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WHIRLWINDS, CYCLONES AND TORNADOES

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Whirlwinds, Cyclones, and Tornadoes.

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W. M. D.

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CONTENTS.

WHIRLWINDS, CYCLONES, AND TORNADOES.

THE general circulation of the winds is at times interrupted by local and temporary disturbances of very varied size and strength, to which the general name of 'storms' is given. Their most constant features are, a more or less pronounced inward spiral whirling of the air near the ground, feeding an up-draught at the centre, and an outflow above; and a progressive motion from place to place, along a tolerably well-defined track. Clouds, and generally rain as well, accompany the larger storms.

It is our object to explain how these disturbances arise, to examine the causes and methods of their peculiar action, and to study their distribution in time and place. With this end in view, the small dust-whirlwinds that commonly arise in the hot dry air of deserts will be first considered. Next will come the great hurricanes and typhoons of the tropical seas, and the less violent rotary storms of our own latitudes, all of which may be grouped together as cyclones. The tornadoes and water-spouts, showing a peculiar concentration of power over a very limited area, will be discussed last.

The dry whirlwinds in flat desert regions suddenly interrupt the calmness of the air, and begin turning, catching up dust and sand, and carrying them upwards through the spiral vortex to a height of many hundred feet. They are therefore not at all like those whirls formed about our street-corners at the meeting of opposing currents of blustering wind, or the eddies of greater strength seen in windy mountain regions; for they arise in a time of quiet, and begin their motion without apparent cause. Hence we must, at the outset, inquire into the condition of the atmosphere when it lies at rest, examining it especially with regard to the kind of equilibrium that then exists, and the changes necessary to produce a tendency to motion.

Equilibrium of the Atmosphere.

When the air is at rest, it is normally densest and warmest next to the earth's surface, and becomes thinner and cooler at successive altitudes above it. It is denser below because the earth's attraction pulls it down, and compresses the lower layers by the weight of the upper ones. It is warmer below, mainly because the air gets nearly all of its heat by contact with, or radiation from, the warm earth, and not directly from the sun's rays, which pass through it with but little obstruction. The average rate of upward cooling, determined by many observations on mountains and in balloons, is about one degree F. for every three hundred feet of ascent. In this restful condition let us take a block of the dry air (the effect of the presence of water-vapor will be considered with the storms at sea) from the earth's surface, where the temperature is, say, 60° (fig. 1), and lift it up three hundred feet, to where the temperature is one degree less, or 59°. The block of lower air expands as it rises, because it is pressed on by less atmospheric weight,—less, at least, by the weight of three hundred feet of air; and, in thus expanding, it is cooled mechanically. It has been shown that this mechanical cooling of an ascending mass of dry air amounts to one degree F. in a hundred and eighty-three feet of ascent, whatever its initial temperature; so that in this special case the block is cooled by 1.6°, and its temperature is reduced to 58.4°. Now, let us compare it, when thus expanded and cooled, with an equal-sized block of air beside it, whose temperature is 59°. Evidently, of these two blocks of the same volume, and at the same pressure, the cooler will be the heavier. The block brought up from the surface, and now at a temperature of 58.4°, will weigh more than the air at 59° beside it, and hence it will tend

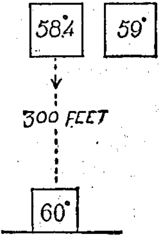


FIG. 1.

to sink; and it must sink all the way down to its original level before it finds any air as heavy as itself. In this imaginary experiment we have disturbed the arrangement of the normal, quiet atmosphere; and the disturbed mass returns to its original position as soon as freed from the constraining force. Such an atmosphere is therefore in a condition of stable equilibrium, like a rod hung by its upper end, which is opposed to any change in its position, and, when displaced, tends to return to its original attitude.

Evidently, when a whirlwind springs up in the calm air of a desert, as is so often the case, the atmosphere cannot possess this normal stability: for then there would be no temptation to any such disturbance; the air would prefer to stand as it is. Before the whirlwind can arise, there must have been a change to a condition of unstable equilibrium, in which the air, like a rod balanced on its lower end, is ready to move on small provocation; and we have now to look for the cause of this change. To be guided properly in the search, the conditions necessary and antecedent to the formation of the whirls must be examined. They are, that the whirls occur generally in level, barren, warm regions, in quiet air, and only in the daytime after the sun has risen high enough to warm the sandy ground, and the air next to it, to a rather high temperature. As the first and second of these conditions may be present at night as well as by day, it must, without doubt, be the heat from the sun that disturbs the quiet equilibrium into which the air tends to settle, and, by warming the lower layers, causes a departure from the ordinary stable condition of rest.

Let a case be supposed: the sun has warmed the lower air of the first example to a temperature of 90° (fig. 2), while the air three hundred feet above the desert sands has, in virtue of its diathermance, risen only to 70°; so that there is now a difference of twenty degrees between these two layers. If we here repeat the experiment of carrying a block of surface-air to a height of three hundred feet, it is again mechanically cooled 1.6°, so that its temperature is reduced to 88.4°; and now, comparing it with an equal volume of adjoining air at 70°, the latter is evidently the heavier, and therefore the block of air brought up from the surface, instead of tending to sink, as in the first case, tends strongly to rise farther, and continue the motion given to it. In other words, the air is now in a condition of unstable equilibrium: it is ready to upset and re-arrange itself. The lower layer may be compared to a film of oil balanced beneath a quiet sheet of water: a little disturbance would cause the two liquids to change places, and the oil would rise

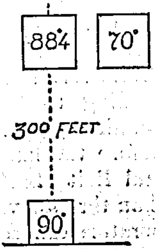


FIG. 2.

through the water, draining itself upwards. In such a condition as this, the desert-whirls may begin. It is clearly not necessary, in order to produce this result, that the vertical decrease of temperature should be as much as twenty degrees in three hundred feet, as in the case just assumed. In order to pass from the stable equilibrium, through the indifferent to the unstable equilibrium, it is sufficient, in dry air, that the vertical decrease should be greater than 1.6° in three hundred feet, or greater than one degree in one hundred and eighty-three feet. Moreover, it is important to notice that according to this theoretical explanation, the condition of indifferent equilibrium is passed before the surface-air is, as Franklin (1753) and Belt (1859) have said, specifically lighter than that above it. This would require a temperature difference of at least 5.4° F. in three hundred feet. It is sufficient that the surface-air shall be potentially lighter, though absolutely (before any motion takes place) heavier, than the higher layers, as Reye first showed (1864); or, in other words, stable equilibrium is lost, and indifferent equilibrium reached, when the surface-air is just enough warmer than any layer above it to make up for the change of temperatures produced in equalizing their densities. Any further excess of surface-warmth brings about theoretic unstable equilibrium. On the other hand, whirlwinds of decided activity will not be formed until the difference of temperature is much in excess of the narrow limits just given, the strength of the up-current increasing with its excess of warmth. Motion of the atmosphere caused by small differences of temperature would be very gentle, and would be perceived only in the 'boiling' of the air, often seen in summer-time over the brow of a hill.

It must be, then, the sun's heat, as was supposed, that destroys the normal stable equilibrium of our atmosphere; and to a disturbance of this kind we can refer more or less directly all storms, and, indeed, all winds that blow about the earth. Without the heat that is constantly showered down on us, we should soon gravitate into a lifeless condition of stable equilibrium, chemical, organic, and physical, and there remain in endless death. But the sun allows no such inactivity on its attendant planets: it keeps them alive and at work.

Action of Whirlwinds.

The further growth of the desert-whirl may be briefly described. The air standing quietly on a flat, dry surface allows the lower strata to be quickly warmed to a high temperature. If the air were in motion, no part of it would remain long enough close to the ground to be greatly warmed; if the surface were not flat, the lower air would flow up the slopes as soon as it was a little heated, and not wait to acquire a high temperature; if the surface were wet, much of the sun's heat would be occupied in evaporating the water (as will be explained below), and would so be lost to the lower air: it is therefore only in calm weather, on a desert plain, that the sun can succeed in warming the lower air to excess, and so produce a very unstable equilibrium, and a strong updraught when the upsetting begins. The longer the delay before the overturning, the more heat-energy is accumulated, and the more violent the motion when it begins. The lower air rises at some point against the oppression of the upper layers. The surrounding warm air flows in from all sides toward this central point, and follows the leader. Soon the motion becomes general and lively, dust and sand are blown along toward the centre, lifted and carried aloft with the ascending air in its rapidly rising current, and then the whirling column becomes visible. When thus established, the increased velocity and the rotary motion of the air near the centre are constant characteristics of the upsetting. Thirty or forty feet to one side, the wind may not be strong enough to brush along the sand, and a few hundred feet away it may not be perceptible; but at the centre it makes a distinct rushing or roaring sound, and carries light objects upwards, sometimes to a height of several thousand feet. This increase of velocity of the surface indraught toward the point of its upward escape is a general feature of the motion of a mass of free particles along a path of varying width: the narrower the path, the faster the motion. The same increase is seen in the growing velocity of a stream running out of a lake, so beautifully shown where the Rhone flows from Lake Geneva, or, more simply and prosaically, in the running of water from a tub by the escape-pipe. In the case of a desert-whirl, the central wind is held by friction with the surface sands much below the velocity it might attain; for it must be remembered, that these whirls are supplied by a comparatively thin layer of superheated air next to the ground, often not more than four or five feet thick. The restraint of friction on such a layer will be very considerable, and its motion can seldom reach a disastrous strength. It is probable that in the desert sand-storms, which are described as overwhelming caravans, there is a much thicker mass of air in activity, and the conditions of motion approach those of the tornado, as will be shown farther on.

The second characteristic feature of the wind's motion gives name to the storm. A whirl must necessarily be formed when the air moves inwards from all sides towards a centre, for the indraughts will surely fail to follow precisely radial lines. Their aim will be a little inexact; and, as they pass to one side or the other of the centre, a turning must begin in a direction determined by the strongest current. This, once begun, is maintained by the centrifugal force that arises from it; and the size of the central whirl will then depend on the balance between the centripetal and centrifugal forces. In ascending at the centre, the wind follows an upward spiral course, like the thread of a screw of steep pitch, with a diameter of five to twenty feet. The direction of turning is indifferently one way or the other, according to the side on which the indraught happens to pass the centre. The height to which the whirling column rises will be determined by its mixture with the adjoining air, and consequent cooling until its temperature is that of indifferent equilibrium; and at this elevation the current will turn and spread laterally to make room for that which follows. Such a whirl will continue as long as its cause lasts; that is, as long as it is supplied with warm air at the base. Manifestly it must stop in the afternoon, as the sun's heat decreases; and it can never occur at night, for then the surface-air is, as a rule, cooler than that above, and the atmospheric equilibrium is correspondingly stable. Further, the whirl will remain at one place, unless, as is often the case, it is carried along by a general motion of the upper air.

There is a very strong point of evidence, if any be needed, in favor of the view that heat applied to the lower layers of the air will produce a whirlwind. This is the fact of their production over fires. Much interest was excited in this question in connection with the artificial causing of rain, some forty years ago, in this country; and observations were carefully made of the whirls formed over burning woods

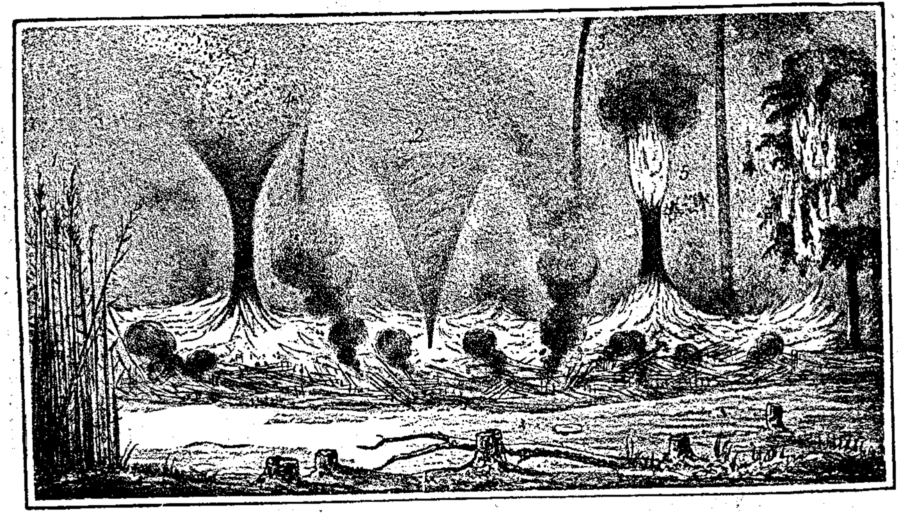


FIG. 3. (Taken from *Amer. journ. sc.*, 1851.)

and canebrakes, showing them to be very similar in form and action to those naturally arising on dry plains (fig. 3). Similar whirls have been seen over volcanoes (fig. 4); and on a calm day the smoke ascending from a factory

FIG. 4. (Taken from *Abhandl. gesellsch. wiss. Gött.*)

chimney may be seen to have a slow rotary motion. Heat is therefore an amply sufficient cause of such disturbances. No other excitement is needed, and electricity has no essential part to play. In recognizing this, we see the chief difference between the older and newer theories of storms.

Sand-whirls are common in all desert or dry regions, where they often have the name of spirits or devils, from the fantastic and apparently evil way in which they flit across the burning sands. They have neither clouds nor rain. When well and frequently developed, they may grow to dangerous strength, and lift much dust and sand into the upper air, where it is blown long distances before falling. In this way they serve as important geologic agents. Vessels west of the Sahara, or east of China, are thus often powdered over with fine dust slowly settling down after a long flight from its desert source.

The smaller water-spouts, doubtless, belong near here in our scheme of classification; but as they are usually aided by vapor-energy, and approach the character of tornadoes, their consideration is best deferred till later.

Finally, before going on to the larger storms, one point of much importance must be emphasized. The change from the stable equilibrium of night and early morning to the unstable of noon is effected entirely by the sun's heat, which warms the lower air, and causes it to expand. In expanding, it lifts all the upper air that rests on it; and this is no small piece of work, for the air that is lifted weighs about a ton over every square foot. When a point of escape is found, the heavy upper air sinks again, as the expanded air is drained off (upwards) at the centre. It is this gravitative force of the sinking air-mass that causes the dust-whirlwind, in re-arranging the disturbed equilibrium of the atmosphere; but gravity would have no chance to show its strength, if the air had not been lifted by energy from the sun. The winds of a dust-storm, therefore, depend on gravitative force brought into play by the sun's heat. All storms and all winds have more or less closely this relation to solar energy and terrestrial gravity.

Tropical Cyclones.

We may now pass on from the small daytime whirls of dry air to the larger, long-enduring storms that are accompanied by rain; and here will be met two new elements, — the effect of condensing vapor, and the effect of the earth's rotation, — both of great importance. As a sample under this second heading, we may take one of the cyclones of the Bay of Bengal; for the storms there are very characteristic of their class, and have of late years received much careful attention. There is good reason for thinking that these cyclones generally spring up in calms, much as the desert-whirls begin. The seasons and regions of their occurrence both point to that conclusion; for tropical cyclones seem never to begin in well-established wind-currents, but rather in a place of quiet, weak, or variable winds. By India, for example, the cyclones are almost unknown during the prevalence of the steady blowing monsoons, but are not uncommon at those seasons when the monsoons change; that is, at times when the air has no well-established motion, but stands about idly, waiting for a decisive command to move on. During these idle times of stagnation, the lower air may become very warm and moist, and so prepare for a stormy overturning. The calm that precedes a cyclone often makes part of the description of a storm at sea: the air is close and oppressively warm; the water settles down to a glassy surface; and now we may see, what is not always clearly expressed, that this calmness of the water, and oppressive heat of the air, are not antecedent effects of the coming storm, but are actually the conditions that allow and determine the beginning of a storm. The warmer the air and the quieter the water, the longer must have been the preparatory stage; the greater the quantity of solar energy collected in the lower atmosphere, the more violent will be the storm when it begins. This warm calm is really the embryo of the cyclone; and, if it lie long enough in a proper latitude, it will grow to well-developed maturity.

It is often stated that tropical oceanic cyclones begin at the meeting of two opposite currents of air rather than at a time of calm. This may be true for some cases, and undoubtedly has a very general application in temperate latitudes; but it seems more probable that in the Bengal cyclones, and most other tropical hurricanes, this stage is a little later than the earliest beginning, and is really the first development of the inblowing winds. A general calm would doubtless be found to precede such opposed currents if observation could trace the antecedent conditions a little farther back than is usually possible. The principal contrasts between the desert-whirls and the Bengal cyclones, at the time of their beginning, may be thus summarized: —

First, The area and uniformity of the surface on which the disturbance is developed is much greater on the ocean than on the desert.

Second, There is a lower temperature, but a much greater amount of heat, surface for surface, in the cyclone's embryo, than in the whirlwind's. The temperature of the air over the ocean seldom exceeds 95°: over the desert sands it may often rise to 140° or 150° close to the ground. But on the desert the stratum of air that is so excessively warmed is very thin; it often fails to reach the height of a man's eye, and so gives the appearance of a mirage: while over the sea, although the lower stratum is not so warm, its thickness is greater, and there is more of it warmed. What it lacks in temperature it more than makes up in quantity.

Third, The presence of water-vapor over the ocean makes a most important contrast between the two cases; and it is on this account that the warm sea-air is cooler than the hot desert-air. Water-vapor is not nearly so diathermous as dry air. Much of the heat that would pass down to the sand on the desert is held back by the vapor over the ocean, and some is caught again from the heat radiated upwards by the water, so that a considerable thickness of air is warmed. Of still more importance is the action of vapor as a great storehouse of solar energy, required in the process of its evaporation, generally known as 'latent heat.' For all these reasons, the accumulation of energy in the preparation for an oceanic cyclone is vastly greater than in the making ready for a desert-whirl.

The beginning of the upsetting in a tropical cyclone is not fully accounted for by observation. It is not so easily explained as the first uprising on the desert, inasmuch as the ocean's calm surface is too smooth to offer any distinct starting-point for the up-draught. There are, however, several plausible ways out of the difficulty. It is possible that localized warmth and expansion where the air is calmest may produce a gentle up-current, which, once begun, will be soon well established. Again: an excess of evaporation will cause a rapid upward diffusion of vapor. It will reach an altitude where it must condense, and form a cloud-layer, and thereby warm the surrounding air both by its latent heat and by catching the warmth of the sun's rays; and, as this will go on at a considerable altitude, it will be especially effective. Finally, if after a time of calm a breeze should opportunely penetrate the district from an adjoining one of higher pressure, an ascending current would surely be started. In some such way a gradual overturning of the unbalanced air must begin, and its further action is now to be traced.

The rising mass expands as it escapes from the pressure of the air that it leaves below, and in expanding it is mechanically cooled. As it cools, some of the vapor with which it is well charged condenses into cloud, and, on accumulating, soon begins to fall as rain. Here we have the entrance of a new and potent cause of disturbance, — the bringing-forth of a great amount of energy in the form of heat from the condensation of the vapor. It is probable that this aid to the up-draught seldom takes the initiative: it waits till some other cause begins the upsetting, and then falls to with a will to help it along.

Action of Water-Vapor in Cyclones.

This effect of condensation is so important that it may well be considered a little more closely. As water evaporates, its molecules are spread widely apart, and take on a very active motion; but in doing so they must be furnished with energy in some form, for they cannot develop out of nothing the energy needed for their increased activity. As a general rule, the desired supply is found in the sun's radiant heat: so, when water evaporates from the sea-surface, it takes to itself nearly all the energy that comes down in the sun's rays, and thereby its molecules are enlivened up to the point of vaporization. It will be readily understood, that, if heat-energy be taken by the water and transformed into vapor-energy, it can no longer make itself felt as heat; and, so far as our senses are concerned, it is lost or hidden, and for this reason is called 'latent heat.' The term is misleading and improper, for it implies that the sun's energy still remains somewhere in the vapor as a kind of heat that we cannot feel; but this is wrong, for as heat it no longer exists. It will be further seen, that, when the vapor is condensed back again into water, all its vapor energy must take some other form: it must abandon the vapor molecules, and allow them to quiet down and approach one another as they resume the liquid condition; and the energy thus thrown out of employment must make itself felt in some other way. We are therefore prepared to find that condensation is attended with the production of just as much heat-energy as was lost in the process of evaporation. This is of capital importance in the understanding of storms.

It has already been seen, that the cause of continued action in a desert-whirl is found in the excessive warmth of the lower strata; in virtue of which the air in the ascending column finds itself warmer, and hence lighter, than the surrounding air, and consequently is impelled to rise as oil rises through water. It was further noted, that the ascending whirl will continue as long as it is supplied with excessively warm air at the base; but, as soon as the bottom air is not more than 1.6° warmer than the air three hundred feet above it, the whirl will die away. In the case of an ascending column of air saturated with vapor, it would also, as in the previous case, expand as it rose to higher levels of less pressure, and, in consequence of this expansion, it would cool. But when saturated air is cooled, some of its vapor must condense; and when vapor condenses, heat is evolved; and the heat thus produced will partly make up for the loss of heat by expansion, and therefore the ascending column of moist air will not be allowed to cool so fast as if it had not been saturated with vapor. Several important consequences now follow. In the first place, a less warming at the base is needed to produce unstable equilibrium in saturated than in dry air. In the latter, the turning-point is reached when there is a difference of 1.6° F. between the temperatures of the surface-air and that three hundred feet above. In the former, if the surface-temperature be 80°, as is common in the Bay of Bengal, a difference of only 0.6° is required. In other words, if a mass of dry air at 80° rise three hundred feet, its temperature falls to 78.4°: if a mass of saturated air at the same temperature (fig. 5) rise through the same distance, it is cooled only to 79.4°; and consequently, for every three hundred feet of ascent it has an advantage over dry air of one degree of warmth (and more at great altitudes), tending to make it lighter than its surroundings, and so intensifying its upward motion.

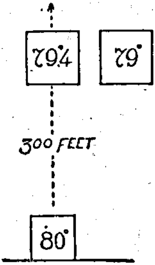


FIG. 5.

Moreover, a storm which is thus nourished may continue its activity through the night, instead of dying away as the sun declines; for it is supplied with energy continually brought out of the vapor storehouse. Of course, in both cases the sun's heat is the source of the disturbance; but on the desert there is no way of storing up the heat, while at sea a great amount of energy may be stored up before the final upsetting begins, and then the storm-winds arise, and show all this accumulated strength in their blowing.

We have much this kind of action, in a small way, in the formation of a heavy cumulus-cloud on a quiet, hot summer day. The air on the ground is warmed, and contains a good share of moisture; and, as it rises and cools, its vapor begins to be condensed. Some of the vapor-energy is given out as heat, and so the ascending current is re-enforced. If the air be very warm or very moist, or both, the ordinary cumulus-cloud may grow into a thunder-shower; and, being then unable to carry up all its condensed vapor, some of it falls as rain. It should be noted, that, when the lower air is not fully saturated, its temperature must be somewhat reduced to bring it to the point of saturation before any cloud is formed. This decrease is mechanically effected at the rate of 1.6° every three hundred feet, by the expansion of the rising air,—essentially the same rate as that already given for the cooling of a rising column of dry air; and, when enough cooling has been thus effected to reduce the air to its temperature of saturation, some of the vapor will be condensed into liquid cloud-particles, and so become visible. It is for this reason that cumulus-clouds have nearly level bases, and that a group of such clouds stands at about the same altitude. The air-currents rising from the warm ground have to ascend a certain distance, and cool a certain number of degrees, before condensation takes place. Their altitude in feet will be about a hundred and eighty-three times the number of degrees between the temperature of the lower air and its dew-point.

All tropical cyclones are attended by clouds and by excessively heavy rain; and this points very clearly to the important part played by the heat evolved in the condensation of so much vapor. The rapid reproduction of the heat stored up through many previous days of sunshine retards the cooling of the ascending current, excites the winds to active motion, and the storm is thus set going. Espy (1835) was the first to recognize the important part played by the condensing vapor in an ascending current of air, but he greatly exaggerated its effects. The proper measure of its action, and convenient statement of the results in tabular form, are chiefly due to Reye (1864) and Hann (1874).

Barometric Gradients.

The ascending current moves outward at a height of one or two miles, spreading itself over the surrounding atmosphere. To show its relation to the storm circulation, we may refer to the following figures. Fig. 6 shows the air in a quiescent state, before the storm begins. At such a time, there being no wind, the weight of the air, or the barometric pressure at sea-level,—say, 30 inches,—is uniform throughout the area preparing for cyclonic disturbance. The pressure is uniform, not only at the sea-surface, but also at any given altitude above it (the effect of the upper winds is here omitted as not being essential to the explanation, as well as unknown) ; so that the lines in the figure will represent level surfaces of equal pressure of 28, 26, 24 inches, or isobaric planes at altitudes of about 1,600, 3,300, and 5,000 feet. As long as the vertical gravitative pressure is at right angles to these planes, the air is not tempted to move, but will remain at rest

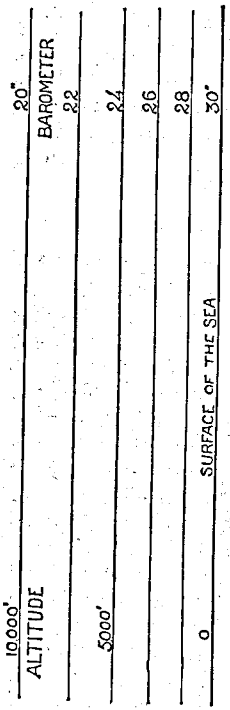
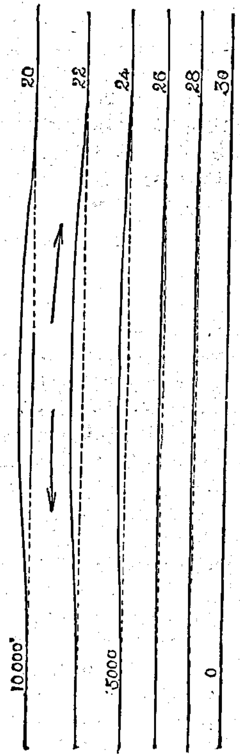

20"
BAROMETER
22
24
26
28
30"
SURFACE OF THE SEA
10000'
ALTITUDE
5000'
0

Fig. 6.


20
22
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10000'
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Fig. 7.

till disturbed by some new condition. This new condition will be some form of the disturbing actions already suggested, by which a central region of greatest warmth is determined, in consequence of which there will be an expansion of the atmosphere at that place. The isobaric planes will become convex there, as in fig. 7; for the altitudes at which barometric pressures of 28, 26, 24 inches are found must now be greater than before. As there has been, as yet, no lateral motion, this produces no change in the pressure at sea-level. But a reason for lateral motion has now appeared: the gravitative pressure of the upper air is no longer at right angles to the convex isobaric surfaces, and consequently there will be a tendency for the air to slide down from the centre. In obedience to this impulse, some of the central expanded air moves laterally or radially outward to the marginal region; and now there is no longer a uniform pressure of 30 inches at sea-level. At the centre, whence the upper air has rolled away, the pressure will be reduced, let us say, to 29 inches: on the surrounding district, over which the air has advanced, the pressure has increased to 30.25 inches. In this new arrangement of pressures there is cause for still further gravitative motion; namely, a rising of the air at the centre, a sinking at the marginal region, and a horizontal motion along the sea-surface, toward the centre of low pressure, in the attempt to restore an equilibrium. But this will not fully overcome the inequality of pressures, or correct the sloping of the isobars; for the existence of an ascending and expanding warm current at the centre requires that the isobaric surfaces there shall be separated by a greater vertical distance than in the normal cooler air of fig. 6. Further, the marginal descending current of air, greatly cooled by radiation in the upper regions, is heavier, volume for volume, than the ascending current, and hence has its isobaric surfaces closer together than usual. A shorter vertical column of it is needed to balance an inch of mercury in the barometer. Fig. 8 shows this final condition,—the diminished pressure and greater separation of the isobaric lines at the warm centre; the increased pressure and the approach of the isobaric lines in the cooler margin. Now, in virtue of the greater distance between the isobars at the centre, the altitude of some surface, say that of 24 inches, will be as great there as over the marginal region, in spite of the inequalities of pressure and inward slope of the isobars at sea-level; and at greater altitudes the isobaric surfaces will become convex, and hence slope outwards, instead of inwards, as below. The two directions of slope will be separated by a level or neutral plane, on which there will be no tendency to motion. Here we have excellent illustration of the convectional motion of the wind in a storm. It ascends at the centre, where it is lightest; it then flows outward, down the barometric gradient; it sinks at the marginal

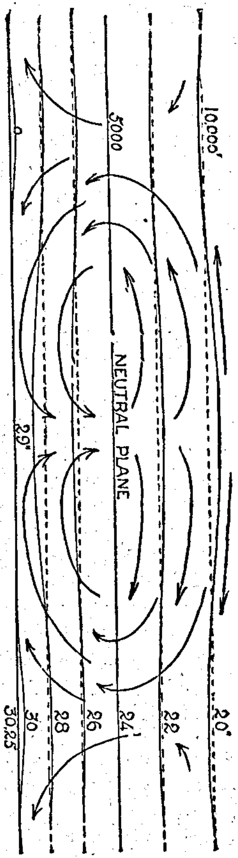


FIG. 8.

region of higher pressure, and then flows inward, down the reversed gradient, back to the centre again. This may be called the vertical circulation of the storm; and it will be continued as long as the central current is warmed to excess, so as to raise its isobaric surfaces. In the desert-whirlwind we have seen that the supply of warm air depends immediately upon contact with the surface-sands heated by direct sunshine. In the cyclone at sea, the greatest part of the warmth needed is given out by the vapor that condenses at the centre, and falls in the heavy rains, without which a cyclone cannot form. Such a storm may last many days.

The explanations thus far given of the beginning of a cyclone apply strictly only to the hurricanes of tropical latitudes; for in the temperate zones our numerous storms are by no means always dependent on local warmth and calmness of the air. The most that can now be safely said of the origin of such storms is, that they depend on some immediately preceding disturbance, somewhat as one water-wave depends on another; for no one has yet been able to trace one of our storms so far back as to show it quite independent of previous storms, as seems to be the case with the tropical cyclones. In the irregular blowing of the winds of higher latitudes, for which no full explanation can be given, too much air is accumulated in certain districts, which then appear as regions of high pressure. In seeking a better balanced re-arrangement, surface-currents are established with a rotary deflection, as explained below, toward intermediate areas of lower pressure; and an up-draught is formed at their meeting. This becomes a storm-centre. It might be said that friction would soon cause all these local disturbances to cease, and atmospheric pressure would then remain more uniform. So it might, if the air were dry; but the condensation of vapor, by which the cooling of the ascending current is retarded, brings out a new supply of energy every time an up-current is established; and thus the disturbed condition of the atmosphere is maintained. It cannot settle down into a condition of equilibrium as long as the sun shines, and water evaporates. Some maintain that it is unlikely that the storms of the torrid and temperate zones should have different causes, and that as temperate storms certainly do not, as a rule, arise in a warm calm, tropical storms cannot have such an origin. But as already stated, and as will be further shown, the regions and seasons of tropical cyclones point very conclusively to this origin; and, moreover, it is not necessary that similar results should have identical causes. All the peculiarities of a rotary storm can be satisfactorily explained from either starting-point. And the essential contrast between the two cases is, that in one, differences of temperature precede and bring about differences of pressure, and, in the other, differences of pressure precede and bring about differences of temperature; so that, in both cases, the established storm differs in temperature and pressure from the surrounding atmosphere: and, once established, the motions of rotation and translation, yet to be described, are closely alike in the two cases.

Effect of the Earth's Rotation.

Cyclonic circulation has thus far been described as if it were effected in radial lines in to and out from the centre; but here, as in the whirlwind, perfect radial motion is impossible. A horizontal rotary motion would soon be established near the centre by the inequality of the inblowing winds. It is found, however, that all storms yet studied turn from right to left in the northern hemisphere, and from left to right in the southern (fig. 9). Such constancy points to something more regular than the accidental strength of the winds,—to some cause that shall always turn the indraughts to the right of the centre as they run in towards it in the northern hemisphere, and to the left in the southern hemisphere; and this cause is found in the rotation of the earth on its axis.

There is a force arising from the earth's rotation that tends to deflect all motions in the northern hemisphere to the right, and in the southern to the left; and this deflecting force varies with the latitude, being nothing at the equator, and greatest at the poles. It may be found that this statement differs from that generally made; namely, that moving bodies are deflected only when moving north or south, and not at all when moving east or west: for it is thus that Hadley (1735) and Dove (1835) explained the oblique motion of trade-winds, and that Herschel and others explained the rotation of storms. But this is both incorrect and incomplete; for a body moving eastward is deflected as well as when moving northward, and the actual deflective force is greater than that accounted for in Hadley's explanation.

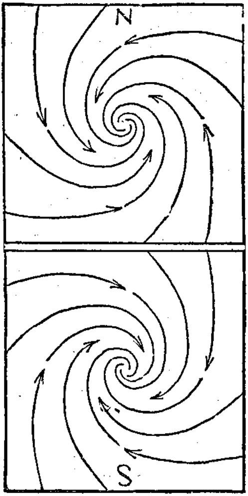


Fig. 9.

It is this deflective force, acting on winds from all sides, as was first shown by Tracy (1843), that combines with the centripetal tendency of the surface-winds to give rise to the inward spiral blowing of the storm (fig. 10), — a constant feature of all cyclones.

Analysis of Forces in Cyclones.

In all hurricanes, the winds greatly increase in strength as they near the centre of the storm, and at the same time their path becomes more nearly circular. A cause of this was briefly stated for the whirlwinds: but it now must be more fully analyzed; and it will be best to begin the attempt by resolving the motion of the wind

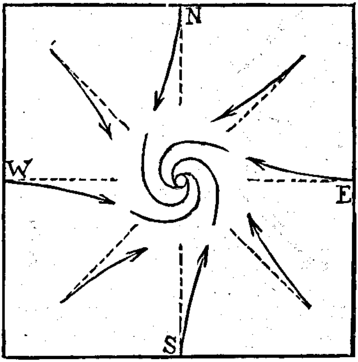


FIG. 10.

at any point of its spiral track into two rectangular components (fig. 11), — one, along a radius toward the centre, *P R*, the centripetal component; the other, circular or tangential, *P T*. Only the first of these comes directly from the convectional circulation, already described as depending on the central warmth; and this one would never produce winds of devastating strength. The second, or tangential, arises first from the deflective force of the earth's turning. The higher the latitude, the less the friction at the bottom of the atmosphere, and the greater the distance from which the wind is derived, then the greater its right-handed departure from a radial path. Hence in a large storm at sea, where the friction is small, and the indraught has its source several hundred or even a thousand miles away from the centre of low pressure, the deflective tangential component becomes very considerable, and may, near the centre, outrank the centripetal.

But there is another and even more important cause of growth in the circular element of the wind's motion; namely, the increase of its rotary velocity as the radius of rotation decreases, in accordance with the very important law of the 'preservation of areas.' Let us suppose, that, when at a distance of five hundred miles from the centre, the inblowing wind has been turned to the right of its radial path by the earth's deflective force so as to have the moderate tangential or rotary velocity of one mile an hour; and, disregarding the further effects of deflection, let us consider the consequences of gradually drawing this mass of air towards the centre. The product of its

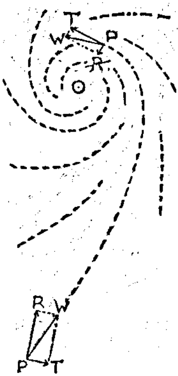


FIG. 11.

radius and its rotary velocity must remain constant; and hence, as the radius is diminished, the velocity must increase, one quantity varying inversely as the other. The wind has no visible, material connection with the storm-centre; but it is slowly moving around that centre, under the control of central forces, derived from differences of temperature and pressure, that drive it inwards, or, in other words, shorten its radius of rotation: and consequently, when, in the case supposed, the radius has been diminished to five miles, the velocity must have been accelerated to one hundred miles an hour, — a violent hurricane-wind. The recognition of this important factor of the storm's strength goes back to Redfield. The theoretical increase of velocity thus provided is never fully realized, for much motion is overcome by friction; but enough is preserved, especially in tropical storms, to give them the greatest share of their destructive strength. The total tangential component of the wind at any point must therefore be considered as the sum of the deflective and accelerative forces, minus the loss by friction. Near the storm-centre, where the velocity of the wind is very great, this tangential component is much greater than the centripetal, and the spiral path becomes almost circular; while the reverse relation holds for the outer part of the storm.

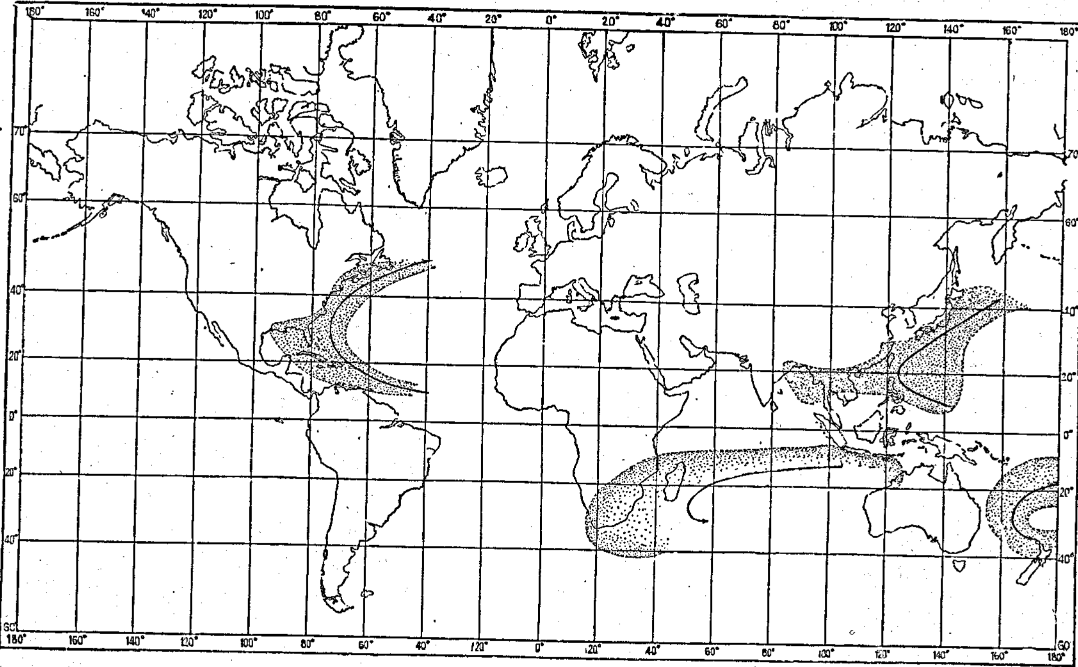
It will be easily understood, that a considerable centrifugal force will be developed by the rapid central rotations, as well as by the earth's deflective force; and, as a consequence, the centripetal force will be partly neutralized, and the winds will be held out from the centre. This must increase the depression already produced there by expansion and overflow; and, as a matter of fact, the low pressure of a storm-centre, especially in tropical latitudes, is chiefly the effect of this dynamic, and not of the earlier named static cause. But so long as the wind maintains its rapid motion, the additional depression is powerless to draw it towards the centre. Only when its velocity is decreased by friction does the barometric gradient, just before produced by the centrifugal force, urge the wind inwards to the middle of the storm. The additional gradient, therefore, represents potential energy, derived from the actual energy of the rotating winds, and all ready to be transformed into actual energy again as soon as friction has destroyed some of the velocity of rotation.

The general interaction of the storm-forces may now be thus summarized: in obedience to a centripetal tendency, produced by differences of temperature or of pressure, or both, the air moves along the surface to the region of low pressure. On its way, the deflective force arising from the earth's rotation turns it continually to one side, and so gives it a more and more nearly circular path; and, in addition to this, its rotary velocity increases as much as its radius of rotation decreases: the tangential component of its spiral motion must therefore continually increase. With the increase of this component, and the decrease of the radius of rotation, the centrifugal force ($v^2 \div r$) must increase rapidly, and soon come to equal and counterbalance the original centripetal force; and at the same time greatly increase the barometric gradients. At this point the wind would blow in a circular path, were it not that friction with the sea or ground is continually consuming some of its velocity, and thus decreasing its centrifugal force, and allowing the potential energy of the steep barometric gradient to produce centripetal motion. This decreases its radius, and at once gives it new life, again to be partly destroyed and renewed as before. Absolutely circular motion can therefore never be attained, although it is approached very closely near the centre. At sea, where friction is small, and in tropical latitudes, where the strength of the storm is great, the wind is unable to reach the storm-centre; for, when the distance from the centre is reduced to only five or ten miles, the centrifugal force is so great, and the wind's course is so nearly circular, that it is carried aloft by the up-draught before it can enter noticeably farther: the central area is therefore left unprovided with violent winds, and is generally a comparative calm, known as the 'eye of the storm,' of which there will be more to say later. The general form of the storm-wind's spiral can be deduced from the preceding considerations. The angle between the tangential component and the actual path of the wind, which is called the inclination (fig. 11.), will vary with the relation of the circular and centripetal elements of the wind's motion; the tangent of the inclination will equal the radial divided by the tangential component: hence in the outer part of the storm the inclination will be large, and the wind will blow almost directly toward the storm-centre; but nearer the centre the inclination will become smaller and smaller, and the wind will blow in a more and more nearly circular path. It will also be understood, that the upper winds, less influenced by friction, will, near the centre, have a greater velocity and a less inclination than the lower ones. Moreover, the inward gradient which they produce will be effective and important in urging along the slower surface-winds, in a manner better illustrated in a tornado, where this action will be more fully described.

Progression of Cyclones.

Having seen how storms arise, and examined the general motions of their spiral winds, we must next consider their progression from place to place. It is now a familiar fact, that storms do not remain stationary, but advance at a velocity of from five to fifty miles an hour along a line known as their track. Although perceived by Franklin about 1750, this, as well as their whirling motion, first found full and satisfactory proof at the hands of Dove of Berlin (1828), and Redfield of New York (1831). The latter gave the more numerous examples, and was the first to explain the motions of storm-winds at sea. The method of his discovery was simple enough. Information concerning the storm was gathered from all attainable records, and the condition of the winds and weather was plotted for certain hours. At once the result stood clearly forth. The apparently lawless winds of a storm could be reduced to system if they were supposed to blow around a centre which itself has a progressive motion. In nearing the centre, the barometer falls, and the winds increase their strength. The manner and cause of the progressive motion must now be examined.

The four regions where tropical storms move into temperate latitudes — the seas south and east of India and China, and south-east of the United States, in the northern hemisphere; and those east of Madagascar and (probably) of Australia, in the southern hemisphere — are all crossed by storm-tracks, running first westward near the equator, then turning toward the pole, and passing around the apex of a parabolic curve near latitude 30°, into an obliquely eastward course. The more numerous storms of temperate latitudes have less regular tracks, but are nearly always characterized by a strong eastward element in their motion; their chief variations to the right or left being dependent on thermal changes with the seasons, and on



THE REGIONS OF TROPICAL CYCLONES. (TAKEN FROM STIELER'S ATLAS.)

the configuration of land and water which they traverse. There have been four causes suggested to determine the progression of the storm-centre: namely, the general winds of the region, and especially the stronger and less variable upper currents; the supply of warm, moist air, and consequent occurrence of heavy rain; the relative strength of the inblowing winds; and a certain effect of the earth's rotation. All these causes of progression are variable in amount, and in relation to one another; and it is therefore natural to find their resultant inconstant.

The first-named cause is the most evident, the most powerful, and was the first recognized. The general or planetary circulation of the winds will require that any disturbance in the moving atmosphere shall partake of its motion, and be carried along in the direction of the current within which it is generated. Thus a storm arising in the equatorial calms is carried westward as soon as it attains sufficient height to reach the upper current, which must there move from east to west. No equatorial cyclone has ever been observed moving eastward. On approaching the western shores of the ocean, a part, at least, of the general winds, turns toward the poles, as may be seen on any wind-chart, and in latitude 25° or 30° passes from the region of the tropical winds into the system of the prevailing westerly winds of temperate latitudes. The storms have a strikingly similar course, and, on the western side of the oceans in these latitudes, never move towards the equator. Their farther progress, and that of the many storms of the temperate zones, is easterly, with a leaning towards the pole while crossing the oceans, and a variable north-easterly or south-easterly advance on the continents. No storm has been found crossing the North Atlantic from east to west, or moving from our Atlantic coast to the plains beyond the Mississippi. Additional evidence of this style of bodily transferrence of storms will be given in considering the relative strength and the direction of their spiral winds on different sides of the centre.

Effect of Rain.

The importance of the condensation of vapor and consequent rainfall in decreasing the cooling of the central up-draught, and so increasing its strength, has already been shown. In the explanation of this process, it was tacitly assumed that all the surface-indraught was equally warm and moist, so that condensation and rain would occur symmetrically about the centre of low pressure. It will now be seen, that, when a storm-centre is supplied from areas of unequal warmth and moisture, symmetrical cloud-forming and rain-falling on all sides will be impossible; there will be more rain, and hence less cooling, on one side than on the other; and just as the liberation of 'latent heat' aided in the formation of the first central barometric depression, so it will now tend to displace this centre to the side where the greatest amount of rain falls. If no other cause but this acted, the storm would advance regularly toward the region of heaviest precipitation: but this advance will not be like the bodily transferrence of the rotating winds effected by the general atmospheric currents; it will be rather the abandoning of one centre of attraction as a stronger one is created beside it, — the continual filling-up of one depression, and production of another. This may be illustrated by a modification of fig. 8, given here in fig. 12, in which the dotted lines show the gradients and winds established at a certain period of the storm. Let it be supposed that warmer, moister winds enter on the right, and cooler, drier winds, on the left. Where cooler, the air will be contracted, and the isobaric surfaces depressed: where warmer, from its own warmth, as well as from that of the condensing vapor, the air will be expanded, and the isobars elevated, as shown in full lines in the figure. The gradients will then be unsymmetrical about the original centre; and the previous motion of the winds will be accelerated at some points, retarded or reversed at others. As a result, the pressures at the surface will be changed from their previous arrangement to a new one, shown in fig. 13, in which the region of least pressure has moved to the side of the warmer winds and heavier rains. Any further inflow of the surrounding air must

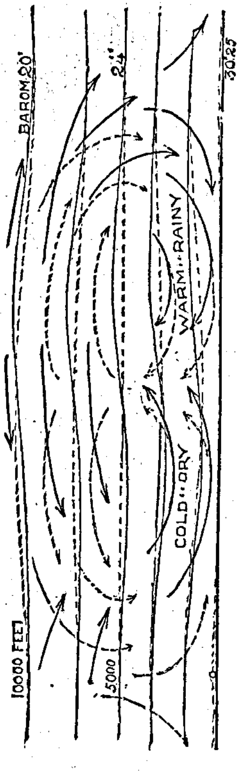

BAROM. 20'
24
30.25
WARM · RAINY
COLD · DRY
10000 FEET
5000
0

FIG. 12.


20'
24
10000
5000
0

FIG. 13.

now be to the new low-pressure centre: in other words, the storm has advanced to the right. The process will be continuous as long as the winds on opposite sides of the storm are unlike.[1] Having thus seen the general action of this cause of motion, it must now be applied more directly. There are two causes of rain in a cyclonic storm, — one from the expansion and cooling of the moist air as it enters the district of low pressure, and rises in the central up-draught; the other from the advance of the wind from a warmer into a cooler region. The first of these will generally be nearly symmetrical about the storm-centre, and hence not productive of any progressive motion: the second will as generally be unsymmetrical. In fig. 14, for the northern hemisphere, the parallel lines represent normal east and west isotherms, showing the usual decrease of temperature to the north. Of the several winds blowing inward to the storm-centre, those which advance almost along the same isotherm will not be seriously changed in temperature by their change of place; others, which come from a cooler to a

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[1] Fig. 12 may serve further to explain the retarded arrival of the centre of low pressure at altitudes of a mile or more above the surface. Observations on Mount Washington have shown the centre of low pressure there to be about two hundred miles behind that at sea level (Loomis), and a similar retardation has been inferred in England from observations of cirrus-clouds (Ley). Fig. 12 shows this to be directly connected with rainfall; for, in this unsymmetrical storm, the former horizontal neutral plane is distorted, so that the centre of low pressure in the upper air is clearly behind, instead of vertically above, the centre on the surface of the earth.

warmer district, will consequently increase in capacity for moisture, and be clear, cold, drying winds; but the south winds will be chilled, and must produce clouds and rain somewhere about the shaded part of the figure; and the storm-centre will then be transferred toward the middle of this rainy district.

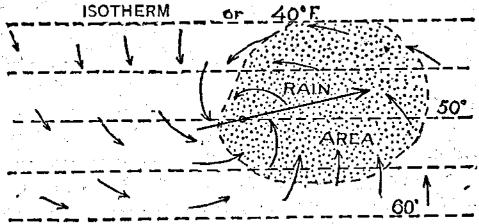


FIG. 14.

Standing on the warm side of the storm, the centre will appear to move nearly along the isotherms to the right. Actual isotherms seldom follow lines of latitude, and always vary their position with the seasons, especially along continental borders. Thus, over western Europe and the eastern margin of the Atlantic, the summer isotherms run to the north-east: so do the storms. In winter the isotherms run south-eastward, and the storms turn in the same direction. Figs. 15 and 16, illustrating this change, are based on diagrams in the 'Laws of the winds,' by Ley, who first, some fifteen years ago, called attention to the control of rain over storm-tracks. It should be noted that the change in the winter and summer prevalent winds would

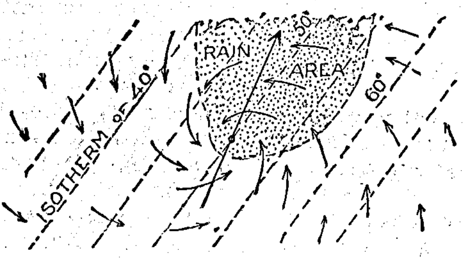


Fig. 15.

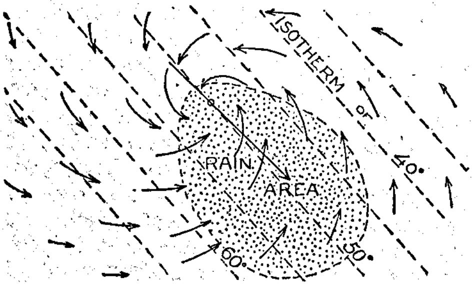


Fig. 16.

have a similar effect on the courses of European storms. In the United States, Professor Loomis has shown that the velocity, as well as the direction of advance, is closely dependent on the position and amount of the rain. In tropical storms the action of this cause of progression is not so clearly marked; for all the winds are moist, and almost equally warm. It is reported that the rainy area often extends farthest ahead of the storm; but it is not at once apparent why it should, for the front of the storm is occupied by winds from the north, which come from a slightly cooler latitude. It may be suggested, that, as their source in a region of high pressure (the 'horse latitudes') causes them to move faster, it also, probably, allows them a greater expansion and cooling, on entering the storm-area, than is permitted in the winds that come more slowly from the equatorial region of low pressure; but tropical storms probably depend chiefly on the prevalent winds for their direction and rate of advance. In Austria none of the winds are very moist, and the rainy area has no definite relation to the advance of the storm: hence here, also, other causes than rain determine the general easterly progression. Whatever effect rain would have is overcome by stronger causes. The separation of a cyclone into two independent storms is probably aided by the irregular distribution of rain.

Inequality in the strength of the inblowing winds is a result of irregular distribution of barometric pressure in the regions around the storm; and the stronger indraught will come from the higher pressure, because the gradients will be steepest on that side. Thus, in the case of the West India hurricanes, the higher pressure is to the north or north-east in the 'horse latitudes' above named, and the lower pressure to the south, near the equator; and the northerly winds will therefore be stronger than the southerly. The stronger the wind, the greater its centrifugal force; and, if this is not equal on all sides, the centre of lowest pressure will be drawn toward the point where it is strongest. This will be where it has to bend sharply around from its original direction, and may average about 135° from the source of the wind: hence, if the stronger wind come from the north-east, the storm-centre will move west; if from the east, north-west, as in fig. 17; and so on. Consequently, this cause will aid the first named in requiring the storm to describe a curved track in passing from the torrid to the temperate zone. It will also aid the coalescing of two neighboring storms, which has not unfrequently been observed; but, as a rule, it plays a subordinate part in determining the direction of advance. The slower advance of such of our storms as have extra strong winds on their western side (Loomis) is probably also due to this cause.

The fourth cause of a storm's advance is a peculiar effect of the deflective force arising from the earth's rotation. It has already been shown that this force increases toward the poles: it will therefore be greatest on the polar side of a cyclone; and the greater the storm's diameter, the more marked the difference between the two sides. Its effect will be to make the centrifugal force on the two sides unequal, as in the previous cause; but the resultant motion will here be always from

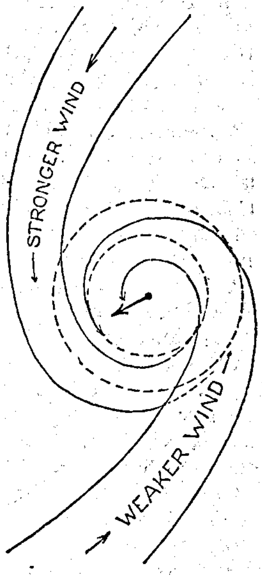


FIG. 17.

the equator. In the absence of other causes of motion, cyclones would therefore move along meridians: as it is, they nearly always have a more or less pronounced polar tendency; and their failure to move directly from the equator is due to the other causes of progression already mentioned.

Cyclonic Regions.

We are now prepared to consider and explain the actual distribution and motion of cyclones.

The limitation of violent cyclones to the ocean is natural enough: the level surface of the sea allows a great accumulation of warm, moist air before the upsetting begins, and permits the full strength of the winds to reach a very low altitude. On land the air never waits so long as it may at sea, before upsetting; it never becomes so moist; and, when in motion, the inequalities of hill and valley hold back the lower winds by friction. On land the strong part of the cyclone is relatively higher than at sea, as the records of mountain observatories show; and we know less of it.

No violent cyclones are known to have occurred within four hundred miles of the equator. Here, — where the air is warm, quiet, and heavily charged with moisture; where heavy, quiet rains are frequent; where the conditions which have been mentioned as essential for starting a cyclone are of common occurrence, — cyclones are nevertheless unknown. They occur often enough, however, in the embryonic form of thunder-showers, but they never reach the adult stage; and this must be because at the equator the deflective effect of the earth's rotation is zero, and the inrushing winds are allowed to move directly toward the low-pressure centre and fill up the depression, instead of increasing it by their deflection and their centrifugal force. From this we learn, that, while warmth and moisture may be sufficient to begin a cyclone, they alone cannot maintain it. There would be no violent cyclones if the earth stood still.

It might be inferred from this, that cyclones should increase in frequency and intensity as we recede from the equator toward the poles, for in the higher latitudes the earth's deflective force is known to increase. It is true that storms are much more frequent in high latitudes than near the equator; and this is very likely due to the greater ease with which moderate indraughts are here deflected so as to produce a central baric depression. But the more intense storms are all within thirty or thirty-five degrees of the equator; because, in more polar latitudes, the air is not warm or moist enough to co-operate effectively with the deflective forces, and produce violent winds. It has already been explained that a rising column of moist air cools more slowly than one of dry air; and on this there was shown to depend much of the greater energy of oceanic storms over that of desert whirls. It should now be added, that, of two ascending currents of saturated air, the warmer will rise much more vigorously than the cooler: hence the warm, saturated air of the tropical sea breeds hurricanes, cyclones, and typhoons of greater strength than the storms that are raised in temperate latitudes, although the latter outnumber the former on account of the more effective aid of the earth's rotative deflection at a distance from the equator.

We must next examine the cause that determines the season of cyclones, throws them near the western shores of their oceans, and requires them to move toward or parallel to the eastern coasts of the adjoining continents. This will be found to depend on the general circulation of the winds, as may be seen on examining the air-currents of the North Atlantic at the seasons of the most frequent hurricanes. Poey has compiled a list of hurricanes observed in the West Indies since 1493, amounting to three hundred and sixty-five in all; and of these, two hundred and eighty-seven, or nearly eighty per cent, occurred in July, August, September, and October. Now, these are the very months when the equatorial calms or doldrums are farthest north of the equator, and hence in a position to allow the embryonic storms to develop by the aid of the earth's deflective force. At other seasons the trade-winds extend nearer to the equator; and then, in a latitude where storms might grow if once started, the steady blowing trades prevent even the formation of an embryo. The few storms that occur at these other seasons have less evident causes: they may arise in conflicting winds, and may be fairly thrown among those unexplained effects that we call accidental. Once formed, the storm is carried along, by the general circulation and by the strong winds, toward the West Indies. On nearing them, it moves to the north-west and north, mostly because branches of the trade-winds here turn to that direction in the cyclone season, so as to avoid the mountains farther west, and to run up over the warm land of our country; partly because of the continual polar tendency, or excess of deflection on the northern side of the storm. Even if the general surface-winds do not blow along the storm-tracks, it is very probable that the upper current, returning from the equatorial calms toward the prevailing westerly winds of the temperate latitudes, follows a course closely parallel to the average of the cyclone paths; and there is good reason to believe that the upper winds have a great control over the storm's progression. If the storm should begin on the eastern side of the Atlantic, it would probably be held so near the equator by the indraught of the trade-winds that it could not reach a destructive size. The greater Atlantic hurricanes are therefore those that begin in the western part of the calms or doldrums when they are farthest from the equator, and then, passing along their curved paths, take the West Indies and our south-eastern coast on their way up into the North Atlantic. As they go, their diameter greatly increases; because they draw their wind-supply from longer distances, and because in the temperate latitudes the earth's deflective force is greater than it was in the tropics. But with this increase in diameter there comes a diminution of intensity, because the winds are cooler and contain less vapor; and finally the storm dies away when the weakened updraught at the centre fails to throw its overflow outside of the limits of the whirl. The storm is then not working its way: friction will soon cause the winds to cease, and the disturbance will come to an end.

As for the South Atlantic, it possesses no cyclone region, because the doldrums never extend south of the equator. In spite of the sun's passing to the south in winter, the heat-equator, which determines the position of the doldrums, hardly passes the geographic equator in the Atlantic; the excess of land in the northern hemisphere, and the strong general winds of the southern hemisphere, keep it back: and so the South Atlantic has no cyclones such as occur in all the other oceans. The cyclones of the Pacific and Indian oceans depend on conditions such as have been described for the North Atlantic. They are commonest in the southern hemisphere in February for the same reason that they are most frequent in the northern in the months about September.

We have now considered the origin and motions of the cyclones and hurricanes, and the regions of their occurrence. This study has its highest aim in giving timely warning of their approach and in devising rules for avoiding them. If their tracks lay over the land, the telegraph could in all cases give sufficient notice of their coming, for their motion is slow; but they are at sea during much of their life, and the questions now arise, How can the captain of a vessel gain the first intimation of their coming? and, What should he best do to avoid their dangerous centre?

Rules for Avoiding Storms at Sea.

The storm's earliest effect on the atmosphere is shown by the barometer. It is ordinarily stated that the first effect is seen in a diminution of pressure; but it is very probable, both from theory and from careful observation, that a slight abnormal increase of pressure precedes this diminution. The tropical seas, where cyclones are most violent, have, as a rule, very small and very rare irregular changes in atmospheric pressure; and careful watching will pretty surely show a rising barometer, as the annulus of high pressure that surrounds the storm (see fig. 8) moves over the observer. The weather may still be clear, and the wind moderate and from its normal quarter; but this change in the glass demands renewed watchfulness. Let us suppose that such an observation be made on board a vessel lying east of the Lesser Antilles. The chart shows the captain that he is in the stormy belt. He may be directly in the path of the advancing storm, where he will feel its full violence; and he must make the best of his way out of it. Following the rising pressure, three other signs of increasing danger may be observed, — first, faint streamers of high cirrus-clouds may be seen, slowly advancing from the south-east to the north-west, or from the east to the west, in the high overflow from the storm's centre; this unpropitious change may accompany the rising of the barometer, or may be first seen when the barometer is highest: second, the barometer begins to fall, slowly at first, but more and more quickly when it reaches and passes twenty-nine inches; the vessel is then within the limits of the storm: third, the wind has shifted so as to blow from a distinctly northern quarter, and its strength goes on increasing; this is the indraught, blowing spirally toward the centre. There is then no longer any question that a storm is approaching; and as soon as a heavy bank of clouds makes itself seen, moving southward across the eastern horizon, then the central part of the storm is in sight. These clouds are the condensed vapor in the rising central spirals, and rain is falling from them. In deciding on a course to be pursued, the first point to be determined is, where is the storm's centre? That being known, its probable path can be laid down with considerable certainty in this part of the ocean; and then, perhaps, the greatest danger may be avoided. But here a very practical difficulty arises. To find the direction of the storm-centre, we must know the incurving angle of the wind's spiral, —the angle of inward inclination that it makes with a circle whose centre is at the storm's centre. The earlier students of the question—Dove, Redfield, Reid, and Piddington—considered the course of wind to be concentric circles, or inward spirals of very gradual pitch; so that they said the inclination of the wind is practically zero, and a line at right angles to its course must be a radius leading to the centre. Later studies showed this to be incorrect. The inclination of the wind inward from the circle's tangent was found to vary from 20° to 40° or 50°: but it was thought that this inclination was symmetrical on all sides; so that, with an average inclination of 30°, the storm's centre must always bear 60° to the left of the wind's course. Finally, the most recent results seem to show that the wind's course is neither circular nor symmetrically spiral; that the wind's inclination is very distinctly different in different latitudes, on different sides of the storm, in the different conditions found on sea and land, at different distances from the centre and at different altitudes. In so complicated a case, much judgment will be required to find where the storm-centre lies.

Inclination of Storm-Winds.

First, in regard to the latitude of a storm. Without considering its progression, the nearer it is to the equator, the less its indraught winds will be deflected to the right by the earth's rotation, — the more nearly radial they will be. But, as they move with much energy, they will gain in rotary motion rapidly as they approach the centre, and there will whirl around in almost perfect circles. Storms in low latitudes will therefore tend to have a comparatively small but violent central whirl, only one or two hundred miles in diameter, within which the winds may be almost circular; and the centre will there be nearly at right angles to the wind's course. Farther from the centre, the winds would be nearly radial; and, if storms could arise on the equator, they would have simply radial indraughts with a very small central whirl. On the other hand, in the temperate zone the inflowing winds will be strongly deflected to the right of their intended path; and they must depart widely from a direct line to the centre of low pressure, forming a whirl often one thousand miles in diameter: but, unless they inclined inward at a distinct angle, it would take them too long to reach the centre, and their strength would be lost in overcoming friction on the way. Their average inclination is therefore well marked. The steeper inclination of the winds close to the centre, observed in some northern storms (Toynbee), may be an effect of the tornado action in the cyclone, yet to be described.

Second, in regard to the sides of the storm, as affected by its progression. The inclination will generally be less than the average in front and on the right, and greater in the rear and on the left of the centre; for in whatever manner the storm advances, either by bodily transference or by successive transplanting, the motion of the wind must partake both of the direction of whirling and direction of progress, when seen by an observer not moving in either of these directions. In the case of bodily transferrence, the direction of the wind as shown by a vane will be the simple resultant of its whirling and progressive motions: in the case of successive transplanting, it will be the resultant of the earth's deflecting force and a curve of pursuit; a curve of pursuit being the path followed by a body moving towards a point that is continually changing its position. In either case, the effect may be sufficiently represented by fig. 18, in which the broken arrows show the motion of the wind with respect to the storm-centre, and the straight dotted lines measure the velocity of the storm's advance. The wind will seem to blow along the resultant of these two directions, as shown by the full arrows; and the resulting inclinations are manifestly less in front than in the rear, and less on the right than on the left. With the variation of inclination, there will be an inverse change in the wind's velocity. It will blow faster on the right and rear or dangerous side of the storm, and slower on the left and front or manageable side. In the North Atlantic, where the storms often move rapidly, while a hurricane prevails south of the centre, very moderate winds may blow on the north; the difference between the two being about twice the storm's progressive motion. The change in inclination has been shown to occur in some of the West-Indian hurricanes, but it is not very pronounced in the land-storms of the

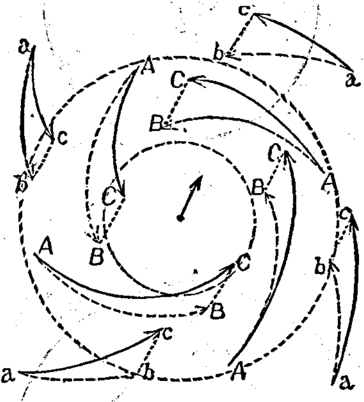


FIG. 18.

temperate zone. Its best application is in storms on mountain summits; as on Mount Washington (fig. 19), and again in the case of the outflowing winds in the upper half of the storm, as shown by the motion of cirrus-clouds, and illustrated in fig. 20. Of course, in this case of outward motion, the less inclination is in the rear, and the greater in the front.

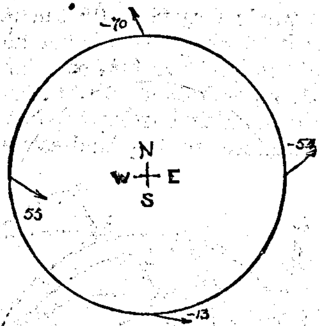


FIG. 19.

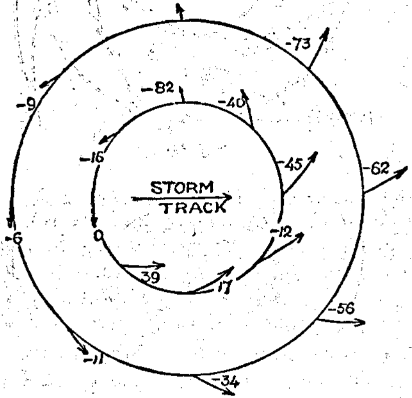


FIG. 20.

Third, in regard to land and sea storms. The inclination will be greater in the former than in the latter. On the sea, the centrifugal force of the earth's deflection will be most pronounced, and the winds will be more nearly circular than on land, where friction will tend to destroy their original motion, and so allow them to run more directly into the storm-centre. This is fully borne out by observation, and is especially well shown in the contrasted cases of storms on the opposite sides of the northern Atlantic. Fig. 21 shows an average storm in the eastern United States, about ready to embark on the ocean; and in this the inclination of the winds is less on the sea than on the land side. This effect is doubtless produced in part by the preceding condition concerning the front and rear sides of the storm. But in examining a storm just about landing on the

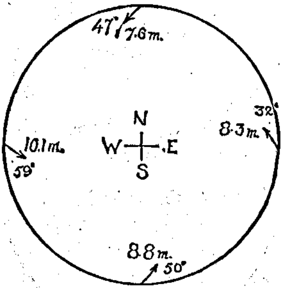


Fig. 21.

western shores of Europe, as shown in fig. 22, it is seen that here the front winds have the greater, not the lesser, inclination: hence position in regard to the centre cannot be the cause

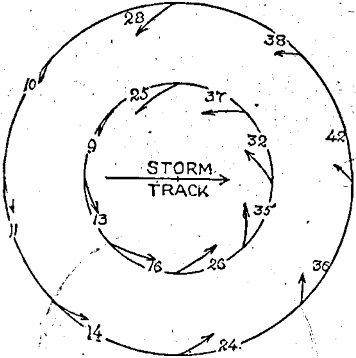


FIG. 22.

of the differing inclinations here. A better explanation is found in the fact that the eastern side of the storm receives its winds from the land, and the western side from the sea; and, in accordance with this, the eastern side should have the greater, and the western side the lesser inclination, as is the case. The fact that European storms have a less velocity of progression than those in this country would still further allow the land and sea conditions to control the inclination in the former region.

Fourth, it is manifest from all the preceding cases that the outermost winds of a storm are nearly radial, and that their direction becomes more circular as they advance. This results directly from the faster motion and less radius, consequently the greater centrifugal force near the centre, and requires no special illustration. It need only be noted, in recalling the first or latitude condition, that, at large distances from the centre, equatorial storms are generally more radial than those of the temperate zones; but, at small distances from the centre, this rule may have to be reversed. This is quite in accordance with the greater size but less intensity of the storms in the temperate zone.

Fifth, in regard to altitude. The absence of strong friction will allow the upper winds to whirl in even more circular paths than they do at sea. Indeed, at a moderate altitude, say 7,000 feet, the winds are probably perfectly circular in the core of the storm; and at a little greater height they assume an outward inclination as they change to the outward spiral of the upper overflow. It is common, therefore, to note that the surface-winds of a storm are not parallel to the motion of the clouds. As the latter are more fully in control of the earth's deflecting force, they will always tend to the right of the former; and, in the extreme contrast of surface-indraught and uppermost outflow, the cirrus-clouds may drift slowly (in appearance) 90° or 120° to the right of the surface-winds. It is therefore usually to storm-disturbances of the general atmospheric circulation that the irregular drifting of different cloud-layers is to be ascribed. And now, after this long digression, we may return to the rescue of the vessel in the West-Indian hurricane.

The Central Calm.

The barometer was falling more and more rapidly, and the wind blowing with increased violence from the north, in the example that was described. Then, if a transparent storm-card, drawn to proper scale after the pattern of fig. 9, be placed on the chart so that its strong north wind shall pass the position of the vessel, it will give the best indication of the general form of the hurricane; and a course may be laid by which the dangerous centre will be avoided. In this case, the safest course will be to run southward, or a point or two west of south, till the barometer begins to rise; and then, if desired, a more easterly course may be followed. Even if the vessel be on its way to a European port, this will be its safest method of avoiding the storm; for, in attempting to beat against the wind and leave the storm to the south, there is too much risk that its increasing strength will prevent the vessel making sufficient headway to escape being caught in the central whirl: it would be better to sail around the southern side of the storm, and, after the centre had passed on the west, then shape a north-easterly course with the wind on the starboard beam. Sometimes it has happened from ignorance of such sailing-rules as these, or from inability, even with their aid, to escape from the sudden violence of a storm, that a vessel finds itself on the storm-track at the time of the passage of the centre; and there is then observed the peculiar and dreadful calm within the whirl, to which sailors have given the name of 'the eye of the storm.' Let us suppose, in the example given above, that the vessel endeavored to force its way against the increasing north wind, and, failing in this, remained on the path of the storm till the centre advanced on it. During its approach there will be no very marked change in the direction of the wind; but its force increases even beyond what seems its greatest possible strength, and goes on increasing, blowing in tremendous and terrible gusts, till the vessel is stripped of its canvas, and the yards and masts are cracked and broken away, and the hull lies helpless and unmanageable. Rain falls in driving torrents, and the sea rolls in great broken waves. The roaring of the winds rises to a screaming pitch; and when at its most fearful strength, it suddenly dies away. In five minutes, perhaps even less, the air is quiet; and only the heavy sea, and the commotion of the clouds, and a distant fading sound of the retreating wind, tell of the violence that has passed by. The vessel is in a cushion of quiet air left under the core of the storm. There is generally but a short time given to suffer the suspense of this unnatural quiet. In half an hour or an hour, according to the size and rate of motion of the storm, the centre passes away, and the opposite side of the whirl suddenly falls on the unhappy wreck, coming again with all the roar and fury that was felt before, but now blowing in the opposite direction, — a terrific hurricane from the south, chopping the waves into the dreaded cross-sea, where the water rises in pyramids instead of in linear crests, and changes its form so rapidly and with such broken rhythm as to strain great leaks in the worn-out hull, and leave it to founder in clearing weather, while the storm goes on in its destructive path.

There is yet much to be learned concerning the curves followed by the winds in these storms. The diagrams, as described above, are based on observation and theory, but must be regarded only as provisional until proved by the average of many more observations than have yet been made. Rules for various cases may be easily devised on the plan above described, but they are not infallible: there is still much to be done in perfecting them. Only one additional point need be mentioned: care is needed to avoid sailing after and overtaking a slow-moving storm, and so falling into its power. This would seldom happen in our latitude, but might well occur in the Indian Ocean, where some storms have been found to rest almost stationary over one district of the sea for more than a day. A case is reported where a vessel thus fell into the dangerous whirl, and could not escape, but was carried round and round the centre, while scudding under bare poles, till it made five complete revolutions before the storm left it behind.

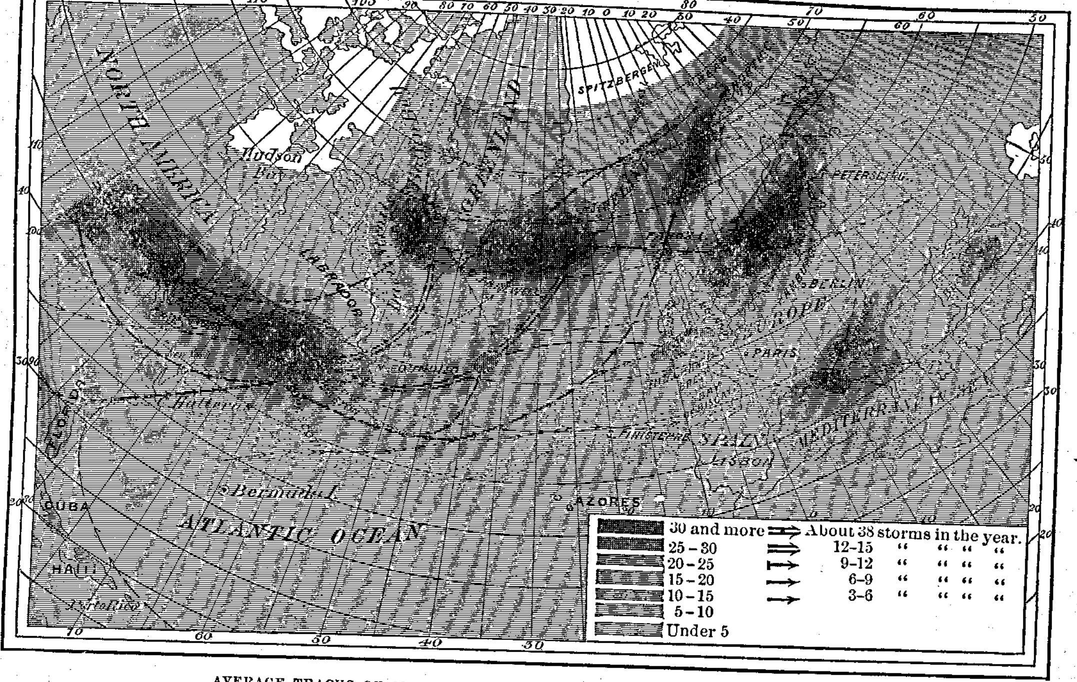
Storm Floods.

There remains to be described the storm-flood produced when a storm runs upon a low shore, as often happens at the head of the Bay of Bengal. The cyclone advances with growing strength till it reaches the flat delta of the great Indian rivers. It finds the land here perfectly level, and so little raised above the water that its cultivated surface has to be protected from river-overflows by dikes ten or twelve feet high built along the shores. But the inblowing winds brush the water of the bay up against the land; the diminished atmospheric pressure about the storm-centre allows the heavier surrounding air to lift the water here, and for every inch that the mercury falls in the barometer the water will rise a foot; the rain alone may contribute nearly a foot of water in a day; and finally, if a strong tide conspire with these other causes, a great flood is produced, that overwhelms even the dikes, and drowns out all the low country; and the poor people, unprovided with sufficient means of escape from the winds and the waters that come from above and below, are lost by the thousand. Six storms alone, that have devastated this coast since 1700, have, if the records can be trusted, destroyed over half a million lives.

The disappearance of a storm has already been alluded to. The storm will fail, or greatly decrease in strength, when running from the sea on the land; for friction here is greater, and there is less moisture in the air from which heat can be obtained to overcome the increased friction and continue the existence of the disturbance. Again: the storm must decrease in intensity as it recedes far from the equator; for it then enters regions of less warmth, and consequently less moisture. Finally, it must end when the updraught caused by heat derived from the falling rain fails to throw the overflow outside of the storm's limits; for then more air enters the storm than flows out of it, and the pressure at the centre will increase. The reverse of this is worth noting: the storm will increase in size and in total strength, although perhaps not in central intensity, as long as the updraught is active enough to throw some of its volume outside of the area occupied by the surface-indraught; for then the pressure at the centre will decrease, and the development of the embryo will continue.

Storms of the United States.

Before proceeding to the consideration of tornadoes, we may devote a little space to the special features of our own storms east of the Rocky Mountains, as determined chiefly by Professor Loomis in his careful study of the signal-service maps.



AVERAGE TRACKS OF STORMS FROM THE ROCKY MOUNTAINS TO THE URAL.

The storm-areas, as indicated by the curved lines of equal pressures, are ovals about twice as long as wide, with the longer axis generally north-east and south-west. The average direction of progression of nearly five hundred storms, in 1872–74, was north 81° east, with a mean velocity of twenty-six miles an hour, or six hundred and twenty-four miles a day: the maximum velocity was above eighteen hundred miles a day. Some of these barometric depressions begin on the Pacific Ocean, or in our north-western territories; most of them are first noted within the western mountainous district; and a good share of the remainder arise on the plains. Very few come from the West Indies. After passing us, they sweep out over the ocean, generally turning well to the north-east, and, if continuing long enough, running to Norway or Iceland rather than to Great Britain. The probability that a storm which leaves our coast will arrive in England is only one in nine. The average tracks of a large number of storms from the Rocky Mountains to the Ural are shown on the accompanying map, prepared by Köppen (*Annalen der Hydrographie*, 1882).

If storms moved only according to these averages, their prediction would be made easy and accurate; but they naturally fail to do so, and hurry or slacken their pace, or turn to one side or the other of their average course, in what seems to be the most capricious fashion. It is the early discovery of these individual peculiarities that tasks the acuteness of the weather-men.

With regard to velocity, storms advance much faster in February than in August (174 : 100), and in the late afternoon and evening than at other hours (125 : 100). If the telegraphic reports show a rapidly rising barometer, and a weak wind in the rear of the storm, it will probably move rapidly. The rain, also, exercises a marked control on the storm, as is shown by comparing the forward extension of the rain-area with the rate of progress: —

Forward extension of rain.	Progression of storm-centre.
640 miles.	40.1 miles an hour.
568 "	29.2 " " "
539 "	22.3 " " "
422 "	15.3 " " "

further, by comparing the axis of the rain-area with the course of the storm: —

Axis of rain-area.	Course of storm.
N. 53° E.	N. 44° E.
S. 65° E.	S. 69° E.

finally, by comparing the rainfall with the increase or decrease of the central barometric depression: —

Average rainfall within isobar 29.80″.	Change of central depression in twenty-four hours.
0.078″	+ 0.10″ (i.e., storm decreasing).
0.149	− 0.05
0.159	− 0.128 (i.e., storm increasing).

Rain, therefore, is shown to aid in determining the velocity, direction, and development of our storms, as has already been inferred.

Thus far in regard to the motion of the storm as a whole. The winds of the storm blow faster, the more marked the central depression and the closer the isobars. If the space on the signal-service maps between adjoining isobars (the difference of their pressure being one-tenth of an inch) measure one hundred and thirty miles, the wind will probably blow five miles an hour; if eighty miles, thirty miles an hour; if forty-five miles, fifty miles an hour. There is, however, much variation from this rule, depending on the form of the ground and the neighborhood of the lakes or the sea. The average direction, inclination, and velocity of our storm-winds in the four quadrants is shown in fig. 21. The relation of the several inclinations here shown has already been discussed. It should be added, that the unexpected approach to equality in the wind's strength on the right and left (south and north) sides of the storm is probably in large part due to the wind on the north coming but little retarded from the sea, while that on the south has lost much of its proper velocity by blowing long over land; so that, while the winds should theoretically show a less velocity on the left than on the right side of the track when the storm moves over a uniform surface, this inequality might be largely counteracted by the relations of sea and land that obtain in the eastern part of our country. This is confirmed by finding the winds on the left side of the storms of northern Europe much weaker than on the right; for here the progression of the storm, and the relation of sea and land, combine to produce this effect. Our space forbids more detailed consideration of the variation of our storms with the seasons; and the reader desirous to pursue the subject farther should provide himself with the government daily weather-maps, which may be had by subscription to the chief signal-officer in Washington, and should consult Professor Loomis's essays in the *American Journal of Science* for recent years, the circular on the practical use of meteorological reports and weather-maps (issued by the signal-service, 1871), and the appendices on the relation of rain and winds, and on the course of storms in the different months, in the signal-service reports for 1878 and 1874.

Tornadoes.

Tornadoes differ from the storms thus far mentioned in their excessive violence over a very restricted area, and their visibly rapid advance. After a great deal of theorizing, it is now possible to explain them very satisfactorily and simply as whirls in the air, a little above the ground, into the vortices of which the surface-winds are drawn up with great velocity. Electricity has no essential share in their action.

Recent studies, especially the reports by Mr. Finley of the signal-service, have done much to show us the regions of, and general conditions preceding, tornadoes. They are most numerous in Kansas, Missouri, and Illinois, although they have been recorded throughout the states east of the Mississippi, except in the far north-east and on the central Alleghanies. So they have occurred in all the months, and at nearly all hours of the day; but their time of greatest frequency is in the afternoons of June and the months adjoining. Where most fully studied, they seem to occur along the contact-line of warm southerly winds and cooler north-westerly or westerly winds. Local quiet and rather excessive warmth commonly precede them, and chilly winds come after their passage. Rain and hail fall in their neighborhood, but usually at a moderate distance away from the destructive wind-centre. Their advance is nearly always to the north-east, at about thirty miles an hour.

When first perceived, the tornado is generally described as a dark, funnel-shaped mass, hanging from heavy, dark, agitated clouds (fig. 23). Its roaring sound is heard as it comes

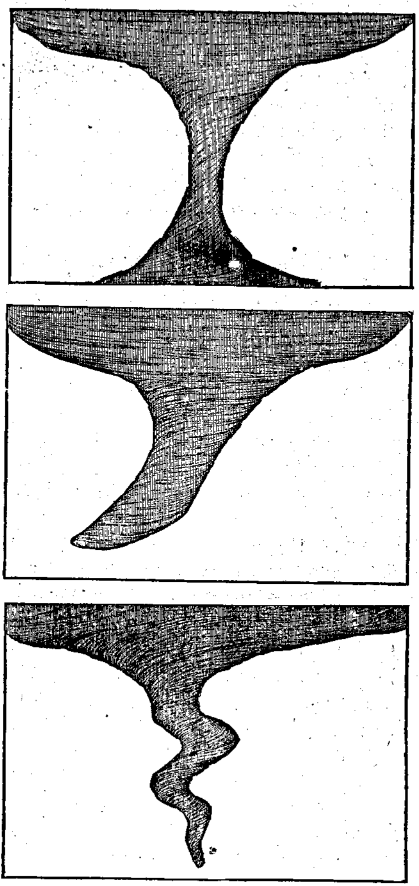


FIG. 23.

nearer; and the whirling funnel is often seen to swing from side to side, and to rise and fall. Within its dark column, various objects snatched from the ground may be seen rising and turning round and round in the eddying winds: pine-trees appear like bushes, and barn-doors are mistaken for shingles. At a certain height these fragments are thrown laterally out of the power of the ascending current, and then fall to the ground, often with violence, from their lofty flight. If such a cloud appear in the west or south-west, one should make all possible haste to the north or south of its probable track; but there is seldom time to escape. The rapidity of the storm's approach, the noise of its roaring, the fear that its darkness and destruction naturally inspire, too often serve to take away one's presence of mind; and, before there is time for reflection, the whirl has come and passed, and the danger is over for those who survive. The force of the wind is terrific. Heavy carts have been carried, free from the ground, at such a velocity, that, when they strike, the tires are bent and twisted, and the spokes are broken from the hubs. Iron chains are blown through the air. Large beams are thrown with such strength that they penetrate the firm earth a foot or more. Children, and even men, have often been carried many feet above the ground, and sometimes dropped unhurt. A velocity of wind exceeding one hundred miles an hour is required to produce such effects. Strange examples of the wind's strength are found in the treatment of small objects: nails are found driven head first firmly into planks; a cornstalk is shot partly through a door, recalling the firing of a candle through a board. More than this, the wind shows signs of very unequal motions in a small space: bedding and clothing are torn to rags; harness is stripped from horses. Nothing can withstand the awful violence of the tornado's centre; and yet, at a little distance one side or the other, there is not only no harm done, but there is no noticeable disturbance in the gentle winds. The track of marked disturbance averages only half a mile, and the path of great destruction is often only a few hundred feet wide.

The whirling at the centre is evident enough, in many cases, from the rotary motion of the funnel-cloud: it is, in all reported cases, from right to left, like the cyclones of this hemisphere. At a little distance from the centre, the wind is probably nearly radial, as is shown fully enough by the direction in which fences or trees are blown over, or houses and all loose objects carried. On the right side of the track the winds are more violent, and their destructive effect consequently reaches farther from the whirl than on the left. This is evidently because, on the right, the motion of the wind and the advance of the storm are combined, as has been explained under cyclones. Here are several examples from the Kansas tornadoes of May, 1879, as described in Finley's report, showing the opposed currents of air.

Fig. 24 shows the fence on the right blown to the east; the fences on the left, to the west and south; and the hay from a stack, scattered in a curved line. When fences are not blown over, rubbish often collects on their windward side.

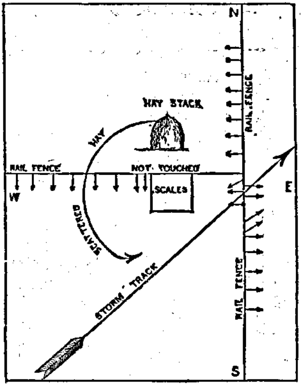


Fig. 24.

Fig. 25 illustrates, by arrows, the direction of the wind, by which several buildings were more or less injured; but most peculiar is the track of a man, who, on coming out of the east side of a barn, was caught up by the winds and carried half way around the building, and there set down very dizzy, but unhurt. At the same time two horses near by were killed, their harness stripped off and torn to pieces. A scantling four inches square and ten feet long was found driven three feet and a half into the ground, only forty-five feet from its starting-point. A large board sixteen feet long was found two miles to the north-east, where it was identified by the color of its paint.

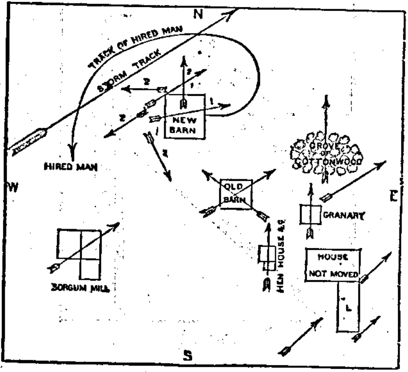


FIG. 25.

Fig. 26 shows a more disastrous case. A house was swept away, and its fragments filled the creek to the south-east. The trees west of the house were not hurt; but those in the grove on the track were blown over to the north-east, their bark and leaves stripped off, and their south-western side blackened as if burnt. On such occasions, branches have been found twisted from right to left about the trunks. As the storm came on, the family occupying the house ran out, turning to the north and west. One by one they were blown away, — first a little girl, who was found dead; then a girl and boy, not seriously hurt; next the mother was thrown against a tree and killed; and last, the father, carrying the baby, and becoming confused in the rushing wind, turned back from his safe flight to the west, was caught up and thrown over one hundred yards to the north-east, and killed. The accounts of tornadoes only too often give a record like this. In six hundred and odd

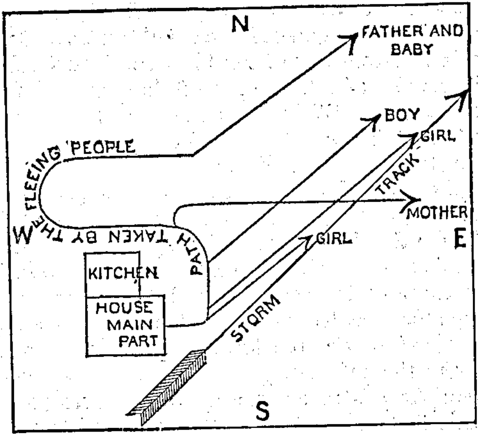


FIG. 26.

tornadoes, forty are recorded as fatal to the people on their track. In these forty, four hundred and sixty-six lives were lost, and six hundred and eighty-seven persons were injured.

In addition to the violence of the whirling winds, an explosive effect is often noted in buildings where the windows and doors are closed. Doubtless this is one reason why roofs are so generally carried away. Doors and windows have been blown outward. The four walls of a house have fallen outward from the centre. Still more definite is the account of a railroad-agent who had barred the window-shutters and locked the door of his station after a train had gone by. A tornado passed over it, and burst the window open outwards. Evidently the air of ordinary density within the building suddenly expands as the outside pressure of the atmosphere is taken off when the storm-centre passes. Possibly this action may aid in the plucking of poultry in tornadoes: the unfortunate chickens that are caught near the centre are nearly always stripped of their feathers. So with the remarkable penetration of mud into clothing, which cannot be cleansed by repeated washings: perhaps the air is drawn out as the storm passes, and then the mud is forced closely into the fabric by the returning atmospheric pressure. The ground is sometimes said to look as if heavily washed on the central path: it may be that the expansion of air in a loose soil aids such a result.

Nothing can be better proven than the existence of a continuous and violent updraught at the centre of the whirl. An observer far enough from the track of the tornado to watch it composedly, and yet near enough to see it with some distinctness, seldom fails to note the rapid rising of *débris* and rubbish in the vortex, whirling as it rises; and a current of air strong enough to lift boards and beams must ascend with great energy. Most of the fragments thus captured by the wind are thrown to one side, and allowed to fall after a short flight; but smaller, lighter objects, such as hats, clothes, papers, shingles, are often carried several miles through the clouds, and dropped far away from home. But observers often report, also, that the extremity of the funnel-clouds is seen to descend, and from hanging aloft it suddenly darts downward to the ground. How can these two contradictory motions be reconciled? Simply enough: for the last is purely an apparent motion. It is simply the downward extension of the cloud-forming space faster than the cloud-particles are carried upward. The same style of apparent motion against the wind may be seen in some thunder-showers where a cloud forms faster than the wind blows, and so eats its way to windward. There has been much needless mystification here, for the point was neatly explained by Franklin a century and a quarter ago. He wrote, that "the spout appears to drop or descend from the cloud, though the materials of which it is composed are all th while ascending;" for the moisture is condensed "faster in a right line downwards than the vapors themselves can climb in a spiral line upwards" (Franklin's Works, Sparks's ed., vi. 153, 154; letter dated Feb. 4, 1753).

Ferrel's Theory of Tornadoes.

Now let us look for the explanation of these varied effects, and discover, if possible, the reason of the extremely local development of such intense motions.

The explanation given for sand-whirls in the desert fails to provide for the excessive force of the tornado. A thin, warm surface-stratum of air would be prevented by friction with the ground from attaining any very excessive velocity; and, moreover, it is often excessively hot without tornadoes following, and tornadoes often happen when the air is not perfectly still. Yet, as they occur most frequently on warm or hot afternoons, surface-warmth very probably re-enforces other causes up to the point of violent storm development.

The existence of conflicting winds, as already noted, gives us more aid. So long as the cold wind passes under the warm, there will be no great disturbance, for the equilibrium will remain stable; but, if the warm wind advances under the cold, an unstable equilibrium may result. We have already seen that warm saturated air requires the smallest vertical difference of temperature to destroy its stability; and also that the saturated condition may often be met in the cloud-stratum, although absent below it. For these two reasons we may infer that a tendency to upset will be more frequently reached a few hundred or thousand feet above the earth than closer to the ground. Suppose that such a condition is reached when a mass of warm southerly wind has pushed itself below the colder north-westerly stratum: the surface-air will often rest quiet and become warm below such a meeting, for the same reason that calms occur along the equator at the meeting of the trades; and a change must soon relieve this unnatural arrangement. The warm wind, feeling about for a point of escape through its cold cover, soon makes or finds a vent where it can drain away upwards; and then the entire warm mass, even a mile or more in diameter, and often more than one thousand feet in thickness, begins the rotary motion already described in whirls and cyclones, rises at the centre, and passes away. Before describing the peculiar tornado features, let us contrast the storm as now developed with the two other kinds of storms already explained. The desert-whirl arises from a thin layer of hot dry air, warmed at the place where the whirl begins, ascending in a small column through a considerable thickness of colder air. Friction with the ground prevents the attainment of an excessive velocity; and the ascending current can lift only sand and light objects. As soon as the bottom-air is drained away, the whirl stops. The cyclone is fairly compared, on account of its great horizontal extension, to a broad, relatively thin disk, with a horizontal measure several hundred times greater than its thickness, having a spiral motion of much rapidity, inward below and outward above, but a central ascending component of its motion so gentle that raindrops can ordinarily fall down through it. Its continuance depends largely on heat derived from vapor condensation: it is therefore self-acting after it has once begun, and goes on drawing in new air long after the original supply is exhausted. The tornado is like a cylinder, with a height equal to or greater than its diameter. Its warmth is chiefly imported to the point where its action begins, partly as sensible, partly as 'latent' heat; but, unlike the cyclone, its action ceases as soon as the original mass of warm air escapes upward through its warm cover. On apprehending these peculiarities, we may better appreciate its farther development.

The tornado has two motions to be considered, in addition to its general progression, — the spiral rotation, and the central updraught. The latter cannot, except under special conditions yet to be mentioned, become very rapid, for it depends primarily, simply on differences of temperature insufficient to produce very active motion; but the former attains a great velocity near the centre in virtue of the mechanical principle already quoted, — the 'preservation of areas.' When a whirling body is drawn toward the centre about which it swings, its velocity of rotation will increase as much as its radius of rotation decreases; the centrifugal force will also increase, and with the square of the velocity, or inversely as the square of the radius. This law claims obedience from air, as well as from solid bodies: hence, if the air of a tornado mass have a gentle rotary velocity of twenty or thirty feet a second at a thousand yards from the centre, this velocity will increase as the central air is drained away and the outer particles move inward; so that, when their radius is only one hundred yards, they will fly around at the rate of two or three hundred feet a second, or over one hundred and fifty miles an hour. It must be understood, however, that this requires that there should have been no loss of motion by friction, and hence can be true only for the air at a distance above the ground; and, further, that, in spite of the great horizontal rotary motion, there is still only a moderate vertical current. And consequently we have not yet arrived at the cause of the violent central and upward winds that distinguish the tornado from other storms, but this cause is close at hand.

Admit for a moment that there is no friction between the air and the ground. We should then have a tall vertical cylinder of air, spinning around near the centre at a terrific speed, at the base as well as aloft, and consequently developing a great centrifugal force. As a result, the density of the central core of air must be greatly diminished. Most of the central air must be drawn out by friction into the whirling cylinder, and prevented from returning by the centrifugal force. The core will be left with a feeling of emptiness, like an imperfect vacuum. If there were any air near by not controlled by the centrifugal force, it would rush violently into the central core to fill it again. Now consider the effect of friction with the ground. The lowermost air is prevented from attaining the great rotary velocity of the upper parts, and consequently is much less under the control of the centrifugal force, which is measured by the square of the velocity. The surface-air is therefore just what is wanted to fill the incipient vacuum: so it rushes into the core and up through it with a velocity comparable to that of the whirling itself; and *this inward-rushing air is the destructive surface-blast of the tornado.*

This explanation, first proposed by Mr. Ferrel a few years ago, is most ingenious and satisfactory. Moreover, he has followed its several parts by close mathematical analysis, and shown that the moderate antecedent conditions are amply sufficient to account for all the violence of the observed results.

There are still several points to be considered. The whirling motion has been described as corresponding in nearly all cases with that of northern cyclones; and yet it cannot be supposed that the indraught winds of a tornado are drawn from sufficient distances to show the effect of the earth's deflective force: it is more probable that the tornado is to be regarded as a small whirl within a larger one, for the warm and cold winds are probably part of a large cyclonic system in which differential and rotary motions are established; and, when such winds form a small local whirl of their own, it will rotate in the same direction as they do, from right to left. For a like reason the planets rotate on their axes in the direction in which they revolve around the sun. The constant direction of rotation in tornadoes may therefore, by itself, be taken as evidence that their cause is not in a stagnant atmosphere, like that of the desert-whirls, but is connected with the conflicting currents of a large, gentle cyclone.

The progressive motion of the tornado-centre is so constant in its direction to the north-east or east, that it cannot depend on local conditions within itself, but must rather result from its bodily transportation by the prevailing winds, with which the tornado-tracks agree very well in direction and rate. It will last till the lower warm air, which constituted the original unstable mass, is exhausted. This generally happens in about an hour, when it has traversed a distance of nearly thirty miles.

The tornado thus constituted may be likened to a very active air-pump, carried along a few hundred feet above the ground, sucking up the air over which it passes. It is for this reason that the surface-winds are so nearly radial. For this reason an enclosed mass of air, as in a house, suddenly explodes as the vacuum is formed over it; and as the air rushes to the centre, and there expands and cools, its vapor becomes visible in the great funnel, or spout, pendent from the clouds above. No rain can fall at the centre. Bodies much heavier than rain are lifted there, instead of dropped: so the rain must rise through the central core, and fall to one side of the storm, or before or behind it. If the expansion be very great, and the altitude reached by the drops rather excessive, then they will be frozen to hailstones before falling. Hail-storms and tornadoes commonly go together: they mutually explain each other. Electricity has no important part to play in the disturbance.

It was stated under cyclones that their central barometric depression had two causes, — the overflow caused by the central warmth, and the dishing-out of the air by centrifugal force. The first of these is ordinarily regarded as the effective cause of the wind's inward blowing. It has already been pointed out that the second and greater part of the depression is also effective in drawing in the winds when friction decreases their rotary velocity. We may now call attention to a third cause of centripetal motion in the cyclone already alluded to, in which it is like the tornado. The upper winds move with great rapidity, and cause a strong barometric depression at the centre of their whirling; but at the base of the storm, where friction with the sea, or still more with the land, reduces the lower wind's motion, and so diminishes their centrifugal force, we may have an indraught of the tornado style, in which the centrifugal diminution of central pressure in the upper winds is an effective cause of centripetal motion in the lower winds. While this is not the principal cause of surface-winds in a cyclone, it may be an important aid to central warmth.

Water-spouts are closely allied to tornadoes: but when seen in small form they approach the character of simple desert-whirls; that is, they then depend merely on air warmed at the place where they occur, and not on the running together of warm and cold winds from other regions. A probable cause for the excess of their strength above that of the sand-whirls lies in the smoothness of the water-surface on which they spring up, which will allow a long time of preparation; and in the moisture in the air, which will cause the warming of a greater thickness than if the air were very dry. The greater the thickness, the more their action will resemble that of a typical tornado. The appearance of the downward extension of the funnel-shaped cloud to meet the rising column of water is almost certainly only an appearance, and has the explanation already quoted from Franklin's ingenious writings.

We have relied largely, in the preceding explanations, on deductions from general principles, checked by the results of observation. The writings of many investigators have been examined, and in a few cases their names have been given; but the literature of the subject is now so extensive that full reference has been deemed unadvisable. Little attention has been paid to the older theories, in which conflicting winds and electricity were looked on as the chief causes of storms. The latter is regarded as an effect rather than a cause; and, while the former has much importance when rightly considered in connection with the earth's rotation, it is of small value as originally stated, and is then limited to the production of short-lived storms in mountainous districts. The more important factors of the modern theory of storms are the consideration of the conditions of stable and unstable equilibrium of the atmosphere, the true measure of the action of condensing water-vapor, the full estimation of the effect of the earth's rotation, and the recognition of the necessary increase in the wind's velocity as it is drawn in toward the storm-centre.