46	34	56	44	46
July	8·4	7·1	8·6	7·6	16·1	14·5	38	55	43	50	43	50
August	10·1	8·1	9·4	7·0	17·0	13·7	47	46	41	52	44	49
September	11·8	6·8	11·1	7·6	10·6	10·6	26	46	40	50	50	40
October	4·1	4·1	4·2	4·2	12·0	9·5	29	31	46	47	40	53
November	3·1	2·1	4·6	3·8	5·4	6·7	44	46	44	46	54	36
December	3·0	2·5	3·4	2·8	4·5	4·0	50	43	44	49	46	47
1912												
January	..	..	2·8	3·6	4·5	4·2	..	..	50	43	40	47

To facilitate discussion the mean values of the interdiurnal variability irrespective of sign have been entered in table 36 together with the mean temperature.

TABLE 36.

Month.	Interdiurnal variability irrespective of sign.			Mean temperature.		
	Cape Adare.	Cape Evans.	Framheim.	Cape Adare.	Cape Evans.	Framheim.
1911						
February . .	..	3·2	..	..	+18·7	..
March . .	2·3	4·1	..	+19·8	+ 7·2	..
April . . .	4·6	4·4	11·1	+ 8·6	− 1·1	−17·8
May . . .	4·4	6·1	11·3	− 0·6	−10·8	−31·7
June . . .	6·9	8·9	13·8	−16·1	−13·5	−29·9
July . . .	7·7	8·1	15·3	−14·9	−21·1	−32·8
August . . .	9·1	8·2	15·3	−13·7	−21·1	−47·7
September . .	9·3	9·3	10·5	− 2·6	−15·8	−35·6
October . . .	4·1	4·2	10·8	+ 0·6	− 3·4	−11·6
November	2·6	4·2	6·1	+18·9	+12·4	+ 4·2
December . .	2·7	3·1	4·3	+27·4	+22·0	+20·0
1912						
January . . .	..	3·2	4·4	..	+21·3	+15·0

The data used in the above table are only for one year, but the interdiurnal variation shows, as did the reduced range, that at Cape Evans the non-periodic temperature changes are largest in the winter and smallest in the summer. So far as the observations go the same is the case at Cape Adare and Framheim. Thus in the yearly variation the non-periodic changes follow closely the mean temperature. In every month the mean temperature at Framheim is lower than either of the other two stations, and the interdiurnal variability is greater. At Cape Evans and Cape Adare the same relationship does not hold so closely, but in six months out of ten Cape Evans has both the lower temperature and the greater variation. Cape Adare was very much nearer to permanent open water than Cape Evans, therefore the horizontal temperature gradient must have been much larger at the former than at the latter station, this was particularly the case in June when the mean temperature at Cape Adare was actually lower than at Cape Evans and the open ocean very much nearer. In spite of this, Cape Evans had on the whole the greater temperature variation, which shows that the horizontal temperature gradient is much less efficient in producing temperature changes than the vertical gradient. The large non-periodic variability at Framheim is particularly instructive. The low temperatures on the Barrier have already been ascribed to the great radiation which is possible over its surface of snow. The large variability of temperature signifies that the low Barrier temperature is confined to a low layer above which the air has a much higher relative temperature. In other words the large interdiurnal variation of temperature at Framheim strongly supports the view already expressed that there is on the average a greater temperature inversion over the Barrier than over McMurdo Sound, so that the temperature of the upper air over the whole region is much more uniform than the temperature near the ground.

If we examine the figures in table 35 for the period April to October we find that with few exceptions at all stations the rises of temperature are greater than the falls, but their frequency is less. Both these conditions are consistent with rapid rises of temperature and slow falls. This is exactly what would occur with the removal and formation of cold layers, for such a layer can be removed almost instantaneously by the setting in of a wind from any direction, but the fall of temperature would take place much more slowly, as the air cools under the abnormal radiation when calm weather sets in again.

Mean Monthly Temperature.

Description of the Data Available.

McMurdo Sound. 'Discovery' Expedition, Hut Point 1902–04.—On pages 373 to 384 of the volume of meteorological results of the National Antarctic Expedition 1901–04 are given a complete set of two-hourly temperature observations made at Hut Point from February 9, 1902, to the end of January, 1904. Thus with the exception of eight days in February, 1902, the record is complete for two whole years. The mean values given on these pages are used in the following and not those given on page 464 of the same work which appear to have been computed from defective data ; the difference, however, is small.

'Nimrod' Expedition, Cape Royds, 1908-09.—The meteorological observations made on Shackleton's expedition have not yet been published, but mean monthly values of the temperature recorded at Cape Royds were given to Professor Hann who has published them on page 690 of volume III of his 'Climatologie.' No information has been given as to the method of obtaining the monthly values, but probably they are based on two-hourly readings of the thermometers.

'Terra Nova' Expedition, Cape Evans, 1911-12.—There is a complete set of hourly data for the period February, 1911, to August, 1912. In addition, observations of daily maximum and minimum temperatures are available for 18 days in January, 1911, and for the remainder of 1912 after the end of August. The maximum and minimum temperatures can be used for finding the true mean temperature if the corrections to be applied are known. Fortunately it is possible to determine a close approximation to these corrections by comparing the observations of mean maximum and minimum with the true mean from observations made in three years when the observations are complete.

In the following table are entered the differences between the true mean temperature based on either hourly or two-hourly observations, and the mean of the maximum and minimum temperatures, from which the corrections to be applied are found.

Table 37.

Corrections to be Applied to the Mean of the Maximum and Minimum Temperatures in Order to Obtain the True Mean Temperature.

Year.	September.	October.	November.	December.	January.
	°F	°F	°F	°F	°F
1902 . . .	+1·3	+1·4	+0·3	−0·3	−0·5
1903 . . .	+1·2	+1·4	+1·9	+0·7	+0·7
1911 . . .	−0·4	+0·6	−0·1	+0·5	+0·6
Mean . . .	+0·7	+1·1	+0·7	+0·3	+0·3

The values for 1902 and 1903 are taken from page 459 of the book quoted above, except that the value for January, 1902, has been reduced to −0·5, because the value given, −1·0, is obviously too large, and is based on defective observations as is pointed out by Dr. Chree on page 460. It is obvious from the above table that if the mean corrections are applied, the temperature derived from the mean maximum and minimum will not depart by one degree from the true mean. They have therefore been applied to the observations for January, 1911, and September to December, 1912, thus giving two years' satisfactory mean temperatures for 1911 and 1912.

The following table summarises the above.

TABLE 38.

Data used for Mean Monthly Temperature in McMurdo Sound.

Station.	Period.	Data available.
Hut Point	February, 1902	Two-hourly values for 20 days.
Do.	March, 1902, to January, 1904	Two-hourly values.
Cape Royds	March, 1908, to February, 1909	Probably two-hourly values.
Cape Evans	January, 1911	Eighteen days, maximum and minimum temperatures corrected by +0·3.
Do.	February, 1911, to August, 1912	Hourly values.
Do.	September, 1912, to December, 1912	Maximum and minimum temperatures corrected by +0·7, +1·1, +0·7 and +0·3 respectively.

Thus for McMurdo Sound we have temperature data for five years from three stations. It will be shown later that Hut Point is probably slightly colder than Cape Evans which is again slightly colder than Cape Royds, but by combining all the observations we obtain a better knowledge of the general temperature conditions in McMurdo Sound than could be obtained by considering separately the observations made at each station.

Cape Adare.—The observations taken at Cape Adare by the Southern Cross Expedition under the leadership of Captain Borchgrevink have been published by the Royal Society in the volume 'Southern Cross Antarctic Expedition, Magnetic and Meteorological Observations, 1902.'

From March 4, 1899, to January 29, 1900, temperature observations were taken every two hours between 9 A.M. and 9 P.M. As the mean of these observations would not give a true mean temperature, the observations at 9 A.M. and 9 P.M. only have been used in obtaining the mean monthly temperature. In this series no observations for February are available, an approximate value has, however, been obtained by completing the curve of yearly variation by freehand.

The members of Captain Scott's Northern Party were at Cape Adare during part of 1911. They took temperature observations as a rule every two hours from 8 A.M. to 8 P.M. In June and July, however, the observations were taken every two hours throughout the day and night. Thermograph records are not available, hence the mean monthly temperatures have been calculated from the means of 8 A.M. and 8 P.M. observations.

The observations are complete from March to December inclusive. The values for the missing months January and February have again been supplied by completing the curve for the remaining months by freehand.

The above is summarised in the following table :—

TABLE 39.

Data used for Mean Monthly Temperature at Cape Adare.

February, 1899	Interpolation.
March, 1899	Mean of 9 A.M. and 9 P.M. for 28 days.
April, 1899, to December, 1899 . .	Mean of 9 A.M. and 9 P.M.
January, 1900	Mean of 9 A.M. and 9 P.M. for 28 days.
January and February, 1911 . .	Interpolation.
March, 1911, to December, 1911 .	Mean of 8 A.M. and 8 P.M.

Framheim.—Temperature observations were taken at Framheim at 8 A.M., 2 P.M. and 8 P.M. Professor Mohn has reduced the mean monthly temperatures for the period April, 1911, to January, 1912, from the 8 A.M. and 8 P.M. observations. Values for the months February and March have been obtained by completing the curve for yearly variation by freehand.

Barrier.—The method of obtaining mean monthly temperatures on the Barrier have been described above (page 32). The values used refer to the Barrier north of One Ton Camp 79° 30′ S., and south of Ross Island.

Mean Monthly Temperatures in McMurdo Sound.—Table 40 contains the mean temperature observed each month during five years in McMurdo Sound.

TABLE 40.

Mean Monthly Temperature. (°F.)

Station.	Year.	January.	February.	March.	April.	May.	June.	July.	August.	September.	October.	November.	December.	Year.
Hut Point .	1902 .	+22·5*	+15·9	+8·0	− 7·1	−12·5	−16·0	− 8·1	−16·5	−12·0	−8·5	+12·0	+23·1	−0·1
Do. .	1903 .	+26·1	+11·2	−0·8	−16·9	−16·0	−13·8	−21·1	−16·5	−18·6	−6·8	+15·4	+25·7	−2·7
Cape Royds .	1908-09	+26·1	+20·5	+4·8	−10·8	− 5·4	− 7·1	−17·0	−15·7	− 5·6	+4·5	+17·1	+30·0	+3·4
Cape Evans .	1911 .	+22·4	+18·7	+7·2	− 1·1	−10·8	−13·5	−21·1	−21·1	−15·8	−3·4	+12·3	+22·0	−0·4
Do. .	1912 .	+21·3	+12·9	+2·6	− 8·0	− 7·6	− 9·2	− 5·6	− 3·1	− 6·7	+3·5	+14·3	+23·8	+3·2
Mean .	5 years.	+23·7	+15·8	+4·4	− 8·8	−10·5	−11·9	−14·6	−14·6	−11·7	−2·1	+14·2	+24·9	+0·7

In the previous section we have shown that daily non-periodic temperature changes are greater in the winter than in the summer, and it is easy to see from the above table that the monthly temperatures are more irregular in the winter than in the summer. Thus the difference between the warmest and coldest July is 15·5°F., while the corresponding difference for January is only 4·8°F. This is still more clearly seen from the following table in which the departures of each month from the mean temperature of the month based on the five years are given.

---

* 1904

Table 41.

McMurdo Temperature.

Monthly Departures from the Average.

Year.	Jan.	Feb.	Mar.	April.	May.	June.	July.	Aug.	Sept.	Oct	Nov.	Dec.	Year.
1902 . . .	−1·2	+0·1	+3·6	+1·7	−2·0	−4·1	+6·5	−1·9	−0·3	−6·4	−2·2	−1·8	−0·8
1903 . . .	+2·4	−4·6	−3·6	−8·1	−5·5	−1·9	−6·5	−1·9	−6·9	−4·7	−1·2	+0·8	−3·4
1908-09 . .	+2·4	+4·7	+0·4	−2·0	+5·1	+4·8	−2·4	−1·1	+6·1	+2·4	+2·9	+5·1	+2·7
1911 . . .	−1·3	+2·9	+2·8	+7·7	−0·3	−1·6	−6·5	−6·5	−4·1	−1·3	−1·9	−2·9	−1·1
1912 . . .	−2·4	−2·9	−1·8	+0·8	+2·9	+2·7	+9·0	+11·5	+5·7	+1·4	+0·1	−1·1	+2·5
Mean . .	1·9	3·0	2·4	4·1	3·2	3·0	6·2	4·6	4·6	3·2	1·7	2·3	3·3/2·1

Taking the mean values for the seasons we have—

Table 42.

Mean Monthly Departures of Temperature from Average in McMurdo Sound

	°F.
Summer Nov., Dec., Jan. .	2·0
Autumn Feb., Mar., April .	3·2
Winter May, June, July	4·1
Spring Aug., Sept., Oct.	4·1
Year	3·3

From the above table we see that the mean variability is twice as great in the winter as in the summer.

In order to compare the above values with those for other places the following data are taken from Hann's Meteorologie, 3rd edition, page 110:—

Table 43.

Mean Monthly Departure of Temperature from Average.

	North Russia	Mid Russia.	North Germany.	Italy.	England.
	°F.	°F	°F.	°F.	°F.
Summer	2·9	2·5	1·6	1·8	1·8
Winter	6·1	5·6	3·6	2·5	2·5
Year	4·1	3·8	2·3	2·2	2·3

The monthly variations in McMurdo Sound, as far as can be judged from five years' observations, are in both summer and winter less than in Russia. In the winter they are greater than in Italy and England, but of about the same value in the summer. On the mean of the year the monthly variations in McMurdo Sound are less than in Russia, but greater than in England, Italy or Germany.

The great dependency of temperature on wind during the winter has already been pointed out, and this is again shown in the mean monthly values of temperature and wind. The following are typical cases:—

Table 44.

Temperature and Wind: McMurdo Sound.

		Mean temperature.	Mean wind.
		°F.	Miles/hour
April	1903	−16·9	9
	1911	− 1·1	16
June	1902	−16·0	12
	1912	− 9·2	32
July	1903	−21·0	9
	1912	− 5·6	29
August	1911	−21·1	17
	1912	− 3·1	25

ANNUAL VARIATION OF TEMPERATURE.

The following table contains the mean monthly temperatures in the Ross Sea area derived from the data described on pp. 79–81. The values are plotted on figure 28.

Table 45.

Mean Monthly Temperatures. (°F.)

Month.	McMurdo Sound.	Cape Adare.	Framheim.	North Barrier.
	5 years.	2 years.	1 year.	Computed.
January	+23·7	(+31·6)	+14·5	+17
February	+15·8	(+27·0)	(+ 4·2)	+ 1
March	+ 4·4	+18·7	(− 6·7)	−15
April	− 8·8	+ 9·4	−17·7	−30
May	−10·5	− 2·2	−31·7	−33
June	−11·9	−14·5	−29·9	−35
July	−14·6	−11·9	−33·7	−36
August	−14·6	−13·6	−48·6	−34
September	−11·7	− 7·5	−35·5	−27
October	− 2·1	− 0·6	−11·6	−13
November	+14·2	+18·5	+ 4·1	+ 8
December	+24·9	+29·5	+19·9	+22
Year	+ 0·7	+ 7·0	−14·4	−15

The curves on figure 28 show a remarkable similarity in the yearly temperature variations at the four positions. At each station the fall from the summer maximum continues at a nearly constant rate for three or four months, and then is suddenly checked; and there are several months during the winter when the temperature is approximately constant.

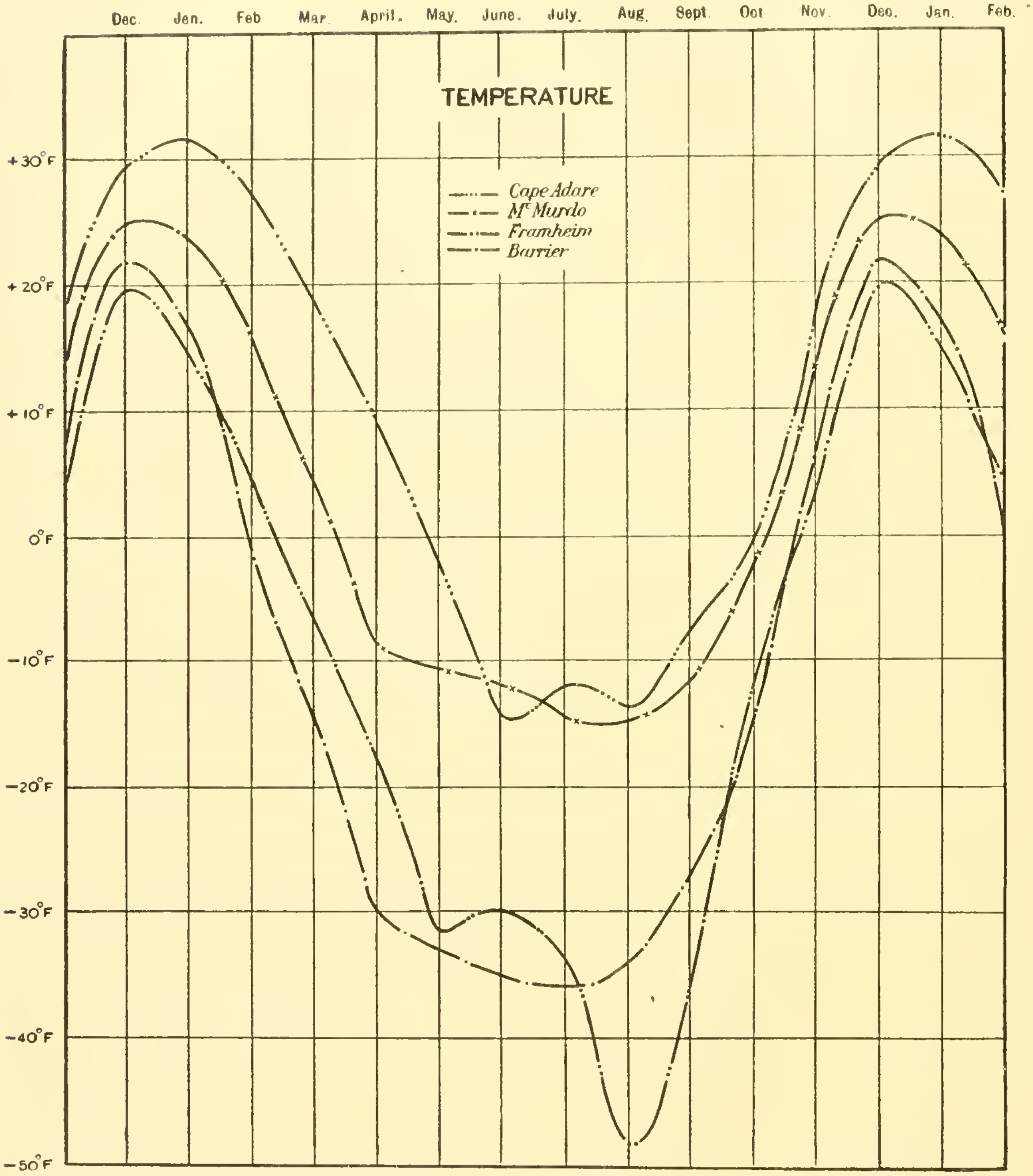

Fig. 28. Annual variation of temperature.

The physical meaning of these curves will best be investigated by comparing the temperature variations on the Barrier with the variations in a similar northerly latitude and also with the changes in solar energy.

Mean Temperature at 78° N.—The mean latitude of McMurdo Sound, Framheim and the north of the Barrier is approximately 78° S. The mean temperature at the corresponding latitude in the north can be found from the values given by Mohn * for each 5° of latitude between 60° N. and the North Pole. Interpolating from these values we find the following as the mean monthly temperatures for 78° N.

TABLE 46.

Mean Monthly Temperature at 78° N. (°F.)

January.	February.	March.	April.	May.	June.	July.	August.	September	October.	November.	December.	Year.
−23·4	−24·0	−20·6	−6·2	+15·1	+30·6	+36·5	+33·8	+20·3	+0·9	−8·5	−16·6	+3·2

Annual Variation of Insolation.—Angot has calculated the total heat received during each month at all ten degrees of latitude from the equator to each pole.† In his calculations he takes as unity 'the quantity of heat which falls on unit horizontal surface at the equator during an equinoxial day, supposing the sun to be at its mean distance from the earth and neglecting atmospheric absorption.' He then calculates the heat received assuming different values of atmospheric absorption, from which we choose the results obtained by taking the coefficient of transmission to be 0·7.

The following table shows the total insolation received in each month at 78° N. and 78° S.

TABLE 47.

Total Insolation Received at 78° N. and 78° S.

	January.	February.	March.	April.	May.	June.	July.	August.	September.	October.	November.	December.
78° N.	0	0	0·8	5·0	11·5	14·9	12·7	6·6	1·5	0	0	0
78° S.	13·2	6·1	1·2	0	0	0	0	0	0·5	4·5	11·5	15·8

Comparison of Temperature with Insolation in the North and South Polar Regions.—The curves on figure 29 represent the following :—

The mean monthly temperature at 78° N.
The mean monthly temperature on the north of the Barrier.
The total monthly insolation at 78° S.

The difference between the insolation for 78° N. and 78° S. is too small to affect the following discussion ; therefore only the curve for 78° S. has been shown. For convenience of reference the curves for the north have been plotted against the corresponding months for the south, *i.e.*, the value of January in the north has been plotted against July in the south and so on.

The curves for the Barrier and 78° N. show several most important differences :

(*a*) Whereas the temperature curve for the Barrier follows that of the insolation very closely, the curve for 78° N. has a lag of a month.

(*b*) During the months of no insolation the temperature on the Barrier undergoes very little change, while in the north the temperature continues to fall after the insolation ceases in April nearly as rapidly as it had fallen previously.

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* Norwegian North Pole Expedition, 1893–1896, page 575.

† Angot. Annales du Bureau Cent. Met. de France, 1883, page B 121.

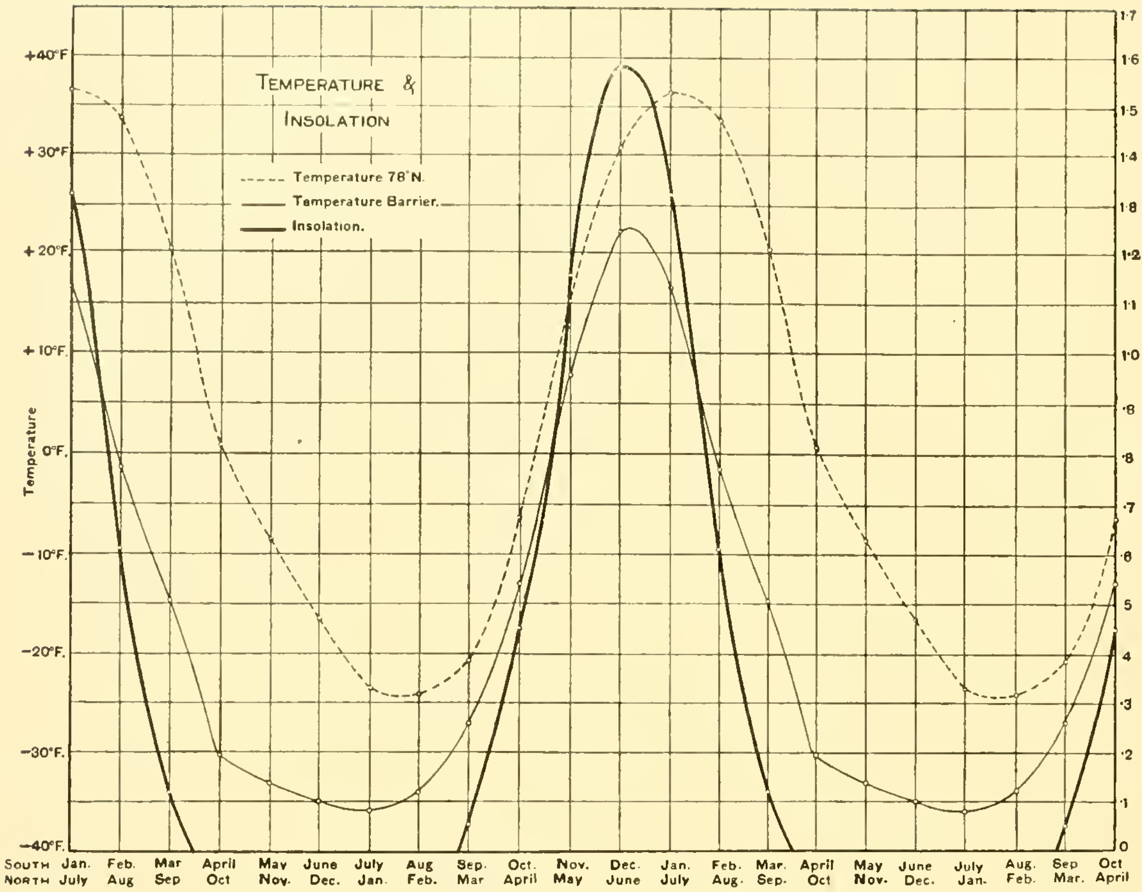

FIG. 29. **Temperature and Insolation.**

(*c*) The temperature in the north oscillates about a mean temperature 18°F. higher than that over the Barrier, and as the amplitude of the oscillation is greater in the north than the south, the maximum temperature in the north is not only higher than in the south but is several degrees above the freezing point.

Before we can explain these differences, it is necessary to understand the local conditions to which the observations refer. We have already described the surroundings of the Barrier. The temperature curve refers to that part of the Barrier between One Ton Camp in 79½° S. and the southern coast of Ross Island. The mean latitude is somewhat greater than 78° to which the other curves refer, but the difference is so small as to be immaterial for our discussion.

The temperature curve for the north does not refer to any one locality, it is based on the mean temperature of latitude 78° N. A glance at the map of the north polar region will show that this latitude, except where it crosses Greenland, runs almost entirely over the Polar Sea, approximately 80 per cent. lies over water and 20 per cent. over snow-covered land. An important point is that within this circle of latitude practically the whole area is a permanently frozen sea, while the great continental masses of Asia and North America surround it on the outside for nearly three-quarters of its circumference.

During the greater part of the year the sea along latitude 78° N. is itself frozen, but during the summer there are occasionally breaks in the ice through which the open water comes to the surface.

It is a well-known fact that owing to the large heat capacity of water it warms up slowly during spring and summer and cools slowly during the autumn and winter. Hann has shown this very clearly by analysing into harmonic terms the mean annual temperature variations of a number of stations in the same latitude having land and sea climates. The results for 60° N. are shown in the following * :—

Table 48.

Yearly Variation of Temperature and Insolation in 60° N. Latitude.

Sea climate . . .	$7{\cdot}9 \sin(253{\cdot}6+x)+1{\cdot}4 \sin(59{\cdot}4+2x)$.
Land climate . . .	$43{\cdot}6 \sin(271{\cdot}3+x)+2{\cdot}4 \sin(311{\cdot}3+2x)$.
Insolation . . .	$9{\cdot}02 \sin(296{\cdot}5+x)+1{\cdot}28 \sin(144{\cdot}2+2x)$.

It will be noticed that in each case the amplitude of the first term is much larger than the second term, therefore its phase gives very approximately the phase of the whole wave. Along 60° N. latitude the temperature variation lags behind the insolation by 15° at land stations and 43° at sea stations. As very approximately 1° lag represents 1 day, the lag is half a month at land stations and nearly one and a half months at sea stations.

Analysing the curves on figure 29 in the same way we obtain the following :—

Table 49.

Yearly Variation of Temperature and Insolation.

Insolation 78° N. . . .	$6{\cdot}9 \sin(117+x)$† $+3{\cdot}2 \sin(143+2x)$.
Temperature 78° N. . .	$31{\cdot}0 \sin(82+x)$† $+4{\cdot}9 \sin(109+2x)$.
Temperature Barrier . .	$28{\cdot}0 \sin(108+x) +7{\cdot}8 \sin(133+2x)$.
Insolation 78° S. . . .	$7{\cdot}1 \sin(116+x) +3{\cdot}6 \sin(142+2x)$.

Barrier temperature lags only 8° (*i.e.*, 8 days) behind the insolation, while the temperature in 78° N. lags 35°. Therefore as regards lag, the Barrier behaves like a land station and 78° N. like a sea station. The amplitude, however, is a difficulty. The lag at a sea station compared with a land station is due to the absorption of heat by the water during the season of rising temperature and the giving up of heat during the season of falling temperature. This process of necessity reduces the amplitude of the temperature variation, and the greater the lag, the greater the reduction in amplitude. But we find that the average station in 78° N. has a larger temperature amplitude than the Barrier, in spite of a slightly less insolation amplitude. It is, therefore, impossible to explain the lag of temperature in the north as being due to its sea climate, for its greater amplitude would then be unexplained.

In order to study more closely the corresponding changes in temperature in the north and over the Barrier, the following table has been prepared giving the change in temperature from each month to the next.

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* Hann Lehrb. d. Meteorologie, 3rd edition, page 98. In the following discussion each month corresponds to 30° and the mean value for January has the zero angle, February 30°, March 60°, and so on.

† For convenience of comparison 180° has been added to the phase of the harmonic terms in the north.

Table 50.

Change of Temperature from Month to Month.

Barrier	Aug. to Sept.	Sept to Oct.	Oct. to Nov.	Nov. to Dec.	Dec. to Jan.	Jan. to Feb.	Feb. to March	March to April	April to May	May to June	June to July	July to Aug.
	+ 7	+ 14	+ 21	+ 14	− 5	− 18	− 14	− 15	− 3	− 2	− 1	+ 2
78° N.	+3·6	+14·4	+21·3	+15·5	+5·9	−2·7	−13·5	−19·4	−9·4	−8·1	−6·8	−0·6
	Feb. to March	March to April	April to May	May to June	June to July	July to Aug.	Aug. to Sept.	Sept. to Oct.	Oct. to Nov.	Nov. to Dec.	Dec. to Jan.	Jan. to Feb.

The minimum temperature occurs over the Barrier in July, at 78° N. in February, which corresponds to August in the south. During the period of increasing insolation (September to December in the south, and March to June in the north), the temperature rises at approximately the same rate in the north and south, 51°, and 49° respectively. The temperature, however, continues to rise in the north after midsummer, and July is 5·9°F. warmer than June, while over the Barrier the temperature commences to fall almost as soon as the insolation decreases, and January is 5°F. colder than December. The continued rise of temperature in the north after the solstice, coupled with the fact that the mean temperature during the two warmest months in the year, July and August, is well above the freezing point, is the key to the problem. Even during July and August, the greater part of the sea in latitude 78° N. is completely frozen over, and where it is not frozen over, the temperature of the sea is between 2 and 3°F. below the freezing point. Hence as the temperature of the surface does not rise above the freezing point, the air during these months is warmer than the surface, and therefore cannot obtain its heat locally. During July and August, the north polar ocean is surrounded by snow-free land, the temperature of which is well above the freezing point, and the winds carry warm air from the land over the polar ocean, so causing a higher temperature than would be produced by the insolation received locally. The course of the temperature in the north between the winter minimum and the summer maximum is now obvious. At the end of the winter, the north polar ocean is frozen over, and surrounded by snow-covered land, which is locally colder than the ocean further north. Thus the first sunshine of the year falls on a snow surface at a temperature much below the freezing point, hence the conditions are simliar to those over the Barrier. The rise in temperature is, therefore, similar in both north and south. But over the land of North Asia and America, the snow commences to melt exposing land and rock on which the insolation acts with greater intensity. The snow covering rapidly decreases, and by the end of May has almost completely disappeared from the land, the temperature of which rises well above the freezing point.

The pressure distribution is then favourable for a considerable interchange of air between the warmer land and the colder ocean. The prevailing wind direction over the whole area may not be from the south, but there are sufficient southerly winds to carry a considerable amount of warm air northwards with a consequent raising of the mean temperature over the ocean. Thus after May insolation is not the only source of heat in 78° N., but to it must be added the winds carrying warm air from the relatively warm continents in the south. The summer temperature is, therefore, well above the freezing point, and the maximum occurs a month after the insolation has commenced to decrease.

The conditions are entirely different in the south. Practically the whole region within the Antarctic Circle is snow-covered land, and completely surrounding this continent is an open ocean, the temperature of which in high latitudes even in midsummer does not rise above the freezing point. On the return of the sun, the air over the Barrier warms up in proportion to the insolation received. At midsummer the temperature is still 10°F. below the freezing point. Compared with the north, there is little inflow of heat from lower latitudes because the prevailing wind is almost entirely from the south, also the few winds which do blow from the north come from a cold ocean instead of from a warm land surface. Thus local insolation is practically the only source of heat even at midsummer, hence when it decreases after the solstice, the temperature decreases with it.

The low summer temperatures in the Antarctic have been a source of difficulty to meteorologists. Mr. Dines, in discussing the results of the Discovery Expedition, wrote * :—

> ‘The low mean temperature of the summer is also strange, and very difficult to explain .... The insolation in the Antarctic in summer is greater than the insolation on any other part of the earth at any other time, this being the date at which the sun is nearest to the earth, and if temperature depended only on solar radiation we should have the highest terrestrial temperature occurring in December in the neighbourhood of the South Pole.† A large mass of ice prevents the temperature from rising above the freezing point, because the air, being nearly pervious to the radiation, takes its temperature chiefly from the surface with which it is in contact, and if that surface be ice or snow, it cannot be above 32° F. But ice, except in its power of evaporation, is in no way more efficacious than any other rock in checking a rise in temperature up to its own melting point. Why then does not the mean summer temperature at least reach the freezing point as indeed it does in the north polar regions, where the insolation is less intense ?’

The answer to the question is now quite clear. Of the solar energy which falls within the Antarctic Circle, such a large proportion is lost by direct reflection from the snow that the remainder is not sufficient to raise the temperature of the air to the freezing point before the solstice is reached, and the energy commences to decrease. The Arctic Circle on the other hand is during the summer surrounded by snow-free continents, the temperature of which rises well above the freezing point, and warm air is carried from them across the whole polar region. Insolation, as Mr. Dines points out, is less in the north than the south, but insolation *plus* warm winds is much greater in the north than the south; hence the difference in the respective maximum temperatures.

During the period of decreasing insolation, the temperature over the Barrier falls slightly less rapidly than it rose giving a small lag behind the insolation, so that the mean temperature in April, when the insolation ends, is 4°F. higher than in August, when the sun appeared after the winter. This, however, is to be expected, for the snow surface and the air above it have some slight heat capacity. The lag, however, is very much greater in the north. At the end of the summer, the ice in the north is thinner than at the end of the winter, there is some open water, and the surrounding land surfaces are still free from snow, and, therefore, have a relatively high temperature. All these effects supply heat, and keep the temperature high, thus when the sun sets for the last time in October, the temperature in the north is 24·9°F. higher than when it rose in February.

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* National Antarctic Expedition, 1901–1904, Meteorology, Part I, page 465.

† In this sentence Mr. Dines neglects the atmosphere. If the atmosphere is considered, the region of maximum insolation is 35° S., while the South Pole receives less heat than the Equator. See Plate B 15 of Angot's work.

We now come to one of the most characteristic differences between the temperature in the north and the south. From April to August in the south, and from October to February in the north, no insolation is received. The temperature in the south during these months is nearly stationary, the fall being only 4°F. on the Barrier, while in the north the temperature continues to fall, and February is 24·9°F. colder than October. Here again we have an effect of the different local surroundings. The Barrier is only a few miles from a sea, the temperature of which, during the winter, is, as we have already shown, 25°F. warmer. Over the Ross Sea, there are vertical convexion currents, while over the Barrier there are none, therefore, the temperature of the sea governs the temperature of the upper atmosphere. Every blizzard which blows removes the cold air from the Barrier surface, and raises the temperature to that in adiabatic equilibrium with the warm upper air. The fall of temperature during the winter over the Barrier is, therefore, retarded, and the temperature remains nearly constant. In the north, the land which was warm in the summer is relatively cold in the winter, therefore, there is no great difference in temperature over a short horizontal distance, and the upper air is likely to be much colder than the upper air over the Barrier. The temperature over the greater part of the north polar regions falls at the same rate, and, therefore, there is no local source of heat after insolation ceases, hence until insolation again commences after the winter, the temperature continues to fall.

The curves for the yearly variation of temperature at the few places in the Ross Sea area given on figure 28, page 84, become of great interest in the light of the previous discussion.

December is the warmest month at the Barrier, Framheim and McMurdo Sound, showing that at these stations the temperature follows the insolation very closely. At Cape Adare, however, the maximum temperature occurs in January, but Cape Adare is much more affected by open water than the other stations, and, therefore, its temperature cannot follow the insolation so closely. The effect of open water is clearly seen in the rates at which the temperature falls after the summer maximum. The Barrier is furthest away from open water, and its temperature falls the most rapidly. Framheim is so situated in the south-east angle of the Ross Sea that it has the Barrier on three sides and open sea only on the fourth ; the temperature fall there is, therefore, not so rapid as on the Barrier, but much more rapid than in the McMurdo Sound, where the sea is open in most years until the end of March. Cape Adare is almost entirely surrounded by open water until May or June, and the lag of temperature is greatest at that station.

The character of the curves during the winter months is most interesting. The temperature at both Cape Adare and McMurdo Sound continues falling until it is between −10°F. and −15°F. The simplest explanation is that this is the temperature at which the partially frozen Ross Sea gives up sufficient heat to counterbalance the radiation to the clear winter sky, and, therefore, it is the lowest mean temperature at Cape Adare and McMurdo Sound which are so much under its influence.

If we neglect for the moment the low temperature of August at Framheim, we see that the winter temperatures are very similar at Framheim and on the Barrier ; this, as explained above, is due to the blizzards which remove the cold air over the Barrier and replace it by air in temperature equilibrium with the upper air whose temperature is governed by the relatively warm Ross Sea. The mean temperature of August 1911 at Framheim may safely be judged to be abnormal ; a longer series of observations would, doubtless, show that during the months May to August the mean temperature at Framheim would be nearly stationary, as it is at other stations in the Ross Sea area.

Annual Temperature.

From table 40, page 81, it will be seen that the mean temperature of two years at Hut Point was −1·4°F., of two years at Cape Evans +1·4°F., and of one year at Cape Royds +3·4°F. Now Hut Point is near the end of McMurdo Sound, and, therefore, very near to the Barrier; Cape Royds is near where McMurdo Sound opens into the Ross Sea and Cape Evans is between the two. It is, therefore, likely that these different temperatures represent a real geographical variation of temperature which decreases as one proceeds south in McMurdo Sound from the Ross Sea to the Barrier.

A few simultaneous temperature observations made during 1911 and 1912 at Cape Evans and Hut Point confirm this conclusion, as will be seen from the following table:—

TABLE 51.

Difference between Simultaneous Observations of Temperature at Cape Evans and Hut Point.

Month.	No. of days of observations.	Temperature difference. Cape Evans—Hut Point.
February, 1911	13	−4·7
March, 1911	10	−5·2
March, 1912	15	−2·4
April, 1911	30	−5 0
April, 1912	30	−5·5
May, 1911	12	−2·0
September, 1911	8	−1·2
October, 1911	26	−0·7
November, 1911	4	+1·4

The average variation of the mean temperature in individual years from the five-year mean is only 2·1°F. (see table 41, page 82); if this is partly due to geographical position, the coldest year 1911 being observed at Hut Point, and the warmest at Cape Royds, it shows a remarkably small variation from year to year, for average variations of this amount are met with at much lower latitudes.

In table 52 are entered the mean temperatures of the stations in the Ross Sea area.

TABLE 52.

Mean Annual Temperature.

Station.	Latitude.	Longitude.	Mean annual temperature.	Period of observation.
			°F.	
Cape Adare . . .	71° 18′	170° 9′ E.	+ 7·0	Two years (three months interpolated).
McMurdo Sound . .	77° 38′	166° 24′ E.	+ 0 7	Five years.
Framheim . . .	78° 38′	195° 30′ E.	−14·4	One year (two months interpolated).
Barrier . . .	79° 00′	170° 00′ E.	−15	See page 30.

The Mean Temperature of the Antarctic.

From a climatological point of view, it is of great importance to know the mean temperature of all parts of the globe. Several attempts have been made to estimate the mean temperature of the Antarctic; but on account of the paucity of data, the results are open to a considerable amount of uncertainty. The latest attempt was made by Professor Meinardus in 1909.* His investigation gave the following values for the mean temperature between 60° S. and the South Pole.

Table 53.

Mean Temperature of the Antarctic (Meinardus).

Latitude	60° S.	70° S.	80° S.	90° S
Temperature	25·7°F.	9·0°F.	−5·1°F.	−13·0°F.

These values have been plotted in figure 30, and the new data for Cape Adare, McMurdo Sound, Framheim, and the Barrier added for comparison.

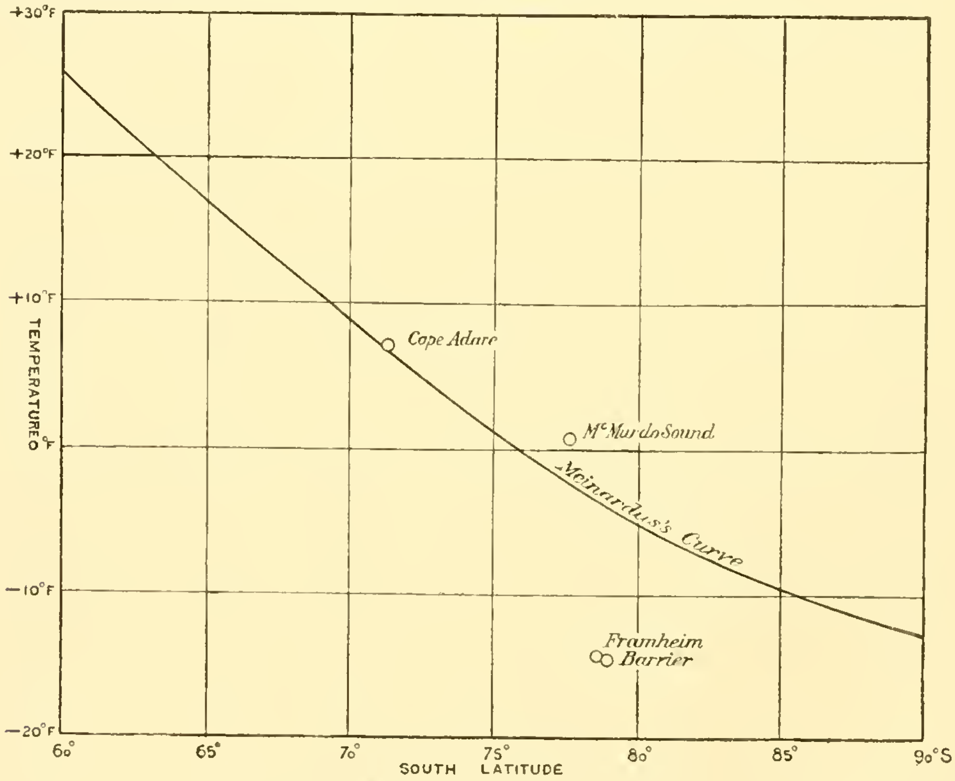

Fig. 30. **Mean temperature of the Antarctic.**

The value for Cape Adare falls almost exactly on the curve, but that for McMurdo Sound is too high, while those for Framheim and the Barrier fall far too low. Meinardus's curve is an estimate of the average temperature over the whole of various latitudes, and it is necessary to review in the light of the new data whether Meinardus's values are satisfactory.

Framheim is only one degree further south than McMurdo Sound, yet they differ in mean temperature by 15°F. We have already shown that this difference is due to McMurdo Sound

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* Scobel's Geographisches Handbuch, page 74.

being so much under the influence of the sea. There can be little doubt that the temperature of all places on latitude 78° S. at any considerable distance from open water have temperatures nearer that of Framheim than that of McMurdo Sound, in fact the temperature of Framheim is probably higher than that of places on the same latitude but further from the sea. So far as we know, the only other part of the Antarctic at which the sea is ever open so far south as 78° S. is in the Weddel Sea, where Filchner penetrated in 1912 to 77° 45′ S. The rest of the 78° S. parallel, in all probability, passes over ice as thick as that of the Barrier. It is thus reasonable to conclude that the average temperature of all places near sea level along latitude 78° S. is near to that found for Framheim and the Barrier, and therefore must be below the value given by Meinardus. As all the temperature data used by Meinardus have been obtained at stations either on the coast or over the sea itself, they are open to the same objection when used to give the average temperature over the Antarctic Continent. Cape Adare is surrounded on three sides by open water during seven or eight months of the year, and during the remainder open water is never far away. It is, therefore, almost certain that Cape Adare has a higher temperature than large tracts at the same latitude which are far away from the sea, and have a snow surface similar to that of the Barrier. But the temperature at Cape Adare has been given by Meinardus as the mean of the latitude on which Cape Adare is situated. Thus we see that at latitudes 71° S. and 78° S. Meinardus's mean temperatures for the whole latitude are too high, and at the latter, the evidence points to an error of about 11°F. It is, therefore, safe to conclude that all Meinardus's values south of the Antarctic Continent are too high, because he has based them on coast temperatures, and not on inland temperatures. Considering how little we know of the inland temperatures of the Antarctic, and of the height of the continent, it seems useless to carry the discussion further. We can, however, say definitely that the temperatures at the various latitudes south of the Antarctic Circle are certainly lower than those given by Meinardus.

This conclusion is of importance when we compare the mean temperatures of the Arctic and Antarctic for Meinardus's values are already considerably lower than those determined by Mohn for corresponding latitudes in the north.

TABLE 54.

Latitude.	Meinardus's mean temperatures for south latitudes.	Mohn's values for north latitudes.	Difference.
	°F.	°F.	°F.
60°	+25·7	+30·0	−4·3
70°	+ 9·6	+12·7	−3·7
80°	− 5·1	− 0·6	−4·5
90°	−13·0	− 8·9	−4·1

According to the above table the temperatures in north polar regions are between 4°F. and 5°F. higher than at corresponding positions in the south and as Meinardus's values are too high the real difference is considerably greater.

CHAPTER III.

WIND.

INSTRUMENTS AND METHODS.

Anemometers.—Three anemometers were used at Cape Evans.

(*a*) A small Robinson anemometer having 3-inch cups on $7\frac{3}{8}$-inch arms and calibrated to the factor 2·73. This instrument was considered to be the standard instrument.

(*b*) An anemometer also having the same size cups and arms, but so arranged that after a certain number of revolutions an electrical circuit was closed for a short time. Wires were taken from the anemometer to a recording instrument within the hut, by means of which a pen, writing on a drum revolved by clockwork, was raised a short distance every time the circuit was closed. Thus a series of steps was drawn on the record each one of which corresponded to a definite amount of wind. A time mark was made on the actual record every hour by means of an electric current from the standard clock. The value of the wind amount corresponding to a step of the record was determined at frequent intervals, by counting the steps on the record corresponding to a day's run of the standard anemometer. Both of these instruments (*a*) and (*b*) were mounted side by side on a wooden frame on the top of Wind Vane Hill.

(*c*) A Dines pressure tube. This instrument had been specially designed to meet the difficult conditions of the Antarctic. The head had been so arranged that it could be easily removed and cleared of snow, and the suction part of the head had been erected separately from the vane. Also a reservoir had been inserted between the head and the float in order to prevent any snow which entered the nozzle accumulating in the connecting pipes. The instrument as designed in London was specially made by Mr. Munro of Cornwall Road, London, and very kindly lent by him to the expedition. The head was erected at the east end of the hut within which was the recording part. The temperature within the hut was generally above freezing point, but it was found advisable to use petroleum as the liquid in the cistern, as on one or two occasions the water and glycerine supplied froze.

The change in design of the head proved a great success in practice. During blizzards a certain amount of snow accumulated just within the nozzle; but every four hours, when meteorological observations were made, this was cleared out and it was only in the worst blizzards that any part of the record was lost owing to the nozzle becoming choked up with snow.

The exposure of this anemometer on the roof of the hut would not have been satisfactory if it had been desired to use its record for obtaining true wind velocities, because the hut was in the lee of Wind Vane Hill and therefore not exposed to the full velocity of the wind. The records however have not been used for obtaining actual velocities, but only for studying the 'structure of the wind.' The velocities recorded by the cup anemometers on Wind Vane Hill varied between 1·25 and 1·50 times the velocities recorded by the Dines anemometer at the Hut, the ratio varying from time to time as small changes in wind direction made appreciable differences in the amount of shielding. On a few occasions the Dines record has been used for supplying missing velocities when the cup anemometer was out of order.

From February 4, 1911, to September 30, 1912, the electrical cup anemometer gave a practically unbroken record of the hourly velocity of the wind. It has been found possible to fill in the few lacunæ either from the records of the Dines anemometer or by reasonable interpolation.

Wind Vane.—A self-recording wind vane was installed during February, 1911, on the top of Wind Vane Hill. From the first trouble was experienced in this position. It was exceedingly difficult to change the paper during high winds, and the first five days' record was lost owing to the blowing away of the paper when it was taken off the drum. The exposure however was so good on the top of this hill that I was very reluctant to move the instrument, but when low temperatures set in, the stopping of the clock became so frequent that it became necessary on May 16, 1911, to remove it to the hut, where it was possible to have the clockwork inside. The hut was however in the lee of Wind Vane Hill and the wind direction was affected to some extent by this obstacle. The change in direction was really very small; but it was just sufficient to cause the predominant wind to be changed from S.E. to E.S.E., and a certain proportion of the E.S.E. winds just crossed the dividing line into the E. division. This small break in the continuity of the series was unfortunate, but practically it has no large significance for, as will be shown later, the wind direction was so largely affected by Mount Erebus, that for all practical purposes the winds may be divided simply into northerly and southerly, the former blowing from the Ross Sea to the Barrier, and the latter from the Barrier to the Ross Sea.

The self-registering wind vane was not entirely satisfactory as it did not turn very freely and the time scale was so small that it was difficult to fix with accuracy the time when the wind changed. Also it gave other troubles so that there was a disappointingly large number of missing records. Owing however to the great preponderance of winds from the directions about E.S.E. and N.N.W. it was possible to fill in a large proportion of the missing record with tolerable certainty.

There is a more or less complete hourly record from February 7, 1911, to the end of August, 1912, and in addition readings of a small vane exposed on Wind Vane Hill were taken each morning from January 13, 1911, to December 30, 1912.

WIND VELOCITY.

Mean Wind Velocity.

The members of our expedition who had been previously in the Antarctic with Scott or Shackleton, constantly remarked on the great amount of wind experienced in 1911 as compared with that of their previous visits. The following year, however, was very much worse, and the mean wind during 1912 at Cape Evans was the highest recorded up to that time during twelve consecutive months in any part of the Antarctic. The large variations from year to year and from month to month are shown in the following table in which the mean velocities for each month are given for the four years 1902, 1903, 1911 and 1912.

TABLE 55.

Mean Wind Velocity (miles per hour).

Month.	Hut Point.		Cape Evans		Mean four years.
	1902.	1903.	1911.	1912.	
January . . .	7 *	6	12·5	10·9	9·1
February	12 †	10	22·7	20·5	16·3
March	10 †	11	25·6	24·8	17·9
April	12 †	9	15·9	20·2	14·3
May	17	10	12·0	25·0	16·0
June	12	11	13·2	31·8	17·0
July	12	9	18·5	28·8	17·1
August	14	11	16·7	25·3	16·8
September	10	11	14·5	22·5	14·5
October	10	12	17·9	17·3	14·3
November	8	11	16·1	18·9	13·5
December	8	8	14·7	11·1	10·4
Mean	11·0	9·9	16·7	21·4	14·8

It is very probable that the exposure of the anemometer at Hut Point was not so free as at Cape Evans, but that would not account for the whole difference between the two periods 1902-03 and 1911-12. We have the opinion of the men who were in the Antarctic during both periods and they were unanimous that the wind conditions in the second period were much worse than in the first. Then again there is the large variation in the two years in the same place. June, 1912, had nearly 2½ times as much wind as June, 1911, and May, 1912, had over twice as much as May, 1911, it is therefore not improbable that the whole year 1912 had over twice as much wind as 1903.

The abnormal amount of wind in the six months April to September, 1912, is remarkable. The mean velocity during these months was 25·6 miles per hour as compared with the corresponding velocities of 13·8, 11·0 and 15·1 in the other years respectively.

The greatest amount of wind was recorded in June, 1911, during which month the mean velocity was over 40 miles an hour during 41·4 per cent. of the hours in the month and over 60 miles an hour during 6 per cent. The mean velocity experienced during this month, 31·8 miles per hour, is the highest yet recorded in the Antarctic, the nearest being 30·6 miles

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* 1904.

† From Beaufort estimates.

an hour during March, 1903, at Snow Hill in the west Antarctic.* The highest velocity of the two years occurred on May 4, 1912, when a wind of 81 miles in the hour was recorded.

Annual Variation of Wind Velocity.

Examining the numbers in the last column of table 55 which give the mean monthly values for the four years (plotted on figure 31), we see that the annual variation has a double period with two maxima and two minima. It would probably be more correct to say that the annual variation has a main period with a minimum in the summer and a maximum in the winter upon which is superposed a pronounced secondary maximum in February and March.

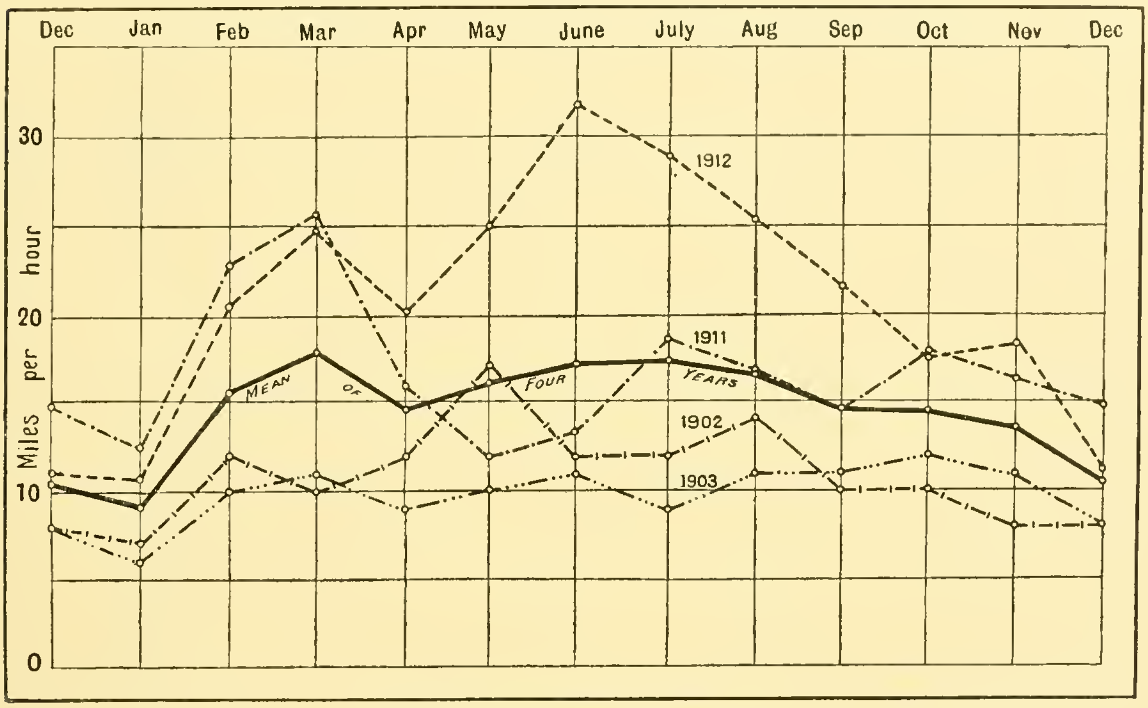

Fig. 31. Annual variation of wind velocity.

With large variations in velocity from year to year which we have already noted it is not surprising to find that the annual variations are not identical from year to year. Thus the absolute maximum of monthly wind velocity occurred in May in 1902, in October in 1903, in March in 1911, and in June in 1912.

Nevertheless by examining the whole trend of each curve we see that the wind in each year does conform more or less closely to the mean of the four years, *i.e.*, in each year there is a marked minimum in January, a maximum in February or March and then a second maximum in one or other of the winter months. We may therefore accept the mean of the four years as representing fairly closely the normal annual variation of wind strength.

The physical explanation of this annual variation would be interesting, but it cannot be given with any certainty. The following considerations may however be useful in indicating the lines along which an explanation may be found.

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* Since this was written Mawson has reported the tremendous wind velocities found in Adelie Land, where the mean velocity for a year was 50 miles an hour.

Taking the annual variation to consist of—

(*a*) a simple period with a minimum in the summer and a maximum in the winter,

(*b*) a pronounced secondary maximum in February and March.

it will be found that the former of these is present at all stations near the Antarctic Continent for which we have data except Framheim and Cape Adare, while the latter is present at all except the *Belgica* station.

TABLE 56.

Annual Variation of Wind at Antarctic Stations (miles per hour).

Station.	December.	January.	February.	March.	April.	May.	June.	July.	August.	September.	October.	November.
Framheim	10·7	7·8	—	—	9·8	6·5	8·9	10·5	9·2	9·8	14·5	11·4
	9·2					8·7						
Hut Point	8·0	6·5	**11·0**	10·5	10·5	13·5	11·5	10·5	12·5	10·5	11·0	9·5
	7·2					12·0						
Cape Evans	12·9	11·7	21·6	**25·2**	18·0	18·5	22·5	23·6	21·0	18·5	17·6	17·5
	12·3					21·4						
Cape Adare	8·3	10·0	—	**10·3**	8·4	9·9	6·0	6·3	6·8	10·1	6·6	6·4
	9·1					6·8						
Belgica *	7·8	8·1	9·8	10·5	12·8	9·4	8·9	5·6	9·6	7·8	9·2	7·4
	7·9					8·4						
Snow Hill *	9·8	11·4	16·8	**30·6**	17·7	19·7	19·9	22·1	20·8	18·3	17·7	19·0
	10·6					20·6						
Gauss Station * . . .	10·3	9·4	**13·2**	10·7	12·5	19·9	11·6	14·5	19·9	11·0	9·2	10·5
	9·8					16·5						
Petermann Island . . .	—	3·2	6·1	**10·1**	8·3	7·6	9·9	15·7	18·5	15·0	13·7	10·7
						12·9						

The cause of the greater wind in the winter than in the summer is without doubt the annual variation of the difference in temperature between the continent and the ocean. We have no actual temperature observations from the interior of the continent during the winter but there can be no question that the temperature difference between the continent and the surrounding ocean is greater in the winter than in the summer. This causes an intensification of the Antarctic anticyclone and in consequence increased wind velocity along the coast.

The explanation of the secondary maximum of wind velocity in February or March is not obvious. It may be connected with the rapid fall of temperature over the continent during these two months while open water extends almost up to the margin of the permanent ice. This would cause a temporary closing up of the isotherms near the edge of the continent and therefore an increased pressure gradient. Further observations are necessary before this point can be settled.

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* From table 62 of Bodman's discussion of the Snow Hill results.

Annual Variation of High Winds and Calms.

An interesting side light is thrown on the conditions affecting the surface air motion by comparing the number of high winds and the number of calms in the different months.

TABLE 57.

High Winds and Calms.

Month.	Wind over 40 miles per hour.	Calms 0—1 mile per hour.	Temperature.
	%	%	°F.
1911.			
February	15·9	..	+18·7
March	19·0	0·0	+ 7·2
April	4·4	5·1	− 1·1
May	7·1	27·2	− 10·8
June	7·4	21·8	− 13·5
July	18·3	17·1	− 21·1
August	16·0	20·3	− 21·1
September	15·0	25·6	− 15·8
October	10·0	9·4	− 3·4
November	2·4	10·4	+ 12·3
December	2·6	16·5	+ 22·0
1912.			
January	1·6	10·2	+ 21·3
February	16·6	5·2	+ 12·9
March	20·6	1·3	+ 2·6
April	12·9	0·4	− 8·0
May	25·8	5·4	− 7·6
June	41·4	2·6	− 9·2
July	35·0	13·3	− 5·6
August	25·9	3·0	− 3·1
September	15·7	3·3	− 6·9

Looking first at the high winds we see that their frequency has the same annual variation as we have already found for the mean velocity. High winds are the least frequent in the summer, the minimum in November, December, and January being most marked. The large proportion of high winds in February and March is clearly shown in both years, and the decrease from March to April is as pronounced in the high winds as it is in the mean velocity. Either June or July has a maximum of high winds in both years. Thus the annual variation of high winds is the same as the annual variation of the mean velocity.

One would anticipate that the occurrence of calms would be the reverse of that of high winds, for if the conditions during any month produce an excess of high winds they can hardly be favourable for calms. This, however, is obviously not the case. August, 1911, had ten times as many high winds as January, 1912, and also had twice as many calms. The frequency of high winds was the same during September in both years, yet September, 1911, had 25·6 per cent. of calms and September, 1912, only 3·3 per cent.

There is obviously a third factor at work, and this is the cold layer of air which forms near the surface during the winter months. When this layer is present the wind moves over its upper surface, while the layer itself remains stationary. It is only when the upper wind becomes great that the cold layer is removed; thus during such periods the wind conditions are a succession of calms or high winds. The presence of the cold layer is shown by the low temperature and we find that months with a high proportion of calms have low temperatures. Thus March, 1911, and July, 1911, had practically the same number of high winds, but the former had no calms while the latter had 17·1 per cent. But the mean temperature of July, 1911, was −21·1°F., while that of March was +7·2°F.

The winter conditions in the two years 1911 and 1912 are very instructive. The whole of McMurdo Sound was firmly frozen over during the winter of 1911, but it was open during the greater part of the winter of 1912. Thus while the cold layer could form with ease over the thick ice in 1911, it could not form over the open water in 1912. It is therefore not surprising to find that from May to September, 1911, with a mean temperature of −16·5°F. the percentage of calms was 22·4, while during the same period in 1912, with a mean temperature of only −6·5°F., it was as low as 5·5.

The contrast between the conditions during these two winters is a good example of how the temperature and wind interact on one another. If there are not many storms, the ice can form over the sea and a stagnant layer of cold air develop above the ice. Over the cold layer moderate winds pass without disturbing it, thus giving a calm near the ground and so reducing still further the mean wind velocity. A few high winds remove this layer and also the ice and in consequence the gradient wind extends down to the ground and so increases the mean wind velocity and also the mean temperature.

Thus during the winter the wind conditions are in a state of unstable equilibrium. High winds make the conditions favourable to more winds, while light winds produce conditions favourable to calms.

Daily Variation of Wind Velocity.

Curves of the daily variation of wind velocity in each season are shown in figure 32.

These curves are based on all the data available, namely: November, December, January two years; February, March, October three years; April, May, June, July, August, September four years. The data will be found in the volume of tables.

As data for the first two years are only given for two hourly intervals it has been possible only to combine two hourly values for the second two years. The mean velocity during the two hours midnight to 2 A.M. has been plotted against 1 A.M. and so on.

Except in the winter months the daily variation of wind velocity has a maximum in the early afternoon and a minimum soon after midnight. This is the usual form of the daily wind variation and is explained by the convexion currents which are set up in the day time. The upper air usually moves with a greater velocity than the lower air and the convexion currents act as a connecting link and convey momentum from the upper to the lower air. Thus when the convexion currents are most active in the early afternoon the lower air moves faster than during the night when, owing to the absence of convexion currents, the upper air moves over the lower air without tending to drag it along.

Evidence of appreciable convexion currents over McMurdo Sound even when the Sound is frozen over and the ice covered with snow was found from the vertical temperature gradient during the summer months. There is therefore no reason to doubt that the explanation given above holds also in McMurdo Sound.

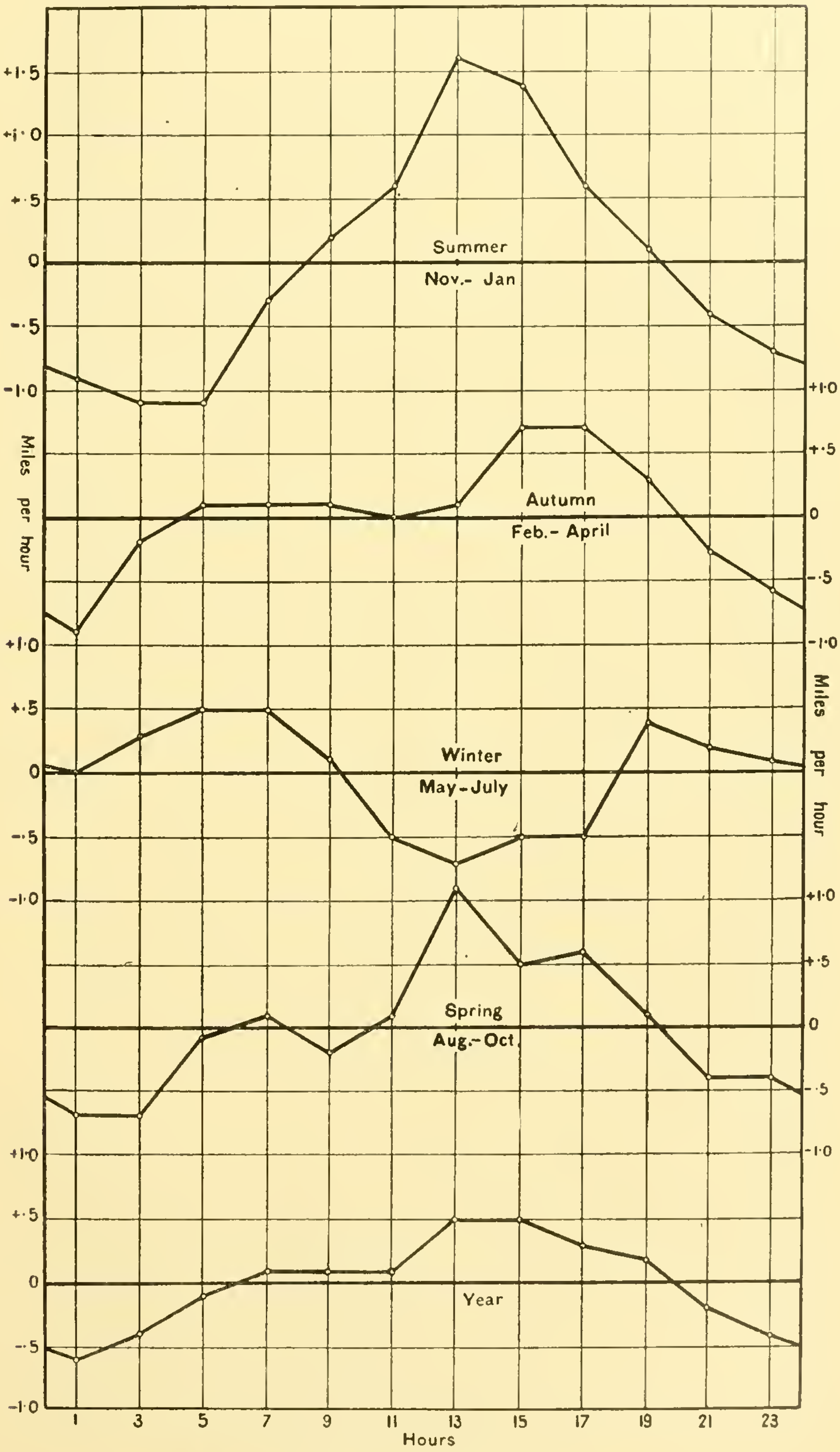

FIG. 32. Daily variation of wind.

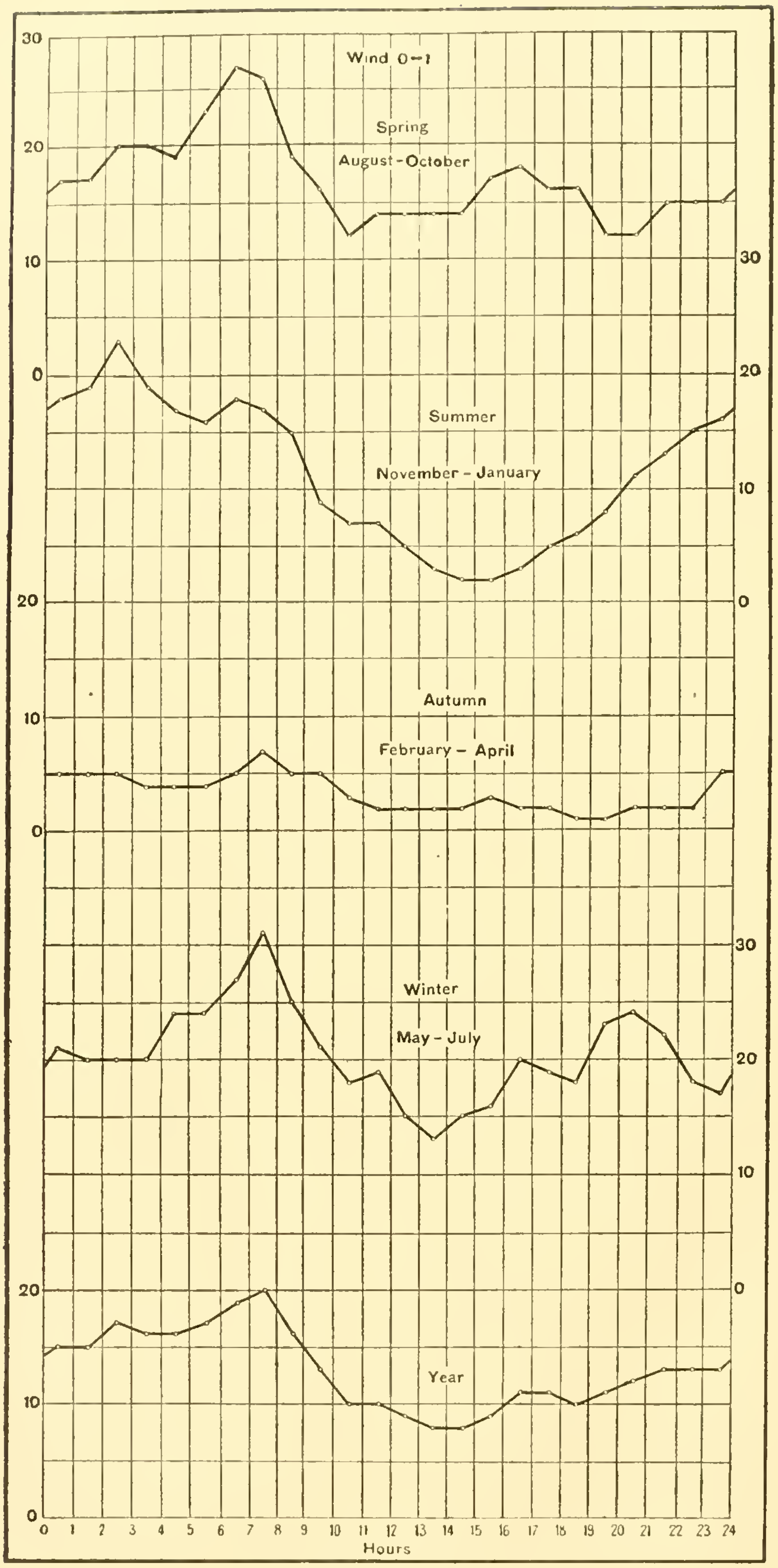

FIG. 33. Daily variation of calms.

The variation during the winter was not the same in the different years. In 1912 when there was an abnormal amount of wind during the winter months the daily variation was very large and quite different from that during the winter of any other of the four years. It is therefore very doubtful whether the variation shown during the winter has any real significance.

Daily Variation of Calms.—The frequency with which calms (0—1 mile per hour) occurred is shown by the curves on figure 33. The data used are for the twelve months March, 1911, to February, 1912. As is to be expected these show the same effect as the mean wind velocity, the calms being most frequent in the night and least frequent in the daytime. There is however one important difference. The character of the curve for the three winter months, May–July, is practically the same as during the other seasons of the year.

It is easy to see why there should be more calms during the night and early morning than in the afternoon during seasons of the year with marked difference of insolation at these times. But why this characteristic should remain during months when the sun was entirely absent is not clear. The effect is most marked and is in all probability quite real.

Frequency of Winds of Different Velocities.

The frequency with which winds of different velocities occur at any place has been strangely neglected in meteorological investigations; although, as we shall show, it is capable of giving important information with respect to the forces at work producing the air motion. If from a record of hourly wind velocities at any place we count the number of times each individual wind velocity has been reported it is possible to plot a curve showing the relative frequency with which each velocity occurs. In practice it is sufficient to choose groups of velocities and in the following the groups will be 0 to 4, 5 to 9, 10 to 14 .... n to n + 4 miles per hour.

The data for three years' hourly observations of wind velocity at Yarmouth on the east coast of England and for the winter months December, January, and February from two years at Jubbulpore in the centre of India have been treated in this way with the following result:—

TABLE 58.

Frequency of Winds of Different Velocities, expressed as a percentage of the whole, at Yarmouth and Jubbulpore.

	0—4	5—9	10—14	15—19	20—24	25—29	30—34	35—39	40—44	45—49	miles per hour.
Yarmouth—year	5·2	23·0	28·4	19·0	11·5	5·7	3·0	2·1	1·5	0·7	
Jubbulpore—Dec., Jan., Feb. .	62·8	28·6	6·6	1·5	0·5	0·1					

These values have been plotted on figure 34. It will be seen at once that the curves for the two places are very different. At Jubbulpore the first group is the greatest, in fact more than 60 per cent. of all the observations fall within the group 0—4 miles an hour. At Yarmouth on the other hand this group contains only 5·2 per cent. of the observations, while it is the third group which contains the greatest number of observations. From the curves it is clear that while at Jubbulpore calms occur more frequently than any wind velocity, at Yarmouth the most frequent wind is one having a velocity of about 8 miles an hour.

The frequency curves for Yarmouth and Jubbulpore are good examples of two distinct types of frequency curves, and before proceeding further we must consider what is their meaning. There can be little doubt that they indicate two different types of weather, namely, the types associated with anticyclonic and cyclonic pressure distribution. It is well known that while air motion is essential to a cyclone it is destructive of an anticyclone. It is therefore clear that a place generally under anticyclonic conditions will have more calms and light winds than high winds, on the other hand a place which is frequently visited by cyclones can have very few calms, and there must, therefore, be some wind velocity which has a maximum frequency.

The interior of India during the winter is subject to strongly anticyclonic conditions, and calms are the most frequent wind values experienced. On the other hand England throughout the year is subjected to a succession of cyclones, and calms are seldom experienced. Thus the pressure types in these two cases agree with the type of wind frequency.

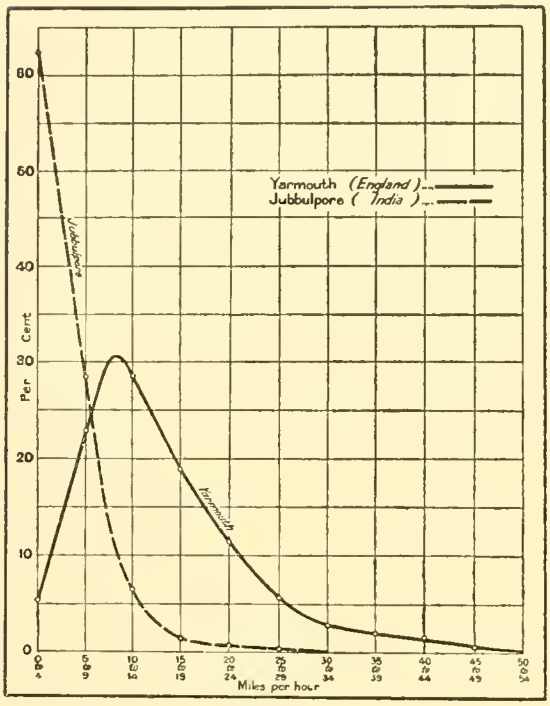

FIG. 34 Frequencies of wind velocities.

That the frequency type changes with the pressure type is shown by the summer observations at Jubbulpore. In June, July, and August the interior of India becomes an area of low pressure. This is a cyclone which although of great extension is of little depth and the gradients on the average are very small. Nevertheless the most frequent wind is no longer in the first group but falls in the second group, the values being :—

TABLE 59.

Wind frequency at Jubbulpore During the Monsoon.

	0—4	5—9	10—14	15—19	20—24	25—29 miles per hour.
Jubbulpore—June, July, August . .	22·5	27·0	18·5	4·7	0·6	0·1

Thus during these months Jubbulpore has the same type of frequency curve as Yarmouth and both are subject to a cyclonic distribution of pressure.

We have thus been introduced to two types of frequency curves. In one the relative frequency increases as the velocity decreases right down to calms ; this type is associated with anticyclonic pressure conditions and therefore will be called the anticyclonic type. In the other the frequency increases as the wind decreases down to a certain velocity after which the frequency decreases as the velocity decreases and calms may have a very small frequency ; this type is associated with cyclonic pressure distribution and therefore will be called the cyclonic type.

The wind observations at Cape Evans, Framheim, Cape Adare, Gauss Station and Snow Hill have been investigated to find the type of their frequency curves, with the result that all prove to be of the anticyclonic type. The data are contained in table 60 and the curves have been plotted in figure 35. In view of Meinardus's opinion that the stations on the edge of the Antarctic Continent are under cyclonic influence this is an important result and one which will prove useful when we come to discuss the pressure and wind conditions of the Antarctic as a whole. To make the investigation complete the observations taken during two years on the drift of the *Fram* (1894 and 1895 between latitudes 79° and 85½° N.) were analysed in the same way. The first group, 0—4 miles per hour, contained only 8·7 per cent. of the observations, while the second group was the maximum with 41·4 per cent., thus the frequency curve in north polar regions is of the cyclonic type.

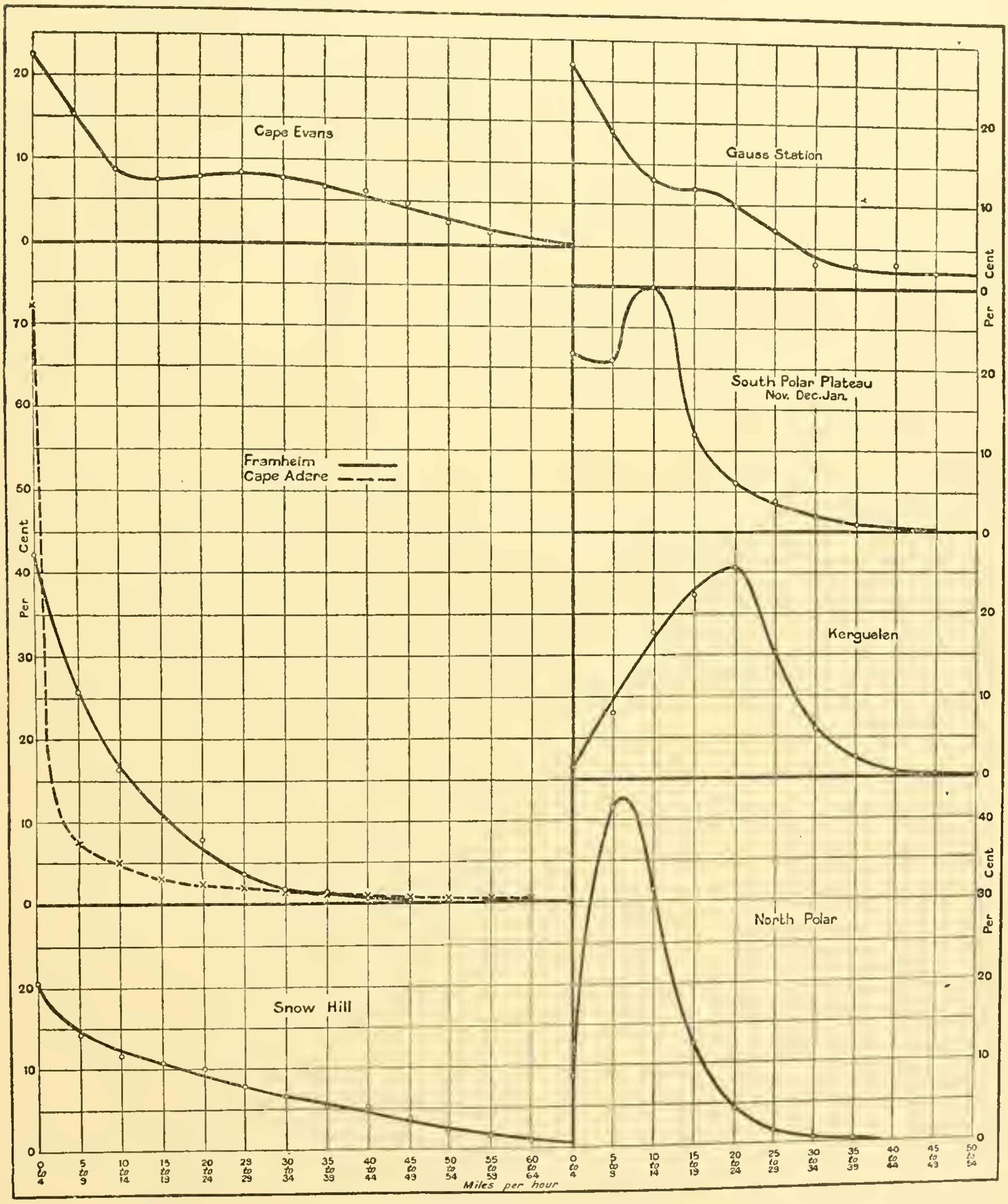

FIG. 35. Frequency of wind velocities.

TABLE 60.

Frequency of Winds of Different Velocities, per cent.

Station.	Period investigated.	0 to 4	5 to 9	10 to 14	15 to 19	20 to 24	25 to 29	30 to 34	35 to 39	40 to 44	45 to 49	50 to 54	55 to 59	> 60 miles per hour.
		0 to 1·8	1·9 to 4·0	4·1 to 6·3	6·4 to 8·5	8·6 to 10·7	10·8 to 13·0	13·1 to 15·2	15·3 to 17·4	17·5 to 19·7	19·8 to 21·9	22·0 to 24·1	24·2 to 26·4	> 26·4 metr per second.
Framheim . .	10 months.	42·2	25·9	16·1	8·0	3·6	1·9	1·4	0·6	0·3	..	..	..	..
Cape Evans .	20 months.	22·4	15·3	8·6	7·6	7·7	8·2	7·7	6·7	6·2	4·8	2·6	1·3	1·0
Cape Evans northerly winds only.	20 months.	22·6	19·8	14·8	14·3	12·1	8·2	4·5	2·0	1·2	0·3	0·1	0·1	..
Cape Adare .	10 months.	72·0	7·5	5·0	3·0	2·5	2·0	1·5	1·0	1·0	0·5	0·5	0·5	3·0
Snow Hill . .	19 months.	20·3	14·4	11·7	10·7	9·9	7·8	6·8	5·2	5·1	3·9	2·2	1·3	0·8
Gauss Station .	11 months.	27	19	13	12	10	7	3	3	3	2	..	..	..
Kerguelen . .	12 months.	1·1	8·0	17·8	22·4	25·6	15·2	6·0	2·9	0·6	0·2	0·1	..	..
North Polar .	2 years .	8·7	41·4	31·4	12·3	4·2	1·4	0·5	0·1	..	..	..	..	..

For comparison with the curves for the stations near the Antarctic Continent, the wind observations made at Kerguelen were examined. This station, although near to the Antarctic, is certainly under the influence of frequent and deep cyclones. The frequency curve for this station is also shown on figure 35. It is most strongly of the cyclonic type, the first group containing only 1·1 per cent. of the observations, and the maximum frequency does not occur before the fifth group with wind velocities from 20 to 24 miles an hour.

The frequency curves have not been calculated for other stations than those discussed in this section, but it is very unlikely that two curves could be more widely different than those for Cape Adare and Kerguelen, which are both marine stations on the same ocean.

Although all the curves for the true Antarctic Stations are of the anticyclonic type they show most instructive differences. The curves for Cape Adare and Framheim are similar to those for Jubbulpore during the winter, they all decrease rapidly and regularly from their maximum. The curve for Snow Hill is somewhat different: it has the maximum in the first group, but the maximum is only 20 per cent. of the whole and the curve decreases very slowly although regularly. A curve of the simple anticyclonic type with 43 per cent. of the winds of a greater velocity than 20 miles an hour must be very unusual. The curve for the Gauss Station shows a departure from the simple anticyclonic type. Instead of decreasing regularly from the maximum the curve decreases at first fairly rapidly and then after the third group much more slowly so that the curve has an upward bulge between the third and the seventh groups showing that the frequency of the winds between 15 and 30 miles an hour is greater than they would be at a place having the same mean velocity and the anticyclonic type of frequency. This anomaly is much more marked at Cape Evans in fact after the fourth group, the frequency actually increases to the sixth group after which it decreases even more slowly than the curve for Snow Hill. Framheim is about three hundred miles to the east and Cape Adare is nearly the same distance to the north of Cape Evans. Yet neither of these stations shows the anomaly which is so strongly marked at Cape Evans. There is obviously at Cape Evans and to a lesser extent at the Gauss Station some factor affecting the winds other than the simple anticyclonic distribution of pressure.

As to what this factor is at Cape Evans there can be little doubt. When the winds are investigated with reference to their direction it is seen that the winds from the north do not show the abnormality, their frequency decreasing quite regularly from light winds to high winds. The southerly winds—the blizzards—are alone responsible for the large excess of winds of an average velocity of about 30 miles an hour. We shall show in chapter VI that blizzards are neither cyclonic nor anticyclonic winds, but owe their origin to changes of pressure brought about by waves of pressure which travel from the south-east and affect the pressure over the whole Ross Sea area. Thus the presence of blizzards superposed on an anticyclonic pressure distribution produces the peculiar form of the frequency curve at Cape Evans.

The similarity of the curves for Cape Evans and the Gauss Station indicates similar conditions in the two localities, and we shall use this evidence later when discussing the conditions at the latter station (see page 247).

This discussion of the frequency curve has taught us the following:—

(*a*) McMurdo Sound, Framheim, the Gauss Station, Cape Adare and Snow Hill are all under the influence of an anticyclonic pressure distribution.

(*b*) Kergulen and the north polar regions are under the influence of a cyclonic pressure distribution.

(*c*) The shape of the curve at McMurdo Sound and to a lesser extent at the Gauss Station, shows the presence of some factor neither cyclonic nor anticylonic which factor at McMurdo Sound is clearly the blizzard, it is therefore likely that blizzards having a similar origin exist at the Gauss Station also.

As the investigation of the frequency curves is worthy of considerably more attention than it is possible to give them here, especially as to certain periods of high winds and seasonal changes, the data for each month used in table 60 are given in full in the volume of tables where the method used in treating wind velocities measured on the Beaufort Scale is also described.

WIND DIRECTION.

Hourly observations of wind velocity and direction at Cape Evans are available for the period February 6, 1911, to August 31, 1912.

The following table summarises all the data:—

TABLE 61.

Wind Directions at Cape Evans.

	W.S.W.	W.	W.N.W.	N.W.	N.N.W.	N.	N.N.E.	N.E.	E.N.E.	E.	E.S.E.	S.E.	S.S.E.	S.	S.S.W.	S.W.	Calm.	Variable and doubtful.
Percentage of total wind.	0·0	0·1	0·5	2·3	4·0	2·5	0·2	0·1	0·0	17·0	47·2	20·2	2·2	0·1	0·0	0·0	0·0	3·6
Percentage of frequency.	0·0	0·2	0·7	2·8	4·2	3·5	0·3	0·2	0·0	9·2	34·8	17·1	2·5	0·3	0·0	0·1	10·4	13·7
Mean velocity miles per hour.	0	9	13	16	19	14	14	11	8	37	27	23	17	7	9	8	0	5

A glance at the upper diagram in figure 36 which exhibits the total wind from each direction shows at once how insignificant the air motion was from all directions except E., E.S.E. and S.E. which together had 84·4 per cent. of the total. Of the remaining 12 per cent. (neglecting variable and doubtful) 8·8 per cent. came from the three directions N.W., N.N.W. and N.

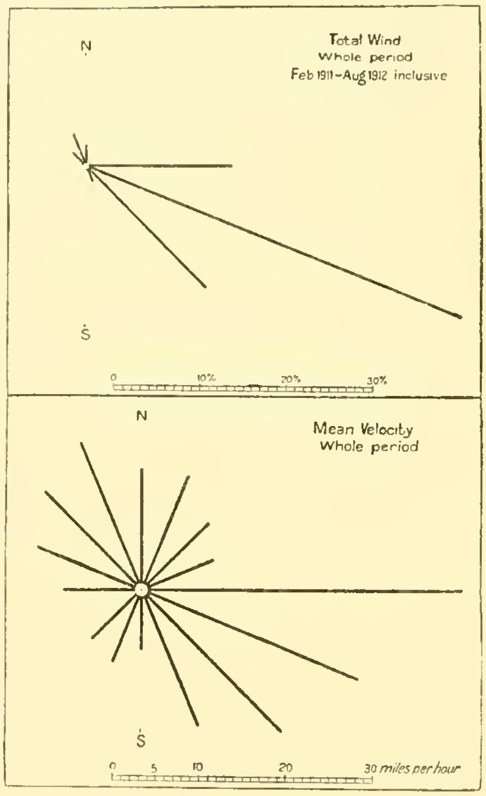

Fig. 36. Total wind and mean velocity.

The mean wind velocity for each direction is shown on the lower diagram of figure 36. There is little difference in the velocity of the three northerly directions which have any appreciable air motion, but N.N.W. which has the greatest air motion has also the greatest velocity.

The velocities of the three important winds in the S.E. quadrant are instructive. The E.S.E. direction has the greatest air motion, but the E. has the greatest velocity. This is not only true in the mean, but it was frequently noticed in individual storms. During blizzards the wind vane generally pointed to the E.S.E., the percentage frequency in this direction being very much higher than for the directions on either side, but as the wind increased to its most violent efforts the vane swung slightly to the left and the direction became nearer E. than E.S.E. although it practically never reached due E. On the other hand during lulls the vane swung slightly to the right, so that S.E. and very occasionally S.S.E. directions were recorded. From figure 36 we see that all the directions from S.S.E. to E. have high velocities, but that the mean velocity increases as the wind becomes more easterly. We shall find the reason for this in our further discussion.

The predominance of the winds from the S.E. quadrant was so great throughout the year that the resultant direction varied very little from month to month. A good measure of the steadiness of the wind direction is given by the ratio of the velocity of the resultant wind to the mean velocity independent of direction. It is obvious that with winds all from the same quarter this ratio would be 1, while if the winds were uniformly spread over the whole compass the resultant velocity would be zero and the ratio would fall to nothing.

TABLE 62.

Cape Evans Wind.

Month.	Resultant direction.	Resultant velocity.	Mean velocity.	Ratio.	Maximum velocity during one hour.	Mean direction.
1911.		Miles per hour.	Miles per hour.			
February . .	S. 46 E. (S. 61 E.)	22·5	22·7	1·0	61	S. 46 E.
March . . .	S. 49 E. (S. 64 E.)	22·3	25·6	0·9	57	S. 51 E.
April . . .	S. 63 E. (S. 78 E.)	9·2	15·9	0·6	55	S. 73 E.
May . . .	S. 80 E.	4·9	12·0	0·4	54	S. 88 E.
June . . .	S. 67 E.	9·7	13·2	0·7	56	S. 67 E.
July . . .	S. 78 E.	16·1	18·5	0·9	66	S. 72 E.
August . . .	S. 78 E.	12·5	16·7	0·8	66	S. 74 E.
September . .	S. 77 E.	11·8	14·5	0·8	57	S. 76 E.
October . . .	S. 85 E.	13·0	17·9	0·7	59	S. 85 E.
November . .	S. 78 E.	13·5	16·1	0·8	43	S. 74 E.
December . .	N. 89 E.	8·2	14·7	0·6	48	N. 88 E.
1912.						
January . . .	S. 77 E.	8·6	10·9	0·8	54	S. 70 E.
February . .	S. 68 E.	18·2	20·5	0·9	63	S. 68 E.
March . . .	S. 80 E.	19·0	24·8	0·8	68	S. 79 E.
April . . .	S. 72 E.	13·9	20·2	0·7	60	S. 78 E.
May . . .	S. 78 E.	18·8	25·0	0·8	81	S. 80 E.
June . . .	S. 68 E.	26·3	31·8	0·8	73	S. 67 E.
July . . .	S. 66 E.	24·7	28·7	0·9	79	S. 68 E.
August . . .	S. 63 E.	21·4	25·3	0·8	56	S. 64 E.
Year {June 1911 to May 1912}.	S. 77 E.	13·7	17·8	0·8	81	S. 76 E.

It has already been explained that in May, 1911, the position of the wind vane was changed in consequence of which the wind directions recorded were shifted somewhat to the E. To allow for this change and to make the series homogeneous, about 15° needs to be added to the resultant direction for February, March, and April, 1911; this has been done and shown by the figures in brackets. Throughout the period February, 1911, to August, 1911, the resultant direction only varied from S. 61 E. in February, 1911, to N. 89 E. in December, 1911, *i.e.*, a change of only 30° (a little over one compass point). The average ratio of the resultant velocity to the mean velocity was ·8 showing the concentration of the wind into a few directions about the resultant direction.

Taking the twelve months from June, 1911, to May, 1912, the resultant velocity was 13·7 miles per hour and the resultant direction S. 77 E.

The resultant velocity and direction for the year 1903 recorded at Hut Point were 6·7 miles per hour and N. 80 E. respectively. Thus the resultant direction was 23° more to the north at Hut Point than at Cape Evans. As the places are so near together this can be only the result of local deflections of the wind. We must therefore discuss the effect of the land masses which influence the direction of the wind in the McMurdo Sound region.

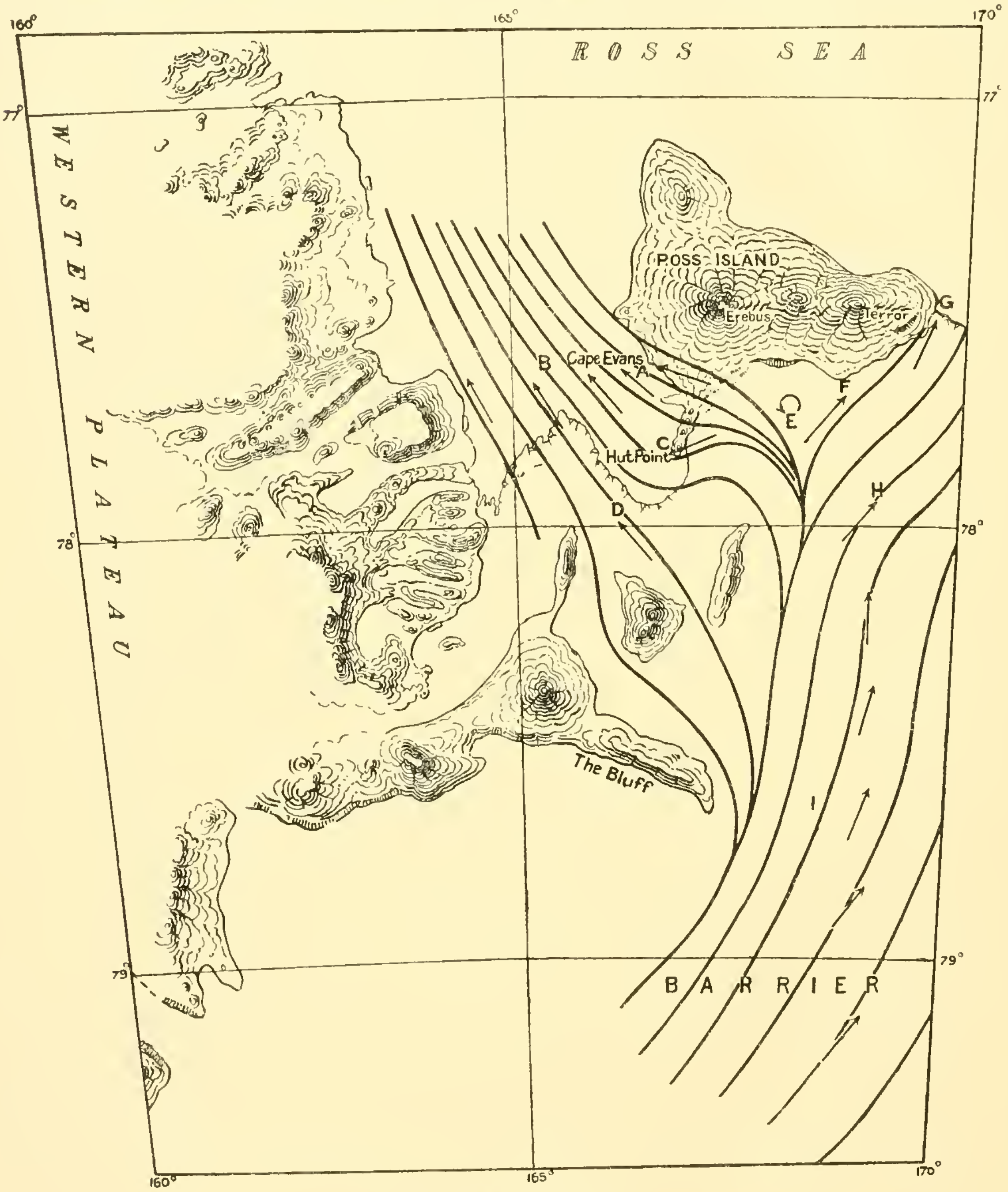

FIG. 37. Wind directions.

The general distribution of land can be seen on figure 37. The great mass of Ross Island is separated from the Western Plateau by the McMurdo Sound. Erebus is 13,000 feet high and its summit is only 12 miles from Cape Evans and between 40 and 50 miles from the tableland 9,000 feet high just across the Sound. It is quite clear therefore that these two masses which rise well above the lower winds must affect the flow of air in their neighbourhood.

We are chiefly concerned with blizzard winds, we will therefore examine first the effect of the land distribution on these winds. If there had been a large number of observers taking simultaneous observations at many different points it would have been possible to show the actual motion of the air at any given time during a blizzard. As these observers were not present the next best thing is to examine observations taken at different times in different places during blizzards. This it is possible to do from the meteorological records kept by the various sledging parties. Also the directions of the sastrugi give valuable information as to the directon of high winds.

Stream Lines during Blizzards.—In figure 37 the results of such an investigation are shown. The stream lines indicated on the diagram are what one would expect from the configuration of the land, but in support the following evidence for several of the most important positions is added.

Position A.—Cape Evans.—Wind E.S.E. During blizzards the wind was constantly from S.E., E.S.E. and E., of these E.S.E. was the most frequent and this direction is shown.

Position B.—The prevailing winds over McMurdo Sound were clearly indicated by the direction of the sastrugi. There were two distinct sets of sastrugi on the line joining Cape Evans and Butter Point. One set, the most marked, indicated a wind from somewhat south of east and the other set a wind from between S.E. and S.S.E. There can be little doubt that the former were formed during the violent winds which were deflected by the shoulder of Erebus; while the latter were formed by the moderate south-easterly winds which constantly blew through McMurdo Sound from the Barrier. Both sets of sastrugi became more southerly as the Sound was crossed from east to west; the actual observations were:

TABLE 63.

Sastrugi in McMurdo Sound.

	1st set.	2nd set.
5½ miles from Cape Evans	E.byS.	S.E.
12 ,, ,, ,, ,, ...	—	E.S.E.
25 ,, ,, ,, ,, ...	E.S.E.	S.S.E.
Near Cape Bernacchi on the western coast .	No definite sastrugi.	

Position C.—Hut Point.—Wind E. to N.E. Both the records of the Discovery Expedition and of the men of our expedition who remained at Hut Point show winds between E. and N.E. during the most violent blizzards. There can be little doubt that the wind is here deflected by the high ridge running N.N.E. from Hut Point.

Position D.—Wind S.E. On March 12, 13 and 14, 1911, a party was at the point marked D during a very violent blizzard. S.E. winds were recorded throughout.

Position E.—Variable winds. On July 4, 1911, the Cape Crozier party was at the point indicated by E. Throughout this day an east-south-easterly blizzard blew at Cape Evans with velocities up to 52 miles an hour, but the party recorded:

> 'Overcast all day with steadily falling snow. Wind 3 to 4 with occasional gusts from E.N.E. to S.E. and light breeze from S.S.E.'

thus showing variable winds during a blizzard which was giving steady high winds from the E.S.E. at Cape Evans.

Further within the large bay in the south of Ross Island the wind is always light and variable. The bay was explored right up to the coast by members of Captain Scott's first expedition and it was found to be full of light snow showing little or no signs of heavy winds. Dr. Wilson called this bay Tranquil Bay.

Position F.—Wind S.W. While the Cape Crozier Party was at F. on July 10 and 11, 1911, there was a blizzard at Cape Evans throughout which a high wind blew from the E.S.E. and E. The wind experienced by the party was just as high and as steady but it was from the S.W. and S.S.W.

Position G.—Cape Crozier.—Wind S.S.W. As is well known the Cape Crozier Party experienced an exceedingly violent blizzard on July 22 and 23 while at Cape Crozier. During the height of this blizzard the wind at Cape Crozier was S.S.W. while at Cape Evans it was steadily from the E.

Position H.—Corner Camp.—In the autumn of 1911 a small wind vane was erected at Corner Camp which was so arranged that a steel point connected to the vane pressed on to the aluminium base plate, the idea being to deduce from the position of the maximum scratching the direction of the prevailing wind. When Captain Scott saw this vane in November, 1911, after it had been exposed throughout the winter he found that the maximum scratching indicated 'a predominance of wind from the S.W. quarter.'

Position I.—The winds at I and to the south are clearly indicated by the sastrugi which all point to the high winds coming from the S. or S.S.W.

From figure 37 it appears safe to conclude that during blizzards the wind streams along the west of the Barrier parallel to the edge of the high land. When this southerly stream impinges on Ross Island it breaks up into two branches one of which passes Cape Crozier as a S.W. or S.S.W. wind, and the other enters McMurdo Sound as a S.E. wind.

Thus the easterly components of the wind at Cape Evans and Hut Point are the result of the air being compelled to move round the south-west shoulder of Erebus. During the most violent blizzards there is a great crowding of the stream lines on to the slopes of Erebus and then the wind becomes due E. at Cape Evans, while at Hut Point there is a local ridge which still further deflects the wind, and the wind which is E. at Cape Evans becomes E.N.E. or even N.E. at Hut Point.

The fact that a high easterly wind at Cape Evans occurs when there is a violent southerly wind along the west of the Barrier, will be of great importance when we come to construct isobaric charts.

The conditions which give S. to S.W. winds over the Barrier are isobars running more or less from south to north with the low pressure in the east; when isobars are drawn in this way on a small scale map it often appears as though the easterly wind at Cape Evans is blowing from low to high pressure.

We have now seen that the majority of winds at Cape Evans are the deflected winds of the air stream which flows from the south during the blizzards. It is quite clear that there can be no true winds blowing across the Sound for the Western Mountains on the one side and Erebus on the other prevent such air motion. As seen from Cape Evans Mount Erebus occupies the horizon from E. to N.N.E., hence winds from the directions between these points are practically impossible. The three directions E.N.E., N.E., and N.N.E. have only ·5 per cent. of wind frequency. The horizon becomes open from N. to N.W. and the frequency of the winds from these directions increases, forming as we have already seen the only winds of any importance beyond those from the S. to E. quadrant—the three directions N., N.N.W., and N.W. have 12·2 per cent. From the W.N.W., though W. to S. the horizon is again closed by the Western Mountains and the six wind directions from W.N.W. to S. have together only 1·4 per cent. of the total winds.

Thus we see that the only motion possible in the McMurdo Sound is from the Ross Sea to the Barrier and from the Barrier to the Ross Sea. From the position of Cape Evans it happens that there are two directions which sharply divide off the two kinds of air motion. During nineteen months not a single wind from the W.S.W. was recorded, and from the opposite direction E.N.E. only six. These two directions divide the winds into the two classes, and all winds between E.N.E. and W. through N. blow from the Ross Sea to the Barrier, and all winds between S.S.W. and E.N.E. through S. blow from the Barrier to the Ross Sea.

It is clear from the above discussion that the wind observations at Cape Evans give no indications beyond the fact that the pressure is such that the air flows in one or other of the directions through the Sound. Beyond this there can be no close connexion between the wind direction and the pressure gradient or any other meteorological factor. It has therefore been found very useful to group together all the winds of one class and neglect the small variations within that class. Thus all the winds enumerated above which blow from the Ross Sea through the Sound to the Barrier have been grouped together and will in future be referred to as northerly winds. Similarly all the winds which blow in the opposite direction have been grouped together and will be referred to as southerly winds.

The following table shows the result of combining the winds into these two main classes.

TABLE 64.*

Month.	Frequency per cent.			Mean velocity miles per hour.		Total motion in 100 hours. miles.	
	Calms 0—1 mile per hour.	N.	S.	N.	S.	N.	S.
1911.							
February . . .	0·0	5·5	94·5	10·6	25·1	58	2,375
March . . .	0·0	11·0	88·8	12·1	27·1	133	2,410
April	5·1	31·0	63·8	12·6	18·8	389	1,200
May	27·3	27·8	44·9	14·1	18·0	392	810
June	21·8	10·8	67·4	12·4	17·6	134	1,184
July	17·2	2·8	80·0	16·7	22·4	47	1,787
August . . .	20·3	11·2	68·4	14·9	21·9	166	1,500
September . . .	25·5	10·3	64·3	8·7	21·1	89	1,366
October . . .	9·4	18·3	72·4	13·2	21·4	240	1,550
November . . .	10·4	9·9	79·7	13·0	18·6	128	1,482
December . . .	16·5	25·0	58·5	15·0	18·7	374	1,094
1912.							
January . . .	10·3	8·2	81·5	10·9	12·3	89	996
February . . .	5·2	6·3	88·5	12·8	22·2	81	1,979
March	1·3	18·3	80·2	15·9	27·3	289	2,186
April	0·4	19·6	80·0	13·0	21·9	255	1,755
May	5·4	19·1	75·4	16·6	29·0	317	2,181
June	2·6	10·7	86·7	23·5	33·7	251	2,923
July	13·3	10·2	76·6	18·0	35·1	184	2,685
August . . .	3·0	12·6	84·3	14·4	27·8	182	2,343
Mean	10·3	14·1	75·6	14·1	23·2	200	1,779

* In this table the wind for which the direction was variable or unknown has been divided amongst N. and S. in proportion to the recorded frequency, thus if the frequency of the S. winds was twice that of the N. winds one-third of the doubtful winds has been included under N. and two-thirds under S.

During three-quarters of the whole period the wind was blowing from the Barrier through McMurdo Sound, during a little more than half of the remaining period the wind was blowing from a northerly direction, and during the rest of the time the air was entirely still. The average velocity of the wind from the south was nearly twice that of the wind from the north. The total flow of air from the south was nearly nine times that from the north. All of which shows the predominant part played by the winds from the south.

Later on we shall have occasion to study in greater detail the weather conditions which accompanied the two types of wind and also the causes which give rise to them. For this purpose it is useful to group the observations not only according to direction but also according to velocity. As already stated the recording wind vane was not very satisfactory for low velocities, but above a velocity of 10 miles an hour the direction record during nineteen months is practically complete. It has therefore been decided to divide the winds having velocities up to 10 miles an hour into two groups irrespective of direction, these being 0 to 5 miles an hour and 6 to 10 miles an hour. Above 10 miles an hour the winds of each direction have been grouped into two classes of (*a*) 11 to 30 miles an hour and (*b*) above 30 miles an hour. As these groups will be used very frequently it is convenient to give here a table showing the number of observations which fall under each head.

TABLE 65.

The number of Observations in the six Chief Groups of Wind.

Month.	NORTH.		IRRESPECTIVE OF DIRECTION.		SOUTH.	
	>30	11 to 30	0 to 5	6 to 10	11 to 30	> 30 miles per hour.
1911.						
February	0	13	114	31	226	160
March	5	35	55	104	253	288
April	1	115	221	87	192	100
May	24	74	364	108	79	86
June	1	35	359	69	146	104
July	1	12	299	88	109	233
August	11	28	318	106	94	180
September	0	23	371	65	82	174
October	3	69	212	111	179	165
November	2	34	231	85	235	124
December	19	92	251	88	221	73
1912.						
January	0	30	300	161	200	52
February	0	30	186	92	161	222
March	9	79	81	101	237	233
April	5	50	68	164	219	152
May	12	85	100	134	144	256
June	33	19	94	59	133	379
July	9	46	151	29	147	354
August	0	63	105	104	135	330
TOTAL	135	932	3,880	1,786	3,192	3,665
Percentage	1	6	29	13	24	27

It is interesting to see from this table that southerly winds of over 10 miles an hour were blowing for more than half of the whole time. Northerly winds of more than 30 miles an hour were very rare occurring only during one per cent. of the time.

Structure of the Wind.

As stated above (page 94), a Dines pressure tube anemometer was used at the Hut. The exposure of this instrument left much to be desired as a recorder of the true velocity, but for a study of the 'structure of the wind' the traces are of unique value.

This instrument, as is well known, records the instantaneous wind velocity at each moment, and as the wind is never steady from moment to moment, the recording pen is constantly moving up and down the record. Whenever there is a gust the pen moves up the sheet to indicate a high velocity, but the next minute it may be low on the paper to record a lull.

Three characteristic charts of winds from the south are shown on figure 38, and three of winds from the north on figure 39.

As the wind charts were changed each morning just after 8 A.M., the times printed on the chart were not convenient, also the clock did not revolve the drum at the exact rate for which the charts had been printed, therefore the correct time is shown on a line about half-way up each chart, the hours being numbered from 1 to 24. The direction of the wind during each hour has also been entered on the chart.

Gustiness.—The most striking difference in the two sets of records is the great gustiness of the wind from the south compared with that from the north. In fact the record (A) of figure 38 exhibits a gustiness which is remarkable: during the hour 20 hours to 21 hours the wind rose to 74 miles an hour in a gust and fell a few minutes later to 10 miles an hour in a lull, *i.e.*, a change of wind velocity of 64 miles an hour within a very few minutes.

The gustiness which is so marked on this record was a characteristic feature of the winds at Cape Evans and will be discussed first.

In order to get a numerical value for the gustiness, we proceed as follows:—

The vertical lines on the chart represent an hour of time, taking each hour we tabulate—

(*a*) the velocity of the wind in the highest gust,
(*b*) the velocity of the wind in the lowest lull,
(*c*) the mean velocity during the hour.

The latter (*c*) is obtained by estimating the position of a line which has as much of the trace above it as below during the hour.

The gustiness is then defined as $\frac{a-b}{c}$.

Thus, in the hour 20—21 on figure 38 (A) $a=74$, $b=10$, $c=32$ $\therefore$ gustiness$=\frac{74-10}{32}=\frac{64}{32}=2\cdot00$.

In the following discussion the results of calculating gustiness in this way are used. It should be mentioned, however, that the gustiness was only determined for hours during which there was no sudden change in the mean wind velocity. That neglecting this rule would lead to errors can be seen by considering the hour 10—11 on figure 38 (A). In this hour the lowest lull occurs with quite a different mean velocity from that when the highest gust occurs. If one uses such hours it is obvious that the gustiness is made to appear larger than it ought to be. Similarly, if the wind suddenly rises from a calm and a gust of, say, 30 miles an hour is recorded towards the end of the hour the difference between the maximum and minimum velocity would be 30 and the mean velocity during the hour, very small, say, 5 miles an hour. This would give a gustiness of 6 which would obviously be too high and quite misleading.

The mean values of the gustiness obtained by the method used in this discussion will therefore be smaller than values derived from all hours irrespective of changes in the mean velocity during the hour.

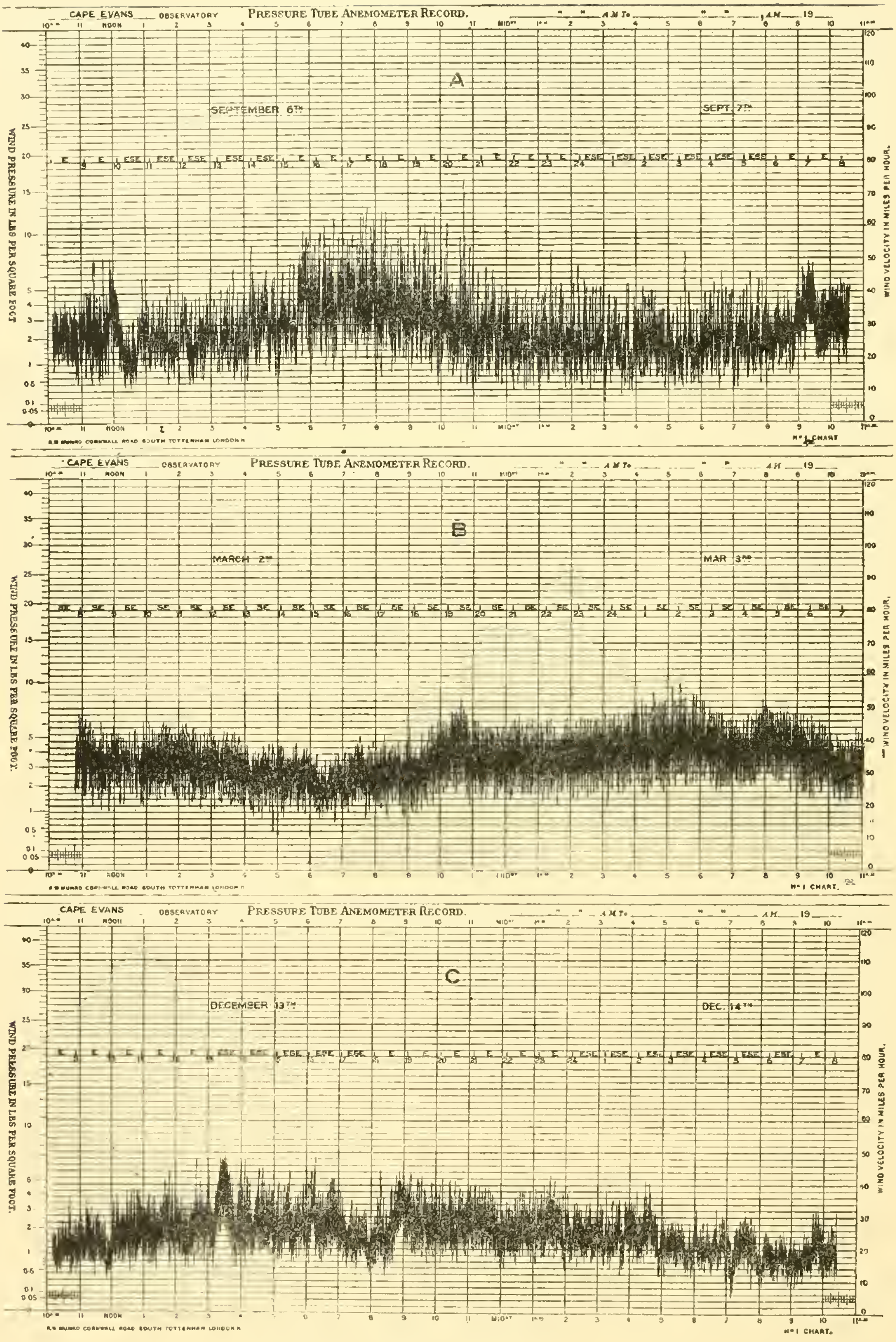

FIG. 38. Anemograms, southerly winds.

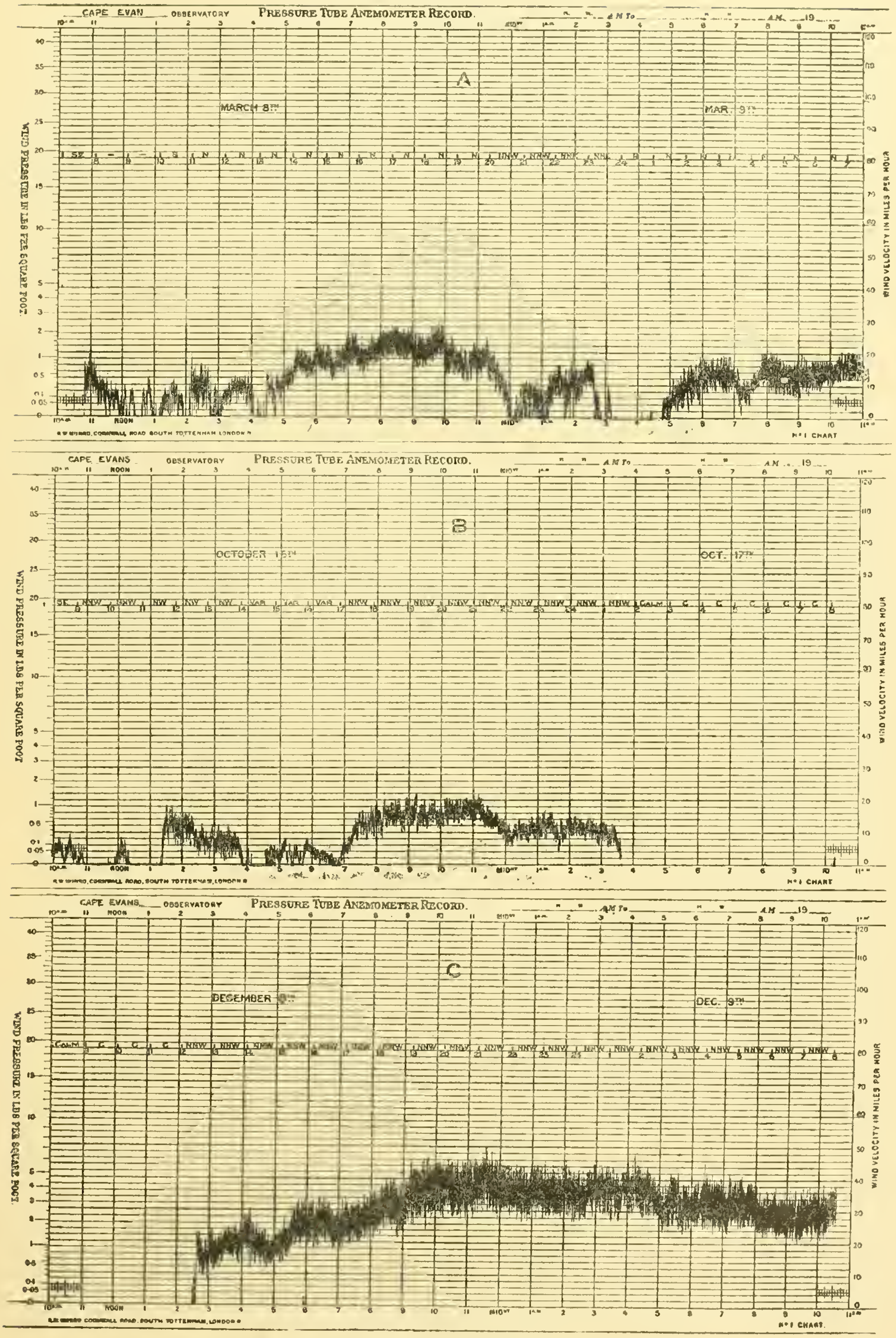

FIG. 39. Anemograms, northerly winds.

In connection with an investigation into the velocity equivalents of the Beaufort Scale * made by the writer in 1905, a determination of gustiness was incidentally made for two coast stations in the British Isles, *viz.*, Scilly Isles and Holyhead.

The gustiness was only investigated with reference to the average velocity and no account was taken of wind direction or season. The mean value was also obtained from all hours hence it is somewhat greater than the value which would have been obtained if the method used in this discussion had been followed. The result showed that at both stations the gustiness was the same and was independent of wind velocity. The mean gustiness for all velocities was found to be ·68. In other words the average difference between the highest gust in an hour and the lowest lull was ·68 times the mean velocity. As this is the only determination of this nature of which I am aware we must take it as the standard with which to compare our Antarctic results.

The Antarctic records have been worked up for the twelve months, March, 1911, to February, 1912, inclusive.

The mean gustiness for the period was 1·04.

Thus the conclusion reached by an inspection of the traces is confirmed: the winds at Cape Evans are more gusty than those on the coast of Great Britain in the ratio of 1·04 to ·68, which ratio would have been still further increased if the British records had been reduced by the method used for the Antarctic records.

While in the Antarctic we soon noticed the characteristic difference in the gustiness of northerly and southerly winds shown on figures 38 and 39, and we could as a rule determine the direction of the wind from an examination of the anemometer trace without going outside the hut. Whenever the trace was uniform without marked gusts and lulls we knew that the wind was from the north while a gusty wind was nearly always from the south.

By examining the mean gustiness of northerly and southerly winds separately we find that southerly winds are more gusty than northerly winds, and the higher the mean velocity the more the gustiness of the southerly winds exceeds that of the northerly winds, this is shown by the last line of table 66 which gives the ratio of the gustiness of winds for different velocities.

TABLE 66.

Gustiness of Wind according to Mean Velocity.

Mean velocity miles per hour.	10—20		20—30		30—40		40—50	
Direction	N.	S.	N.	S.	N.	S.	N.	S.
Gustiness	·99	1·16	·81	1·06	·67	·99	—	·90
Ratio	1·2		1·3		1·5			

The gustiness of the wind at Scilly and Holyhead was found to be the same for all velocities; this however was not so at Cape Evans for table 66 shows that with an increase of velocity for both northerly and southerly winds the gustiness decreases. This does not mean that for high winds the actual difference in the velocity of gusts and lulls decreased, but that the ratio of this difference to the mean velocity decreased. Thus for a wind of 15 miles an hour the average difference between gust and lull was 15×1·16=17·4 while for a velocity of 45 miles an hour the corresponding difference was 45×·90=40·5, hence while the actual difference in the wind changes increased from 17·4 to 40·5 the gustiness fell from 1·16 to ·90.

The gustiness of the wind varied considerably during the year.

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* G. C. Simpson: "The Beaufort Scale of Wind Force," M. O. No. 180.

TABLE 67.

Yearly Variation of Gustiness.

	1911.										1912.	
	Mar.	Apl.	May.	June.	July.	Aug.	Sept.	Oct.	Nov.	Dec.	Jan.	Feb.
All winds	1·06	·98	·82	·99	1·02	1·25	1·36	1·26	·92	·97	1·02	·92

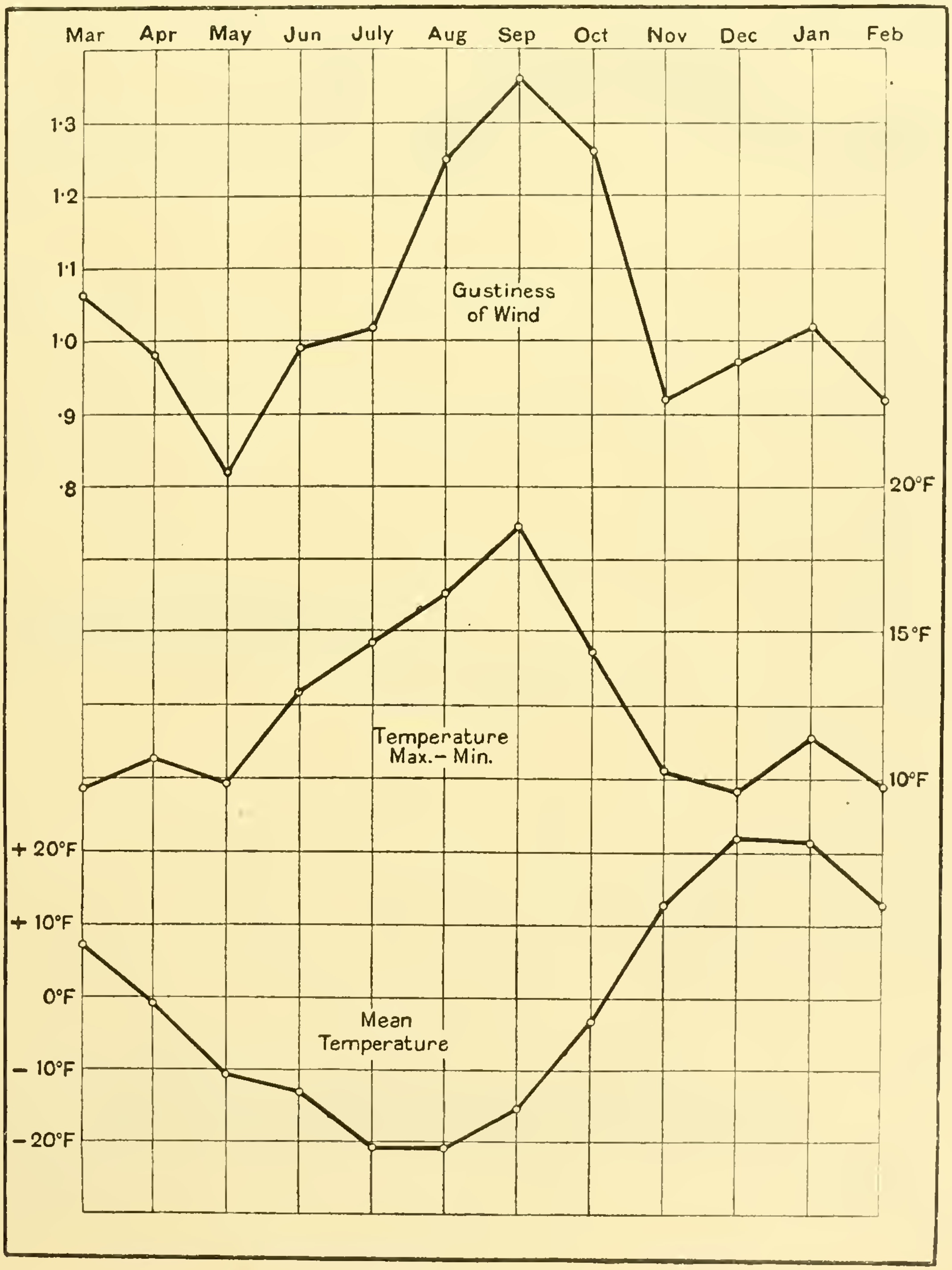

FIG. 40. Gustiness of wind.

These values are plotted in the upper curve of figure 40, from which it will be seen

Fig. 41. Anemograms, squalls.

that the gustiness rose rapidly from May to September, remained high in October and then decreased rapidly and remained nearly constant during November, December, January, and February. This variation from month to month is just as marked with winds from the north as with winds from the south. Also if we fix our attention on any given wind velocity the variation from month to month is exactly the same, thus the variation is not connected with the increased or decreased violence of the wind. It is purely a seasonal change which affects equally all winds.

Cause of gustiness.—It is known that the gustiness of the wind depends largely on the character of the country over which the wind blows. For instance the gustiness is much greater in a town than over flat marshy country,* the reason being that obstacles to the wind's motion set up eddies which show themselves by increasing and decreasing the wind's steady motion.

At first one might be inclined to say that this is the cause of the high gustiness of the wind in McMurdo Sound, for there the wind is sweeping round the great obstacle of Mount Erebus at the foot of which the anemometer was installed. But this explanation fails entirely when we try to apply it to the variations in the gustiness which our investigation has revealed.

If the gustiness is due to the violence with which the wind strives to pass obstacles why should it decrease as the wind velocity increases? Also the obstacles were exactly the same during August, September, and October as during November, December, and January, yet during the former months the gustiness was 33 per cent. greater than during the latter months.

The following appears to be the most satisfactory explanation.

We have frequently referred to the layer of abnormally cold air which forms near the ground during the cold months. In the next section we shall see how this cold layer is able to underrun a wind and raise the moving air above the ground so that at ground level the air is calm while above the wind continues to blow.

The effect of such a cold layer of air is easily seen. When the pressure gradient tends to set the whole mass of air into motion, the lower layer of cold air is in contact with the ground and does not readily move while the warm air above slides over the cold layer with little or no friction. Thus the upper warm air is soon moving more rapidly than the lower cold air.

It is the interaction of these two layers of air which causes the unsteadiness in the resulting wind. One can picture a gusty wind as being analogous to a dirty stream of water entering a clear but stagnant lake. An observer situated at the bottom of the lake would be surrounded at one moment by dirty water and the next by clear, and he would find that the masses of dirty water were generally moving more rapidly than the clear water. The dirty water corresponds with the warm upper current, which drags along with it masses of the cold stagnant air like the dirty stream drags along the clear water of the lake.

In the way that the observer on the bottom of the lake is able to distinguish the origin of the water which passes him by its colour, so we are able to distinguish the successive masses of air by their temperature. The thermographs at Cape Evans were not particularly sensitive nor rapid in action, but their records give conclusive evidence of rapid changes in temperature during winds. Particularly during blizzards the thermograph trace became very thick, and frequently the trace was thickened over more than five degrees showing that the pen was constantly oscillating by this amount, which must have been much less than the

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* Shaw: Reports and Memoranda No. 9 of the Advisory Committee for Aeronautics, page 4.

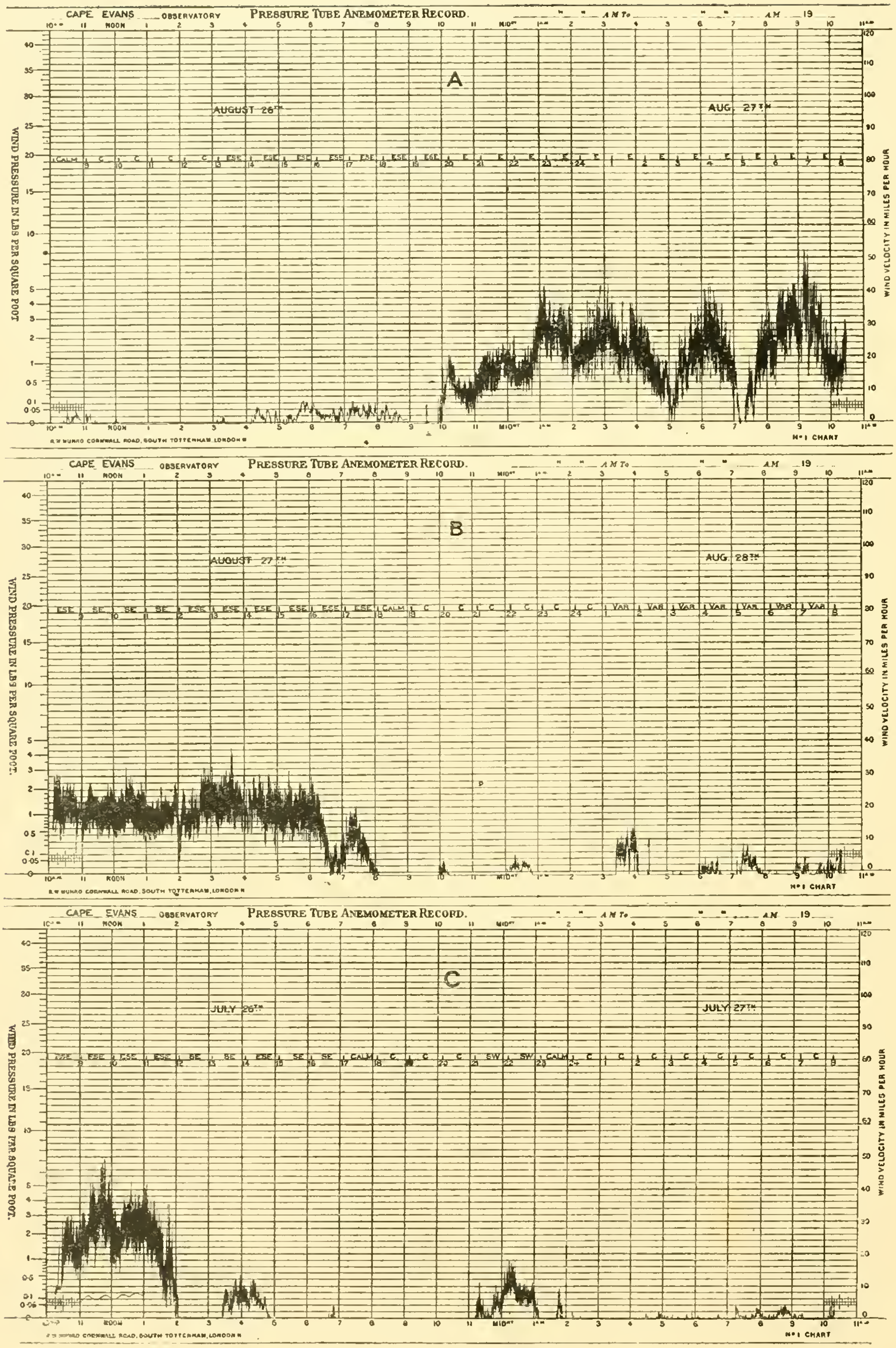


Fig. 42, Anemograms, recrudescences.

actual changes in air temperature owing to the sluggishness of the instrument. Figure 43 shows a very typical example (September 19—22).

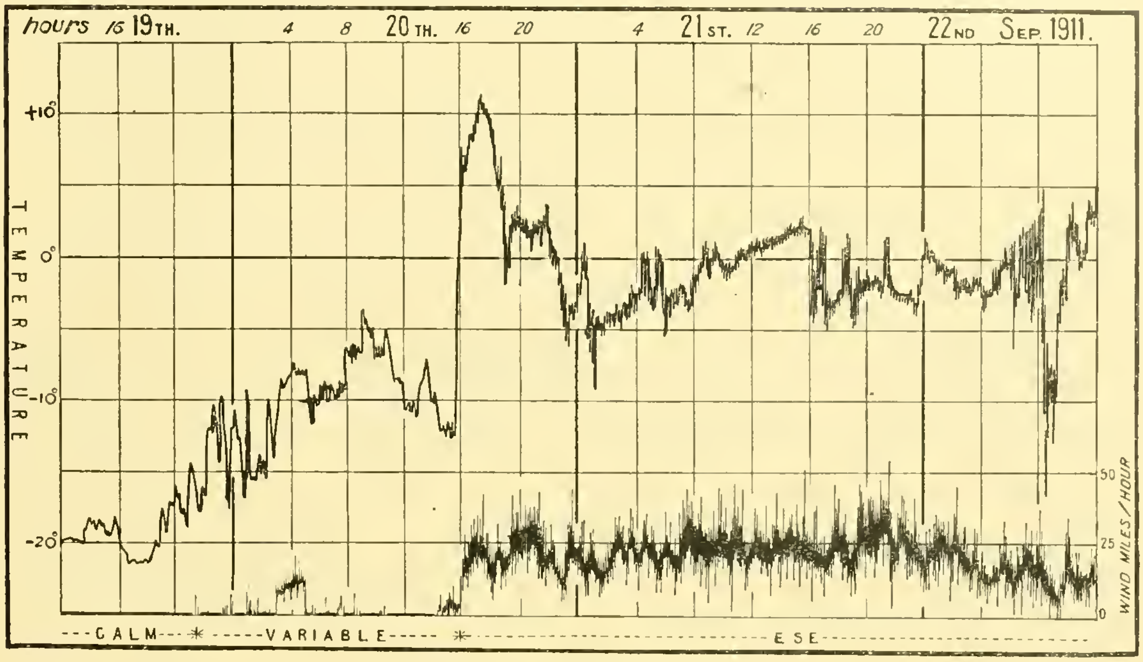


FIG. 43. Wind and temperature.

During the calm weather of the 19th the cold layer formed near the ground. During the 20th the temperature slowly rose probably due to the presence of the southerly current which was sliding over the cold layer, occasionally it dragged some of the stagnant air with it as shown by the fitful gusts of wind recorded by the anemometer and the rapid changes of temperature. At 16 hours on the 20th the upper current descended to the ground removing the cold layer and causing a rapid rise of temperature of over 20° F. After this the blizzard blew for many hours, and the thermograph trace is very thick—compare the thermograph trace during the 19th and 21st—showing that air masses of very different temperatures were moving past the thermograph. The gustiness of the wind is clearly shown on the reproduction of the anemograph record. During the 22nd the thermograph trace was particularly disturbed and shows very large variations of the temperature.

We have shown above that the gustiness was much greater during August, September, and October than during the remaining nine months. This lends very great support to the present explanation. On page 76 we discussed the unperiodic temperature changes as shown by the average difference between the readings of the maximum and minimum thermometers and it was shown that these changes were mainly due to the formation and removal of the cold layers which we are now considering. A large average difference of the maximum and minimum temperatures was shown to indicate the prevalence of the cold layer. The values of this difference have been plotted on the middle curve of figure 40 for the same months as the values of the gustiness are shown on the to pcurve. It will be seen that the curves are very similar, thus indicating that both phenomena are due to the same cause. The significance of the similarity between these two curves is increased by the fact that no other meteorological factor has a marked maximum or minimum in September, 1911. The curve of mean temperature is added to figure 40 for comparison.

If our explanation is correct we should expect that conditions which remove the surface layer would reduce the gustiness. Now no factor is so efficient for removing this layer as a

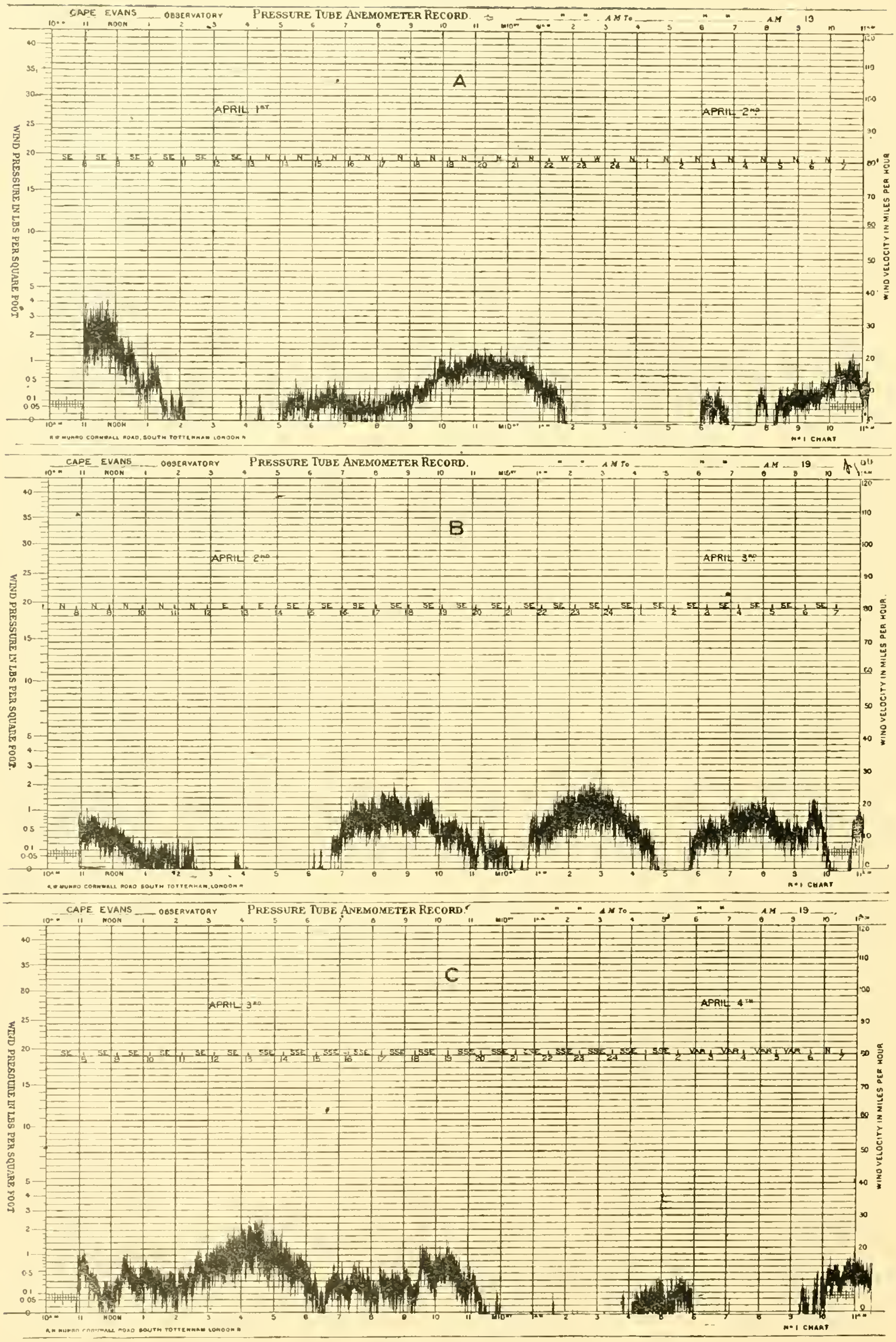


Fig. 44. Anemograms.

high wind, and we have on several occasions referred to the efficient mixing of the air brought about by high winds. This is without doubt the cause of the decrease of gustiness with increase in wind velocity. Light winds only disturb the layer and do not remove it, hence they are abnormally gusty, while during high winds the layer has disappeared and the winds are less gusty.

Other features of the structure of the wind.—In addition to gustiness the Cape Evans' winds show a considerable amount of squalliness. If one examines the trace for October 15—16, figure 41A, p. 120, a series of waves of wind intensity will be noticed; between 12 hours and 20 hours four distinct periods of maximum wind strength were recorded. For the rest of the day recurrences of similar waves appear. Each one of the increases in wind strength was accompanied by a swing of the wind vane slightly towards the S., the change in direction only being small, from about E. by S. to E.S.E. The change in wind direction indicates that the waves were really of the nature of squalls. Squalls of this nature are recognisable in nearly all the wind records, but with considerable variations in intensity and period. In the example just discussed the period of the squalls was about two hours, similar squalls but with a period of considerably less than an hour will be clearly seen between 1 A.M. and 3 A.M. on the morning of October 21st—figure 41B.

Squalls occurred in winds from the north and the south. A typical example of squalls with northerly winds is shown in figure 41C.

An interesting development of squalls is shown in the three charts reproduced on page 122. The first two of these are charts of consecutive days, so that the second is the continuation of the first. The chart for the first day shows fully developed squalls of great intensity, these died out and for the first eight hours on the second chart the wind was not squally. Just, however, as the wind was dying away a squall was recorded after which there was an almost complete calm broken by recrudescences of wind for short intervals. There appears to be little doubt that the calm was due to a layer of stagnant air above which the southerly wind continued to blow, and the recrudescences of wind were the result of squalls which broke through the surface layer for a few minutes at a time. This explanation is supported by the thermograph trace which shows a rapid fall of temperature when the wind ceased at 18 hours on the 27th, and each of the recrudescences of wind was accompanied by a large rise of temperature, showing that the cold layer was temporarily removed each time the wind reached the surface.

The third chart on this diagram shows the same effect, the irruptions of wind being obviously due to an upper moving layer of air extending down to the ground for short periods.

The wind traces for April 1, 2, and 3 shown on the opposite page are very remarkable. It will be noticed that at 8 hours on the 1st a fairly high south-easterly wind was blowing, this died down to a calm and at about 14 hours a northerly wind commenced to blow, and blew until just after 22 hours, this was followed by a calm until at about 3 hours on the 2nd the northerly wind again sprang up and lasted until nearly noon. After this another calm until nearly 16 hours when a south-easterly wind commenced. The variations in the south-easterly wind are interesting, three periods being shown with calms in between. The changes in temperature with the wind are instructive. The temperature during the south-easterly wind at 8 hours on the 1st was +4°F., during the northerly wind between 14 and 20 hours +11°F., thus showing a rise of 7°F. With the next calm the temperature fell again to its previous value and only rose slightly with the succeeding northerly wind. During the calm from 12 to 15 hours on the 2nd the temperature was about + 7° F.; with the setting in of the southerly wind at 15 hours there was a sudden drop of temperature to −2°F.,

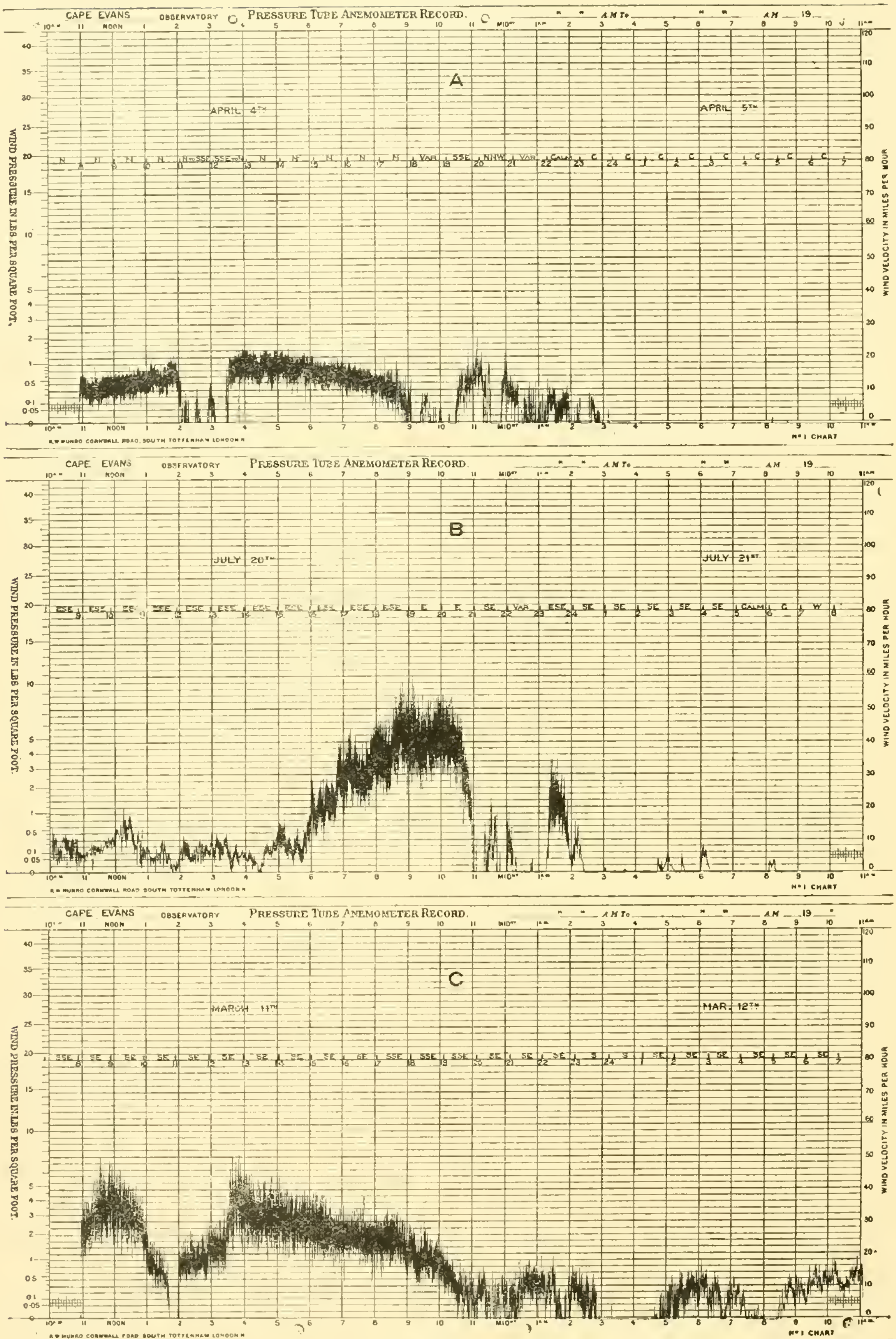


FIG. 45. Anemograms.

i.e., a fall of 9°F. The temperature rose again as the wind fell, only to go still lower in the following peroid of wind.

Thus the northerly winds were warm and the southerly winds cold. There is little difficulty in explaining these wind and temperature changes. On these days there was little pressure difference between the Ross Sea and the Barrier and the wind passed backwards and forwards through McMurdo Sound under local differences of pressure. The cold southerly wind and the warm northerly wind simply brought the temperatures from the Barrier and Ross Sea respectively with them.

The trace for the next day, figure 44C shows a continued wind from the south but with varying intensities and two periods of calm. After the latter, at 6 hours on April 4, the northerly wind again appeared accompanied by a rise of temperature. The continuation of this wind is shown on figure 45A. This trace is most remarkable, the sudden break in the northerly wind between 11 hours and 12 hours 30 minutes has all the appearance of the instrument having gone out of order. But this was not so, the break in the curve was the result of a real interruption in the northerly wind current and during the interval there were a few gusts of wind from the S.S.E. When the northerly wind commenced again at 12 hours 30 minutes it blew exactly as if it had not been interrupted, and the wind trace on each side of the break obviously forms a single continuous curve. Coincident with the break in the wind trace there was a similar break in the temperature curve, during which the temperature fell three degrees. The temperature curve before and after the break is continuous in the same way as the wind trace. It is impossible to believe that a northerly wind of fifteen miles an hour could be stopped and restarted in the sudden way shown on the curve, with a slight wind from the south in the interval. There can be no doubt that the northerly wind was continuous but that during the interval cold air from the south was able to force its way under the northerly current and raise the latter above the recording instruments.

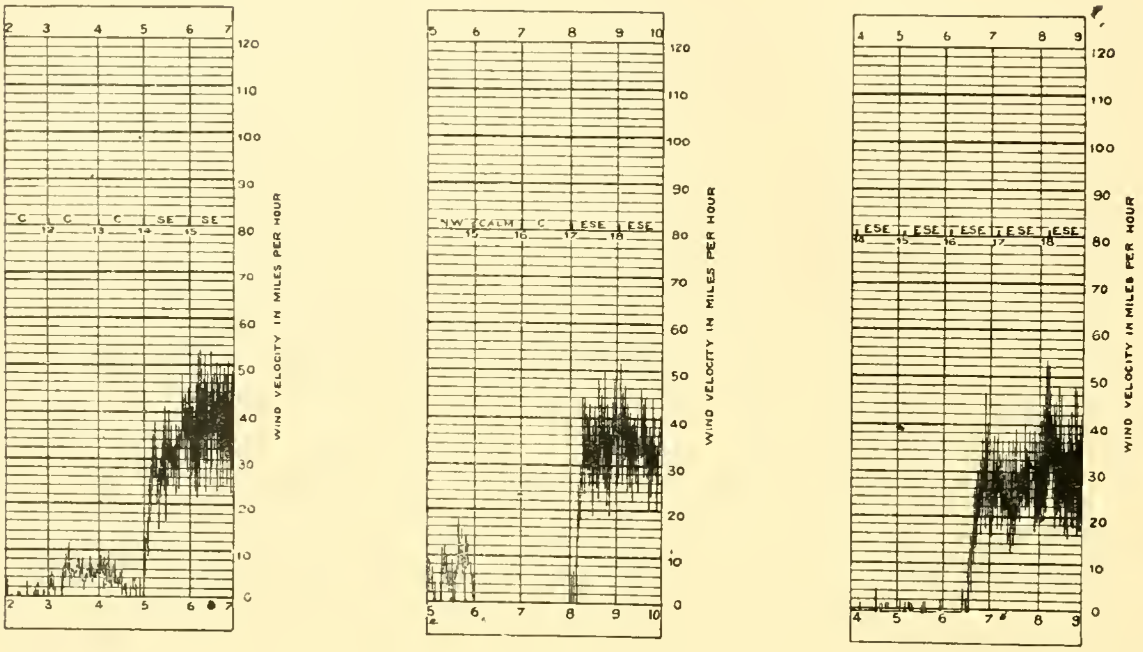
An interesting example of a similar nature but with the break occurring in a southerly wind is shown in figure 45B. There can be little doubt that the part of the curve between 23 and 24 hours is a continuation of the main curve which was broken at 21 hours. The wind at the commencement of the blow was from the E.S.E. and gradually worked to the E. as the wind increased. During the break the wind vane swung first to the south then back through E. to N. and then back to the south. It was then unsteady between S. and E. until the main current again set in soon after 23 hours when it remained steady at E.S.E. until the calm. The temperature curve showed a sudden rise of about 3°F. when the break in the wind curve occurred and the temperature returned to its previous value when the main air current was re-established. There can therefore be little doubt that in this case a flow of air from the north lifted the air current from the south above the instruments, thus it was an exact reversal of the previous case.

Figure 45C is another example of the same phenomenon. The temperature record is interesting in this case also. At 10 hours a sudden drop took place in the wind velocity with no appreciable change in wind direction, at the same time the temperature commenced to rise until the calm occurred. When the wind rose again after the calm the temperature fell and reached its original value at the same time that the wind returned to its full strength.

During the interval shown as a calm on the wind record, the wind vane appears to have made a single swing to the E.N.E. and back again; otherwise the wind direction remained practically constant throughout.

The lifting of the air current again is the only possible explanation.

A remarkable characteristic of southerly winds was the suddenness with which they often commenced. Three typical examples are shown in figure 46. One would expect that such a sudden change in wind conditions would be connected with a sudden change in the barometer. The relationship between the barometer and blizzards will be discussed in the chapter on blizzards, but it may be mentioned here that there is no obvious connection between the sudden commencement of a blizzard and the barometer. In fact it would be quite impossible to say when a sudden commencement of a blizzard occurred from the barograph trace although in some cases there was an almost instantaneous rise in the wind velocity of over 30 miles an hour.*



April 30th. 1911 *May 31st. 1911.* *September 1st. 1911*

FIG. 46. Sudden setting in of blizzards.

CAPE ADARE WINDS.

The winds at Cape Adare are one of the paradoxes of the Antarctic. We have already seen that the frequency of light winds is very high. The Beaufort Scale was used for estimating the wind strength and from March to September, 1911, 69·3 per cent. of all the observations were recorded as either 0 or 1 on this scale. In other words, during considerably more than half the time there was practically no wind. On the other hand Cape Adare was visited by winds of hurricane strength. The observers were experienced men and were not inclined to overestimate the wind strength, yet there are many estimates of wind strength of 11 and 12 on the Beaufort Scale.

When forwarding the meteorological records of Cape Adare, Priestly sent to me a personal letter. This was not intended for publication, nor was it intended as a contribution to science, yet it would be impossible to give a clearer idea of the conditions during these storms than is contained in this colloquial description, and this must be my excuse for quoting from it here.

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* In a few instances a very slight discontinuity in the barograph trace accompanied a sudden change in the wind velocity, but in most cases even this was absent.

Priestly wrote :—

> 'The anemometer has been a fertile source of trouble to us. I don't know whether you have had an exceptional season at Cape Evans but there is no doubt that I never have experienced anything like the force of the wind we have had here.
>
> I have made very full notes on the wind in a sort of meteorological diary that I have kept, and it appears that our wind is governed entirely by the presence of Cape Adare and the particular direction from which the wind happens to strike the cliff. Very often we don't get the wind at all, and when it does come it seems to be very gusty and with its force in the gusts intensified beyond the average force of the winds I have experienced elsewhere in the Antarctic. It is impossible to walk against the gusts sometimes even on a good holding ground, and I have frequently had to hold on, crouching low, and wait for a lull before it was possible to make way against the wind on my return to the hut from the screen. Occasionally pebbles were hurled against the hut with some violence and I have been struck myself several times when taking observations. The first real gale we experienced was somewhat of a surprise to us for we all thought we knew pretty much what the wind could do. As long as the anemometer lasted I took one minute observations for estimating the force of the wind, but it did not last long, and I was divided between a very unscientific relief at the cessation of the observations, and a more scientific regret that the anemometer had not proved equal to its task. Curiously enough it was not the cups that gave way but something went wrong in its inside.
>
> Since then we have been estimating the wind and therefore are liable to the charge of overestimating, which I am afraid is certainly one of the things we shall have to face, but I refuse to abate one single one of the 11's and 12's that I have entered in the books. The only fate I shall wish for my critics is that they could be planted down here in this delectable climate and take observations in a gale every two hours and then see if they don't run into three figures instead of being content with a modest 12 hurricane.'

There was certainly no overestimating of the wind strength at Cape Adare. Before the anemometer broke, minute eye readings show that a wind which was estimated as of wind strength 11 attained velocities of 84 miles an hour, while the average velocity generally ascribed to force 11 is 68 miles an hour. The storms in which these high wind velocities occurred appear to have been true cyclones. The wind attained its maximum at the time of the lowest barometer after a large and rapid fall. The surroundings of the station prevented the wind direction changing in the regular way associated with cyclones, but each storm was followed by wind from between N.E. and N. The highest winds were generally from E.S.E., but on one or two occasions high S.E. and E. winds were observed. The pressure distribution in these storms is discussed on page 239. Storms of this nature in which force 11 or 12 was recorded occurred once in March, once in April, five times in May, twice in June, once in July, twice in August, and twice in September.

In the following discussion the Beaufort estimates have been converted into miles per hour by the following values given on page 34 of 'The Beaufort Scale of Wind-force,' M.O. No. 180.*

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* In this publication are given two equivalent values of each Beaufort number, one derived by Curtis's method and the other by Koppen's method. It is stated that the former should be used in reducing estimates to velocities. The latter has however been used here because the frequency distribution on which Curtis's numbers largely depend is so different at Cape Adare from the British Isles that Curtis's values are inappropriate.

Table 68.

Equivalent values of Beaufort numbers in miles per hour.

Beaufort number	0	1	2	3	4	5	6	7	8	9	10	11	12
Miles per hour	0	2	5	10	15	21	27	35	42	50	59	68	>75

Table 69.

Cape Adare wind.

Month.	Mean velocity.	Resultant velocity.	Resultant direction.	Mean direction.	Maximum Beaufort number.
	Miles per hour.	Miles per hour.			
March	8·7	7·1	S. 60 E.	S. 56 E.	11
April	6·9	4·9	S. 41 E.	S. 10 E.	12
May	15·9	13·1	S. 53 E.	S. 24 E.	12
June	3·6	2·6	S. 56 E.	S. 17 E.	11
July	2·9	1·9	S. 37 E.	S. 18 E.	11
August	6·5	4·7	S. 23 E.	S. 8 W.	12
September	13·2	12·3	S. 58 E.	S. 41 E.	12
October	4·3	2·8	S. 37 E.	S. 13 E.	9
November	4·2	2·5	S. 25 E.	S. 21 W.	8
December	6·3	3·3	S. 47 E.	S. 31 W.	8
Period	7·3	5·4	S. 49 E.	S. 17 E.	12

Table 70.

Cape Adare wind.

	Calm.	N.	N.N.E.	N.E.	E.N.E.	E.	E.S.E.	S.E.	S.S.E.	S.	S.S.W.	S.W.	W.S.W.	W.	W.N.W.	N.W.	N.N.W.
Frequency	38·4	2·4	0·2	0·8	0·3	1·7	9·0	10·6	4·0	15·7	1·2	2·8	0·5	3·6	1·8	6·3	0·6 per cent.
Mean velocity	0·0	3·1	6·0	4·2	11·4	22·0	29·6	15·2	10·0	5·9	8·1	3·2	5·0	2·6	4·1	3·2	4·7 miles per hour.
Total miles in 100 hours.	0	8	1	3	4	38	672	161	40	93	9	9	3	9	8	21	3 miles.

TABLE 71.

Cape Adare wind.

Beaufort number.	0	1	2	3	4	5	6	7	8	9	10	11	12
Frequency, per cent. .	36·8	32·5	9·4	4·5	4·2	2·5	2·6	2·2	1·0	1·1	1·2	1·4	0·5

The outstanding feature of the Cape Adare wind is the large number of calms and the consequent small mean velocity. It is remarkable to find 36·8 per cent. of calms and a mean velocity of only 7·3 miles an hour at a place situated on the coast of the stormiest ocean in the world. It is possible however that the surrounding land masses are largely responsible for the large number of calms. Robertson Bay in which the station was situated is nearly surrounded by high masses of land except on the north (see figure 3, page 7); it may have been that the air was calm within the bay while moderate winds blew outside. On the other hand Cape Adare shows the storminess of its situation by the relatively large number of high winds. During the 10 months 3·1 per cent. of the time the wind was blowing with a wind strength of 10, 11 or 12 on the Beaufort Scale, or reduced to miles per hour 3 per cent. of the time the wind was over 60 miles per hour.

The mean direction was S.E. but the direction with the greatest total wind and also the greatest mean velocity was E.S.E. It is likely however that the wind direction was affected by the surrounding mountains, but there can be no doubt that even with a free exposure the chief wind direction would have been between S. and E.

As far as it is possible to judge the yearly variation of the wind is very different at Cape Adare and Cape Evans. The two winter months, June and July, were the most calm of the ten, while May and September were the most windy. During eleven months in 1899-1900 August had the least wind and March the most. Two years are too few to give the true yearly variation, but there can be little doubt that there is less wind in the winter months than at any other time of the year.

MOTION OF THE UPPER ATMOSPHERE.

The winter stations of the British Antarctic Expeditions in McMurdo Sound have been fortunate in having within sight the active volcano Mount Erebus the smoke cloud from which, issuing at 13,000 feet (4,000 metres), gives a ready index of the air motion at and above this height. It must, however, be pointed out that it is not at all easy to judge the direction in which smoke is moving especially when, as often happened, the smoke cloud is small and has disappeared at a small distance from the top of the mountain. I believe however, from my personal experience, that after a little practice the direction of the cloud when visible can be judged with accuracy to one of eight points of the compass. But it often happened that little or no smoke could be seen. This was due to two causes, first because no smoke was issuing, and secondly because the smoke as it issued was going directly away and was therefore hidden by the mountain. A small amount of cloud like a small knob could often be seen just at the position of the crater. At first I thought this indicated that only a very small quantity of smoke was issuing and I entered in the register 'knob' to record it. I afterwards recognised that this knob was in all probability the stem of the smoke column up to the point reached by the cloud before being blown directly away by a S.W. wind, Erebus being due N.E. from Cape Evans. It was impossible to be certain of the point from the appearance of the cloud itself, but on working up the results it was found that by accepting it as an indication of a S.W. wind, the number of S.W. winds became intermediate between the number of south and west winds, while if it were neglected the number of S.W. winds would be negligible.

The motion of the clouds also gives valuable indications of the air movements in the upper atmosphere. A Besson nephoscope was taken as part of the meteorological outfit, but after being set up it was not used; for the very simple reason that it was found practically impossible to stand exposed to the wind, when the temperature was low, sufficiently long to determine with certainty and accuracy the movements of the clouds when they were moving at anything but a rapid rate. It was at once realised that for reliable work it was absolutely necessary that the observer should be sheltered when making cloud observations. A long focus lens was therefore fixed in the roof of the absolute magnetic hut, which was made dark with shutters. This lens cast an image of the clouds near to the zenith on to a horizontal board carried on a vertical axis so that it could turn about its centre and had parallel lines drawn on its surface. The images of the clouds were watched and the board turned until successive clouds appeared to travel along the lines. An index attached to the axis of the board then gave the direction of motion of the clouds. By aid of this apparatus it was possible to determine the motion of the higher fine cirrus clouds, the motion of which was exceedingly slow and certainly could not have been measured by an observer exposed to the cold and wind. The importance of some such arrangement is clear when it is realised that 40 per cent. of the cloud observations were made in winds of over 20 miles an hour. As this nephoscope could not be used in the dark very few observations were taken in the winter months, and I regret to say that after I left the Antarctic in March 1912 the cloud motion observations were discontinued, so that the number of observations is not very large.

It was practically impossible to determine the motion of the clouds accompanying blizzards owing to the want of detail in the cloud mass (see page 148) and as these formed practically the whole of the low clouds I did not attempt to record the motion of the low clouds at all. The clouds whose motions were measured were practically all either cirrus, alto-stratus or alto-cumulus.

No direct measurement of the height of the clouds was attempted, but there can be little doubt that the cirrus clouds were well above the summit of Mount Erebus, while the alto-stratus or alto-cumulus were lower than the summit as they frequently hid from view the smoke cloud. In the following discussion all the observations of cirrus clouds have been grouped together and called high clouds, while the alto-stratus and alto-cumulus have been grouped together and called medium clouds. The cloud and smoke observations thus give information of the air motion at three heights which may approximately be taken to represent the atmosphere at heights of 10,000—13,000 feet, 13,000—16,000 feet and above 16,000 feet.

The motion of Erebus smoke and of the clouds could only be observed when they were visible. It often happened that the motion could be recorded every time observations were made on one day and only once or twice on another day. If during the whole of the first day the motion remained constantly from say the north and on the second day constantly from the south there would be six entries of the north motion and only one or two of south motion, although the south motion continued just as long as the north motion. In order to reduce as much as possible this source of error whenever a sequence of the same direction was recorded on any one day it was only entered once in the reduction of the data. Thus 544 observations of Erebus smoke were reduced to 364, 166 of medium cloud to 133, 73 of high cloud to 67. The same procedure was followed in reducing the observations of cloud motion at Cape Adare; so that out of 405 observations of the direction of low clouds at Cape Adare only 229 were used and out of 45 of high cloud only 41 were used.

The following table gives the results of the observations:—

TABLE 72.

Percentage frequence of air motion at different heights in the atmosphere over Cape Evans and Cape Adare.

	CAPE EVANS.				CAPE ADARE.		
	Wind.	Medium clouds.	Erebus smoke.	High clouds.	Wind.	Low clouds.	High clouds.
Calms	10·4	8·3	1·1	3·0	38·4	0·0	0·0
N.	3·5	8·3	9·9	13·4	2·4	6·1	12·2
N.N.E.	0·3	3·8		6·0	0·2	2·6	0·0
N.E.	0·2	0·8	2·5	4·5	0·8	6·6	12·2
E.N.E.	0·0	0·0		6·0	0·3	0·9	0·0
E.	9·2	2·3	3·3	9·0	1·7	3·9	2·5
E.S.E.	34·8	3·8		10·5	9·0	11·8	4·9
S.E.	17·1	11·3	13·5	6·0	10·6	24·0	14·7
S.S.E.	2·5	9·8		4·5	4·0	3·1	0·0
S.	0·3	6·8	12·1	3·0	15·7	14·8	9·8
S.S.W.	0·0	0·8		1·5	1·2	0·4	0·0
S.W.	0·1	1·5	14·8	0·0	2·8	3·1	0·0
W.S.W.	0·0	0·8		1·5	0·5	0·0	0·0
W.	0·2	4·5	20·6	9·0	3·6	3·9	14·7
W.N.W.	0·7	2·3		7·5	1·8	1·7	0·0
N.W.	2·8	14·3	22·3	4·5	6·3	14·0	26·9
N.N.W.	4·2	21·1		10·5	0·6	3·1	2·5
Variable and no observations .	13·7						
Mean direction	S. 77 E.	N. 26 W.	S. 82 W.	N. 27 E.	S. 17 E.	S. 54 E.	N. 23 W.

Before proceeding to discuss the directions it may be pointed out that calms were surprisingly frequent in all layers of the atmosphere. This can be seen from the numbers entered in the line of calms in the above table. It should be remarked however that the air motion described as calm was entirely different in each of the regions discussed. Thus at the ground at Cape Evans, calm means a wind velocity of less than 1 mile an hour, and at Cape Adare, an estimate of 0 on the Beaufort Scale. In the case of Erebus smoke a calm was recorded when the smoke rose so vertically that no direction could be assigned to it. This means that the air through a great thickness was for all practical purposes actually still and yet this phenomenon was observed four times in twelve months. Of the observations of medium clouds 8·3 per cent. showed a motion so small that it could not be detected by means of the nephoscope described above, and the same was true of 3 per cent. of the observations of high clouds.

On November 19, 1911, a balloon was sent up with an instrument which was arranged to be detached by a time fuse. After about 25 minutes the instrument was seen to fall

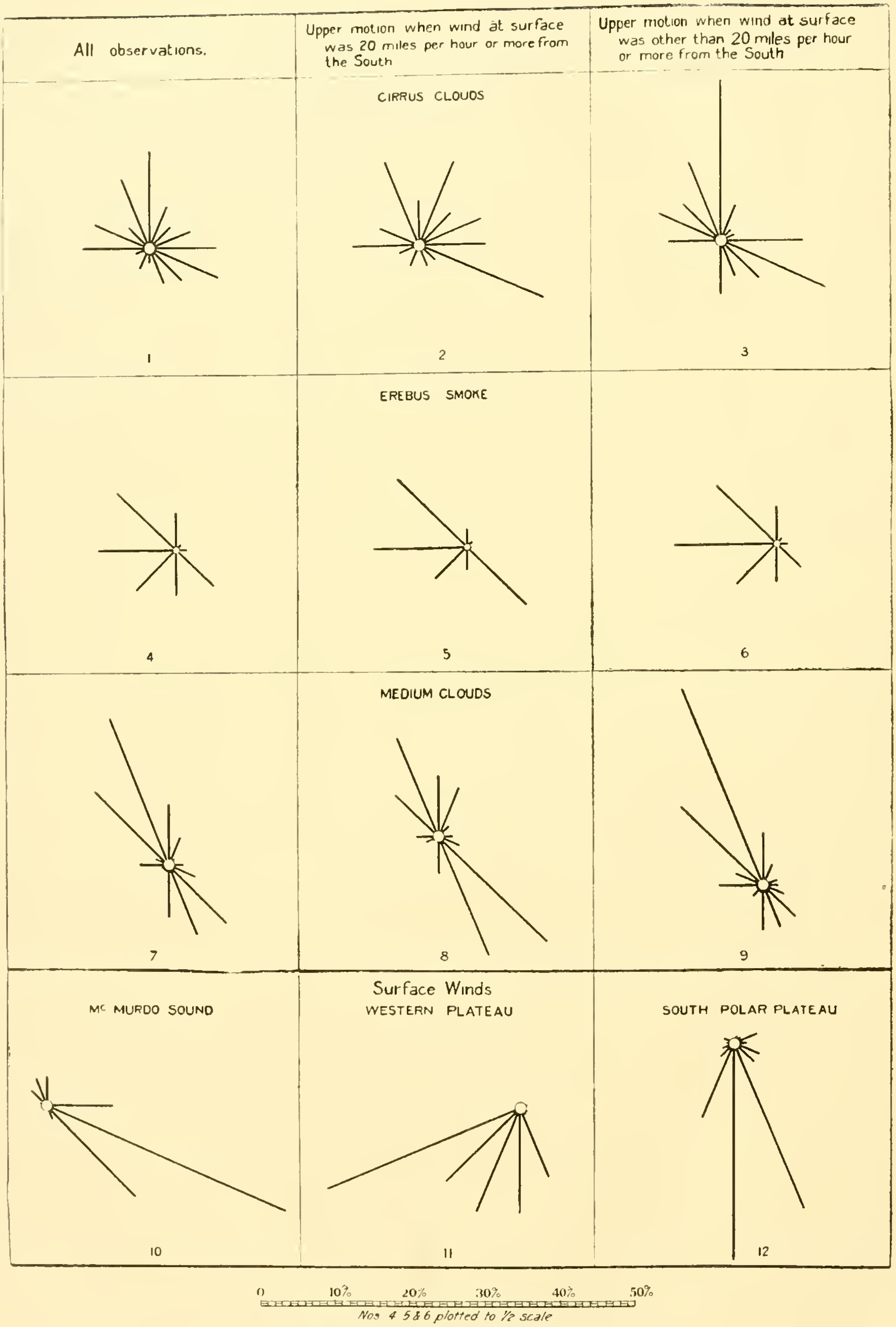

Fig. 47. Motion of atmosphere. Percentage frequency.

within 100 metres of its starting point. The instrument record showed that it had risen 4,000 metres. hence up to this height the atmosphere was absolutely calm (see page 278).

The directions of motion in the different layers over Cape Evans are best discussed with the aid of figure 47. In this figure the diagrams down the left hand side, Nos. 1, 4, 7 and 10, represent the percentage frequence with which air motion from each direction was recorded from the high clouds down to the ground, these diagrams will first be considered.

Air motion at the ground.—The lowest diagram, No. 10, shows the winds. It has already been explained that the wind motion at Cape Evans is limited by the Western Mountains on the west and Mount Erebus on the east, so that there is practically no motion except through McMurdo Sound: from the Barrier to the Ross Sea, represented by the winds between south and east, and motion from the Sea to the Barrier, represented by winds between north-west and north.

Air motion at the height of the medium clouds, 10,000 *to* 13,000 *feet.*—The diagram for the medium clouds 7, shows that the motion at this height is also mainly limited to two directions more or less parallel to those of the wind at the surface, which might be expected from the statement made above that the medium clouds were mainly at a lower level than the top of Mount Erebus. A comparison of the diagram for the surface winds with the one for the medium clouds shows an important difference, namely that the motion from northerly direction is much more frequent at the level of the medium clouds than at the surface. Even when periods only are considered during which the surface winds are over 20 miles an hour from the south the medium clouds move nearly as frequently from northerly as from southerly direction (see figure 47(8)).

Air motion at the height of Erebus smoke, 13,000 *to* 16,000 *feet.*—The summit of Erebus is above all the surrounding land masses and the direction of its smoke gives the first clue to the unimpeded air motion over the Ross Sea area. It will be seen that the diagram for the Erebus smoke, No. 4, differs from that for the medium clouds only in one particular, namely in the addition of considerable motion from the west and south-west; there is still little or no motion from the east and north-east, while the relative amounts from the north-west and south-east are practically the same.

The mean direction of the motion of the atmosphere at the height of Erebus is from S. 82° W. which is slightly to the south of west. It will be shown later that the frequence of south-west motion of Erebus smoke has probably been somewhat under-estimated at Cape Evans, if this possible error were corrected it would bring the mean direction slightly further south, at the same time it will be shown that the mean direction of Erebus smoke observed by the Discovery Expedition, S. 56° W., was probably too much to the south. The true direction is therefore probably between S. 82° W. and S. 56° W. and so may be taken as S. 70° W. or W.S.W.

The direction of the motion of the air shown by Erebus smoke is in marked contrast to the direction of the wind at ground level. The surface winds are almost entirely from an easterly direction while those at the height of Erebus smoke are nearly as exclusively from a westerly direction. This means that between the ground and about 15,000 feet the pressure gradient is reversed, the low pressure being over the Barrier and the high over the Ross Sea. There can be little doubt that this is a direct consequence of the large difference of temperature between the Barrier and the Ross Sea. Owing to the higher temperature over the Ross Sea than the Barrier the decrease in pressure with height is less over the former area than the latter, thus at a certain height the low pressure over the Ross Sea is compensated for by the less dense air column and the pressure difference between the Barrier and the Sea disappears. It is a simple matter to calculate the height at which this occurs. On the mean of the year the following values are probably correct :—

TABLE 73.

	Mean temperature.	Mean pressure.
Ross Sea	7 F. = −14 C.	29·05″ = 738 mm.
Barrier	−10 F. = −23 C.	29·25″ = 743 mm.

With these values the pressure over the Sea and Barrier are equal at 5,500 feet = 1,680 metres, which height is considerably below the height of Erebus which is approximately 13,000 feet. At the top of Erebus the gradient from the south to the north is almost exactly the same as that from the north to the south at sea level. The isobars will almost certainly run nearly parallel to the edge of the Barrier and will therefore be almost due east and west. Hence the gradient wind at the height of Erebus will be due west and this is the cause of the great preponderance of wind from the west shown by the Erebus smoke.

At first sight it would seem strange that at the height of the medium clouds the wind blows so much more frequently from northerly directions than it does either below or above as shown by the surface winds and Erebus smoke respectively. The gradient on the ground is from south to north and the gradient is reversed well below the height of the medium clouds where it becomes from north to south. In the free air above Erebus a north to south gradient produces west to east motion, but in the confined space below Erebus, where the medium clouds form, the air cannot move to the east and therefore moves along the gradient, *i.e.*, from north to south. Thus most of the westerly winds shown by the Erebus smoke are represented by northerly winds at the height of the medium clouds. Thus northerly motion is much more frequently shown by the medium clouds than by Erebus smoke.

Air motion at the height of the cirrus clouds, above 16,000 *feet.*—The cirrus clouds form at a distinctly higher altitude than that normally reached by Erebus smoke and figure 47(1) shows that the air motion revealed by them is essentially different. Reasons will be given in the next section for believing that the winds in the south-east quadrant both at the height of Erebus smoke and the cirrus clouds are connected with the southerly blizzards and if we provisionally neglect these, the diagram for the cirrus cloud is almost the same as that for the Erebus smoke rotated through a right angle. Thus, in so far as the motion is not affected by the local blizzards Erebus smoke shows an almost exclusive motion from the west to the east while the cirrus clouds show an equally exclusive motion from the north to the south. Without the south-easterly winds the mean motion at the height of the cirrus clouds would be from somewhat to the west of north, including these winds brings the mean motion to N. 27° E. which is approximately N.N.E.

Blizzards and upper air motion.—An examination of the four diagrams in the first column of figure 47 shows that at all heights in the atmosphere the frequency of the winds from the south-east quadrant is greater than would be expected from the frequency in the south-west and north-east quadrants.

The question at once arises as to the connexion between this relatively large frequency in all layers of the atmosphere and the surface blizzards. To investigate this question the upper currents were classified according to the simultaneous winds at the surface. Owing to the small number of observations of the cirrus clouds it was not possible to classify the cloud motion according to all wind directions and velocities on the ground ; it was therefore decided to separate out the upper motions when the wind at the surface was 20 miles per hour or more from the south, and compare these with the remaining observations. The former class will then represent blizzard winds and a comparison with the remaining observations will show if the blizzards do affect the motion of the upper atmosphere.

The following table gives the numerical results and they have been plotted in the second and third columns of figure 47.

TABLE 74.

Upper air motion according to winds at the surface.

Percentage frequency.

	MEDIUM CLOUDS.		EREBUS SMOKE.		HIGH CLOUDS.	
	Southerly winds > 20 miles per hour.	Other winds.	Southerly winds > 20 miles per hour.	Other winds.	Southerly winds > 20 miles per hour.	Other winds.
N.	8	7	5	10	6	21
N.N.E.	7	3			12	5
N.E.	2	0	2	2	6	2
E.N.E.	0	2			9	2
E.	2	2	1	3	9	11
E.S.E.	3	3			18	5
S.E.	20	6	22	9	3	7
S.S.E.	17	6			3	5
S.	5	6	6	10	0	7
S.S.W.	0	1			3	0
S.W.	0	2	12	15	0	0
W.S.W.	2	1			3	0
W.	3	6	25	27	9	7
W.N.W.	0	4			6	9
N.W.	8	15	26	22	0	7
N.N.W.	14	28			12	11
No motion	8	8		1	3	2

Examining first the diagrams for medium clouds we see that with blizzard winds the frequency from the S.S.E. and S.E. has grown at the expense of the winds from the N.N.W. and N.W. Remembering that these clouds are contained in the channel over McMurdo Sound, this is the result we should expect, if the pressure conditions causing the blizzards extended so high as the medium clouds. It is interesting to notice that there is a not inconsiderable number of winds at the height of the medium clouds which move against the high southerly winds at the surface, which only emphasises the fact pointed out several times previously that large differences of air motion exist separated by very small vertical distances.

The diagrams for Erebus smoke are interesting, for the southerly wind diagram is very similar to that for the remaining winds, except that the frequency of the south-east winds is more than doubled. This seems to point to blizzard conditions being superposed on the normal conditions, and not that the normal conditions undergo a change which results in blizzard conditions. In other words the blizzards at the surface do not as a rule affect the normal conditions at the height of Erebus smoke, but every now and then the blizzards reach as high as Erebus and then give south-easterly winds there.

The number of observations of high clouds is too small to insist on small differences in the two diagrams, but the greatly increased frequence of motion from the E.S.E. during blizzards at the surface almost certainly points to the fact that occasionally during blizzards the south-easterly motion does extend right up to the cirrus cloud layer.

It must be remembered that the upper air motion could not be observed owing to low clouds when the most violent blizzards occurred. The occasional observations of cloud and smoke motion with high southerly winds were made when the sky was more or less free from lower clouds, hence the diagrams do not represent true blizzard conditions. We may therefore conclude that the increase of southerly motion at the different cloud levels would have been more marked if the motion could have been observed during the more violent blizzards.

It will be noticed that there is still a considerable amount of wind from the south-east quadrant throughout the upper air when the blizzards were not blowing at the surface. This however is not surprising, for blizzard conditions in the upper air may start before and remain after they are active at the surface. With the data available it is impossible to prove that all the winds from the south-east quadrant in the upper air are connected with blizzards, but we have shown a sufficiently close relationship to make this probable.

We can now sum up the above discussion and state the general outlines of the mean air motion over Cape Evans from the ground upwards.

Ground level.—The air motion is entirely backwards and forwards through McMurdo Sound and the motion through the Sound from the south far outbalances the motion from the north, the relative frequency in the two cases being 64 per cent. and 12 per cent. (24 per cent. being accounted for by calms, variable winds and no observations).

Height of the medium clouds (10,000 *to* 13,000 *feet* and therefore below the level of the *top of Erebus*).—At this height the motion is still backwards and forwards through the Sound, but the motion from the north is now more frequent than the motion from the south, the relative frequencies being 55 per cent. and 37 per cent. (8 per cent. being accounted for by no motion of the clouds).

Height of Erebus smoke (13,000 *feet to* 16,000 *feet*).—At this level the motion of the atmosphere is no longer affected by the surrounding land masses. There is now considerable motion from the west and south-west—directions which were not possible below the summit of Erebus. If we assume that the winds from the south-east are mainly due to blizzards and therefore of local origin, the observations of Erebus smoke show that between 13,000 and 16,000 feet the general motion of the atmosphere is almost entirely from the western half of the horizon with north and south added. The mean direction from all the observations corrected by observations made on the Discovery Expedition is probably from the west-south-west, and if the local blizzard winds are neglected the mean motion is practically from due west.

Height of the high clouds (*above* 16,000 *feet*).—The high clouds show a certain amount of motion from the south-east quadrant which in all probability is due to the local blizzards. If these winds are neglected practically all the motion at this height is from the northern half of the horizon with east and west motion added. The mean motion excluding the winds in the south-east quadrant is slightly from the west of north and including these winds N. 27° E.

Thus at the ground level the transference of air is almost entirely from the south, at the height of Erebus smoke the motion is from the west and at the greatest height observed the motion is from the north.

Motion of the Upper Atmosphere at Cape Adare.—The above conclusions are borne out by the observations made of cloud motion at Cape Adare, the results of which have been included in table 72, page 133. In figure 48 three diagrams are shown, for the winds, the low clouds and the high clouds. At the level of the low clouds the chief motion is from the S.E. and the mean motion is S. 54° E. showing an excess of motion from the south over the north. The clouds described as high at Cape Adare were in all probability lower than the high clouds observed by means of the camera obscura at Cape Evans, and therefore their mean height was probably between the high clouds and Erebus smoke as observed at Cape Evans. It will be noticed that the diagram is intermediate between those for Erebus smoke and high clouds at Cape Evans, and the mean direction N. 23° W. is also intermediate. Thus at Cape Adare also the transference of air at the ground level is from south to north and in the upper atmosphere from north to south.

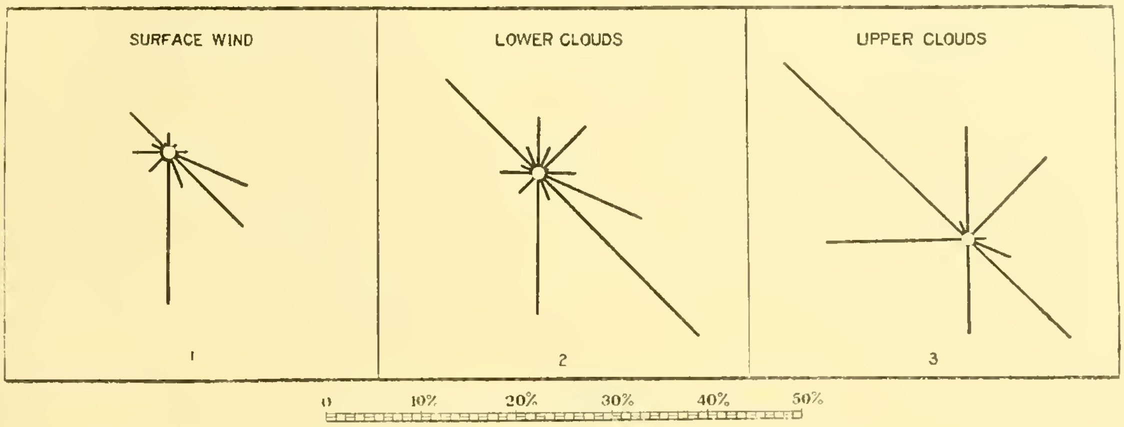

Fig. 48. Motion of atmosphere. Percentage frequency at Cape Adare.

Hut Point Observations.—The observations of upper air motion made at Hut Point (within 15 miles of Cape Evans) by the Discovery Expedition need to be reviewed in the light of the new observations. For this purpose the diagram from page 496 of the Meteorological Results of the National Antarctic Expedition 1901–04 has been reproduced here, figure 49.

With regard to the surface winds we have already explained that the east and north-east winds at Hut Point were really the southerly winds of the Barrier deflected by the foothills of Erebus and therefore correspond to the south-east winds at Cape Evans. Comparing the lower clouds with the surface winds we see nothing to correspond with the prevailing direction of the surface winds. Now if the clouds were really lower clouds their directions should not depart largely from the directions of the surface winds for they are largely carried along in the lower current. Further there can be no doubt that the frequency with which the lower clouds moved from the south must have been much greater than the frequency with which they move from the north, for all over the west of the Ross Sea area the lower atmosphere moves mainly from the south, yet on this diagram the frequency is practically the same from the north as from the south. On looking up the actual meteorological register the reason is obvious. The direction of the motion of the clouds was never entered when the sky was completely overcast with low clouds! Hence all the cloud motion during blizzards which is exclusively from southerly directions has been neglected, thus the diagram of frequence of motion of lower clouds is useless for giving the mean motion of the lower atmosphere.

The difference in the diagrams for the Erebus smoke as observed from Hut Point and Cape Evans is large, the chief discrepancies being in the north-west and south-west directions.

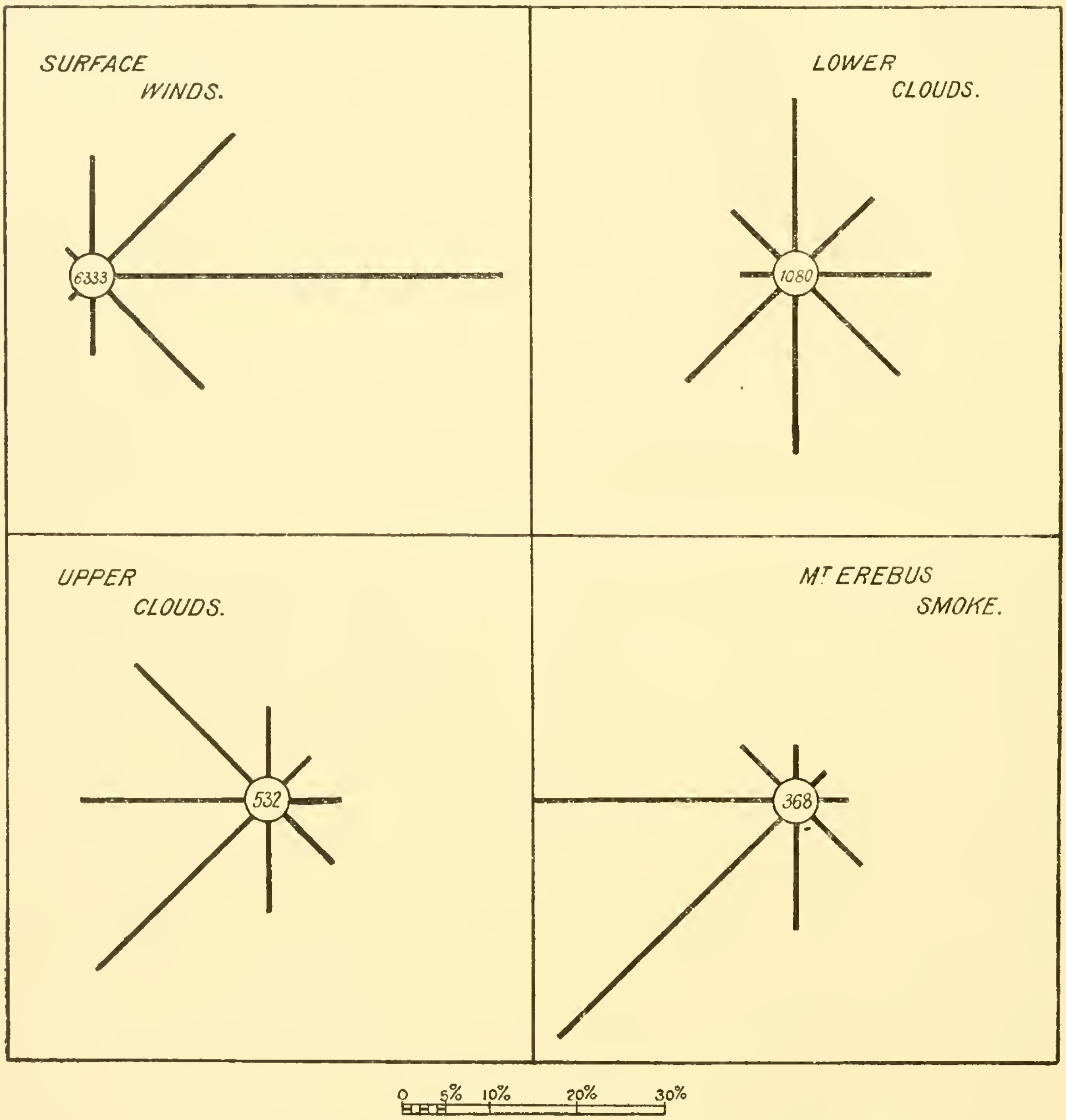

Fig. 49. Motion of atmosphere. Percentage frequency, Hut Point

It is probable that the cause is the difference in the point of view of the mountain from the two stations. It is quite possible that the observations of south-west direction at Cape Evans were affected for the reason already stated, namely, that the mountain itself, being to the north-east, hid much smoke travelling away in that direction, hence the south-west directions in the Cape Evans diagram very likely need to be increased. It is not clear why the north-westerly directions were so few as seen from Hut Point and so many as seen from Cape Evans, but that this was due also to the point of view is supported by the observations made on sledge journeys from Hut Point which gave 10 per cent. of observations from the north-west as compared with only 3 per cent. as observed from Hut Point itself. This indicates that the position at Hut Point was not good for observing motions of Erebus smoke from the north-west, while as one got into a better position during the sledge journeys the relative number of observations from the north-west increased. A perfectly free view would no doubt have increased the relative frequency still further. It therefore appears safe to conclude that the frequency from the north-west as observed at Hut Point should be increased.

If the south-west frequency at Cape Evans and the north-west at Hut Point were increased as here suggested, the two diagrams would become the same in all essentials.

On the Discovery Expedition cloud motion was determined without instrumental aid and therefore the high clouds, the direction of which could be determined, were lower than those observed at Cape Evans. From internal evidence I am inclined to believe that the high clouds observed at Hut Point were those described as medium at Cape Evans, with a few of the lower cirrus clouds included. As Hut Point is not within McMurdo Sound westerly and south-westerly motion is possible at the height of the medium clouds above that station, therefore the motion of these clouds over Hut Point was different from their motion over Cape Evans. It will be noticed that the diagram for high clouds at Hut Point is almost exactly the same as the diagram for Erebus smoke as observed at Cape Evans, especially if the latter is corrected as suggested above by increasing the observations from the south-west. Thus the motion of the so-called high clouds over Hut Point confirms the mean motion of the atmosphere deduced from the observations of Erebus smoke at both stations, leaving the motion of the upper atmosphere to be indicated by the true cirrus clouds observed by aid of the camera obscura at Cape Evans.

PLATEAU WINDS.

The plateau which exists behind the Western Mountains and extends from north of Cape Adare to well beyond the South Pole is at an elevation of between 6,000 and 10,000 feet. The winds on its surface are therefore important in discussing the motion of the atmosphere. This plateau has been reached six times: (1) by Captain Scott in November 1903 when he ascended the Ferrar Glacier and travelled westwards over the Western Plateau to 78° S. and 146½° E.; (2) by Shackleton in 1908-09 when he ascended the Beardmore Glacier and reached the Polar Plateau for the first time; (3) by David who in the same year ascended by means of the Drygalski Glacier in his successful attempt to reach the south magnetic pole; (4) by Captain Amundsen who reached the South Pole on December 17, 1911; (5) by Captain Scott in 1911-12 on his ill-fated journey to the Pole; and (6) by members of Mawson's Australian Expedition who in 1913 attempted to reach the south magnetic pole from their base in Adelie Land.

Of these six visits to the plateau detailed meteorological results are only available at present for Captain Scott's two journeys and for Amundsen's. It is only possible therefore to discuss the wind records in any detail for these three journeys, although from the descriptive accounts of the other journeys more or less fragmentary information about the winds can be obtained.

Winds on the Plateau near the magnetic pole.

Members of Mawson's expedition led by R. Bage * left their main base in Adelie Land on November 10, 1913, and proceeded towards the magnetic pole. Their journey took them

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* The Home of the Blizzard, Vol. 1, page 274.

in a S.S.E. direction, and they reached a height of 3,650 feet in a little over 30 miles from the coast, after which they descended somewhat owing to crossing the Mertz Glacier valley. After passing the valley they regained their previous height and then slowly ascended to their furthest point in 70° 36′ S. and 148° 10′ E. where the height was just over 5,900 feet. In the description of their journey a great deal is said about the strength of the wind, but very little about the direction. This is not to be wondered at considering the strength of the wind which was so great as to be a constant handicap to their efforts. While crossing the Mertz Glacier valley they experienced a wind from the S.W. which was obviously blowing down the valley. On November 24, while still in the depression due to the valley and moving to the S.E., the remark is made 'we were marching a little to the east of the wind,' so I gather that here the wind was between S.S.E. and S. They continued to encounter head winds, but there is only one more entry giving a definite direction. On December 5 'for the first time on the trip the wind veered round to the south-east.' From this remark I conclude that the general trend of the wind was from the south. Until we have the meteorological observations taken on this important journey we can only say that on the plateau between the magnetic pole and Adelie Land the wind is very strong and from some direction near the south.

Professor David's Party, which ascended the plateau to the magnetic pole from the Ross Sea side in December 1908, experienced on first reaching the plateau winds from the west, or slightly north of west. These were apparently winds blowing down the declivity which continued the valley up which they had ascended. As far as I can gather from Professor David's account as soon as the effects of the glacier valley were left behind the wind generally blew from some direction between south and south-east, and the sastrugi confirmed this to be the prevailing direction. Thus both David's and Bage's observations point to a southerly wind over the plateau near the magnetic pole, but that near the heads of the large glaciers the air motion is towards and down the glacier valleys.

Winds on the Plateau to the west of Ross Island.

Captain Scott was on the Western Plateau for 30 days reaching 78° S., 146° 30′ E. The height of the plateau increased slowly from about 7,500 feet to a little over 7,700 feet at his most westerly point. The frequency of the winds observed is shown diagrammatically in figure 47(11), page 134. It will be seen that the winds blew almost entirely from directions between S.S.E. and W.S.W., the mean direction being S. 31° W. It is impossible to say whether the observations made on these 30 days can be taken as typical of the general wind conditions at this position, but as the sastrugi were mainly from the S.W. and occasionally from the W.S.W. it is probable that they are fairly typical. The chief result is that the winds on the plateau are from a more southerly direction than those revealed by the motion of Erebus smoke. When near to the edge of the plateau Captain Scott encountered both on going and returning stormy winds from the W.S.W., *i.e.*, from the plateau into the head of the glacier valley.

Winds on the South Polar Plateau.

Amundsen reached the plateau on November 21, 1911, in 85° 36′ S., 167° 42′ W. and arrived at the Pole on December 17, he returned along the same track and left the plateau on January 5, 1912. Scott reached the plateau on December 22, 1911, in 85° 10′ S., 159° 30′ E. and the Pole on January 17, he left the plateau from the same position on February 4. Thus Amundsen made wind observations on the plateau during 44 days (November 22 to

January 4 inclusive) and Scott during 45 days (December 22 to February 4 inclusive, observations are wanting on the 5th and 6th February). As a rule each observer recorded the wind direction and force three times each day, but occasionally they observed more frequently and occasionally less frequently. In order to obtain a regular series of observations, when more than three observations were taken on one day only three of the recorded observations have been used, while on the few occasions on which less than three observations were recorded probable values have been inserted when possible. In this way the series is homogeneous and complete except for two directions in Amundsen's series which it was impossible to supply. Scott's Party recorded wind forces on the Beaufort Scale, these have been reduced to velocities by the equivalent values given on page 130. Amundsen estimated the wind strength in metres per second, which have been converted into miles per hour.

It is necessary to say a few words with regard to the directions used by the two observers.

Scott approached the Pole almost exactly along the 160° E. meridian while Amundsen approached it along a mean meridian of approximately 170° W. Now each observer naturally recorded a wind as south when it blew along the meridian on which he was situated, thus for Scott a south wind blew along the 160° E. meridian and for Amundsen along the 170° W. meridian, thus the winds recorded as south by the two observers were inclined to one another by 30°, and other directions differed by the same amount. In other words a flow of air which was south for Amundsen was 30° to the west of south for Scott. In order to correct for this difference of designation of the same wind all the observations made on the plateau by Amundsen have been rotated clockwise through one compass point ($27\frac{1}{2}$°), thus making them agree very nearly with the direction which Scott would have experienced. This may be stated by defining a south wind on the plateau as air motion parallel to the 160° E. meridian with other directions related in the normal way to this main direction. The following tables summarise the chief results of the wind observations.

TABLE 75.

Wind on South Polar Plateau (S.=parallel to 160° E. meridian).

		N.	N.N.E.	N.E.	E.N.E.	E.	E.S.E.	S.E.	S. S. E.	S.	S.S.W.	S.W.	W.S.W.	W.	W.N.W.	N.W.	N.N.W.	Calm.
Frequency %	Scott . .	1·5	0·0	0·0	0·0	2·2	0·7	3·7	26·7	32·6	13·3	3·0	0·7	2·2	0·7	1·5	0·7	10·4
	Amundsen .	0·0	2·3	2·3	6·9	1·5	6·9	3·8	20·8	24·6	8·5	2·3	3·1	0·0	2·3	0·0	0·0	14·6
	Combined .	0·8	1·1	1·1	3·4	1·9	3·8	3·8	23·8	28·7	10·9	2·6	1·9	1·1	1·5	0·8	0·4	12·5
Mean velocity, miles per hour	Scott . .	3·5	—	—	—	9·0	10·0	7·4	16·6	10·4	18·2	14·0	15·0	2·0	15·0	12·5	10·0	0·0
	Amundsen .	—	9·7	8·3	19·8	12·5	16·7	17·8	14·8	11·3	7·8	6·0	6·0	—	5·0	—	—	0·0
	Combined .	3·5	9·7	8·3	19·8	10·4	16·0	12·6	15·9	10·8	14·3	10·6	7·8	2·0	7·5	12·5	10·0	0·0
Total wind in 100 hours, miles	Scott . .	5	0	0	0	20	7	27	444	340	243	42	11	4	11	19	7	0
	Amundsen .	0	22	19	137	19	115	68	308	278	66	14	18	0	12	0	0	0
	Combined .	3	11	9	67	20	60	48	377	309	156	28	15	2	11	9	4	0
	Total wind per cent.	0·3	1·0	0·8	5·9	1·8	5·3	4·2	33·4	27·4	13·8	2·5	1·3	0·2	1·0	0·8	0·4	0

TABLE 76.

Wind on South Polar Plateau (S.=parallel to 160° E. meridian.)

	Scott.	Amundsen	Combined
Mean velocity, miles per hour .	11·8	10·7	11·2
Resultant direction	S. 3° E.	S. 30° E.	S. 14° E.
Resultant velocity	10·0	7·4	8·5
Mean direction	S. 3° E.	S. 19° E.	S. 10° E.

Frequency.—It will be seen that in essentials Scott's and Amundsen's observations give the same results. The most frequent winds were the S.S.E., S. and S.S.W. these three directions containing 73 per cent. of Scott's observations and 54 per cent. of Amundsen's or 63 per cent. of all the observations, no other direction has 4 per cent. of the total winds. The mean direction as determined from Scott's observations was S. 3 E. and from Amundsen's S. 19 E. and combined S. 10 E.

The frequences of the combined observations are shown in figure 47(12).

Velocity.—The mean velocity according to Scott's observations was 11·8 miles an hour and according to Amundsen's 10·7 miles an hour. This is a very close agreement and the combined velocity 11·2 miles an hour is probably very near to the velocity during December and January, 1911-12. The average velocity during the same two months at Cape Evans was 12·8 miles an hour and at Framheim 9·4 miles an hour. Thus, there was little difference in the velocity on the plateau and on the Barrier nearly 10,000 feet below. The mean velocities for the different directions do not show any very pronounced features, but in the next section it will be shown that the majority of high winds blew from the S.S.W., S. and S.S.E. The resultant direction is, Scott S. 3 E., Amundsen S. 30 E. This is a larger difference than was found in the case of the mean direction and is mainly due to a period of three days, during which a high wind blew from directions between S.E. and E.N.E. shortly after Amundsen reached the plateau. This period will be discussed below.

Total Wind.—The air motion from all directions except S.S.E., S. and S.S.W. is practically insignificant, these three directions together take 75 per cent. of all the air motion. This result combined with the high frequency of the winds from these directions points to an almost constant pressure gradient driving the air along the resultant direction, *i.e.*, along S. 14 E. or parallel to the 146° E. meridian. A glance at the map, which forms the frontispiece of this volume on which the probable edge of the plateau is indicated, shows that this direction is very nearly parallel to the main trend of the plateau escarpment. As the wind friction must be small on the plateau the air motion is probably very nearly along the isobars, hence the wind observations on the Polar Plateau indicate isobars running more or less parallel to the edge of the plateau, with the high pressure over the plateau and the low pressure over the Barrier.

Plateau Winds and Blizzards.

Until the meteorological observations made by the Shackleton and Mawson expeditions are published, we have not sufficient data to discuss the blizzards on the plateau near the magnetic pole; we must, therefore, limit our discussion to the observations made on the Western Plateau and Polar Plateau.

Western Plateau.—During the period that Captain Scott was on the Western Plateau he experienced several periods of high winds. In order to investigate whether these high winds were from the same direction as the less strong winds his observations have been divided into two classes: the first containing winds up to strength 4 on the Beaufort scale and the second those of greater strength. The result reduced to percentage frequency is shown in the following table.

TABLE 77.

Wind frequency on the Western Plateau.

Beaufort scale.	No. of obs.	N.	N.N.E.	N.E.	E.N.E.	E.	E.S.E.	S.E.	S.S.E.	S.	S.S.W.	S.W.	W.S.W.	W.	W.N.W.	N.W.	N.N.W.
1 to 4 . . .	71	0	0	0	1	0	0	0	16	13	14	23	34	0	0	0	0
5 and over . .	23	0	0	0	0	0	4	4	4	31	31	4	22	0	0	0	0

For the lower wind strength the most frequent direction was W.S.W., while for the higher winds the greatest frequency was from the S. and S.S.W. It will be noticed that with the higher winds there is a second maximum at the W.S.W. It should be pointed out, however, that all the winds in this class occurred when Captain Scott was very near to the head of the Ferrar Glacier valley and therefore were probably more westerly than they would have been on the open plateau, on account of the tendency of winds to blow down the glacier valleys. These few observations point to the blizzards on the Western Plateau being slightly west of south, while the normal fair weather winds are more nearly from the W.S.W. Thus, the conditions associated with blizzards add a strong southerly component to the prevailing W.S.W. winds.

South Polar Plateau.—We have already shown that the prevailing winds on the South Polar Plateau are from the S.S.E., S. and S.S.W., these three directions taking 63 per cent. of the wind observations and 75 per cent. of the total air motion. While Scott was on the plateau he recorded wind of force 5 and over on 23 occasions, 22 of which were from these same directions, the remaining observations being from the S.W. Thus, Scott's observations show practically no high winds from any direction except S.S.E., S. and S.S.W. During the first five days that Amundsen was on the plateau, he experienced high winds from the S.E., E.S.E. and E.N.E., during the remaining 40 days like Scott he experienced high winds only from S.S.E., S. and S.S.W. Grouping all Scott's and Amundsen's observations together, we get the following percentage of high and low winds under each direction.

TABLE 78.

Percentage frequency of High and Low Winds on the South Polar Plateau (November 22 to February 4; S.=parallel to 160° E.).

Beaufort scale.	No. of obs.	N.	N.N.E.	N.E.	E.N.E.	E.	E.S.E.	S.E.	S.S.E.	S.	S.S.W.	S.W.	W.S.W.	W.	W.N.W.	N.W.	N.N.W.
1 to 4 . . .	186	1	2	2	2	3	3	4	24	38	11	3	3	2	2	1	0
5 and over * . .	46	0	0	0	13	0	9	7	39	13	17	2	0	0	0	0	0

* Amundsen 8 metres per second and over.

Thus of all the high winds 69 per cent. were from the three directions S.S.E., S. and S.S.W., while during the period November 27th to February 4th all the high winds except one were from these three directions. There can be little doubt therefore that the direction of the blizzards on the plateau corresponds with that of the prevailing winds, and that only rarely are high winds experienced from directions removed by more than one point from south, south being defined as parallel to the 160° E. meridian. It may be remarked that as far as can be gathered from Shackleton's popular account of his journey on the Polar Plateau he experienced exactly the same conditions.

CHAPTER IV.

CLOUD AND PRECIPITATION.

Of all meteorological elements cloud is the most difficult to discuss either by simple description or by statistics. This is particularly the case in high Antarctic latitudes where one constantly observes a thin haze all over the sky, which is often so thin as hardly to be noticeable. The difficulty has then to be faced whether the cloud amount is 0 or 10. A factor which frequently leaves no room for graduated estimate but must be classed as either in the minimum or maximum class is obviously unsuited for statistical investigation. Again, while in other factors the mean value is, as a rule, the most frequent value, this is not so in the case of cloud amounts, for with cloud the most frequent cloud amounts are those at the end of the scale, 0 and 10, and the mean value is often one of the least frequently observed. Thus at Cape Evans the mean cloud amount was 6, and as it happened this was the cloud number which was by far the least often entered as being the actual amount present, and was only recorded on 1·6 per cent. of the whole observations.

Again, when describing the cloud forms great difficulty is encountered. Even low clouds are frequently formed of ice crystals and therefore are really of the nature of cirrus clouds, so that even an experienced observer often finds difficulty in deciding whether the cloud should be described as stratus or cirro-stratus.

It is obvious therefore that the same rigid analysis cannot be applied to the cloud observations as to other meteorological factors. In the following paragraphs the kind of cloud will be described in general terms without any statistical data, although the kind of cloud was recorded whenever cloud observations were made. The reason for this is that observations were taken by several members of the expedition who varied greatly amongst themselves as to the names to be given to the clouds. Further, the main cloud conditions are so simple that nothing would be gained by counting the number of times each cloud form was recorded. After the description of the clouds, the annual and daily variation of cloud amount will be considered. In this latter section no account will be taken of the kind of cloud, so that a sky so thinly overcast that the stars could be dimly seen will receive the same weight as a heavily overcast sky during a blizzard.

KIND OF CLOUD.

Fog.—Only on a very few occasions was fog observed at Cape Evans and then it was generally associated with the open water in McMurdo Sound. When the temperature was low and the wind high, a peculiar kind of surface mist or fog was seen over the water; this generally went by the name of frost smoke. Once or twice this was blown over the station, when it was seen to be composed of minute ice crystals which gave rise to the usual system of rings and mock suns around the sun.

On the Barrier fog was often reported during the night and early morning. The cause of this fog is discussed on page 268.

Stratus (*overcast*).—The most frequent entry in the cloud column of the meteorological register is '10' or 'overcast,' without any description of the kind of cloud. This is because the sky was frequently covered with a uniform layer of cloud which had no distinguishing features and the height of which could not be determined. This layer was often very thin, so that the moon and stars could be seen through it. It was usually associated with blizzards. In some cases, the layer would gradually spread over the sky from the south, but much more often, a clear sky would become hazy, and then the haze would thicken into cloud which would get thicker and apparently lower until the blizzard commenced. During many blizzards the drift snow would be so thick that the clouds could not be seen, there would only be a general darkening of the sky. The chief difference between the overcast sky of the Antarctic blizzard and that accompanying prolonged rain of more temperate regions was that in the latter case the clouds usually have features, the motion of which can be followed, while in the former the layer was so uniform that it was quite impossible to determine the movement of the cloud. In fact, it is very questionable whether in the latter case true clouds were present; there was no appearance of vapour or cloud particles, but the whole sky had the appearance as if the air were full of very fine ice crystals which fell as powdery snow. The end of a blizzard appeared to arrive in two different ways, which may be described as ceasing from the top and ceasing from the bottom. In the former case, while the wind still carried along with it much drift snow, the sky would get lighter and the drift less, until finally there would be a low drift of snow swept up from the surface with a clear sky above. In the other case, the wind and drift would stop, while the sky retained its layer of uniform cloud.

The stratus cloud which remained after a blizzard and the stratus cloud which had formed without a blizzard resulting would disappear in the same way. Sometime the sky would gradually get lighter and the whole cloud mass melt into a thin haze which slowly disappeared, or, what was more frequently the case, the layer would take on the characteristic features of an alto-stratus or cirro-stratus cloud, which would break up into patches of alto-cumulus or cirro-cumulus clouds.

There can be little doubt that the cloud formation and precipitation in a blizzard is due to air forced to ascend in some way analogous to the upward draught in a barometric depression.

In chapters VI and VII we shall discuss in some detail the mechanics and thermodynamics of the blizzard; here I only wish to examine the blizzard in so far as the cloud is concerned. We will therefore assume that the air is forced to ascend sufficiently for precipitation of the water vapour into ice particles to take place. The whole phenomenon as described above is then clear. As the air rises, condensation takes place in the upper atmosphere, whence snow falls. This snow cannot settle, as the wind sweeps it along, and the whole atmosphere below the condensation level becomes filled with driven snow. This is the blizzard at its height. If now the ascending current stops before the wind ceases, new snow is no longer formed and the sky clears above and the snow gradually settles out of the air, until only a little surface drift is left. On the other hand, the ascending current and the wind may both cease before the cloud has had time to clear away; this leaves the cloud of ice crystals at the height of the condensation layer, which then becomes an ordinary stratus cloud to be absorbed in the way that all other layer clouds are absorbed, which may be either by a gradual disappearance of the layer as a whole or by its breaking up in parts.

Cumulus.—Cumulus clouds are due to unequal heating of the air adjacent to the ground, which gives rise to local ascending currents. In McMurdo Sound cumulus clouds only occurred very rarely in the summer and then they were generally associated with the open water or the bare expanses of rock on the Western Mountains. Although so much sledging was done during the summer over the Barrier, cumulus cloud was not once recorded in the sledging diaries except when seen over the mountains. It would appear, therefore, that ascending currents sufficiently strong to produce cumulus clouds are never formed over the snow surfaces in these high latitudes.

Cumulo-stratus.—It sometimes happened that during the summer the cloud left after a blizzard was sufficiently thick and low to break up into clouds which were described as cumulo-stratus. These were summer clouds and were practically never recorded except in the months from December to February.

Alto-stratus, alto-cumulus, cirro-stratus, cirro-cumulus and cirrus.—These were the chief clouds observed in the Antarctic after the stratus referred to above. As is well known, these clouds are not due to ascending currents from the lower atmosphere, but are generally caused either by the interaction of two currents of air, or by the raising in the atmosphere of a layer of air as a whole, in which case cloud appears throughout the upper boundary. This is a natural consequence of the absence of ascending currents, for the air settles into layers which are differenciated by their temperature or direction of movement.

This description of the cloud forms may be summed up very shortly by saying that there was an almost total absence of clouds due to convexion currents, while clouds due to the stratification of the air into layers were abnormally developed. At the same time the most frequent cloud was a complete uniform covering of the sky due to the forced ascent of air during blizzards.

CLOUD AMOUNT.

Mean Cloud Amount.

The mean amount of cloud for the two years 1911 and 1912 was 6·2 and 6·4 respectively, giving 6·3 as the average. This is considerably higher than the value found, 5·0, during 1902 and 1903 by the Discovery Expedition. The explanation appears to lie in the fact that when the sky was thinly overcast with the thin haze mentioned above, the cloud amount was entered by the observers on that expedition as 0. Thus against the entry of clear sky one often finds in the remarks column such phrases as 'misty in sky' (April 8, 1903), 'Snow crystals falling, stars very misty' (June 27, 1903), 'Faint halo, and slight tendency to paraselene' (June 5, 1903), 'Moon misty' (April 26, 1902), 'A few stars visible' (May 15, 1902), 'Slight precipitation' (June 1, 1902), 'Stars visible but dim' (June 7, 1902). Also haloes and coronæ are frequently noted when the cloud amount is given as 0; thus on July 21, 1902, a lunar coronæ was recorded at every observation from 8 A.M. to 10 P.M., yet during the whole time the sky was reported to be quite free from cloud. There appears, therefore, no doubt that on the Discovery Expedition the sky was reported clear when we should have reported it completely overcast.

It is remarkable that the mean cloud amount for 1911 [*] at Cape Adare was 6·2, exactly the same as at Cape Evans. It will also be shown later that the frequency of overcast and clear skies was very nearly the same at the two stations. Also the Southern Cross Expedition found the mean cloud to be 6·5 at Cape Adare. There appears to have been very little difference between the cloud at Cape Evans and at Framheim. Observations were only taken regularly at the latter station during April and from September to January; during these six months the mean cloud amount was 6·2, while during the same months at Cape Evans it was 6·4.

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[*] 10 months' observations and 2 months' interpolation.

It therefore appears that 6·3 is probably the mean value of the cloud amount for the whole of the Ross Sea area. This is a very low value compared with that of other Antarctic stations as is shown in the following table.

TABLE 79.

	Mean cloud yearly average.	
Cape Evans	6·3	Two years.
Cape Adare	6·3	Two years (three months interpolated).
Snow Hill	7·3	19 months.
Port Charcot	7·5	One year.
'Belgica'	7·3	One year.
'Gauss'	7·3	One year.
L'Ile Petermann	8·1	317 days.
Laurie Island	8·2	One year.

As stated above, the mean value of the cloud amount does not give the most satisfactory indication of the cloud conditions. It is much better to count the number of times each grade of cloud 0, 1, 2............... 10 was recorded and express the result in percentages of all the observations.

TABLE 80.

Percentage frequency of each Cloud Amount at Cape Evans (yearly mean; obtained from March to October two years, November to February one year).

Cloud amount	0	1	2	3	4	5	6	7	8	9	10
Cape Evans	17·9	5·1	4·0	3·6	2·6	4·8	1·6	4·5	6·0	6·2	43·7
						3·0 *					

We see here the usual feature of cloud observations, that clear skies and overcast skies are observed more frequently than any other cloud number. That the frequency decreases from each of these maxima towards the centre of the scale shows a strong tendency for the sky to be either entirely clear or entirely overcast.

The following table gives similar data for Cape Adare.

TABLE 81.

Percentage frequency of each Cloud Amount at Cape Adare (yearly mean). (Observations, March to December. January and February, taken the same as December and March respectively).

Cloud amount	0	1	2	3	4	5	6	7	8	9	10
Cape Adare	5·5	15·4	7·9	5·0	3·4	4·6	3·2	4·3	5·1	11·7	33·6
						3·7 *					

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* It is well known that in all estimations there is a natural tendency for the group 5 to be increased at the expense of groups 4 and 6. This is clearly shown in the table, and therefore the three groups 4, 5 and 6 should be considered together.

Here we see a relationship similar to that found for Cape Evans with one important difference, namely, that class 1 is greater than 0. This brings out a difficulty which has been commented on in previous discussions of cloud amount. It sometimes happens that cloud lingers about some local geographical feature when it has disappeared from the sky as a whole. Thus the following remark appears in the discussion of the cloud observations made at the Gauss Station :

> 'Cloud amounts of 9 and 10 had practically the same significance, because the number chosen depended on the presence or absence of a blue cloudless segment in the south, which was probably connected with the anticyclone over the inland ice. The same held for the classes 0 and 1, which were governed by the appearance of a bank of cloud (sometimes not seen because of dark nights) on the northern horizon.'

In the case of Cape Adare, which was surrounded by high mountains, cloud often lingered about their summits when otherwise the sky was clear, thus accounting for the frequency with which cloud 1 was reported.

In order to remove as far as possible such disturbing factors as these, it is found advisable to consider only the three groups of cloud amounts : 0—1, 2—8, 9—10 ; and this will be done in the future discussion. Reduced to these three groups, the cloud observations at Cape Evans and Cape Adare are shown in the following table, to which corresponding data for the Gauss Station, Snow Hill and Laurie Island are added.

TABLE 82.

Percentage frequency of three groups of Cloud Amount (yearly means).

	0—1	2—8	9—10	Mean cloud amount.
Cape Evans . . .	23·0	27·1	49·9	6·3
Cape Adare	20·9	33·5	45·3	6·3
Gauss Station	15·0	25·0	60·0	7·3
Snow Hill	15·0	24·3	60·7	7·3
Laurie Island	10·1	15·4	74·5	8·2

From this table the distribution of cloud over the Antarctic regions is obvious. The cloud amount is high over the Southern Ocean and relatively low over the Ross Sea area. Also the frequency of clear skies increases and of overcast skies decreases, as one passes from the centre of the Southern Ocean towards the south. This relationship is best explained by the presence of an anticyclone over the Antarctic continent, which is bounded on the north by the cyclones of the Southern Ocean. This result is important as it is an indication that, in spite of the low pressure area over the Ross Sea, the weather conditions there are governed by the Antarctic anticyclone.

Cloud and Wind at Cape Evans.

When discussing the cloud forms (page 148), it was stated that blizzards were generally accompanied by overcast skies. The following table shows the relationship between cloud and wind.

TABLE 83.

Cloud and Wind at Cape Evans.

March, 1911, to August, 1912.

Wind. Miles per hour.		NORTH.		0—5	SOUTH.	
		>30	11—30		11—30	>30
	Cloud amount.					
Percentage frequency .	0—1	64	34	37	21	8
Do. do. .	2—8	15	30	27	30	18
Do. do. .	9—10	21	36	36	49	74
Mean cloud amount .		3·0	5·0	4·9	6·4	8·4

It is a noteworthy fact that during calms and light winds, 0—5 miles per hour, clear skies and overcast skies occur with equal frequence and the mean cloud amount is practically 5. Moderate winds from the north have similar cloud conditions as those during calms. On the other hand, the effect of strong northerly winds is remarkable, for during 64 per cent. of the time they blow, the sky is practically cloudless, and the mean cloud amount is as low as 3·0. The effect of southerly winds is quite clear. Even with moderate winds the sky is overcast during half the time and clear only during one-fifth. With increasing southerly wind strength, the contrast becomes greater, and when the wind strength is greater than 30 miles an hour, the sky is overcast during 74 per cent. of the time and clear only during 8 per cent., the mean cloud amount reaching the high figure of 8·4.

Annual Variation of Cloud.

For reasons already given (page 149), the cloud amounts recorded on the Discovery Expedition were too low and therefore have not been used in obtaining the mean cloud amount for McMurdo Sound. There seems no reason, however, to doubt that the yearly variation is more or less accurately given by them and therefore they will be used to obtain this variation. Besides recording the actual amount of cloud, the observers recorded in their weather remarks the state of the sky according to the four grades b, bc, c, and o. The former of these corresponds to the cloud amount 0 and 1 and the latter to 9 and 10, therefore they can be used in combination with the estimates of the frequence of these grades of cloud made at Cape Evans.

TABLE 84.

Monthly variation of Cloud Amount (0—10) *from mean of the year.*

	January.	February.	March.	April.	May.	June.	July.	August.	September.	October.	November.	December.	Mean.
1902	+1·5*	0·0	−0·1	+0·5	+0·3	−2·2	−1·3	+0·1	+0·4	+1·5	0·0	−0·4	5·6
1903	+0·9	+0·6	+0·9	−1·1	−0·9	−0·4	−2·6	−0·6	0·0	+1·7	+2·0	−0·8	4·5
1911	−0·6	+1·3	+1·6	+1·1	−0·6	−1·6	−1·3	−0·8	0·0	+1·1	0·0	−0·1	6·2
1912	−1·1	+1·8	+1·2	−0·1	−2·1	−0·7	+1·0	+0·9	0·0	+1·3	−1·3	−1·3	6·4
Mean	+0·2	+0·9	+0·9	+0·1	−0·8	−1·2	−1·0	−0·1	+0·1	+1·2	+0·2	−0·6	..

* 1904

TABLE 85.

Monthly variation of percentage frequency of Clear Skies (*b in* 1902 *and* 1903 *and* 0—1 *in* 1911 *and* 1912) *from mean for each two years.*

	January.	February.	March.	April.	May.	June.	July.	August.	September.	October.	November.	December.
1902 and 1903 . . .	−16	− 6	− 1	+8	+ 7	+20	+17	+4	−5	−18	−17	+4
1911 and 1912 . . .	+ 4	−17	−15	−6	+13	+19	+ 7	+3	+2	−12	− 1	+1
Mean	− 6	−12	− 8	+1	+10	+19	+12	+4	−2	−15	− 9	+2

TABLE 86.

Monthly variation of percentage frequency of Overcast Skies (0 (*overcast*) *in* 1902 *and* 1903 *and* 9—10 *in* 1911 *and* 1912) *from mean of each two years.*

	January.	February.	March.	April.	May.	June	July.	August.	September.	October.	November.	December.
1902 and 1903 . . .	+15	+ 2	+ 4	−10	− 2	−9	−14	−1	+1	+16	+10	− 6
1911 and 1912 . . .	−15	+17	+12	+ 5	−12	−7	+ 3	+5	−1	+11	− 9	−12
Mean	0	+10	+ 8	− 2	− 7	−8	− 5	+2	0	+13	0	− 9

These values have been plotted on figure 50, the curve for clear skies being inverted so that its variations may be compared directly with the other two.

It will be seen that the annual variation of cloud amount is well marked, while its variations are followed very closely by the frequency of clear and overcast skies. Also an examination of the values for the individual periods given in the tables clearly indicates that the main variations are repeated in each. The curve of variation is a simple one: cloud is at a maximum near the equinoxes and at a minimum in both summer and winter.

There is little difficulty in explaining the summer minimum. November, December and January are the fine weather months of the Antarctic. There are then relatively few blizzards and in their absence the Antarctic anticyclone produces clear unclouded skies. The frequency of blizzards in February and March, to which attention has already been drawn in the section on wind, is directly responsible for the large increase then in cloud above the summer value. Winds of more than 30 miles an hour from the south are from three to four times as frequent in February and March as in November and December, and as these winds have on the average a cloud amount of 8·4, it is quite understandable that the average cloud for these months is high. Coming now to the winter months we at once find difficulties. During May, June and July blizzards are somewhat more frequent than during February and March, and they are accompanied by nearly as much cloud—the mean cloud during winds > 30 miles an hour from the south was 8·9 in February and March and 8·0 in May, June and July—but the average cloud amount is less than during the three summer months. We therefore have the paradox that the months with the maximum blizzards have the minimum cloud amount.

It is clear that we must seek for some action which clears away the clouds as soon as the blizzards have ceased to produce them. Such an action was described by Sir Napier Shaw in 1902.* Shaw pointed out that when thin clouds lose their heat by radiation evaporation takes place and they disappear. The more rapid the radiation the more rapidly does the cloud disperse. Now during the winter in the Antarctic the conditions are eminently suitable for large and rapid radiation from the clouds. In the first place the clouds are very thin and therefore every part is able to radiate to the clear sky above, secondly they receive no heat from the sun and practically none from the ground. Thus the radiation from the clouds during the winter months is greater in polar regions than in any other part of the world. This explanation is strongly supported by figure 51. In this figure the mean cloud amount has been shown for each month during (*a*) winds from the south greater than 30 miles an hour, (*b*) winds from the south between 11 and 30 miles an hour, and (*c*) winds from calms to 5 miles an hour. The data used are September, 1911, to February, 1912, and March to August, 1911 and 1912, thus the most important part of each curve is based on observations from two years. Except in January the cloud amount with high southerly winds is nearly constant from month to month, showing that blizzards are the cause of cloudy skies throughout the year. The cloud amounts during moderate winds from the south and during calms

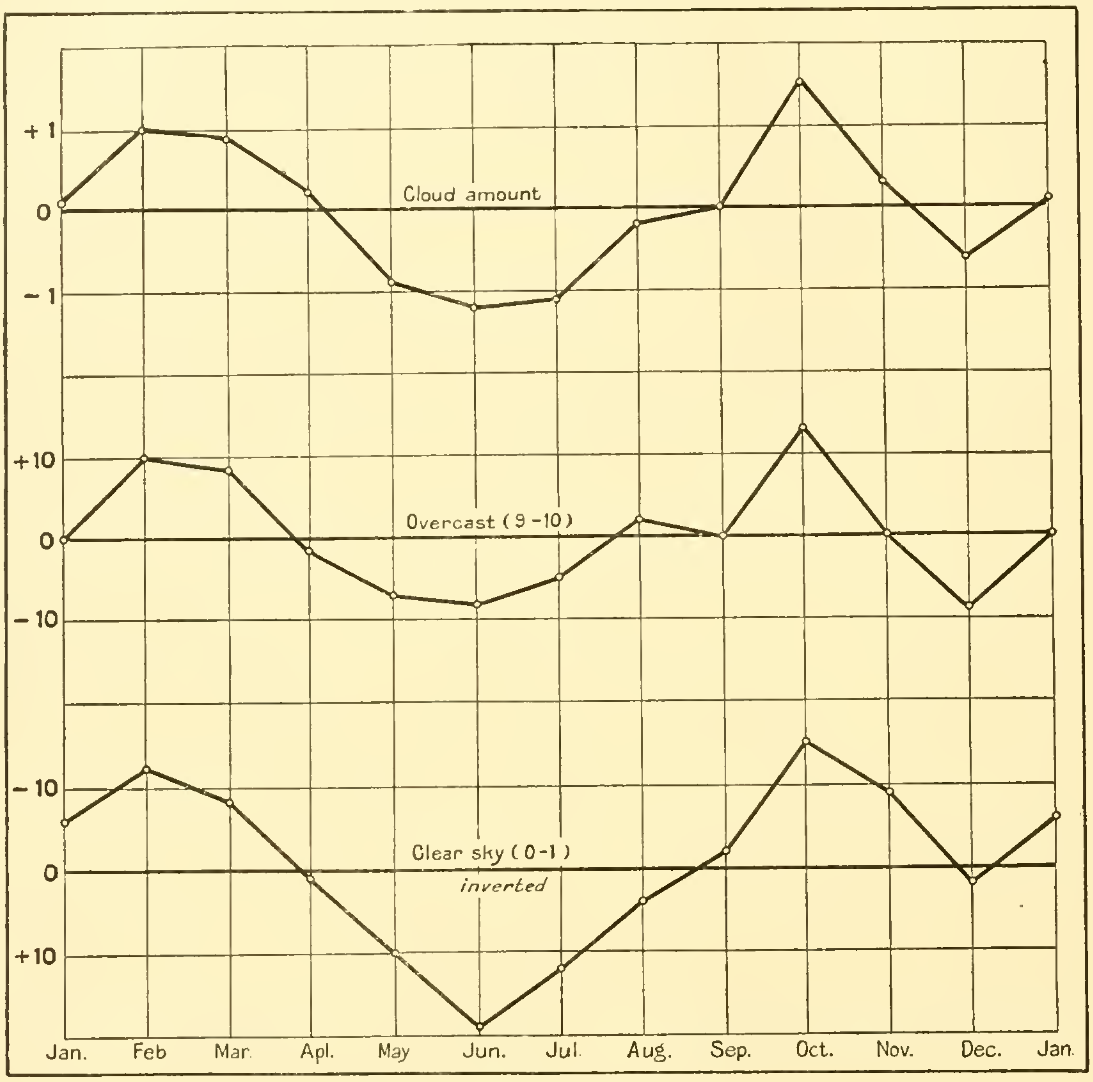

FIG. 50. Annual variation of cloud.

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* W. N. Shaw. 'La lune mange les nuages.' Quarterly Journal of the Royal Meteorological Society, Vol. XXVIII, page 95, 1902.

and light winds are in all months less than during blizzards, but the difference is very much greater from May to July than from October to March. During the former of these periods there is no direct sunlight and radiation is great, hence as soon as the wind drops the clouds disappear and the average amount of cloud during the intervals between the blizzards is only half that during the blizzards. On the other hand, during the period of nearly constant sunlight this force does not act, but the reverse holds, the radiation received by the clouds from the sun tends to increase rather than diminish them. Hence during these months there is only a small decrease in cloud amount in the intervals between the blizzards.

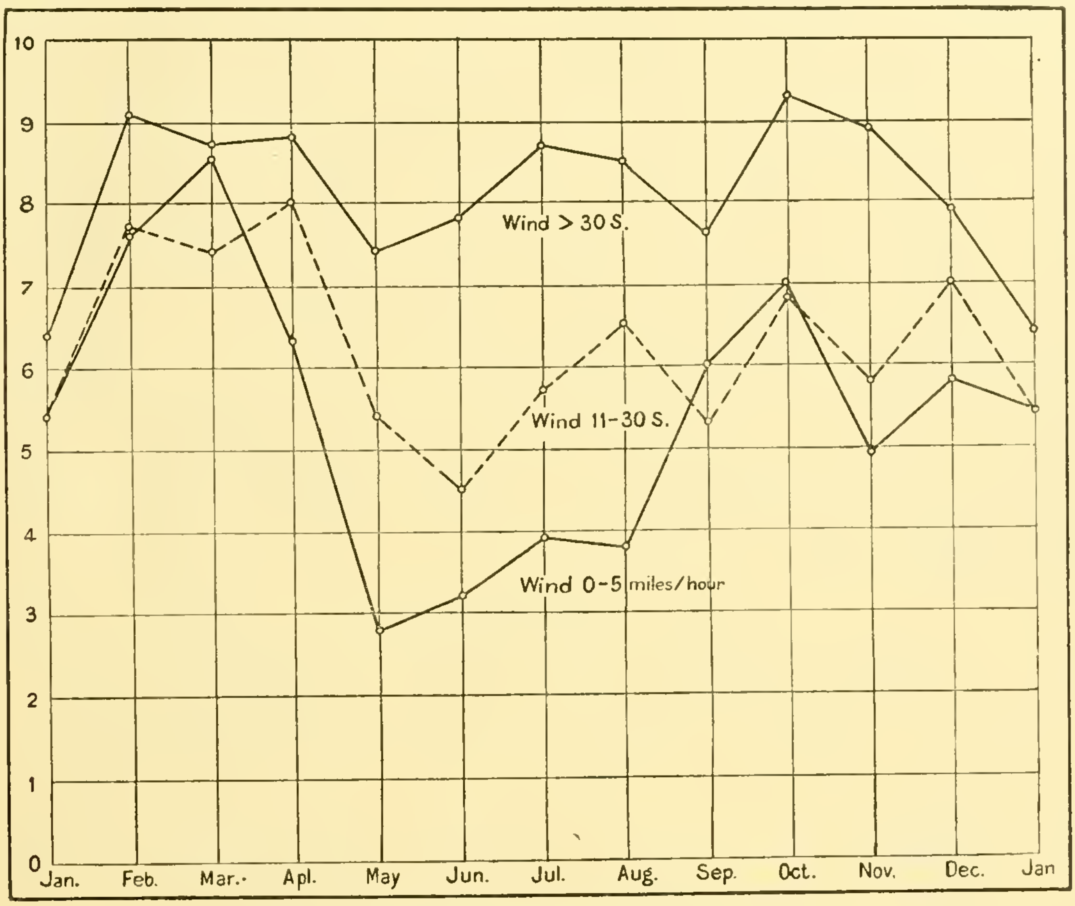

FIG. 51. **Annual variation of cloud according to wind.**

We now see that the yearly variation of the cloud amount is a complex phenomenon, depending on two variables.

(*a*) The frequency of blizzards which if acting alone would give a maximum of cloud in the winter and a minimum in the summer.

(*b*) The amount of radiation received and emitted by the cloud particles which if it acted alone would give a maximum of cloud in the summer and a minimum in the winter.

The combination of these two effects is that minima of cloud occur in summer and winter and maxima in the months near to the equinoxes.

Daily Variation of Cloud.

Observations of the amount of cloud were made at Cape Evans every four hours at midnight, 4 A.M., 8 A.M., midday, 4 P.M. and 8 P.M. As however station time was used, these observations must be put one hour earlier in local time. The record is not quite complete, but it has been possible to interpolate the missing observations between 1st March, 1911, and the end of October, 1912, so that the daily variation has been obtained for twenty months, with a fair degree of accuracy.

A casual glance at the results for individual months shows that one or even two years' observations are quite insufficient for giving a true value of the variation. The data for the individual months have, therefore, been given in the volume of tables, and we shall consider here only the results obtained by combining the new data with those obtained at Hut Point during the Discovery Expedition. Unfortunately in the discussion of the Discovery results the monthly mean cloud amounts at the different hours are only given in whole numbers. As the daily variation in most months is of the order of one unit, this rounding makes it impossible to combine the results there given with the new series. It was therefore necessary to recalculate the whole of the cloud data for the two years' observations at Hut Point. These new values will also be found in the volume of tables.

On the Discovery Expedition observations were taken at the even hours of local time, therefore to combine the results with those of Cape Evans, which were taken at the odd hours of local time, it has been necessary to take the mean value between the successive observations at Hut Point. Thus the values for 7 A.M. local time at Cape Evans have been combined with the mean values for 6 and 8 A.M. at Hut Point, and so on.

The following table gives the departure from mean for the months and seasons based on all the available data.

TABLE 87.

Daily variation of Cloud Amount (Hut Point and Cape Evans).

Month.	No. of years.	3 hours.	7 hours.	11 hours.	15 hours.	19 hours.	23 hours.	Amplitude.
January	2	0·0	+0·1	−0·1	−0·2	−0·1	+0·3	0·5
February	3	−0·1	+0·2	0·0	+0·2	−0·5	+0·1	0·7
March	4	0·0	0·0	−0·2	−0·1	+0·3	−0·1	0·5
April	4	−0·2	+1·0	+0·6	+0·2	−0·6	−1·1	2·1
May	4	−0·4	+0·2	+0·6	+0·4	−0·3	−0·4	1·0
June	4	−0·2	+0·2	0·0	+0·1	−0·2	0·0	0·4
July	4	−0·2	+0·1	+0·4	+0·4	−0·1	−0·6	1·0
August	4	−0·7	+0·3	+0·2	+0·2	0·0	−0·1	1·0
September	4	−0·4	+0·2	+0·1	+0·9	0·0	−0·8	1·7
October	4	0·0	0·0	−0·2	+0·1	+0·2	0·0	0·4
November	3	−0·1	−0·4	0·0	+0·6	+0·2	−0·3	1·0
December	2	+0·6	+0·7	+0·1	−0·4	−0·5	−0·5	1·2
Seasons.								
November–January	..	+0·2	+0·1	0·0	0·0	−0·1	−0·2	0·4
February–April	..	−0·1	+0·4	+0·1	+0·1	−0·2	−0·3	0·7
May–July	..	−0·3	+0·2	+0·3	+0·3	−0·2	−0·3	0·6
August–October	..	−0·4	+0·2	+0·1	+0·4	+0·1	−0·3	0·8
Year	..	−0·1	+0·2	+0·1	+0·2	−0·1	−0·3	0·5

The values for the seasons and year have been plotted on figure 52.

In all seasons except summer the maximum cloud amount is recorded at either 7 hours, 11 hours or 15 hours and the minimum at either midnight or 3 A.M. In other words, except in summer, the maximum occurs during the day hours and the minimum during the night hours.

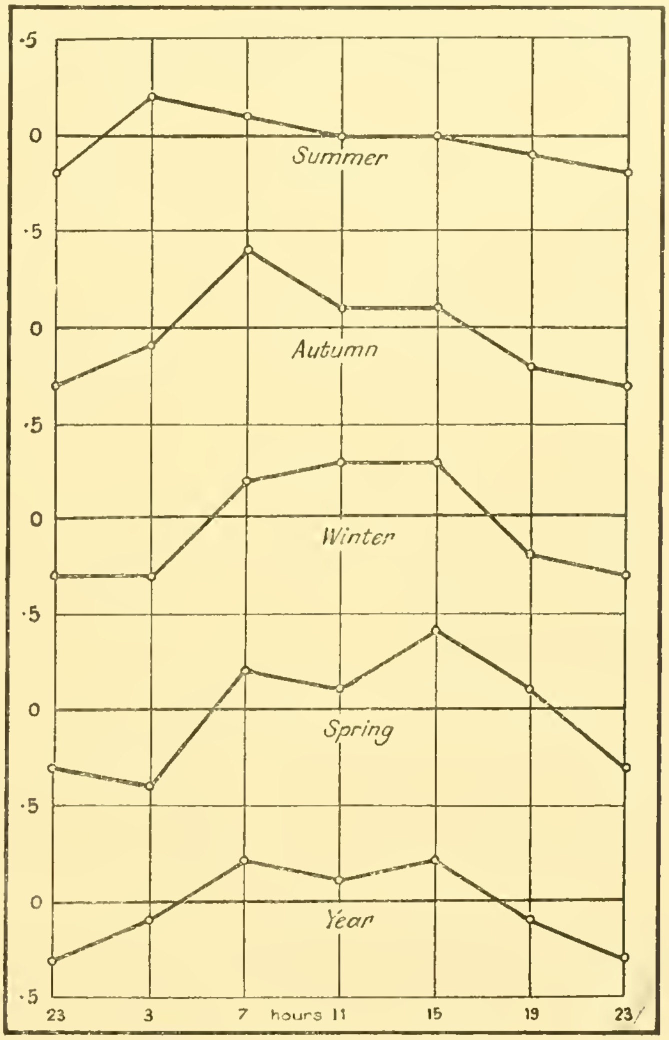

Fig. 52. Daily variation of cloud.

Unfortunately the measurement of cloud amount is not made by instruments and the estimates depend partly on subjective factors. Any one who has tried to estimate the amount of cloud at night is aware of the difficulty of coming to a right decision. Even the casual observer must have often been surprised to see clouds clearly visible on what he thought to be a cloudless sky when a distant lightning flash has lit up the horizon. A long and careful survey of the sky is necessary to detect clouds on a moonless night, and even then an experienced observer may miss some. Now in the Antarctic all the observers were not experienced, and also the conditions on a cold windy night are not conducive to a deliberate survey of the sky to detect small masses of cloud. On the other hand, when there is daylight even an inexperienced observer taking only a rapid glance at the sky can form a very good estimate of the amount of cloud. Thus the amount of daylight plays an important part in the estimate of the amount of cloud. If there was the same average amount of cloud throughout the day and night, the effect of the daylight would be to produce a fictitious daily variation having a maximum during the hours of daylight and a minimum during the hours of darkness, *i.e.*, exactly the same variation as is found during all seasons in the Antarctic except summer, and we must therefore attempt to decide in how far the observed variation is affected by the variation of daylight.

There are three periods to be considered.

(*a*) When there is sufficient daylight throughout the twenty-four hours for the clouds to be clearly seen. For our purpose this may be taken as the whole period between which the sun does not sink more than 10° below the horizon, *i.e.*, in McMurdo Sound the period from September 30 to March 14. Thus the months October to February are included in this period, and March may also be added as observations were taken at 1 P.M. local time which extends the period slightly.

(*b*) The period during which the sky is too dark for clouds to be seen by the aid of the sunlight. We may take this period as lasting during the time the sun does not rise within 10° of the horizon, *i.e.*, in McMurdo Sound the period from June 5 to July 8. Thus the month of June is the only month which is included in this period.

(*c*) The remaining period, during which there is daylight during part of the twenty-four hours and darkness during the remainder, *i.e.*, in McMurdo Sound the periods from March 14 to June 5, and from July 8 to September 30. Thus April and May, July, August and September may be considered as belonging to this period.

Now during the periods (*a*) and (*b*) daylight cannot affect to any appreciable extent the observations of cloud at any time of the day, while during the period (*c*) it affects the observations to its maximum extent.

In figure 53 the amplitude of the daily variation of cloud has been plotted for each month, and we see that during the period (*a*), October to March, the amplitude is very small in five of the seven months. Also in the period (*b*), June, the amplitude is very small. On the other hand each of the two periods into which (*c*) is divided has a month of maximum amplitude. This alone would make us strongly suspect that the daylight plays a large part in determining the apparent daily variation of cloud amount; but when we find that almost exactly the same variation of the amplitude during the year is shown by the observations made on the *Fram* drift when the variation of daylight were nearly the same, the suspicion becomes almost a certainty. Curve (*b*) of figure 53 shows the amplitude of the daily variation of the cloud for each month as observed on the *Fram*, the months being arranged so that the same seasons in the north and south correspond. The similarity of the curves for McMurdo Sound and the *Fram* drift is striking. In the north the months of constant daylight, August and September, have very small amplitudes and also the winter months November and December. Between these two minima there are large maxima during the period when each day has a period of daylight and total darkness.

FIG. 53. Amplitude of daily variation of cloud.

It is therefore very questionable whether the curves in any month except those of complete daylight and complete darkness give any information about the yearly variation of cloud, and in these months the amplitudes are so small that no reliance can be placed on them. In fact the summer variation based on the Hut Point observations is almost the exact reverse of that based on the Cape Evans observations, showing that the small amplitude is mainly the result of chance.

We are therefore reluctantly compelled to conclude that the daily variation of cloud amount teaches nothing reliable as to the true changes in the cloud amount during the day, except that it is very small, so small in fact that during the greater part of the year it is masked by the subjective effect of the varying amount of daylight.

Precipitation.

No rain fell during the whole of our stay at Cape Evans, and up to the present there is no record of rain at either Cape Adare or in McMurdo Sound. On the other hand, a well-developed rainbow was seen to the north-north-east of Cape Evans on February 14, 1911.

Every one who has taken meteorological observations in the Antarctic has been faced with the difficulty of finding some way to record the amount of snowfall. Up to the present this problem has not been solved. The difficulty is that practically all the snowfall occurs during high winds. The snow is carried along in the air and does not settle except in the lee of any obstacle to the winds motion. Any ordinary snowgauge would become full of drift snow in a very short time, while the surrounding ground might not have received any increase to its snow-covering. Also it very frequently happens that with a perfectly clear sky from which no snow is falling the wind raises clouds of loose snow from the ground which enters the gauge and so gives a false record. I had many ideas as to measuring the effective snowfall on my arrival in the Antarctic, but none of them proved of any practical use.

It was no use trying to measure the depth of snow on the ground, nor to keep a space clear and measure the snow on it each morning. For no snow accumulated on ground subject to the full force of the wind, while in sheltered places the snow would accumulate to a depth determined entirely by the size and shape of the obstacle, and be entirely unrelated to the quantity of precipitation.

My experience is that it is totally impossible to form even an approximate idea of the quantity of snow precipitated from the atmosphere. Even on a perfectly level plain the snow accumulation would be no gauge of the precipitation, for it would receive snow which had fallen miles away and been driven forward by the wind.

All that is possible in this section is to give a general statement of the snow-covering existing around the station at different times of the year, and to give some idea of the frequence with which snow fell.

When we arrived at Cape Evans, the small promontory on which the station was built was—as future experience showed—remarkably free from snow. The beach on which the hut was built had no snow-covering at all, so that there were several hundred square yards of black volcanic debris fully exposed to the warm sun. When the expedition left twenty-four months later, the beach was buried in several feet of snow and the hut itself was almost invisible under a great snow-drift which had formed around it.

After our arrival in January, 1911, there was a slow but steady diminution in the snow and ice accumulations on the Cape, so that the size of the small glacierettes obviously decreased. This was due mainly to ablation, for it continued throughout the first winter when thawing was quite imposible. A cave had been dug for the magnetic instruments in a small glacierette—in reality the permanent drift which had consolidated into firm ice in the lee of

Windvane Hill—and the roof of this cave became so thin that towards the end of the summer of 1912 I began to have serious doubts as to its safety. Thus from January, 1911, to the end of February, 1912, there was a marked diminution in the snow and ice accumulations on the Cape.

When the sea froze in March, 1911, a thin deposit of snow accumulated on the sea ice to a depth of one or two inches, this never increased all through the winter and when in September we made a sledge journey across the Sound the only places where we could find sufficient snow for erecting the tent were the drifts in the lee of broken ice. The blizzard at the end of September (25th to 28th) left large drifts about the hut and hills, but no accumulation of snow on the sea ice. During October and November there was a great loss of snow. The drifts near to the hut diminished and all the snow disappeared from large tracts of the sea ice. From Cape Evans to Cape Barne on November 29, 1911, the floe was entirely clear of snow exposing the smooth blue sea ice.

Thus in the neighbourhood of Cape Evans the total snowfall for eleven months had produced no addition to the snow accumulations, but on the contrary the permanent snowdrifts had become visibly smaller.

On December 6, 1911, the first heavy snowfall unaccompanied by high wind was experienced. This left 18 inches of snow on the floe which, in consequence of a high northerly wind on the 8th, settled down to a depth of about 4 inches over all the frozen sea in our neighbourhood. At the end of this snow-storm the accumulation of snow about the hut was the greatest we had experienced; large drifts covered most of the stores around the camp, and large tracts of the hill which had always been clear before were now buried under snow. From this time on successive blizzards added to the accumulation and 1912 was just as marked for the increase of snow as 1911 had been for its disappearance.

Only during the summer months was there anything equivalent to the snowfall with which we are familiar in temperate regions. The snow fell on December 6 in ordinary flakes, but at other times of the year flakes were never observed. The snow was chiefly in the form of small grains showing little crystalline structure, but occasionally crystal stars would fall. In the absence of wind the snowfall was always light, and from March to October the ground never received more than a mere sprinkling of snow in the absence of blizzards. During blizzards the air became filled with snow literally in the form of dust. It was then practically impossible to say whether new snow was falling or whether the whole mass of snow in the air was simply fallen snow carried along by the wind.

In the meteorological log we have three kinds of entries referring to snow and drift. First, the meteorological symbol for snow is entered, to which is almost always attached the remark 'slight snow' or 'very little snow falling.' Secondly, the two symbols for snow and drift are entered together, but very frequently the sign for snow is queried, or the remark is added 'probably snow,' thus showing the great difficulty of deciding whether new snow was falling or not. Finally, there is the symbol for drift alone, and to this the remark 'surface drift' is sometimes added. In the latter case, there would certainly be no new snow falling, but it is impossible to say how often the symbol for drift refers to drift with and without snow, hence the records of drift include drift with and without snowfall.

From March, 1911, to October, 1912, observations were taken every four hours and the number of time the symbols for snow, snow with drift and drift were recorded have been counted. In the following table these have been expressed for each month reduced to one hundred observations. The numbers therefore in the table give for each month the average frequency with which each sign was recorded in one hundred hours.

Table 88.

Number of times Snow and Drift recorded in 100 hours.

Month.	Snow.	Snow and Drift.	Drift.	Total.
1911.				
March	10	4	9	23
April	22	6	7	35
May	9	10	6	25
June	6	4	2	12
July	6	7	9	22
August	5	2	13	20
September	4	2	11	17
October	9	11	15	35
November	7	5	1	13
December	8	4	12	24
1912.				
January	11	1	2	14
February	11	12	11	34
March	13	7	16	36
April	8	2	12	22
May	11	8	8	27
June	2	24	24	50
July	10	28	22	60
August	10	18	26	54
September	1	15	26	42
October	8	10	18	36

From the purely human point of view this table shows the disagreeableness of the climate in McMurdo Sound. Out of twenty months there were only four in which there were less than 20 per cent. of hours with snow or drift. In twelve months the percentage of snow and drift was more than 25 per cent. and in three it was over 50 per cent.

The great excess of bad weather during 1912 over 1911 is clearly indicated. From March to October 1911 there were 25 hours out of every hundred with snow or drift; in the same months of 1912 the percentage was 41. Collecting the results according to seasons we have the following:—

TABLE 89.

Number of times Snow and Drift were recorded in 100 *hours.*

Season.	Snow.	Snow and Drift.	Drift.	Total.
Spring—August to October . . .	6	10	18	34
Summer—November to January . .	9	3	5	17
Autumn—February to April . . .	13	6	11	30
Winter—May to July	7	14	12	33
Year	9	8	12	29

The summer has the least frequency of snow and drift, while the other seasons have practically the same. For the summer we have only observations for one year, but the expedition was at Cape Evans for another, and there is little doubt that the relative freedom from bad weather found during November, 1911, to January, 1912, was repeated during these months in other years.

CHAPTER V.

PRESSURE.

INSTRUMENTS AND METHODS.

Barometers.—The following table shows the barometers used on the expedition and their corrections as determined at Kew before leaving England.

TABLE 90.

Barometers.

Where used.	Pattern.	Number.	Kew correction
Ship	Kew	1163	−·005″
Cape Evans (general use) . . .	Kew	1157	−·010″
Cape Evans (for comparison) . .	Fuess	1667	−·010″
Cape Adare (general use) . . .	Kew	1156	−·012″
Cape Adare (for comparison) . . .	Fuess	1668	−·010″

Owing to the danger of air entering the barometers during the journey and before they could be set up at the land stations, the two Fuess barometers were taken, because with these instruments it is possible to detect and correct for any air which might enter. These barometers are not, however, convenient for general use, it was therefore intended to use them only for checking the Kew barometers, which were to be used for taking the actual observations.

Just before the *Terra Nova* left Lyttleton, in New Zealand, all the barometers were set up in a room on shore and compared. About twelve readings of each barometer were taken, and the results were compared after each reading had been corrected for temperature and instrumental error as determined at Kew. As it is impossible to say that any one of the instruments had undergone no change, the difference is given in table 91 between the barometer shown at the end of each line and the one shown at the head of the column.

TABLE 91.

Barometer Comparison in Lyttleton.

	1163.	1157.	1667.	1156.	1668.
1163	..	+·015	+·019	+·020	+·017
1157	−·015	..	+·004	+·005	+·002
1667	−·019	−·004	..	+·001	−·002
1156	−·020	−·005	−·001	..	−·003
1668	−·017	−·002	+·002	+·003	..

From this table it will be seen that at Lyttleton all the barometers agreed with one another except the ship's barometer, No. 1163, which appears to have been reading about +·018″ too high.

After this it was impossible to make another general comparison, but it is possible to show that the instruments when in the positions in which they were used were in good order. The following is the evidence for the different barometers.

Cape Evans' Barometers, No. 1157 *and No.* 1667.—The two instruments were compared on five occasions during the two years, with the following result, after their Kew corrections have been applied.

Table 92.

Barometer Comparisons at Cape Evans.

Date of comparison.	1157—1667.
August 21, 1911	·000
January 11, 1912	·000
May 13, 1912	—·001
October 1, 1912	·000
January 1, 1913	—·003

From these comparisons it is safe to say that both barometers were in good order after landing at Cape Evans.

Cape Adare Barometer, No. 1156.—Unfortunately the Fuess barometer which was taken to Cape Adare for purposes of comparison was broken in landing. Therefore no comparisons could be made after setting up the Kew barometer, No. 1156. On the return of this barometer to Lyttleton it was compared with the standard barometer in the observatory there (No. 1121, made by Hughes, London) and found to be exactly correct. It is tolerably safe therefore to assume that it was correct while in use at Cape Adare. This conclusion is made quite certain by the following observations. On January 3, 1912, the *Terra Nova* reached Cape Adare at nine o'clock in the morning to take away the party. The observation made on the ship at 8 A.M. was 29·54″, while that made at the same time at Cape Adare was 29·537″, thus showing that the Cape Adare barometer was in good order.

The Ship's Barometer, No. 1163.—This barometer was compared at Kew before and after the expedition, the comparisons giving —·005 and ·000 as the corrections, respectively. From a comparison, however, with the other barometers in Lyttleton and with the Cape Evans' barometer in the Antarctic, this barometer appeared to read ·020″ too high while used in the Antarctic. The barometer, however, was of the ship's pattern and only graduated to ·010″, therefore a very high degree of accuracy is not to be expected. In reducing the readings of this barometer I have used a correction of —·010 as being the mean of the corrections found in England and in the Antarctic.

Framheim Barometer.—When the results of the pressure observations at Cape Evans and Framheim were first examined, it caused great surprise to find that the pressure at Framheim was so much lower than at Cape Evans. Framheim is further south than Cape Evans and has a much lower average temperature, therefore for both these reasons one expected the pressure at Framheim to be the higher. Although there was no reason to doubt the accuracy of the barometers at either Cape Evans or Framheim, it was felt that a comparison of the barometers at the two stations was desirable. Unfortunately no direct comparison was then possible, but that there was no appreciable instrumental error could be determined indirectly, as follows.

At the end of January 1911 the *Terra Nova* left McMurdo Sound to proceed to King Edward VII Land, where it was intended to establish the eastern party. When she was in McMurdo Sound her barometer was compared with the one in use at Cape Evans. As she proceeded eastwards the ship's barometer fell continually compared with the readings at Cape Evans, thus confirming the fall in pressure over the east of the Ross Sea. As is well known the *Terra Nova* encountered the *Fram* in the Bay of Whales and during February 4, 1911, the two ships were near to one another. From their meteorological logs the following comparison of the barometer readings is possible.

TABLE 93.

Barometer Comparison.

	Cape Evans.	*Terra Nova.*	*Fram.*
February 4th, 1911, 4 hours . . .	29·29	28·91	28·90
8 hours . . .	..	..	..
12 hours . . .	29·29	29·00	29·00
16 hours . . .	29·28	29·00	28·99
20 hours . . .	29·26	28·96	28·99
Mean . . .	29·28	28·97	28·98

From this it will be seen that the two ships' barometers were in satisfactory agreement while the Cape Evans' pressure was ·30″ higher than the simultaneous pressure in the Bay of Whales (Framheim). This result, so far as it goes, confirms the relative low pressure near Framheim, but as the barometer on the *Fram* which is shown to agree with the one on the *Terra Nova* was not the one which was subsequently used at Framheim, the desired comparison of the Cape Evans and Framheim barometers was not effected. This final comparison, however, is possible from the log of the *Fram* and the records of Framheim during the period in January 1912 when the *Fram* was waiting in or near the Bay of Whales for the return of Captain Amundsen's party from the South Pole. From January 14 to January 27, 1912 (inclusive), there were simultaneous observations on the *Fram* and at Framheim and these with all corrections applied agree within ·2 mm. of each other, the Framheim barometer reading being the higher by this amount.

Thus the Framheim barometer, through the intermediary of the barometers on the *Terra Nova* and the *Fram*, was compared with the Cape Evans' barometer, and the comparison shows that, if anything, the Framheim barometer read slightly higher than the Cape Evans' barometer, which would tend to reduce and not increase the large pressure difference found between the two stations.

Method of Reduction of the Observations.—At Cape Evans two Richard barographs were in use from January 27, 1911, to the end of December, 1912.

On January 24, 1911, the barometer was set up, but owing to the large amount of work entailed in setting up the magnetic and meteorological instruments it was impossible at first to take more than one set of meteorological observations each day. On March 2, 1911, however, barometer observations were commenced at intervals of four hours. These were continued almost without break until the end of October 1912. In November 1912, owing to nearly all the members of the expedition taking part in the different search parties, the barometer observations became irregular, but on every day the barometer was read at least once and on most days three or four times.

The eye readings of the barometers were reduced to sea-level and constant gravity. The barograph traces were measured at each hour and the readings tabulated. Against the corresponding barograph measurement each reduced barometer reading was entered, and the difference taken. These differences were then plotted on the actual barograph sheet to a scale 10 times larger than the barograph scale. As most of the changes in the difference were due to lag in the barograph, it was found that the curve of differences was very similar to the actual barograph curve. This similarity made it very easy to draw the curve of differences and is a great advantage of this method of reducing a barograph trace. When the curve of differences had been drawn, it was read off at every hour and the value entered against the corresponding value from the barograph curve. The barograph and difference values were then added together, giving the correct barometer reading at each hour. These measurements were all made to $\frac{1}{100}$th of an inch, which is the greatest accuracy possible with a barograph. The mean values of the month from the barograph reductions for each of the hours at which the barometer was read were found to agree to $\frac{1}{1000}$th of an inch with the mean of the barometer readings.

During the period when barometer observations were not taken every four hours the reduced barograph records are correspondingly less accurate, but there is no doubt that even in these periods the mean monthly value is as accurate as the barometer correction, and the mean daily variation for the month is probably as accurate as could be obtained with the full set of observations, for this element is more affected by the non-periodic pressure changes than by the method of reduction.

A similar method was used in reducing the Cape Adare barograph record, but as during the greater part of the year eye observations were not taken during the night, the reduction is not so perfect. It was therefore considered sufficient to reduce the Cape Adare barograph trace only at every second hour. During a few periods all the members of the Cape Adare Party were away from the station for several days. The values of the pressure for these days have been obtained whenever possible from the barometer observations taken in the field.

MEAN PRESSURE AND ANNUAL VARIATION.

*McMurdo Sound.**

The following table contains the monthly values of pressure at McMurdo Sound for the four years for which data are now available.

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* Since this chapter was finished and ready for the press, Mr. Mossman has very kindly drawn my attention to the fact that while the pressure data contained in tables 1 and 3 of chapter XI, pp. 476–482 of the volume of results of the Discovery Expedition have been reduced to gravity at latitude 45°, those in table 2 have not. As there is nothing to point this out in the chapter itself, I had used the mean monthly pressures given in table 2 under the impression that they were fully reduced. Thus half the data used in this chapter was wrong by ·070 inch. This necessitated recalculating most of the tables of pressure and also altering many of the diagrams. All the tables have been corrected, but it was too late to alter all the diagrams. Those diagrams which were materially affected have been corrected, but the remainder have been left unchanged. Thus in a few diagrams the plotted points do not agree with the figures in the tables, but in none of these cases is the character of the diagram affected. One cannot too strongly deprecate the use of pressure data, some of which are fully and the remainder only partially corrected.

TABLE 94.

Monthly pressure in McMurdo Sound.

Reduced to 32°F., sea-level and gravity at 45°. (Inches.)

20″+

Year.	January.	February.	March.	April.	May.	June.	July.	August.	September.	October.	November.	December.	Year.
1902 . . .		9·327	9·399	9·478	9·344	9·315	9·398	8·911	9·384	9·078	9·634	9·505	9·353 (a)
1903 . . .	9·461	9·298	9·488	9·359	9·227	9·562	9·169	9·215	9·059	8·995	8·947	9·294	9·229 (b)
1904 . . .	9·131												
1911 . . .	9·296	9·308	9·211	9·317	9·227	9·110	9·078	9·188	9·156	8·825	9·630	9·752	9·258
1912 . . .	9·431	9·527	9·171	9·354	9·151	8·882	8·998	9·132	9·442	9·090	9·261	9·188	9·219
Mean . .	9·330	9·365	9·317	9·377	9·237	9·217	9·161	9·112	9·260	8·997	9·368	9·435	9·265
Smoothed	9·365	9·344	9·341	9·327	9·267	9·208	9·163	9·161	9·157	9·155	9·292	9·392	9·265

(a) Feb. 1902 to Jan. 1903. (b) Feb. 1903 to Jan. 1904.

The above values have been plotted in figure 54 and the months of the same year connected up by a characteristic line. The resulting diagram is exceedingly instructive showing as it does the tremendous variations of the pressure for the same months from year to year compared with the normal yearly variation. It also shows the impossibility of forming even an approximate idea of the yearly variation from one year's observations. Thus the year 1903 showed the maximum pressure in June while in 1912 the minimum pressure occurred in this month. Similarly November was the month of maximum pressure in 1912 and the month of minimum pressure in 1903.

When the mean values of each month for the four years are taken the irregular changes from month to month are still large (thin curve in figure 55*a*) and it is clear that many more years would be required before a smooth curve showing the true yearly variation would be obtained.

When one has to deal with a curve subject to such large accidental variations it is legitimate to endeavour to eliminate them by smoothing the curve. I have tried several methods of smoothing this curve and find that the most satisfactory result is obtained by applying the formula $b=\frac{a+2b+c}{4}$. The numerical results are given in the last line of table 94 and the thick line in figure 55*a* shows the resulting curve. In its main features this curve is probably correct.

The numbers given in the last line of table 94 have therefore been taken throughout this work as the normal values of the monthly pressure in McMurdo Sound.

The result that the pressure is lowest during the cold winter months and highest during the warm summer months is very surprising, but there can be little doubt of the reality of the phenomenon.

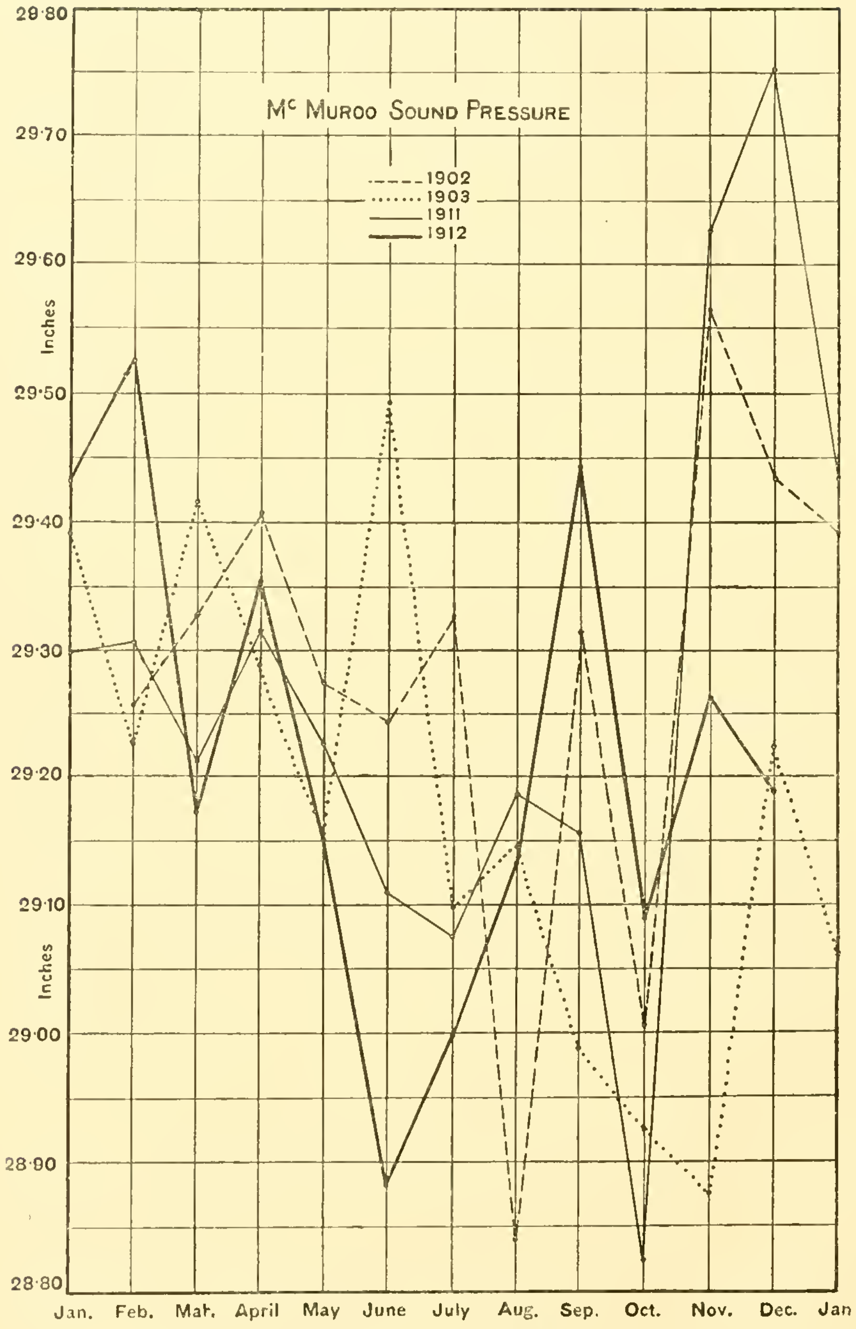

Fig. 54. Mean monthly pressure. McMurdo Sound.

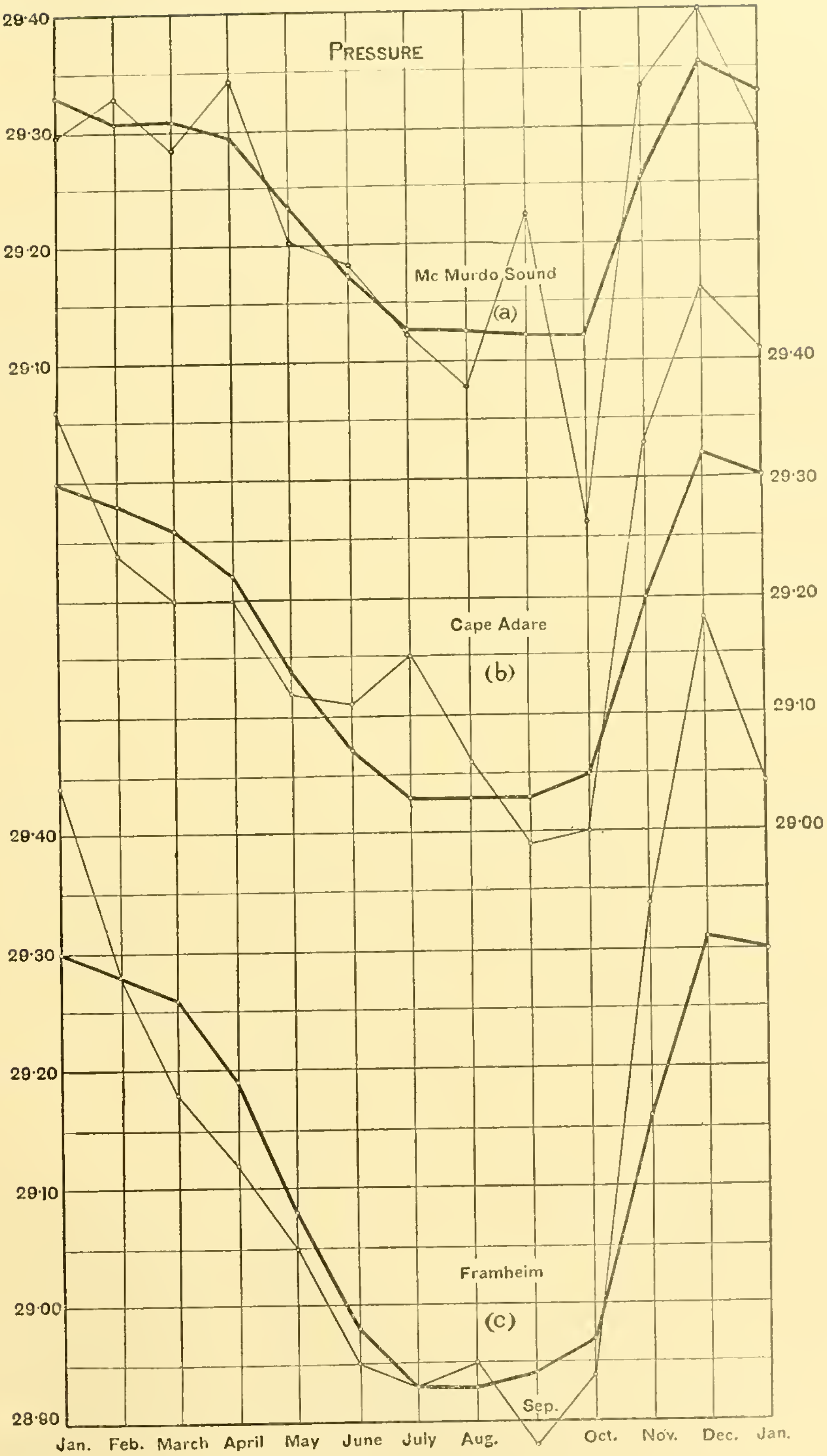

FIG. 55. Annual variation of pressure.
(*Note.*—Values in curve (*a*) plotted ·035″ too low.)

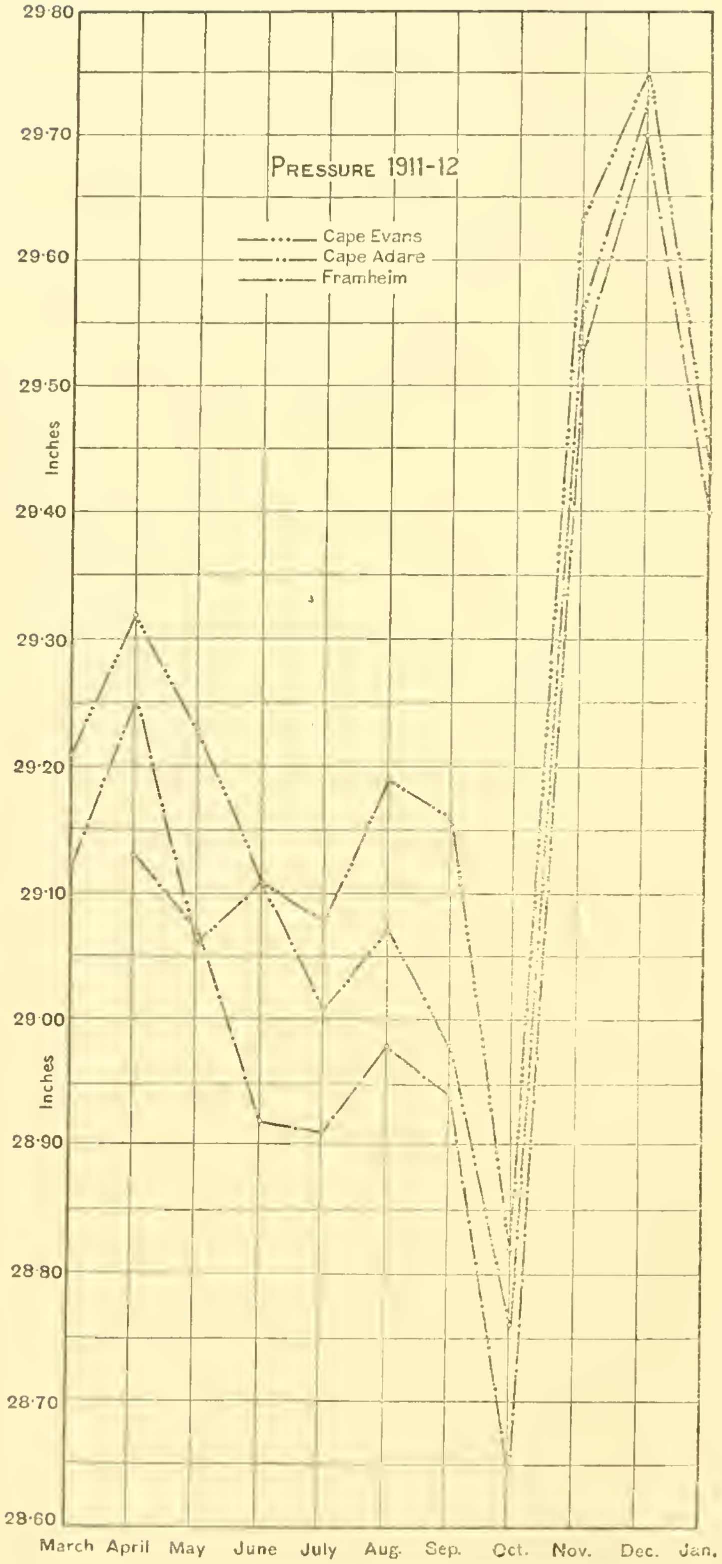

FIG. 56. Mean monthly pressure, 1911-12.

Comparison of the pressure at Cape Evans, Framheim and Cape Adare.—The following table gives the simultaneous mean monthly pressure reduced to sea-level and gravity at latitude 45° at Cape Evans, Framheim and Cape Adare.

TABLE 95.

Mean monthly pressure.

Reduced to 32°F., sea-level and gravity at 45°. (Inches.)

Month.	Cape Evans.	Framheim.	Cape Adare.	Cape Evans –Framheim.	Cape Evans –Cape Adare.
1911.					
March . . .	29·21	. .	29·12	. .	·09
April . . .	29·32	29·13	29·25	·19	·07
May . . .	29·23	29·07	29·06	·16	·17
June . . .	29·11	28·92	29·11	·19	·00
July . . .	29·08	28·91	29·01	·17	·06
August . . .	29·19	28·98	29·07	·21	·12
September . .	29·16	28·94	28·98	·22	·18
October . . .	28·82	28·65	28·76	·17	·06
November . .	29·63	29·53	29·56	·10	·07
December . .	29·75	29·70	29·73	·05	·02
1912.					
January . . .	29·43	29·40	. .	·03	. .

These values are plotted on figure 56 and it will be seen at once how closely related are the pressure changes at all the three stations. The series contains only ten months' observations for Framheim and Cape Adare and these, extending over less than a year, are not sufficient to give either the mean pressure for a complete year nor the yearly variation, but by the aid of the close relationship between the pressure at the three stations it is possible to amplify the data, and in the following two sections approximate values of the normal pressure and the yearly variation will be obtained for Framheim and Cape Adare by the aid of the more complete data for McMurdo Sound.

Framheim.

The pressure differences between Cape Evans and Framheim for each month are entered in column 5 of table 95. There is a large yearly variation in the pressure difference, the difference being largest in September and least in January. When the differences are plotted (curve I, figure 57) it is seen that they lie approximately on a curve which is much more regular than the curves of the pressures themselves.

This curve is so regular, being almost a sine curve, that it is reasonable to conclude that the two missing values for February and March if they had been available would have been on or near the curve. We may therefore use the values given by the curve for supplying the missing data. According to the curve the difference between the pressure at the two stations in February and March is ·03″ and ·05″ respectively. Applying these differences to the pressure for February and March 1911 at Cape Evans, we obtain the following values for a complete year's observations at Framheim.

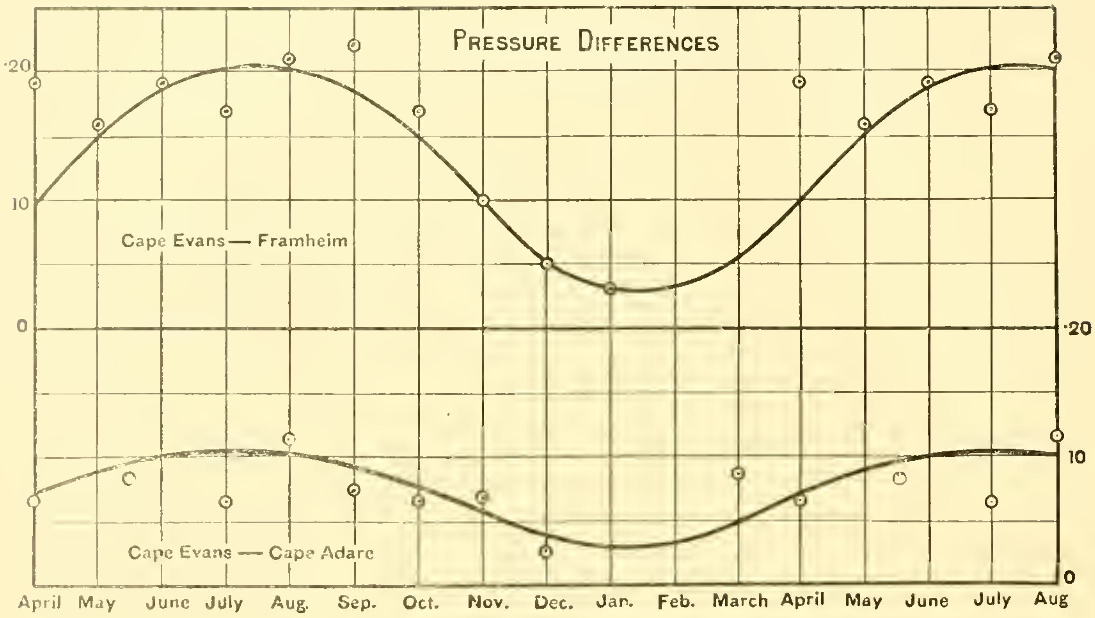

Fig. 57. Pressure differences.

Table 96.

Pressure at Framheim, February 1911 *to January* 1912.

Reduced to 32 F., sea-level and gravity at 45°. (Inches.)

Year.	February.	March.	April.	May.	June.	July.	August.	September.	October.	November.	December.	January.	Year.
Pressure . .	29·28	29·16	29·13	29·07	28·92	28·91	28·98	28·94	28·65	29·53	29·70	29·40	29·13
Smoothed . .	29·28	29·18	29·12	29·05	28·95	28·93	28·95	28·88	28·94	29·34	29·58	29·44	29·13

In the last line the values have been smoothed by $\frac{a+2b+c}{4}$ and these are the best values obtainable for the yearly variation from the single year's observations. But these values share in the abnormalities shown by the 1911 curve for McMurdo Sound in figure 54, which are very large; hence the above series cannot be taken as a very near approach to the normal yearly variation for Framheim.

It is well known that the difference in pressure between two stations not too far apart is much more constant than the pressure itself. It is therefore very likely that the smooth curve of pressure difference between Cape Evans and Framheim given in figure 57 is not widely different from the normal curve of differences which would be obtained from a much longer period of comparison. We may therefore apply the appropriate monthly difference to all the monthly values available for McMurdo Sound and get the normal pressure at Framheim from the four years' observations in McMurdo Sound. The following table contains in the first line the smoothed pressure difference Cape Evans — Framheim measured from curve 1 of figure 57 and in the second line these differences have been applied to the normal pressure of McMurdo Sound to obtain the normal pressure at Framheim.

TABLE 97.

Normal pressure at Framheim as determined from four years' observations in McMurdo Sound and the smoothed differences found in 1911.

Reduced to 32° F., sea-level and gravity at 45°. (Inches.)

	January.	February.	March.	April.	May.	June.	July.	August.	September.	October.	November.	December.	Year.
Difference . . .	·03	·03	·05	·10	·15	·19	·20	·20	·18	·15	·10	·05	·12
Framheim . . .	29·33	29·31	29·29	29·23	29·12	29·02	28·96	28·96	28·98	29·00	29·19	29·34	29·14

The yearly pressure variation for Framheim given in table 96 and table 97 are shown in figure 55*c*. It will be seen that the variation for the single year, thin curve, has the same general characteristics as the variation obtained from the four years' observations in McMurdo Sound, thick curve, the chief difference being in the high values of the pressure during the months of November, December 1911 and January 1912. Either curve shows that the yearly variation is very similar at both McMurdo Sound and Framheim, but that the latter has the larger amplitude.

From a physical point of view the most interesting feature of the pressure relationship between McMurdo Sound and Framheim is that the pressure difference is not that which would be expected from the temperature relationship. At both stations the pressure is least in the coldest months. Further Framheim is colder than McMurdo Sound and its mean pressure is less, also in the months in which the temperature difference between the two stations is the greatest the pressure difference is the greatest. Such a relationship would be impossible if the density of the air only controlled the pressure; we shall show later that the solution of the apparent paradox is to be found in the motion of the air as constrained by the Western Mountains (see page 238).

Cape Adare.

In addition to the pressure values for Cape Adare given in table 95 further data are available from the observations made in 1899–1900 by the Southern Cross Expedition. For the eleven months, March 1899 to January 1900, we have pressure observations made twice a day, at 9 A.M. and 9 P.M.; although these are not so good as observations taken more frequently they give values for the mean monthly pressure which are not far from the true values.

We have then two separate series of pressure data, the first consisting of eleven monthly values and the second of ten monthly values. It is possible to extend these two series into complete years with a considerable amount of certainty.

Consider first the second period which commences with March and ends with December 1911. From figure 56, page 170, it will be seen that during the period when simultaneous observations were taken at Cape Evans, Cape Adare and Framheim the mean monthly pressure at Cape Adare, with one slight exception, lay always between the values for Cape Evans and Framheim. It therefore seems reasonable to conclude that the pressure for January 1912 at Cape Adare lay somewhere between the values which we have for that month at Cape Evans and Framheim. As it happened these values were near together, being 29·43″ and 29·40″ respectively. It is almost certain therefore that the pressure at Cape Adare during that month could not be far from 29·42″. Taking this value we have now two complete sets of mean monthly pressure from March to January. February is therefore the only missing month, and we cannot do better than take for this month the mean of the values for January and March. Completed in this way we have the following two years' pressure data for Cape Adare, the values not actually observed being entered in brackets.

TABLE 98.

Mean monthly pressure at Cape Adare.

Reduced to 32°F., sea-level and gravity at 45°. (Inches.)

	January.	February.	March.	April.	May.	June.	July.	August.	September.	October.	November.	December.	Year.
1899–1900 . . .	29·26	(29·24)	29·14	29·35	29·08	29·02	29·46	29·07	28·69	28·94	29·40	29·31	29·16
1911–1912 . . .	29·42	(29·24)	29·12	29·25	29·06	29·11	29·01	29·07	28·98	28·76	29·56	29·73	29·19
Mean	29·34	29·24	29·13	29·30	29·07	29·06	29·24	29·07	28·84	28·85	29·48	29·52	29·18
Smoothed . . .	29·36	29·24	29·20	29·20	29·12	29·11	29·15	29·06	28·90	29·00	29·33	29·46	29·18

In addition to this determination of the yearly pressure variation at Cape Adare based on two incomplete years of observation we are able to reduce the four years' observations at McMurdo Sound to Cape Adare by means of the ten months' simultaneous observations in 1911.

The monthly differences Cape Evans—Cape Adare are given in the last column of table 95, page 171, and they are plotted in curve II of figure 57.* It will be seen that the points lie on a curve similar to the one found for Framheim, but that the amplitude is much less. The first line of the following table gives the values of the smoothed difference measured from the curve and in the second line these differences have been applied to the normal pressure of McMurdo Sound to obtain the normal pressure at Cape Adare.

TABLE 99.

Normal pressure at Cape Adare as determined from four years' observations in McMurdo Sound and the smoothed difference found in 1911.

Reduced to 32°F., sea-level and gravity at 45°. (Inches.)

	January.	February.	March.	April.	May.	June.	July.	August.	September.	October.	November.	December.	Year.
Difference . . .	·03	·03	·05	·07	·09	·10	·10	·10	·09	·07	·06	·04	·07
Cape Adare . . .	29·33	29·31	29·29	29·26	29·18	29·11	29·06	29·06	29·07	29·09	29·23	29·35	29·19

The values for the yearly variation found by the two methods, table 98 and table 99, are shown in the thin and thick curves, figure 55(*b*). The two curves are similar, varying appreciably only in July and the summer months. The high value on the thin curve for

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* The differences for May and June have been combined as individually they lie rather far from the curve, but combined fit well with the other points.

July is due to the abnormally high July pressure found in 1899, and the high summer values are due, as in the case of Framheim, to the unusually high pressure during the summer of 1911-12.

Summary.—From this discussion of the monthly values of pressure at the three Ross Sea stations we see that whether we take only the actual observations made at Framheim and Cape Adare or the values for those stations deduced from the four years' observations at McMurdo Sound we arrive at the same general type of annual pressure variation at all three stations. There seems little doubt therefore that in the Ross Sea area pressure is highest in December and lowest in September or October. The pressure falls fairly regularly from December to July, remains more or less constant until October and then rises very rapidly to its maximum in December.

The annual variation of pressure has been determined in other parts of the Antarctic, but except at Snow Hill where observations were made for twenty months, the data are only for twelve months or less at each station. It has already been pointed out that the yearly variation based on a single year's observations in the Antarctic can lead to very erroneous conclusions. It would therefore be unprofitable to compare the individual results from other stations, and a general comparison can best be made when the meteorology of the Antarctic as a whole comes to be reviewed.

GEOGRAPHICAL DISTRIBUTION OF PRESSURE.

We have now determined the mean annual pressure at the three stations in the Ross Sea area to be :—

Cape Evans	29·26″
Cape Adare	29·19″
Framheim	29·14″

The winds at Cape Evans are so affected by the surrounding mountains that they give us little information of the actual pressure gradient in the neighbourhood of the station. There can however be little doubt that the air motion over the west of the Barrier is mainly from the south, therefore we must assume that the isobars over that part of the Barrier run more or less parallel to the Western Mountains with the highest pressure close to the mountain range. The resultant wind direction at Framheim during the ten months—April 1911 to January 1912—was from S. 74° E. The exposure for winds at Framheim was almost perfect, we must therefore conclude that the isobars run very approximately in this direction with the low pressure to the north. If the wind velocity is proportional to the gradient the isobars must be closer together near Cape Evans than near Framheim, for the resultant wind velocity during the ten months mentioned above was 10·7 miles an hour at Cape Evans and only 3·1 miles an hour at Framheim. The isobars over the Barrier and the south of the Ross Sea shown on figure 58 have been drawn to conform with these conditions. The distribution of the pressure near Cape Adare cannot be judged from the wind direction and pressure at that station. The pressure distribution shown over the north of the Ross Sea in figure 58 has been deduced from the general pressure distribution shown in the weather maps contained in Volume II.

The pressure distribution shown in figure 58 is probably correct in its main outlines, but the distance between the isobars is only to be taken as indicating the gradient, for in the absence of free wind observations at Cape Evans and Cape Adare it is impossible accurately to determine the gradient. The diagram shows that the mean pressure over the Barrier is higher than over the Ross Sea, and there is every indication that the pressure is lower over the south of the Ross Sea than over the north. Whether there is on the mean of the year a depression over the Ross Sea with closed isobars must be left an open question.

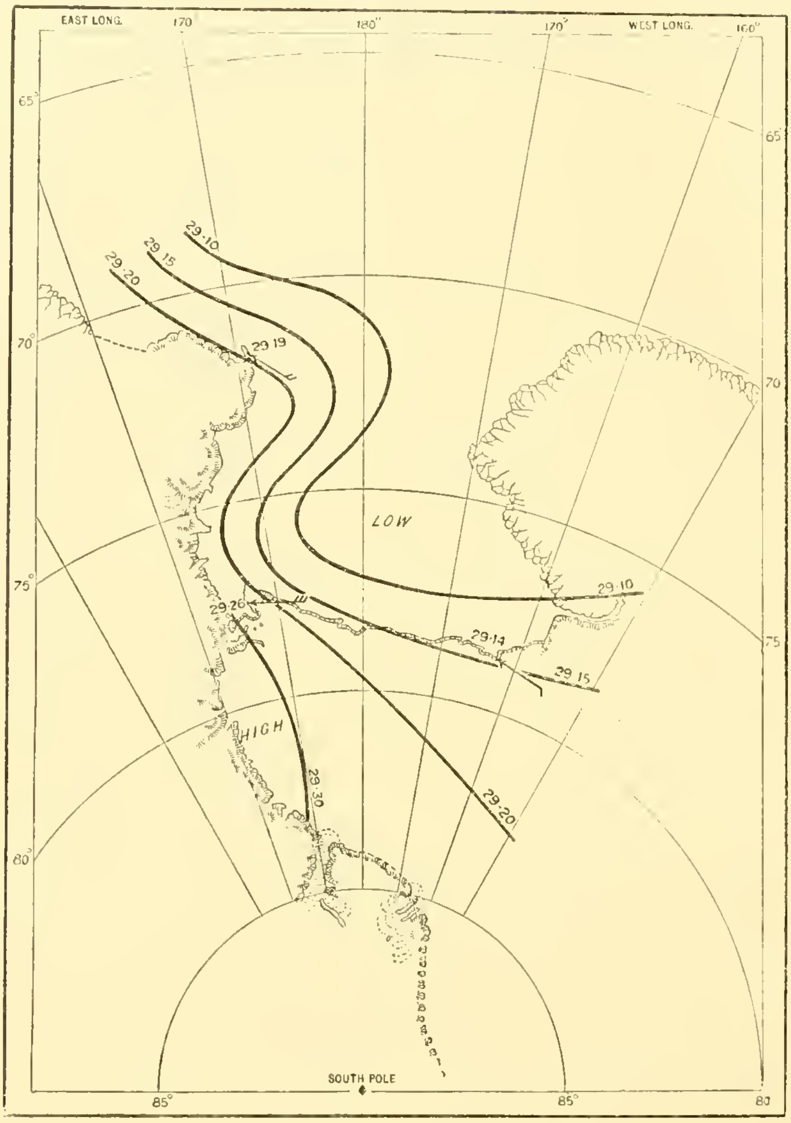

Fig. 58. Pressure distribution year.

Daily variation of pressure.

It has already been explained how hourly values of pressure were obtained at Cape Evans from the barographs corrected every four hours by means of the readings of the mercury barometer. This series of observations extends from January 1911 to December 1912, *i.e.*, for 23 months. There are also available the two hourly readings of the barometer made during 24 months, from February 1902 to January 1904, at Hut Point.

The secular barometer changes are so great in McMurdo Sound, that a single month's observations are practically useless for determining the true daily variation. It has therefore been decided to give the data for each month separately in Volume III and to discuss here only the final result obtained by combining the four years' observations for each month, which give fairly regular and constant values for the daily variation. As only two-hourly barometer readings were made on the Discovery Expedition the mean values for the four years can only be given at intervals of two hours, but these are sufficient for showing the trend of the daily variation.

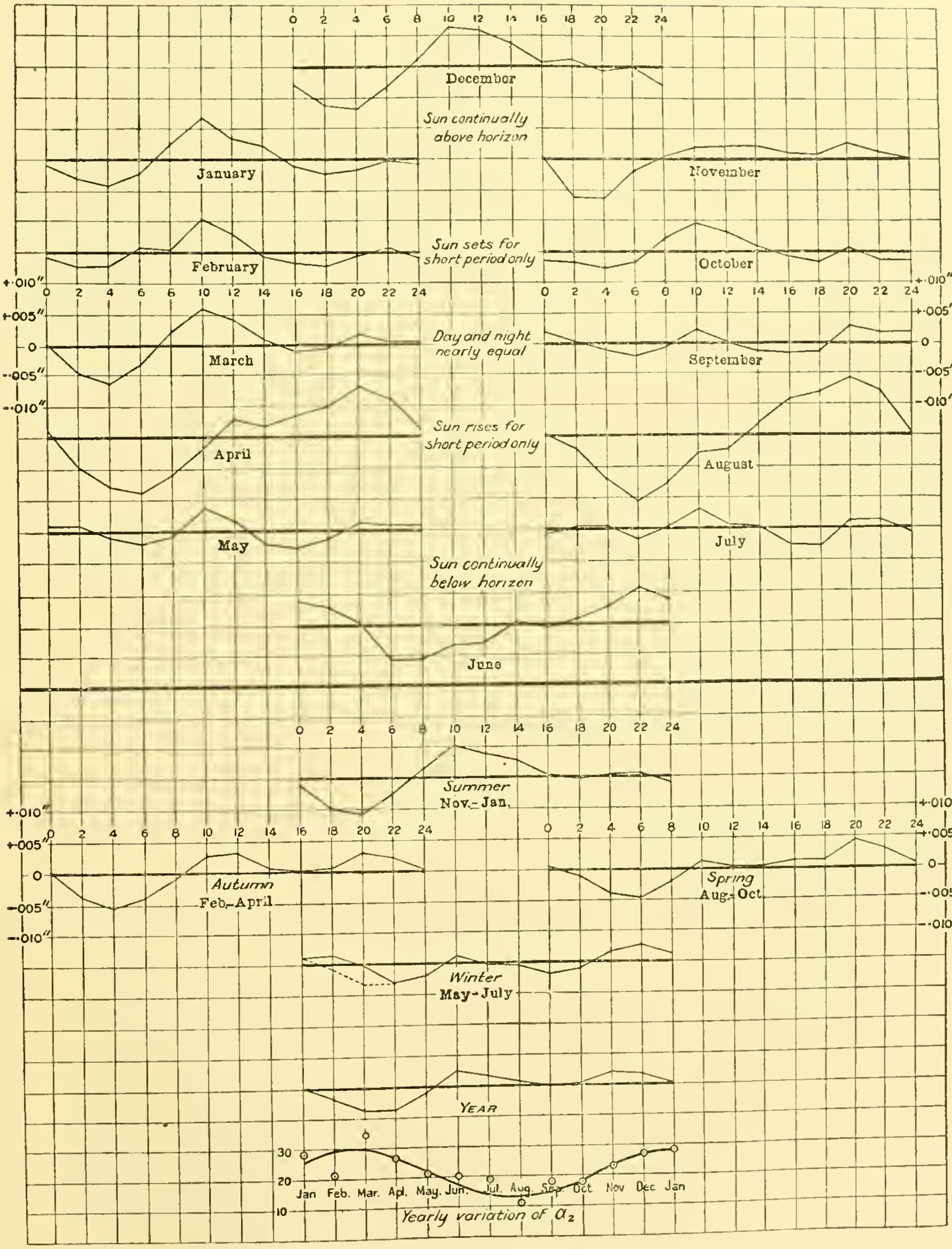

FIG 59. Daily variation of pressure. McMurdo Sound, 4 years.

In order to bring out the dependence of the daily variation of the barometer on the times of rising and setting of the sun, the curves have been plotted in pairs on figure 59 so that months having similar solar conditions are brought into juxtaposition.

In every month throughout the year there is more or less marked evidence of two maxima and two minima. On the mean of the year (bottom but one curve) there is a minimum near 4 hours and a maximum at 10 hours, these will be referred to as the morning minimum and maximum. The second minimum occurs at 16 hours and the second maximum at 20 hours, these will be called the evening minimum and maximum.

During the months November, December and January the sun was above the horizon the whole time. It will be noticed that the curves for January and December are very similar, but that the curve for November is somewhat different. This difference is due to 1911 and 1912, for in 1902 and 1903 the November curve was almost exactly the same type as that for January and December. It is very probable that with a sufficient number of years of observations the variation for November would prove to be similar to that of January and December. The combined curve for these three months, shown as the summer curve in the lower half of the figure, is probably typical of the period during which the sun is above the horizon the whole time. In this curve the morning minimum and maximum are highly developed while the evening minimum and maximum are almost absent.

During February and October the sun only sets for a short period during a few of the days, and these two months have remarkably similar daily pressure variations which are not very different from those of March and September, when the days and nights are of approximately equal lengths. All the four curves, except for September, show the double daily variation in which the morning maximum is larger than the evening one.

The sun rises only for a short time on some of the days in April and August, and is below the horizon on the remaining days. These two months have almost identical variations, which are different from those of the months on either side. In both months the morning minimum and the evening maximum are abnormally developed, so that, except for a slight irregularity at midday, the curves are simple with a minimum at 6 hours and a maximum at 20 hours, the amplitude being abnormally large. It is difficult to see any reason why the appearance of the sun for a short time at midday should produce this effect on the pressure variation.

The sun is entirely below the horizon during May, June and July. It is therefore surprising to find that while the curves for May and July are similar, the curve for June is different from them.

The following points appear of importance in this survey:—

(*a*) The great similarity of the curves placed together in pairs in figure 59 shows that the daily barometer variation depends largely on the relative length of day and night.

(*b*) During the months that the sun is more above the horizon than below, October to February, the morning maximum is more developed than the evening one—the chief feature of all the curves (the November curve qualified as stated above) being the pronounced maximum at 10 hours.

(*c*) Three of the five months during which the sun is more below than above the horizon, April, June and August, show an almost total absence of the morning maximum; but, on the other hand, the intermediate months, May and July, have the morning maximum well developed and larger than the evening one.

It is difficult to combine (*b*) and (*c*) into a single statement giving the dependence of the type of variation on the position of the sun. If it were not for May and July, it would appear that the morning maximum was developed with a high sun and absent when the sun was low, or entirely below the horizon; but as the morning maximum is better developed than the evening one during May and July, this generalisation does not hold.

Fourier Coefficients.

The Fourier coefficients have been obtained as follows. The coefficients have been calculated from the actual departures from the mean for

(*a*) each month and season in 1911 and 1912 separately, using 24-hourly values ;
(*b*) each month and season in 1911 and 1912 combined, using 24-hourly values ;
(*c*) each month and season in 1902 and 1903 combined, using 12-hourly values.

In order to combine the two periods 1902-03 and 1911-12, one of which has 24-hourly values and the other only 12, two methods were adopted. First, the actual departures for every two hours were combined from the four years' observations giving twelve values in the day (those plotted in figure 59) which were then analysed in the usual way ; and secondly, the coefficients obtained by (*b*) and (*c*) were combined algebraically. The latter method is preferable, as it uses all the observations made, while the former discards all alternate hours in the 1911 and 1912 period. As a matter of fact the results of the two methods varied very little, but the double calculation was a useful check. The results for the four years combined, published and discussed here, are those obtained by the second method.

The series used is the ordinary one :

$$dB = a_1 \sin (A_1 + x) + a_2 \sin (A_2 + 2x) + a_3 \sin (A_3 + 3x).$$

TABLE 100.

Fourier coefficients of the daily variation of the barometer at McMurdo Sound based on the periods February 1902 to January 1904 and February 1911 to December 1912.

	a_1	A_1	a_2	A_2	a_3	A_3
January	·0032″	278°	·0028″	140°	·0006″	69°
February	·0017″	291°	·0021″	150°	·0005″	282°
March	·0029″	248°	·0034″	149°	·0007″	49°
April	·0071″	179°	·0026″	143°	·0007″	260°
May	·0005″	50°	·0021″	129°	·0011″	324°
June	·0046″	124°	·0020″	71°	·0002″	269°
July	·0006″	342°	·0019″	141°	·0008″	286°
August	·0086″	170°	·0011″	142°	·0006″	338°
September	·0010″	106°	·0018″	146°	·0004″	326°
October	·0024″	272°	·0018″	149°	·0003″	348°
November	·0032″	220°	0023″	162°	0009″	160°
December	·0030″	232°	0027″	146°	·0003″	359°
Summer { November December January }	·0035″	248°	·0025″	148°	·0003″	110°
Autumn { February March April }	·0029″	208°	·0027″	147°	·0005″	298°
Winter { May June July }	·0014″	113°	·0017″	116°	·0007″	304°
Spring { August September October }	·0029″	179°	·0015″	146°	·0004″	336°
Year	·0020″	204°	·0020″	141°	·0003″	320°

Twentyfour-hourly period.

This term reflects the characteristics which we have already noticed from our survey of the actual curves. The months with the largest whole day amplitudes are April and August. The strange difference between June and the months on either side of it is also shown by the large amplitude of June and the small amplitudes of May and July. It will also be noticed that the amplitudes and phases for the whole day period of months forming pairs in figure 59 are very similar.

Naturally the phases depend largely on whether the morning or evening maximum is the most developed. Thus the phase for the months having the morning maximum highly developed—October to February—have phases varying about 250°, while the phase for those with the evening maximum developed—April, June and August—is nearer 150°.

For the year the amplitude of the whole day wave is only ·002″ and the phase 204°, which brings the maximum of this wave at 16 hours 24 minutes, and the minimum at 4 hours 24 minutes.

Twelve-hourly period.

From the point of view of the physics of the atmosphere this is by far the most important term of the harmonic series.

Examining first the amplitude this shows a marked yearly variation with a maximum in March and a minimum in August. The values of a_2 are plotted as the bottom curve of figure 59 and it will be seen that they lie very nearly on a sine curve having its maximum in February and its minimum in August, the variations in a_2 therefore do not coincide with the seasons, the maximum occurring two months after midsummer and the minimum two months after midwinter.

The phase of the half daily period is remarkable. During nine out of the twelve months the phase lies between 140° and 150°, *i.e.*, during these months the time of the maxima and minima does not vary by twenty minutes.* Of the three remaining months, May, June and November, the latter really departs from the above rule by accident due to a very abnormal November in 1912. The three years 1902, 1903 and 1911 combined give a phase for November of 148° and therefore we are justified in saying that only two of the months, May and June, have phases varying appreciably from the other months. Looking at the seasons this result comes out even more forcibly, for the phase in the summer, autumn and spring only varies by 1 degree from 147°, *i.e.*, the phase in these seasons does not vary by more than two minutes from the mean. On the other hand the phase for the winter months is only 116°, *i.e.*, it varies from the mean phase in the other seasons by a whole hour.

That this is not an accidental result is seen from the following statement of the phase in the individual winter months.

TABLE 101.

Values of A_2.

	May.	June.	July.	Season.
1902–03	131°	61°	164	133°
1911–12	106°	74	118	93°
4 years	129	71°	141	116°

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* A variation in A_2 of 30° is equivalent to a variation of one hour in the time of the maxima and minima.

With the exception of July 1902-03 each of these sub-divisions shows the reduced phase, the greatest reduction taking place in June—the midwinter month.

If we now examine the curve for the winter in figure 59, we see that it varies from the curves for the other series in one important particular. The fall from the evening maximum to the morning minimum is irregular. After commencing to fall from 22 hours to 24 hours the fall is arrested and it rises slightly from 0 to 2 hours and then falls to a minimum at 6 hours. On the analogy of the other curves the fall should have been something like that shown by the dotted line in the figure. The whole effect has the appearance as if an increase of pressure had been imposed on the normal daily variation between midnight and 6 A.M.

If we examine the curves for May, June and July, this same abnormality is clearly visible on each. It is also shown on the curves for each of these months in each of the separate periods 1902–03 and 1911–12. There can be no doubt that this abnormal rise of pressure between midnight and 6 A.M. is a real effect during the winter months. If we eliminate the effect to some extent by correcting the curve as shown by the dotted line in figure 59 the value of A_2 for the winter season becomes 136°, instead of 116°, *i.e.*, the phase has become much more nearly equal to the phase in other months.

It appears reasonable to conclude that the half daily period has the same phase 146° throughout the year, but in the winter, the abnormal rise in pressure between 0 hours and 6 A.M. alters the apparent phase by nearly 30°.

This abnormal rise in the pressure is exceedingly interesting. As stated above, an examination of the curves of the individual months leaves little doubt of the reality of the phenomenon. In our discussion of the daily variation of the temperature a similar abnormality of the temperature at 4 A.M. was noted. It is impossible not to connect the two phenomena. It was shown that the temperature effect was visible in the records of Snow Hill and the Gauss Station. The pressure effect is shown in the Snow Hill records, but not in those for the Gauss Station.

No simple explanation of either of these two effects is obvious, and they are worthy of a much fuller investigation than it has been possible to give them here.

Cause of the twelve-hourly barometer oscillation.—In low latitudes the twelve-hourly barometer oscillation is very strongly marked and at all places within 50° latitude of the equator the maxima and minima occur at every place at approximately the same local time. The conclusion that this oscillation is due to a wave travelling around the world parallel to the equator is therefore irresistible.

In 1882 Lord Kelvin * suggested that this wave was due to a natural oscillation of the atmosphere. Since then a great deal of research has been undertaken to calculate the amplitude and phase of this oscillation by applying mechanical laws to the known constants of the atmosphere. Theory shows that such a wave should have a constant phase at all places on the same latitude when local time is used and that the amplitude should be largest at the equator and zero at the poles.

When the results of meteorological observations made in north polar regions came to be examined it was found that there the oscillation conformed with neither of these conditions. In the first place the amplitude of the oscillation was found to be much larger than it ought to have been according to the theory and that the phase was nothing like constant in local time.

When discussing the results of the Lady Franklin Bay Expedition, 1881–83, Greely † remarked that in high latitudes the phase of the half daily barometer oscillation was much more nearly constant if Greenwich time was used than if local time was used. In other

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* Thomson. P. R. S. Edin. 11, 1882.

† See Hann. Met. Zeit. 7, p. 8, 1890.

words instead of the maxima and minima occurring at each place at the same local time, they occurred at each place at the same absolute time. Thus in north polar regions the barometer oscillation appears not to be due to a wave travelling round the circles of latitude, but the whole cap of air appears to oscillate outwards from the Pole.

In table 102 are collected together all the observations of the twelve-hourly barometer oscillations available from high southern latitudes.*

TABLE 102.

Constants of the half daily barometer oscillation in the Antarctic.

Station.	Latitude.	Longitude.	a_2	A_2	TIME OF MAXIMA.		No. of years
			mm.		Local time.	Greenwich time.	
					hrs.	hrs.	
McMurdo Sound .	77 38′ S.	166 30′ E.	·051	141°	10·0	10·9	4
Belgica . . .	70 35′ S.	86° 24′ W.	·038	307°	4·7	10·4	1
Gauss . . .	66 02′ S.	89 38′ E.	·043	221	7·7	1·7	1
Snow Hill . .	64 22′ S.	57 00′ W.	·026	194	8·5	12·3	1½
Laurie Island † .	60 44′ S.	44 39′ W.	·084	183°	8·9	11·9	7
South Georgia . .	60 30′ S	36° 00′ W.	·214	161	9·7	12·1	1

It is clear from this table that the times of maxima are not constant in either local time or Greenwich time. The oscillations cannot therefore be due to waves travelling round the earth parallel to the circles of latitude, which would cause the maxima to occur at the same local time at all stations; nor to the oscillation of the polar cap which would cause the maxima to occur everywhere at the same Greenwich time. It is possible, however, that the oscillation observed at each station might be due to the sum of two oscillations, one round the earth and the other to and from the Pole, for the sum of two oscillations of the same period is another oscillation of the same period but with a different amplitude and phase.

In order to investigate this solution I was led to review the work done previously on the twelve-hourly barometer oscillation in the northern hemisphere and the results of this work have been published in the Quarterly Journal of the Royal Meteorological Society, Volume XLIV, No. 185, p. 1, 1918.

It was shown in that work that the observed amplitude and phase of the twelve-hourly barometer oscillation in all parts of the world can be explained by the existence of two atmospheric vibrations—

(*a*) a vibration around the world parallel to the circles of latitude, and

(*b*) a vibration between the equator and the poles parallel to the circles of longitude. The former is expressed by

$$b \sin (2x+\mathrm{B})$$

and the latter by

$$c \sin (2x+\mathrm{C}-2\lambda)$$

in which x is the local time, B and C are constants, and b and c are functions of the latitude.

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* Observations are also available for Port Charcot, but they are so widely different from those obtained at the neighbouring station of Snow Hill that they are clearly wrong; they have therefore not been used in this discussion.

† Anales de la Oficina Meteorologica Argentina. In this publication the values given on page 63 for the Fourier coefficients are wrong, the values used here have been calculated from the data given in table 44, page 62.

It was also found from observations made in the northern hemisphere that

$$b = 0{\cdot}937 \cos^3 \phi$$
$$B = 154^\circ$$
$$c = {\cdot}137 \left(\sin^2 \phi - \tfrac{1}{3}\right)$$
$$C = 105^\circ$$

Thus the amplitude and phase at any place can be obtained at once from the relationship

$$a_2 \sin (2x + A_2) = 0{\cdot}937 \cos^3 \phi \sin (2x + 154^\circ) + 0{\cdot}137 \left(\sin^2 \phi - \tfrac{1}{3}\right) \sin (2x + 105^\circ - 2\lambda)$$

in which ϕ and λ are the latitude and longitude of the place.

The necessary calculations have been made for the Antarctic stations and are included in table 103.

Table 103.

Twelve-hourly barometer oscillation.

1	2	3	4	5	6	7	8	9	10	11	12
Station.	Latitude.	Longitude.	b	c	A_2		A_2—Ac		a_2		$\frac{a_2 \text{ calculated}}{a_2 \text{ observed}}$
					Calculated.	Observed.	Angle.	Time.	Calculated.	Observed.	
	°	°	mm.	mm.	°	°	°	hrs.	mm.	mm.	
McMurdo Sound .	77·6 S.	166·5 E.	·009	·085	134	141	+ 7	+ ·2	·094	·051	1·9
Belgica . .	70·6 S.	86·4 W.	·034	·076	251	307	+56	+1·9	·064	·038	1·7
Gauss Station .	66·0 S.	89·6 E.	·063	·069	226	221	− 5	− ·2	·054	·043	1·3
Snow Hill .	64·4 S.	57·0 W.	·076	·066	184	194	+10	+ ·3	·120	·036	3·4
Laurie Island .	60·7 S.	44·6 W.	·110	·058	168	183	+15	+ ·5	·158	·084	1·9
South Georgia .	60·5 S.	36·0 W.	·184	·045	158	161	+ 3	+ ·1	·226	·214	1·1

In column 4 the calculated values of b, *i.e.*, the amplitude of the wave travelling round the earth, are given, and in column 5 the calculated values of the amplitude of the oscillation outwards from the Pole. In column 6 are given the values of A_2 as calculated for each station, while in column 7 are given the observed values. Columns 8 and 9 contain the difference between the observed and calculated values of A_2 in angles and time respectively. From column 9 we see that at five of the six stations the observed time is within half an hour of the calculated time.

The calculated and observed values of a_2 in columns 10 and 11 do not agree quite so well. The ratio of the calculated to the observed values of a_2 are given in column 12, from which it will be seen that all the calculated values are too large. It is, however, significant that the two stations which have the best agreement between the calculated and observed values of A_2, South Georgia and Gauss Station, have also the best agreement between the calculated and observed values of a_2, and roughly speaking the agreement of a_2 at the other stations is in the same order as the agreement of A_2.

Considering the smallness of the amplitudes—all but one less than one-tenth of a millimetre—and the fact that they are obtained in a region where the non-periodic barometer changes are so large, it is amazing that such short periods of observations give values which agree so well with the calculated values. Thus the theory of the two natural oscillations of the atmosphere receives very great support from the Antarctic observations.

NON-PERIODIC PRESSURE CHANGES.

It is much more difficult to discuss the non-periodic pressure changes than the periodic, for there is no simple way in which they may be reduced to numerical values.

Numerous methods have been suggested and used for comparing the pressure changes at different stations and each has its peculiar advantages and disadvantages.* The data for McMurdo Sound have been analysed by several of these methods and the results included in table 104.

TABLE 104.

Non-periodic pressure changes. (Inches.)

1	2	3	4	5	6	7	8	9	10
Month	Absolute value in 4 years.			Average difference between highest and lowest in each month of four years.	Mean difference between daily maximum and minimum.	Highest monthly mean in four years.	Lowest monthly mean in four years.	Difference between highest and lowest monthly mean.	Average departure of monthly mean from smoothed normal.
	Highest.	Lowest.	Difference.						
January . .	29·81	28·74	1·07	·798	·121	29·461	29·131	·330	·116
February .	29·94	28·83	1·11	·691	·147	29·527	29·298	·229	·071
March . .	29·88	28·53	1·35	·853	·158	29·488	29·171	·317	·126
April . .	30·15	28·72	1·43	1·074	·171	29·478	29·317	·161	·055
May . .	30·25	28·26	1·99	1·351	·211	29·344	29·151	·193	·068
June . .	30·11	27·82	2·29	1·440	·249	29·562	28·882	·680	·221
July . .	30·13	28·24	1·89	1·438	·237	29·398	28·998	·400	·123
August . .	30·10	28·36	1·74	1·265	·229	29·215	28·911	·304	·090
September .	30·02	28·29	1·73	1·436	·203	29·442	29·059	·383	·153
October . .	29·76	28·20	1·56	1·180	·163	29·690	28·825	·265	·158
November .	30·18	28·58	1·60	1·093	·141	29·634	28·947	·687	·264
December .	30·04	28·49	1·55	·900	·127	29·752	29·188	·564	·194
Mean . .				1·127	·180				·137

The highest pressure recorded in the four years was 30·25 inches (May 19, 1902) and the lowest 27·82 inches (June 23, 1912), the difference being 2·43 inches. The month with the greatest absolute range of pressure is June with 2·12 inches and the month with the least range January with 1·13 inches.

Köppen † considers that the best measure of the non-periodic pressure changes is obtained from the mean difference between the highest and lowest values in each month. He has

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* Köppen. Met. Zeit. **29**, p. 97, 1912.

† Köppen. Met. Zeit. **29**, p. 501, 1912.

published two maps giving the mean values for three summer (December, January and February) and for three winter (June, July and August) months. For comparison with those maps the McMurdo Sound values have been given in column 5. The mean value for the three summer months, ·796″=20·2 m.m., and for the three winter months, 1·381″=35·1 m.m., agree fairly well with the lines entered on the maps, although the winter value is somewhat high and the summer somewhat low.

The value of the mean difference between the daily maximum and minimum pressure has been calculated for many stations. The monthly values for McMurdo Sound are given in column 6. It will be seen that this measure of the non-periodic changes gives the most regular yearly variation, the least value being in January and the highest in June with a steady change from month to month in between. The mean value for the year is ·180 inch. From the following table it will be seen that the value in McMurdo Sound is smaller than at stations further to the north. The highest value in the world is found at South Georgia, from which the values decrease as one proceeds to the south. In other words, the non-periodic pressure changes are greatest over the Southern Ocean and diminish as the Antarctic Continent is approached.

TABLE 105.

Average difference between the daily maximum and minimum of pressure.

Place.	Latitude.	Mean daily max.-min.
		Inches.
South Georgia	55° S.	·311
Cape Horn	56° S.	·268
Snow Hill	64° S.	·244
Gauss Station	66° S.	·248
McMurdo Sound	78° S.	·180

The non-periodic changes so far considered give no indication of the steadiness of the pressure over long intervals of time. Thus a place might have a large difference between the maximum and minimum pressure in a given month, yet the mean pressure of that month might be the same year after year. For the weather of a given place the rapid barometer changes which give a large difference in maximum and minimum pressure, whether the month or the day is taken as the unit of time, are of the chief importance, but for the influence which the pressure of that place exerts on the pressure of the rest of the world, the steadiness of the pressure over a longer interval of time is of more importance. The variations of the mean monthly pressure from year to year are therefore of great interest and columns 7 to 10 of table 104 give the data for McMurdo Sound.

The mean variation of monthly pressure from normal ·137″=3·48 m.m. is very large, being almost equal to that found in the neighbourhood of Iceland, 3·56 m.m., where the pressure is more unsteady than in any other part of the known world. As the mean value for each month is derived from only four years' observations, the yearly variation is not very reliable, but it is significant that the three summer months November to January show larger variation than the three winter months May to July, being ·191″ and ·137″ respectively. It would therefore appear that although the barometer is more steady during short periods in the summer than in the winter as shown by columns 5 and 6, yet the variations of the mean monthly pressure from year to year are larger in the summer than in the winter.

An interesting point with regard to the variation of the monthly pressure is the great change in mean pressure from October to November 1911. The monthly means at Cape Evans were October 28·825 and November 29·630 inches. Thus the mean pressure rose ·805 inch during two consecutive months. The rise was even greater at Framheim, ·88 inch, and only slightly less at Cape Adare, ·80 inch.

I called attention to this rapid change in pressure in a letter to 'Nature' (April 13, 1913) and asked for information of other similar large changes. Mr. R. C. Mossman in reply very kindly sent me the following list of large changes at Stykkisholm in Iceland.

TABLE 106.

Large changes of pressure in Iceland.

Year.	Month.	Pressure.	Month.	Pressure.	Change.
		Inches.		Inches.	Inches.
1850	February	29·191	March	30·000	+ ·809
1853	January	29·105	February	30·083	+ ·978
1867	February	29·397	March	30·198	+ ·801
1883	February	29·083	March	30·135	+1·052
1890	January	28·937	February	29·752	+ ·815
1900	January	29·225	February	30·051	+ ·826

Thus similar large pressure changes occur in Iceland about once in ten years. The region near Iceland has the largest pressure changes of any part of the globe previously known, it now appears that changes of the same magnitude occur in the Ross Sea area, thus these two regions may be linked as the northern and southern regions of unstable barometer. It may be mentioned that the changes in these two areas are apparently unrelated, the correlation between the monthly pressure in the two regions during the four years for which observations are available in McMurdo Sound being +·02 with a probable error of ·10.

Pressure Waves.

When the height of the barometer at any place is plotted against time, the resultant curve has the form of waves. The curves for two neighbouring places are similar, but the maxima and minima generally occur at one station before the other. At first sight therefore it appears as though true pressure waves travel through the atmosphere affecting first one and then the other station. We know however that in medium latitudes the pressure changes are not handed from station to station by true air waves, but by a succession of more or less circular areas of high and low pressure, which, while travelling, retain their characteristic pressure distribution.

The pressure curves for the Antarctic show well developed waves and later we shall have to consider whether they are due to the passage of cyclones and anticyclones, but we shall first make a study of their frequency, length and depth at several Antarctic stations without considering their physical meaning.

If one examines the plates given in Volume II, on which the pressures of five stations are plotted, it will be seen that at each station there are large pressure waves with well marked maxima and minima, but on these there are numerous smaller undulations like ripples on a large sea wave. It is obvious that we cannot include the latter in a discussion of the former, we must therefore define the magnitude of the pressure changes which we will consider in our discussion. There have been several similar investigations made previously and it has been the nearly general practice to consider only pressure changes which exceed 5 m.m. The data we are considering are given in inches and as ·2 inch is very nearly 5 m.m., this has been taken as the corresponding limit in the following investigation.

The tabulated data have been examined and all successive maxima and minima which differ by more than ·2 inch have been noted. The results for the four years' observations in McMurdo Sound are contained in the following table.

Table 107.

Pressure waves in McMurdo Sound (four years).

	Mean length of wave.	Mean variation in wave.	Mean hourly change.
	Hours.	Inches.	Inches.
1902	151	·555	·0073
1903	146	·567	·0078
1911	160	·592	·0074
1912	155	·576	·0074
Four years	152	·572	·0075
Autumn {Feb. Mar. April} four years .	152	·482	·0064
Winter {May June July} ,, ,, .	131	·675	·0104
Spring {Aug. Sept. Oct.} ,, ,, .	145	·614	·0085
Summer {Nov. Dec. Jan.} ,, ,, .	194	·469	·0049

The mean yearly values based on four years' observations are: average depth of wave from crest to trough =·572 inches, average length =152 hours which gives an average change per hour of ·0075 inches. There is an appreciable yearly variation in the character of the waves, the amplitude being greatest and the period shortest in the winter, thus giving in that season rapid barometer changes. The summer is the period with the greatest steadiness of the barometer.

Pressure waves at Cape Adare and Framheim.—At Cape Adare and Framheim we have not a complete year's observations, but fortunately we are able to obtain approximate values by a comparison with the McMurdo Sound results. Table 108 contains the data at Cape Adare, Cape Evans and Framheim for the period April to December, 1911.

TABLE 108.

Pressure waves in the Ross Sea area. April to December 1911.

Station.	Latitude.	Mean length of wave.	Mean variation in wave.	Mean hourly change.
	°S.	Hours.	Inches.	Inches.
Cape Adare . . .	71	111	·580	·0110
Cape Evans . .	78	142	·605	·0082
Framheim . . .	79	152	·660	·0087

During the missing months the waves are longer and not so deep as during the rest of the year, therefore the above results are different from what would have been obtained if a complete year's observations were available. It is reasonable to suppose that by applying the factor necessary to convert the above values for Cape Evans to the mean value found for four years to the data for the other stations an approximate yearly mean will be found. Thus in McMurdo Sound the mean length of the waves for the four years was 152 hours, while during the period considered in table 108 it was only 142, hence the factor necessary to convert the mean for the broken period into the four-yearly mean is $\frac{152}{142}$. Similarly the factor for converting the amplitude of the waves is $\frac{572}{605}$. Applying the same factors to the observations at Cape Adare and Framheim we obtain the mean yearly values given in table 109.

Comparison of pressure waves at Antarctic stations.—In table 109 the mean length of the waves, the mean pressure variation in the waves and the mean hourly change are given for eight stations in or near the Antarctic.

TABLE 109.

Pressure waves greater than ·2 inch (5 m.m.) in the Antarctic (yearly average).

Station.	Latitude.	Mean length of wave.	Mean variation in wave.	Mean hourly change.
	°S.	Hours.	Inches.	Inches.
Kerguelen	49	69	·634	·0184
South Orkneys	61	91	·642	·0141
Snow Hill	64	107	·567	·0106
Gauss Station	66	122	·642	·0106
Belgica	70	124	·630	·0094
Cape Adare	71	119	·549	·0092
McMurdo Sound	78	152	·572	·0075
Framheim	79	163	·624	·0077

In this table the stations are arranged in order of latitude and three important results are at once apparent:—

(*a*) The length of the waves increases steadily as the latitude increases.

(*b*) The amplitude of the waves is nearly constant.

(c) The result of (a) and (b) is a steady decrease in the rapidity with which the pressure changes take place as high latitudes are attained.

The physical explanation of these relationships will be taken up in chapter VI.

Pressure surges.

The pressure changes which we have studied so far have been actual changes of the barometer from hour to hour and we have shown that the pressure variations are equivalent to waves having a period of five or six days. When the pressure changes are plotted on a much smaller time scale, it is seen that the waves we have so far considered are themselves superposed on waves of a much longer period. These long waves, which I propose to call pressure surges, are clearly seen on plate I. On this plate the mean daily pressures at Cape Adare, Cape Evans and Framheim have been plotted and the points connected by a thin line. The irregularities on the thin line are due to the pressure waves which we have already considered, and as we wish to study the longer pressure waves we must eliminate them. This is most conveniently done by arithmetically smoothing the curves. If instead of plotting against each day the mean pressure of the day we plot the mean pressure of ten days about it, small irregularities are smoothed out while the resulting curve follows closely the larger waves. Thus the thick curves on plate I have been obtained by plotting the mean pressure from the 1st to the 10th of any month against the 5th, the mean pressure for the 2nd to the 11th against the 6th and so on. The waves on this thick line are the surges which we are now about to investigate.

Comparison of pressure surges in different parts of the world.

A glance at the plate shows that the same surges affect all three stations in the Ross Sea area and later on we shall discuss the relative intensity of the surges at each station. Before we do this, however, it seems desirable to enquire whether surges of this nature are confined to the Antarctic or are recognisable in other parts of the world.

As far as I know a similar investigation has not been made previously, therefore it is necessary to calculate the ten-day means for the stations at which the comparison is to be made. If the pressure surges are to be compared at several stations this necessitates calculating 365 ten-day means for each year for each station. If data for several years at several stations are to be used, and several years' observations would be necessary for a complete discussion, this will entail a very large amount of computing. I was unable to undertake such a large amount of work, but the important rôle these pressure surges play in the pressure changes in the Antarctic constrained me to do the necessary calculations to compare the surges for one year at least at several typical stations in all parts of the world.

The year chosen for this comparison was from March 1902 to February 1903, as during the greater part of this period there were observations in the Antarctic at the following widely separated stations: Hut Point, Snow Hill, the Gauss Station and on Kerguelen. The stations outside the Antarctic chosen to compare with these were the following:—

Wellington and Adelaide, which with Kerguelen are typical of the Southern Ocean.
Seychelles as typical of a tropical ocean.
Bombay as typical of a monsoon climate.
Greenwich as typical of the northern temperate zone.
Irkoutski as typical of the centre of a large continent.
Stykkisholm as typical of the great Icelandic centre of action.
Vardo as typical of north polar regions, data from stations further north during the period considered not being available.

In order to show the curves for twelve months and for all twelve stations on plate II the scale used for plate I has had to be diminished, but the relationship between pressure and time remains the same on the two plates.

One or two striking results are at once apparent. The curves for Seychelles and Bombay show that for all practical purposes surges do not exist in the tropics. Also the curves for Adelaide, Greenwich and Irkoutski are obviously intermediate between those for the tropics and the circumpolar stations.

Further discussion of the curves can only be undertaken by means of a similar statistical investigation to the one used for the pressure waves. As with the waves, surges of greater variation than ·2″ (5 m.m.) will be selected and their average length and depth calculated. It is quite obvious that one year is far too short a period to give satisfactory results, but a general oversight can be obtained from the following table:—

TABLE 110.

Pressure surges. March 1902–*February* 1903.

Station.	Latitude.	Longitude.	Mean length of surge.	Mean variation in surge.	Mean daily change.
			Days.	Inches.	Inch/day.
Hut Point	77° 51′ S.	166° 45′ E.	35	·628	·036
(McMurdo Sound, 4 years) .			(46)	(·536)	(·024)
Gauss	66° 2′ S.	89° 38′ E	42	·419	·021
Snow Hill. . . .	64 22′ S.	57° 0′ W.	39	·554	·028
Kerguelen. . . .	49 25′ S.	69° 53′ E.	37	·559	·030
Wellington . . .	41° 16′ S.	174° 27′ E.	25	·453	·036
Adelaide	34° 56′ S.	138° 35′ E.	73	·365	·010
Seychelles. . . .	4° 45′ S.	55° 45′ E.	No surges.		
Bombay	18° 54′ N.	72° 49′ E.	No surges.		
Greenwich. . . .	51° 28′ N.	0° 0′	37	·507	·027
Irkoutski	52° 16′ N.	104° 19′ E.	51	·413	·016
Stykkisholm . . .	65° 5′ N.	22° 46′ W.	28	·625	·045
Vardo	70° 22′ N.	31° 8′ E.	34	·535	·031

The surges at Hut Point were very much larger during the year chosen for the above table than in any other of the four years for which we have observations. I have therefore added in brackets the mean values obtained from all the observations and these should be taken into account in comparing the stations.

It is not easy to draw any very simple relationship from the numbers, and it is questionable whether one year's observations are sufficient to give satisfactory results, but the following inferences may probably be correct.

In the southern hemisphere the surges are deeper in high than in low latitudes, also the length of the surges is, on the whole, greater near the continents than over the open ocean.

Similarly in the northern hemisphere Stykkisholm and Vardo have deeper surges than Greenwich and Irkoutski because they are further north. Also the surges are shortest at Stykkisholm which is oceanic and longest at Irkoutski which is continental.

The above indicates a relationship which has been found for pressure instability by other methods; namely, that unperiodic pressure changes increase from the equator to the poles and from the centres of the continents to the centres of the ocean.

Annual variation of the surges.—A glance at the curves on plate II shows that in the northern hemisphere the surges are the most developed in the winter months, the curves being much more disturbed during November, December and January, than during June, July and August. Such a seasonal variation is not clear in the Antarctic. Judging from the curves for the Gauss Station and Snow Hill one would be inclined to put the period of least disturbance from June to September, *i.e.*, in the winter, but the Hut Point curve has the least variation in December, January and February. One year's observations, however, are not sufficient to settle this point with such irregular curves.

Taking the four years' observations for McMurdo Sound and dividing the year into two halves at the equinoxes, we have the following result:—

TABLE 111.

Pressure surges in McMurdo Sound (four years' data).

	Mean length of surge.	Mean variation in surge.	Mean daily change.
	Days.	Inches.	Inch/day
Year	46	·536	·024
Summer half-year	39	·473	·024
Winter half-year	52	·590	·023

This indicates that the surges are longer and deeper in the winter than in the summer, the resulting mean daily change being approximately the same.

We have now to consider three most interesting and important questions with regard to surges:—

(*a*) The extent of country affected by any one surge.

(*b*) The relative intensity of a given surge at the different places affected by it.

(*c*) The origin and cause of the surges.

We shall first consider the surges in the Ross Sea area, where the stations are so near together that the surges are easily recognisable at each station, and then turn to the more widely separated stations in other parts of the Antarctic.

Comparison of surges in the Ross Sea area.—A glance at plate I will show at once that the same surges affect all the stations in the Ross Sea area, but this is not sufficient; we must find some method of comparing the intensity at the three stations. This can only be done by recognising the maximum and minimum of the same surge at each station, and then calculating the average value of a number of surges thus recognized. One gets into difficulties, however, as soon as one attempts to do this, because there is a certain amount of latitude in deciding whether or not a maximum on a curve should be considered as being the maximum of a surge. Thus there is a well-marked maximum on the Framheim curve on April 15, which, if we had this curve alone, we might take as the maximum of a surge; but it will be noticed that while it is just recognisable on the Cape Adare curve, it would not be chosen as the maximum of a surge from that curve.

Such difficulties would not be of so much importance if there were more surges available for measurement; but with only about ten surges recognisable on each curve the result is easily affected by personal bias. It was decided therefore to employ a method as free as possible from personal choice. The procedure followed was the following. For the statistical discussion of these surges (see page 190) it was necessary to consider only surges which were greater than ·2″, and each maximum and minimum which fulfilled this condition was tabulated. The maxima and minima thus chosen were marked on the curves of plate I with the signs + and – respectively.

When this had been done, only those maxima and minima were considered which were marked on all three curves, or those which were marked on two curves and the corresponding maximum or minimum was clearly visible on the remaining curve although not marked.

Six complete surges were thus marked, commencing with the minimum on April 8 and ending with the minimum near December 11. Each of the maxima and minima are tabulated in the following table:—

TABLE 112.

Pressure surges in Ross Sea area.

MINIMA.						MAXIMA.					
CAPE ADARE.		CAPE EVANS.		FRAMHEIM.		CAPE ADARE.		CAPE EVANS.		FRAMHEIM.	
Date.	Pressure.	Date	Pressure.	Date.	Pressure.	Date.	Pressure.	Date.	Pressure.	Date.	Pressure.
	20″ +		20″ +		20″ +		20″ +		20″ +		20″ +
April 8 .	9·019	April 8 .	9·095	April 8 .	8·885	April 29.	9·450	May 8.	9·584	May 8 .	9·369
May 14 .	8·875	May 28.	8·926	June 6 .	8·656	June 16.	9·207	June 17.	9·244	June 16.	9·038
July 10 .	8·773	July 17 .	8·830	July 15 .	8·598	July 28 .	9·335	July 28 .	9·350	July 28 .	9 102
Sept. 15.	8·845	Sept. 14.	9·106	Sept. 14.	8·781	Sept. 21.	9·109	Sept. 20.	9·298	Sept. 20.	9·019
Oct. 5 .	8·606	Oct. 5 .	8·606	Oct. 2 .	8·381	Oct. 15 .	8·886	Oct. 15 .	9·030	Oct. 14 .	8·817
Oct. 22 .	8·692	Oct. 22 .	8·747	Oct. 24 .	8·478	Nov. 25.	9·800	Nov. 26.	9·850	Nov. 27.	9·765
Dec. 16 .	9·644	Dec. 11 .	9·622	Dec. 10 .	9·484						
Mean .	8·922		8·990		8·766		9·298		9·390		9·185

This table shows that the mean amplitudes of the waves which can be recognised on all three curves are:—

	Mean amplitude max.-min.
Cape Adare	·376″
Cape Evans	·400″
Framheim	·419″

The surges are too few for any stress to be placed on the actual values; but considering that the result has been obtained by a method which reduces personal bias to a minimum.

it seems justifiable to conclude that the Antarctic pressure surges increase from Cape Adare to Cape Evans to Framheim.

Surges affecting the whole Antarctic.—Our next step is to examine the data for 1902, to find whether the same surges affect the pressure at stations so widely separated as McMurdo Sound, Snow Hill and the Gauss Winter Station.

For this purpose plate III has been prepared showing the simultaneous observations at the three stations in the same way as was used for plate I.

Surges are very clearly marked on all three curves, and it is now necessary to see if the same surges can be recognised on each. To facilitate the examination, the maxima and minima of the large waves, *i.e.*, of waves of a greater amplitude than ·2″, have been marked as before on each trace, and we shall confine our attention chiefly to the surges thus marked. We will follow the surges on the Hut Point curve and examine the other curves to see if they show corresponding surges.

The first surge at Hut Point extends from the middle of March to the middle of April, with the minimum near the beginning of April. There can be no doubt that this surge is present on the other curves, both of which have marked maxima and minima at approximately the same times.

The next surge on the Hut Point curve extends from the middle of April to the middle of May. This surge is shown quite clearly on the Gauss curve, although the maximum in the middle of May is not marked with a + on account of the subsequent fall being less than ·2″. It appears at first sight that this surge is not shown on the Snow Hill curve, on which there is a pronounced minimum at the time the maximum occurred at the other two stations. But the disagreement is only apparent. A local deep depression apparently affected Snow Hill just as the pressure commenced to rise due to the surge. There can be little doubt that if the local depression had not existed the pressure changes would have been as shown by the dotted line.

The third surge at Hut Point, from the middle of May to the 9th of June, was less intense and it failed to reduce the pressure at the other two stations by ·2″, hence the minimum is marked only on the Hut Point curve; but the curves clearly show that the pressure was affected at all three stations to a greater or less extent, and the pressure rose at all three stations to a maximum before the middle of June.

The next maximum is shown on all three curves in the second half of July. The dip between the two maxima obviously corresponds on all three curves, but the lowest points are somewhat widely separated. This is obviously due to the wave being so shallow that the lowest point is decided rather by the local inequalities superposed on the surge than by the minimum of the surge itself.

From this point until the minimum near the middle of October there are the same number of marked maxima and minima on each curve, and there can be little doubt that each sign refers to the same surge at each station.

The rapid rise and fall on the Hut Point curve during the second half of October has its counterpart on the Gauss curve where, however, it was so reduced in intensity that it was less than ·2″ and therefore not marked. It is questionable whether the maximum and minimum at the beginning of November on the Snow Hill curve are due to the same surge.

The curves come into line again at the maximum in the second half of November, and run parallel to one another until the observations cease.

There can be little doubt from this inspection that the same surges are recognisable on all three curves. But it might reasonably be asked why the maxima and minima of the surges do not coincide more closely on the three curves, for there are often long periods between the appearance of the same maxima and minima at different stations. The reason is not difficult to find. The true surge probably does affect each station at approximately the same time, but superposed upon the long period surges are numerous pressure changes due to local conditions. We attempt to eliminate these by taking the ten-day means, but it is impossible to eliminate them entirely. When a surge is only feebly marked at a station, the position of the actual maximum or minimum is often determined accidentally by the minor irregularities due to these local pressure changes. We have already seen how the local disturbance at Snow Hill about the middle of March completely masked the maximum of a small surge which should have then occurred, and attention has been drawn to the position of the minimum at the end of June, which was decided at Snow Hill and the Gauss Station by small local inequalities of pressure on the very flat trough of a surge. It is probable that in every case where the surges appear out of phase at the different stations the cause is to be found in the local pressure variations.

We will now compare the intensity of the surges at the three stations.

For this purpose only the maxima and minima which are marked on all three curves by a corresponding sign are entered in the following table. This procedure automatically excludes all the doubtful surges.

TABLE 113.

Pressure surges (10 *days' mean*) 1902.

MINIMA.						MAXIMA.					
HUT POINT.		SNOW HILL.		GAUSS.		HUT POINT.		SNOW HILL.		GAUSS.	
Date.	Pressure.	Date.	Pressure.	Date.	Pressure.	Date.	Pressure.	Date.	Pressure.	Date.	Pressure.
	20″+		20″+		20″+		20″+		20″+		20″+
						Mar. 17.	9·607	Mar. 23.	9·294	Mar. 16.	9·415
April 4 .	9·112	April 3 .	8·817	Mar. 31.	9·102						
						April 19.	9·759	April 16.	9·502	April 20.	9·343
May 7 .	9·021	May 15 .	8·789	May 9 .	8·843						
						June 9 .	9·645	June 15.	9·575	June 15.	9·398
July 1 .	8·717	July 10 .	9·003	June 25.	9·095						
						July 16 .	9·667	July 26 .	9·446	July 24 .	9·333
Aug 17 .	8·691	Aug. 6 .	8·799	Aug. 6 .	8·557						
						Sept. 5 .	9·477	Aug. 29.	9·208	Aug. 25.	9·059
Sept. 13.	8·943	Sept. 19.	8·849	Sept. 19.	8·697						
						Sept. 23.	9·548	Sept. 28.	9·327	Sept. 29.	8·991
Oct. 13 .	8·726	Oct. 16 .	8·746	Oct. 10 .	8·775						
						Nov. 21.	9·826	Nov. 21.	9·635	Nov. 16.	9·614
Dec. 21 .	9·313	Dec. 19 .	8·999	Dec. 18 .	9·049						
						Jan. 1 .	9·536	Jan. 5 .	9·521	Dec. 31 .	9·467
Mean .	8·932		8·857		8·874		9·633		9·438		9·328

From this table we see that the mean amplitudes of the waves at the three stations are :—

	Mean amplitude max.-min.
Hut Point	·701″
Snow Hill	·581″
Gauss	·454″

We have now shown that it is possible to recognise the same surges not only in the Ross Sea area but also at places in the Antarctic so far apart as Hut Point, Snow Hill and the Gauss Station. Unfortunately we have had to use different periods of observation for the two groups of stations, and therefore the values of the amplitudes in the two groups are not directly comparable. This is clearly seen when we compare the mean value for Cape Evans in 1912, ·400″, with the mean value for Hut Point in 1902, ·701″, although the two stations are so near together that they may be considered as one for our present purpose. There can be little doubt that the surges were abnormally developed in 1902, and it is largely due to this circumstance that we have been able to recognise the individual surges with such confidence at such widely separated stations.

For McMurdo Sound (Cape Evans and Hut Point) we have four years' observations, and we have used all these to find the mean amplitude of the surges given in table 111, which was ·536″. It is very likely that the relative amplitude at the stations remains fairly constant from year to year, hence by multiplying each of our two sets of observations by the factor necessary to bring the respective values for the McMurdo Sound stations to their average value, we obtain reduced amplitudes for all the stations which are comparable. Thus the amplitudes in 1912 require to be multiplied by $\frac{\cdot536}{\cdot400}$ and those in 1902 by $\frac{\cdot536}{\cdot701}$. When this has been done, we have the following relative amplitudes.

TABLE 114.

Pressure surges, amplitudes reduced to common period.

	Latitude.	Amplitude.
Framheim	79° S.	·558
McMurdo Sound	78°	·536
Cape Adare	71°	·500
Gauss	66°	·347
Snow Hill	64°	·444

It will be noticed that with the exception of Snow Hill and the Gauss Station, the amplitude decreases with the distance from the Pole. It will be found, however, that they are only roughly proportional to the latitude. When the numbers are plotted on a globe, it is found that they are more nearly symmetrical around a position about 10° away from the Pole. By a series of trials and errors it was found that the amplitudes were nearly inversely proportional to the distances of the stations from the position 80° S. 120° W. If one takes as the ampitude of the surges at this position ·677″ and calculates the amplitude of the other stations on the assumption that the amplitude decreases from this position lineally at the rate of ·162″ per thousand miles, the amplitude at the stations are shown in the following table :—

TABLE 115.

Actual and computed amplitude of surges.

	Distance from 80° S., 120° W.	Amplitude calculated.	Actual amplitude.
	Geographical miles.	Inch.	Inch.
80° S., 120° W.	0	·677	—
Framheim	631	·57	·56
McMurdo Sound	856	·53	·54
Cape Adare	1144	·49	·50
Snow Hill	1477	·43	·44
Gauss	1921	·35	·35

The agreement between the actual and calculated values on these simple assumptions gives us good reason to believe that the amplitudes of the surges do decrease from 80° S., 120° W. in all directions, and therefore one is tempted to assign this position as the centre of the pressure system in which the surges take place.

The most simple physical explanation of the relationships we have found is the following: We shall show in a future chapter that in the upper atmosphere over the whole Antarctic the pressure is cyclonic with the centre of lowest pressure over the low-lying region which we have reason to believe exists in the Pacific quadrant of the Antarctic, and in which the position mentioned above is situated (see figure 80). The surges are probably due to increases and decreases in the intensity of this cyclone, and if so, then the surges should be strongest near the centre of the cyclone and decrease roughly in proportion to the distance from the centre.

PRESSURE CORRELATION.

Having shown that the pressure over the Antarctic increases and decreases as a whole, we now proceed to investigate in how far the pressure outside the Antarctic is affected. For this purpose the method used above of identifying simultaneous surges is no further available, for the individual surges die out rapidly over the Southern Ocean. This can be seen by comparing the surges at Kerguelen and Wellington shown on plate II with those for the Gauss Station and Hut Point respectively. No relationship between the curves for these pairs of stations similar to that existing between the curves for the Antarctic stations can be recognised. We must now compare the mean pressure for longer periods if we are to obtain useful results. We shall therefore take as our datum the mean pressure for a month and compare the mean monthly pressures at stations within and surrounding the Antarctic.

Before doing so, we must see whether the intimate relationship between the pressure at different stations in the Antarctic found by means of the surges is still recognisable when we use monthly means.

Correlation of mean monthly pressure within the Antarctic.

For this purpose data are available from McMurdo Sound, Snow Hill, the Gauss Station, Kerguelen, South Orkneys and South Georgia. Unfortunately, however, the observations were not simultaneous but overlap for different periods. The discussion of the records will therefore require different methods for the various stations, and we will commence with the records for Hut Point, Snow Hill, the Gauss Station and Kerguelen during the period March 1902 to February 1903. The following table gives the variation of pressure for each month from the mean of the twelve months.

Table 116.

Pressure departure from mean of twelve months.

Month.	Hut Point.	Gauss Station.	Snow Hill.	Kerguelen.
1902.	Inch.	Inch.	Inch.	Inch.
March	+·049	+·025	+·064	−·001
April	+·128	+·083	+·123	+·223
May	−·006	−·014	−·063	−·118
June	−·035	+·104	+·159	+·003
July	+·048	+·076	+·038	−·002
August	−·439	−·300	−·213	−·020
September	+·034	−·278	−·063	+·029
October	−·272	−·190	−·193	−·078
November	+·284	+·235	+·103	−·017
December	+·155	+·174	+·077	−·086
1903.				
January	+·111	+·069	+·099	−·020
February	−·052	+·018	−·131	(+·089) *

These values have been plotted in the four upper curves of figure 60. The similarity between the curves for the stations on or near the Antarctic Continent is striking; while the relationship is apparent, but much less marked, on the Kerguelen curve.

The intimate relationship is shown by the following correlation coefficients, the probable error of each being shown by the figures in brackets.

Table 117.

Pressure Correlations.

	Gauss.	Snow Hill.	Kerguelen.
Hut Point	+·79 (·08)	+·80 (·07)	+·22 (·19)
Gauss	....	+·80 (·07)	+·08 (·20)
Snow Hill	....	....	+·37 (·17)

* For 13 days only, therefore neglected in the discussion.

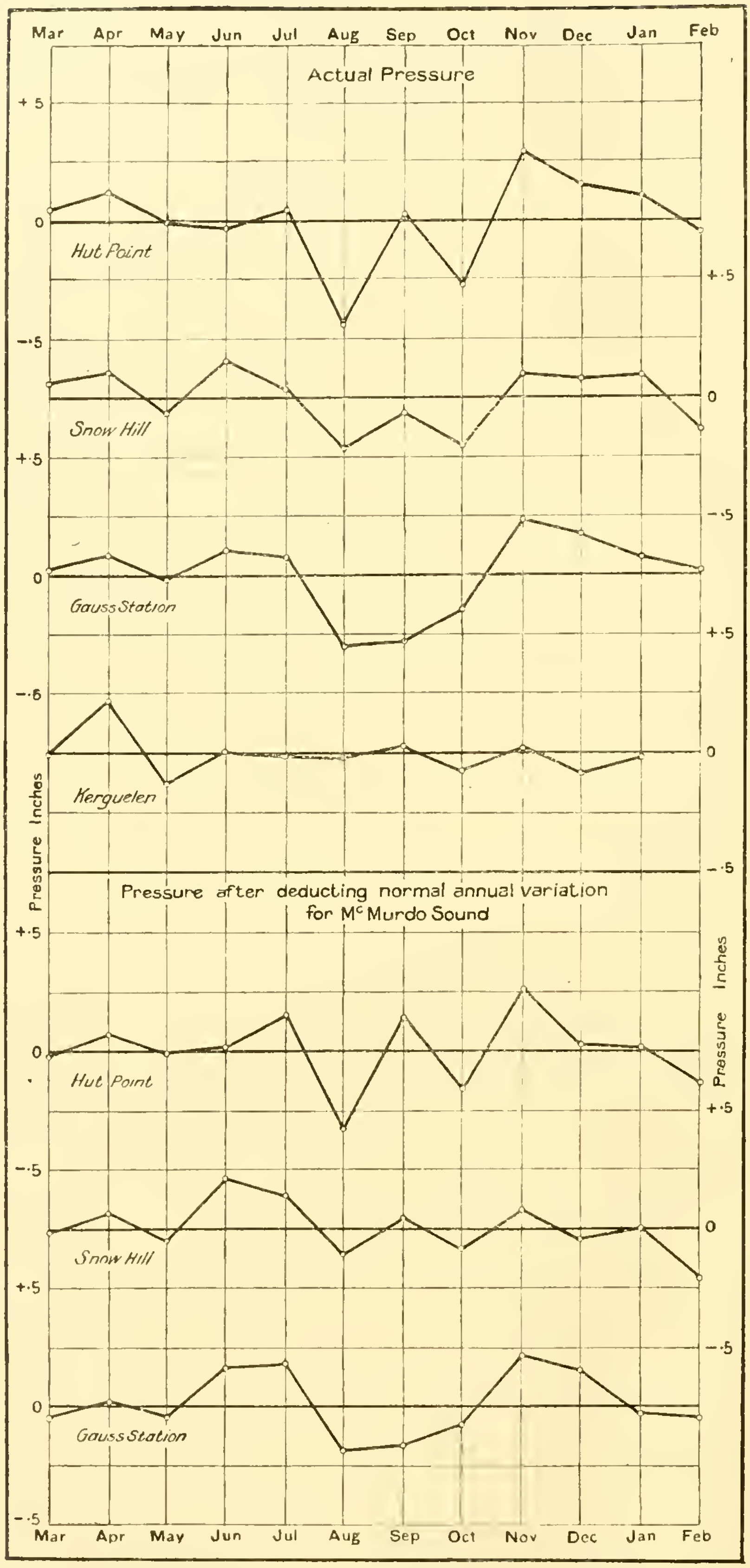

FIG 69. Comparison of monthly pressure in Antarctic.

The correlation coefficients between the stations Hut Point, Gauss Station and Snow Hill are very large, all being ·8 with a probable error of less than ·1.

A certain amount of the high correlation is probably due to the yearly variation of the pressure being similar at all the stations. Unfortunately, however, we do not know the normal yearly variation at the Gauss Station and Snow Hill. We know it approximately for McMurdo Sound from the smoothed values of the four years' observations. If the correlation coefficients are increased by the yearly variation, it can only be because the variation is similar at all three stations; we are therefore justified in deducting the yearly variation of McMurdo Sound in order to free the relationship from some at least of the dependency on the yearly variation.

In the following table the first column contains the normal yearly variation in McMurdo Sound and the three following columns the monthly departures, given in table 116, corrected for this yearly variation.

TABLE 118.

Pressure variation corrected for yearly variations.

Month.	Normal variation at McMurdo Sound.	Hut Point.	Gauss Station.	Snow Hill.
1902.	Inch.	Inch.	Inch.	Inch.
March	+·079	−·030	−·054	−·015
April	+·062	+·066	+·021	+·061
May	+·002	−·008	−·061	−·065
June	−·057	+·022	+·161	+·216
July	−·102	+·150	+·178	+·140
August	−·104	−·335	−·196	−·109
September	−·108	+·142	−·170	+·045
October	−·109	−·163	−·081	−·084
November	+·027	+·257	+·208	+·076
December	+·127	+·028	+·147	−·050
1903.				
January	+·100	+·011	−·031	−·001
February	+·079	−·131	−·061	−·201

These corrected monthly departures have been plotted in the three lower curves of figure 60. It will be seen that even now the curves are very similar especially if the changes from month to month are considered, for eight of the eleven changes take place in the same direction on all three curves.

The correlation coefficients have been reduced somewhat by applying the correction, showing that the annual variation is similar at all three stations.*

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* It should be remarked that if the stations had not the same or similar variation, the effect of deducting the same variation from all three curves would have been to increase their correlation coefficients. This is important in relationship to deciding the type of yearly variation at the Gauss Station and Snow Hill for which we have not sufficient observations to form a true yearly variation.

TABLE 119.

Correlation coefficients after deducting the McMurdo Sound yearly variation.

	Correlation coefficient.	Probable error.
Hut Point–Gauss Station	+·65	·11
Hut Point–Snow Hill	+·66	·11
Gauss Station–Snow Hill	+·60	·12

These numbers leave little doubt that for the year under investigation the monthly pressures at these stations varied in a similar way. In spite of the large margin between the correlation coefficients and the probable error, it would not be right to conclude that all years would show the same high relationship. The observations at Snow Hill continued for another eight months after the twelve considered above, and during this period the relationship was much less marked. It must however be pointed out that the added months were remarkably free from large changes and therefore were unsuited for bringing out the relationship.

Returning now to the data for Kerguelen we see from the curves in figure 60 that the Kerguelen pressure is not very intimately related with the Antarctic pressure, although the changes are somewhat similar. It is remarkable that the Kerguelen curve is more like the curves for Hut Point and Snow Hill than for the Gauss Station, although the latter is so much nearer. This is shown in the correlation coefficients which are +·37, +·22 and +·08 respectively. We cannot correct the Kerguelen observations for yearly variation, for there is much evidence to show that the yearly variation over the Southern Ocean is quite different from the variation over or near the continent. Considering the small amount of data and the small correlation coefficients, it would be unwise to draw any other conclusion than that the correlation between Kerguelen and the Antarctic is small but positive.

Observations in the Antarctic region simultaneously with some of those in McMurdo Sound are also available for the South Orkneys and South Georgia. At the South Orkneys simultaneous observations were made from April 1903 to January 1904 and during the whole of 1911 and 1912, *i.e.*, 34 months in all. At South Georgia only 17 months' simultaneous observations are available from June 1911 to December 1912.

These observations have been treated as follows: The ten years' observations which are available for the South Orkneys * were used for obtaining the annual variation. The variation so obtained was deducted from each of the 34 months mentioned above for which simultaneous observations are available in McMurdo Sound. The annual variation was also deducted from the corresponding monthly pressure in McMurdo Sound. We have then two sets of monthly values which have been freed from periodic change; the variations of the individual months from the mean of the set were then calculated, and the correlation coefficients determined.

Exactly the same procedure was employed with the data for South Georgia. In this case nearly nine years' observations are available for determining the yearly variation.

It will be noticed that this procedure is practically the same as that used for the Antarctic stations except that in the latter case only the mean of 12 months was used as the basis from which to calculate the departures. The aim in both cases is to find departures from the mean pressure of the whole period for which simultaneous observations are available.

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* My best thanks are due to Mr. R. C. Mossman for providing me with these and other valuable data.

The 34 months' observations at South Orkneys give a correlation coefficient with McMurdo Sound of +·15 with a probable error of ·12 and the 19 months' at South Georgia a correlation coefficient of +·24 with a probable error of ·15. These coefficients are small but positive.

Collecting our results we have the following correlation coefficients between the monthly pressure in McMurdo Sound and at five other Antarctic stations.

TABLE 120.

Monthly pressure correlation coefficients.

	Correlation coefficient.	Probable error.	Months of observations.
McMurdo Sound and Gauss Station .	+·65	·11	12
,, ,, ,, Snow Hill . .	+·66	·11	12
,, ,, ,, Snow Hill . .	+·38	·13	20
,, ,, ,, South Orkneys .	+·15	·12	34
,, ,, ,, South Georgia .	+·24	·15	19
,, ,, ,, Kerguelen . .	+	..	11

The absolute value of these coefficients means very little and they are not directly comparable with one another as they refer to different periods, but the fact that they are all positive and are generally considerably larger than the probable error leaves little doubt that the pressure tends to increase and decrease simultaneously over the whole Antarctic Continent and the adjacent seas.

Pressure correlation between the Antarctic and surrounding places.

We can now turn our attention to the correlation between the Antarctic pressure and the pressure at other places, mainly in the southern hemisphere, outside the Antarctic.

If it had been possible, it would have been best to correlate the mean pressure of several places in the Antarctic with the pressure at other stations. But for this purpose we have only the twelve months' simultaneous data from Hut Point, the Gauss Station and Snow Hill which would be insufficient for a reliable correlation. Above every thing a large number of observations are necessary in order to get a reliable correlation coefficient. It was therefore decided to take the four years' data which are available for McMurdo Sound, namely, February 1902 to January 1904 and January 1911 to December 1912, as being representative of the whole Antarctic.

In the Antarctic the changes of pressure from month to month are large in comparison with the yearly variation, but this is not the case with stations nearer the tropics. It is therefore necessary in order to get a true correlation between variations of pressure to eliminate the yearly variation from all the data used.

It is also important to realise that the departures to be compared must be departures from the same datum at all stations. Thus it is not desirable to compare the departures for the Antarctic which are the departures from the mean of a certain four years with the departures for another station from a mean derived from a long series of observations.

In view of these considerations it was decided to follow a common procedure with the data from all stations having the necessary records. The mean monthly pressures for the forty-eight months for which data are available at McMurdo Sound were tabulated for each station. The means of the four values for each month were taken and then smoothed by the formulæ $\frac{a+2b+c}{4}$. From these smoothed monthly means the departures for each of the forty-eight months were calculated.

The departures for the twenty-four months February 1902 to January 1904 were then correlated with the corresponding values for McMurdo Sound, then the departures for the twenty-four months January 1911 to December 1912, and finally the two series were combined to give the correlation for forty-eight months.

The following table contains the results, and the correlation factors for the whole period are shown on the map, figure 61:—

TABLE 121.

Correlation coefficients of monthly pressure departures from normal between McMurdo Sound and 31 stations mainly in the southern hemisphere.

	Station.	Latitude.			Longitude.			1902 and 1903.	1911 and 1912.	4 years.	Change 1902-03 to 1911-12.
		°	′		°	′					
Australasia.	Thursday Island .	10	34	S.	142	12	E.	+·20	+·11	+·15	−·09
	Port Darwin . .	12	28	,,	130	51	,,	+·41	·00	+·22	−·41
	Daly Waters . .	16	16	,,	133	23	,,	+·35	+·02	+·19	−·33
	Townsville . .	19	14	,,	146	31	,,	+·45	+·13	+·29	−·33
	Onslow . . .	21	43	,,	114	57	,,	+·39	−·14	+·13	−·53
	Charlotte Waters .	25	56	,,	134	55	,,	+·25	−·29	−·03	−·54
	Brisbane . .	27	28	,,	153	2	,,	+·23	−·23	·00	−·47
	Perth . . .	31	57	,,	115	51	,,	+·22	−·24	−·03	−·46
	Eucla . . .	31	45	,,	128	58	,,	+·03	−·38	−·18	−·41
	Adelaide . .	34	56	,,	138	35	,,	−·04	−·39	−·22	−·34
	Sydney . . .	33	52	,,	151	12	,,	−·11	−·40	−·26	−·30
	Melbourne . .	37	50	,,	145	0	,,	−·13	−·42	−·28	−·28
	Hobart . . .	42	53	,,	147	20	,,	−·37	−·52	−·45	−·15
	Wellington . .	41	16	,,	174	27	,,	−·45	−·51	−·49	−·06
South America.	Manaos . .	3	0	S.	60	0	W.	−·35	−·19	−·28	+·15
	Recife . . .	8	4	,,	34	53	,,	−·01	−·13	−·07	−·12
	Cuyaba . .	15	36	,,	56	0	,,	−·33	−·16	−·23	+·17
	Curytiba . .	25	20	,,	49	30	,,	−·21	−·19	−·20	+·02
	Santiago . .	33	27	,,	70	41	,,	−·43	−·37	−·40	+·06
	Cordoba . .	31	25	,,	64	12	,,	−·66	−·40	−·54	+·26
	Buenos Aires . .	34	36	,,	58	22	,,	−·70	−·30	−·48	+·40
	Punta Arenas .	53	10	,,	70	54	,,	−·17	−·17	−·17	·00
Indian Ocean.	Bombay . .	18	54	N.	72	49	E.	−·06	+·02	−·03	+·08
	Madras . . .	13	4	,,	80	14	,,	+·09	+·02	+·05	−·07
	Batavia . .	6	11	S.	106	50	,,	+·24	−·28	+·04	−·52
	Seychelles . .	4	45	,,	55	45	,,	−·29	−·34	−·32	−·05
	Mauritius . .	20	6	,,	57	31	,,	−·37	−·27	−·31	+·10

TABLE 121—*concld.*

	Station.	Latitude.	Longitude.	1902 and 1903.	1911 and 1912.	4 years.	Change 1902-03 to 1911-12.
South Africa.	Cape Town	33° 56′ S.	18° 29′ E.	−·11	−·23	−·17	−·12
South Pacific.	Makatea	15 47 S.	150 34 W.	..	−·26	..	..
	Samoa	13 48 ,,	171 46 ,,	−·26	−·63	−·44	−·37
	Fiji	18 6 ,,	178 30 E.	+·21	−·16	+·01	−·38

Probable errors.

Correlation coefficient.	0	·1	·2	·3	·4	·5	6
24 observations	·14	·14	·13	·13	·12	·10	·09
48 observations	·10	·10	·09	·09	·08	·07	06

The map shows that encircling the Antarctic is a region in which all the correlation coefficients are negative. It is impossible to define this region with exactitude, but as the maximum coefficients both in the American and Australian regions lie near to latitude 40° S., this latitude is probably near the axis of the zone, and the region is probably fairly accurately shown by the shaded area on the map. This region includes the large areas of high pressure which encircle the globe near to latitude 30° S., and the most simple explanation of the pressure relationship under discussion is that there is a sea-saw of pressure between the Antarctic and the belt of anticyclones over the Southern Ocean.

The largest correlation coefficients are −·49 at Wellington, New Zealand, and −·54 at Cordoba in South America. The probable error of these coefficients is as low as ·07, therefore the coefficients are seven times greater than their probable errors. Thus there can be little doubt that a month of high pressure over the Antarctic is accompanied by a month of low pressure in latitude 40° S. and adjacent regions.

It is interesting to notice that there is considerable difference between the correlation coefficients in the two periods 1902-03 and 1911-12, but the differences are not random. In the last column of table 121 the change in the coefficients from 1902-03 to 1911-12 has been entered for each station. Over the whole of the Australian region including Samoa and Fiji the change was negative, while with two exceptions the change was positive over the American region. It would appear as if the interchange in the air during 1902-03 was mainly between the Antarctic and the American region, while in 1911-12 the change was between the Antarctic and the Australian region.

The positive coefficients in the north of Australia are interesting. One would have expected the coefficients to have become less and less negative as one receded from the region of maximum correlation. That they should become positive and decidedly positive, is very remarkable. It will also be noticed that in 1902-03 the region of positive correlation included the whole of the Australian Continent except the extreme south-east corner, and in the

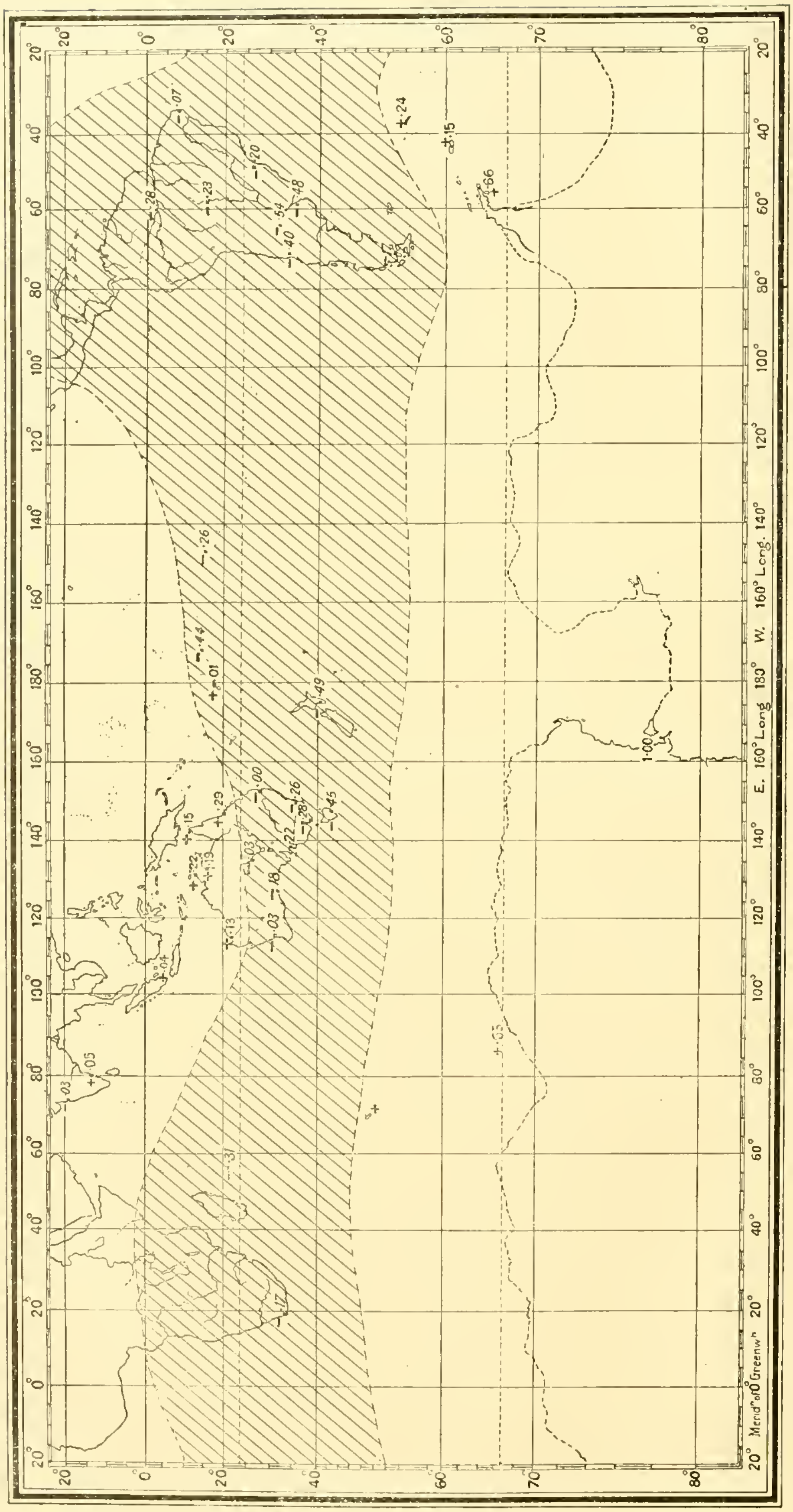

FIG. 61. Map of pressure correlation coefficients.

extreme north the positive correlation was very great, being +·45 with a probable error of ·10 at Tounsville.

It appears as though to the north of Australia there is a large region in which the pressure changes take place in the same sense as the changes over the Antarctic and between the two a region in which the changes are reversed. The boundary of the two regions appears to vary and to swing backwards and forwards. In 1902-03 the northern area of positive correlation was highly developed, and it encroached on the area of negative correlation, the boundary between the two areas being near Sydney. In 1911-12 the area of negative correlation was more strongly developed, and the boundary of negative correlation was pushed north to near the northern coast of Australia; Thursday Island, Daly Waters and Townsville, being the only Australian stations then having positive correlation coefficients.

This connexion between the pressure departures over the Antarctic and surrounding regions is most interesting and still more important. It appears that the Antarctic is one of the great 'centres of action' of the world and further investigation is imperatively demanded. A great deal more work has been done than is given in the above summary, amongst other results it has been found that all the correlations are more pronounced when the means of three months' pressure are compared instead of the means of single months. The investigation is not yet finished, and as its value will be greatly increased if it is founded on more observations than those at present available, it has been decided to await the publication of the pressure data obtained on Shackleton's two expeditions to McMurdo Sound, which will increase the data available from four years to seven, before closing the investigation.

CHAPTER VI.

PRESSURE, WINDS AND WEATHER.

Until quite recently it was the general idea that from the belt of high pressure in about latitude 35° S. pressure decreased right up to the South Pole. In other words that the pressure distribution around the South Pole was very similar to that found in an ordinary cyclone, the isobars running parallel to the circles of latitude and the centre of the system at the Pole itself. According to this idea the 'roaring forties' were simply the high westerly winds which under such a distribution of pressure would circulate completely round the globe.

Sailors however realised that the winds in the region of the 'roaring forties' were anything but consistently from the west. For example the *Terra Nova* on her journey from Cape Town to Australia in 39° S. and 35° E. encountered a strong east-south-easterly gale with wind forces up to 9 on the Beaufort Scale. In fact over the Southern Ocean the winds back and veer with changes of the barometer exactly as they do in other temperate regions. Further, Antarctic expeditions have shown that the pressure is lowest near to 60° S. latitude, beyond which the barometer rises as far as observations have been made at sea-level towards the Pole, and over the southern half of the ocean there is an easterly wind as strong and persistent as the westerly wind over the northern half.

Thus the Gauss Expedition during her stay of eleven months in 66° S. had easterly winds, often extremely strong, during 73 per cent. of the total time. Naturally when the results of the expeditions which were in the Antarctic during 1902–04 came to be discussed the old conceptions had to be revised. The most important work in this revision was done by Hepworth, Lockyer and Meinardus, all of whom were writing at approximately the same time. The conclusions of all three are practically the same in one important particular, namely, that over the Southern Ocean there is a constant succession of true cyclonic depressions passing from west to east having westerly winds on their northern sides and easterly on their southern sides, giving rise respectively to the 'roaring forties' north of latitude 60° S. and strong easterly winds south of this latitude.

The conclusions of Hepworth and Lockyer are in general agreement, but as Lockyer has carried his investigations further than Hepworth we will consider his work in some detail.*

Lockyer first plots the mean daily barometer at a large number of stations, then assuming that the rises and falls of the resulting curves correspond to the passage of high or low pressure systems—anticyclones and cyclones—he adjusts curves of neighbouring stations until the chief maxima and minima agree as far as possible. If curve A agrees best with curve B when their time scales differ by say three days, then three days is considered to be the average time the pressure systems take to travel from A to B. In this way he obtains the average rate of travel of the pressure systems in each part of the southern hemisphere. The next step is to find the intensity of the pressure changes at each place. This is done by comparing the average difference between the successive maxima and minima on the pressure curves. The method used is somewhat arbitrary but gives a satisfactory qualitative

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* 'Southern Hemisphere Surface Air Circulation,' by J. S. Lockyer. Published by the Solar Physics Committee, 1910.

measure of the pressure changes at each station. Places having the same average pressure amplitudes are connected by a series of lines called by Lockyer 'isanakatabars,' which are found to run approximately parallel to the circles of latitude. The pressure amplitudes increase from near the equator to 60° S. and thence decrease towards the Pole. As we are interested only in the region south of latitude 40° S., we will limit our attention to this region. From 40° S. to 60° S., the pressure amplitudes increase and the average pressures decreases; from 60° S. to the Pole, the pressure amplitudes decrease and pressure increases.

It is then pointed out that this same relationship would hold if a series of cyclones having their centres in latitude 60° S. passed from west to east, for the average pressure would be low and the pressure amplitude high near the track of the centres, *i.e.*, along latitude 60° S. Lockyer gives reasons for believing that to the north of such a belt of cyclones there would be a similar belt of anticyclones, while to the south of it there would be an intense, but comparatively small (in area), anticyclone central about the South Pole.

Figure 62, which is taken from Lockyer's monograph, represents his conclusions. Over the Southern Ocean we see the belt of cyclones, each of which is of such a size that its southern

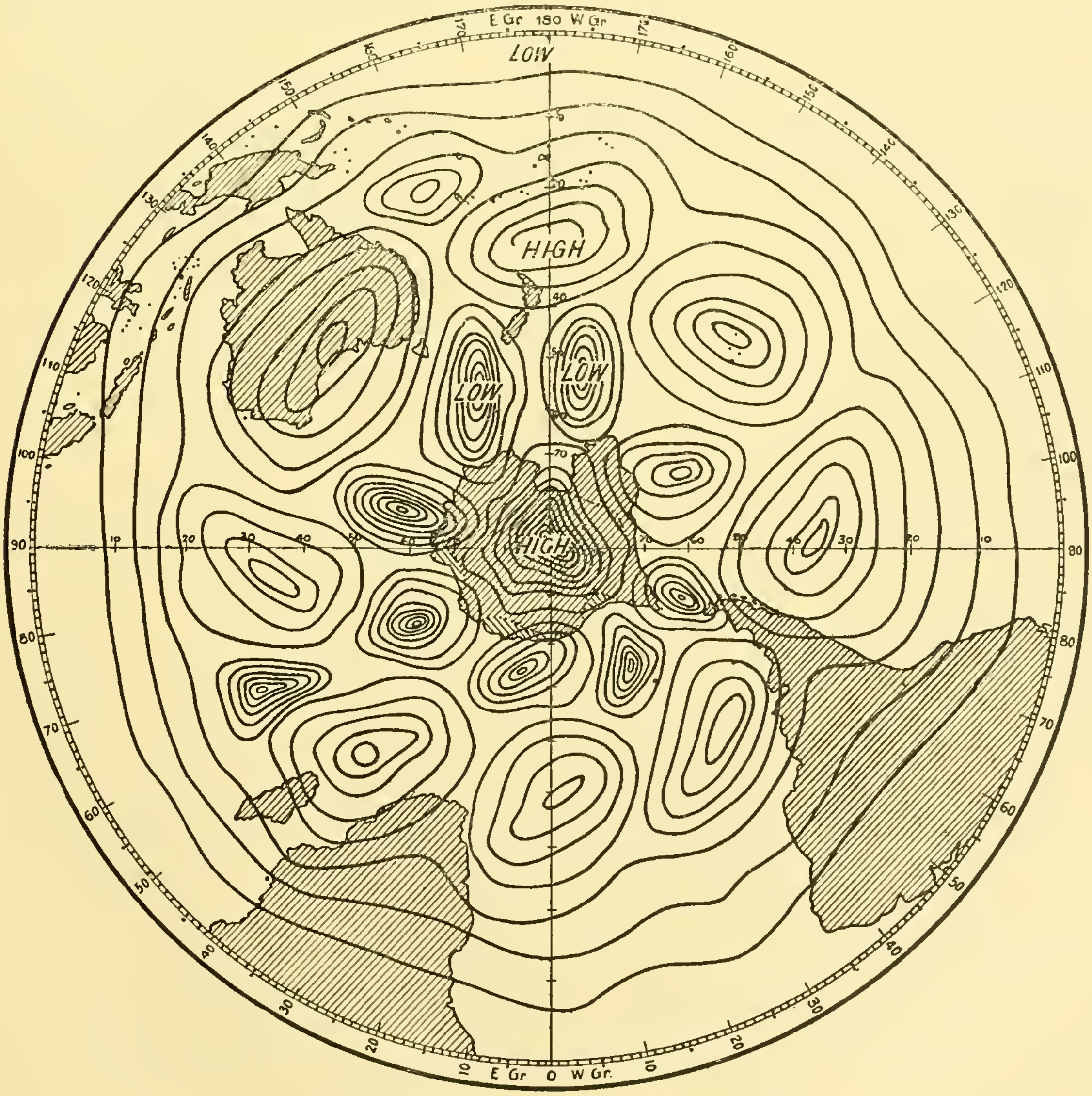

FIG. 62. Lockyer's diagram of pressure distribution.

extremity touches or overlaps the ice barrier and its northern extremity reaches up to, or near to, latitude 40° S., and eight of them encircle the earth. The rate of travel of the cyclones is determined by the method described above to be 9·5° of longitude a day.

This scheme deserves close attention, for it appears to explain satisfactorily many of the characteristics of the weather in the southern hemisphere.

(*a*) It accounts for the 'roaring forties,' for as the depressions move from west to east the regions between 40° S. and 60° S. being to the north of the centres of the cyclones constantly come under the influence of strong westerly winds, which change direction and intensity with variations of the barometer. It does not, however, explain the easterly winds sometimes observed in the region of the 'roaring forties.'

(*b*) It also explains the easterly winds experienced in high southern latitudes, for they are complementary to the westerly winds on the other side of the centres of the depressions.

(*c*) The mean pressure in such a system would agree fairly well with the actual mean pressure observed, for the centres of the cyclones travelling along 60° would give on the average a trough of low pressure in this region.

The scheme, however, has several weak points. In the first place it is not based on synoptic weather charts, no attempt apparently having been made to fit simultaneous observations together and show how they agree with such a system of high and low pressure areas. It must also be remembered that it is based on two assumptions: (*a*) that the pressure variations from day to day—especially in the Antarctic—are produced by travelling cyclones or anticyclones; and (*b*) that the cyclones have their centres all on or near 60° S. latitude. This latter is very important, for the large area of the cyclones is a direct consequence of the assumed positions of the centres of the cyclones. If the centres could be in any latitude, the cyclones would of necessity be smaller and irregular, and the simplicity of the system with many of the consequences drawn from it would be lost. Lockyer's system may then be tested by these two criteria, and we shall have occasion later to apply both tests and to find them both wanting.

Meinardus in his discussion of the results of the Gauss Expedition also considers the general pressure distribution over the Southern Ocean. His main conclusions on the point we are now considering are summed up in the following quotations:—

> 'When one reviews the weather conditions as a whole, which are associated with the storms at the Gauss Station, there can be hardly a doubt that they are governed by cyclonic pressure systems which, except in a few cases, pass from west to east to the north of the winter station. The following may be mentioned in support of this conclusion: the shape of the pressure curve (passage of wave crests and troughs), the change of wind direction during storms from E. by N. or E. towards the direction of the south-east quadrant, the changes of wind strength during storms, as well as the precipitation and cloud conditions, particularly the direction of the cloud motion before and after the storms.'*

So far Meinardus and Lockyer are in agreement, but the former goes on to say:

> 'During storms the winter station comes under the influence of the central area of the cyclones and is not simply passed over by the outer regions. This is clearly shown by the relationship between the strength of the wind and the depth of the

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* Deutsche Sudpolar-Expedition, 1901–03, p. 294.

> depression, by the high and uniform temperature, by the great humidity and by the cloud and precipitation which were greater during storms than at any other time.'*

This last conclusion of Meinardus's does not fit in with Lockyer's scheme at all. A storm, the centre of which passes near to 66° S., is nearly 6° out of the path assigned by Lockyer, in fact the centre is very near where Lockyer places the southern extremities of his cyclones.

We will now pass on to consider the conditions in the Ross Sea area as found by the observations during 1911 and then return with the knowledge gained to reconsider these more general questions. Before doing so, however, it will be interesting to see what we may expect according to the ideas of Hepworth, Lockyer and Meinardus.

Hepworth writes:

> 'It seems probable that areas of low pressure, on their passage eastwards north of Victoria Land, after passing the meridian of Cape Adare, not infrequently take a more southerly path, striking south-eastward and penetrating into or skirting the Ross Sea.'†

Meinardus writes:

> 'In the Ross Sea the development of an independent depression is weaker (than in the Weddel Sea) on account of the extensive high land in the west, the small width of the Sea, and finally the proximity of the Antarctic anticyclone. Depressions which penetrate the Ross Sea come therefore almost entirely from the north and never from the west.'‡

Writing of Cape Adare Lockyer says:

> 'The meteorological conditions noted at this station favour, then, the suggestion that a series of low depressions travel in higher latitudes eastwards, their lowest portions only traversing the Cape Adare quarters.'§

But he also says that the observations made in McMurdo Sound

> 'are in conformity with the assumption that the southern extremities of low pressure areas pass over the stations, and the absence of westerly winds proves that the centres of these systems always lie to the northward of these stations.'||

It is difficult to understand how the lower or southern extremities of the same cyclones can be at Cape Adare and also in McMurdo Sound, considering that the latter station is 400 miles further south than the former. After a description of a typical Antarctic blizzard in McMurdo Sound Lockyer says:

> 'This experience . . . . . . convinces one that the air movement in these storms is only part of a series of very large systems travelling eastward.'¶

A depression with its centre in 60° S., able to produce a blizzard of 40 to 60 miles an hour in 78° S., is of course quite inconceivable. Whatever blizzards may be due to they are certainly not part of the circulation around a cyclone the centre of which is more than a thousand miles away.

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* Deutsche Sudpolar-Expedition, 1901–03, p. 295.

† National Antarctic Expedition, 1901–04. Meteorology, Part 1, p. 429.

‡ Deutsche Sudpolar-Expedition, 1901–03, p. 338.

§ Southern Hemisphere Surface Air Circulation, p. 73.

|| *Ibid*, p. 87.

¶ *Ibid*, p. 88.

Pressure Waves and Pressure Distribution.

From 1st April to the end of December 1911 observations of pressure and wind are available at Framheim, Cape Evans and Cape Adare. These stations are sufficiently near one another to make it possible for us to detect the same series of pressure changes at each station, and we can therefore investigate in what way the pressure variations are handed from station to station and what changes of wind accompany the changes of pressure.

Two methods of investigation have been found to be of great use in the study:

(*a*) A series of sheets was prepared each showing the pressure curves during twelve days for the stations under investigation, the wind directions being shown by arrows attached to the curves.

(*b*) The pressure and wind observations were entered on to maps and an attempt made to draw isobars to fit them.

The curves and maps will be found in Volume II and the reader will find it necessary to have this volume at hand when reading the present section. It will frequently be necessary to compare the various maps with the corresponding barometer curves, the plates have therefore been so bound that each can be unfolded and exposed to view when the book is open at the corresponding map.

At first we shall discuss only the plates showing the pressure curves and it will be found convenient at this point to unfold all the plates so that they can be rapidly turned over in succession.

The plates.—On each plate there are six curves which represent

(1) The barometer and wind at Melbourne in Australia
(2) ,, ,, ,, ,, the Bluff in New Zealand
(3) ,, ,, ,, ,, Cape Adare
(4) ,, ,, ,, ,, Cape Evans
(5) ,, ,, ,, ,, Framheim
(6) The pressure difference between Cape Evans and Framheim, on this curve the winds at Cape Evans have been repeated.

It will be noticed that the first five curves are arranged according to latitude, Melbourne the most northerly being at the top and Framheim the most southerly at the bottom.

The curves are plotted to simultaneous time. The arrows are drawn to fly with the wind and the number of feathers indicates the strength of the wind according to the Beaufort Scale.

The two upper curves will not be considered at present, but we will fix our attention on the curves for the three Antarctic stations—Cape Adare, Cape Evans and Framheim. A cursory glance through the plates will show at once that the pressure changes at these three stations are very similar, a succession of waves of various length and depth affecting all three stations in a very similar way. An excellent example is contained in plate 5. A large wave of pressure having a minimum on May 24th and maximum on the 27th or 28th affected all three stations. It will be noticed further that the wave affected first Framheim, then Cape Evans and finally Cape Adare. Framheim is slightly to the south and 400 miles to the east of Cape Evans, and Cape Evans is slightly to the west and 400 miles south of Cape Adare. It is therefore obvious that the pressure system which gave rise to this wave moved from east to west and from south to north, which is the exact opposite of what we should have expected if these waves are due to depressions moving in a south-easterly direction from the Southern Ocean into the Ross Sea. This is not an isolated case, for it will be seen that in the vast majority of cases the waves affect the three stations in the same order. To bring out this point with greater certainty the curves were examined and whenever a maximum pressure could be said with the certainty to affect all three stations a + was entered against each curve, similarly a minimum which affected all three stations was marked —. During the nine months April to December 1911, 38 maxima and 35 minima were recognised and marked in this way. All are shown on the plates and can therefore be examined by the reader to satisfy himself that the method used is free from personal bias. Of the 73 maxima and minima marked in this way 31 occur at the stations in the order Framheim, Cape Evans, Cape Adare, while all but 8 occur at Framheim before Cape Adare. This is conclusive evidence that these waves are not due to depressions entering the Ross Sea after passing Cape Adare while moving in a general west to east direction. By tabulating the pressure and time when each wave passed each station it is possible to determine the mean amplitude of the waves at each station and the mean time it takes for the waves to pass from station to station. The results of such an investigation are shown in the following table:—

TABLE 122.*

Height and times of the Antarctic Pressure Waves.

	Framheim.	Cape Evans.	Cape Adare.
Average height of waves (*i.e.*, mean max.—mean min.)	·70″	·67″	·73″
Mean time of maxima after time at Framheim .	—	6 hours.	17 hours.
Mean time of minima after time at Framheim .	—	12 hours.	19 hours.
Mean time of waves after time at Framheim .	—	9 hours.	18 hours.

It will be noticed that the average height of the waves is practically the same at all three stations, the differences being too small to be considered real.

The last line of table 122 gives the average time the waves take to pass from Framheim to Cape Evans and Cape Adare, these being nine and eighteen hours respectively. There can therefore be no doubt that the waves travel from the south-east to the north-west. A significant fact is that the maxima travel from Framheim to Cape Evans more rapidly than the minima. This can only be accounted for, if real, by a deformation of the waves as they travel. We shall see later that as the waves pass over the Ross Sea they produce winds which modify the pressure and this may be the cause of the deformation.

The question now arises: what is the nature of these waves, are they associated with travelling cyclones and anticyclones, or are they true waves of pressure?

This point is best investigated by examining the weather maps to see whether the passage of a wave of low pressure is associated with a travelling cyclone or a wave of high pressure with a travelling anticyclone.

Weather maps, method of construction.—For constructing isobaric charts, simultaneous, or nearly simultaneous observations are necessary. As observations were made at Framheim

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* In this table only waves which can be recognized at all three stations are included and therefore the results are somewhat different from those contained in table 108.

only at 8 A.M., 2 P.M. and 8 P.M., these hours fixed the times for which maps are possible. The observations at corresponding times at Cape Evans and Cape Adare were extracted from the registers and the data for all three places were entered on to outline maps. Whenever sledging parties were making observations their results have also been used. As a rule observations during sledging journeys are taken at irregular hours, curves of temperature and barometer were therefore plotted from the observations and the values at the exact time required read off from them. The wind at the nearest time of observations has been used. During the greater part of the year, however, there are only the observations from the three base stations available, and it appeared at first hopeless to construct isobars over such a large area from such scanty information, especially as the wind directions at both Cape Adare and Cape Evans are so largely affected by the configuration of the surrounding land masses. But after attempting many maps and getting an idea of the general pressure distribution, it was found possible to draw isobars to fit the pressure values and to arrange them so that the gradient was in fair agreement with the wind direction and wind force at all three stations. No claim is made for the accuracy of the charts in detail, and in some cases other arrangements of isobars would no doubt fit the observations equally well; still the whole series of charts must give a fairly accurate idea of the pressure distribution in the Ross Sea area. In Volume II two maps for each day are shown: those for 8 A.M. and 8 P.M. Framheim time, which corresponds to 6 A.M. and 6 P.M. Cape Adare time and 7 A.M. and 7 P.M. 180 meridian time used at Cape Evans.*

We will first examine the maps during periods when large pressure waves are shown on the plates in order to see if they are connected with moving pressure systems. The first example will be the large wave, the trough of which passed Framheim on 24th May, 1911. Plate 5 should therefore be unfolded and the maps opened at May 24th.

If this deep pressure trough were due to a cyclone we should expect the central area of the depression to pass over Framheim between 8 A.M. and 8 P.M. The map for 8 A.M. of the 24th shows high pressure over Cape Adare and low pressure to the south-east of Framheim. The wind at Framheim is much too light for the central area of a deep cyclone to be just about to pass over the station. At 8 P.M., when the centre of the cyclone should be passing Cape Evans, we find that that station is still under the influence of the high pressure area near to Cape Adare. There are no indications of a cyclone on this map, as it is impossible to dignify the low pressure area near Framheim by such a name.

During the next twelve hours the pressure trough has passed beyond Cape Adare and the pressure is rising over the whole area. A comparison of the 8 P.M. map for the 24th with that for 8 A.M. on the 25th makes it quite clear that no cyclone passed Cape Adare at midnight, for in spite of the large absolute pressure changes at all stations, the relative pressure is little different and the pressure distribution is practically unchanged. Throughout the whole period that the low pressure wave was passing over the area, from 8 A.M. on the 23rd to 8 P.M. on the 25th, Cape Adare has been under anticyclonic conditions with calm or light wind and only a little cloud.

We will pass on to the consideration of the passage of the crest of the same wave which arrived at Framheim at midday on the 27th, leaving for future consideration the blizzard at Cape Evans on the afternoon of the 25th.

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* The hours for which the wind directions are shown on the plates for Cape Evans and Cape Adare do not happen to be those for which the maps are shown. Generally this leads to no confusion when comparing the maps and the plates, but sometimes the wind shown on the map appears not to agree with the wind shown on the plate. This is because at the time the wind was changing direction and the direction shown on the map was recorded during the interval between the wind observation entered on the plates.

At 8 A.M. on May 27th the highest pressure is at Framheim and the lowest at Cape Adare. The easterly wind at Framheim, although light, is the only indication we have of the run of the isobars. The lines have been drawn to show high pressure over the Barrier and low pressure over the Ross Sea. At 8 P.M. of the 27th the wave crest is over Cape Evans and this station now has the highest pressure, but instead of anticyclonic conditions we find a blizzard blowing at Cape Evans which together with the easterly wind at Framheim shows that there is an area of low pressure over the Ross Sea, just where one would expect the maximum pressure to be if an anticyclone were travelling from Framheim to Cape Adare. At 8 A.M. on the 28th the crest of the wave has arrived at Cape Adare where the pressure is now highest. Thus since 8 A.M. on the 27th the crest of the wave has travelled from Framheim to Cape Adare, but it is quite clear that an anticyclone has not crossed the Ross Sea. Thus the trough of this wave was not connected with a travelling cyclone nor the crest with an anticyclone.

Another example is the wave which passed Framheim during September 30th and October 1st and 2nd, plate 16. At 8 A.M. on September 30th the pressure is lowest over the Ross Sea just to the north of Framheim. The barometer is falling rapidly at all stations but the most so at Framheim where the trough of the pressure wave arrives just after the 8 P.M. observation on the 30th. At 8 A.M. on October 1st the pressure is rising at Framheim and the trough of low pressure is just over Cape Evans. By 8 P.M. the trough has arrived at Cape Adare and the pressure crest is about to reach Framheim. At 8 A.M. on the next day the trough has passed Cape Adare and the maximum is half way between Framheim and Cape Evans. The crest has just arrived at Cape Evans on the evening of the 2nd and passes on to Cape Adare where it arrives much reduced in intensity at 8 A.M. the next morning. During the whole period there has been no essential change in the pressure distribution over the whole area. When the trough was over Cape Evans on the morning of October 1st the only effect was, by reducing the pressure over the west of the Ross Sea, to bring the Ross Sea depression nearer to Cape Evans. It is quite clear from the maps from 8 A.M. on the 30th September to 8 P.M. on the 3rd October that neither a cyclone nor an anticyclone has travelled from Framheim to Cape Adare, yet in this interval a wave, $\frac{3}{4}$ inch in depth, has travelled across the whole area. It is important to notice that here again the depression over the Ross Sea was highly developed when the crest of the wave was between Framheim and Cape Adare on the evening of October 2nd.

If the reader will now take the trouble to turn over the pages of maps and compare the pressure distribution with the pressure waves, he will soon be convinced that the waves are not caused by the movements of cyclones and anticyclones.

As the pressure waves are not due to travelling cyclonic and anticyclonic systems, we are compelled to assume that they are true pressure waves traversing the upper atmosphere in the same way that water waves travel across the sea. If this is so, we ought to find evidence of them on the surrounding plateau. The observations made there have, therefore, been investigated.

For this purpose two sets of data are available:

(*a*) The observations made by the Polar Party during their journey to and from the Pole after mounting to the plateau by way of the Beardmore Glacier. Latitude 87° S. was reached on December 31st, 1911, and from this point to the Pole the surface was very uniform consisting of a rise at the rate of 7·3 feet per geographical mile to about latitude 88° 10′, then level until 88° 40′ and finally a descent to the Pole at the rate of 8·3 feet per geographical mile (see page 292). The barometer readings have been corrected for this change of height and plotted as the lower curve on plate V at the end of this volume, the two upper curves being those for Cape Evans and Framheim respectively.

(*b*) The observations taken by Captain Scott when he made his journey to the Western Plateau by way of the Ferrar Glacier in November 1903. The part of the plateau visited on this occasion lay due west of McMurdo Sound and a point nearly 200 miles to the west of the edge of the plateau was reached. Owing to the want of sufficient details as to the position of the party when each set of observations was taken, it has not been possible to correct the observations for change of height, but it is obvious from the curves shown on plate V that the change of height does not affect our present discussion.

We will now examine plate V showing the changes of the barometer on the Polar Plateau between December 31st and January 30th, 1910-11. Unfortunately during this period the pressure waves were not very pronounced even at sea-level, but fairly well marked positions of maximum and minimum pressure can be detected on the Framheim curve. These are marked on the curve by the numbers I to IV. There is no doubt that each one of these points of inflexion can be detected on the curve for the plateau. The rise of pressure on the 14th January with the following maximum on the 15th is particularly well marked. The respective changes of pressure and the times of occurrence are tabulated for each station in the following table. Owing to the observations being made at Framheim and on the plateau only three times each day the exact time of maximum and minimum can not be stated.

TABLE 123.

	Plateau.			Framheim.			Cape Evans.		
	Height of bar.	Change.	Time.	Height of bar.	Change.	Time.	Height of bar.	Change.	Time.
	″	″		″			″		
I Minimum ..	19·81		6 hours 8-1-12	29·03		11 hours 8-1-12	29·05		1 hour 9-1-12
		+·18			+·33			+·36	
II Maximum ..	19·99		6 hours 10-1-12	29·36		17 hours 10-1-12	29·41		24 hours 10-1-12
		−·35			−·35			−·36	
III Minimum ..	19·64		20 hours 12-1-12	29·01		20 hours 13-1-12	29·05		2 hours 13-1-12
		+·39			+·51			+·40	
IV Maximum ..	20·03		6 hours 15-1-12	29·52		20 hours 15-1-12	29·45		9 hours 16-1-12

From this table we see that the waves are not so large on the plateau as at Framheim, but the number of observations is too small to give a mean of real value. It is important to find how much earlier the phase of the waves is on the plateau than at the other stations and we notice that the four epochs occurred earlier on the plateau by the following amounts:—

TABLE 124.

	TIME ON PLATEAU BEFORE TIME AT	
Wave number.	Framheim.	Cape Evans.
I	14 hours	28 hours
II	11 ,,	18 ,,
III	24(?) ,	6(?) ,,
IV	14 ,	27 ,,

Neglecting the minimum III, the epoch of which is not clearly marked at any of the stations, we see that the phase on the plateau is about twelve hours ahead of Framheim and twenty-four ahead of Cape Evans. These values can only be approximate for three waves cannot possibly give an accurate mean (they give the difference Cape Evans – Framheim, 12 hours, while the true mean is nine hours), but it is important to know that these well-marked waves as well as several minor ones which have not been discussed here prove that the waves arrive on the Polar Plateau before they affect Framheim and Cape Evans and that they take something like twelve hours to advance from the plateau to Framheim.

The pressure observations made by Amundsen when on the Polar Plateau have also been examined. The route taken by Amundsen was nothing like so level as that followed by Scott and as he travelled more rapidly I find it impossible to rid his pressure curves from the effect of changing height. It happens, however, that from December 15th to 18th he was at or near the Pole and therefore his height did not vary appreciably during this period. During these days a very small pressure wave passed over the sea-level stations which is clearly shown by the Polar observations, the maximum occurring at 6 A.M. on the 16th at the Pole and fourteen hours later at Framheim. Thus this single wave confirms the results made by Captain Scott's Party. The pressure curve at the Pole during this period has been added on plate 22, Volume II, for comparison with the curves at the sea-level stations.

Turning now to the observations made on the plateau behind the Western Mountains near to McMurdo Sound which are plotted on plate V, we see that here also there is no doubt that the waves of pressure which affect McMurdo Sound are recognisable on the plateau Unfortunately during this period the pressure waves were less in evidence even than during the Polar journey. There is only one clear point of inflexion, the one recorded on the 23rd November, but from this and a few of the smaller irregularities one can conclude with some certainty that the waves affect the plateau, and the phase is either equal to or slightly behind that at McMurdo Sound. The waves are also slightly smaller than at sea-level.

We have now shown that the pressure waves can be detected at sea-level in the Ross Sea area and also on the surrounding plateau. They appear first on the Polar Plateau, then about twelve hours later at Framheim, nine hours later at Cape Evans, and finally nine hours later still at Cape Adare.

If we assume as a first approximation that the waves travel with a linear wave front, these observations are sufficient to fix the direction in which they travel.

Figure 63 is a rough sketch map of the region under consideration. The South Pole is marked S.P., the mean position of the Polar Plateau P.P., Framheim F., Cape Evans E. and Cape Adare A.

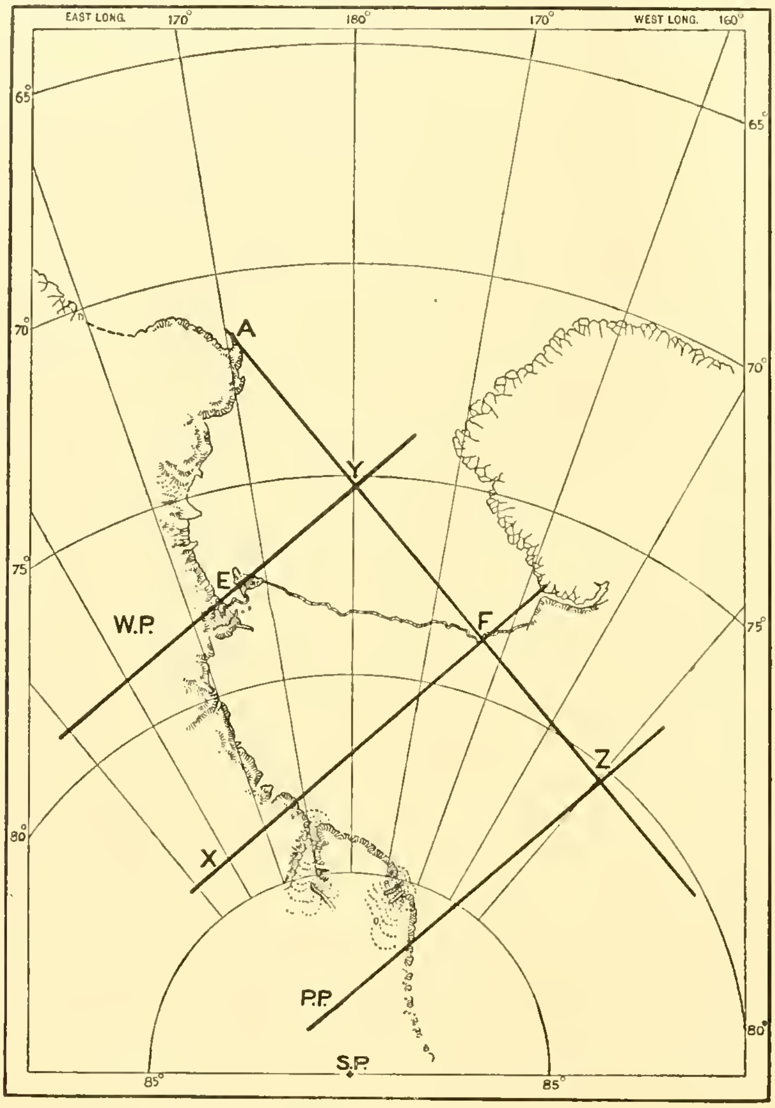


Fig. 63. Diagram of pressure wave front.

Now the wave takes twice as long to travel from Framheim to Cape Adare as from Framheim to Cape Evans, hence if we bisect the line A F in Y the wave must reach Y at the same time as Cape Evans, hence E Y is the position of the wave front at the moment it reaches Cape Evans. As it happens E Y is practically perpendicular to the line joining Framheim and Cape Adare, hence this latter line gives the direction of movement of the waves.

Now if we draw lines F X and P.P. Z, parallel to E Y they give the position of the wave front as the wave arrives at each station, and the perpendicular distance between them is proportional to the time taken for the wave to travel from place to place.

It will be seen that the distance F Z is similar to F Y, hence the wave would take approximately the same time to travel from the Polar Plateau to Framheim as from Framheim to Cape Evans, and we found this to be the case. We also see that the wave would affect the Western Plateau, W.P., very shortly after it arrived at Cape Evans, which also was shown to be so by the observations.

There can therefore be little doubt that we have to do with waves of pressure travelling outwards from the centre of the Antarctic Continent along directions parallel to a line joining Cape Adare and Framheim. It is interesting to notice that this line produced passes very near to the position 80° S., 120° W., about which the pressure surges were found to have their maximum intensity (see page 195).

Pressure Waves and Winds.

It becomes necessary now to examine the pressure waves to see if there is any intimate relationship between them and the winds at Cape Evans, Framheim and on the Barrier. The conditions at Cape Adare will be considered separately later.

If one examines the wind arrows placed along the pressure curves for Cape Evans the periods of blizzards, calms and northerly winds are clearly seen. If, however, one examines the pressure curve for Cape Evans alone it is difficult to find any certain relationship between the pressure changes at that station and the accompanying wind conditions. To fix our attention we will examine the pressure and winds on plate 17. The first blizzard on this sheet occurred on October 10th with a nearly steady barometer at Cape Evans. The second commenced on the evening of the 12th just when the barometer commenced to rise sharply; but the blizzard stopped, for no apparent reason, while the barometer was still rising rapidly. The third occurred on the night of the 15th-16th while the barometer was rapidly falling. It ended at midday on the 16th by the wind suddenly turning completely round and blowing strongly from the north. When this occurred there was no apparent change in the pressure curve such as is usually associated with a complete reversal of the wind. The two remaining blizzards on this plate are associated with the crests of two small pressure waves, while the trough between the two waves passed during calm weather with an occasional light wind from the north. This is exactly the reverse of what happened when the large wave passed on the 14th, for then the crest of the wave was accompanied by a calm and the blizzards occurred before and after the crest passed. The same will be found on all the plates, blizzards start and stop at all phases of the actual pressure waves and for no obvious reason so far as the pressure alone is concerned. Take as another example plate 7. Here we see a large pressure wave between a trough on June 16th and a trough on the 22nd. During the passage of this wave there is first a period of calm, then a period of high northerly winds which suddenly changed into a southerly blizzard. Then a period of calm with an occasional wind from the north followed by a blizzard, then another high wind from the north. All these changes took place while the crest of a single wave passed over the station. On such evidence as this one is tempted to say that the winds are entirely independent of the pressure waves and occur under the influence of some other motive force. The case, however, takes on a different light when instead of the actual pressure at Cape Evans one examines the difference in pressure between Cape Evans and Framheim. The bottom curve on each plate shows the pressure difference Cape Evans – Framheim, plotted for convenience to twice the scale used for the pressure curves. On this curve are repeated the winds at Cape Evans. Looking now at the lower curve corresponding to the last example, June 16th to 21st, we see that the wind changes which occurred so capriciously when compared with the actual pressure at Cape Evans are very closely related to the changes in the pressure difference between Cape Evans and Framheim. The blizzards all occur when the pressure difference curve is rising, and the calms and northerly winds when the curve is falling. The wind changes direction almost exactly at the moment the lower curve starts to rise or fall. Turning back to plate 17 we see that there was no blizzard when the large crest passed on the 14th because this wave produced little or no effect on the pressure difference. on the other hand each of the small waves on the 19th and 21st was accompanied by large rises on the bottom curve and therefore blizzards occurred while they passed. This relationship which is so clear on these two plates will be found to be the general rule throughout all the plates. There are certainly exceptions, but compared with other meteorological rules this is a very rigid one. We can therefore conclude that a blizzard will occur when the pressure difference between Cape Evans and Framheim increases and high northerly winds, calms or light southerly winds will occur while the pressure difference decreases.

We have now found that it is difficult to see any close relationship between the winds at Cape Evans and the actual pressure waves, as would be the case if the pressure waves were due to the passage of high and low pressure systems which are maintained by the winds circulating round them—good examples of which are to be seen in the curves for Melbourne at the top of each plate. On the other hand there is a close relationship between the winds at Cape Evans and the changes in pressure difference between that station and Framheim, 300 miles to the east.

Theoretical Discussion of the Effects of Pressure Waves.

We will now investigate what effect the passage of pressure waves would have on the pressure distribution and winds supposing that the waves are imposed on the Ross Sea area from without; this is reasonable in view of the fact that we have been able to identify the same pressure waves on the surrounding plateau and at the sea-level stations. These waves will be supposed to travel over the area adding their pressure to the existing sea-level pressure and in consequence changing the pressure distribution and air motion.

We have therefore first to determine the pressure distribution without the waves, and then to impose a series of waves on this distribution and examine the result.

For simplicity in the following discussion we will assume that the three stations Cape Adare, Cape Evans and Framheim are situated at the corners of an isosceles right angle triangle of which the line joining Cape Adare and Framheim is the hypotenuse. In figure 64*a* the three stations are represented by the points A, E and F, the line A E B then represents the line of the Western Mountains and the line E F the edge of the Barrier.

We will first consider what would be the pressure distribution if all air motion could be restrained. In the absence of a difference of temperature between the Ross Sea and the Barrier, pressure would increase slowly from the north to the south owing to the general increase of pressure with latitude which is a common feature of the Antarctic. This would cause the pressure to be higher over the Barrier than over the Sea to the north of it.

There is, however, a large temperature difference between the Barrier and the Sea and the chief pressure difference would be due to it.

Both effects then give high pressure over the Barrier and low over the Sea. If there were no air motion the isobars would run something like those shown on figure 64*a*. That is, they would run approximately east and west and parallel to the edge of the Barrier.

We have now to examine how this simple pressure distribution will be affected when motion of the air takes place.

In the southern hemisphere, owing to the influence of the earth's rotation, the air motion takes place along the isobars in such a direction that the high pressure is on the left of the direction of flow and the low pressure on the right. Under the pressure distribution shown on figure 64*a* the whole air over the Ross Sea area would tend to flow to the west as an easterly wind. This, however, is not possible owing to the Western Mountains which act as a wall running north and south at right angles to the easterly wind induced by the pressure distribution. It is easy to see that the air from the eastern half of the Barrier would flow over to the west and would then be forced, along with the air from the western half, to travel to the northwards parallel to the line of the Western Mountains.

There would therefore be an easterly wind over the east of the Barrier and a southerly wind along the line of the mountains. It is also clear that the intensity of the southerly wind must increase as it flows towards the north because it is constantly receiving air both from the south and from the east of the Barrier. In fact practically the whole of the air set in motion on the Barrier is concentrated in the current which flows across the north-west corner of the Barrier near to Cape Evans. This is shown diagrammatically by the arrows in figure 64*b*.

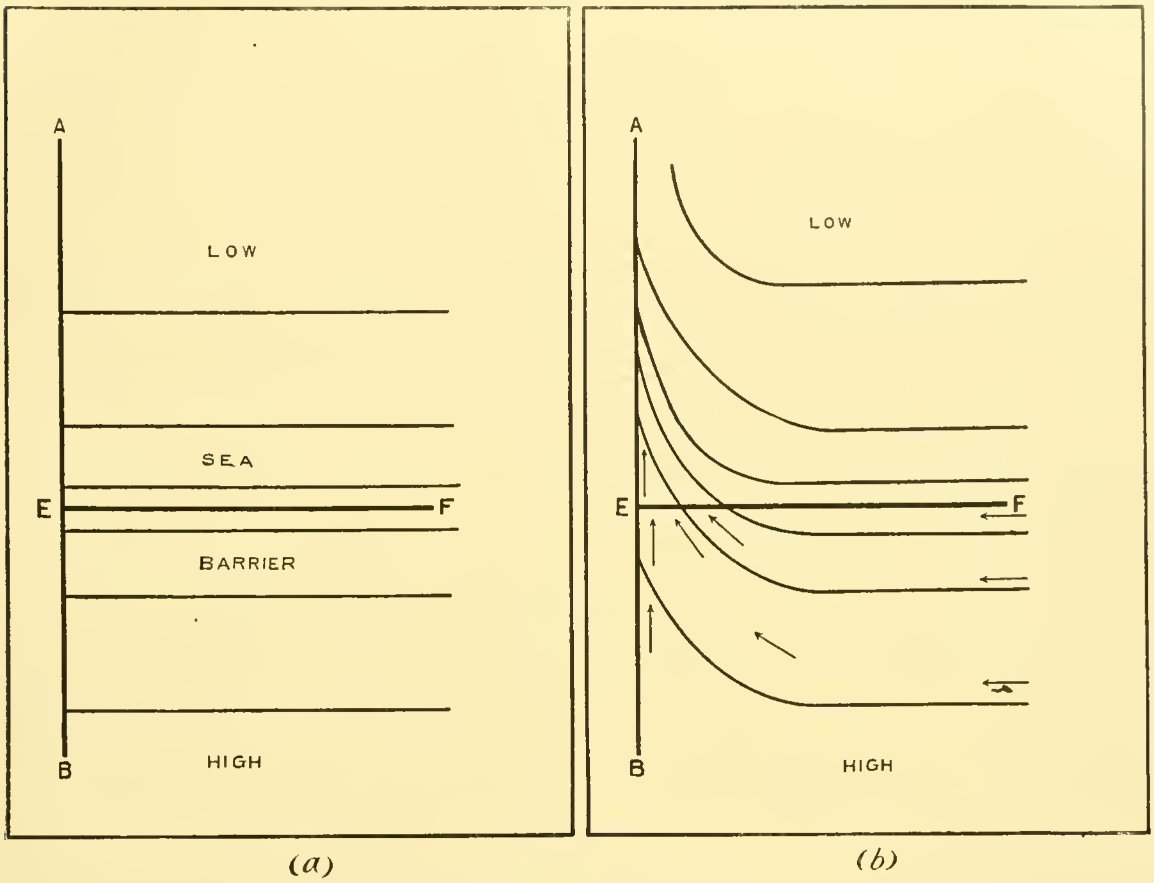


Fig. 64. Theoretical pressure distribution.

Now it does not matter how the motion of air is deflected or restrained the pressure and wind velocity will always adjust themselves in time until (neglecting the effect of friction) the air is travelling along the isobars with the high pressure on the left and the low pressure on the right and the distance between the isobars will be inversely proportional to the wind velocity. When the wind flow shown in figure 64*b* has become established the isobars will have adjusted themselves to be parallel to the flow and near together where the wind is strong. We therefore get a system of isobars like that shown on the same figure. We see that over the east of the Barrier where the air can move from east to west the original isobars are not affected, but near the Western Mountains the isobars turn sharply to the north and crowd together near Cape Evans where the air current is strong. Whereas before the air motion started the pressure at Framheim and Cape Evans was the same, we see from figure 64*b* that when motion occurs it is necessary to cross two isobars in going from Framheim to Cape Evans, hence the pressure is now appreciably higher at Cape Evans than at Framheim. This increase of pressure is due to the concentration of the air motion over the north-west of the Barrier, but it is brought about in two ways, first the stoppage of the easterly wind over the west of Barrier causes the piling up of the air there and a consequent increase of pressure, also the air moving rapidly from south to north near the

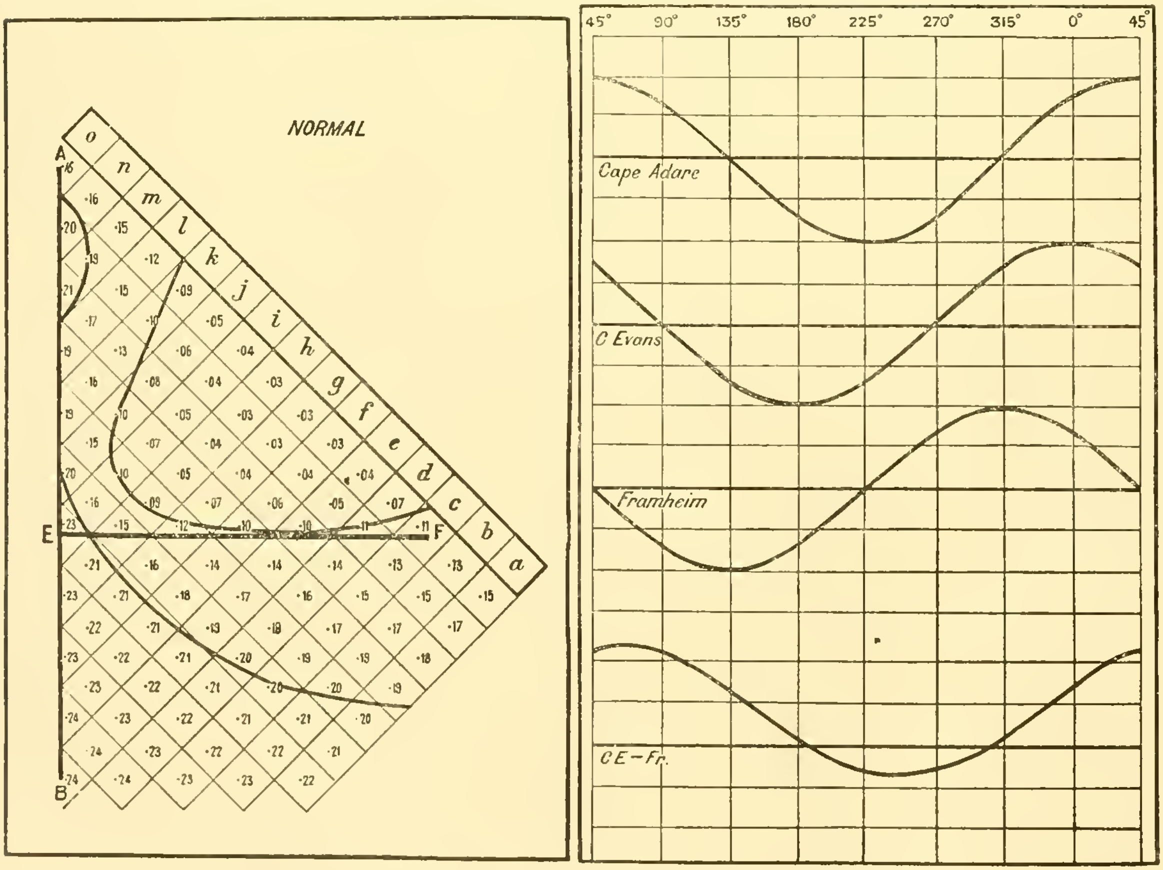
Western Mountains is pressed to the west by the force due to the earth's rotation and this produces a pressure gradient away from the mountains. Both effects raise the pressure and cause the isobars to adjust themselves to the direction of the air movement.

Going further we see that an increase of the pressure difference between the Barrier and the Ross Sea increases air flow over the west of the Barrier with a greater concentration of the motion near to Cape Evans where the pressure rises. Thus a uniform lowering of the pressure over the Ross Sea or a raising of the pressure over the Barrier increases the southerly wind at Cape Evans and causes the pressure at Cape Evans to rise relatively to the pressure of Framheim.

We have now to investigate the result of impressing travelling pressure waves on this general distribution. So far we have not considered the magnitude of the pressure differences, the isobars shown on figures 64*a* and 64*b* being only diagrammatic.

The required values are found and the theory substantially supported by noticing that in all essentials the pressure distribution shown on figure 64*b* which has been derived from first principles is the same as that of the average pressure distribution found from the actual observations and already given in figure 58, page 176. In the latter we have numerical values for the isobars and therefore in the future discussion we will use it in place of the approximate diagram of figure 64*b*

On figure 65*a* the isobars from the average pressure distribution have been entered to fit our diagrammatic representation of the geography of the Ross Sea area.* The whole area



(*a*) (*b*)

FIG. 65 (*a*) Actual pressure distribution. (*b*) Imposed pressure waves.

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* Figures 65 to 73 were all prepared before the error described in the footnote to page 166 was detected. Hence the pressures used in these diagrams are all ·03″ too low. This, however, is quite immaterial to the present discussion as the pressure distribution is unaffected.

has been divided into squares, and in each square the pressure has been entered in agreement with the isobars. The waves which are to be impressed on this pressure distribution travel from Framheim to Cape Adare, *i.e.*, in the direction of the line of squares a, b, c, . . . n, o. The wave fronts are at right angles to this line. Values will be given to the letters a, b, c, etc., according to the pressure of the wave which is travelling from a to o. As the pressure due to the wave is the same along the whole wave front the values of a, b, c, etc., must be added to the pressures in the line of squares to which the letter is attached. Thus the value of i determined by the position of the wave has to be added to the pressure entered in each of the squares along the line E to i.

The wave to be investigated may vary in two particulars, (*a*) in amplitude and (*b*) in the difference in phase with which it arrives at the three stations. A large number of waves having different amplitudes and phases have been investigated, and it is found that the result is not affected in principle, but only in detail by changing these variables. From these waves the one has been chosen for discussion here which gives the best general result.

This wave is given at Cape Evans by $dp = \cdot 3'' \cos \theta$ and it travels from Framheim to Cape Adare in a quarter of its period. So that the pressure changes at Framheim are $dp = \cdot 3'' \cos (\theta + 45^\circ)$ and at Cape Adare $dp = \cdot 3'' \cos (\theta - 45^\circ)$.

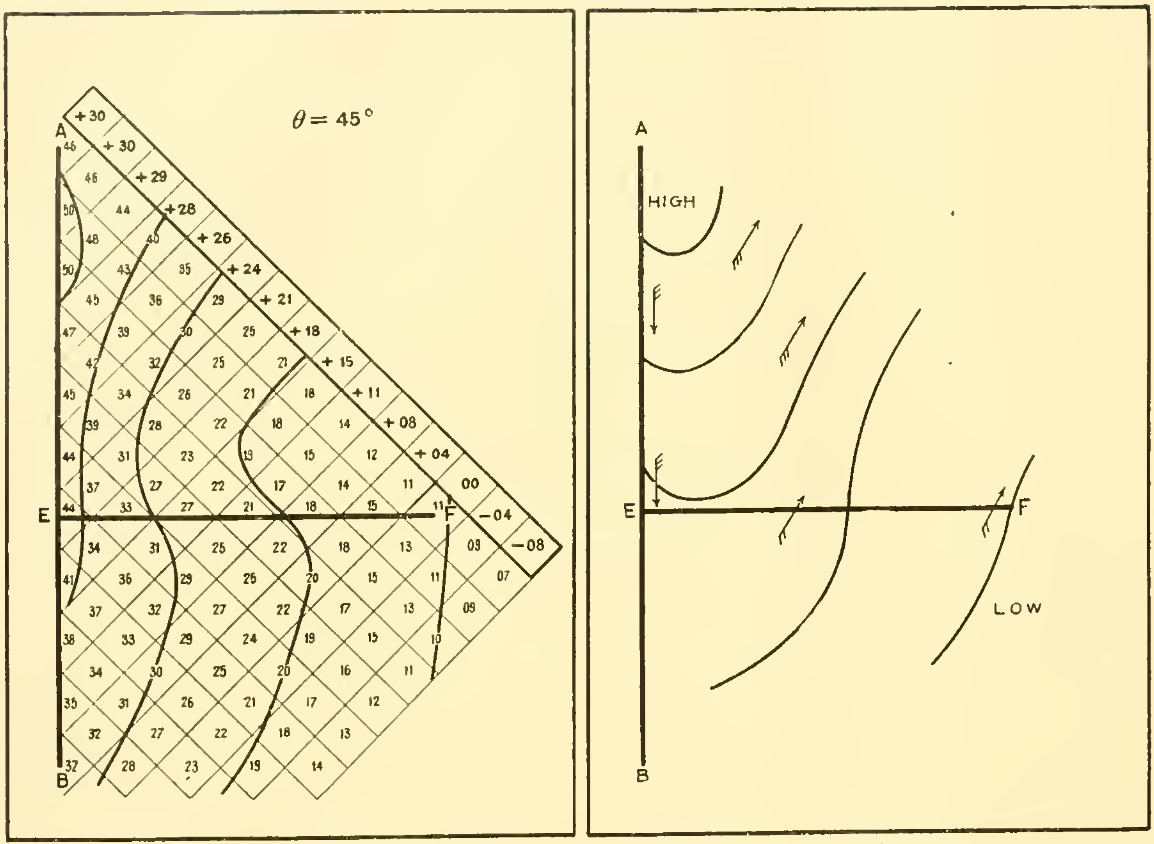
In figure 65*b* the wave to be investigated is shown in the same way as the pressure curves on the plates in Volume II. The abscissa represent equal intervals of time, but as we are not concerned with absolute time, which involves the rate of travel of the waves, but only with time in so far as it affects the phase of the wave when it arrives at the different stations, the phase of the wave at each interval at Cape Evans is given instead of the time. The wave arrives at each station an eighth of a period after it left the last. Thus if the phase at Cape Evans is θ, it is $\theta + 45^\circ$ at Framheim and $\theta - 45^\circ$ at Cape Adare.

The most important curve on the plates in Volume II was found to be the one giving the difference in pressure between Cape Evans and Framheim, a similar curve therefore has been added to figure 65*b*.

We shall consider the effect of the wave at eight intervals during its passage commencing from the epoch when the maximum of the wave has just reached Cape Adare. The positions of the wave at each of the epochs considered are shown in figure 65*b* by the vertical lines at

$$\theta = 45^\circ,\ 90^\circ,\ 135^\circ,\ 180^\circ,\ 225^\circ,\ 270^\circ,\ 315^\circ \text{ and } 360^\circ.$$

For each position of the wave two diagrams are given. In the first the pressure which results by the simple addition of the pressure wave to the normal pressure is shown. In the second an attempt has been made to allow for the alteration in the pressure which the air motion would produce, taking into account the inertia of the air and the obstacles to its motion. Thus for each position of the wave there will be two diagrams similar to figures 64*a* and 64*b*, which are the corresponding diagrams for the conditions in the absence of the pressure waves.

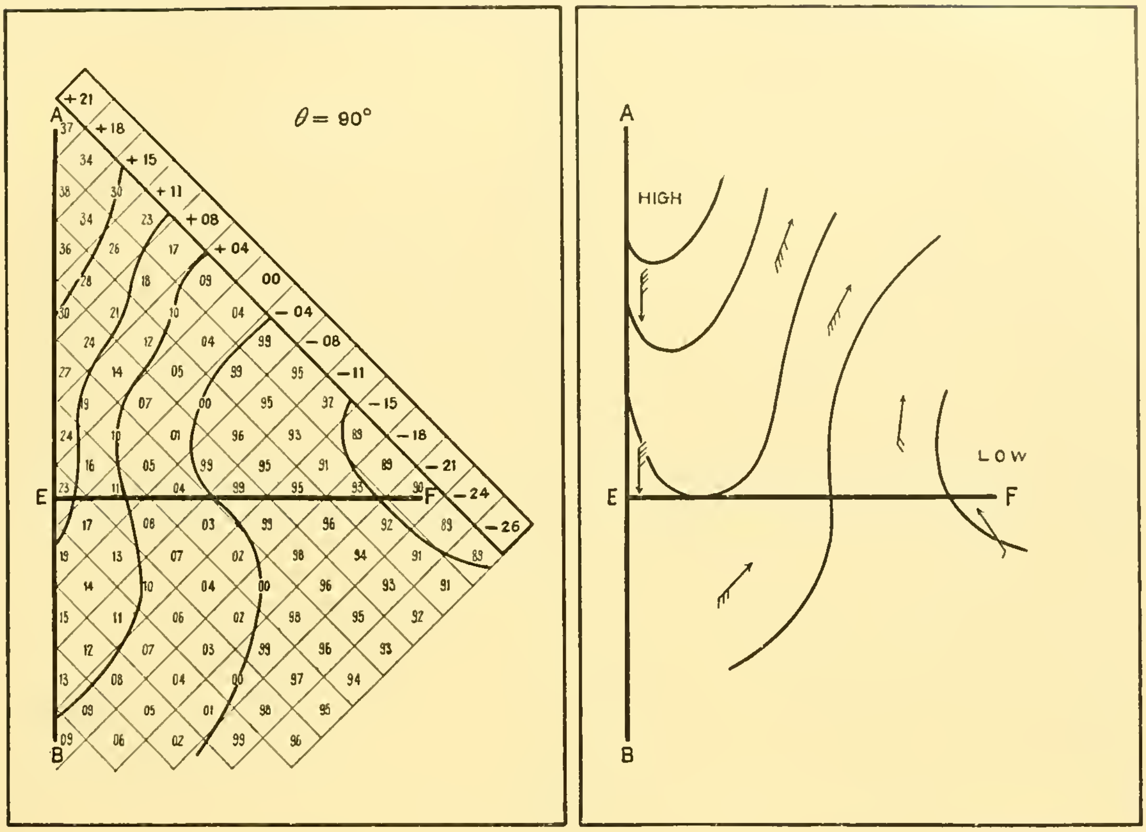


(a) (b)

Fig. 66. **Modified pressure distribution** θ=45°.

θ = 45°, *figure* 66.—Starting with the crest of the pressure wave at Cape Adare the change of pressure due to the impressed wave has been shown in the upper line of bold figures. These values have been added to the lines of figures against each in the normal diagram, figure 65*a*, with the resulting pressure over the whole area shown by the figures in the squares. Isobars through these figures show the resulting pressure distribution. The added pressure is sufficient to reverse the normal pressure distribution and the highest pressure is near Cape Adare and the lowest over the Barrier to the south-east of Framheim.

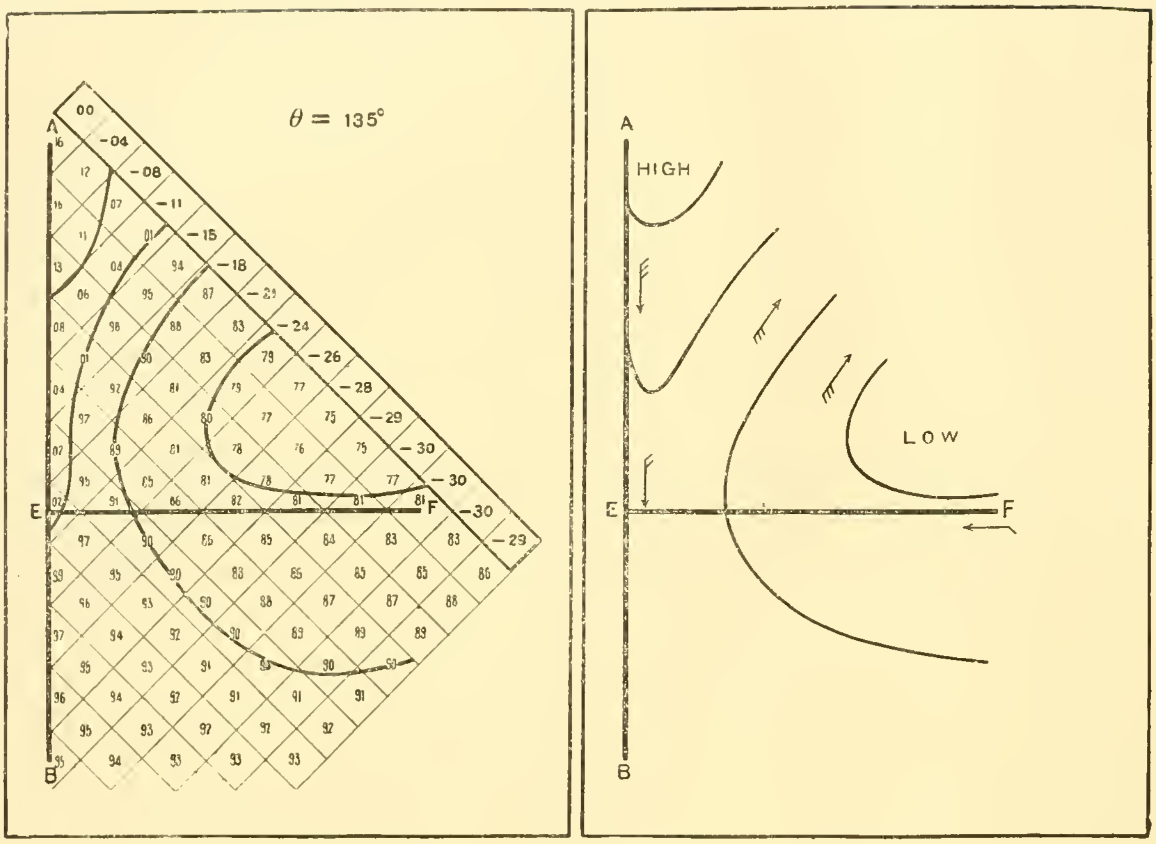
The simple addition of the pressure makes the isobars as shown on figure 66*a* start on the Western Mountains and run to the north-north-east. The air motion would be in this direction except that it obviously cannot flow away from the mountains along their whole length. The air motion near the mountains will be from high to low pressure but parallel to the range, *i.e.*, the wind will be from the north to the south near the mountains. Over the Ross Sea at some distance from the mountains the air motion will be along the isobars, *i.e.*, from the south-west. These directions have been shown by arrows in figure 66*b* in which the isobars have been changed to be in accordance with the air motion. This adjustment of the isobars to the air motion lowers the pressure at Cape Evans by about ·15″, as will be seen by comparing the isobars in the two halves of the diagram. The probable wind strength has been shown by the number of feathers on the arrows, which, however, are only qualitative as no calculation seems feasible.



(*a*) (*b*)

Fig. 67. Modified pressure distribution. $\theta = 90°$.

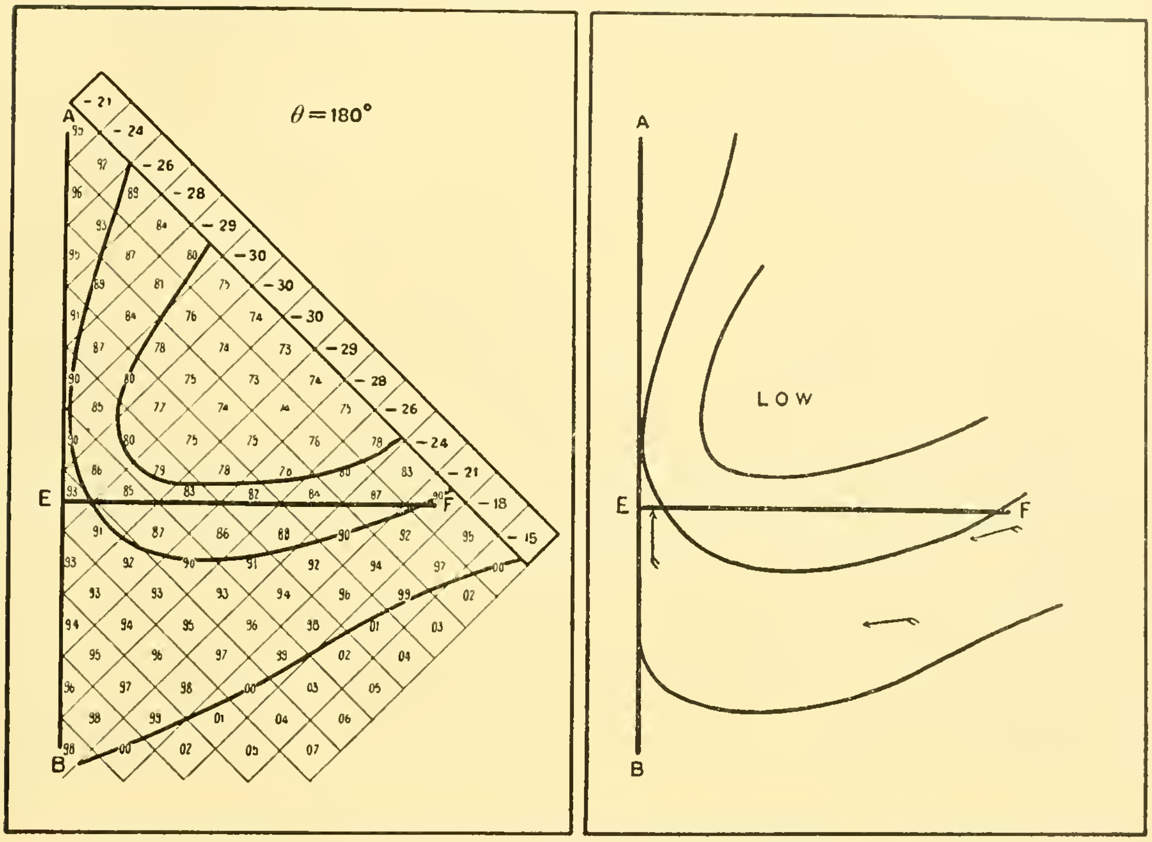
$\theta = 90°$, *figure* 67.—The wave has travelled on an eighth of its length, but the change in pressure has not been sufficient to affect materially the pressure distribution. The wind is still northerly at Cape Evans, but has become south-easterly at Framheim.



(a) (b)

Fig. 68. Modified pressure distribution. $\theta = 135°$.

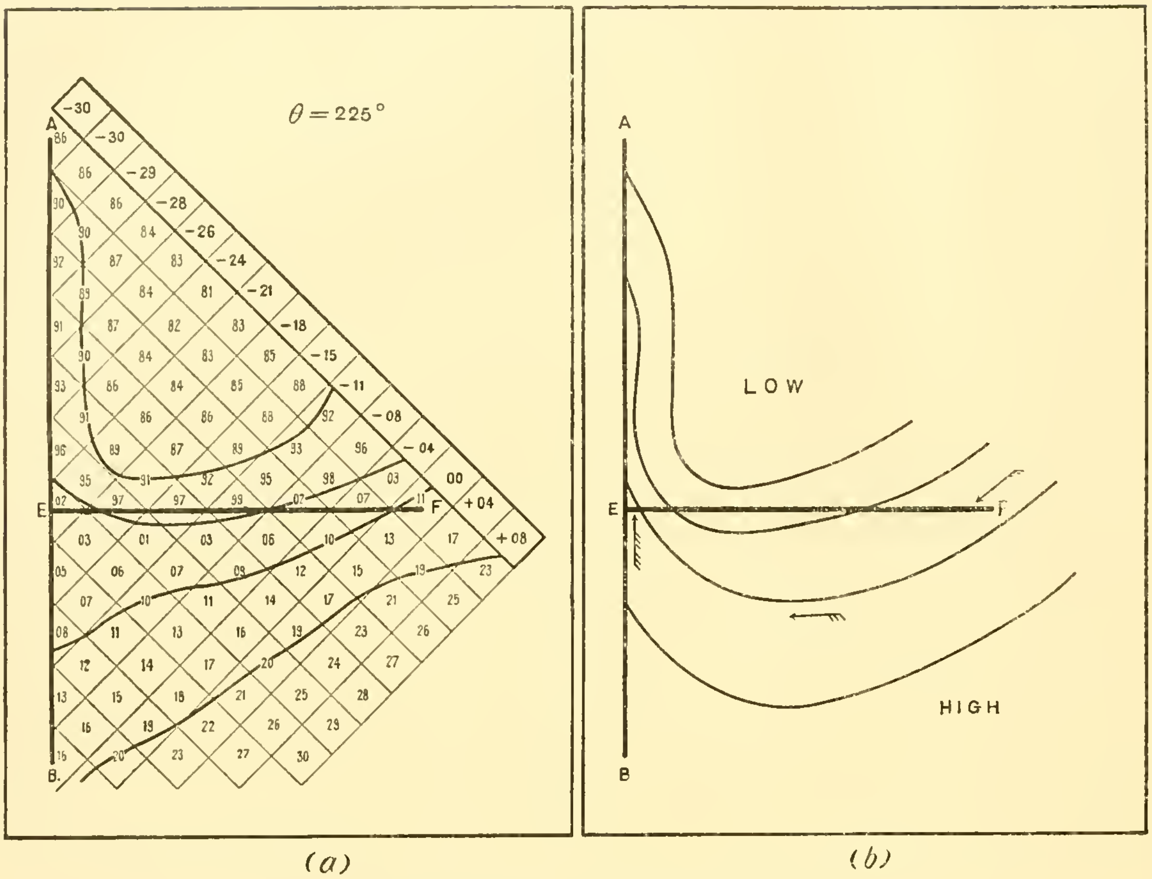
$\theta = 135°$, *figure* 68.—During the interval the pressure distribution has undergone an important change, the lowest pressure is now over the south-east corner of the Ross Sea near to Framheim. There is still an appreciable gradient for south-west winds over the east of the Ross Sea and the pressure decreases from north to south along the Western Mountains so that the west of the Barrier has a lower pressure than the west of the Ross Sea. Northerly winds will therefore continue near the mountains. The pressure is now nearly uniform over the Barrier where there can be little or no air movement.



(a) (b)

Fig. 69. Modified pressure distribution. $\theta = 180°$.

$\theta = 180°$, *figure* 69.—The pressure distribution is now undergoing very rapid change. There is an appreciable gradient for easterly winds over the east of the Barrier. If this distribution continued without change the air from the east of the Barrier would flow over to the west, raise the pressure there and give a strong southerly wind near to Cape Evans. The pressure distribution has, however, only just been established and there can as yet be very little air motion near Cape Evans where there is little pressure gradient. There would probably be a light southerly wind and all the premonitions of a coming blizzard.

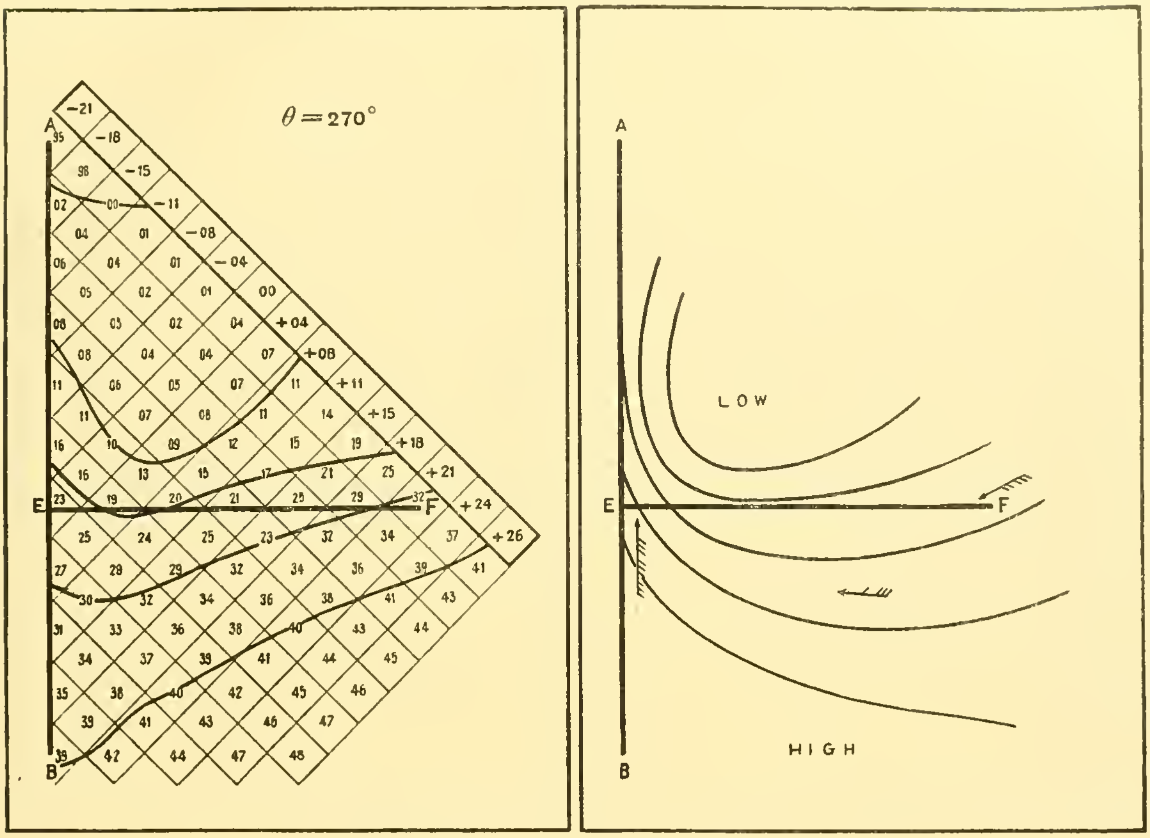


(a) (b)

FIG. 70. Modified pressure distribution. θ = 225°.

θ = 225°, *figure* 70.—There is now a still stronger pressure gradient for easterly winds over the Barrier and now it extends right up to the Western Mountains. There has also been time for the air from the east of the Barrier, moving all the time under increasing gradient, to have commenced to pile up along the Western Mountains, to raise the pressure there and to give rise to a violent flow of air across the north-west corner of the Barrier near to Cape Evans. The blizzard has commenced!

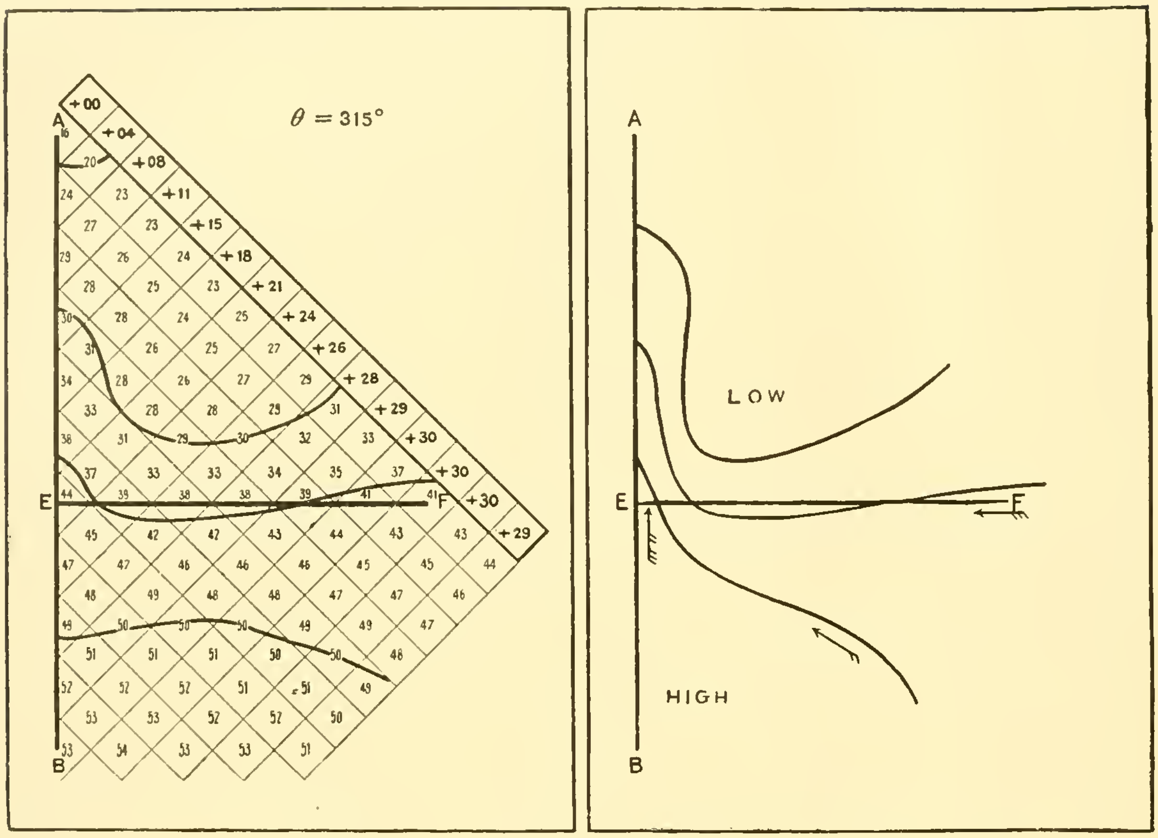
The raising of the pressure along the Western Mountains has caused the isobars to turn northwards in that region. This change is shown in figure 70*b* in which the pressure at Cape Evans is about ·09″ above that shown in figure 70*a*.



(a) (b)

FIG. 71. Modified pressure distribution. $\theta = 270°$.

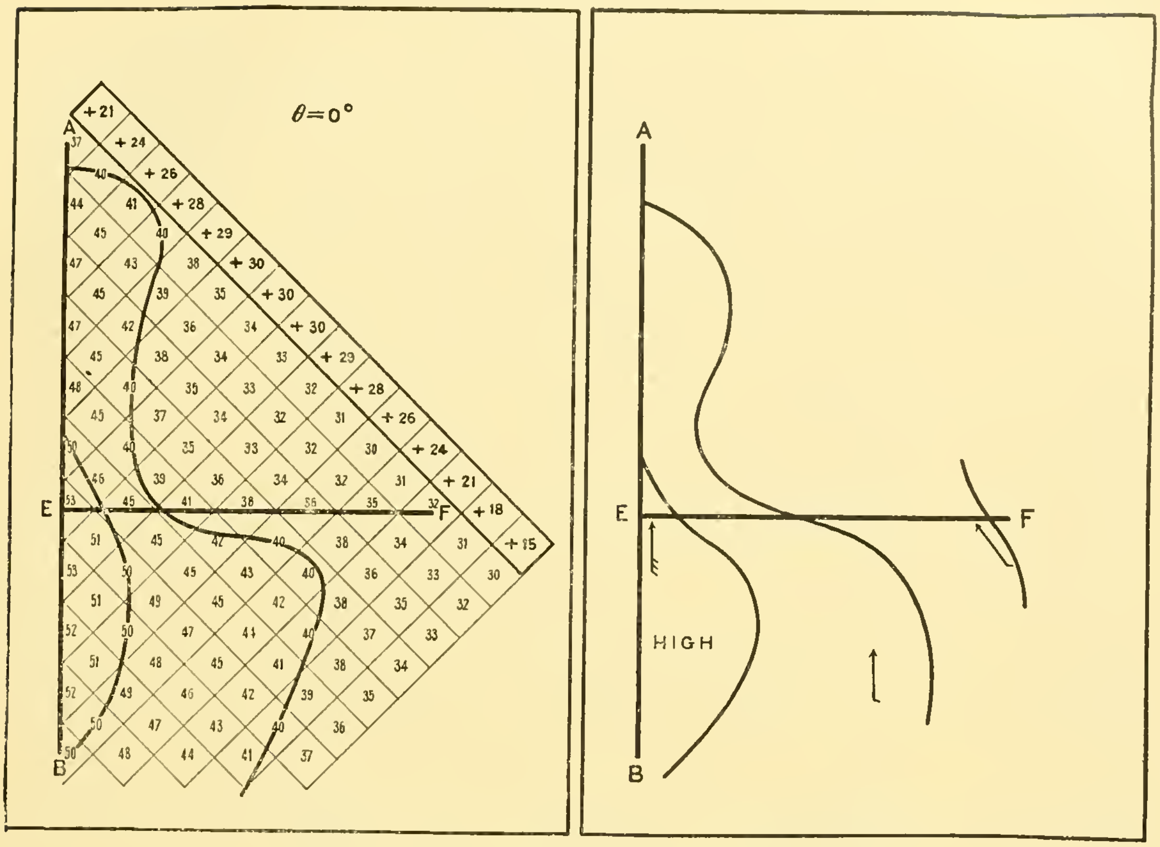
$\theta = 270°$, *figure* 71.—There has been little change in the pressure distribution due directly to the wave although the pressure over the whole area has risen. As, however, the air has now had time to get into motion over the whole of the Barrier the blizzard is probably at its maximum at this epoch. The pressure is now ·20″ higher at Cape Evans in figure 71*b* than in figure 71*a*.



(a) (b)

Fig. 72. Modified pressure distribution. $\theta = 315°$.

$\theta = 315°$, *figure* 72.—An important change is now taking place. The highest pressure has been transferred from the east to the west of the Barrier. The wind is still from the south over the west of the Barrier, but the gradients are being reduced. The blizzard is approaching its end.



(a) (b)

FIG. 73. Modified pressure distribution. $\theta = 360°$.

$\theta = 360°$, *figure* 73.—The high pressure is still over the Barrier and just to the south of Cape Evans where the wind must still be southerly. In fact, southerly winds exist over the whole area. The area of high pressure is steadily moving northwards and in a short time after this epoch it passes over Cape Evans when there is a sudden reversal of the wind from the south to the north. The blizzard is over and a northerly wind sets in. The whole series then repeats itself as the next wave comes along.

Comparison of Theory with Observations.

The passage of a complete wave over the three stations has now been followed and we have seen how the air is set in motion with a consequent modification of the pressure. This modification has been the most marked at Cape Evans, less so at Framheim and has hardly affected the Cape Adare pressure at all. The actual pressures are not the sums of the waves and the normal pressures as shown in the left hand diagrams; but are as shown, at least qualitatively, in the right hand diagrams. Figure 74 has been prepared from the right hand halves of figures 66 to 73 in exactly the same way as the plates in Volume II have been prepared from the actual observations. The three upper curves show the actual pressures at Cape Adare, Cape Evans and Framheim, and the lowest curve the pressure difference between Cape Evans and Framheim. By comparing these curves with those in figure 65*b* the modifications due to the air motion are clearly seen, and they have two very important results.

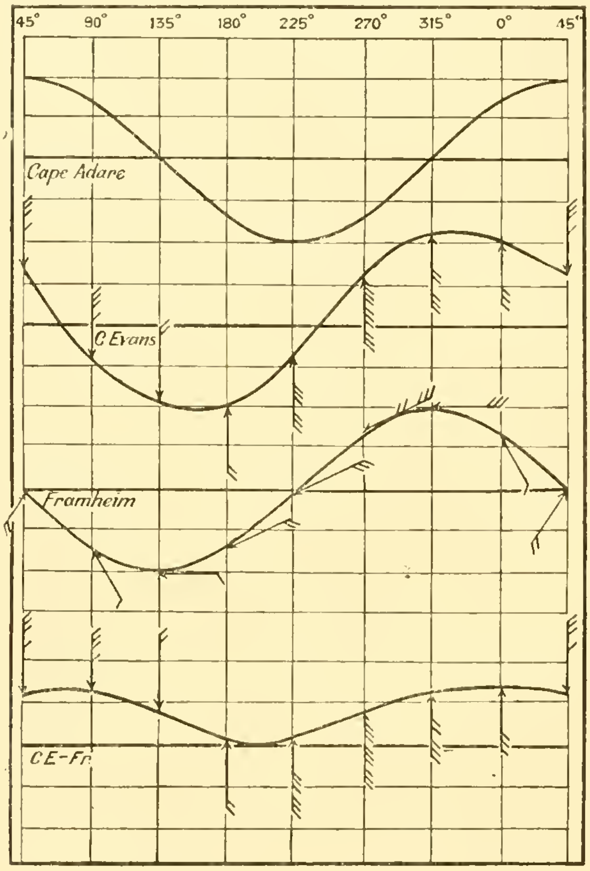


FIG. 74. Modified pressure waves.

In the first place they accelerate the arrival of the maximum pressure at Cape Evans. In the case considered, which of course is only qualitative, the maximum pressure arrives at Cape Evans while the crest of the wave is still over Framheim. On the other hand the minimum is hardly affected. This, no doubt, is the explanation of why the maxima appear to travel faster than the minima from Framheim to Cape Evans as found from the actual observations (see table 122).

In the second place it will be noticed that as soon as the blizzard commences the pressure at Cape Evans commences to rise relatively to Framheim, so that the lower curve of figure 74 is appreciably different from that of figure 65*b*.

On comparing the curves and winds shown in figure 74 with those shown on the plates in Volume II, we see a most striking resemblance. Examining first the bottom curves, giving the pressure difference between Cape Evans and Framheim and the winds at Cape Evans, we see that on both the blizzard winds occur when the curves rise, and the northerly winds when the curves fall. We also see that the blizzard commences on figure 74 just when the pressure difference between the two stations is zero. From the actual observations as shown on the plates it appears that a blizzard commenced whenever the curve approached its zero and seldom at any other time. On the other hand northerly winds, as a general rule, commenced when the difference curve reached its maximum.

Turning now to the relationship between the winds and actual pressure at each stations we shall also find important resemblances between the theoretical and the actual conditions.

According to the theoretical curve, figure 74, S.E., S. and S.W. winds at Framheim are associated with a falling barometer at that station, while easterly to northerly winds occur when the pressure is rising. The actual observations plotted on the plates show the same relationship. There are many exceptions, and we have seen that we are to expect them, but there can be little doubt of the general relationship, see in particular plates 4, 5, 10, 11 and 22. According to Mohn S.E., S. and S.W. winds occurred with a rising barometer in 135 cases and with a falling barometer in 144 cases; while N.E. and E. winds occurred in 181 and 143 cases respectively. The differences are not large but they are in the right direction. If one considers only periods during which the pressure changes are large the result is much more satisfactory.

At Cape Evans, according to the theoretical curves, northerly winds occur with a falling barometer and southerly with a rising barometer. This relationship can be seen on the plates particularly with the northerly winds. It is, however, clearly brought out by calculating the average rise and fall of the barometer with different winds. The barometer changes during four hours about each wind observation have been tabulated for 17 months with the following result :—

TABLE 125.

Cape Evans change of barometer and wind.

	NORTH WIND.		Calm.	SOUTH WIND.	
	>30 miles per hour.	11–30 miles per hour.		11–30 miles per hour.	> 30 miles per hour.
Barometer change in four hours.	−·017	−·015	−·003	+·004	+·014

We thus see that the theoretical relationship between the winds and pressure does agree in the main with the actual observations.*

The pressure curves on the plates show that the actual waves which travel across the area vary greatly in amplitude and phase and we have considered only one in which $a = \cdot 3''$ and $\phi = 45^\circ$. If we investigate other waves in the same way we find that the theoretical northerly and southerly winds at Cape Evans commence and end at very nearly the same positions on the difference curve, but vary much more on the actual pressure curves. This agrees with the fact which we have just discussed, that the actual winds are not so closely related to the pressure as to the pressure difference between Cape Evans and Framheim.

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* See, however, paras. (4) and (5) on page 237.

We now see that both theoretically and actually the pressure waves themselves give little information as to the winds to be expected while the difference curve is of primary importance.

We will now pass on to study in detail the theoretical pressure distributions shown in the *b* diagrams on figures 66 to 73.

It must, however, be pointed out that for purposes of calculations we have had to use a pure harmonic pressure curve which ends with the same pressure at each station that it started with. In reality the waves were far from being harmonic, they were nearly always very unsymmetrical, the crest and the trough being of unequal size. They changed their form and also their relative phases as they travelled from Framheim to Cape Adare.

We must not therefore expect to find the whole sequence of changes carried through in the same order for each individual wave. For any given position of an actual wave we must choose the position of the theoretical wave which most nearly represents the actual conditions, and compare the actual and theoretical pressure distribution at those epochs.

It will be seen at once that the eight diagrams may be divided into two main types, which are associated with southerly and northerly winds at Cape Evans respectively. We shall call these the blizzard type and the northerly wind type. The former of these includes the four diagrams 69 to 72. In each of these the highest pressure is over the Barrier and the lowest over the Ross Sea. The most typical distribution is that in which the blizzard is the strongest, figure 71. In all these diagrams the wind at Framheim is from the east or slightly from the north of east. The northerly type includes the two diagrams 66 and 67, in each of these the wind at Framheim is southerly. Diagrams 68 and 73 are intermediate. It will be noticed that the theoretical pressure distribution gives at Framheim only winds between N.E., through S. to S.W.; and these are closely related to the winds at Cape Evans, for during southerly winds at Cape Evans the winds at Framheim are strong and between N.E. and E., while with northerly winds at Cape Evans the winds at Framheim are light and between south-east and south-west.

To investigate whether these relationships hold in the actual observations the following table has been prepared:—

TABLE 126.

Winds at Framheim.

	PERCENTAGE FREQUENCY.																
Winds at Cape Evans.	N.	N.N.E.	N.E.	E.N.E.	E.	E.S.E.	S.E.	S.S.E.	S.	S.S.W.	S.W.	W.S.W.	W.	W.N.W.	N.W.	N.N.W.	Calm.	Mean velocity miles per hour.
All winds. . .	2	1	6	4	29	3	5	1	10	3	12	2	2	0	1	0	21	8
>10 miles per hour, south.	1	0	8	3	42	6	7	1	7	2	4	1	0	0	1	0	17	10
>10 miles per hour, north.	1	0	6	0	14	1	4	0	15	6	15	4	4	0	3	2	23	7

The first line shows the preponderance of winds from the direction between N.E. through S. to S.W. The remaining directions from W.S.W. to N.N.E. have only 8 per cent. of the wind between them.

The remaining two lines show how the winds at Framheim vary during blizzards and northerly winds at Cape Evans. The relationship comes out more clearly if we group the Framheim winds as in the following table:—

TABLE 127.

Winds at Framheim.

Winds at Cape Evans.	PERCENTAGE FREQUENCY.		RESULTANT.	
	NE, ENE, E, ESE, SE.	S, SSW, SW.	Direction.	Velocity miles per hour.
All winds	47	25	S. 74° E.	3·7
>10 miles per hour, south .	66	13	S. 88° E.	7·8
>10 miles per hour, north .	5	36	S. 8° W.	2·3

During blizzards N.E. to S.E. winds at Framheim are nearly five times as frequent as S. to S.W. winds, while during northerly winds at Cape Evans the S. to S.W. are actual more frequent than the N.E. to S.E. winds.

The relationship comes out still more clearly by taking the resultant direction and velocity of the winds at Framheim during blizzards and northerly winds at Cape Evans. From table 127 we see that during blizzards the resultant wind at Framheim is nearly due east, while during northerly winds it is from slightly to the west of south. Also the resultant velocity at Framheim is nearly three times as great during blizzards as during northerly winds. Thus the theoretical winds and the actual winds are in excellent agreement.

We have now to examine the maps showing the isobars based on the actual observations to see if they agree with the theoretical diagrams which we have constructed.

A rapid glance through the maps is sufficient to show that the two main types of which figures 71 and 66 are representatives are constantly repeated, while the great majority of the maps vary only in detail from one or other of the theoretical diagrams.

It would be too tedious to describe in detail many of the maps and to point out where they agree and where they differ from the theoretical diagrams. The reader will be able to see these points for himself if he is sufficiently interested to spend some time in comparing together the maps, plates and diagrams.

It will therefore be sufficient if one or two typical examples are shortly discussed here to indicate what should be looked for in a further study of the data.

The first plate contains a very typical example of the effect of a moving pressure wave on the pressure distribution. The actual pressure wave between the 6th and 10th was not very large, but it produced a normal difference wave (bottom curve).

The two maps for April 6th are similar to the two figures 66 and 67 which represent the crest of a wave at Cape Adare with the difference wave decreasing.

During April 7th the pressure distribution was changing and the two maps on this day are similar to figures 68 and 69. The evening map shows that the easterly wind has started near to Framheim, but it has not yet reached Cape Evans.

At midnight on the 7th the blizzard started at Cape Evans and the maps for April 8th are similar to the theoretical diagrams for the blizzard, figures 71 and 72.

The map for 8 A.M. on the 9th is similar to figure 73 with the high pressure to the south of Cape Evans. In the next map, 8 P.M. on the same day, the high pressure is shown to have passed Cape Evans and the distribution is now becoming similar to that with which we started, figure 66. The map for 8 A.M. on April 10th is almost exactly the same as figures 67 and 68.

It will be seen that a complete wave has passed during this period and the maps have gone through the complete sequence shown in the theoretical diagrams.

A similar complete sequence is seen if the maps from April 13th, 8 P.M., to April 17th, 8 A.M., are compared with the theoretical diagrams.

In fact for every well-marked wave on the lowest curve of the plates the maps will be seen to go through the same sequence in a more or less complete manner.

It will be felt that the paucity of observations over such a large area leaves a great deal of freedom in drawing the isobars, and that if there had been more stations their observations might not have fitted in with the simple scheme of pressure changes here discussed. From October to the end of the year there were parties on the Barrier which provided so many more stations, and one therefore turns with interest to the maps for this period to see whether the sledging observations do or do not confirm the theory. Unfortunately during this period the pressure waves are not well marked and for days together the pressure was nearly constant over the whole area (see plates 19 to 23). Thus while the pressure distribution will be found to conform to the main types there are few occasions when the passage of waves makes it possible for us to follow the complete sequence of changes. There are, however, one or two examples which are worth studying.

During the period October 23rd to October 29th the lowest curve of plate 18 shows that two complete waves passed over the area, and as at this time Captain Amundsen was taking observations on the Barrier the period is suitable for our discussion. Both maps for October 23rd show a distribution similar to that of figure 66 or 67. During the next day, 24th, the pressure changes to the blizzard type and is therefore on the whole similar to figures 70 and 71. At 8 A.M. on October 25th the distribution is the same as that shown on figure 73 except that the gradient is stronger. The high pressure is just south of Cape Evans and is passing northward so that with the next map 8 P.M., October 25th, we have returned to the starting point with the high pressure over the north-west of the Ross Sea, figure 66.

A similar sequence is repeated during the next four days so that at the end of the sequence, 8 A.M. on October 29th, the pressure distribution is the same as at the beginning, 8 P.M. on the 25th.

These and other examples, which the reader will see on turning over the following maps, on all of which there are observations from the Barrier, show that when there are large changes of pressure the Barrier observations fit in as well as can be expected with the theoretical distributions of pressure which we have deduced on the assumption of travelling pressure waves.

There can be no doubt now that the passage of the pressure waves alters the pressure distribution making it at one time favourable for blizzards and at another favourable for northerly winds, but it must not be forgotten that the first step in our theoretical discussion was to show that in the absence of pressure waves the conditions are favourable for blizzards. We will now examine one or two interesting cases of blizzards in the absence of well-marked pressure waves. A good example is shown on plate 12.

On and after August 18th there are no large pressure waves shown on this plate. On August 19th, however, a blizzard commenced at Cape Evans. The map for 8 P.M. on August 17th shows a nearly complete calm at all stations, the north-westerly wind at Framheim being only a light local breeze of 1·4 miles an hour. From the actual pressure at the three stations it is obvious that the isobars must run from the east to the west as in figure 64*a*, the Barrier being at a higher pressure than the Ross Sea. Throughout the 18th a light easterly wind was blowing over the east of the Barrier as shown by the wind at Framheim, while the air was calm at Cape Evans. It will be noticed from the lowest curve on the plate that during the whole of the 18th the pressure at Cape Evans was slightly rising relatively to Framheim. This has been explained as due to the piling up of air over the west of the Barrier along the Western Mountains. At 8 A.M. on the 19th a blizzard has started at Cape Evans and now with the increased motion the pressure difference between the west and east of the Barrier rapidly increases, and the pressure difference Cape Evans - Framheim rises by nearly half an inch.

Another important and interesting example is the blizzard which commenced at midnight of November 15th. At 8 A.M. on November 15th a very shallow low pressure area appears over the south of the Barrier. During the day this disappears and by the evening it is replaced by a high pressure area. Although the wind at Framheim is from the south-east, it is almost certain that it is from the east over the greater part of the north of the Barrier. The pressure now rises in the west relative to the east and by the next morning typical blizzard winds are reported from all parts of the Barrier. It is interesting to notice that there has been practically no change in the height of the barometer at any of the five stations between 8 P.M. on the 15th and 8 A.M. on the 16th and yet there is a very large change in the wind conditions which has resulted in a new distribution of the isobars. Similar large changes in wind conditions with little, if any, change in pressure are quite common and many examples will be found if the maps are examined in detail.

In drawing the maps many interesting facts attracted one's attention, but it would not be wise to discuss the maps in detail as one feels that it is very questionable whether the run of the isobars is anything more than a rough approximation to the actual conditions. There can, however, be little doubt that the general pressure distribution and the sequence of pressure changes is that shown by the maps.

One point, however, must be discussed before we review our conclusions. We have repeatedly shown that the consequence of the flow of air from the east to the west of the Barrier, when its motion is stopped and the air is forced by the Western Mountains to flow northwards, is a rise of pressure at Cape Evans relative to Framheim.

We have just examined two cases of blizzards which were accompanied by these relative changes of pressure in the absence of pressure waves, and we found that the pressure difference Cape Evans - Framheim was nearly as large as in the case of blizzards accompanying large pressure waves. The question at once arises may not the blizzards be the cause of the pressure waves and not the pressure waves the cause of blizzards? A study of the curves on the plates will soon dispose of this idea. On plate 17 there is a large pressure wave with its crest at Framheim and Cape Evans on the 14th. There was a short blizzard just before, and a longer one just after, the crest passed Cape Evans. Now it will be noticed that both these blizzards were accompanied by a rise in the difference curve although the absolute pressure at both Cape Evans and Framheim was rising throughout one blizzard and falling throughout the other. In this case the pressure wave affected Cape Evans and Framheim almost simultaneously, therefore for practical purposes the pressure wave did not affect the pressure distribution. The blizzards occurred exactly as they would have done if the pressure curve had been a straight line, and the pressure differences shown on the lowest curve were due to the blizzard.

The way that the induced pressure difference is impressed on the pressure wave is clearly seen in the case of the second blizzard, for the fall of pressure is decreased at Cape Evans and increased at Framheim. In this case it is obvious that the pressure difference is due to the blizzard and is superposed upon the pressure wave. It is therefore clear that the large pressure wave itself cannot be due to the blizzard.

Granted that pressure waves exist independently of blizzards the fact that they arrive at Framheim before Cape Evans and at Cape Evans before Cape Adare proves that they travel. If they travel they must cause pressure difference between the stations. We have therefore two causes at work producing pressure difference between Cape Evans and Framheim, first the passage of the pressure waves and second the dynamical effects of the blizzards. On account of the coincidence that the line joining Cape Evans and Framheim is at right-angles to the Western Mountains and at the same time cuts the wave fronts at an angle of 45°, the two causes increase the pressure difference at the same time. Some pressure waves do not produce blizzards, the difference curve in this case is due to the travelling wave alone, examples are seen on May 22 and 23, June 27 to 29, July 30 to August 1, etc. We have just discussed a typical case, in which changes of pressure due to the blizzards are superposed on the pressure waves and we have examined several cases of pressure differences produced by blizzards in the total absence of pressure waves. Thus there are examples of all the possible effects to be expected according to the theory.

To these considerations we also have to add the fact that the pressure waves are recognisable on the surrounding plateau and appear on the Polar Plateau before they reach the Barrier, hence the waves cannot be caused by the blizzards. There is no escape from the conclusion that the pressure waves are imposed on the Ross Sea area from outside.

During the study of the records, which led finally to the theory sketched above, a large number of statistical investigations was made to find the relationship of the pressure conditions and changes at the three stations which accompanied the blizzards, northerly winds and calms at Cape Evans. The results of these investigations are contained in table 128. Six classes of wind were taken, five of which are shown in the table; the class of wind 6 to 10 miles an hour has been left out because it adds nothing to the discussion.

TABLE 128.

Pressure and Winds.

	WINDS AT CAPE EVANS.				
	North.		Calm. 0–5	South.	
	>30	11–30		11–30	>30
(1) Pressure difference, Cape Evans–Framheim.	+·032	+·189	+·193	+·191	+·243
(2) Pressure difference, Cape Evans–Cape Adare.	−·011	−·012	+·071	+·105	+·143
(3) Change of pressure difference in 4 hours, Cape Evans–Framheim.	−·038	−·023	+·007	+·007	+·021
(4) Change of pressure in 4 hours at Cape Evans.	−·017	−·016	−·005	+·004	+·015
(5) Change of pressure in 4 hours at Framheim.	+·021	+·007	+·002	−·003	−·006
(6) Pressure at Cape Evars, departure from mean of month.	−·201	−·112	+·028	+·008	−·005
(7) Pressure at Framheim, departure from mean of month.	−·054	−·107	+·031	−·008	−·040
(8) Pressure at Cape Adare, departure from mean of month.	−·091	−·020	+·045	−·029	−·060

(1) *Pressure difference, Cape Evans–Framheim.*—It is interesting to notice that the pressure difference remains positive with all kinds of air motion. In other words the pressure on the average is higher at Cape Evans than Framheim in all winds. This result is obvious from the lowest curve on the plates which is practically never below the zero line. The difference, however, is least with high northerly winds and greatest with high southerly winds. This is in agreement with the whole theory which makes the high southerly winds increase dynamically any pressure difference existing between the west and east of the Barrier.

(2) *Pressure difference, Cape Evans–Cape Adare.*—With northerly winds the pressure at Cape Adare is higher than at Cape Evans, while with southerly winds the reverse is the case. This requires no explanation, for the theoretical diagrams show a high pressure area near Cape Adare during northerly winds and a low pressure area over the Ross Sea during southerly winds.

(3) *Change of pressure difference, Cape Evans–Framheim.*—This gives numerically the obvious relationship between the wind and the pressure difference shown on the lowest curves of the plates. Of all the relationships this is the most consistent. High northerly winds are associated with the falling parts of the curve and high southerly winds with the rising parts, hence the change in the pressure difference is negative in the former case and positive in the latter. The change is regular, from $-\cdot038''$ in 4 hours with high northerly winds through calms to $+\cdot021''$ with high southerly winds.

(4) & (5) *Change of pressure at Cape Evans and Framheim.*—It is interesting to notice that the change in pressure at the two stations is of opposite sign during all winds at Cape Evans. That is, during northerly winds the pressure falls at Cape Evans and rises at Framheim, while during southerly winds it rises at Cape Evans and falls at Framheim. This does not appear to agree with the theoretical curves on figure 65*b*, according to which the blizzards occur while the pressure is rising at both Cape Evans and Framheim, and the northerly winds while it is falling at both stations. Nor does it seem consistent with the fact that there is very little difference in phase between the waves at Cape Evans and Framheim. For the pressure to change in opposite directions at the two stations would necessitate a difference of phase of about 180°, this is obviously not the case as can be seen from the pressure curves on the plates. It has however been pointed out that the change in the wind direction may occur at very different parts of the actual pressure curves according to the shape, size and rate of travel of the various waves. The one thing, however, which does not change is the dynamical pressure difference which always raises the pressure at Cape Evans and depresses it at Framheim. Thus it is this effect which comes to light in the mean of the whole series of observations.

(6), (7) & (8) *Departure of pressure from mean of the month at Cape Evans, Framheim and Cape Adare.*—We have here a very unexpected result. With the exception of a small excess at Cape Evans during winds of 11–30 miles an hour from the south, the pressure is below normal at all three stations during both northerly and southerly winds and above normal only during calms. It will also be noticed that the higher the winds both north and south the greater the defect of the pressure.

This is a result which would never be suspected from the curves. No indication can be seen that the high winds, both northerly and southerly, are associated more with the troughs of the waves than with the crests, nor do the crests as a rule appear to be associated with calms. The only explanation I can offer is that the winds and calms are distributed uniformly over the waves, but when the average pressure about which the waves oscillate is low the air motion is intensified both from the northerly and southerly directions.

Pressure distribution and temperature.—When discussing the mean pressure at Cape Evans and Framheim, (page 173) it seemed a paradox that the station with the lower mean temperature should have the lower mean pressure, and also that this apparently inverted pressure gradient should increase as the temperature difference increased.

The cause is now obvious. Framheim is on the east of the Barrier and shares in the temperature of the Barrier. The low temperature of the Barrier is the principal cause of the high winds over the west of the Barrier, and the high winds over the west of the Barrier, being constrained to travel parallel to the Western Mountains, produce the pressure difference between Cape Evans and Framheim; at the same time the high winds through McMurdo Sound constantly remove the layer of cold air which forms during calm weather and so raises the mean temperature at Cape Evans. Thus it is the very fact that Framheim is cold which causes the relative high pressure and temperature at Cape Evans.

During the winter the action is intensified, the temperature difference between the Barrier and Ross Sea is increased producing greater air motion and with it a greater difference in temperature and pressure at the two stations.

Weather.—It remains now for us to consider the type of weather associated with each type of pressure distribution.

We have seen from our previous discussion of the actual data that southerly winds are associated with cloud and snowfall while northerly winds are associated with cloudless skies and absence of precipitation (pages 11 and 151). These are the conditions which we should expect from the pressure distribution associated with the two types of wind. The southerly type of pressure distribution is practically that of a cyclone with its centre situated over the south of the Ross Sea. Also the crowding together of the stream lines of air-flow over the north-west corner of the Barrier must cause forced ascensional air motion in that region. Thus cloud and precipitation would be the natural consequence of such a pressure distribution and of such constrained air motion. Thus the weather associated with blizzards is explained. When northerly winds occur at Cape Evans there is a high pressure area over the Ross Sea. In such a case the whole of the Ross Sea area is practically under anticyclonic conditions. Also the high northerly wind itself indicates that considerable outflow of air is taking place from the region of high pressure. This air can only be supplied by descending currents which would effectively prevent the formation of cloud and the precipitation of snow.

An important characteristic of the blizzards is the suddenness with which they frequently commence.

It appears to me that two factors are responsible for this feature. When the pressure difference which is ultimately to result in a blizzard becomes established gradually the air over the Barrier slowly gets set into motion, but the cold surface layer tends to remain stationary while the upper layers slide over it. Thus the upper air may be in rapid motion while a calm continues on the ground; the cloud observations frequently showed this to be the case. This condition cannot continue indefinitely, the cold surface layer gets disturbed, broken up locally and finally swept away. Then the blizzard commences with a sudden burst of wind and an appreciable rise of temperature. The pressure difference, however, is not always established gradually. When a pressure wave travels across the country at about 30 miles an hour it sets up its pressure gradient faster than the air can get into motion. In these conditions the air behind is moving faster than the air in front, and so no air motion takes place at each point until this mass of moving air arrives with a sudden burst. Similar effects are seen when tidal waves enter an estuary and are impelled forward by the water behind faster than the water in front can be set in motion, the result being the well-known phenomenon of the tidal bore.

Now both these factors, the cold layer and the travelling pressure wave, are much more developed in the winter, and a study of the records shows that nearly all the sudden commencement of blizzards occurred in the winter and early spring months. In the summer when there were few and small pressure waves and no cold layer, the blizzards commenced with light winds which slowly developed into storms.

Summary.—On account of its geographical position and temperature conditions the pressure over the Barrier tends to be higher than the pressure over the Ross Sea immediately to its north. The air moving under the pressure distribution is deflected to the left by the rotation of the earth and moves towards the west. Its westerly motion is arrested by the range of mountains which runs approximately north and south along the western edge of the Barrier and Ross Sea. The deflected air current flows northwards as a concentrated stream over the north-western corner of the Barrier near to Ross Island on which Cape Evans is situated.

A system of parallel pressure waves has been shown to travel over the whole area in an approximately north-westerly direction. These waves modify the normal pressure distribution, sometimes intensifying it, when the normal air current over the west of the Barrier develops into a blizzard, and sometimes completely reversing it when northerly winds are experienced at Cape Evans.

PRESSURE, WINDS AND WEATHER AT CAPE ADARE.

We are now able to consider the conditions at Cape Adare which have not entered into our previous discussion. If one turns over the plates of pressure curves it is quite clear that Cape Adare comes under the influence of the pressure waves which we have found to be the governing factor of the wind and weather over the Barrier. On examining the pressure curve for Cape Adare in detail, however, we shall find an important difference between it and the curves for Cape Evans and Framheim. The pressure waves at Cape Adare will be seen frequently to have irregularities which are not shown on the curves for the other two stations. To take a concrete example the curve for June 19th on plate 7 should be examined. It is quite obvious that here we have at Cape Adare a sudden dip imposed on what would otherwise have been the crest of the pressure wave which passed over Framheim twelve hours previously. Several similar dips in the Cape Adare curve will be seen and as the majority of them are connected with hurricane winds it is natural to associate them with passing cyclones. Luckily just as the *Terra Nova* approached Cape Adare at the end of December 1911 to remove the party, one of these depressions passed, and the simultaneous observations made on the ship and at the Cape give us valuable information which we shall be able to use in our discussion. We will therefore unfold plate 23 and examine the pressure curves and maps for the period December 29th to January 2nd. It will be noticed that on plate 23 a curve has been added giving the pressure and winds as observed on the ship. The position of the ship was constantly changing, therefore its latitude and longitude at noon each day have been entered below the pressure curve. The maps for this period show the passage eastwards of a depression, the centre of which passed at a short distance to the north of Cape Adare. These maps teach several important lessons.

(*a*) The local conditions in the south of the Ross Sea are not appreciably affected by the relatively deep depression passing near Cape Adare. Also the high south-east winds at Cape Adare are not the continuation of Barrier blizzard winds. Although we have no actual observations between Cape Evans and Cape Adare to prove this statement yet it is quite impossible to draw isobars to fit the pressure and wind observations without the ridge of high pressure over the north-west of the Ross Sea which makes such a continuation impossible (see maps for December 31st).

(*b*) It will be noticed that the winds at the ship change from northerly to southerly directions as the depression passes, while at Cape Adare the wind, as soon as it comes under the influence of the depression, remains practically constant in direction varying little from south-east. There is not the slightest doubt that this is the result of the land masses surrounding the meteorological station on Cape Adare. The northern coast of

Victoria Land consists of a range of mountains between 6,000 and 10,000 feet high which runs from the south of Cape Adare in a north-westerly direction to Cape North. This range limits the air motion to be parallel to itself. Also the promontory of high land on the west side of which the station was situated would protect it from all winds between south-east and north. Thus when a depression is approaching Cape Adare from the west the wind cannot flow along the isobars from the north or north-east as would be the case away from the land, but a flow of air passes from the north of the Ross Sea over the hills into Robertson Bay when it becomes at Cape Adare a wind from the south-east. Now when winds are constrained to travel directly from the high to the low pressure in this way, they attain under a given gradient a much higher wind velocity than they would if they were left free to travel along the isobars under the deflecting force due to the earth's rotation.

The map for 8 A.M. on December 30th shows all these features clearly. The wind at the ship is nearly parallel to the isobars and so from the N.N.E. The isobars at Cape Adare are from the north-east to the south-west, but the wind is constrained to travel parallel to the range of mountains and is therefore from the south-east. The air motion is nearly directly across the isobars and is therefore much more violent than it would be if it were not constrained to move in this direction, hence while the ship recorded only force 4, force 8 was recorded at Cape Adare.

When the depression has passed the isobars run from the south-east to the north-west, the wind can then travel along them and as the storm moves away to the east the wind velocity falls while the direction changes little. Thus while a depression is approaching the station from the west the winds are very high, but as soon as it passes the wind velocity decreases, but the wind remains from some direction near S.E. the whole time. We should therefore expect the hurricanes to occur while the barometer is very low at Cape Adare and to cease almost as soon as the pressure commences to rise; the observations show that this is the general rule.

From this example we are justified in assuming that each dip in the pressure curve at Cape Adare which is superposed on the main pressure waves and accompanied by high southerly winds indicates the passage of a cyclone. To these we may also add the few cases in which a high wind occurs at Cape Adare without any marked change of the barometer.

The following is a list of all the occasions on which depressions of this nature have left clear indications on the meteorological records taken at Cape Adare:—

TABLE 129.

Depressions passing Cape Adare. April–December 1911.

Month.	Dates.	Number in month.
April	8, 11, 14, 18, 28	5
May	6, 8, 9, 12, 16, 18	6
June	1, 9	2
July	7	1
August	2, 15, 18, 31	4
September	3, 9–11, 16, 20, 26	5
October	14, 17	2
November	15, 23	2
December	19, 22, 31	3
9 months	....	30

Thus we have good evidence that during 9 months 30 depressions passed near to Cape Adare and it is clear from the maps that in every case the centre could not have been far to the north of the station.

But for our purpose the most important conclusion is that the large pressure waves which affect the whole of the Ross Sea area are not associated with travelling depressions over the Southern Ocean. On the contrary the pressure changes due to such travelling depressions are clearly superposed upon the larger pressure waves.

Usually the depressions only affect the pressure curve at Cape Adare, but there are a few exceedingly interesting exceptions to this rule. The depression which passed Cape Adare just before midnight on August 2nd, plate 11, is one of the most interesting examples.

During August 1st the barometer was falling at all three Antarctic stations under the influence of an Antarctic pressure wave. There can be little doubt that if there had been no disturbance the minimum of this wave would have occurred at each station in some such way as that shown by the dotted line on the diagram. A deep depression, however, passed just to the north of Cape Adare and its effect on the barometer curves at the three stations is interesting. The dip at Cape Adare was deep and rapid, the fall between 20 hours on the 1st and 20 hours on the 2nd being no less than 1·15″. This rapid fall at Cape Adare appears to have induced a rise of the barometer at Framheim and Cape Evans which if we may take the dotted curves as being approximately the undisturbed barometer conditions was ·6″ at Framheim and ·3″ at Cape Evans. If this example had stood alone it would have been natural to assume that the rise at Framheim and Cape Evans was not really, but only accidentally related to the Cape Adare depression, but there are several other examples. Another and probably better example occurred on August 15th and as in this case there was no pressure wave the increase in pressure is clearly shown on both the curves for Framheim and Cape Evans. In both these cases the fall of the barometer at Cape Adare was large and rapid and the wind at that station reached hurricane force. With lesser depressions at Cape Adare the rise in pressure at the other stations was naturally much smaller and is generally lost in the larger pressure waves. If, however, the Framheim curve is carefully examined many cases can be seen of the induced rise of pressure at Framheim when a depression passed Cape Adare, generally as a slight increase in the rate of rise or a decrease in the rate of fall. The following examples may be mentioned: April 14th, May 16th, August 31st, September 16th. The explanation of this rise of pressure is not obvious, and as far as the writer knows it is a unique phenomenon. Any explanation in the absence of more information is of the nature of a guess; but there can be little doubt that it is a dynamical effect due to the system of rotating winds suddenly appearing in the opening of the Ross Sea.

The conditions at Cape Adare are seen from the above discussion to be different from those at Cape Evans and Framheim. The two latter stations are dominated by conditions which are truly Antarctic, while at the former station the weather is affected by cyclones which form over the Southern Ocean and move on the whole from west to east. It is however to be strongly insisted upon that the main pressure changes at Cape Adare are not due to travelling cyclones, but to pressure waves which travel in a north-westerly direction and affect the whole of the Ross Sea area and the surrounding plateau.

PRESSURE, WINDS AND WEATHER AT THE GAUSS STATION.

Having discussed in detail the weather conditions in the Ross Sea area and having come to the conclusion that the weather there is not governed by travelling cyclones and anticyclones, but by travelling pressure waves moving outwards from the continent it is natural to examine the weather at other Antarctic stations to see if further evidence in support of this conclusion can be found. In view of Meinardus's full discussion of the observations made at the Gauss Station this offers a suitable example.

The Gauss Station was in 66° 2′ S., 89° 38′ E. only 53 miles from the edge of the Antarctic Continent. The situation was ideal for observing the force and direction of the wind as there were no high lands in sight.

The most remarkable feature of the weather of the Gauss Station was an almost uninterrupted succession of high easterly winds. Meinardus devoted a large amount of work to investigating the weather characteristics of these winds and found that they were accompanied by

(*a*) high temperature,
(*b*) vapour pressure and relative humidity in excess,
(*c*) large amounts of cloud,
(*d*) large amounts of precipitation.

He sums up his discussion of these winds with the remark:

> 'All these weather characteristics correspond in every detail with the type of weather found in both hemispheres in the eastern half of depressions near to their centres. This leads to the conclusion that the weather during the east winds is governed by depressions the centres of which lie in the northern or north-west quadrant of the horizon.'

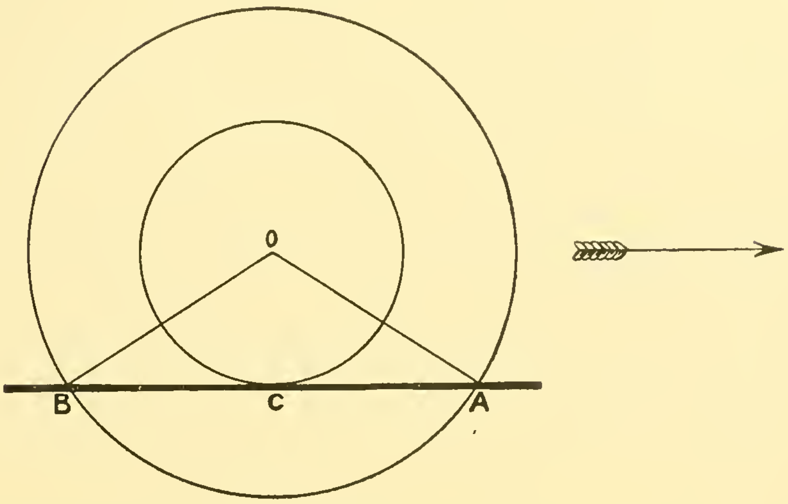
Further these cyclones are supposed to travel from west to east along the parallels of latitude; and the geometrical position of their centres is along the trough of low pressure which he fixes, in the longitude of the Gauss Station, as varying between 59° S. and 64° S.

This conclusion is little different from that of Lockyer, except that Meinardus appears to consider that the centres of the cyclones often pass over or near to the edge of the Antarctic Continent, while Lockyer considers that the conditions are best represented by cyclones of large extent the centres of which actually travel on or near 60° S.

We will now examine a few typical records of the barometer changes at the Gauss Station and then build up a cyclone which would account for the pressure changes and see how the winds observed agree with those which the passage of the cyclone would cause.

On plate IV of this volume the pressure and wind observations made at the Gauss Station have been plotted for eleven periods during which there were large and rapid changes of the barometer. In the following discussion we shall fix our attention on the portion of the pressure waves in which the barometer falls and rises by half an inch. A line has therefore been drawn in the hollow of each wave half an inch above the minimum and the time taken for the barometer to fall and rise the half inch has been entered above each line. Now if these waves are caused by the passage of cyclones the wind changes below the line should correspond to the changes observed when the 'trough' of a cyclone passes over a station. What these changes would be can be found by the method indicated by Gold in his paper 'Barometric Gradient and Wind Force' (M. O. No. 190, 1908).

Suppose that the circular cyclone represented in the following diagram is moving from the west to east, and that the centre O passes to the north of the station which successively occupies the positions A, C and B relatively to the centre. From A to C the barometer falls and from C to B it rises. Let us consider that A is so chosen that the barometer falls half an inch in going from A to C, then from the geometry of the figure we can calculate the gradient, the wind force and the change in wind direction, as the cyclone passes the station.



There are three variables:

(*a*) The velocity at which the cyclone is moving to the east.

(*b*) The distance that the centre of the cyclone passes to the north of the station.

(*c*) The time taken for the barometer to fall and rise half an inch.

We will at first consider that the cyclone travels at the mean rate deduced by Lockyer, *viz.*, 9·5° of longitude in a day, this leaves us with only two variables, (*b*) and (*c*).

The following table gives the results of a calculation made in this way for four values of (*b*) and three of (*c*):—

Table 130.

	Distance of centre.	Wind velocity half way between A and C.		Change of wind direction between A and B.
	Degrees of latitude.	Miles per hour.	Beaufort number.*	Degrees.
Barometer falls and rises ½″ in one day.	6°	251	>12	35
	4°	179	>12	51
	2°	105	>12	88
	0°	44	9	180
Barometer falls and rises ½″ in two days.	6°	102	>12	65
	4°	77	>12	88
	2°	54	11	125
	0°	34	8	180
Barometer falls and rises ½″ in three days.	6°	58	12	88
	4°	47	10	111
	2°	36	8	142
	0°	26	6	180

* Scale given on page 99 of Meinardus.

From the first line of the table we see that a cyclone travelling from west to east at 9·5° of longitude a day with its centre 6° of latitude to the north of the station and causing a fall and rise of the barometer of half an inch in one day would produce a wind velocity of 251 miles an hour, and the wind direction would change 35° between the commencement and ending of the change of half an inch in the pressure. Now Beaufort force 12 was never recorded at the Gauss Station, hence the cases which give the wind force as 12 or over have to be excluded. This leaves us with one case in the first group, two cases in the second, and three in the third. It will be noticed that the change in the wind direction in these six remaining cases is always above 100°. In other words no cyclone travelling with the given velocity could cause a fall and rise of the barometer of half an inch in less than three days without the wind changing direction at the station by more than 100°.

The impossibility of Lockyer's cyclones which have their centres 6° to the north of the Gauss Station producing the observed effect is particularly obvious. For such a cyclone to produce a fall and rise of half an inch at the Gauss Station, *even in three days*, would necessitate a hurricane wind and a change of direction of 88° there, so what the conditions would be nearer the centre can best be left to the imagination.

The case is not improved by considering other rates of travel or other shapes of isobars, for a little consideration will show that any change which decreases the angle through which the wind should change will increase the wind strength. Thus any wind change of less than 100° would always be accompanied by hurricane winds.

Thus at the latitude of the Gauss Station, no cyclone, no matter what its rate of travel or distance of its centre from the station, could produce a fall and rise of the barometer of half an inch in three days or less without either changing the wind direction by more than 100° as it passed, or causing winds of more than hurricane force.

Now at the Gauss Station we see barometer changes of much more than half an inch in considerably less than three days *without any appreciable change of wind direction* and the only conclusion to be drawn is that these pressure changes are not produced by moving cyclones.

There seems no alternative but to assume that the Gauss Station is subjected to travelling pressure waves similar to those in the Ross Sea area. If such waves travel outwards from the continent in all directions their wave fronts will be approximately parallel to the coast. Now along the coast there must be a steep barometric gradient similar to the one between the Barrier and the Ross Sea and the waves will modify this pressure, increasing and decreasing it. Thus we see that the pressure waves will increase and decrease the gradient and with it the wind velocity, but as the isobars and wave fronts are parallel there will be little change in the wind direction.

Just as we found it impossible to say *a priori* what relationship should exist between the pressure waves at Cape Evans and the wind changes there, so it is impossible to say whether at the Gauss Station the easterly winds should be stronger or weaker with high or low barometer or should increase or decrease with rising and falling pressure.

It is very significant that at the Gauss Station the wind frequently changed direction suddenly from east to west, and next to the nearly constant winds from the east, winds from the west had the greatest frequency. This would be the natural consequence of pressure waves, but cannot be explained by cyclones unless one makes the impossible assumption that the centres of the cyclones passed frequently exactly over the station when travelling from north to south or from south to north and never passed over the station when travelling from west to east.

The weather characteristics which Meinardus found to accompany high easterly winds at the Gauss Station are as easily explained by the travelling wave theory as they are on the cyclonic theory. All these characteristics were found at McMurdo Sound to accompany blizzards and therefore may be expected to occur during the high winds at the Gauss Station. In fact they should be more pronounced at the latter station for the high winds there were from slightly north of east and so indicate an indraft of air from the open ocean which would on this account be warm and humid.

It is true that there are considerable difficulties in explaining all the relationships between wind and pressure at the Gauss Station on the wave theory, but there are none so great as the cyclone theory encounters in the large pressure changes with a nearly constant wind direction. Before the problem can be finally solved we must have simultaneous observations from neighbouring places as was the case in the Ross Sea area. It is possible that the results of the Australian Expedition, which recently wintered near to the Gauss Station, will help in this desired direction.

The data for Kerguelen and Snow Hill have also been examined to see if the conditions there are governed by pressure waves or cyclones.

The observations at Snow Hill show large pressure changes with little or no change in wind direction, but there are many cases in which the wind changes as the barometer rises and falls. There can be little doubt that cyclones pass over this station, but it is equally true that all the pressure changes cannot be ascribed to them.

At Kerguelen there is a much more intimate relationship between the changes of wind direction and changes of pressure than at any of the stations on or near the Antarctic Continent. But even at this station, not infrequently, there are large barometer changes without appreciable changes of wind direction, which may or may not be due to similar pressure waves to those recognised over the Antarctic Continent.

Turning now to the two top curves on the plates in Volume II giving the pressure and winds at Melbourne in Australia and The Bluff in New Zealand we see a most close relationship between the winds and the pressure changes. This is most clearly seen in the case of Melbourne because on that curve the wind observations are more complete. The relationship is extremely close: the falling barometer is accompanied by winds from some northerly direction, at the instant the barometer ceases to fall and commences to rise the wind changes and then blows from some southerly direction while the barometer is rising. We know from the daily weather charts of Australia that the weather at Melbourne and The Bluff is entirely dominated by travelling cyclones and anticyclones.

Conclusions.

Cape Evans and Framheim.—At these stations the evidence is almost conclusive that the barometer changes are not due to travelling cyclones and anticyclones but to real waves of pressure which travel outwards from the Antarctic Continent.

Gauss Station.—According to Meinardus the barometer changes at this station are due entirely to travelling cyclones. Evidence has been brought forward to show that this is impossible and reasons have been given for believing that at this station also pressure waves are mainly responsible for the barometer changes.

Cape Adare.—The evidence indicates very clearly that at Cape Adare the main barometer changes are due to pressure waves while secondary changes are occasionally due to travelling cyclones and anticyclones.

Kerguelen and Snow Hill.—The records for these stations show both pressure waves and cyclones, but the latter predominate at Kerguelen and the former at Snow Hill.

The Bluff and Melbourne.—At these stations there is little if any evidence of pressure waves, the barometer changes being almost entirely due to travelling cyclones and anticyclones.

From these results we are led to recognise long and deep pressure waves radiating out from the Antarctic Continent and extending over the Southern Ocean to some unknown distance from the continent, traces of which can still be seen in the pressure curves for Kerguelen. Over the Southern Ocean there are cyclones and anticyclones which travel on the whole from west to east. These systems are nothing like so large as those described by Lockyer, but in all probability are in all parts of the ocean of a similar size to those shown on the Australian Daily Weather Reports, and their centres may pass anywhere between the coast of Australia and the coast of the Antarctic Continent.

This result explains completely the results obtained in the statistical investigation of the non-periodic pressure changes. The waves over the Antarctic are long, regular and deep as can best be seen on the curves for Framheim. The barometer changes due to passing cyclones over the Southern Ocean are deep but short. Hence as we pass from the region of cyclones over the ocean to the pressure waves over the continent the length of the waves steadily increases, but there is little change in the amplitude, which is the conclusion already reached on page 188 from the observations.

Returning now to the theories of Lockyer and Meinardus with which we commenced this discussion, we see that there is no evidence of the large cyclones having their centres on 60° S. and covering the whole area from the south coast of Australia to the ice barrier around the Antarctic, which are the chief features of Lockyer's work. We have also shown that the pressure changes at the Gauss Station, Cape Adare and Hut Point used by Lockyer in his discussion are not due to cyclones over the Southern Ocean and therefore give no indications of the frequency, intensity or rate of motion of such cyclones. Further we have seen that the centres of small intense cyclones pass quite near to Cape Adare and we know from the daily weather charts of Australia that the centres of cyclones often pass near to the southern coast of that continent. It is therefore reasonable to suppose with Meinardus that the centres of cyclones occur in all parts of the Southern Ocean, but probably more frequently near 60° S. than in any other latitude. Thus Lockyer's scheme of southern hemisphere air circulation, simple as it is, does not fit the facts and must be abandoned. On the other hand there seems to be no justification for Meinardus's conclusion that the weather at the Gauss Station is governed by these Southern Ocean cyclones, and not by the Antarctic anticyclone. He admits that along the whole coast of the Antarctic Continent and for some distance over the surrounding sea the mean isobars are concave towards the high pressure in the south, but holds that the mean pressure distribution is not the governing factor in the weather. The mean pressure distribution, he says, is the result of the sum of the instantaneous pressure distributions and the latter are mainly due to the cyclones which pass to the north of the station. Thus the weather at the Gauss Station in spite of the shape of the mean isobars is not under the influence of the Antarctic anticyclone but under the influence of the cyclones which give rise to the easterly winds. Now we have shown that the easterly winds at the Gauss Station and the pressure change there are not due to cyclones, therefore the whole of Meinardus's scheme falls. In place of it we consider that the Antarctic anticyclone extends outwards from the continent to some distance over the sea, and that the pressure and wind changes are due to pressure waves radiating outwards from the continent as they do in the Ross Sea area. That the Gauss Station is under the influence of anticyclonic conditions is made very probable by the large percentage of clear skies which it has (see table 79) while it is made almost certain by the shape of its wind frequency curve (see figure 35). A station which has such a large proportion of calms and light winds could not possibly be dominated by a cyclonic pressure distribution. We have also shown (page 107) that the shape of the wind frequency curve indicates pressure conditions similar to those of McMurdo Sound, which, although so near to the low pressure area over the Ross Sea, is governed by the Antarctic anticyclone and pressure waves.

CHAPTER VII.

THE GENERAL AIR CIRCULATION OVER THE ANTARCTIC.

As stated at the commencement of the last chapter it was originally thought that atmospheric pressure decreases from the belt of high pressure near latitude 35° S. right up to the South Pole. The discovery of the high easterly winds south of latitude 40°, however, shows that this is impossible.

In 1893 * the significance of these easterly winds was clearly recognised and the existence of an anticyclone over the Antarctic was postulated to account for them. Later expeditions confirmed an increase of pressure with increasing latitude south of about latitude 60° S. and the idea of an anticyclone over the region within the Antarctic Circle was confirmed. The Antarctic anticyclone now became as firmly fixed in the minds of meteorologists as the idea of the Polar cyclone had been previously.

We have already seen that it occupies a very prominent part in Lockyer's scheme of the air circulation over the southern hemisphere, and Hepworth and others speak of it as if it were an undoubted feature of the Antarctic. Hobbs goes still further and contends that an anticyclone exists over every extensive snow-covered land, and takes the Antarctic and Greenland as the two most pronounced examples. To the anticyclones which owe their origin to a snow-covered land Hobbs has given the name ' glacial anticyclone ' and he has worked out at considerable length the meteorological features of such anticyclones. His conclusions as to the conditions over the Antarctic are so important that they must be considered in detail here.

Hobbs' Theory of the Glacial Anticyclone.†—Hobbs summarizes the evidence for fixed glacial anticyclones under the following eight heads‡ :—

(1) Centrifugal flow of surface air currents above inland-ice masses.

(2) Outward (centrifugal) sweeping of surface snow largely derived from the central areas, and its deposition and accumulation as a marginal fringe about the inland-ice.

(3) Snow in large part wind-driven above the sloping portions of the ice mass.

(4) Sudden warming of the air at the end of the blizzard—föhn effect in descending currents.

(5) Behaviour of upper air currents and movements of the cirri.

(6) The evolution of the Antarctic blizzard and its termination.

(7) Areas of relative calm corresponding to the flat central bosses of the ice domes.

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* Fricker. Journal of the Royal Geographical Society, Volume II, page 254, 1893.
Murray. Journal of the Royal Geographical Society, Volume III, page 17, 1894.

† The Role of the Glacial Anticyclone in the Air Circulation of the Globe, by W. H. Hobbs. Proc. American Philosophical Society, Volume LIV, No. 218, August 1915.

‡ *Ibid.*, page 689.

(8) Air highly charged with moisture within the flat central area of calms and precipitation of snow or ice near the glacier surface.

We will now consider this evidence and Hobbs' conclusions in so far as they apply to the Antarctic. We shall find it more convenient not to follow the order in which the heads are given above, but at the beginning of each of the following paragraphs the numbers of the heads which are considered in the paragraph are given.

(1). At every place where prevailing wind directions have been observed at the edge of an inland-ice mass there has been found a larger or smaller component in the outward direction. This is not only true at sea-level, but the air is found to be flowing outwards from the high plateaux both in Greenland and the Antarctic. Special attention is drawn to the winds observed by David, Shackleton, Scott and Amundsen, all of whom on their ascents to the Antarctic plateau encountered winds blowing down the valleys.

(7) & (8). This outward motion necessitates anticyclonic pressure distribution, with descending air currents in the centre, where the air will be relatively calm. The deposition of ice to supply the permanent snow under these anticyclonic circumstances is described as follows. The frequency with which cirrus clouds are observed over Greenland and the Antarctic is pointed out. It is then considered that the ice of these clouds is brought down with the descending air current and deposited as ice crystals on the surface of the plateau. Hobbs says:—

> 'There is however the probability that in general this snow and ice is adiabatically melted and vaporized during its descent to the plateau, and subsequently frozen as it mixes with the cold air above the plateau surface.'*

This method of explaining Antarctic snow especially the large quantities associated with blizzards is quite unsatisfactory and the following remarks by Meinardus are very much to the point:—

> 'I will consider next a possibility, which however has very little probability. It is that in the central area of an anticyclone the dynamical warming of the descending air is reduced by radiation, which in the dry air of high latitudes may be taken to be very great, and in the regions near the ground the cooling by radiation may be so great that the air is cooled below its dew point. In this case the small amount of aqueous vapour in the air would be in part condensed as rime, which would replace falling snow as the cause of the ice sheet over the Polar region. Does this process take place to any appreciable extent? In my opinion it hardly does, for the descending air in the anticyclone is very poor in vapour so that in order to reach the desired end very large masses of air would have to be brought into contact with the surface and in addition would have to be cooled very much in order to bring it under its exceedingly low dew point. Now in the central part of an anticyclone the air is usually very calm, hence the renewal of air necessary for appreciable condensation can only take place very slowly and only small quantities of water can be given to the surface. If on the other hand one assumes strong air motion, then the action of radiation and with it the cooling below the dew point ceases to act, and evaporation of rime previously deposited might even occur. On these grounds I greatly doubt whether the ice-covering of the central Antarctic can be due to the formation of rime to any extent.'†

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* *Loc. cit.*, page 208.

† Deutsche Sudpolar-Expedition, page 327.

One must agree with Meinardus in this matter and there can be little doubt that Hobbs has left unsolved what we shall see in the next section is the greatest problem of the Antarctic anticyclone, namely, the origin of the precipitation within the anticyclone.

(2) & (3). Hobbs shows from the records obtained in Greenland and the Antarctic that all along the coast and at the outlets from the plateaux there are great accumulations of snow which have been deposited by the wind and he says:—

> 'What may be characterised as the centrifugal snow broom which sweeps out snow deposits from the central areas and collects them upon and about the margins of continental glaciers, is a necessary consequence of strong anticyclonic conditions and its work is in evidence within all areas where inland ice has been extensively explored.'*

Hobbs is not very happy in his line of reasoning here, for the snow accumulations do not themselves prove anticyclonic conditions, they only show that the winds blow outwards, of which the actual wind observations have given conclusive evidence. The snow accumulations do however prove that the conditions are not cyclonic, for if they were the greatest accumulations would be in the interior where the forced ascending currents would be accompanied by great precipitation.

(4) & (6). The blizzard is considered by Hobbs to be one of the strongest factors in support of the general theory of the glacial anticyclone. He therefore goes somewhat fully into the mechanism of the blizzard. As similar explanations have been given elsewhere it is worth our while to examine this theory in some detail. According to it the blizzard is the result of the cooling of the lower air layers which is supposed to proceed until the dense cold air over the inland ice becomes unstable when there is a great outrush of cold air towards the surrounding warm air over the ocean.

I will give Hobbs' explanation of blizzards in his own words,† and add a series of remarks to point out weak places in the theory.

> 'The sequence of events during a blizzard begins with gentle northerly winds which continue for a day or two during which temperatures are low.'

Except that northerly winds naturally occur only in the interval between blizzards, there is nothing to indicate their connexion. As a matter of fact northerly winds most often occur immediately on the termination of a blizzard and might therefore more justly be connected with the blizzard just passed than with the blizzard to come. We have already shown in the discussion of temperature that the temperature during northerly winds is higher than during similar winds from the south.

> 'David has suggested that during this time air is flowing south to take the place of air whose volume has been reduced as a result of the heat abstracted from it on the ice surface.'

This suggestion is obviously impossible. Any loss of volume due to cooling would be made good by air flowing inwards in the upper atmosphere and not along the surface where it would encounter the increased pressure due to the dense air. Also a very little consideration of the change of volume with temperature would have shown the fallacy of the suggestion even assuming that all the motion takes place along the surface.

> 'Then there follow two or three days of absolute calm, during which the temperature continues to fall. Still further cooled upon the ice surface, the air, a week or

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* *Loc. cit.*, page 198.

† *Loc. cit.*, page 208.

> more after the calm begins, starts to move outwards in all directions and so develops (on the edge of the Barrier) a south-easterly blizzard.'

It would be interesting to know what has been holding the cold heavy air in place on the ice surface during 'the week or more' that it has been cooling. All theories similar to this neglect the fact that the air will start to move as soon as it commences to cool, the consequence of which is that the cooling might produce a flow of air, but it could never produce a typical blizzard with its sudden commencement and its violent air motion.

> 'Simultaneously with this movement the steam cap over the volcano of Erebus, which normally indicates an upper current from the south-west, swings round to the north and takes on an accelerated movement as though it were being drawn from that direction to supply air to the void resulting from the violent surface current towards that direction.'

No such action of blizzards on Erebus smoke as that mentioned here was observed by us. We have already discussed the motion of Erebus smoke during blizzards and have found that the only change is a considerable increase in the frequency of motion from the south-east, so that the relative frequency with which the Erebus smoke moved from the north was less during blizzards than at other times.

> 'Corresponding to the increased velocity, the normal föhn effect near the Pole must be much increased as it is also on the descent of the surface current from the plateau. As soon as the warming of the Polar air from this cause has become general, the high air pressure of the central area is automatically reduced, and thus the blizzard gradually brings about its own extinction. To the warming effect of the descending air current there is rather suddenly added the latent heat of condensation of the moisture when it is precipitated in the form of fine ice crystals within the air layer just above the snow-ice surface. The rather sudden termination of the blizzard may be thus in part explained.'

Unfortunately for this very ingenious explanation of the end of a blizzard, the temperature observations do not support it in any way. The main rise in temperature which is such a well-marked feature of *winter* blizzards occurs at the instant the wind rises. The highest temperature is generally reached when the blizzard is at its height, and in nearly all cases the temperature falls appreciably during the last few hours of the blizzard's duration (see the diagrams showing simultaneous wind and temperature during typical blizzards given on pages 48 and 49 above). If Professor Hobbs' theory of blizzard action were correct, we should expect a steady rise of temperature from the beginning to the end of the blizzard and a sudden fall of temperature as soon as the wind dropped.

On considering the whole of Hobbs' paper one cannot help feeling that in spite of his failing to explain the origin of the precipitation and the mechanism of blizzards he has made out a very strong case for the existence of an anticyclone over all extensive masses of inland ice and over the Antarctic in particular. One would therefore be inclined to agree with the generally accepted idea that there is an intense anticyclone concentric with the Pole and covering the whole of the Antarctic Continent.

On the other hand, however, Meinardus in his discussion of the results of the Gauss Expedition attacks the theory of the Antarctic anticyclone with great vigour and one must admit with most convincing success. We will therefore now examine the problem from Meinardus's point of view.

Meinardus's Theory of the Air Circulation over the Antarctic.*—Meinardus starts his discussion from the generally accepted statements: (1) In regions of relatively low pressure there exists an ascending air current which, if the consequent cooling is great enough, leads to the condensation of water vapour first in the form of clouds and then of precipitation; (2) in regions of high pressure, on the contrary, there is a descending current in which on account of dynamical warming, not only is the condensation of water vapour prevented, but the air becomes abnormally dry. His reasoning then proceeds as follows:

Further one can lay down the law that, excluding very complicated pressure systems, the precipitation will exceed the evaporation in regions having a cyclonic air circulation while in regions with anticyclonic circulation the reverse will be the case. In regions where there are changing cyclonic and anticyclonic systems the pressure type which has on the yearly average the greatest frequency, intensity, or duration will decide whether precipitation or evaporation will predominate. It is also possible to proceed in the reverse direction and from the observed conditions of precipitation and evaporation deduce the prevailing type of weather. Now it is known that there is a constant transfer of water chiefly in the form of ice from the interior to the surrounding sea along the whole circumference of the Antarctic and this necessitates, if the climate is not undergoing change, that more water in the form of vapour must enter the Antarctic than leaves it. This consideration carries with it the conclusion that the Antarctic, considered as a whole, resembles a region in which cyclonic conditions predominate over anticyclonic.

Having thus proved the necessity for cyclonic conditions over the Antarctic, Meinardus proceeds to show how in spite of the increase of pressure at sea-level in high latitudes cyclonic conditions prevail over a large area. His method is as follows: With the values of pressure and temperature found by the different expeditions, mean sea-level values for the whole of the Antarctic are calculated for January, July and the year. With these average values at sea-level and assuming a constant fall of temperature with height it is a matter of arithmetic to calculate the pressure at different heights. The results of such a calculation are given in the following table:—

TABLE 131.

From Meinardus.

S. Latitude.	MEAN TEMPERATURE °C.			Sea-level year.	MEAN PRESSURE (MM.).					
					2,000 m.			4,000 m.		
	January.	July.	Year.		January.	July.	Year.	January.	July.	Year.
60°	2·8	−10·6	− 3·5	740	575	568	572	443	431	437
70°	−1·3	−22·0	−12·8	743	575	563	569	441	423	431
80°	−4·3	−28·7	−20·6	748	577	563	567	441	420	427
90°	−6·0	−33·3	−25·0	750	578	562	566	441	416	424
Diff. 90°—60°	−8·8	−22·7	−21·5	+10	+3	−6	−6	−2	−15	−13

Columns 2 to 5 give the assumed values of temperature and pressure at sea-level, the sea-level pressure being considered constant throughout the year and to increase by 10 mm. between 60 S. and the Pole The remaining columns contain the calculated pressure at 2,000

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* Meinardus. Deutsche Sudpolar-Expedition, page 326.

and 4,000 metres for January, July and the year at the different latitudes. The last line contains the difference of the factors between 60° S. and the Pole.

The conclusions to be drawn from this table are in Meinardus's own words * :—

> 'The table shows the following: The Antarctic anticyclone under the assumptions made is no longer present at 2,000 metres in the winter and on the average of the year, it has clearly given place to the Polar cyclone at this level. In January on the other hand there is still a slight increase of pressure towards the Pole at the 2,000 metre level, but even in this month there is a small decrease at the 4,000 metre level. In other words the anticyclone in January reaches up to about 3,000 metres or a little higher, above this the surfaces of equal pressure are nearly horizontal. The conditions deduced for January probably hold for December also; in November and February the gradient will be similar in sign to that for the winter because the temperature of these months is considerably lower than that for December and January.'
>
> The calculations have been based on the assumption amongst others that the anticyclone is as fully developed in January as in July. In view of the yearly variation of wind strength this is hardly likely. If the January pressure is decreased relatively to the July pressure the anticyclonic gradient in 2,000 metres is naturally decreased also, and it is possible that it might then even disappear at this height, in other words the anticyclone might not reach 2,000 metres even in January. In spite of the uncertainty of the main assumptions, the important result may be accepted that the anticyclone is a phenomenon of the lower atmosphere in all months and only in the summer rises above the 2,000 metre layer.'

Meinardus then refers to his calculation of the height of the Antarctic Continent † by which he has shown that if one-third of the area within the Polar circle is at sea-level the mean height of the remainder must be 2,000 metres. And the conclusion is drawn that the surface of the high land within the Antarctic is above the anticyclone and therefore subjected to cyclonic conditions. In this way he relegates the Antarctic anticyclone to a relatively small fringe of the whole region within the Antarctic Circle, and gives the greater part of the area over to the dominance of the Polar cyclone which he calculates exists above 2,000 metres.

The consequence of Meinardus's reasoning is most clearly shown by a series of three diagrams which he published in the April 1914 number of the Washington Monthly Weather Review and which are reproduced here.

The diagram reproduced as figure 75 represents 'Diagrammatic cross section of the south Polar regions to show the position of the isobaric surfaces and directions of the winds.

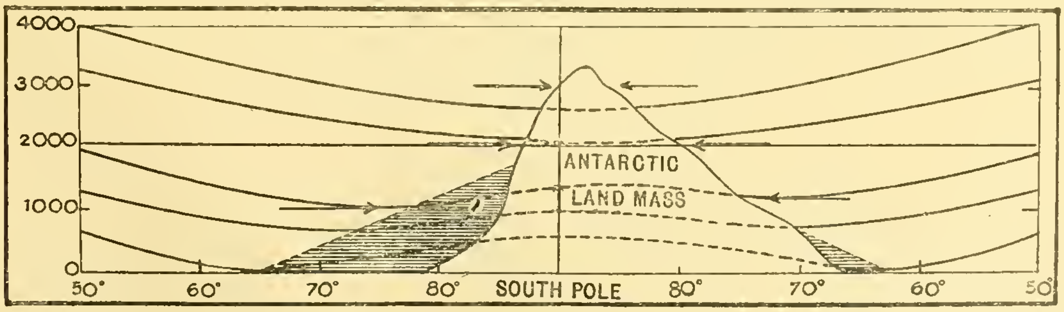

Fig. 75. Meinardus's diagram of Antarctic pressure, vertical.

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* *Loc. cit.*, page 331.

† See page 294 below.

Arrows show the meridianal components of the wind, shaded areas show the region of the prevailing easterlies. Altitudes in metres.'

This diagram is based on the values of the pressure at different heights given in table 131 above. The conditions which would hold if there were no land mass have been represented diagrammatically, and the outline of the continent superposed without altering the position of the isobaric surfaces, the isobaric surfaces eliminated by the land mass being shown by dotted lines.

This diagram shows clearly how according to the theory the greater part of the land surface is subjected to cyclonic air motion. The air streams in from all sides and therefore is compelled to rise over the land surface producing cloud and precipitation to supply the water which flows northwards in the great ice streams. The edges of the land mass only are subject to anticyclonic conditions with descending air currents.

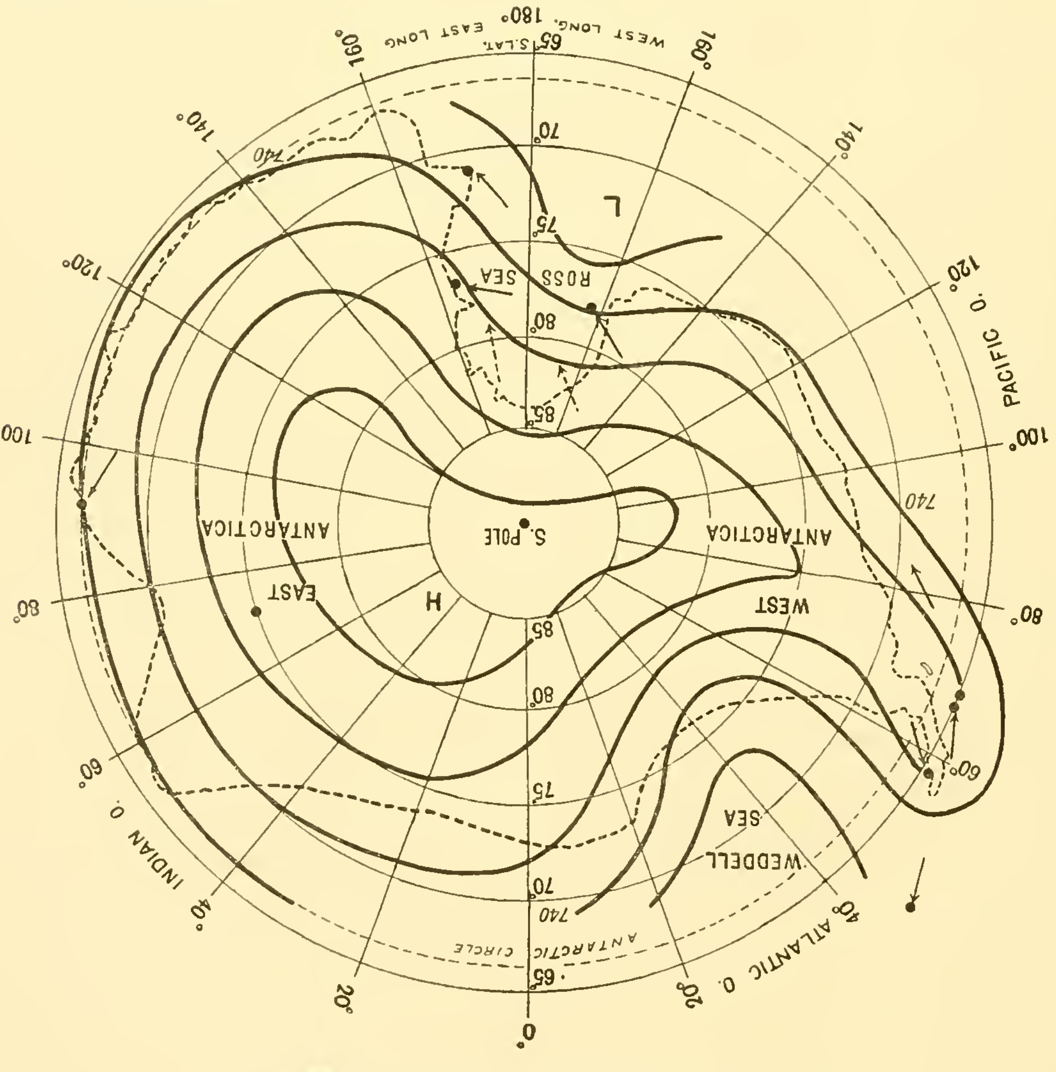

FIG. 76. Meinardus's diagram of Antarctic pressure, sea-level.

The next diagram, figure 76,* shows the sea-level isobars, it is explained in the original as follows :—' Sketch of the course of the isobars at sea-level within the south Polar regions. The isobars are intentionally unnumbered except the curve for 740 mm. whose position can

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* Figures 76 and 77 have been inverted in order that they may be easily compared with other diagrams in this volume, in which the Ross Sea area is always shown above the South Pole.

be plotted with some certainty by aid of past observations. The drawing is planned to present only the *probable form* of the isobars, considering the observed sea-level winds. H, high pressure; L, low pressure; arrows, average wind direction.'

This diagram then represents what the sea-level pressure would be if the existing sea-level pressure could be extrapolated under the high continent which is supposed to cover two-thirds of the area. The anticyclonic distribution is clearly shown with the maximum of the high pressure near to the South Pole.

Figure 77 is a reproduction of Meinardus's remaining diagram, it is described as 'Sketch of the isobars at the 4,000 metre level within the south Polar region. Arrows show the average direction of the upper clouds and the prevailing winds on the plateau.' As stated in the text, this diagram has been drawn by making the isobars run parallel to the winds keeping the low pressure on the right of the air motion. The diagram is convincing and the

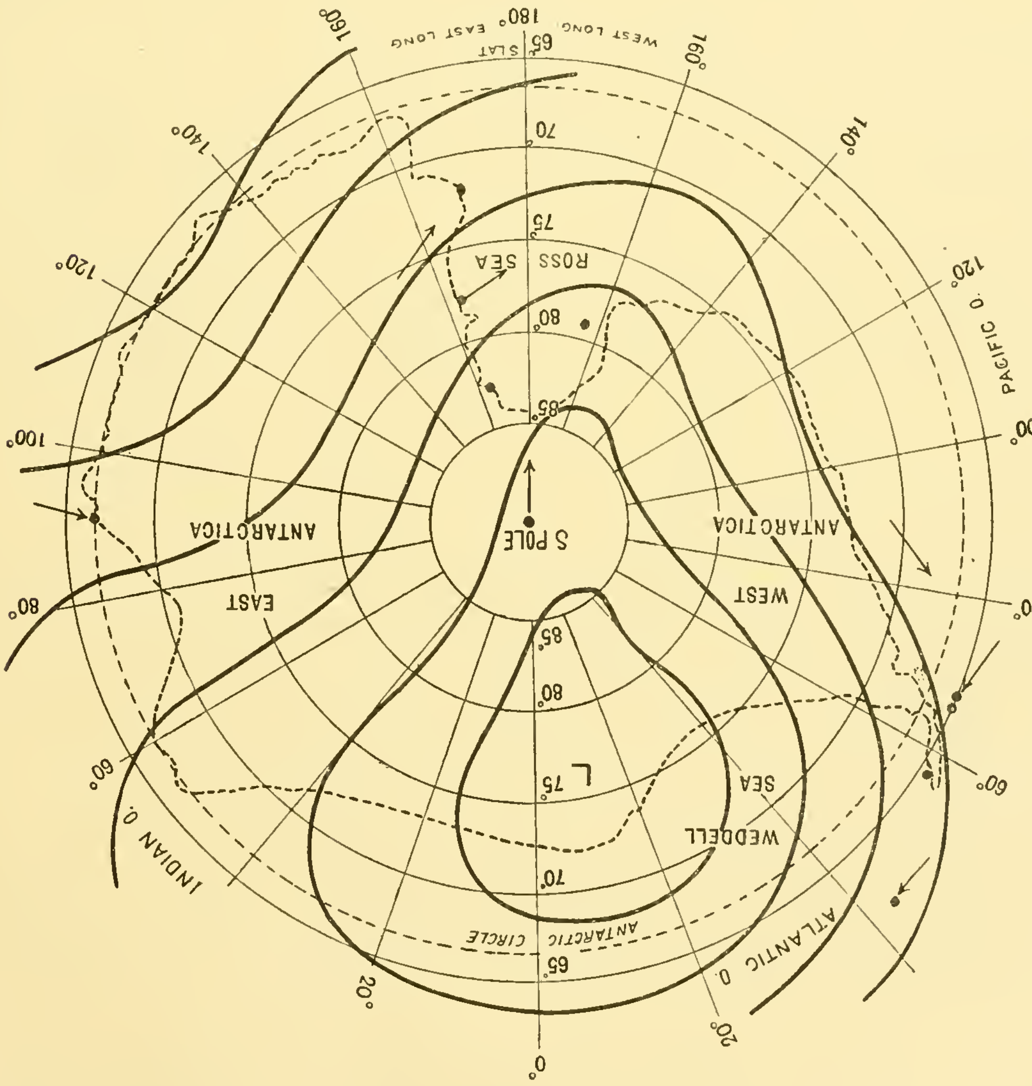

FIG. 77. Meinardus's diagram of Antarctic pressure, 4,000 metres.

winds shown * do fit in fairly well with a low pressure area somewhere near where it has been drawn in the diagram.

Meinardus's reasoning and conclusions may be summed up as follows:—

As there is an excess of precipitation over evaporation in the Antarctic, as revealed by the outward flow of great ice masses, the conditions cannot be anticyclone.

There is certainly an anticyclone over the Antarctic at sea-level, but a calculation shows that at 2,000 metre altitude this has already given place to a large cyclone which is more or less central about the South Pole.

Other calculations indicate that the average height of the Antarctic Continent is 2,000 metres or more, hence the surface of the high land is within the region of the cyclone. Thus the surface over the greater part of the Antarctic is subject to cyclonic conditions with the associated excess of precipitation over evaporation.

Thus the theories of Hobbs and Meinardus are totally opposed, the latter deducing that the greater part of the Antarctic is subject to a cyclonic pressure distribution while the former declares that over the whole Antarctic there is a strong anticyclone. In spite of the repetition entailed we must set out clearly the crucial points on which each theory is based.

Hobbs' paper practically reduces to proving that whenever observations have been made in the Antarctic, both at sea-level and on the plateau, the surface winds blow outwards from the centre; this is only possible if the air descends from above in a central calm area and flows outward under an anticyclonic distribution of pressure. To this Meinardus objects that in such a pressure distribution and air circulation the large precipitation necessary to feed the huge glaciers and produce the constant supply of icebergs is quite impossible.

On the other hand Meinardus deduces from the few observations of pressure and temperature available a probable distribution of these two elements at sea-level over the whole Antarctic. With these values he calculates the pressure distribution in the upper air and shows that at 2,000 metres it becomes cyclonic. As the mean height of the continent is probably more than 2,000 metres, its surface is under the influence of this cyclone in which unlimited precipitation is possible. Hobbs' criticism of this theory is hardly worthy of its importance, he shortly states it and then dismisses it in the following curt paragraph.

'Referring to the observations by Captain Scott and others upon the plateau back of the Admiralty Range in South Victoria Land, Meinardus is quick to seize upon the westerly winds which there prevail as evidence that the anticyclone has at these levels given place to the supposed overlying cyclone; failing utterly to note that the winds are here blowing directly down slope from the ice plateau—that is, radially, other statements in the report are likewise strikingly at variance with facts either known at the time or revealed by later exploration.'†

When two eminent scientists, each of whom knows what he is talking about, come to such diametrically opposite conclusions on the same evidence it is generally safe to conclude that both have some of the truth and neither all the truth. We will therefore now examine the whole question anew and seek a solution, which I believe is not very deeply hidden.

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* On page 264 below it will be shown that strong objection can be taken to some of the wind directions shown by Meinardus in this diagram. When these are corrected the pressure distribution must be radically changed to fit them.

† *Loc. cit.*, page 212.

Whatever may be the actual distribution of high and low land within the Antarctic, there are two extremes between which it must lie: (*a*) the whole area at sea-level, and (*b*) the whole, or the greater part, at some unknown elevation.

I therefore propose to show by means of diagrams similar to the one prepared by Meinardus and reproduced as figure 75 above, the vertical distribution of pressure in each of these two extreme cases, and then combine them along a section of the Antarctic the configuration of which we know to some extent.

Figures 78, 79 and 80 represent these hypothetical vertical sections of the Antarctic south of latitude 50° S. In these diagrams I have chosen a much more contracted vertical scale than the one used by Meinardus. This is in order to reduce as far as possible a fallacious impression which one receives on examining Meinardus's drawing. Any one looking at figure 75 cannot help associating the great mass of the continent, as there represented, with an isolated mountain rising from a level plain. In the latter case the mountain would have very little effect on the pressure distribution, which would be very nearly the same near to the mountain as at some distance from it in the free air. Hence one unconsciously accepts Meinardus's drawing without realising that the great Antarctic highlands will affect the pressure distribution in a very different manner from that of an isolated mountain peak. If, as we have good reason to believe, the Antarctic Continent is an elevated tableland many hundreds of miles across, it is necessary to construct our diagram to give this impression and this can best be done by keeping the vertical scale as small as possible. When this is done one is no longer tempted to run isobars up to and over the surface without pausing to consider how the tableland will affect the pressure.

In these diagrams an attempt has been made to represent the pressure changes in the atmosphere by means of lines. If one calculated the air pressure at each point of the diagrams and joined all points at a given pressure by means of a line, we should have a series of isobars similar to those with which we are so familiar on weather charts, except that they would represent pressures in a vertical instead of a horizontal plane. Such lines would rise and fall as one passed through regions of high and low pressure. Unfortunately, however, the actual change in height of such lines is far too small to be represented on our diagrams. For instance, if the sea-level pressure at the Pole were 10 mm. higher than at 60° S., the isobar which touches the sea-level at 60° S. would be raised less than 90 metres at the Pole. This amount is much too small to be shown on any diagram, which extends to 8,000 metres in the vertical direction. In order, therefore, to let the eye easily take in the changes in pressure, the vertical variation of the isobars is greatly exaggerated. This has the disadvantage that the lines drawn to represent the pressure changes are no longer true isobars, for they do not give the true pressure at each height. All that one can say is that the lines on these diagrams show by their rise and fall how the true isobars rise and fall.

It must also be clearly understood that the position of the lines in these diagrams is not calculated, they are simply sketched and made to rise and fall according to the conditions which they are drawn to represent. The vertical distance between the lines is constant over each place, but it varies from place to place according to the mean temperature of the air over that place. Thus the vertical distance between the lines in all the diagrams is greatest at the edges on account of the relatively high temperature at 50° S. latitude, and least over the Pole where the temperature is supposed to be least. Again the vertical separation of the lines has not been calculated, but convenient distances taken in order to bring out clearly the general effect of raising and lowering the temperature.

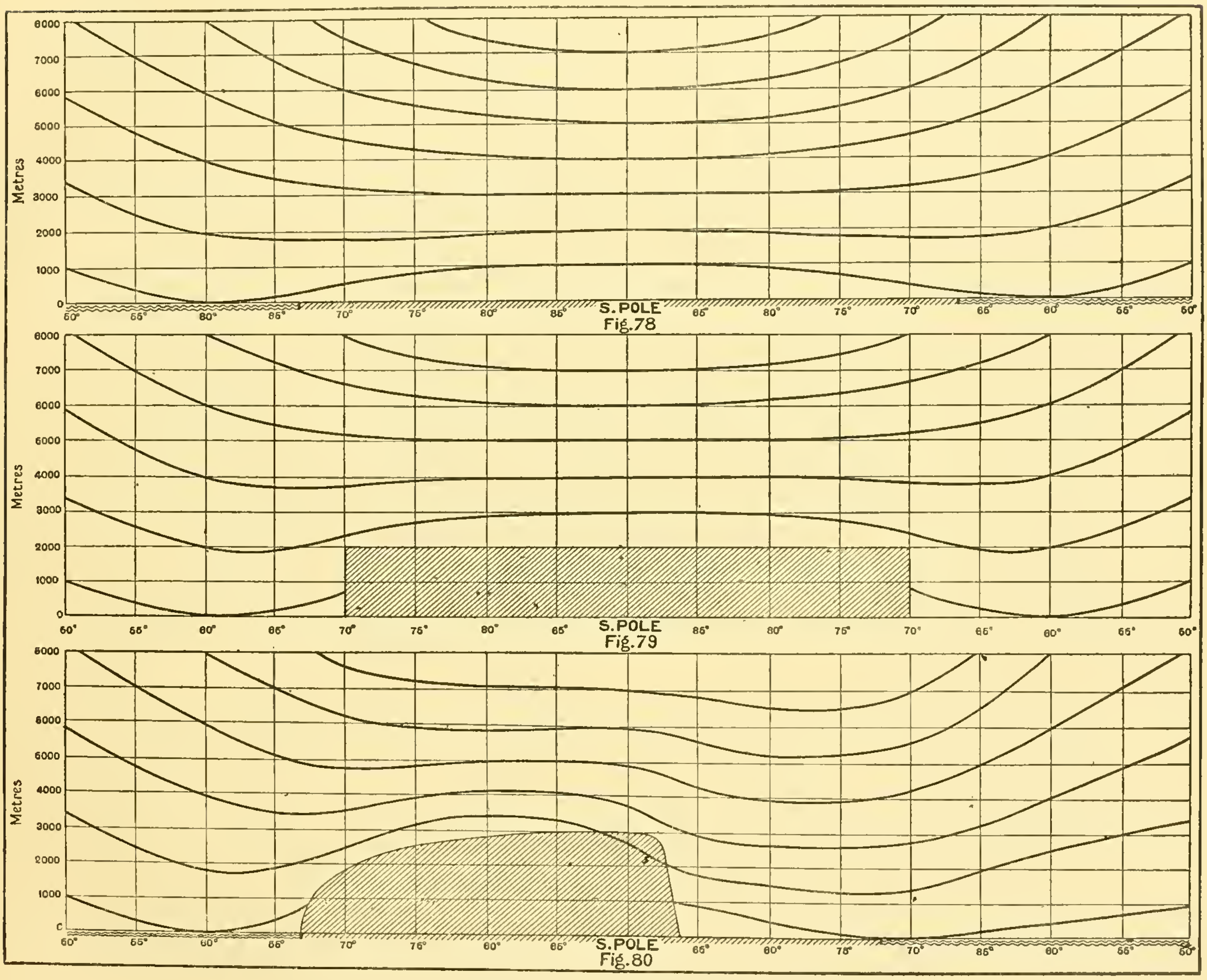
Figure 78 has been drawn to represent what would be the pressure distribution if the whole area within the Antarctic were at sea-level. The lowest pressure at sea-level is shown at 60° S. and the pressure rises from this point to the Pole. The vertical distance between the isobars depends on the temperature, hence this vertical distance decreases from the edges of the diagram to the centre. The consequence is that the rise of pressure south of 60° S. at sea-level is compensated in the upper atmosphere where the pressure decreases all the way from 50° S. to the Pole. In accordance with Meinardus's calculations I have made the height at which anticyclonic conditions over the Polar area give place to cyclonic to be between 2,000 and 3,000 metres. The pressure distribution in this diagram is practically the same as that shown in figure 75 prepared by Meinardus and that it represents the conditions which would hold if the whole area within the Antarctic were at sea-level no one will doubt. But what does it signify? Simply that the ice surface causes the sea-level pressure at its centre to be higher than at its edges.

This comes about from two causes: (*a*) the geographical position of the ice surface, which being concentric with the Pole has a lower temperature at its centre than at its margin; (*b*) the formation of a glacial anticyclone due to excessive radiation which Hobbs' work shows forms over any large ice surface whether it is concentric with a pole or not. These two causes acting together would produce a relatively intense anticyclone over the Antarctic, if it were at sea-level.

We will now turn to the second extreme case and consider the consequences of a high tableland within the Polar area. Figure 79 has been constructed to represent this case. The tableland has been represented as occupying the whole area within 70° S., and to be at a uniform height of 2,000 metres.

What is the pressure distribution likely to be over such a vast tableland? Meinardus assumes that it would be the same as if there were no tableland there at all. With this conclusion I cannot agree. The pressure distribution in the upper air without the tableland shown in figure 78 depends on the presence of heavy cold air in the lowest atmosphere, when this is removed by the land mass the upper air pressure distribution must be altered. I can see no reason why the general pressure distribution over a level surface at 2,000 metres should be different from that of a similar surface at sea-level, so long as the raised surface is of sufficient extent to be the governing factor in the pressure distribution. The causes which produce the high pressure over the Antarctic specified in (*a*) and (*b*) above both come into play on this raised tableland and it is therefore reasonable to conclude that the pressure will be higher over the centre of the tableland than over its margin. In other words that an anticyclone will exist over the tableland. This has been represented in figure 79. Comparing the isobars shown in figures 78 and 79 we see that the lowest is similar in both except that in the latter it only extends as far as the edge of the tableland near to which it takes a slightly greater upward turn. The second line in figure 78 is nearly horizontal within the Polar region. In figure 79, however, as it approaches the upper margin of the tableland it rises and then passes over the surface indicating the increased pressure towards the centre. If we assume that the free-air temperatures are approximately the same whether the tableland is present or not, the vertical distance between the isobars will be the same at each latitude in figures 78 and 79. The lines have been drawn on this assumption and it is seen that at about 2,000 metres over the tableland the isobars are again nearly horizontal and above this height cyclonic conditions again hold. The difference between this diagram and figure 75 drawn by Meinardus is fundamental: while he neglects the effect of the high land on the pressure distribution I simply raise the pressure distribution by the height of the land, so that instead of piercing the Polar anticyclone the tableland raises the anticyclone with it and so anticyclonic conditions are retained over its whole surface.

Before we can apply the conclusions thus arrived at to the actual area within the Antarctic, we must have some idea of the general distribution of the high and low lands.



FIGS. 78, 79, 80. **Probable Antarctic pressure, vertical cross section.**

I do not propose to attempt to solve the problem of the geographical features within the Antarctic, but it is possible to form some idea of which parts are likely to be high and which parts low, and we may take these as giving the general configuration of the land.

We know that the plateau at the Pole is about 3,000 metres high, at the position reached by Scott west of Ross Island about 2,500 metres, at the magnetic pole about 2,200 metres.

Behind Adelie Land the land rises in 30 miles to 1,000 metres; and then in a series of undulations to the magnetic pole. Near the Gauss Station Wild found that the land rises to 1,000 metres in about 30 miles and Filchner concluded that a similar rise occurs at Prinz Leopold Land. It is reasonable to assume therefore that at all these points on the coast there is a rapid rise to the plateau. I therefore conclude that the plateau covers the whole segment of the Antarctic between Cape Adare and the Weddel Sea, decreasing in height from the Pole outwards, at first slowly and then fairly rapidly near the coast. We know that the edge of the plateau on the Ross Sea side is very steep and edged by a range of high mountains. Amundsen has shown that this range of mountains is continued beyond the Pole in such a direction that it probably connects up with Graham Land or with Prinz Leopold Land. As either is equally probable and makes little difference to our discussion I have assumed that the great escarpment which we know runs from Cape Adare nearly to the Pole continues towards Prinz Leopold Land.

Thus the Antarctic is supposed to consist of two parts divided by this escarpment, as indicated in figures 81 and 82. The area on the Pacific side of the great escarpment, single hatched in the figures 81 and 82, is supposed to be at sea-level or nearly so, while the area on the Atlantic and Indian sides, shown in the same figures by cross hatching, is high tableland, the highest region being near the South Pole.

In figure 80 a section of the continent is shown along the 90° E. meridian which is continued beyond the Pole as the 90° W. meridian. This section is shown in figure 82 by the thick line AB. From 50° S. latitude on the left of the diagram we have open water to the Antarctic Circle just north of which the *Gauss* wintered. From the Circle the land rises to the plateau, at first rapidly and then more slowly, the exact contour of the surface is not known nor is it material to our qualitative discussion. The high land continues a little way beyond the Pole when the rapid descent through the Queen Maud range of mountains occurs. From this point to nearly 70° S. there is either barrier or land ice of no great elevation. Near to 70° S. on this meridian the *Belgica* wintered and therefore sea is known to extend from about 70° S. towards the north. These features are reproduced in elevation on figure 80.

The diagram shows clearly how the pressure variation is supposed to be affected by this distribution of land, but the following points should be noticed. On the *Gauss* side of the plateau the pressure is lowest near to 60° S. in accordance with the observations made by the Gauss Expedition. From 60° S. towards the plateau the pressure at sea-level rises. Over the plateau the pressure also rises, the highest pressure occurring just before the Pole is reached.* Over the area at sea-level between the plateau and the *Belgica's* position there is a well-developed anticyclone in the lower atmosphere and a marked cyclone in the upper atmosphere. Thus in this diagram we have been able to combine the pressure distribution shown in figures 78 and 79.

We are now in a position to indicate the probable distribution of pressure at sea-level and at 3,000 metres over the whole Antarctic, if the distribution of high and low land is that assumed.

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* The remarks made above about the lines in these diagrams which represent the pressure variation being greatly exaggerated must be borne in mind. Thus the fact that one of the pressure lines runs nearly parallel to the surface of the plateau does not mean that the pressure on the surface is nearly constant. The best interpretation of the lines is that *at any given height* the pressure varies in the same sense that the nearest pressure line rises or falls.

Figure 81 shows the sea-level pressure. The greater part of the isobars shown are based on actual observations and may be taken as correct, these have been represented by full lines. The dotted lines represent the hypothetical pressure distribution, over regions from which we have no observations. The latter are confined to the area at sea-level between the Ross Sea and Graham Land where an anticyclone is shown in accordance with our conclusion that the sea-level pressure increases towards the Pole. No attempt has been made to indicate the sea-level pressure over the region occupied by high land, for such a result would have no meaning.

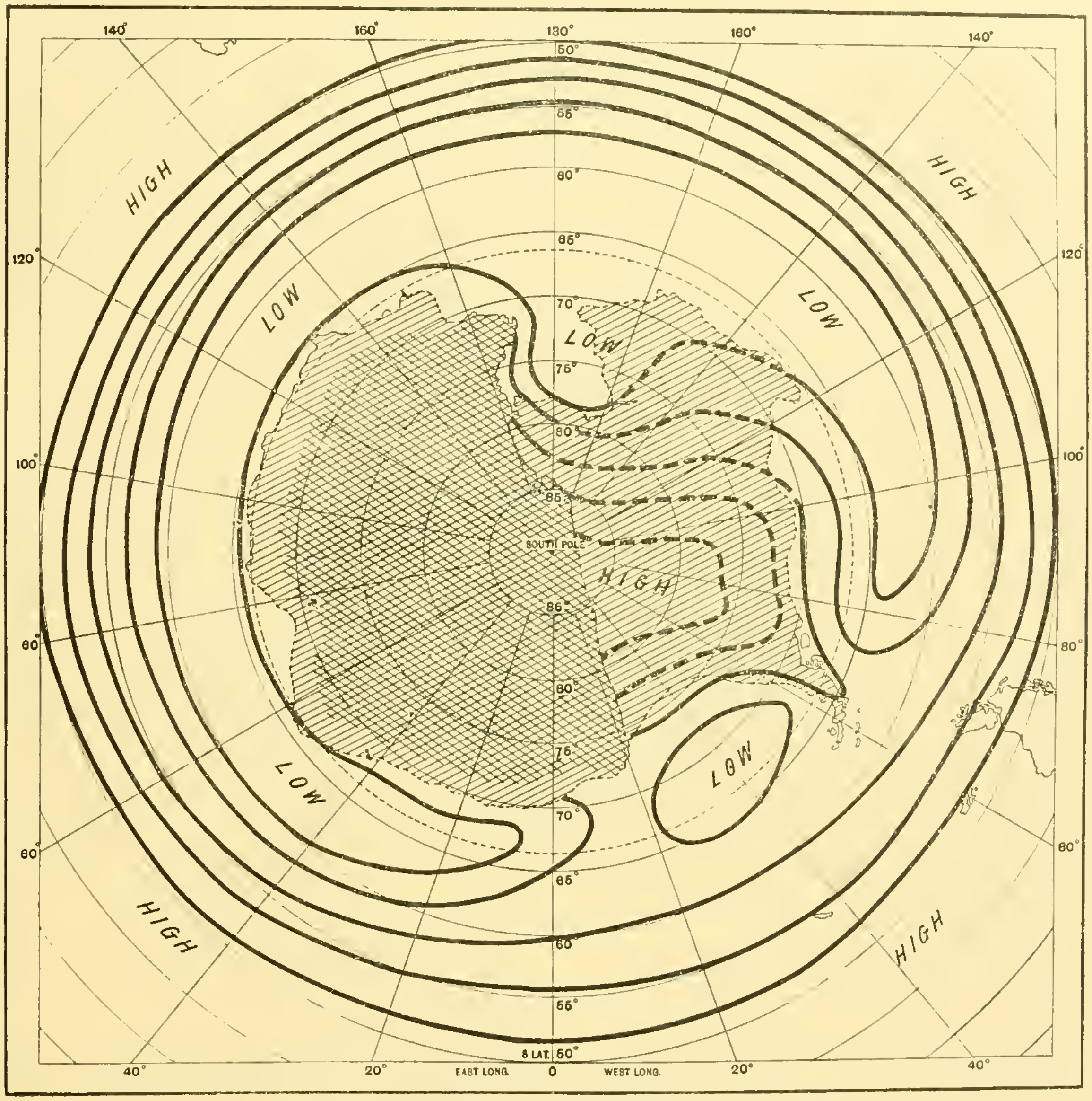

Fig. 81. Probable Antarctic pressure, sea-level.

It will be noticed that in its main features this diagram does not depart largely from the corresponding one prepared by Meinardus and reproduced in figure 76. We have in each the bending southwards of the isobars over the Ross and Weddel Seas and the high pressure over the central parts of the area.

In our next diagram, figure 82, an attempt has been made to show the probable pressure at 3,000 metres. This height has been chosen instead of the 4,000 metres used by Meinardus for reasons which will be given in the next section. It is possible to outline the pressure distribution at this height from the principles used in preparing figure 80. Isobars * are shown and the method followed in drawing them will be their justification.

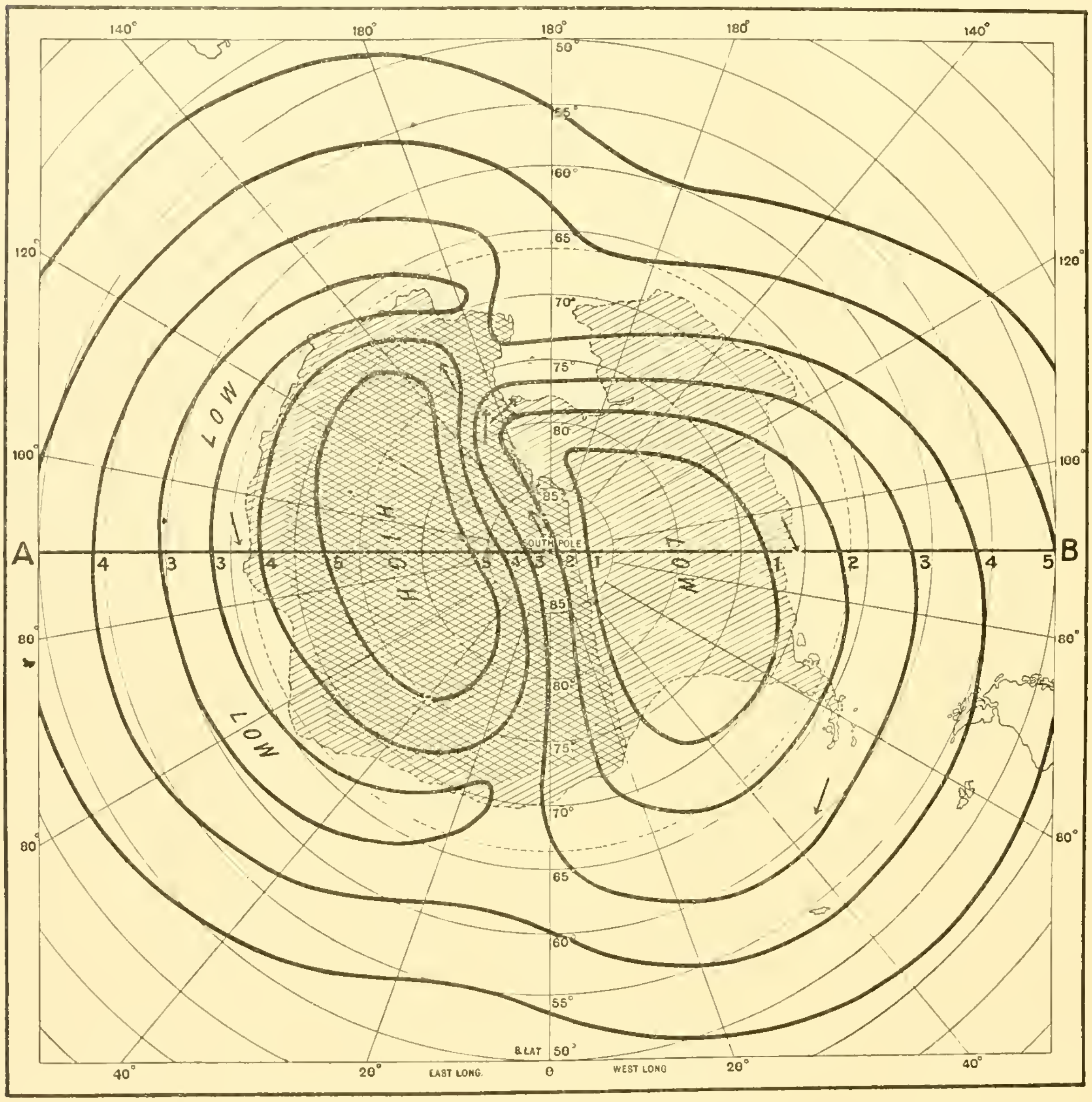

FIG. 82. Probable Antarctic pressure, 3,000 metres.

We know from the pressure and temperature conditions over the Ross Sea and the Barrier that the gradient between these two areas is reversed above about 1,700 metres, so that at 3,000 metres the pressure over the Ross Sea is distinctly higher than over the

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* It may be as well to point out here that the actual pressure to which the isobars refer is not known and therefore they have simply been numbered 1, 2, 3, etc. The number of isobars drawn has been determined solely with the idea of giving a clear picture and they may be increased or decreased at pleasure, over either the low or high pressure systems, if it is considered that the gradients in each are not in keeping with the wind velocities.

Barrier (see page 136). The starting point was therefore a series of parallel lines over the Ross Sea running approximately parallel to the Barrier edge. As the lowest pressure is doubtless over the coldest region, it has been shown over the low-lying area on the Pacific side of the Pole. Round this area the isobars already drawn over the Ross Sea must pass. Leaving for the moment the ends of the isobars over the Ross Sea, the other ends were continued round the low pressure area until they came to 40° W. longitude. Returning then to the ends over the Ross Sea, near the Western Mountains, it was realised that the pressure near the edge of the plateau must be in equilibrium with the pressure at the same height over the sea. The lines were therefore continued on to the plateau. But according to our assumption the pressure of the plateau increases inland, this necessitated that the lines should bend away from the centre and pass around the edges of the plateau.

A few trials showed that these conditions were best met by carrying isobars Nos. 2 and 3 to the south and isobar No. 4 to the north.

Isobars Nos. 2 and 3 after turning to the south run nearly parallel with the edge of the plateau and join up with their other ends, completing the closed cyclonic system over the low-lying land.

A high pressure system was then indicated over the plateau by means of the closed isobars 4 and 5. Round these two high and low pressure systems encircling isobars were drawn indicating that the pressure increases northwards over the whole region outside the Antarctic.

If this pressure distribution is correct, it will be in accordance with the isobars shown in the vertical section of figure 80. The line along which this section has been made is indicated in figure 82 by the thick line AB. We will pass along this line from A to B and compare the pressure changes shown on it with the corresponding changes shown at 3,000 metres on figure 80. Starting on the left of each diagram we see that from 50° S. to about latitude 64 S. the pressure lines at 3,000 metres fall in figure 80, and we cross isobars 4 and 3 to a shallow trough of low pressure in figure 82. From 64° S. to 80° S. the pressure lines at 3,000 metres rise on figure 80 and on figure 82 we cross isobars 3, 4 and 5 to the centre of the high pressure area over the plateau. From 80° S. to 75° S. on the other side of the Pole the isobars fall on figure 80 and we pass across isobars 5, 4, 3, 2 and 1 to an area of low pressure on figure 82. From 75° S. to the right hand edge of figure 80 the pressure lines at 3,000 metres rise, indicating increasing pressure, while in the same distance in figure 82 we cross isobars 1, 2, 3, 4 and 5 in the direction of increasing pressure. Thus the horizontal pressure distribution shown in figure 82 agrees with the vertical pressure distribution represented in figure 80.

We have now, from considerations of pressure and temperature alone, drawn a system of isobars which enclose a high pressure area over the plateau and a low pressure area over the part of the Antarctic which is supposed to be at or near sea-level. The crucial test of this pressure distribution is whether the observations of wind direction agree with the general run of the isobars.

The pressure distribution at 3,000 metres has been chosen because this is the height in the atmosphere from which we have the most information about the air motion.

(*a*) Erebus smoke gives the air motion over the Ross Sea area at a height somewhat greater than 3,000 metres.

(*b*) The height of the plateau varies between 2,000 and 3,000 meters, hence wind observations made on its surface give useful information.

(*c*) Observations made in McMurdo Sound showed that the height of the alto-cirrus and alto-stratus clouds was a little lower than the top of Erebus, so that their mean height may be taken as about 3,000 metres. This enables us to use the direction of these clouds observed at the Gauss Station, and at the South Orkneys. The motion of these clouds over McMurdo Sound was affected by the surrounding land and therefore cannot be used for this purpose.

The following table contains all the available data:—

TABLE 132.

Air motion at approximately 3,000 *metres.*

Position.	Motion determined by	Air motion from	Reference.
McMurdo Sound	Erebus smoke	W.S.W.	Page 135 above.
Magnetic Pole Plateau	Wind	S. to S.E.	Page 142 above.
Western Plateau	Wind	S. 31° W.	Page 142 above.
Polar Plateau	Wind	Parallel to 160° E. meridian	Page 144 above.
Gauss Station	Medium cloud	N. 74° E.	Deut. Sudpolar-Exped., page 143.
South Orkneys	Medium cloud	S. 66° W.	Analos d.l. Officina Met. Argentina, Volume XVII, page 124
Belgica	High cloud *	S. 66° W.	Mossman. Tran. Roy. Soc. of Edinburgh, Volume XLVII, page 127.

These directions of air motion have been shown on figure 82 by means of arrows flying with the wind. It will be seen at once that all the arrows are approximately parallel to the isobars. At the three last stations, however, the direction of motion is inclined somewhat towards the high instead of towards the low pressure. It must, however, be remembered that each of these directions has been found from cloud observations and the presence of cloud itself indicates that the weather is disturbed and if clouds are generally associated with one type of weather their motion cannot be accepted as showing the *mean* direction. If allowance is made for these considerations, it must be admitted that the air motion is in excellent agreement with the pressure distribution deduced for this height from consideration of pressure alone.

If we compare the pressure distribution at 3,000 metres shown on figure 82 with that deduced by Meinardus for 4,000 metres and shown on figure 77, it will be seen at once that they are radically different. While we show a cyclone and an anticyclone over the region, Meinardus shows only a cyclone and there is no indication of an anticyclone on his diagram. One naturally enquires how is it that the wind observations, on which Meinardus admittedly based his pressure distribution, can agree with such totally different pressure distributions. The answer is that some of the upper air motions shown on Meinardus's diagram are not those which should have been used. Over the Gauss Station Meinardus shows a north-north-easterly wind at 4,000 metres. This is because he has used the mean direction of the cirrus clouds. The observations made in McMurdo Sound show conclusively that the cirrus clouds are much higher than 4,000 metres and move in an entirely different direction from the wind on the plateau or from the direction of Erebus smoke. We have used the motion of the

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* Observations of medium cloud are not available, but there is every indication that at this station the high and medium cloud motions are nearly parallel.

medium clouds for the Gauss Station for there is no doubt that if observations of the motion of Erebus smoke and of the winds on the plateau are to be used in one part of the area the medium and not the cirrus clouds must be used in another. This applies also to the air motion over the west Antarctic where Meinardus has also used the direction of motion of the cirrus clouds, but in this area there is little difference in the direction of the alto-cumulus clouds and the cirrus clouds* so that no radical mistake has been made in this region.

Further the prevailing wind on the plateau near the magnetic pole is shown by Meinardus as W.S.W. Now this direction was observed by David only when he was under the influence of winds blowing down the glacier valley through which he ascended. As soon as he reached the true top of the plateau the winds observed and the sastrugi all pointed to the prevailing winds on the plateau itself being from the south or south-east, a conclusion confirmed by Mawson's Expedition.

Finally, although the isobars over the plateau near the South Pole have been drawn out by Meinardus to almost a point to make them roughly parallel to the wind there shown, the result is very unconvincing for the wind is blowing straight out of the area of low pressure. This would be even more striking if the true wind direction over the plateau as now known had been entered; for this direction is parallel to the 150th east meridian and not to the 180th meridian as shown on the diagram.

If the reader will enter on figure 77 these corrected wind directions namely, on the South Polar Plateau wind parallel to the 150 E. meridian, on the Magnetic Pole Plateau S.S.E., over the Gauss Station N. 74° E., he will see at once that it is quite impossible to reconcile them with the pressure distribution shown by Meinardus.

If then we may accept figures 81 and 82 as correctly representing the pressure distribution at sea-level and at 3,000 metres respectively we reach the following conclusions:—

(*a*) The pressure distribution over the surface of the plateau and also of that part of the Antarctic at sea-level is anticyclonic.

(*b*) At 3,000 metres over the part of the Antarctic at sea-level the pressure distribution is cyclonic.

Thus Hobbs appears to be right in his main contention that the surface of the land both high and low is subject to anticyclonic conditions, but we are still faced with Meinardus's main contention, that under such conditions evaporation will exceed precipitation and the Antarctic should be denuded of its permanent snow-covering.

This problem we must now consider; it may be stated as follows:

Owing to the anticyclonic conditions which predominate over the whole surface of the Antarctic air flows towards the Antarctic in the upper atmosphere, then descends to the surface and there flows outwards, at a much lower level than it entered. If the air were saturated at the moment it entered the Antarctic it would be warmed up dynamically as it descends and so when it reaches the surface it will be far from saturated. Even allowing for a large amount of radiation, air under these conditions could not deposit appreciable moisture on the surface and as Meinardus points out, the conditions when precipitation is known to take place to the greatest extent, *i.e.*, during cloudy weather and high winds, are exactly those when cooling by radiation is least effective. We have therefore to explain how air can enter the Antarctic in the upper atmosphere and leave it in the lower atmosphere and yet deposit moisture in the process.

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* According to the Argentine observations at South Orkneys alto-cumulus and alto-stratus S. 66° W., cirrus S. 77° W., *loc. cit.*, page 124.

The solution of the problem will be greatly facilitated by the use of a diagram similar to that first prepared by Hertz to show the changes in the physical state of air as it rises and falls in the atmosphere.

Figure 83 has been drawn by the method described by Hertz in 1884,* and a description of which is found in most text-books of meteorology. The abscissa represent temperatures

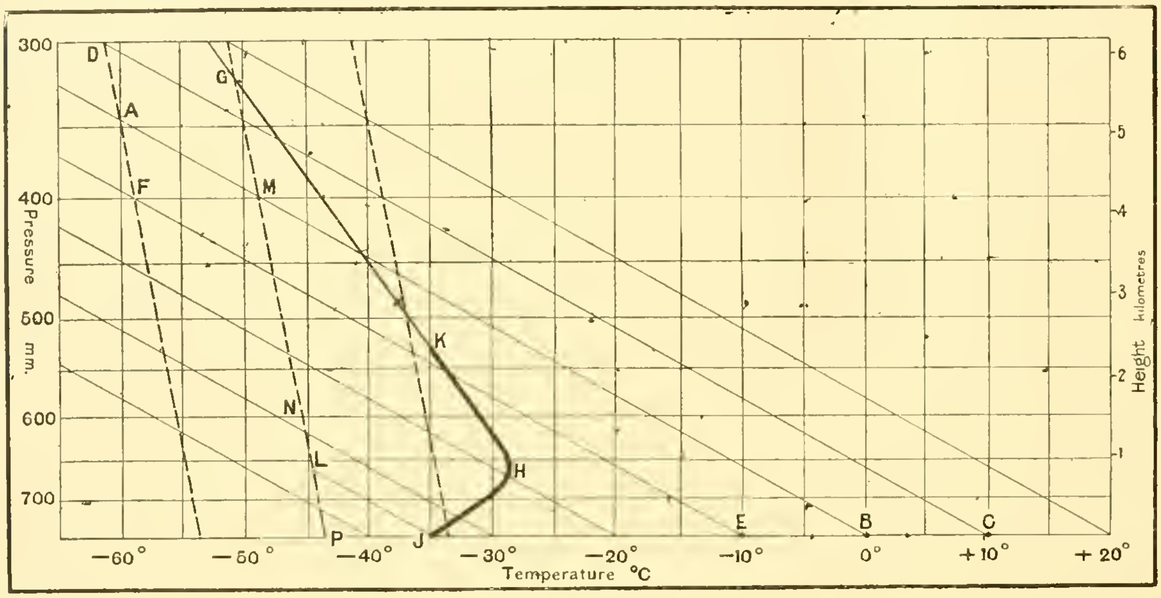

FIG. 83. Hertz diagram.

and the ordinates when read on the logarithmic scale shown on the left of the diagram represent pressure, and if read on the linear scale shown on the right of the diagram represent approximate heights in the atmosphere.

The thin inclined lines, *e.g.*, D C, are the lines of adiabatic change. Thus if a mass of air is taken at a temperature of −60°C. and 350 mm. of pressure, represented in the diagram by the point A, it will be nearly 5 kilometres high in the atmosphere. At any other height in the atmosphere its temperature and pressure will be determined by the line A B, so long as no heat is allowed to enter or leave it. Thus if it is depressed to one kilometre above the ground its pressure will be 650 mm. and its temperature −10°C. approximately.

The broken lines are 'lines of saturation.'

If air having the temperature and pressure represented by any point on one of these lines is saturated with moisture, its temperature and pressure may be altered at will, but if no water is added or subtracted, whenever its temperature and pressure are those given by another point on the same dotted line it will be saturated. For example if air, saturated under the conditions represented by the point A, has its pressure and temperature altered by any method until they are those represented by the point F it will be saturated. One way to do this will be to depress it rapidly in the atmosphere, until its pressure is the same as that of F. This would raise its temperature from that represented by A to that represented by M, for M is on the adiabatic line A B through A and also on the horizontal pressure line through F. If now the air radiates its heat and so cools without changing its height in the atmosphere it will cool down to the temperature at F. It will then be found to be saturated.

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* Met. Zeit., 1884, page 421. See also Neuhoff Abhdlg d. Preuss. Met. Inst. I, No. 6, Berlin, 1900.

Imagine that the air at about 5,000 metres altitude is saturated with moisture and has a temperature of $-60°C$. its condition will then be represented on the diagram by the point A. If this air is now carried downwards without receiving or losing any heat to the ground, its temperature and pressure at the ground will be represented by the point B. If while it is at the ground it receives heat its temperature will change, but not its pressure. If its temperature rises 10° its condition will be represented by the point C. Now let it be carried upwards without receiving or losing any further heat and its condition at each height will be represented by the line C D. At D it meets its saturation line and a further increase in height will cause precipitation. It will be noticed that D is higher than A. Let another mass of the same air from the same layer be lowered from A to B and then lose heat by radiation, or any other method, until its temperature is reduced 10°C. Its condition will then be represented by E, now let it rise adiabatically along the line E F it will then be saturated at F, *i.e.*, it will be saturated at a lower height than that from which it started. In these two cases the point of saturation has been raised and lowered in consequence of adding and subtracting heat respectively. This relationship is true generally; the formal proof is very easy, but need not be given here; it is sufficient to state that if air is saturated at any height in the atmosphere and subsequently receives heat it must rise to a greater height before it becomes saturated again and conversely if heat is abstracted from it, it will become saturated at a lower altitude than it had originally.* This is true no matter how or where the heat is added or subtracted. We at once see why it is that as a general rule an anticyclone in temperate and tropical regions produces dry weather. The air enters the anticyclone in the upper atmosphere and descends towards the ground which has been made hot owing to the bright sunshine due to the absence of clouds. In consequence the air in such an anticyclone on the whole receives more heat from the hot ground than it loses by radiation, it would therefore have to rise to a greater height than that where it entered the anticyclone before precipitation occurs. This is practically impossible and therefore precipitation is of exceedingly rare occurrence in the anticyclones with which we are the most familiar.

In the Antarctic, however, the conditions are reversed. It is only during a very short period of the year and then only during parts of each day that the air receives more heat than it radiates. This is shown by the tendency to form 'temperature inversions' near the ground which are especially well marked during the winter.

We will now consider an actual case. The curve J H K in figure 83 represents the actual temperature found at different heights on August 17th, 1911. The temperature gradient actually found between 1 and 2 kilometres, represented by the part of the curve H K, has been assumed to be representative of the gradient throughout the upper atmosphere; this part of the curve has been continued as a straight line to the top of the diagram. Now suppose that the air enters the Antarctic as a saturated current at about 6 kilometres altitude. Its temperature and pressure will then be represented by the point G approximately and G P will be its saturation line. Now a mass of air which has just entered the Antarctic under these conditions is radiating heat and in consequence becoming denser, it therefore descends. If it descends rapidly it warms up owing to adiabatic compression, its temperature at each height being given by a line through G parallel to the adiabatic lines. It will be seen from the diagram, however, that this would cause its temperature to be higher than that of the surrounding air the temperature of which is given by the line G H. Its higher

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* To be quite correct pressure instead of height ought to have been used as the criterion in this statement. But our whole discussion is simplified by assuming that the relationship between pressure and height remains constant, so that the two terms are synonymous. Also it is easier to visualise height than pressure and the use of the height instead of the pressure tends to a clearer exposition.

temperature would reduce its density and its downwards motion would be stopped. Finally its rate of descent would be adjusted so that at each height it has the temperature of the surrounding air, this will necessitate the loss by radiation of the heat due to adiabatic compression. In other words air could not descend through an atmosphere having the vertical temperature gradient represented by the line G H without losing heat by radiation, and a measure of the heat lost in the descent from say G to K is given by the horizontal distance from K to the adiabatic line through G. When the air through its loss of heat due to radiation arrives at H it will then descend much more slowly, but will finally reach the ground at J, when its temperature will be −35°C. Now during periods of calm and excessive radiation the ground may be 10°C. colder than the air just above it. If therefore the air after reaching the ground at J is cooled by contract another 10° its temperature will be −45°. It will be noticed from the diagram that this temperature is to the left of the saturation line G P and therefore the air actually in contact with the ground would be saturated and a deposition of moisture on the ground would occur. This is the method by which Hobbs supposes that the Antarctic receives its covering of ice. There can be little doubt that such conditions are frequently met with, especially on the Barrier, and the early morning fogs so often reported from the Barrier are due to the air near the ground being cooled in this way below its saturation temperature. But as Meinardus points out in the paragraph quoted above, the conditions are not those which would produce much precipitation and the whole process could not occur during high winds or overcast weather.

We will therefore not consider further this method of obtaining precipitation, but return to the condition of the air represented by the point J. Now let us see what would be the consequence of raising the air which has descended from G to J. Such elevation of the air would result if a pressure distribution were imposed which set the surface air moving faster than the air in front of it, the air from behind would then be forced to rise over the air in front. This is the case during blizzards.

If this occurred very rapidly the cold surface layer would be raised under adiabatic conditions and its pressure and temperature conditions as it rose would be represented by the line J L which is parallel to the adiabatic lines. In these circumstances it would reach its saturation line in L where condensation and precipitation would take place. This would give a cloud layer from which snow would fall at a height of less than 1 kilometre although this same air entered the Antarctic as a saturated current at 6 kilometres. In reality, however, the cooling would not be adiabatic, but somewhat less. Let us assume that instead of cooling at the adiabatic rate (a little more than 10°C. per kilometre) it cooled at the rate found by the balloon ascents in the summer, *i.e.*, at 6½°C. per kilometre. Its condition then during ascent would be given by the line J N. In this case cloud and precipitation would occur above the height of N which is well below 2 kilometres.

We have thus shown that owing to the large radiation within the Antarctic the air, even after it has descended from the upper atmosphere, is in a state that a moderate amount of forced ascent is sufficient to cause condensation of the contained moisture and so snowfall. Thus although Meinardus was correct in saying that radiation alone is not sufficient to account for the large precipitation he was wrong in not considering the effect of forced ascent on air already cooled by radiation.

A statement of the general air circulation over the Antarctic is now quite simple. Over the snow-covered surface of the Antarctic whether at sea-level or at the height of the plateau radiation is so strong that the air is abnormally cooled especially in the layers of air immediately above the surface. This cooled air is heavier than the surrounding air and therefore the pressure increases from the exterior to the interior of the Polar area ; in other words the pressure distribution is anticyclonic and the air motion is in general outwards. Above each anticyclone a cyclone forms on account of the relatively rapid vertical pressure change caused by the cold dense air. These cyclones convey air from higher latitudes over the Polar region and supply the air which passes outwards near the surface. In the normal steady state the air circulation takes place slowly and the descending air is warmed up dynamically so dissolving cloud and giving clear cloudless skies, thus accounting for the decreasing cloud amounts observed as one penetrates the Antarctic (see page 151).

The clear skies in their turn facilitate radiation as also does the small absolute humidity of the air. In consequence the air and the snow surface become abnormally cold and there is a great tendency to the formation of temperature inversion especially in the lower atmosphere. On these normal fine weather conditions are superposed a series of pressure waves which travel more or less radially outwards from the centre of the continent. These waves alter the surface pressure distribution and cause air motion which is frequently, and especially over the west of the Barrier accompanied by forced ascending currents. The abnormally cold surface air is forced upwards in these currents, rapidly cooled in the ascent, and the water contained is precipitated as snow, which when combined with the high surface winds produces the typical Antarctic blizzard.

CHAPTER VIII.

UPPER AIR OBSERVATIONS MADE BY MEANS OF BALLOONS.

(*Metric units and centigrade temperatures used in this chapter.*)

The balloons used were made of thin gutta-percha tissue. They had a cubical contents of one cubic metre so that their diameters were approximately 126 cm. The weight of each balloon was 227 grams, and the average rate of ascent of a free balloon was about 3·8 metres a second.

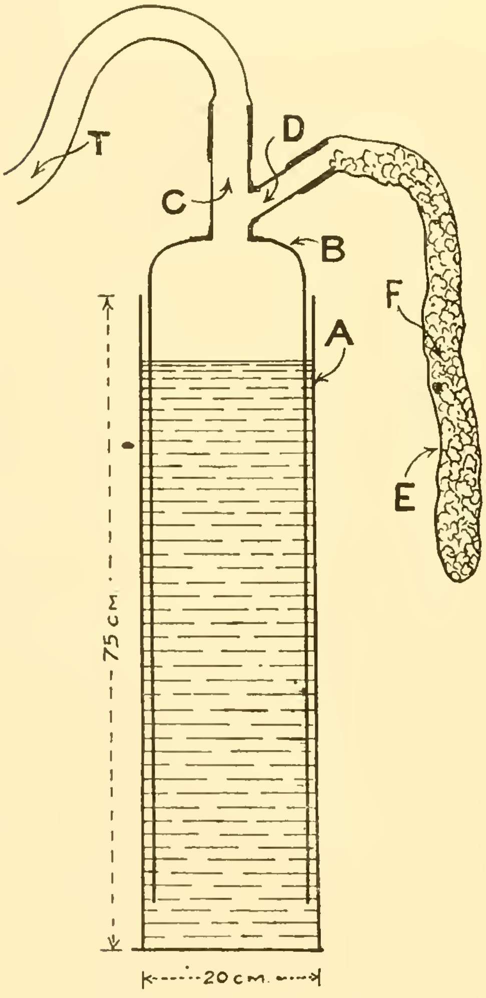

Fig. 84. Hydrogen generator.

The hydrogen used was obtained from calcium hydride. A very simple form of generator was devised by Mr. Dines and proved entirely satisfactory in use.

A vertical cylinder A, figure 84, 75 cm. high and 20 cm. in diameter was filled with water. Inside this a similar but somewhat smaller cylinder, open at the bottom and closed at the top B, acted as a gasometer. The latter had a tube C fastened to the top through which the gas passed by way of the tube T to the balloon. A side tube D was attached to C and the inner tube of a motor-cycle tyre was fitted to it. The rubber motor tyre had been filled with small pieces of calcium hydride and it was a simple matter to feed these by hand into the water to provide the gas. The large excess of water allowed of complete disassociation of the hydride, and also the temperature did not rise to too high a value, especially if the cylinder had been filled with a mixture of snow and water as was usually the case.

The instruments used were made by Mr. Dines and have been described by him in the publications of the London Meteorological Office.

Considerable thought was given in England to devising some method for retrieving the instruments sent up with the balloons. There was little difficulty with the method to be used in the summer, and as this was very successful it will be described first. The details of the method were actually worked out in the Antarctic, but it will be unnecessary to describe the experiments made. There is nothing new in the method as a similar method has been used by Hergesell over the ocean. The instrument was attached to the balloon filled with hydrogen by means of a slow match which was of such a length that it burnt away and detached the instrument after the time required. To the instrument itself a second balloon *filled with air* was attached and fell with it. This balloon was of red indiarubber and was blown up to be about 45 cm. in diameter when at ground-level. The function of this balloon was simply to mark the position of the fallen instrument. On liberating the large balloon with instrument and small red balloon attached, its course was watched through an ordinary balloon theodolite. When the instrument was detached its fall was followed generally to quite near the ground; but it was always lost before it actually reached the ground. The direction was then noted in which the instrument was last seen, and the bearings taken. With few exceptions this direction was over the sea ice, and then one walked straight ahead in this direction and by the aid of a powerful pair of field glasses the small red rubber balloon was generally seen and the instrument recovered. The method was used on the occasion of the highest ascent about which the following is taken from the note book:—

> '*Monday, December 25th,* 1911.—An attempt was made to reach as high as possible. A fuse for forty minutes was attached. Besides the small red balloon a frame carrying four sheets of silver paper was attached to the instrument. The instrument was detached 43 minutes after the ascent; but for some time before this the silver paper, and at times the instrument, was all that could be seen below the large balloon. When the instrument fell its course was followed by the flashing of the silver paper. The latter however slowly broke away, and when about 15° above the horizon became invisible. The theodolite was lowered and a bearing of the direction was taken, but as this cut right across Inaccessible Island it was not a good one. On setting out to find the instrument I travelled on ski for 2½ hours as near the bearing as possible, then I saw the small red balloon through glasses about a mile and half away. The instrument was safely picked up about ten miles from Cape Evans in a S.S.W. direction.' (The instrument had risen 6,743 metres.)

Obviously this method could not be used to reach even moderate heights if there was an appreciable wind. Hence it was only tried on days when Erebus smoke showed that the air was nearly calm throughout the lower atmosphere.

This method was quite impossible in the winter because in the great cold the moisture from the eye crystallised on to the eyepiece of the theodolite making it unusable. To meet this difficulty a number of cones of fine silk thread were taken south. On each cone was five miles of silk thread the total weight of which was only 4 oz. It was intended to attach one end of this silk thread to the instrument before liberating the balloon. The instrument was then to be detached from the balloon after a given time by means of a fuse, and the thread followed until the instrument was picked up. Naturally difficulties were encountered, but they were of an entirely unexpected nature. A simple method for liberating the balloon and paying out the silk without breaking it was developed, and on most occasions there was little doubt that all went well and the silk thread was intact until the instrument was detached. But occasions occurred with annoying frequency when on following along the thread it was found to be broken and the instrument could not be found. The cause of the breaking of the silk after the instrument had been detached from the balloon long remained a mystery, and numerous expedients were employed to find either the cause or a remedy. The opportunities for doing balloon work were very few, nothing could be done in the dark months, and the intervals between the periods of wind were so short and occurred so irregularly that by taking advantage of every opportunity the problem was not solved until the work was near its end. The cause for the breaking of the silk was really very simple. So long as the balloon was rising and drawing out the thread there was no strain to break it. As soon however as the instrument fell it left a great bight of silk in the air, the instrument after it had fallen on the ground anchored one end of this bight, and soon there was enough silk lying on the ground at the other end to anchor that end also. Thus while a great length of silk was still in the air and falling only slowly both ends were fastened. If there was any wind at all the long length of thread which remained in the air was subject to a considerable pressure which it was unable to withstand, and it therefore broke.

The method devised for minimising this difficulty was as follows: The instrument was attached as before by a fuse, timed to release the instrument in about fifteen minutes. After the silk thread had run out for about ten minutes it was broken near to the reel and a small rubber balloon filled with air rapidly attached to the end. This was then allowed to go free, and it was raised on the end of the thread until the instrument was released about five minutes later. The length of thread used was reduced in this way by one-third. After the instrument had fallen, for some time the balloon remained in the air for it fell quite slowly, during this period it was free to move under the tension of the thread and so allowed the thread to lay itself in the direction of the wind. After the red balloon had been released its course was watched through field glasses, and as the time was only short the chance of the glasses becoming fogged was much reduced. The position in which the small balloon fell was noticed, and on going out to it the thread was found and followed up to the instrument. When this method was used the thread was never found broken, but it had only just been successfully developed when the weather improved so much that the summer method described above could be used.

The first method—theodolite used for watching the ascent and descent of the instrument which had a small red balloon attached to mark its position—was used for five ascents, and on each occasion the instrument was recovered. The second method—simple thread—was used on twelve occasions. Five times it was successful, and the instrument was recovered by following the thread; six times the thread was found broken; and on the remaining occasion the thread led on to new thin ice and so could not be followed. The third method—short thread with small red balloon used to mark the end—was employed four times, on three occasions the instrument was recovered, while on the fourth occasion the balloon moved in the direction of the sun so that it was lost sight of and not found again.

Thus out of twenty-one ascents, thirteen instruments were recovered at once, one instrument was found later on the floe giving fourteen records in all. Two records were not satisfactory, so that there remain twelve for discussion.*

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* The results of the observations are plotted on figure 13, page 42.

WINTER ASCENTS.

TABLE 133.

Record I.

August 13, 1911.

Time 12-20. Erebus smoke from S.

Height.	Pressure.	Temperature.	Gradient.	Height.	Pressure.	Temperature.	Gradient.
Metres.	mm.	°C.	°C. per 100 m.	Metres.	mm.	°C.	°C. per 100 m.
0	741	−39·0		1,760	575	−34·8	
392	700	−37·1		**2,000**	**556**	**−35·9**	**+·38**
500	**688**	**−37·0**	**−·40**	2,069	550	−36·3	
644	675	−36·9		2,391	525	−37·4	
906	650	−36·0		**2,500**	**517**	**−37·9**	**+·40**
1,000	**642**	**−35·6**	**−·28**	2,727	500	−38·2	
1,178	625	−34·7		2,937	485	−38·7	
1,463	600	−34·0		**3,000**	**480**	**−39·0**	**+·22**
1,500	**598**	**−34·0**	**−·32**				

The previous day had been calm with a clear sky. The temperature had been slowly falling for the previous forty hours from −27° to −39° C. due to the clear sky and absence of wind. At the time of ascent there was some (7) cirrus stratus cloud but no appreciable wind. On ascending the balloon moved slowly towards the N.W. and then came back. The instrument was found about 2½ kilometres to the N.W. of the station. The temperature increased from the ground to 1,500 metres, the rise being just 5° giving a mean negative gradient * of −·33°C. per 100 metres. From this point the temperature fell slowly, the decrease being at the same rate as the previous increase so that the temperature at 3,000 metres was exactly the same as on the ground. It is probable that the point of inversion of the temperature corresponded with the change in the very slight air movement, the lower cold layers slowly moving to the N.W. with the air above moving somewhat more slowly in the opposite direction.

TABLE 134.

Record II.

August 16, 1911.

Time 10-55. Erebus smoke from N.W.

Height.	Pressure.	Temperature.	Gradient.	Height.	Pressure.	Temperature.	Gradient.
Metres.	mm.	°C.	°C. per 100 m.	Metres.	mm.	°C.	°C. per 100 m.
0	742	−35·0		1,230	625	−26·4	
163	725	−33·0		**1,500**	**603**	**−28·5**	**+·62**
411	700	−29·0		1,523	600	−28·7	
500	**690**	**−27·5**	**−1·50**	1,827	575	−30·5	
673	675	−25·0		1,953	565	−31·0	
947	650	−25·2		**2,000**	**562**	**−31·2**	**+·54**
1,000	**644**	**−25·4**	**−·42**				

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* Throughout this work a negative sign prefixed to the gradient signifies that the normal temperature gradient was reversed, so that the temperature rose with the height.

The balloon moved first to S. and then to N.W., but the velocities were very small. The instrument fell about 2 kilometres to the W.N.W. of the station. There was again some (5) cirrus stratus cloud. The temperature rose from the surface to about 750 metres and the gradient was much larger than in the previous ascent, being –1·5°C. per 100 metres. At 750 metres there was a point of inflexion in the temperature curve and from this height to the highest point reached (1,953 metres) the temperature fell at a mean rate of ·58°C. per 100 metres. It is very probable that in this case also the change in the wind direction took place at the point of inflexion of temperature.

TABLE 135.

Record III.

August 17, 1911.

Time 12-30. Erebus smoke from W.

Height.	Pressure.	Temperature.	Gradient.	Height.	Pressure.	Temperature.	Gradient.
Metres.	mm.	°C.	°C. per 100 m.	Metres.	mm.	°C.	°C. per 100 m.
0	739	–35·0		1,480	600	–30·8	
134	725	–32·8		**1,500**	**599**	**–31·0**	**+·36**
381	700	–29·8		1,781	575	–32·0	
500	**691**	**–29·3**	**–1·14**	**2,000**	**558**	**–33·2**	**+·44**
641	675	–28·5		2,093	550	–33·7	
911	650	–29·0		2,379	528	–35·0	
1,000	**642**	**–29·2**	**– ·02**	**2,500**	**515**	**–35·4**	**+·44**
1,190	625	–29·7					

Just below the summit of Erebus there were some stratus clouds and in other parts of the sky a little alto-stratus or low cirro-stratus. The latter appeared to be moving from the S. or S.E., but the motion could not be decided with certainty. The balloon travelled to the south as long as it could be seen, but the motion in the upper part of the ascent was not determined. The temperature inversion was still present, but the gradient was not so great and the inflexion was less sharp and somewhat lower than on the previous day. From the ground to 500 metres the gradient was –1·14°C. per 100 metres, while above the point of inflexion it was +·44°C. per 100 metres. In this case it is impossible to say whether the wind direction changed at the point when the temperature commenced to fall instead of rising with increase of height.

TABLE 136.

Record IV.

August 30, 1911.

Time 14-45. Erebus smoke from S.E.

Height.	Pressure.	Temperature.	Gradient.	Height.	Pressure.	Temperature.	Gradient.
Metres.	mm.	°C.	°C. per 100 m.	Metres.	mm.	°C.	°C. per 100 m.
0	733	–32·0		1,414	600	–33·2	
500	**683**	**–31·0**	**–·20**	**1,500**	**594**	**–33·8**	**+·48**
583	675	–31·0		1,712	575	–35·0	
850	650	–31·0		**2,000**	**551**	**–36·7**	**+·58**
1,000	**638**	**–31·4**	**+·08**	2,020	550	–36·8	
1,127	625	–31·8		2,210	535	–37·8	

During the morning of this day there had been a strong wind from the N.W., the velocity being between 10 and 15 metres a second from near midnight to 11 A.M. In the early afternoon the wind dropped and a balloon was sent up. It did not rise very high and its motion was very irregular showing a considerable difference of wind direction in the different layers. At the time of the ascent there was a slight breeze from the S.E., but the balloon moved slowly to the south almost immediately on rising. It then returned and passed almost overhead and travelled away to the N. The instrument was found about 1½ kilometres to the N.W. of the station. The trace for the lower part of the ascent is very much blurred and cannot be reduced with so much certainty as the previous records. It is almost certain, however, that there was only a very little inversion and that the temperature from the ground to 800 metres was almost uniform. The mean gradient given in the table for the first kilometre of ascent is only –·06°C., and this is probably fairly near to the correct value, and is what one would expect after so much wind and while the different currents at different heights indicate a disturbed atmosphere. Above 1,000 metres the gradient was positive and tended towards a value between ·5° and ·6° C. per 100 metres.

These four records were all that it was possible to obtain from the 12 balloons sent up during the winter months. They give, however, very useful information. The temperature gradient found in each of the ascents is given in table 137. By applying the mean gradient to the mean temperature on the ground at the time of the ascents the values given in table 138 have been obtained, and they give the average conditions in the lower atmosphere during cold calm weather at the end of the winter.

TABLE 137.

Temperature gradient in the winter.

Date.	0 m. to 500 m.	500 m. to 1,000 m.	1,000 m. to 1,500 m.	1,500 m. to 2,000 m.	2,000 m. to 2,500 m.	2,500 m. to 3,000 m.
	°C. per 100 m.	°C. per 100 m.	°C. per 100 m.	°C. per 100 m.	°C. per 100 m.	°C. per 100 m.
August 13th . .	−0·40	−0·28	−0·32	+0·38	+0·40	+0·22
August 16th . .	−1·50	−0·42	+0·62	+0·54	..	..
August 17th . .	−1·14	−0·02	+0·36	+0·44	+0·44	..
August 30th . .	−0·20	+0·08	+0·48	+0·58	..	..
Mean . . .	−0·81	−0·16	+0·28	+0·48	+0·42	+0·22
	−0·49		+0·38			

TABLE 138.

Mean vertical temperatures during the winter.

Height.	Temperature.
0 Metres.	−35·0° C.
500	−31·0
1,000	−30·2
1,500	−31·6
2,000	−34·0
2,500	−36·1

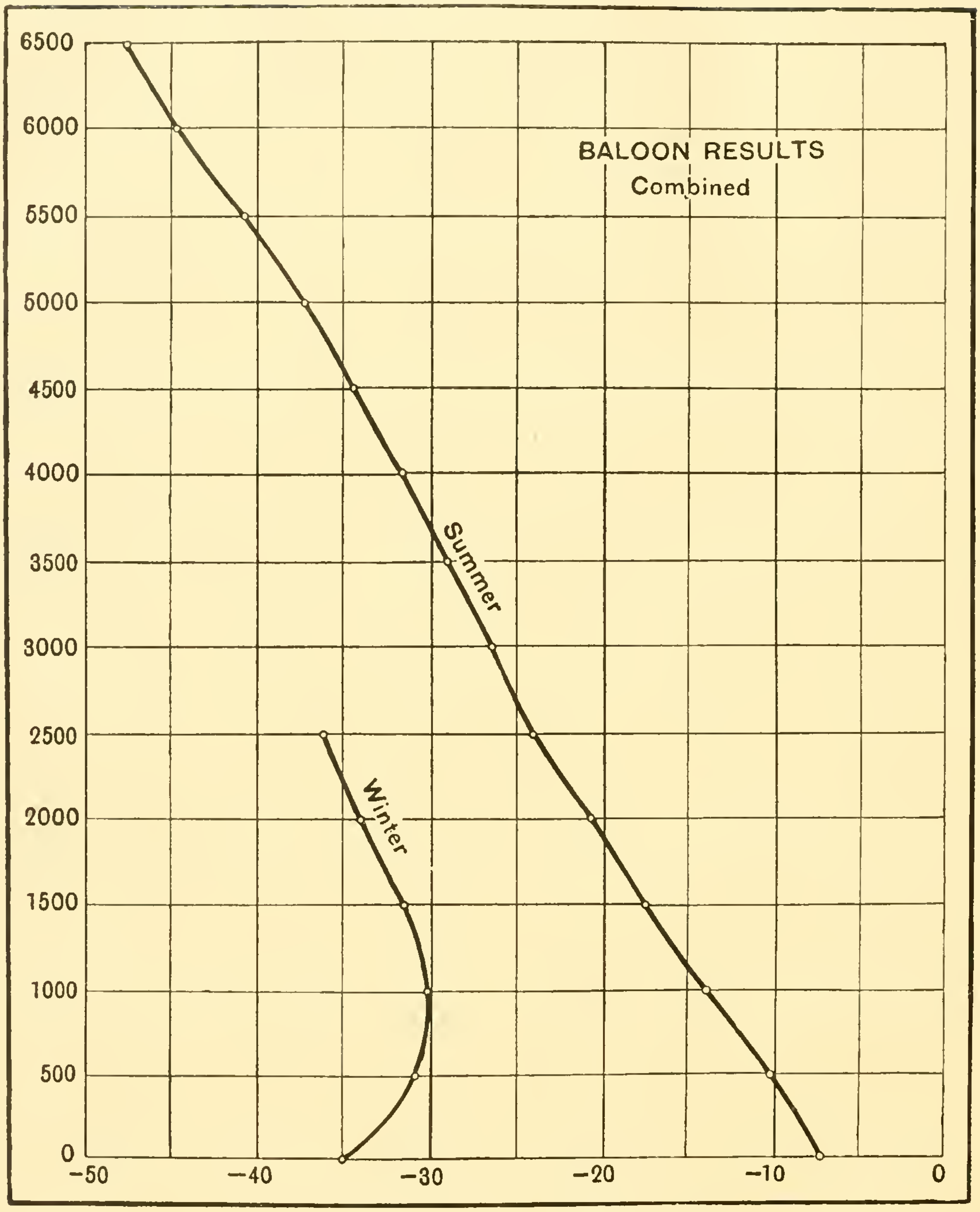

Fig. 85. Upper air temperatures, summer and winter.

The numbers given in table 138 have been plotted in figure 85.

Summary of winter conditions.

(*a*) During cold calm weather in the winter there is a temperature inversion in the lower atmosphere which, however, does not appear to extend much higher than 1 or 1½ kilometres.

(*b*) The mean temperature gradient above the inversion is between 0·40° and 0·50° C. per 100 metres.

(*c*) There is generally a discontinuity in the wind direction at the place where the gradient changes sign.

These conditions can best be explained by considering that the air in the upper atmosphere is being cooled by radiation and in consequence sinking. The fact that the temperature gradient is much smaller than the adiabatic gradient indicates that the downward motion is so small that a large amount of the heat generated by compression is lost by radiation. Near the ground the radiation is so great and the downward motion of necessity so small that the air is abnormally cooled. Thus a layer of cold dense air forms near to the ground which the descending current cannot move and over which it must flow, thus accounting for the different winds found at the upper surface of the lower cold layer.

SUMMER ASCENTS.

TABLE 139.

Record V.

November 12, 1911.

Time 11-15. Erebus smoke from the W.

Height.	Pressure.	Temperature.	Gradient.	Height.	Pressure.	Temperature.	Gradient.
Metres.	mm.	°C.	°C. per 100 m.	Metres.	mm.	°C.	°C. per 100 m.
0	746	− 9·2		1,641	600	−20·8	
220	725	−11·0		1,954	575	−22·5	
487	700	−13·0		**2,000**	**574**	**−22·8**	**·56**
500	**699**	**−13·0**	**·76**	2,279	550	−24·0	
763	675	−15·0		**2,500**	**537**	**−25·5**	**·54**
1,000	**656**	**−16·1**	**·62**	2,617	525	−26·5	
1,047	650	−16·5		2,757	515	−28·0	
1,339	625	−19·0		**3,000**	**498**		
1,500	**613**	**−20·0**	**·78**				

A blizzard occurred throughout the 10th and continued until the morning of the 11th. The wind dropped during the afternoon, and from 17 hours on the 11th until the time of the ascent (11-15 on the 12th) a breeze between 1·5 and 2·5 metres a second continued from the S.E. During this period the temperature was fairly constant, being about +12°C. Three hours before the ascent the temperature commenced to rise, and when the ascent took place it was −9°C. The sky was nearly overcast with alto-cumulus clouds, and it is probable that the instrument went into, if not through, these. At first the balloon travelled in the surface S.E. wind until the alto-cumulus clouds were reached, and then it moved with them nearly due west. Soon after the balloon had ascended the surface wind increased and the weather became thick. Some snow fell and it appeared as if a blizzard were starting but although the wind continued at about 20 miles an hour the sky cleared, and the blizzard did not become marked until the next day. The mean temperature gradient up to 1,500 m. was ·72°C. per 100 metres. At this height the gradient became smaller for the next 1,000 metres, being only ·55° from 1,500 metres to 2,500 metres. This probably was the region of movement from the west and of the alto-cumulus clouds. At 2,250 metres the temperature commenced to fall more rapidly again, and from 2,250 to 2,750 metres the fall was at the rate of ·84°C. per 100 metres. It will be found that in most of the summer ascents there is a similar region in which there is a smaller gradient than in the regions above and below.

TABLE 140.

Record VI.

November 15, 1911.

Time 10-30. A cumulus cloud moving from N. 10° E.

Height.	Pressure.	Temperature.	Gradient.
Metres.	mm.	C.	°C. per 100 m.
0	750	−10·5	
261	725	−11·0	
500	**703**	**−12·6**	**·42**
528	700	−12·8	
804	675	−14·8	
1,000	**658**	**−16·5**	**·78**
1,088	650	−17·2	
1,380	625	−18·7	
1,500	**617**	**−19·2**	**·54**
1,683	600	−20·0	
2,000	**575**	**−21·0**	**·36**
1,997	575	−21·0	
2,324	550	−22·8	
2,500	**536**	**−24·7**	**·74**
2,663	525	−26·2	
2,831	513	−27·2	
3,000	**500**	**−28·2**	**·70**

The weather conditions during this ascent were very similar to those during the previous one. The ascent was made during a few calm hours between two blizzards. As before, the temperature had been fairly steady until the calm weather set in when it commenced to rise. The sky was 8/10ths overcast with alto-stratus and alto-cumulus clouds. The balloon moved very slowly towards the S.E. and did not appear to change its direction; evidently the current of air which was moving the clouds from N. 10° E. extended to the ground with only a small change of direction.

The gradient in the first 500 metres was smaller than in the previous record, being ·42° and ·78° C. per 100 metres respectively. Above 1,000 metres the gradient became much smaller, and between 1,500 and 2,000 metres it was only ·36°C. per 100 metres. This reduced gradient obviously belonged only to a layer, for at 2,000 metres the rate of fall of temperature again increased, and from 2,000 to 3,000 metres the mean gradient was ·72°C. per 100 metres.

The characteristics of the vertical temperature distribution during this ascent were as before—a region in which the gradient was considerably smaller than in the regions above and below.

Record VII a, b and c.

November 19, 1911.

The three balloon ascents made on this day are very interesting. For the first time balloons without silk thread were used, the ascent of the large balloon and the descent of the instrument with the small marking balloon attached being followed through a theodolite.

At 11-30 the first balloon was sent up. The fuse used for liberating the instrument was timed to burn through in fifteen minutes. The balloon rose almost vertically, and a few minutes before the instrument should have been detached, it was right overhead. In this position a small motion of the balloon required a very large motion of the theodolite in azimuth to keep it in the field of view, and it was found impossible to make this rapid motion and the balloon was lost to sight. After waiting until the instrument was estimated to have had time to fall, the theodolite was used to scan the surrounding ice floe to see if the red balloon attached to the instrument was in sight. No trace of it could, however, be seen, and the instrument was given up for lost, when it was seen to fall less than one hundred metres away. The fuse had evidently burnt longer than was expected, and when the record was worked out it was found that it had been up nearly 4,000 metres. That after such an ascent the instrument should fall so near to the starting point showed that the lower atmosphere was remarkably calm, and I at once determined to make a more serious attempt to get a high ascent.

A new balloon and instrument were prepared and a longer fuse attached. The second balloon ascended at 12-30; but unfortunately the fuse became wrapped round the string attaching the instrument to the balloon and burnt it through within fifteen minutes of the start. The instrument was picked up ½ kilometre to the N.W., the height reached proved to have been only about 3,000 metres.

Later in the day (at 4-30 P.M.) another attempt was made to get a high ascent and this time all went well, but the height reached was only a little over 4½ kilometres, thus only surpassing the first by a little over half a kilometre. The instrument was found on the slopes of Erebus about ¾ kilometre to the north-east of the station. Throughout the day the sky was cloudless.

TABLE 141.

Record VII a, b and c.

ASCENT 1 (*a*) EREBUS SMOKE FROM W. 11 H. 30 M.				ASCENT 2 (*b*) EREBUS SMOKE FROM W. 12 H. 30 M.				ASCENT 3 (*c*) EREBUS SMOKE FROM W. 16 H. 30 M.			
Height.	Pressure.	Temperature.	Gradient.	Height.	Pressure.	Temperature.	Gradient.	Height.	Pressure.	Temperature.	Gradient.
Metres.	mm.	°C.	°C. per 100 m.	Metres.	mm.	°C.	°C. per 100 m.	Metres.	mm.	°C.	°C. per 100 m.
0	754	−11·5		0	754	−10·5		0	754	−11·0	
301	725	−12·6		312	725	−12·8					
500	**706**	**−13·5**	**·40**	**500**	**706**	**−14·0**	**·70**	**500**	**708**	**−13·6**	**·52**
567	700	−13·8		577	700	−14·6		567	700	−14·0	
842	675	−15·7		851	675	−16·6		840	675	−16·0	
1,000	**660**	**−17·0**	**·70**	**1,000**	**661**	**−17·7**	**·74**	**1,000**	**662**	**−17·0**	**·68**
1,125	650	−18·1		1,133	650	−18·8		1,123	650	−18·0	
1,416	625	−20·0		1,423	625	−20·7		1,414	625	−20·0	
1,500	**617**	**−20·5**	**·70**	**1,500**	**619**	**−21·1**	**·68**	**1,500**	**618**	**−20·4**	**·68**
1,717	600	−22·0		1,723	600	−22·0		1,714	600	−21·5	
2,000	**578**	**−23·9**	**·68**	**2,000**	**579**	**−23·8**	**·54**	**2,000**	**577**	**−23·6**	**·64**
2,029	575	−24·0		2,035	575	−24·0		2,026	575	−23·7	
2,351	550	−27·0		2,358	550	−26·3		2,350	550	−25·0	
2,500	**540**	**−27·9**	**·80**	**2,500**	**540**	**−27·1**	**·66**	**2,500**	**539**	**−25·9**	**·46**
2,685	525	−28·3		2,693	525	−27·4		2,686	525	−26·7	
3,000	**503**	**−28·8**	**·18**	**3,000**	**502**	**−27·8**	**·14**	**3,000**	**502**	**−27·8**	**·38**
3,034	500	−28·8		3,040	500	−27·8		3,037	500	−27·8	
3,400	475	−30·0						3,405	475	−28·7	
3,500	**469**	**−30·5**	**·34**					**3,500**	**470**	**−29·0**	**·24**
3,783	450	−32·1						3,790	450	−30·5	
4,000	**436**	**−33·6**	**·62**					**4,000**	**438**	**−31·7**	**·54**
								4,193	425	−32·7	
								4,500	**410**	**−34·4**	**·54**
								4,617	400	−35·0	

Taking the mean temperature at sea-level as −11·0°C. during the three ascents and applying to this temperature the mean gradients, we obtain the following as the mean temperature at the different heights throughout the day :—

Table 142.

November 19, 1911.

Height.	Temperature.	Mean gradient.
Metres.	°C.	°C. per 100 metres.
0	−11·0	
500	−13·7	·54
1,000	−17·2	·71
1,500	−20·7	·69
2,000	−23·8	·62
2,500	−27·0	·64
3,000	−28·1	·23
3,500	−29·6	·29
4,000	−32·5	·58
4,500	−35·2	·54

From the figures in table 141, it will be seen that from 500 to 2,000 metres the temperature remained practically the same from 11 hours 30 minutes until 16 hours 30 minutes.

Above this height the temperature changed in the course of the day by about two degrees, the later ascent showing the higher temperature.

It will also be noticed that at about 2,250 metres a different layer of air was met with, for at about this height there is a distinct change in the gradient. The change in the gradient was most marked during the morning ascent, the gradient being more uniform throughout at the afternoon ascent. Thus the gradient from 500 metres to 2,000 was in the three ascents, ·69°, ·65° and ·67° C. per 100 metres respectively, while the gradient from 2,500 to 3,500 metres was ·26° at the first ascent and ·31° at the third ascent.

The first and third ascents again reveal a region of the atmosphere in which the gradient is less than in the regions above and below, and no doubt the same would have been found to hold if the second ascent had gone high enough. On the mean of the three ascents we have the following gradients :—

Table 143.

Mean gradient on November 19, 1911.

1,500 m. to 2,500 m.	2,500 m. to 3,500 m.	3,500 m. to 4,500 m.
·63	·26	·56°C. per 100 m.

The weather preceding the ascent was as follows: On the 17th a southerly blizzard had existed, which, as was usually the case in the summer, was cold, the mean temperature when the blizzard was strongest being about −19°C. During the 18th the wind gradually dropped and the temperature rose. The air became calm at 17 hours on the 18th, so that a calm had existed for about 10 hours before the first ascent.

TABLE 144.

Record VIII.

November 29, 1911.

Time 12-30. Erebus smoke from N.W.

Height.	Pressure.	Temperature.	Gradient.	Height.	Pressure.	Temperature.	Gradient.
Metres.	mm.	°C.	°C. per 100 m.	Metres.	mm.	°C.	°C. per 100 m.
0	757	− 7·0		**2,500**	**543**	**−27·7**	**·92**
336	725	−10·0		2,729	525	−29·0	
500	**711**	**−11·0**	**·80**	**3,000**	**507**	**−30·2**	**·50**
604	700	−12·0		3,076	500	−30·5	
881	675	−14·0		3,440	475	−32·0	
1,000	**664**	**−15·1**	**·82**	**3,500**	**471**	**−32·1**	**·38**
1,166	650	−16·3		3,822	450	−32·8	
1,458	625	−19·0		**4,000**	**438**	**−33·0**	**·18**
1,500	**621**	**−19·4**	**·86**	4,223	425	−33·3	
1,760	600	−21·2		**4,500**	**408**	**−35·3**	**·46**
2,000	**580**	**−23·1**	**74**	4,645	400	−36·3	
2,073	575	−23·6		4,865	388	−37·0	
2,396	550	−26·7		**5,000**	**381**	**−37·6**	**·46**

The balloon ascended practically vertically moving first somewhat to the N.W. and then to the S.E. The instrument fell about 2½ kilometres to the south-east. At the time of the ascent Erebus smoke was travelling from the N.W., so that the balloon entered the current of air indicated by the movement of the smoke. There were a few cirrus clouds and during the afternoon these thickened, and at 16 hours 7/10ths of the sky were covered with thick cirrus or alto-cumulus clouds which showed fine iridescent colours. Over all the mountains to the west there were heavy cumulus clouds and Erebus became obscured at about 14 hours 30 minutes.

There had been very little wind for the preceding forty hours, and during this time the temperature had been fairly steady, varying only a degree or so on either side of −8°C. The temperature gradient was unusually high, the mean gradient in the first 2,500 metres of the ascent being ·83°C. per 100 metres. Near to 2,500 metres the gradient became less, and from this point the gradient decreased steadily until between 3,500 and 4,000 metres it was only ·18°C. per 100 metres. At about 4,250 metres the gradient again became greater and from 4,223 to 4,865 metres the temperature fell 3·7°C., this being a gradient of ·50°C. per 100 metres.

In this ascent again the region of small gradient is clearly shown with greater gradients above and below, but the height at which it occurred was somewhat higher than on the previous occasions.

TABLE 145.

Record IX.

December 24, 1911.

Time 12-15. Erebus smoke from N.E.

Height.	Pressure.	Temperature.	Gradient.	Height.	Pressure.	Temperature.	Gradient.
Metres.	mm.	°C.	°C. per 100 m.	Metres.	mm.	°C.	°C. per 100 m.
0	761	− 3·3		2,157	575	−19·2	
116	750	− 3·7		2 480	550	−20·9	
383	725	− 5·3		**2,500**	**548**	**−21·0**	**.62**
500	**714**	**− 6·1**	**·56**	2,822	525	−22·8	
656	700	− 7·3		**3,000**	**513**	**−24·0**	**·60**
938	675	− 9·5		3,179	500	−25·3	
1,000	**671**	**−10·0**	**·78**	**3,500**	**479**	**−27·5**	**·70**
1,227	650	−11·9		3,547	475	−28·0	
1,500	**628**	**−14·0**	**·80**	3,933	450	−29·9	
1,525	625	−14·2		**4,000**	**447**	**−30·1**	**·52**
1,833	600	−16·6		4,159	436	−30·8	
2,000	**587**	**−17·9**	**·78**				

The weather had been calm for 18 hours before this ascent took place, and the temperature had shown a well-marked daily variation. The balloon rose almost vertically for 18 minutes when the instrument was detached and fell about 1½ kilometres to the W.N.W. The gradient in the lower atmosphere (neglecting the part near the ground where the record is doubtful) up to 2,000 metres was about ·78°C. per 100 metres. Above this the gradient decreased, being only ·60 C. per 100 metres between 2,500 and 3,000 metres. In the next 500 metres the gradient increased to ·70°C., but above this it again decreased. The direction of Erebus smoke was very abnormal and it is possible that the second decrease in the gradient was caused by this upper current.

TABLE 146.

Record X.

December 25, 1911.

Time 13 hours. Erebus smoke from E.

Height.	Pressure.	Temperature.	Gradient.	Height.	Pressure.	Temperature.	Gradient.
Metres.	mm.	°C.	°C. per 100 m.	Metres.	mm.	°C.	°C. per 100 m.
0	759	− 3·0		3,167	500	−22·9	
96	750	− 3·9		**3,500**	**478**	**−25·6**	**·70**
363	725	− 5·4		3,541	475	−25·8	
500	**711**	**− 6·0**	**·60**	3,931	450	−28·6	
636	700	− 6·7		**4,000**	**448**	**−29·1**	**·70**
918	675	− 8·9		4,337	425	−31·0	
1,000	**668**	**− 9·5**	**·70**	**4,500**	**417**	**−32·2**	**·62**
1,209	650	−11·5		4,764	400	−34·0	
1,500	**626**	**−13·5**	**·80**	**5,000**	**387**	**−35·5**	**·66**
1,508	625	−13·6		5,214	375	−37·0	
1,816	600	−16·0		**5,500**	**358**	**−39·0**	**·70**
2,000	**585**	**−17·1**	**·72**	5,685	350	−40·0	
2,135	575	−17·6		**6,000**	**335**	**−42·1**	**·82**
2,465	550	−20·0		6,208	325	−43·2	
2,500	**548**	**−20·2**	**·62**	**6,500**	**314**	**−44·8**	**·54**
2,808	525	−21·2		6,743	300	−46·2	
3,000	**513**	**−22·1**	**·38**				

On the morning of December 25th, 1911, it was obvious from the smoke of Erebus that the lower atmosphere was remarkably calm, and therefore an attempt was made to get a very high ascent. A fuse burning for over 40 minutes was used, and silver paper was attached to the instrument to make it more visible when far away. The ascent has already been described (page 217) and it was so successful that the instrument was recovered after it had been nearly 7,000 metres high. The record revealed four regions in the atmosphere:

(*a*) From the ground to 2,000 metres the gradient was moderately high with a mean value of ·71 C. per 100 metres.

(*b*) From 2,000 to 3,000 metres the gradient was irregular, indicating various layers. In this region the gradient was small, being on the average ·50°C. per 100 metres, but from 2,500 to 3,000 metres only ·38°C.

(*c*) From 3,000 to 6,000 metres the gradient was again higher, being on the average 70°C. per 100 metres.

(*d*) Above 6,000 metres the gradient fell to ·54°C. per 100 metres; the ascent, however, ceased at 6,743 metres.

In (*a*), (*b*) and (*c*) we recognise the three layers which have been such a marked feature in all the previous ascents in the summer. The decrease of the gradient at 6,000 metres is significant, but the ascent was not sufficiently high to make sure that this was caused by an approach to the stratosphere. It is exceedingly disappointing that this ascent did not continue for another 1,000 metres higher, as it proved to be the last one which we were able to make. The mean gradient from sea-level to 6,750 metres shown by this ascent was ·64° C. per 100 metres.

Combined Summer Results.

Ascents were made on six days during the summer months of November and December. It has been shown that in each one of these ascents a region was met with in which the gradient was smaller than in the regions above and below.

The following table gives the approximate height of this region:—

TABLE 147.

Approximate height of the beginning and end of the region of small gradient.

Date.	Lower limit.	Upper limit.
	m.	m.
November 12th .	1,500	2,300
November 15th .	1,100	2,000
November 19th .	2,500	3,500
November 29th .	2,500	4,200
December 24th .	2,200	3,000
December 25th .	2,000	3,000
Mean .	2,000	3,000

In the following table the gradient measured in each ascent is shown:—

Table 148.

Mean gradient during the summer. °*C. per* 100 *metres.*

Date.	0 m. to 500 m.	500 m. to 1,000 m.	1,000 m. to 1,500 m.	1,500 m. to 2,000 m.	2,000 m. to 2,500 m.	2,500 m. to 3,000 m.	3,000 m. to 3,500 m.	3,500 m. to 4,000 m.	4,000 m. to 4,500 m.	4,500 m to 5,000 m.	5,000 m. to 5,500 m.	5,500 m. to 6,000 m.	6,000 m. to 6,500 m.
November 12th .	·76	·62	·78	·56	·54								
November 15th .	·42	·78	·54	·36	·74	·70							
November 19th .	·54	·71	·69	·62	·64	·23	·29	·58	·54				
November 29th .	·80	·82	·86	·74	·92	·50	·38	·18	·46	·46			
December 24th .	·56	·78	·80	·78	·62	·60	·70	·52					
December 25th .	·60	·70	·80	·72	·62	·38	·70	·70	·62	·66	·70	·82	·54
Mean	·61	·73	·74	·63	·68	·48	·52	·50	·54	·56	·70	·82	·54
	·67		·68		·58		·51		·55		·76		

By combining the results in this way the region of least gradient appears to be between 2,500 and 4,000 metres, but this is due to the irregularity in the number of ascents which reached higher than 2,500 metres.

Taking the mean temperature on the ground at the times of the ascents and applying the mean gradients as shown in the above table we get the following as the mean state of the atmosphere during the summer months as shown by these few ascents:—

Table 149.

Mean vertical temperatures during six days in the summer.

Height.	Temperature.	Height.	Temperature.
m.	°C.	m.	°C.
0	− 7·3	3,500	−29·2
500	−10·3	4,000	−31·8
1,000	−14·0	4,500	−34·4
1,500	−17·7	5,000	−37·2
2,000	−208.	5,500	−40·8
2,500	−24·2	6,000	−44·8
3,000	−26·6	6,500	−47·6

These numbers have been plotted in figure 85.

Summary of Summer Conditions.

(*a*) The mean gradient from the ground to 2,500 metres is approximately ·68°C. per 100 metres, but individual ascents showed gradients of between ·8° and ·9° in parts of this region.

(*b*) Between 2,000 to 4,000 metres every ascent showed a region in which the gradient was less than in the regions above and below. The mean gradient in this region was ·54°C. per 100 metres.

(*c*) Above the region described in (*b*) there was an increase in the gradient.

(*d*) In the highest ascent the gradient again decreased above 6,000 metres.

These results show a gradient in the lower atmosphere as large as that found over land in temperate regions during summer, and occasionally approached the adiabatic gradient in dry air. Such a gradient indicates considerable forced motion in the atmosphere and as at the times of the ascents there was practically no wind this motion could only have been caused by convexion currents resulting from the sun shining on the snow surface.

The decrease in temperature gradient which occurs between 2,000 and 4,000 metres is probably due to the fact that in this region the air has to adjust itself to the different conditions of pressure and temperature which exist at this height over the Ross Sea area and over the high tableland to the west. The height of this tableland as found by Captain Scott in November 1903 is approximately 2,500 metres and as the temperature gradient over the high snow-covered plateau must be different from that in the free air at the same height over a region at sea-level, some adjustment must take place which is shown by the reduced temperature gradient. Above this region of adjustment normal temperature gradients are re-established.

CHAPTER IX.

THE HEIGHT OF THE BARRIER AND THE SOUTH POLAR PLATEAU.

THE HEIGHT OF THE BARRIER.

Nearly all the sledging parties which visited the Barrier had aneroid barometers and from their records it is possible to determine the mean height of the Barrier with some certainty.

The barometers were compared with the standard at Cape Evans when each party left and when it returned. From these comparisons the corrections to be applied were determined.

The corrected readings have been compared with the simultaneous pressure at Cape Evans and the differences tabulated.

The track of all the parties on the Barrier was practically the same and has been shown on the map which forms the frontispiece to this volume. After leaving Hut Point the Barrier was reached at Safety Camp from which point the track went almost due east to Corner Camp in 78° 3′ S., 168° 59′ E. At this camp, as its name implies, the track turned sharply to the south and the whole of the remainder of the journey to the foot of the Beardmore Glacier was made on or near to the 169° E. meridian.

The observations have been collected into convenient geographical groups and the mean difference between the simultaneous pressure on the Barrier and at Cape Evans determined for each group. The results are contained in the following table:—

TABLE 150.

Mean pressure difference between Cape Evans and the Barrier during the period November 1911 *to January* 1912.

Position.	Number of observations.	Mean pressure difference.	Position.	Number of observations.	Mean pressure difference.
		Inches.			Inches.
Hut Point . .	9	−0·01	80° 10′ to 80° 30′	21	+0·20
Hut Point to Corner Camp.	38	+0·08	80° 30′ to 80° 50′	40	0·22
Corner Camp .	32	0·09	80° 50′ to 81° 10′	16	0·17
Corner Camp to 78° 30′ S.	41	0·15	81° 10′ to 81° 30′	15	0·20
78° 30′ to 78° 50′	32	0·18	81° 30′ to 81° 50′	10	0·21
78° 50′ to 79° 10′	36	0·20	81° 50′ to 82° 10′	14	0·25
79° 10′ to 79° 30′	44	0·19	82° 10′ to 82° 30′	12	0·19
79° 30′ to 79° 50′	28	0·19	82° 30′ to 82° 50′	13	0·19
79° 50′ to 80° 10′	24	0·20	82° 50′ to 83° 10′	15	0·15

The numbers in this table have been plotted on a curve in figure 86, from which it will be seen that the pressure relative to Cape Evans falls to 79° S. and then remains constant to 83° S.

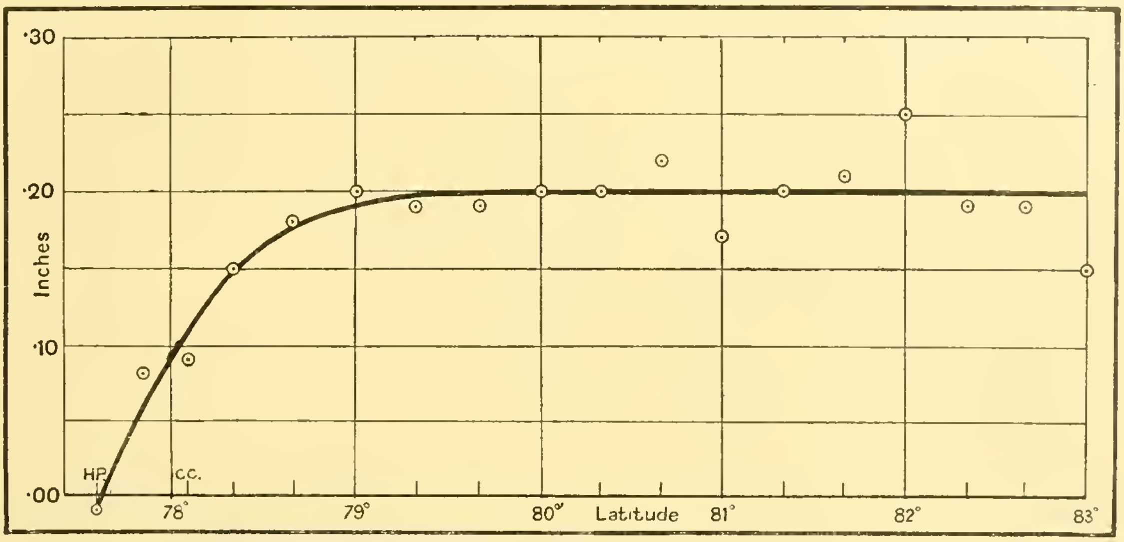

FIG. 86. Difference of pressure between Cape Evans and positions on the Barrier.

The first question we have to decide is how much of this pressure difference is due to pressure gradient and how much to difference in height ?

It is quite impossible from the barometer observations alone to answer this question, but the air motion throws considerable light on the subject. Both the wind observations and the sastrugi show that the prevailing wind over the west of the Barrier is from the south. Thus over this region the isobars must run almost parallel to the track followed by the sledging parties. This leads us to the conclusion that there can be little or no pressure gradient along the track, if there is any change at all it will be a slight increase towards the south. Thus the whole fall of pressure observed must be due to change of height, but there may be a slight additional change of height compensated for by a slight increase of pressure. The latter, however, cannot be determined beyond the fact that it is small and therefore may safely be neglected. We will therefore assume that the whole pressure difference between Cape Evans and the Barrier is due to difference of height; the height of the Barrier can then be determined from the pressure and temperature observations. The average pressure and temperature on the Barrier during the period over which the observations extend was 29·50″ and 15°F. respectively. South of 79° S. the pressure on the Barrier is uniformly ·20″ below the pressure at Cape Evans. These data give 170 feet = 52 metres as the mean height for the Barrier south of 79° S. At Corner Camp the pressure is ·09 inches below that at Cape Evans which corresponds to an elevation of 80 feet.

It is interesting to notice that Mohn calculates from Amundsen's observations that the mean height of the east of the Barrier is 60 metres, it therefore seems very probable that the true height of the Barrier is between 50 and 60 metres above sea-level over the greater part of its immense expanse.

Thus the chief heights along the track from Cape Evans to the Beardmore are :—

Cape Evans—Sea-level.

Corner Camp—80 feet.

One Ton Camp (79½° S.) to the Beardmore—170 feet.

Heights on the Beardmore Glacier.

The barometer used by the Polar Party was compared during the ascent of the Beardmore Glacier 24 times with a hypsometer, the mean correction found was –·05″. As the hypsometer was broken before the top of the Beardmore was reached, the comparisons could not be continued throughout the journey. The barometer had been set to be correct when leaving Cape Evans, and as it did not return for recomparison it has been assumed that the small change of –·05″ found by the hypsometer tests was real and this value has been used throughout. The barometer thus corrected agrees well with other barometers which were being read by other parties in its neighbourhood.

For purposes of the calculation of heights the journey from the Barrier to the Pole and back will be divided into four parts, namely :—

(1) From Pony Depôt on the Barrier to Mid-Glacier Depôt.
(2) From Mid-Glacier Depôt to Upper Glacier Depôt.
(3) From Upper Glacier Depôt to 3° Depôt.
(4) From 3° Depôt to the Pole.*

In the first three intervals the method of determining the height was as follows: When going from A to B the last barometer reading at A and the first at B were extracted from the meteorological register and the mean temperature in the interval determined. From these the difference of height was calculated as though the pressure observations had been made simultaneously.

As there was usually several days between the actual observations it was necessary to correct for any general change of pressure during the interval. To do this the pressure and temperature at Cape Evans were taken for the same times and from these the equivalent change in height was calculated. It was then assumed that the whole of the atmosphere had been raised or depressed by this amount so that this value was applied as a correction to the observations made on the Beardmore. Luckily there were no large pressure changes during the period the Polar Party was on the Glacier so that this correction is always small and therefore any error in the assumption is of subordinate importance. An example will indicate the method.

Detailed Calculation of the height between the Barrier and Mid-Glacier Depôt.
Polar Party Outward.

Date.		Pressure.	Change.	Mean temperature
December 9th. 6 hrs.	Pony Depôt ..	29·65	3·47	20°F.
December 17th, 19 hrs.	Mid-Glacier Depôt	26·18		

	Approximate height from table 20 Smithsonian Tables		Temperature correction from table 21 Smithsonian Tables	
	228		3,000 feet	– 184
	3,611		300 ,,	– 18
			80 ,,	– 5
Difference ...	3,383			
Temperature correction ...	– 207			– 207
	3,176			
	– 173	Correction for pressure change.		
	3,003	Difference in height.		

	Cape Evans pressure.	Mean temperature.	Approximate height, table 20.
December 9th. 6 hrs.	29·96	23°F.	– 55
December 17th, 19 hrs.	20·76		+ 128
			182
	Temperature correction ...		– 9
	Error due to pressure change		173

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* For geographical positions, see table 152, page 291.

No correction has been applied for the humidity of the air and for latitude as both of these are much too small to be considered.

Difference in height between Pony Depôt and Mid-Glacier Depôt.

		Feet.
(*a*) Polar Party Outward		3,003
(*b*) Polar Party Return		3,205
(*c*) First Return Party		3,231
	Mean	3,147
(*d*) Simultaneous Observations		3,117
	Mean	3,132

(*a*), (*b*) and (*c*) were obtained by the method described above. The same barometer was used for (*a*) and (*b*) and a different one for (*c*), it is therefore gratifying to see that the values for (*b*) and (*c*) are so nearly alike.

The mean value from the three sets of observations (*a*), (*b*) and (*c*) is 3,147 feet. When the Polar Party was at Mid-Glacier Depôt on their outward journey Meares was on the Barrier only a short distance from the foot of the Beardmore (82° 21′). Thus we have simultaneous observations with the two stations not very far apart. The observations reduced in a similar manner give the value (*d*) which is for all practical purposes identical with the mean of (*a*), (*b*) and (*c*). As a simultaneous observation is of more value than observations taken by the method used for (*a*), (*b*) and (*c*); (*d*) has been given the same weight as the mean of the other three observations and the difference in height between the Pony Depôt and Mid-Glacier Depôt is thus determined to be 3,132 feet. This determination must be considered highly satisfactory as the values obtained by the two methods and with three different barometers agree so well together.

Difference in height between Mid-Glacier Depôt and Upper Glacier Depôt.

		Feet.
(*a*) Polar Party Outward		3,870
(*b*) Polar Party Return		3,839
(*c*) First Return Party		3,838
	Mean	3,849

These three determinations agree so well that their mean may be accepted with great confidence. (*c*) was again obtained with a different barometer from (*a*) and (*b*).

Difference in height between Upper Glacier Depôt and 3° Depôt.

		Feet.
(*a*) Polar Party Outward		2,353
(*b*) Polar Party Return		2,177
	Mean	2,265

For this interval observations made by the Polar Party only are available, and the two determinations do not agree with one another so well as the previous ones. Fortunately there is a simultaneous observation which checks the whole determination for the Barrier to 3° Depôt.

The First Return Party left the main Polar Party at the Upper Glacier Depôt and by the time the Polar Party was at 3° Depôt the First Return Party was on the Barrier in 80 54′ S. The simultaneous observations give the difference in height between the Barrier and 3° Depôt as 9,198 feet; while adding the three values for the stages we have 3,132+3,849+2,265=9,246; these two values agree better than might have been expected their difference being only 48 feet, we therefore can take their mean 9,222 feet as being the true difference in height between the Barrier and 3° Depôt.

HEIGHT OF THE SOUTH POLAR PLATEAU BETWEEN 3° DEPÔT AND THE SOUTH POLE.

The changes of height on the plateau are relatively small and the method used above is no longer applicable. The secular changes of pressure are now of the same order as the changes of pressure due to change of height and therefore cannot be eliminated by the changes of pressure at the base station which also is now much further away. The new method was the following: The daily routine of the Polar Party was very regular, each day the march occupied about 14 hours and the night rest 10 hours. The barometer was read always, at the beginning of the march, at the lunch camp and at the end of the march. Thus before and at the end of each march the barometer was stationary for 10 hours. The change in barometer during each of the periods of rest was determined and the mean rate of change before and after each march calculated. This mean rate was then assumed to have remained constant during the period of march and the observed difference of pressure corrected accordingly. The following example will make the method clear:—

Calculation of change in pressure due to change in height during a march on the plateau.

1	2	3	4	5	6	7	8	9	10	11	12
	Date.	Time.	Difference of time.	Bar.	Difference of bar.	Rate of change of bar. during rest per hour.	Mean.	Change of bar. during march due to pressure change (8)×(4)	Change of bar. due to change of height (6)−(9)	Temperature. °F.	Mean temperature. °F.
	January.										
Rest . .	1	9 P.M.	9	20·14	−·02	−·0022					
	2	6 A.M.		20·12							
March . .			14		−·16		−·0036	−·05	−·11	−15·0	−13
	2	8 P.M.		19·96		−·0050				−11·5	
Rest . .	3	6 A.M.	10	19·91	−·05						

In this example we see that during the first night rest the barometer changed at the rate of −·0022″ per hour and during the second at the rate of −·0050″ per hour. From this we conclude that the barometer changed, due to pressure change, at the mean rate of −·0036″ per hour during the march. As the march lasted 14 hours the total barometer change due to pressure change was −·0036×14=−·05″, while the actual observed change was −·16″ thus leaving −·16+·05=−·11″ to be caused by change of height. A change of −·11″ with a mean barometer of 20″ and mean temperature of −13°F. gives a change of height of 131 feet.

By this method we find that the change of height in each half degree of latitude between 87° S. (3° Depôt) and the South Pole to be as follows:—

TABLE 151.

Change of height in each half degree of latitude on the Polar Plateau along the 160° E. meridian.
Ascent +, Descent −.

	87° 87° 30′	87° 30′ 88°	88° 88° 30′	88° 30′ 89°	89° 89° 30′	89° 30′ South Pole.
Outward . .	+232	+160	+100	−320	−270	−210 feet.
Return . . .	+287	+160	+000	−151	−370	−260 feet.
Mean . . .	+260	+160	+ 50	−235	−320	−235 feet.

From this table we see that the height of the plateau increases to about 88½° S. and then decreases to the Pole. The mean values have only to be added successively to the height of 3° Depôt, determined above, to give the height of the various positions on the plateau.

The following table gives the heights of the various points from Pony Depôt to the Pole.

TABLE 152.

Station.	Latitude.	Longitude.	Height above Barrier.	Height above sea-level.	Distance from Pony Depôt along track.
	S.	W.	Feet.	Feet.	Geo. miles.
Pony Depôt . .	82° 47′	170° 45′	0	170	0
Lower Glacier Depôt . .	83° 30′	171° 30′	355	525	45
Mid-Glacier Depôt . . .	84° 24′	170°	3,132	3,302	99
Upper Glacier Depôt .	85° 07′	163°	6,981	7,151	154
3° Depôt	86° 56′	163°	9,222	9,392	273
Plateau . . .	87° 30′	160°	9,482	9,652	307
Do.	88° 00′	160°	9,642	9,812	337
Do. 1½° Depôt . . .	88° 30′	160°	9,692	9,862	367
Do.	89° 00′	160°	9,457	9,627	397
Do.	89° 30′	160°	9,137	9,307	427
South Pole	90° 00′	—	8,902	9,072	457

The height of the stations have been plotted against the distance along the track in figure 87.

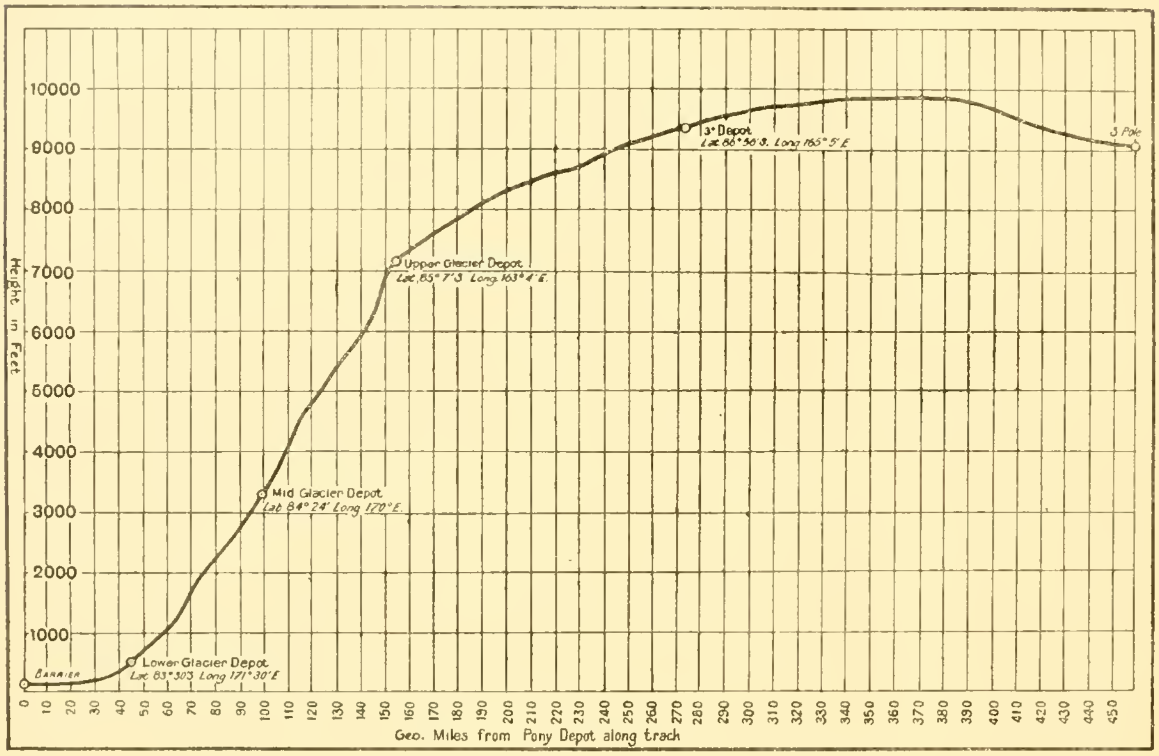

FIG. 87. Heights on the Beardmore Glacier and South Polar Plateau.

This determination of the height of the various depôts from the Barrier to the Pole leads to the conclusion that the height of the South Pole is 9,072 feet, or 2,765 metres, above sea-level.

Mohn in his discussion of the meteorological observations made on Amundsen's journey to the South Pole has also determined the height of the different points on Amundsen's track and has found the height of the South Pole to be 2,454 metres or 8,051 feet.

It will be seen that the difference between the two determinations—311 metres or 1,021 feet—is extreme and much beyond the limits of accuracy to be expected. Mohn calculates that his determination of the height of the Pole is accurate to ±196 metres.

Mohn treated Amundsen's barometric observations rather differently from the way Scott's observations have been treated here. Instead of dividing the journey from the Barrier to the Pole and back into a small number of distinct stages, he calculated the change in height during each day's march. This method appears to me to be objectionable in that the unavoidable errors in reading the barometer enter into the determination of the height each day and the errors may or may not cancel out. This, however, is not the chief error, for a much more serious one is that Mohn has not made any allowance for the general change in barometer pressure. As it happens this is rather serious. Amundsen left the Barrier on November 15th, was at the Pole on December 17th and reached the Barrier again on January 9th. The mean pressure at Cape Evans and Framheim on these days was the following:—

TABLE 153.

Pressure change at sea-level.

Date.	Cape Evans.	Framheim.	Mean.	Change.
November 15th . .	29·58	29·54	29·56	+·22
December 17th . .	29·80	29·76	29·78	—·62
January 9th . .	29·12	29·20	29·16	

It will be noticed that the general pressure rose as Amundsen went from the Barrier to the Pole and fell as he returned, both these changes would make the difference in height between the Barrier and the Pole appear less than it really was. The mean change in pressure was ·42 inches. This is equivalent to a change of height of approximately 400 feet, by which amount the height of the Pole would be underestimated. Even with this correction, Mohn's determination of the height of the Pole would only be about 8,500 feet, leaving another 500 feet to be accounted for. I have tried to apply the method used in reducing Scott's observations to those taken by Amundsen but have not been successful, as Amundsen's marches on the plateau were more irregular than those of Scott and his track on the plateau was much less level. I have, however, been able to use Amundsen's observations to show that the height of the Pole determined from Scott's observations is not in error by 200 feet.

It seemed very desirable in the first place to be assured that there was no radical error in either of the barometers. This seemed very unlikely for Amundsen's barometer was frequently checked by two hypsometers while on the plateau and Scott's barometer was also checked by a hypsometer a short time before the plateau was reached. Luckily a direct comparison is possible which shows that the barometers were reading with the accuracy to be expected under such conditions. On December 31st, 1911, Amundsen was at 87° 9′ S., 167° 7′ W. and Scott was at 86° 56′ S., 165° 6′ E., thus they were approximately only 87 geographical miles apart. According to Mohn's calculation Amundsen was then 1 metre below the elevation of the Pole; while Scott was, according to the above calculations, 320 feet above the Pole. As the positions were so near to the Pole, both these differences may be accepted quite independently of the actual height assigned to the Pole.

Thus on this day Amundsen was 323 feet below Scott. The pressure and temperature recorded were the following: Amundsen 6 P.M., barometer 20·67″, temperature −2°F.; Scott 2 P.M., barometer 20·28″, temperature −10·5°F. If the difference of height is correct Scott's barometer should have read ·27″ below Amundsen's while we see that it was ·39″ lower. Thus the barometers differ by only ·12″ from their true relative readings. Part of this difference may be due to the fact that the barometers were not read simultaneously, part to the distance between the two observers, and part to errors in the determination of their relative heights. In any case it is quite obvious that there was no difference in the barometers sufficient to account for the discordant determinations of the height of the Pole.

Determination of the height of the Pole by simultaneous observations of Amundsen's Barometer at the Pole and one on the Barrier near to the foot of the hills.—Amundsen was at, or within six miles of, the Pole throughout January 16th, 17th and 18th. The mean pressure and temperature observed by him during these three days (three observations each day) were 20·48″ and −7°F. At the same time Meares with Captain Scott's dogs was near to the foot of the Beardmore in 82° S. His mean pressure and temperature for the same days (also three observations each day) were 29·62″ and 24°F. These observations give the difference in height between the Pole and the Barrier as 9,170 feet. Taking the height of the Barrier to be 170 feet as before, this gives the height of the Pole as 9,340 feet above sea-level; which is only 238 feet higher than the value determined above. Thus it strongly supports our determination, but is still further away from Mohn's determination of 8,051 feet. It will be noticed that this is a determination quite independent of Scott's barometer, and depends only on Amundsen's observations and those of a barometer which was compared with the standard at Cape Evans only a few days later.

Determination of the height of the Pole by simultaneous observations of Scott's and Amundsen's Barometers.—On January 12th Scott was in 88° 52′ S., *i.e.*, within 68 miles of the Pole, while Amundsen was on the Barrier in 84° S. This day has been chosen for the comparison because the pressure was very steady both on the plateau and on the Barrier, also Amundsen was then travelling rapidly northwards and if we delay the comparison until Scott was at the Pole, Amundsen would then be so far north (in 82° S.) as to make the comparison less valuable. Scott's position was then 660 feet above the Pole as determined by concordant observations made on the journey to and from the Pole. The observations were: Amundsen 2-30 P.M., barometer 28·77″, temperature +20·0°F.; Scott 1-30 P.M., barometer 19·36″, temperature −22°F. These reduced in the usual way give the difference in height between the two positions to be 9,649 feet, deducting the 660 feet which Scott was above the Pole and adding 150 feet for Amundsen's height on the Barrier (according to Mohn) we find the height of the Pole to be 9,104 feet above sea-level.

This value is only 32 feet different from our main determination and may be considered to support it completely.

Summing up we have the following independent estimates of the height of the South Pole above sea-level:—

	Feet.	Metres.
(1) Mohn's determination from Amundsen's observations .	8,051	2,454
(2) Our chief determination mainly from Scott's observations *	9,072	2,765
(3) Comparison of Amundsen's barometer at the Pole and a barometer on the Barrier	9,340	2,847
(4) Comparison of Scott's barometer near the Pole and Amundsen's on Barrier	9,104	2,775

The mean of the last three determinations is 9,172 feet = 2,796 metres which is probably very near to the true height of the South Pole above mean sea-level.

THE HEIGHT OF THE ANTARCTIC CONTINENT.

Our knowledge of the land masses within the Antarctic is very limited, it is therefore exceedingly interesting to find that an estimate of their extent can be made from purely meteorological considerations. This has been done by Meinardus who concludes that if land occupies two-thirds of the whole area within the Antarctic Circle its average height must be 2,000 ± 200 metres. Such a mass of land is so great that it raises the mean height of the earth's whole surface from 205 to 240 metres, or the mean height of all known land is raised from 700 to 825 metres. Such a result is of great scientific importance. Now that Shackleton's attempt to cross the Antarctic Continent has failed, we are unlikely to obtain confirmation of Meinardus's conclusion from actual exploration for many years to come, hence in the interests of both geodesy and meteorology Meinardus's conclusions need critical discussion. This must be my excuse for the following pages.

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* In Volume III will be found the detailed data on which this determination is based, and the height of all the camps.

Meinardus's work * may be summarised as follows :—

The barometric pressure at any place is a direct measurement of the mass of air lying over that place. If therefore we integrate the pressure over the whole surface of the globe (actual pressure, not pressure reduced to sea-level) we obtain the total mass of the earth's atmosphere. This mass must be constant, hence the integral of the pressure over the whole world must be the same at all seasons of the year. The pressure conditions are sufficiently well known over the globe outside the Antarctic Circle to make it possible to effect this integration, and Meinardus has made the necessary calculations for the two months January and July from charts of the normal pressure for these two months. The result of the calculations shows that outside the Antarctic Circle the total mass of air is greater in July than in January. Thus in order to have the total mass of air the same all over the world in these two months there must be less air over the Antarctic in July than in January. In other words the integral of the pressure over the area within the Antarctic Circle must be greater in January than in July and the mean difference in pressure January–July must be 11 mm. This seems contrary to what one would expect, for in July the temperature of the air is much lower than in January, hence we should expect the air to be denser and therefore the pressure higher in July than in January.

Meinardus shows that this apparent paradox can be explained by assuming that the land surface within the Antarctic Circle is at a relatively great height above sea-level. To do this he first discusses the mean pressure and temperature over the Antarctic in the months of January and July respectively, using all the data available in 1909. This leads him to believe that the mean pressure over the Antarctic at sea-level is the same in these two months and equal to 745 mm. The mean temperature which he deduces are January −3°C., July −26°C. He assumes further that the temperature decreases by 5°C. for each 1,000 metres of ascent during both months.

Meinardus's reasoning then proceeds as follows :—

Let A, figure 88, represent a column of air over the Antarctic Continent in January. The pressure at the base (sea-level) is then 745 mm. and the temperature −3°C. The

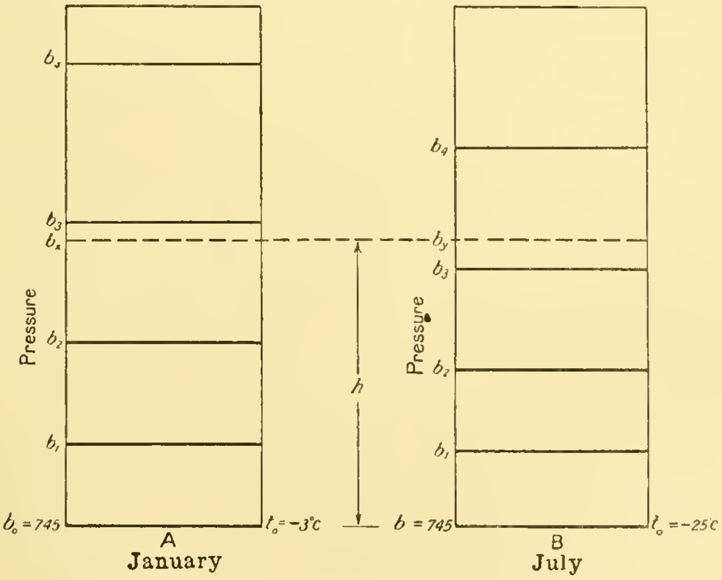

FIG. 88. Diagram of vertical pressure, summer and winter.

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* Meinardus, 'Die mutmassliche mittle Hohe des antarktischen Kontinents,' Petermanns Mitteil., 1909, Heft 11 and 12.

vertical temperature gradient being fixed at 5°C. per 1,000 metres the temperature at all points in the atmosphere is known. It is therefore a simple matter to calculate the height at which the pressure has any given value. In figure 88 horizontal lines are drawn in column A to represent the height at which the pressure has the consecutive values b_1, b_2, b_3, b_4, etc.

In the same figure column B represents the same column of air in July. The pressure at sea-level is again 745 mm., but the temperature is -26°C. Lines have again been drawn to represent the height at which the pressure has the same values b_1, b_2, b_3, b_4, etc. It will be noticed that in B each of these lines is lower than in A and the difference is greater in the upper than the lower part of the figure. This is because the pressure decreases more rapidly in a cold air column than in a warm one. At the height h represented by the dotted line in the figure the pressure has changed from b_x in January to b_y in July, and it is a simple matter to calculate the value $b_x - b_y$.

Conversely it is as easy to calculate the height at which $b_x - b_y$ has any given value. Under the conditions assumed Meinardus calculates that at 1,350 metres above sea-level the pressure is 11 mm. less in July than in January.

If therefore the air below this height over the Antarctic did not exist the total pressure over the Antarctic would be that required to make the total pressure over the whole globe the same in January as in July. The obvious way to account for the absence of this air is to assume that the average height of the land within the Antarctic Circle is 1,350 metres.

From this he concludes that there does actually exist within the Antarctic Circle a continent so high that its mass spread uniformly over the Polar cap within the Antarctic Circle would give an average level of 1,350 ± 150 metres. Assuming that one-third of the area in question is at sea-level, the average height of the continent over the remaining two-thirds works out as stated above to be 2,000 ± 200 metres.

We do know that there is high land within the Antarctic, the Pole itself being on a vast plateau over 2,500 metres above sea-level, and there is no reason to doubt that this high land does act as suggested by Meinardus. There can therefore be little doubt that qualitatively his theory is correct and that it is a most important contribution to our knowledge of meteorology and geodesy; but whether reliance can be placed on the accuracy of his numerical results which he assumes by the ±150 metres attached to the estimated average height remains to be examined.

The accuracy of the numerical calculation depends on two main considerations:

(*a*) The physical principles on which the relation between meteorological data and height is calculated, and

(*b*) the accuracy of the meteorological data on which the calculation is based.

The physical principles.—The physical principles underlying Meinardus's calculation have already been stated, but it is advisable to restate them in the form in which they are actually applied. The area considered is that within the Antarctic Circle and is therefore concentric with the South Pole. Part of this area is at sea-level and part is occupied by high land, the relative sizes of the two parts are unknown. Meteorological data, all of which have been obtained at sea-level, are available from certain stations in or near the area under consideration. By making the assumption that these observations are typical of the whole Antarctic at sea-level and that meteorological conditions depend on latitude only, the average pressure and temperature at sea-level over the whole area are determined.* The pressure at different heights in the free atmosphere over the area at sea-level is then calculated for January and July, and the height is determined at which the pressure difference between

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* In this section we are not considering the nature or accuracy of the data used by Meinardus, the argument proceeds independently of the actual values used.

these two months has a definite value. Finally it is assumed that the pressure changes on the surface of a high land at this height will be the same as those found for the free air.

It is this latter assumption which it is necessary to investigate.

Why should the pressure over the high continent bear any relationship to the pressure in the free atmosphere over the low-lying area? There is no air under the continent to expand and contract with changes of the season and so to regulate the pressure on the surface. Probably the idea which underlies the assumption is that the pressure at the edge of the high land must be in equilibrium with that in the surrounding free air, and that this equilibrium decides the pressure over the whole of the adjacent continent.

But we know quite well that the pressure conditions within any area cannot be determined from a knowledge of the pressure conditions around the boundary of that area. The interior pressure conditions can be changed indefinitely without altering the boundary pressure conditions provided that the air is free to move. For example, the 760 mm. isobar of an anticyclone may occupy at one time exactly the same position as was occupied at another time by the 760 mm. isobar of a cyclone. In this case the boundary pressure conditions are identical but the interior pressure conditions are entirely different.

Thus the pressure at the boundary of the high land might always be in equilibrium with the pressure of the adjacent free atmosphere without giving any indication of the pressure over the interior of the high land. We must therefore conclude that the average pressure on the surface of the high land may bear no relationship to the average pressure existing at corresponding heights in the free atmosphere.

It may be contended, however, that the present problem is not concerned with the actual pressure, but with the change in pressure between January and July, and if the pressure in the free air is 11 mm. higher in January than in July it is probable that the mean pressure over the high land will be higher by the same amount.

If this were the case it would mean that the pressure over every element of the land surface had changed by the same amount as the boundary, the consequence of which would be that the pressure gradients would remain the same over the high land in January as in July.* Now it is almost inconceivable that the pressure gradients, whatever they may be, are the same over the Antarctic high land in the winter as in the summer. Let the pressure distribution be cyclonic as supposed by Meinardus or anticyclonic as is more generally supposed, the system is bound to be more intense in the winter than in the summer, which means that the gradients are steeper in winter than summer and the change in mean pressure greater or less, according to which system is chosen, than the change of pressure at the boundary.

The physical principles underlying Meinardus's theory thus indicate that the changes in pressure over the high land from January to July may bear no close relationship to the changes in pressure at corresponding heights in the surrounding free atmosphere. Hence calculations based on the pressure changes in the free atmosphere may give an entirely wrong value for the average height of the Antarctic Continent.

We will, however, for the sake of a thorough investigation of this important and interesting problem, now consider the meteorological data used by Meinardus to see the accuracy of his calculations irrespective of the above conclusions.

The pressure data.—The actual sea-level pressure is of only secondary importance in the calculation, the result depending chiefly on the difference in pressure between January and

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* It is of course possible to conceive an entirely new pressure distribution which would give the correct change in the mean pressure, but this would be a matter of pure chance and therefore cannot be taken into account.

July. To realise this it is only necessary to remember that there would be no problem if the pressure actually found by observation at sea-level were 11 mm. higher in January than in July, for then the pressure over the whole globe would be equal in these two months without the presence of the continent. The high continent is only necessary to account for the fact that sea-level observations do not give this difference in pressure between January and July.

From his discussion of the pressure data Meinardus concluded that the average pressure at sea-level over the whole Antarctic was the same in January as in July.

Since Meinardus wrote the following additional data have become available: two years' observations in McMurdo Sound, and one year's observations at Framheim, Cape Adare, L'ile Petermann and in the Weddel Sea. All these new observations show a lower pressure in July than in January.

In the following table all the available data from Antarctic stations have been collected.* The average difference of pressure is given for each station as determined from the actuals for each month, and then again after the data have been smoothed in the usual way by applying the formula $b \text{ (smoothed)} = \frac{a+2b+c}{4}$ to the monthly values.

With the large unperiodic changes of pressure from month to month which are such a feature of the Antarctic conditions there can be little doubt that the smoothed values are the better, for they eliminate to some extent large irregularities and therefore more nearly approach what would ultimately be obtained from a longer series of observations.

In obtaining the means of the groups of stations in columns 5, 6, 8 and 9 the differences have been weighted according to the number of months from which the individual means have been derived.

TABLE 154.

Pressure differences January–July in mm.

1	2	3	4	5	6	7	8	9	10	11
Place.	Latitude.	Longitude.	ACTUAL.			SMOOTHED.			NUMBER OF MONTHS	
			January –July.	Mean.	Mean.	January –July.	Mean.	Mean.	January.	July.
Snow Hill . .	64° S.	57 °W.	+ 4·91	+ 0·50	+ 3·00	+ 2·63	+ 0·58	+ 3·87	1	2
Port Charcot . .	65°	63 °W.	− 6·50			− 2·50			1	1
L'ile Petermann .	65°	63 °W.	+ 2·39			+ 2·67			1 †	1
Gauss Station . .	66°	90 °E.	− 0·18			+ 2·37			1	1
Belgica Drift . .	70°	86 °W.	− 0·80			− 3·30			1	1
Cape Adare . .	71°	170 °E.	+ 2·54	+ 4·97		+ 5·27	+ 6·31		2	2
McMurdo Sound .	78°	166 °E.	+ 4·30			+ 5·15			4	4
Framheim . .	79°	195 °E.	+12·50			+13·00			1	1
Weddel Sea ‡ . .	..	..	+			+				

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* For actual values used and references see Volume III.

† Five days' observations for December, thirteen for January and twenty-eight for February only are available. In obtaining the smoothed values these have been weighted according to the number of days, double weight being given to January thus $\frac{5 \text{ December } + 2\times13 \text{ January } + 28 \text{ February.}}{59}$

‡ See figure 1 and table I of Veroffen des K. Preuss. Met. Institutes, No. 265, Bd. IV, No. 11

From this table it will be seen that out of the nine sets of observations seven show an excess of pressure in January when smoothed values are considered and six when the actual values are considered.

The stations have been divided into two groups, one containing the stations in the Ross Sea area and the other the remainder. The latter are all situated on the northern edge of the continent and within a few miles of the open Southern Ocean. With the exception of Cape Adare, the stations in the Ross Sea area are much further south than the remaining stations.

Now from these observations it is necessary to decide what is the difference of pressure between January and July over the whole region within the Antarctic Circle. Personally I feel that the data are far too few to give anything like the required information, but we can obtain some conclusion to compared with the one used by Meinardus in his calculation.

Baschin has found that over the Southern Ocean between 50° and 60° S. latitude the pressure difference January–July is $-0{\cdot}73$ mm., and this result may be accepted with considerable confidence. From fewer observations he determines the mean difference within 60° and 66½° S. (the Polar Circle) to be zero. The group of stations on the edge of the Antarctic Continent as shown in the above table have a mean difference of $+0{\cdot}58$. This indicates that the difference is changing from negative values over the Southern Ocean to positive values over the Antarctic Continent. It is therefore significant that the three most southerly stations all show a high positive value for the difference. Unfortunately these three stations are all in the Ross Sea area and therefore it may be argued that the positive values are local and are due to the Ross Sea and do not really represent the conditions in high latitudes.

In this connexion the observations at Framheim are of great importance. Meteorologically Framheim is more under the influence of the Antarctic Continent than any other station, as is seen from its low temperature and absence of wind. The observations in July 1911 and January 1912 show a difference of pressure for January–July of $+12{\cdot}5$ mm., which is by far the largest pressure difference between these two months recorded anywhere in the Antarctic. Taken alone this great difference—larger than the 11 mm. required by Meinardus—might be considered to be accidental and no doubt to some extent it is. We have remarked above * that the *difference* in pressure between two stations undergoes much smaller changes than the actual pressure itself, and further we concluded that the yearly march of the pressure difference between Cape Evans and Framheim shown in figure 57, page 172, was so regular that it probably represents very nearly the true normal difference of pressure between these two stations. By applying these differences to the normal pressure of McMurdo Sound based on four years' observations we found that the normal pressure at Framheim in January and July is 745·0 and 735·6 mm. respectively (see table 97, page 173). This gives a probable normal difference of pressure January–July at Framheim of 9·4 mm. as compared with 5·15 mm. in McMurdo Sound. If such large and similar variations exist between coast and continental stations elsewhere, it shows the futility of attempting to determine even approximately the average pressure difference between January and July for the whole Antarctic from the few available observations, all of which have been made at coast stations.

As the considerations we have just been discussing are difficult to apply I see no other way to treat the observations available than to take their arithmetic mean. It must not be

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* Page 172.

forgotten, however, that the mean obtained from coast stations in all probability gives a value too low by several millimeters. Table 154 shows that the mean of all the observations taken in the Antarctic is a difference for January–July of 3·00 mm. or 3·87 mm. according as actual or smoothed values are considered. From this I think we are justified in saying that the average pressure difference at sea-level over the Antarctic from January–July is as likely to be +3 mm. as it is to be 0, which is the value accepted by Meinardus.

If we apply the value +3 mm. instead of 0 mm. in Meinardus's formula, leaving all other assumptions unchanged, we find that the average height of the land within the Antarctic Circle works out to be 966 metres, which is very different from Meinardus's value of 1,350± 150 metres.

The temperature data.—It is as necessary to know the average temperature in January and July over the whole Antarctic as it is to know the pressure, and again it is the difference, much more than the actual values, which affects the result.

After a careful discussion of all the data available in 1909, Meinardus concluded that the average temperature at sea-level over the whole Antarctic in January is −2·7°C. and in July −25·2°C., giving a difference of 22·5°C.

Again Meinardus neglected the fact that all the observations used by him were obtained at coast stations. Who would think of determining the average range of temperature over any other continent from a few scattered observations at coast observatories? Here our discussion of the Barrier temperatures comes to our help. In table 45, page 83, it is shown that the difference in temperature between January and July is 21°C. at Cape Evans and 29°C. on the Barrier. This indicates that the temperature difference January–July may be 8 C. more at a land station than at a coast station in the same latitude only a few miles distant.

It therefore does not seem unreasonable to conclude that, considering how much of the Antarctic is far removed from the sea, Meinardus's value of 22·5°C. for the difference in temperature between January and July obtained entirely from coast stations is much too small.

If Meinardus's value for the July temperature is lowered by only 5°C., leaving all other of his assumptions unchanged, the average height of the surface within the Antarctic Circle is reduced to 1,050 metres.

The vertical temperature gradient.—Meinardus assumes that the vertical temperature gradient is −·5°C. per 100 metres both in January and July. Now the balloon observations made in McMurdo Sound and by Barkow in the Weddel Sea have proved that during the winter there are large temperature inversions in the lower atmosphere. There are not sufficient balloon observations to give an average value of the temperature gradient during July, but there cannot be the slightest doubt that it is much less in July than in January. In fact it is not improbable that over inland areas where the temperature is very low and where the wind is much less than near the coast there is a nearly permanent temperature inversion up to heights of at least 2,000 metres. It therefore appears to me that the average vertical temperature gradient over the whole Antarctic in July is as likely to be 0 as ·5°C. per 100 metres.

Putting this value in Meinardus's formula and leaving all other values unchanged the average height of the surface within the Antarctic Circle is raised to 1,610 metres.

It is of interest to see what is the effect on the calculation of height if all three of the above new values are introduced into the formula. In the following table the new and old values are shown, and in the last line the average heights of surface within the Antarctic Circle calculated from them by Meinardus's formula have been entered:—

Table 155.

At sea-level.	Meinardus's values.	Possible new values.
January pressure	745 mm.	Same.
July pressure	745 mm.	742
January temperature	− 3°C.	Same.
July temperature	−26°C.	−31°C.
January vertical temperature gradient .	·5°C. per 100 m.	Same.
July vertical temperature gradient .	·5°C. per 100 m.	0
Average height .	1,350 metres.	852 metres.

Thus Meinardus's value of 1,350 metres is reduced to 852 metres, which is a considerable change.

This review of the meteorological data on which Meinardus has based his calculation of the average height of the Antarctic Continent has shown that by making assumptions which have as much probability as those of Meinardus, the resulting height can be very much changed. My own opinion is that considering the vast extent of the continent and the few observations, none of which have been taken under true continental conditions, but only on the sea-coast, it is quite hopeless to get even an approximate solution of the problem. For this reason I have been careful in the above discussion not to claim that my values are nearer the truth than those of Meinardus, I have simply claimed that they are at least as probable as his, and have contented myself by pointing out that the alternative data alter Meinardus's result so much that the accuracy he has claimed is far too great.

Conclusions.

(*a*) If it is true that the average pressure over the Antarctic must be 11 mm. higher in January than in July in order to keep the mass of air over the whole globe the same in these two months, then it is probable that qualitatively Meinardus has given the correct explanation.

(*b*) The method used, however, to calculate the height of the land is open to serious objection, being based as it is on the assumption that the pressure over the surface of a great continent can be determined by the pressure at the boundary.

(*c*) Further the meteorological data used are far from being certain. By using other data which at least are as probable as those of Meinardus, the mean height is reduced from 1,350 metres to 852 metres. But in view of conclusion (*b*), both these estimates may be far from the truth.

CHAPTER X.

ATMOSPHERIC ELECTRICITY.

Owing to the large amount of work entailed by the ordinary meteorological and magnetic investigations undertaken by the expedition, it was found impossible to do more in atmospheric electricity than to measure the potential gradient and the radio-active contents of the atmosphere. Both of these unfortunately came to an end after the first year's work, as the few men who remained in the south during the second year had their hands full with other duties.

POTENTIAL GRADIENT.

Only those who have attempted measurements of atmospheric electricity under Polar conditions can have any idea of the great difficulty of the work and the constant attention which the apparatus requires. The difficulties met with in the ordinary meteorological observations have not been described in the above discussion as they can be overcome with a little forethought, and each observer must work out the best means to meet his own difficulties, but with atmospheric electricity so few observers have had the necessary experience that a few words here of the difficulties met with and the way they were overcome may not be out of place.

The method of recording the potential gradient is well known. We have first the collector which is exposed in a suitable position in the open air. The function of the collector is to bring itself and the apparatus attached to it to the potential of the air in its immediate neighbourhood. Until the discovery of the radio-active substances only two practical collectors were known, (*a*) the Kelvin 'water dropper' and (*b*) the flame. The first of these is quite unusable in Polar regions owing to freezing, and the difficulties connected with the second make its continuous use with self-recording instruments practically impossible. The radio-active collector does not freeze and does not blow out, but in its usual form it can only dispose of such a small amount of electricity that the question of insulation becomes very important. Unless the insulation is practically perfect, the collector cannot dispose of the electricity which leaks to the insulated system rapidly enough, and the apparatus charges up to a potential more or less below the potential of the air near to the collector and the apparatus then records a mixture of changes of potential and changes of insulation.

The collector used was a small copper rod about 3 mm. in diameter and 5 cm. long. This had been coated with polonium which has the great advantage of emitting only α rays, so that only the air in the immediate neighbourhood of the collector is ionised. The collector was mounted on a thin wooden rod which in turn was fixed to an iron pole, so that the collector itself was about ten feet above the ground. The wooden rod was insulated from the iron pole by means of a plug of ebonite covered in sulphur. An inverted tin can was placed over the insulator in the method shown in figure 89. This was found necessary in order to protect the insulator from hoar frost which in certain conditions of the atmosphere was found to be deposited on every thing exposed to the sky.

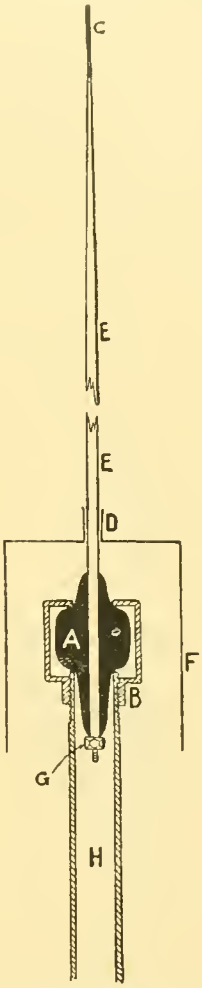

Fig. 89. Insulator for collector rod.

During blizzards fine driven snow entered this can and settled over the insulator and destroyed the insulation. There is no means of getting over this difficulty, for the drift during blizzards enters every small crevice and no matter how the protecting device is arranged it soon becomes full of snow which connects the insulated parts to earth.

This, however, was not a serious difficulty for one is chiefly concerned with the potential gradient only during fine weather, so the loss of part of the record during blizzards did not affect the main results of the work. Also during blizzards the potential was far above the limits of the recording electrometer and so could not have been measured if the insulator had remained perfect. The chief practical effect was the necessity to clean the insulator at the end of each blizzard and to put it in good order for the subsequent fine weather.

The Benndorf self-recording electrometer had of necessity to be within the living hut, the temperature of which was kept, except occasionally, well above the freezing point. A very liberal share of the hut was apportioned to the physical laboratory but unfortunately it was in the coldest corner of the hut. In the hut twenty-five men lived in one large room in which all the cooking was done. In consequence the humidity was always high and water vapour literally distilled into the physical laboratory. This vapour condensed on to the walls which were generally covered with a coating of ice or water. It was through this wall that the wire to the potential gradient instrument had to pass, and the method of doing this was the first difficulty which had to be solved.

In ordinary observatories, the connecting wire is usually passed through a hole in the wall sufficiently large for the wire not to touch it when slightly displaced by the wind. Such a hole was quite impossible in our hut, for it would have let in cold air, but much more serious it would have been the entrance for drift snow during the blizzards. The wall of the hut consisted of two thicknesses of wood, then an air space of three inches, and then two more thicknesses of wood. The first attempt made was to pass a metal tube through the wall, plug it up at each end with sulphur and pass a thin wire through the centre. The sulphur then not only closed the tube but acted as supporting insulators for the wire. This method soon proved unusable, for the water vapour which was deposited on the well-insulated wooden wall was deposited still more rapidly both inside and outside the metal tube. The water was in itself sufficient to destroy all insulation, but on account of the metal tube projecting into the cold air outside the hut, the end within the hut was so cold that the water froze and a large mass of ice crystals formed upon it which were pretty to look at but totally destructive to the insulating properties of the sulphur. Some method had to be found which would not only protect the insulator from the water deposited all over the wall but would also not conduct cold from the outside, and so cause an intensified deposition on the insulator.

There is no need to go into all the experiments made; but the final solution of the problem will be given. As is usually the case, the solution is so simple that one wonders why it was not the first thought of. Figure 90 shows the completed insulator. A and B are the two separate parts of the wall through which the insulator was to convey the conductor. C C is a brass rod about one-eighth inch thick. Around this rod a coating of sulphur D was cast to a diameter of about one inch, and so long that it projected two inches within the hut and one outside. E was a round tin box which had contained a Kodak film, the lid was removed and a small brass tube, F, soldered to the bottom so that it could be pushed along the rod C and completely surround the end of the sulphur. G was an ordinary tin canister. The lid had a hole made in it of the size of the sulphur rod and it was tacked on to the wall at H. In the bottom of the canister a small hole, just larger than the rod C, was pierced; then when the canister was pushed home into its lid H it completely surrounded the whole end of the insulator and the rod C passed freely into the hut.

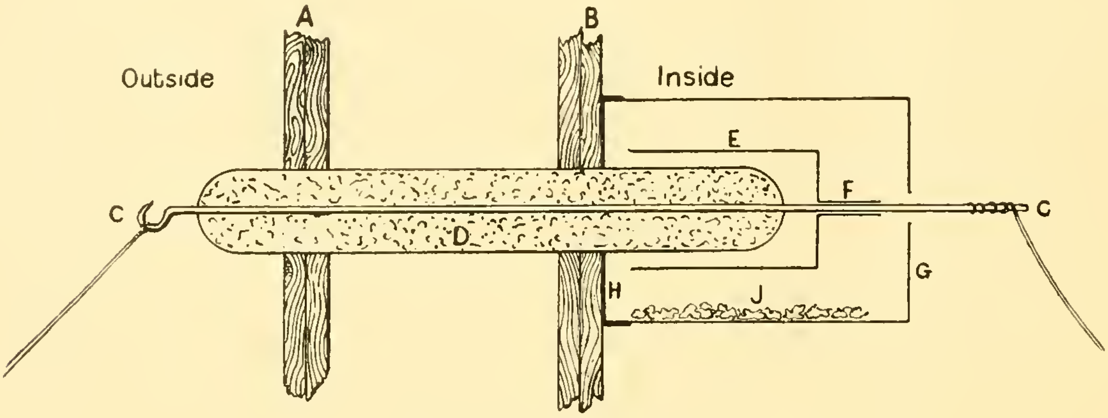

FIG. 90. Insulator through wall.

It will be noticed that the tin canister was not connected with the outside and therefore did not become excessively cold, on the contrary it exposed so much of its surface to the air of the hut that it quickly took the temperature of the air, and so water vapour was not deposited on it excessively. The metal rod which connected with the outside air had the inner cylinder attached to it and this tended to keep its end from remaining very cold. Any moist air which entered the outer tin canister was deposited on the outside of the inner tin cylinder and very little found its way within the latter to the insulator. A few pieces of calcium chloride placed in the canister at J absorbed moisture and kept the air within fairly dry. This insulator worked splendidly and gave practically no difficulty for several months, but then the sulphur cracked and the insulation failed. When this happened a new insulator on the same principle was constructed except that the rod of sulphur was replaced by a rod of ebonite, and thereafter no further difficulty was experienced, so long as the surface of the ebonite was periodically cleaned with a piece of emery paper.

The end of the insulator outside the hut did not need the elaborate protection which was necessary within the hut, so a simple tin can was placed around it to keep off the deposit of hoar frost.

A wire was then taken in a single stretch from the end of the insulator outside the hut to the collector ten yards away. During the summer months this wire was a constant source of trouble, for it was continually being broken down by skua-gulls flying into it. These gulls living in a country without trees, wires or other obstructions in the free air never looked where they were going when flying about the hut and not only flew into the wire but on one or two occasions actually collided with the collector rod itself. It was distinctly annoying to lose many hours of record during fine weather owing to the clumsy habits of these birds.

The self-recording Benndorf electrometer inside the hut was also not free from its difficulties. It has already been explained how the physical laboratory was the coldest corner of the hut. The instruments in it were therefore always colder than the general temperature of the room, especially in the morning when the breakfast was cooked while the instruments were particularly cold after the night. Under such circumstances it was practically impossible to maintain high insulation when the air had free access to the insulators. The insulators on the Benndorf self-recording electrometer are peculiarly badly situated from this point of view, for they are under the instrument and exposed to the air. The insulators holding the quadrants are not important, for the battery which charges the quadrants is quite capable of supplying the electricity for a relatively large leak; but not so the insulator through which the wire from the collector passes, for unless this insulator is practically perfect the potential to be measured may be greatly reduced. On the Benndorf electrometer there are three insulators connected with the system which is charged by the collector: (*a*) an insulator between the needle and the suspension, (*b*) an insulator supporting the metal plate on which the acid pot rests, and (*c*) the above mentioned insulator through which the connecting wire passes. (*a*) and (*b*) are completely within the case while (*c*) is half within and half without. It was the latter which gave all the trouble and therefore it was done away with entirely. A stout wire was soldered on to the plate carrying the acid pot and a narrow slit cut in one of the panels of the body of the electrometer through which it freely passed.

All the essential insulators were now within the body of the electrometer which was supposed to be kept dry by the acid. Still the insulation was far from perfect. Every time the electrometer was opened to adjust or examine the instrument, warm damp air entered the cold interior and the insulation was immediately destroyed. Also the body of the electrometer was not airtight and even when closed damp air entered. It was at once realised that the only hope was to keep the interior of the electrometer at a higher temperature than the air of the hut. This was done by inserting a small heating coil which was supplied with a current of ·11 ampere from the accumulators. After this had been done there was comparatively little difficulty with the insulation of the electrometer and the case could be opened at any time for examination without the insulation materially suffering.

There is one more cause of difficulty and worry to be mentioned. The polonium collector could not be protected from the formation of hoar frost over its whole surface. This coating of ice reduced its activity greatly and caused an appreciable reduction of the potential registered. This difficulty could not be entirely removed but it was reduced as follows:

We happened to have with us two identical polonium collectors, these were so arranged that they could be rapidly fixed to and removed from the top of the collector rod. Whenever meteorological observations were made, every four hours, the polonium rod in use was examined and if it had a coating of frost it was removed and replaced by the other one. The frost-coated rod was then suitably suspended in a canister containing calcium chloride, which dried it and kept it always ready for immediate use.

When all these changes had been made as the result of bitter experience it was only by constant attention to the electrometer, insulators and collector that satisfactory records could be obtained.

Two or three times each week the sensativeness of the electrometer and the state of the insulation were tested. To do this the polonium collector was removed, then the electrometer to which the whole insulated system was attached, was connected to a Wulf electroscope and charged.

The electroscope reading was noted when three successive points were registered by the electrometer. The electrometer registered every two minutes and it was easy to see whether there was an appreciable leak from the change in the electroscope reading during the interval. The whole system was then connected to earth for ten minutes or so to mark the zero line. Thus on the trace itself were frequently recorded, the state of the insulation, the position of the zero, and the deflection corresponding to a known potential.

It was necessary to find the reduction factor for converting the voltages recorded by the electrometer to the potential gradient in volts per metre over a level surface. The frozen sea within a few yards of the collector made this an easy matter. The necessary observations were made on five days during November, December and January, 1911-12. The reduction factor proved to be linear over the whole scale which was a great convenience in working up the records.*

Potential Gradient and Drift.—When the air was full of drift snow the potential gradient was as a rule very high. Also a very little drift would increase the potential above the extreme range of the electrometer, *i.e.*, 367 volts per metre. This is most clearly seen when the average potential during different wind strengths is examined. When the observations for the whole year are arranged according to wind strength we get the following result :—

TABLE 156.

Potential Gradient and Wind.

Wind, miles per hour.	0—10	11—20	21—30	31—40	>40
Potential gradient, volts per metre.	104	>159	>212	>260	>304
Frequency > maximum .	·7%	10%	24%	45%	65%
Number of observations .	3,240	948	848	626	302

It will be seen that with winds of 0 to 10 miles an hour the potential gradient was 104 volts per metre, while it steadily increased to > 304 volts per metre with winds over forty miles an hour. The range of the electrometer would only record 367 volts per metre, hence the value of the higher potentials could not be recorded. When the needle reached the extreme for only a short time in an hour, one could form some idea from the shape of the existing curve what would have been the shape of the missing portion, and in this way a rough estimate of the mean potential in the hour could be determined. When the needle was against the extreme stop for an appreciable time, it was only possible to say that the mean potential during the hour was > 367 volts per metre. In taking the mean value of the potential the sign > had to be neglected, hence all the values of the potential gradient for wind strengths over 11 miles an hour are smaller than they would have been if the true high potentials had been measured. Thus the sign > has been prefixed to the values in table 156. It is clear that the highest mean potential which could be recorded in this way is 367 volts per metre, and it will be noticed that this value is nearly reached

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* A description of the method of obtaining the reduction factor and of many other details of the apparatus used in the atmospheric electricity work will be found in my paper entitled 'Instrumente zur Beobachtung der atmospharischen Elektrizitat' published in Physikalische Zeitschrift, Volume 14, page 41, 1913.

with winds above forty miles an hour. The numbers in the first line of table 156 are therefore only qualitative, but they clearly show that the higher the wind, *i.e.*, the more the drift the higher the potential. The same result is shown in the second line. The numbers in this line were obtained as follows: The number of times that the mean hourly potential gradient exceeded the limits of the electrometer was counted for each group of winds. This number was then divided by the total number of observations in that group and multiplied by one hundred, the result being the percentage frequency with which the mean hourly potential gradient exceeded the maximum range of the electrometer during winds of the specified velocity.

We see that with winds of 0 to 10 miles an hour the maximum was exceeded in only ·7 per cent. of the cases, while with winds greater than 40 miles an hour the maximum was exceeded in 65 per cent. of the cases. In other words excessively high potentials were seldom recorded during light winds, when there was little, if any, drift, while with high winds which were practically always accompanied by heavy drift the potential was as a rule excessively high.

Drift occurred in two forms: there was first the drift which appeared to fill the atmosphere darkening the sky and making it almost impossible to see more than a few yards away; and there was the low surface drift which only extended a short distance from the ground and above which the air was clear and the sky frequently cloudless. Both kinds of drift usually affected the potential in the same way, for as soon as the slightest drift commenced the potential became very high and remained so until the drift ceased.

Negative potential gradient.—During the whole year the potential gradient was negative only on nine days; as these are important in the following theoretical discussion each will be described in detail:—

(1) *April* 20, 1911.—Throughout this day there was a high S.E. wind of between 30 and 40 miles an hour. The sky was thickly clouded, and there was either no drift or a very little low surface drift. From midnight to 9 A.M. the potential was positive and high, then it decreased rapidly, and just after 10 o'clock it became negative. For several hours afterwards the needle oscillated from one to the other side of the zero. The potential was never negative for long and high negative values were not recorded. At this time the Sound was not frozen over and there was some raised fog over the open water. The temperature was about −10°F.

(2) *June* 1, 1911.—During the early morning there was some new snow and excessive drift; during this period the potential was positive and high. By midday, although the wind was still between 40 and 50 miles an hour, the drift had entirely ceased. From 13 hours to 16 hours the potential was frequently negative, but only for short intervals, the mean potential being just on the positive side. Later in the day the potential became high on the positive side, but without drift. The sky was overcast throughout the day.

(3) *September* 4, 1911.—There was little or no wind on this day. Until midday the sky was practically cloudless and the potential was normal. At about 1 P.M. heavy clouds came up from the north and by 4 P.M. a thick mist lay over the station. With the approach of the clouds the potential decreased and between 2 P.M. and 3 P.M. it crossed the zero and was negative for about fifteen minutes. After this the potential rose again and was fairly normal for the rest of the day. There can be little doubt that the cloud was the cause of the reduction and

reversal of the potential gradient. In this case the changes in the potential were comparatively regular, there being few of the rapid changes which generally accompanied the reversed potential.

(4) *October* 2, 1911.—There was a heavy blizzard on this day with much new snow and drift. It was impossible to prevent the insulators becoming covered with snow, therefore the record is doubtful; but for several hours between 4 A.M. and 9 A.M. the needle was frequently on the negative side of the zero, therefore it is almost certain that during this period the potential was negative.

(5) *November* 6, 1911.—This was another day with a high southerly wind between 30 and 40 miles an hour. Until 9 A.M. there was some surface drift and the potential as usual was positive and high. The drift then ceased, but the wind continued, and the potential steadily decreased to zero at about 3 P.M. and then became negative for about 40 minutes, after which it became positive again. The clouds were heavy and low throughout the day.

(6) *December* 8, 1911.—This is the most instructive case. Two days previously there had been the greatest snowfall of the year, which had been in the unusual form of large flakes. The whole of the frozen Sound was covered with about 18 inches of light loose snow. At 1 P.M. a high wind from the north sprang up driving the loose snow before it. The potential at first was high and positive, then at 4 P.M. it commenced to fall rapidly, at 6 P.M. it had become negative and the needle of the electrometer had swung to its extreme negative position where it remained with a few short breaks until 11 P.M. There is no doubt that during this period high negative potential occurred and it was the longest period of continuous reversed gradient recorded. Throughout the whole period of negative gradient the sky was clear, but there was a very heavy surface drift of light snow caused by the high wind. The drift, however, was not higher than about 3 or 4 feet, above which the air was quite clear. The whole of the drifting snow was therefore well below the collector.

(7) *December* 9, 1911.—The high wind of the previous day continued, but when it had removed the upper layer of soft loose snow the drift decreased and none was reported after 8 A.M.

On the whole the potential was high and positive, but it was most irregular, the needle of the electrometer constantly swinging to, and occasionally across, the zero. Between 10 A.M. and 1 P.M. the conditions were reversed, for then the potential was negative and high with occasional swings to the positive side. Afterwards the potential returned to the positive side and remained high until the wind dropped, when it became normal. In this case we have an unsteady potential and a long period of negative potential with little or no drift, but again a high wind.

(8) *December* 30, 1911.—Throughout this day there was a moderate wind 20—30 miles an hour from the E.S.E. with snow and drift. The potential was very low all day and was sometimes positive and sometimes negative. The record is almost exactly like one obtained on a rainy day in temperate regions. The temperature was between 20° and 25° F.

(9) *February* 10, 1912.—Between 3 P.M. and 4 P.M. a little snow fell and the potential gradient became negative for about half an hour. There was a light wind

19 miles an hour, from the N.N.W. At this time the Sound was nearly free from ice.

Of these nine records of negative potential gradient four (1), (2), (5) and (7) occurred with a high wind but no drift; three (4), (8) and (9) occurred during snowfall; one (6) occurred with a clear sky but very heavy low surface drift; and one (3) occurred during the passage of heavy low cloud but without wind, drift or snow.

The explanation of the high potentials during drift proves to be very difficult. I did not realise this at first and considered that the whole phenomenon was due to the ice particles becoming charged positively by collision amongst themselves and with the snow-covered ground. Rudge has experimented on the well-known electrical effects accompanying the raising of clouds of dust, and shown that when dust is blown into the air or even let fall through the air it becomes highly charged. Treating air full of snow-drift as a dust cloud of great extent, it is reasonable to suppose that the snow would, like the dust, become highly charged. Thus, when the whole lower atmosphere is full of positively charged snow, there would be a high positive potential gradient. It follows as a consequence that if the positively charged snow was all or mainly below the level of the collector of the potential gradient apparatus the registered potential gradient would be reversed. This is easily seen, for the normal positive potential gradient is caused by the negative charge on the earth, and if this charge is replaced temporarily by a layer of drifting snow highly charged with positive electricity, the gradient must be reversed. By far the heaviest surface drift I observed in the Antarctic occurred on December 8, 1911, when a high northerly wind carried along the recently fallen loose snow. This drift was not only very heavy, but it was also very low, and all well under the collector; it seemed, therefore, very strong support to the theory of positively charged snow to find that during this period the potential gradient was negative and high.

The first difficulty encountered was, when preparing this chapter, I searched for other cases of surface drift accompanied by negative potential gradient. I then found that instead of being accompanied by negative potential gradient surface drift was nearly always accompanied by very high positive potential gradient. At first it occurred to me that this might be due to the clouded sky which usually accompanied the drift, surface or otherwise, while the surface drift of December 8th occurred under a perfectly clear sky. I therefore searched the records for cases of surface drift with a clear sky and found seven cases beyond that of December 8th. In *all* these new cases the potential during the surface drift was positive and very high. This disposes at once of the explanation that the drift snow has a high positive charge, for if it had, so long as it was mainly below the collector, the potential should be reversed and only when it extended more above than below the collector should the positive potential gradient be increased. Stated in other words it is quite impossible to explain the observed facts by considering only the charge on the driven snow, for charged snow would cause the sign of the potential gradient to be reversed when the distribution of the snow changed from being mainly below the collector to being mainly above; while the observations show that the potential gradient is nearly always positive and high both when there is only a little surface drift and when the drift is so great and extends so high in the atmosphere that there must be more drift above than below the collector. One is forced, therefore, to seek the electrification elsewhere than on the driven snow. It is inconceivable that the surface of the earth can become electrified, for this would necessitate the surface being highly insulating, otherwise the charge would be neutralised at once. There is no doubt that a snow surface is a bad conductor of electricity, for we used for our telephone from Cape Evans to Hut Point, a distance of 15 miles, a bare aluminium wire laid over the snow surface while the return was the sea. During the winter the 'speaking' over the wire was perfect, showing that the insulation was sufficient, but after the middle of November no electrical signals could be sent through the wire showing that then the snow had lost its insulating power. If the snow could not insulate for the low voltages and high current density used in the telephone circuit during the summer, it certainly could not insulate for the high potentials and small charge produced by friction. As the positive potential gradient was as high during blizzards in the summer as in the winter, it is obvious that the charge concerned is not on the ground. The only remaining place to look for the charge is the air itself, and I believe that the charge carried by the air is the solution of our problem.

There can be no doubt from Rudge's work quoted above and from experiments made by the writer that the cause of the electrification of dust when blown into the air is not friction electricity as commonly understood, but an effect similar to that found when water is splashed or water drops broken, in which the solid or liquid particles retain one kind of electricity while the opposite electricity is given to the air, probably in the form of slowly moving ions. Let us imagine an isolated cloud of ice particles which on account of the turbulent motion of the air are constantly colliding with one another. The result would be that the ice particles would be charged with one kind of electricity (the sign of which will be discussed later) and the air would receive the opposite charge. There would, however, be no exterior field produced, as the two charges would neutralise one another at an appreciable distance from the cloud. If, however, the snow particles slowly settled in the air, the charge on the snow would become concentrated in the lower half of the cloud and that on the air in the upper half. This would produce an electrical field in the cloud itself. Now imagine that the cloud comes into contact with the ground, then every time an ice crystal touches the ground its charge is lost, but the opposite charge remains in the air above. The cloud in this way would soon have an excess of the electricity associated with the air and in course of time might become very highly charged. It is now only necessary to assume that the snow in the process becomes negatively charged and the air positively charged to have a complete explanation of the normal relationship found between the drift and the potential gradient.

Let us consider first the case of surface drift. The term surface drift is never used when the driven snow rises more than a few feet above the ground. The ice particles in this drift are constantly colliding with one another and with the fixed snow on the ground. According to the theory every collision is accompanied by a separation of electricity, the ice particles becoming negatively charged and the air receiving a positive charge. The snow, however, is constantly coming into contact with the ground when it gives up any charge it has, it will probably become charged again at the instant of separation, but every contact with the ground while adding more positive electricity to the air adds no further charge to the snow. Thus the air in which the drift is carried along becomes more and more highly charged with positive electricity, without the snow retaining the corresponding quantity of negative electricity. Owing to the irregularities of the air motion the charged air near the ground mixes with the air above and in a short time the whole of the air above the ground probably to several hundred feet becomes more or less highly charged with positive electricity. Between this positively charged air and the ground an intense electrical field may be set up. The direction of the field is the same as the normal field of the atmosphere and therefore the effect of the surface drift is to produce a high positive potential gradient.

Let us now consider that the whole of the lower atmosphere becomes full of drifting snow to a great height. The collisions of the snow particles produce the same separation of electricity, but owing to the constant downward motion of the snow relatively to the air containing it, there tends always to be an accumulation of positive electricity in the air of the upper part of the cloud. The field set up in this way is again parallel to the earth's normal field and therefore increases it, thus there is no reversal of the field when the drift snow extends from the ground to heights well above the collector. In other words the potential gradient will be positive and high whenever there is drift quite independently of whether the drift is surface drift or true drift throughout the lower atmosphere.

We have now explained the vast majority of the observations and it is only necessary to prove the rule by explaining also the exceptions. The most important case is the high negative potential observed during heavy surface drift on December 8th. It has been found that when dust is raised in the air the resulting charge is affected by the character of the dust. Fine dust has been found to be charged with the opposite kind of electricity from that associated with coarser dust of the same material. Thus the loose snow in the drift of December 8th might have the opposite charge from the hard grains of ice of which surface drift in the vast majority of cases consisted. This assumption seems, however, unnecessary. On December 8th the surface drift was unusually heavy on account of the large amount of loose snow lying on the ground after the recent heavy fall of large flake snow. In such a drift the separation of electricity would be excessive, therefore the air immediately above the drift would be very highly charged with positive electricity. If at the same time there was little tendency to the formation of ascending air currents, the concentration of positive electricity would remain in the air near the upper limit of the drift. It is not difficult to conceive that under such conditions there would be more positive electricity below the collector, which was 10 feet above the ground, than above it. This would fully account for the reversed potential gradient. It also explains why later on the potential became positive, but very unsteady, with occasional returns to the inverted direction; for then the positively charged air extended higher into the atmosphere and the collector had generally more positive electricity above it than below it, but occasionally the original conditions were re-established for short periods.

That the potential should be occasionally reversed during periods of snowfall, as in cases (4), (8) and (9) above, is not difficult to explain. Snowfall is a sign of ascending currents, for they are necessary to supply the water vapour necessary to the production of snow. The air of these ascending currents must constantly pass out of the top of the cloud and take with it positive electricity. If this air then enters an air current from a different direction from the lower wind, it will be removed from the region of the cloud. The whole cloud will then have a residual charge of negative electricity associated with the snow. This being above the collector will reverse the field and a negative potential gradient will be recorded.

The five cases of negative potential gradient without appreciable drift cannot be explained by the above consideration which are based on the separation of electricity associated with drift, and as no explanation of the reversed gradient is obvious it will serve no useful purpose to make assumptions, which cannot be tested, to provide an explanation.

The above discussion leads to the conclusions—

(*a*) The electricity which affects the recorded potential gradient during drift is not associated with the driven snow;

(*b*) but with the air in and above the drift;

(*c*) the separation of electricity takes place when ice crystals collide, the ice becoming negatively charged and the air positively charged.

These conclusions are based entirely on the observed potential gradient, it is obvious that the only satisfactory test would be to examine the sign of the charge on the drift snow itself. If this were found to be negative, the conclusions would be proved beyond doubt. The need to make such an investigation was realised while we were in the Antarctic, and I had devised the method to be used, but my unexpected recall at the end of the first year prevented the experiments being actually made. It is to be hoped that the simple experiments will be made by the first observer who has the opportunity.

Yearly variation of the potential gradient.

It is customary always to exclude periods of disturbed weather when obtaining the normal potential gradient. This practice has been followed in the following discussion, with the further limitation that all periods when the wind velocity was greater than 5 miles an hour have also been excluded. This was necessary in order to rid the observations of the effect of drift. The procedure adopted was to tabulate the values of the mean hourly potential gradient during periods in which the wind velocity was 0 to 5 miles an hour. To rid the observations still further of the effect of recent or approaching high wind and drift, the first and last hours of each period were also rejected. Thus every value used in determining the normal potential gradient was not only obtained during periods in which the wind was 5 miles an hour or less, but also at least one complete hour separated it from past or approaching bad weather. Needless to say all hours during which snow fell during calm weather were also excluded.

Table 157 contains the mean potential gradient for each month * and the number of hours used in the determination.

TABLE 157.

Mean monthly potential gradient at Cape Evans. Volts per metre.

	Jan.	Feb.	Mar.	April.	May.	June.	July.	Aug.	Sept.	Oct.	Nov.	Dec.	Year.
Potential gradient .	96	89	75	79	67	80	85	78	105	90	88	107	87
Number of hours used .	154	94	21	43	221	112	179	233	213	105	173	148	

These values are plotted on figure 91, from which it will be seen that the yearly variation is fairly regular with a minimum in May and a maximum in December.

In other words the potential in the summer is distinctly higher than in the winter. A similar variation of the potential gradient has been found wherever observations have been made in the Antarctic. These are the Belgica Expedition, 71° S., 87° W.; Hut Point, 78° S., 38 E.; Port Charcot, 65° S., 64° W.; and Petermann Island, 65° S., 64° W. It can therefore be accepted without question that the potential gradient in the Antarctic is higher in the summer than the winter. This is a most important result, for it is the exact opposite of the conditions in the northern hemisphere, where numberless observations have shown that the potential is higher in the winter than the summer. The question at once arises are the observations made in the Antarctic typical of the conditions over the whole of the southern

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* I very much regret that the values of yearly and daily potential gradient given in my paper 'Chief Results of the Meteorological Observations made on Captain Scott's Antarctic Expedition' published in the Quarterly Journal of the Royal Meteorological Society, Volume XL, page 221, 1914, are not quite accurate. This was due to the carelessness of one of my clerks who made many mistakes in computing the tables of potential gradient. The errors are not important and cannot affect any conclusion which may have been drawn from the published values.

hemisphere? If so, then we have that the potential gradient is at its maximum and minimum at the same times over the whole world, which would be a most important conclusion. It would mean that the total charge on the earth's surface is highest when the earth is near the sun and lowest when furthest away, thus connecting the electrical state of the earth and its atmosphere with cosmical rather than terrestrial factors. This important and interesting conclusion cannot, however, in the present state of our knowledge be accepted. It is a remarkable fact that we know more about the electrical state of the atmosphere in the Antarctic than in the rest of the southern hemisphere put together. So far as I can find there are only five series of observations in the southern hemisphere outside the Antarctic; these are the observations made at (*a*) Melbourne in Australia by Neumayer during 1858–63, (*b*) Cape Horn by the French Mission in 1882-83, (*c*) Batavia in 1890–95, (*d*) Samoa in 1906–08, and (*e*) Buenos Aires in 1911-12. Assuming that all these determinations are satisfactory we find that two, at Cape Horn and Batavia, show the highest potential in the southern summer and so are in agreement with the Antarctic result while the remaining three, at Melbourne, Buenos Aires and Samoa, show the reverse, the highest potential being in the winter and the lowest in the summer. With such conflicting evidence, some of which does not come up to the modern standard of reliability, we cannot do more than wait for more and better observations; but in the meantime with the observations at Melbourne, Buenos Aires and Samoa before us we cannot accept the conclusion that the potential gradient over the whole world is at its maximum and minimum at the same times.

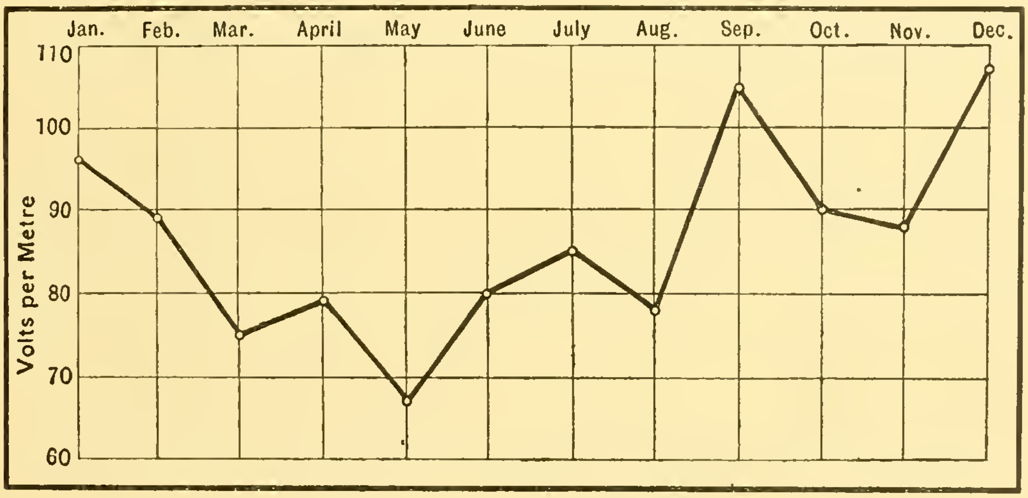

FIG. 91. Yearly variation of potential gradient.

The harmonic analysis of the yearly variation of the potential gradient at Cape Evans gives

$$P = 86{\cdot}6 + 12{\cdot}5 \sin\,(132^\circ\,53' + x) + 3{\cdot}7 \sin\,(48^\circ\,25' + 2x),$$

in which $x = 15$ for January, 45° for February, and so on.

Daily variation of potential gradient.

The mean hourly potential gradient during fine weather as defined in the last section was investigated to find the daily variation for each of the four seasons and for the year. In the following table the results are entered and against each of the mean values the number of hours used to determine it is given.

TABLE 158.

Daily variation of potential gradient.

Fine weather and wind 0—5 miles an hour.

	AUG.-OCT.		NOV.-JAN.		FEB.-APRIL.		MAY-JULY.		YEAR.	
Local time.	P.G.	No. of hours.	P.G.	No. of hours.	P.G.	No. of hours.	P.G.	No. of hours.	P.G	No. of hours.
0—1	94	21	116	20	105	7	75	25	95	73
1—2	87	21	115	21	129	7	77	28	95	77
2—3	89	24	106	22	102	7	81	29	92	82
3—4	93	23	110	24	105	7	86	30	97	84
4—5	93	24	116	21	95	8	84	27	96	80
5—6	90	27	110	21	107	9	86	24	96	81
6—7	99	29	109	25	96	11	92	20	100	85
7—8	121	28	101	24	92	10	88	20	104	82
8—9	109	25	93	24	87	9	91	20	97	78
9—10	96	22	81	20	70	10	84	18	85	70
10—11	98	20	76	18	63	9	77	14	81	61
11—12	84	22	81	19	58	9	78	15	78	65
12—13	90	18	75	21	48	5	69	19	75	63
13—14	92	20	72	21	56	1	66	21	76	63
14—15	79	21	67	16	60	1	57	22	67	60
15—16	76	22	77	15	67	1	62	18	72	56
16—17	83	20	82	17	71	3	71	16	78	56
17—18	83	19	87	16	52	5	65	21	75	61
18—19	83	19	100	17	67	6	65	21	80	63
19—20	86	21	90	19	78	7	71	22	82	69
20—21	93	22	110	19	91	8	77	21	92	70
21—22	87	26	107	22	72	6	71	22	87	76
22—23	79	29	109	16	67	6	72	20	83	71
23—24	85	27	103	17	86	7	73	19	86	70

The curves based on this table are the thick ones shown in the upper part of figure 92. It will be seen at once that the daily variation is very similar in all seasons, the maximum occurring during the forenoon and the minimum during the afternoon. From the few observations made by Bernacchi on Captain Scott's first expedition C. T. R. Wilson drew the same conclusion, so there can be little doubt that this is the normal course of the potential gradient in McMurdo Sound. It is a surprising result for it is very abnormal. At all other places in the world where reliable observations of the potential gradient have been made the main minima and maxima occur near 4 A.M. and 8 P.M. respectively.

The question at once arises is the abnormal daily course of the potential gradient in McMurdo Sound due to the local meteorological conditions or is it a true electrical effect ?

If the two last columns of table 158 are compared, it will be seen that there is a remarkable parallelism between the value of the potential gradient and the number of hours

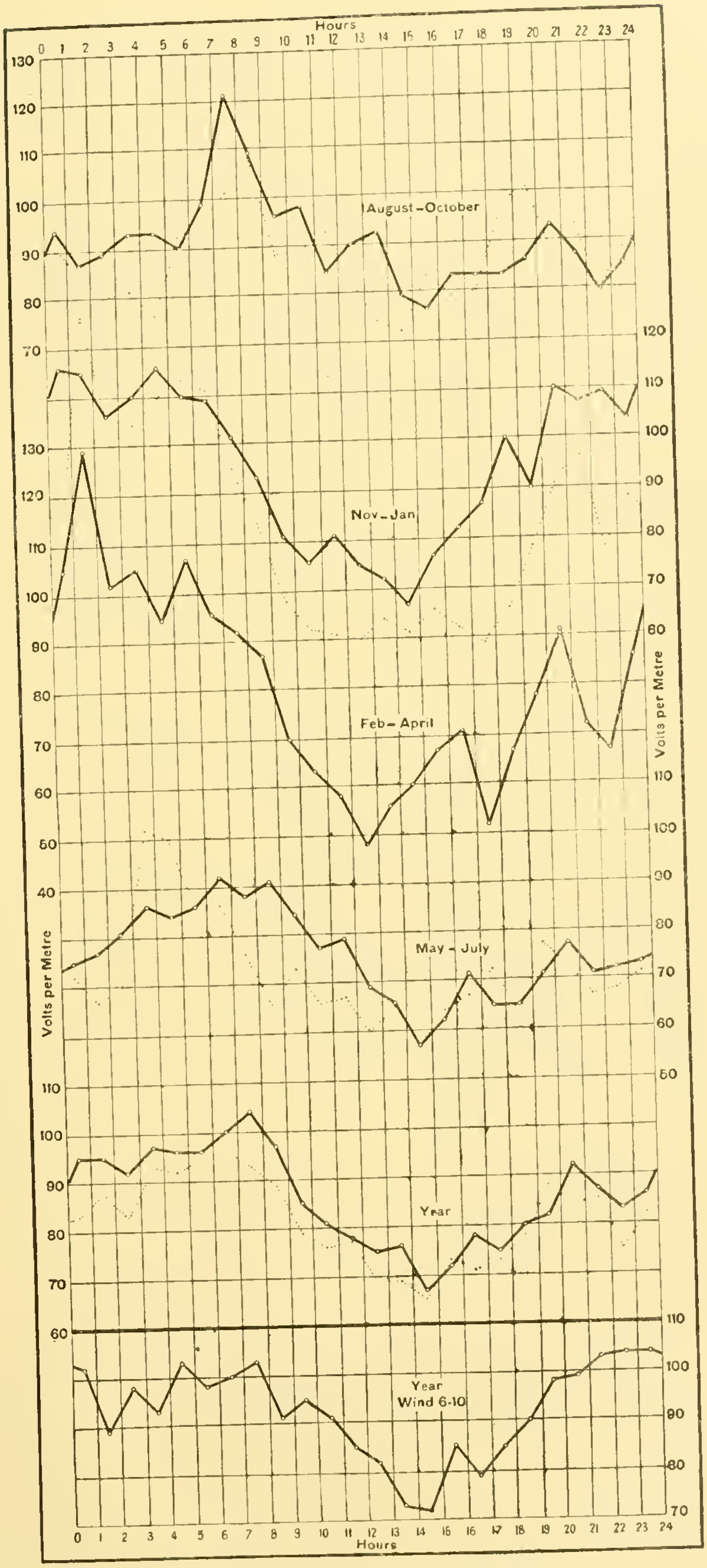

Fig. 92. Daily variation of potential gradient.

used in the determination. Thus during the early morning from 5 A.M. to 10 A.M. the potential is high and the observations are numerous. During the period of minimum potential from 1 P.M. to 7 P.M. there are relatively few observations. If the numbers are examined in more detail, it will be seen that the parallelism is very close. It will also be seen that the same relationship is repeated in each of the four seasons, the period of high potential coincides with the period of numerous observations and *vice versâ.*

That there are more observations in the early morning and fewer in the early afternoon is not chance, it is due to the fact that the air is more often calm in the early morning than in the afternoon. This is clearly brought out in the curves on figure 33, page 102, which show the frequency with which calms (0—1 miles per hour) occurred during the same period as that for which we have the potential gradient observations. The similarity between the curves showing the daily variation of calms and the daily variation of potential gradient (figures 33 and 92) is most remarkable and points to some close relationship between the two phenomena.

Reasons for such a relationship do not appear difficult to find.

It is a well-known fact that, generally speaking, when the electrical conductivity of the air is low the potential gradient is high, also that a high humidity of the air causes a lowering of the conductivity. Thus one would expect periods of high humidity to coincide with high potential gradient. Unfortunately no humidity measurements were made at Cape Evans, but during calm weather one might expect the humidity to depend largely on the temperature.

Now during the greater part of the year the temperature is lowest in the early morning and highest in the afternoon, we might therefore conclude with a certain amount of justification that the humidity is highest in the early morning and lowest in the early afternoon. Thus we see that the high potential might be accounted for in this way during the greater part of the year; but what about the remaining part? We have already shown (page 67) that during the three winter months, May, June, and July, the temperature variation is very small, and what there is of it makes the afternoons warmer than the night and early morning. It must, however, be pointed out that all hours were used in this determination. Would the effect be the same if only the calm hours had been considered? The fact that there are more calms during these months in the early morning than in the afternoon would lead us to expect that the afternoons would be the warmer; for we have repeatedly shown that the more the wind the higher the temperature.

To test whether or not this is so the temperature of every hour during May, June, and July, for which the potential gradient has been used, has been tabulated and the daily variation of the temperature of these hours determined. The following table contains the results and shows that the temperature is practically constant throughout the twenty-four hours and that there is no temperature variation at all similar to that of the potential gradient variation:—

TABLE 159.

Mean temperature of the hours from which the potential gradient variation has been determined in May, June and July. °F.

	1	2	3	4	5	6	7	8	9	10	11	12
A.M.	−22	−23	−22	−22	−22	−22	−21	−21	−21	−20	−19	−20
P.M.	−22	−22	−21	−23	−23	−22	−20	−21	−23	−23	−22	−23

We thus see that during May, June, and July the potential gradient variation cannot be ascribed to changes in the conductivity of the air caused by the variation of temperature and humidity. It is therefore reasonable to assume that the potential changes in other seasons of the year also are not due to this cause.

The next step was to investigate whether the daily variation of potential gradient which shows itself in the mean of a large number of broken periods exists when the weather remains calm throughout twenty-four hours. There are not many periods during which the wind did not rise above five miles an hour during twenty-four consecutive hours. There were none during February, March, and April; but six were found during May, June, and July, eight during August, September, and October, and four during November, December, and January. Each of these periods generally extended over a few more than twenty-four hours, but in each case the best series of twenty-four consecutive hours was chosen. From these few observations the daily variation was obtained and the result has been shown by the thin curves in figure 92. It will be seen at once that the character of the variation is the same and the differences between the thick and thin curves are to be expected on account of the few observations used to obtain the latter. This has confirmed the character of the variation for calm weather, but there is still the possibility that meteorological conditions are the determining factor. For example during May, June, and July, in spite of the absence of any appreciable temperature variation there is a pronounced tendency for the air to be calmer in the morning than in the afternoon. This tendency for which no physical explanation can be given probably acts during all periods of calm and may affect the potential gradient as well as the air motion. If the potential gradient variation is not due to this meteorological condition, whatever it may be, the variation should be the same when the air is not calm, *i.e.*, it should be similar during winds as during calms. Unfortunately the presence of drift so affects the potential gradient during appreciable air motion that its daily variation is completely masked. The drift, however, does not become serious until the wind rises above 10 miles an hour. If therefore we investigate the potential gradient during periods in which the wind velocity was between 6 and 10 miles an hour the daily variation of the potential, if it exits, should be recognisable. The hourly values of the potential gradient during winds of 6 to 10 miles an hour were therefore tabulated and it was found that in all seasons they showed the same general daily variation as during calms. The number of observations, however, in each season is very small, so that the curves are irregular. On the mean of the whole year, however, the observations are sufficient to give a reliable result; numerical values are contained in table 160 and the curve is shown at the bottom of figure 92.

TABLE 160.

Potential gradient during winds of 6 *to* 10 *miles an hour.*

Volts per metre (Number of observations in brackets).

	0—1	1—2	2—3	3—4	4—5	5—6	6—7	7—8	8—9	9—10	10—11	11—12
A.M.	102 (31)	89 (28)	98 (28)	93 (30)	103 (28)	98 (15)	100 (21)	103 (28)	91 (23)	95 (35)	91 (44)	85 (49)
P.M.	82 (38)	73 (42)	72 (47)	85 (36)	79 (38)	85 (43)	90 (33)	98 (34)	99 (36)	103 (30)	104 (33)	104 (26)

The curve for the potential gradient during winds of 6 to 10 miles an hour is practically the same as that during calms; it is therefore quite clear that the variation of the potential gradient is not caused by the peculiar meteorological conditions existing during calm weather and as it is difficult to conceive of any meteorological condition which is the same during calms and winds and during summer and winter, we are forced to the conclusion that the variations in the potential gradient are real and not due to local meteorological conditions.

It has already been remarked that the daily variation of the potential gradient found in McMurdo Sound is very abnormal. It was also shown above that the yearly variation in the Antarctic appears to be different from that of the rest of the world; are the abnormal yearly and daily variations in the Antarctic related? The only other observations of the daily variation of the potential gradient made in the Antarctic (other than those made by Bernacchi in McMurdo Sound) are two series made by members of Charcot's two expeditions on the coast of Graham's Land.* Both of these show a variation very similar to the normal variation found in other parts of the world: the main minimum is near to 4 A.M., but the main maximum is early, occurring at 3 P.M. instead of at 8 P.M. as is more usual.

We are thus led to conclude that the daily variation of the potential gradient in McMurdo Sound is not only different from that in other parts of the world but is different from that of other places in the Antarctic. In other words not only is the daily variation abnormal but so far as observations go it is unique. The question at once arises is there anything in the geographical position of McMurdo Sound which also is unique? McMurdo Sound possesses one feature which is different from all other places for which atmospheric electricity observations are available. On account of its position between the magnetic and the geographical poles the direction of the earth's magnetic field relative to the direction of rotation of the earth is practically reversed from what it is at all other stations.† In other words in this part of the world if an observer stands with his face looking along the lines of magnetic force he moves on account of the earth's rotation from right to left instead of from left to right. In view of our total ignorance of any relationship between terrestrial magnetism and atmospheric electricity it is impossible to say what effect one would expect from this reversal, but a comparison between the daily variation of the potential gradient in McMurdo Sound with that of the most northerly station for which we have a complete set of data is instructive and suggestive.

During 1903-04 the present writer spent fourteen months in the Lapp village of Karasjok (69° 17′ N., 25° 35′ E., 129 metres above sea-level) with the object of investigating the electrical conditions of the atmosphere there.‡ The results of the daily variation of the potential gradient for a whole year are shown in the upper curve of figure 93. As the amplitude of the daily variation in Karasjok was much larger than in McMurdo Sound, the scale has been reduced in the ratio of 25=10. A comparison between the curve for Karasjok and the curve for Cape Evans given in figure 92 shows a great similarity in the general shape of the two curves, but the times at which the maxima and minima occur are different. The chief minimum occurs at 14½ hours at Cape Evans and at 5 hours at Karasjok, a difference of 9½ hours; while the chief maximum occurs at 7½ hours at Cape Evans and at 21 hours at Karasjok, a difference of 10½ hours. It is obvious, therefore, that if the time at Cape Evans were put back 10 hours, the curves would agree not only in shape but also in phase. To bring this out more clearly the curve for Cape Evans has been smoothed by the formula $\frac{a+2b+c}{4}$ and plotted under the curve for Karasjok with its time values put back 10 hours. The similarity of the two curves is now very apparent.

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* I. I. Rey. Expedition antarctique française, 1903–05. Hydrographie, Physique du Globe, Paris, 1911, page 191.
I. Rouch. Deuxieme Expedition antarctique française, 1908–10. Sciences physiques, Paris, 1913, page 14.

† The declination at Cape Evans is 153° E.

‡ G. C. Simpson. Philosophical Transactions, A, 205, pages 4–97, 1905.

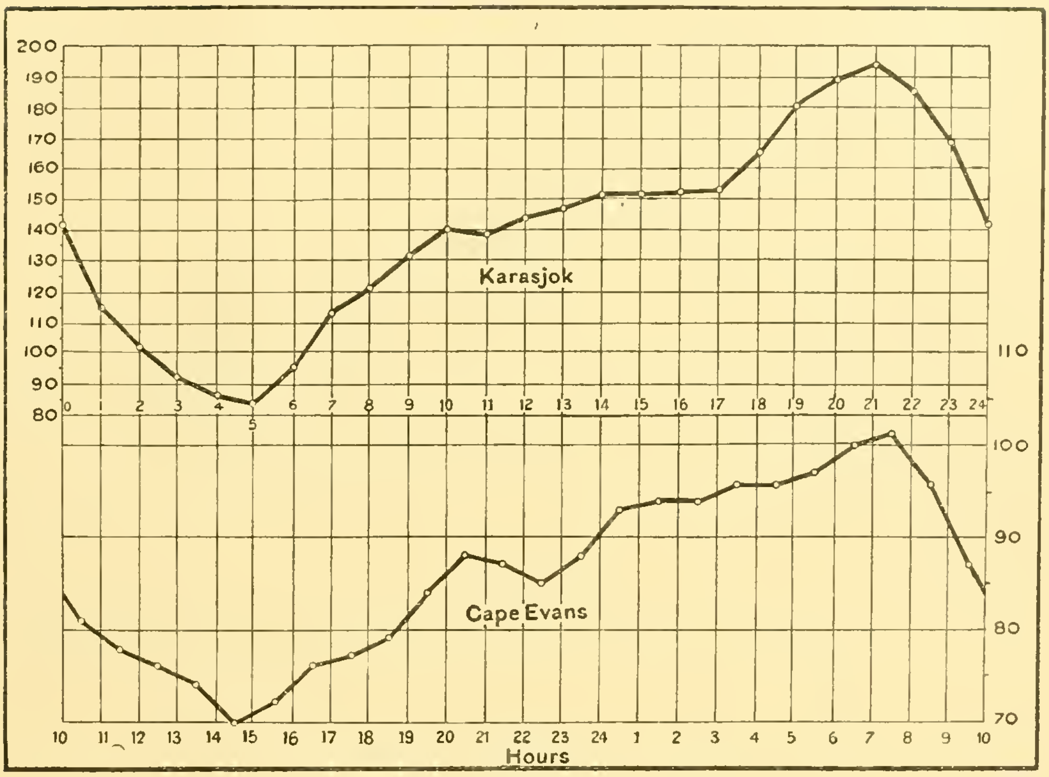

FIG. 93. Daily variation of potential gradient.

The same conclusion is reached if we analyse the two curves into Fourier's series. The equations to the two curves are

Karasjok $P=139+39 \sin(\theta+177^\circ)+23 \sin(2\theta+158\ )$

Cape Evans $P=86+12 \sin(\theta+33^\circ)+5 \sin(2\theta+228^\circ)$

in which in each case θ is measured from local midnight and equals 15° for each hour.

Now the difference in phase between the two first terms is $177^\circ-33^\circ=144^\circ$, which is equivalent to 9·6 hours and the difference in phase between the two second terms is $158^\circ-228^\circ=290^\circ$, which is equivalent to 9·7 hours. Hence if we change the time at Cape Evans by 9·6 hours, the phase of both terms becomes practically identical at both stations.

Now is it only coincidence that this value of the change in phase is almost the same as the difference in magnetic declination at the two places? The declination at Karasjok is approximately 0° and at Cape Evans 153° E., *i.e.*, a difference of 153°, which is very near the phase corresponding to 9·6 and 9·7 hours (144° or 145°).

This result is very suggestive, but we are not justified in discussing it in detail, for many more observations at places having different values of declination are necessary before we shall be able to say with certainty that there is any relationship between the direction of the earth's magnetic field and the daily variation of the potential gradient.

ATMOSPHERIC RADIO-ACTIVITY.

Forty-six measurements of the radio-activity were made during the winter months, May to August, and twenty-eight during the summer months, December to February. The method used was the same as that employed on the *Terra Nova* on her voyage from England to New Zealand.* The object of the work was to compare the atmospheric radio-activity in

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* Simpson and Wright. Proceedings of Royal Society, A, Volume 85, page 175, 1911.

the Antarctic where there is a permanent covering of snow and ice with that of ordinary land and the open ocean.

On the arbitrary scale used (approximately that defined by Elster and Geitel and denoted by A)* we found during our voyage the following results :—

Table 161.

Radio-activity.

	A mean.	A max.	A min.
Over land (Matjesfontein) .	124 (17)	256	52
Over ocean	6 (102)	21	1

Exactly the same instruments and methods were used in the Antarctic with the following results :—

Table 162.

Radio-activity at Cape Evans.

	A mean.	A max.	A min.
May to August . . .	20 (46)	60	6
December to February .	16 (28)	30	6

We see that the radio-activity in the Antarctic is higher than over the open ocean and lower than over the land of South Africa. This is exactly what we should expect if the origin of the emanation is the radium contained in the rocks of the earth's crust.

When the effect of the meteorological conditions are considered, we find here as in every other part of the world that the meteorological conditions which favour stagnation of the air near the ground result in relatively high radio-activity. Thus we should expect the radio-activity to decrease with increasing wind force and to increase with decrease of temperature and this is found to be the case. The mean values of the radio-activity for various wind strengths and temperatures are shown in the following table :—

Table 163.

Radio-activity, wind and temperature.

	Wind.			Temperature.			
	0—10	11—30	>30	<—15	—15 to 0	0—15	>15
A	20	17	14	22	17	15	16
No. of observations . .	(40)	(27)	(6)	(26)	(14)	(5)	(28)

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* Elster and Geitel. Phys. Zeit., 1902, Volume 3, page 305.

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PLATE I


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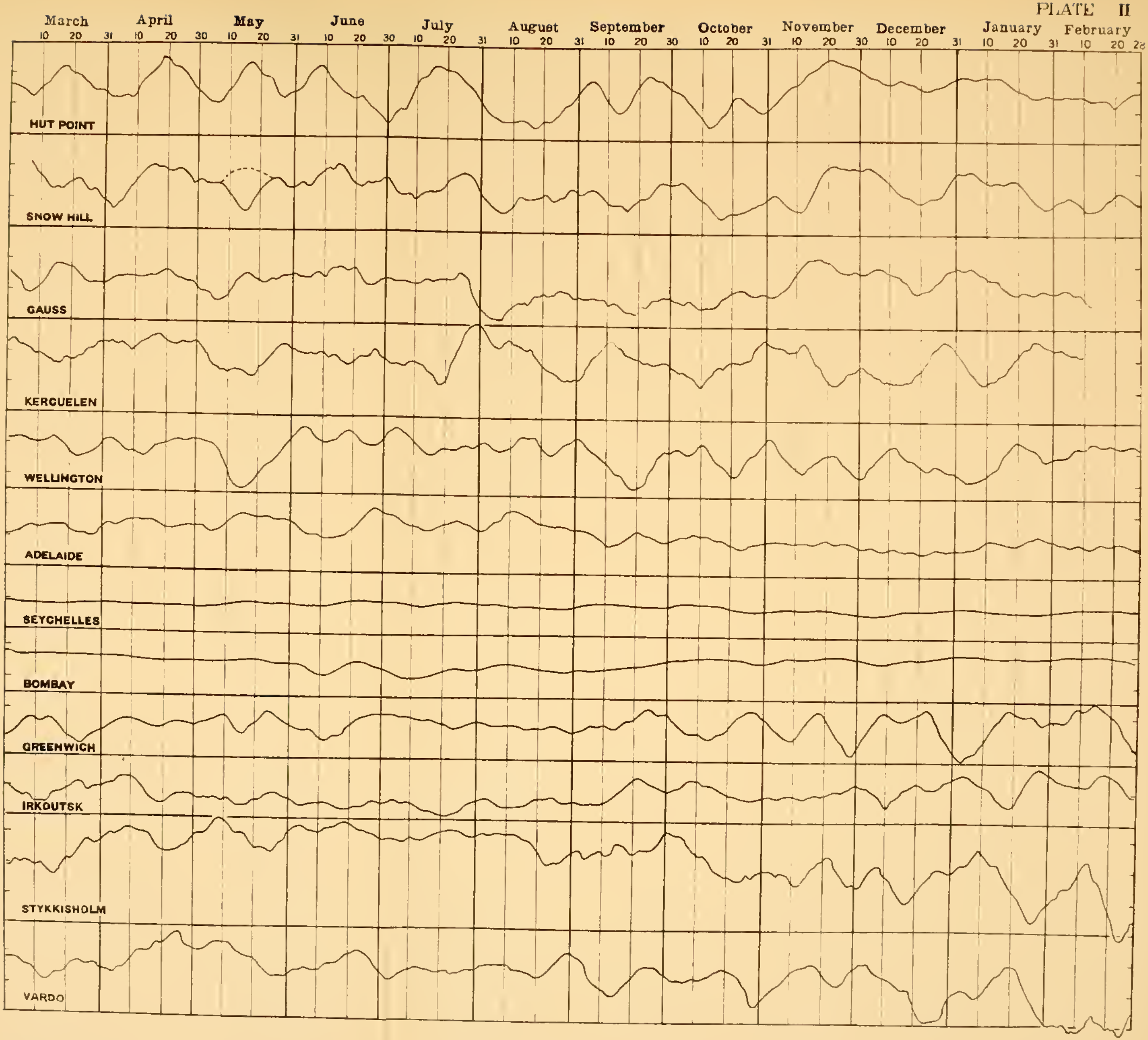
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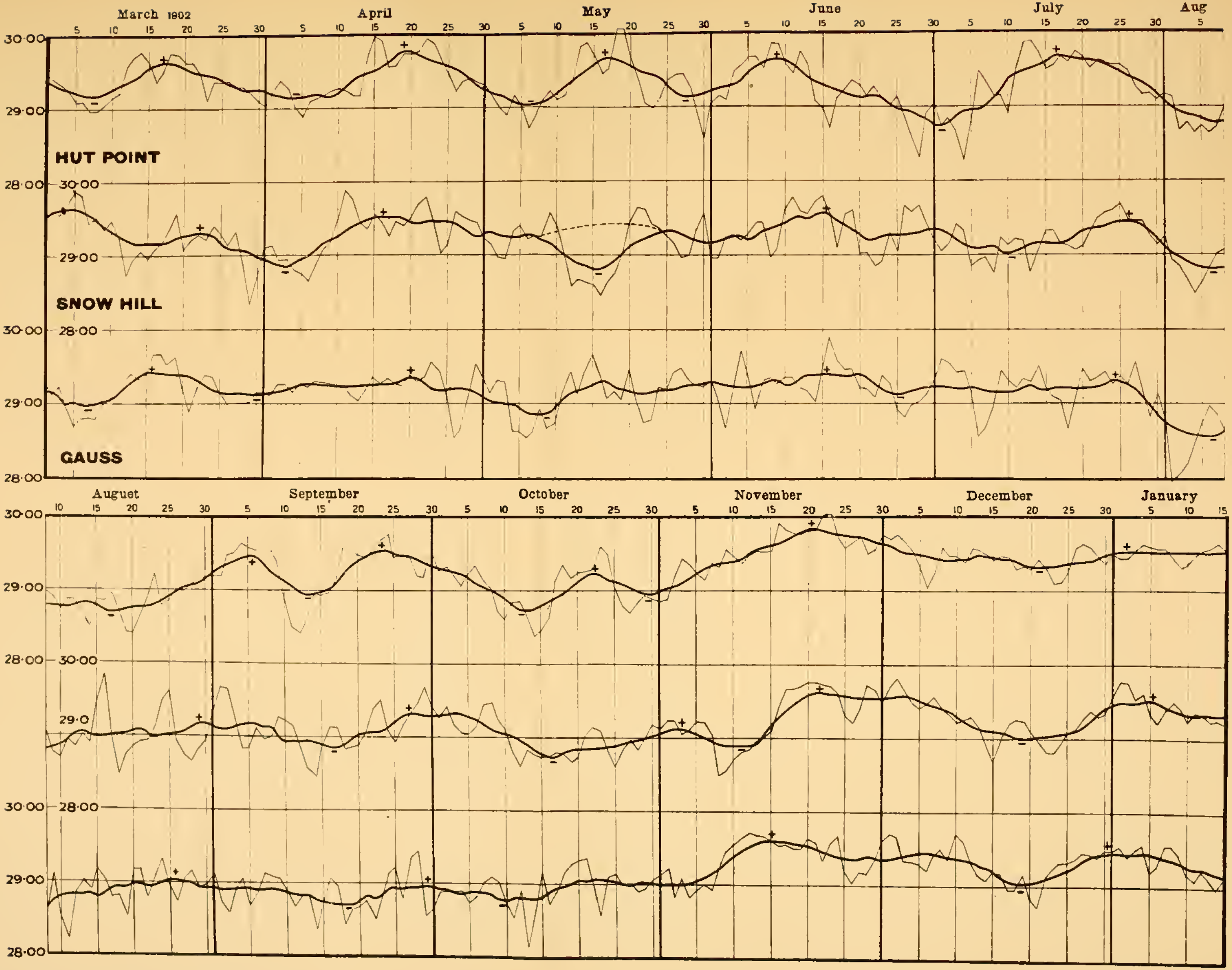
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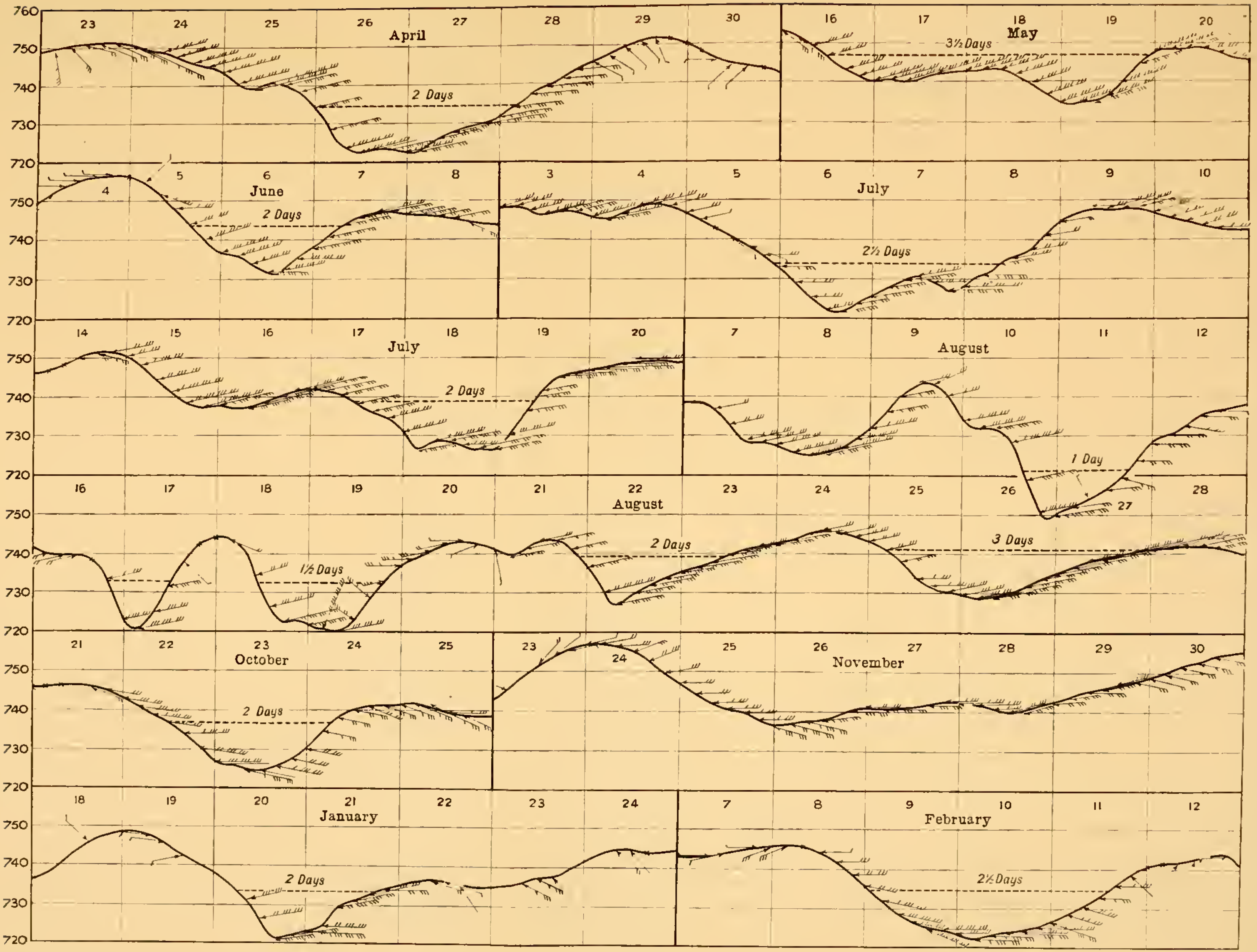

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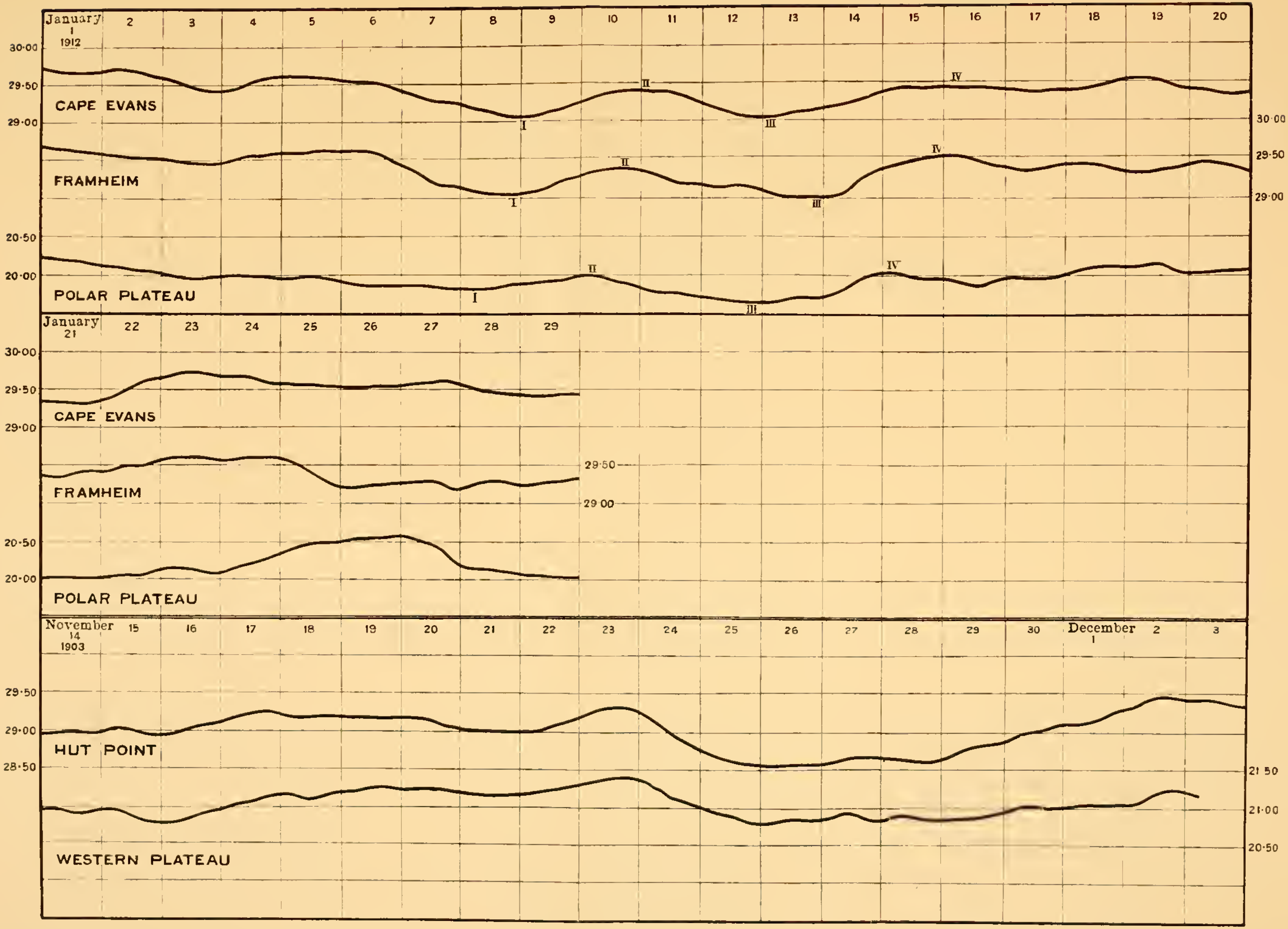
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