UNITED STATES
DEPARTMENT OF AGRICULTURE
Miscellaneous Publication No. 236

Washington, D. C.
Issued April 1936
Revised June 1940

FORECASTING FROM SYNOPTIC WEATHER CHARTS

By
RICHARD HANSON WEIGHTMAN
Principal Meteorologist (Forecaster), Weather Bureau

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CONTENTS

INTRODUCTION

The first publication of the Weather Bureau that discussed weather predicting in a general way was in 1916 by Henry, Bowie, Cox, Frankenfield, and others *(24)*.[1] This edition became exhausted and in March 1930 Henry prepared Weather Forecasting from Synoptic Charts *(23)* to meet an insistent demand for a publication of this nature. An edition of 3,000 copies of this second work was exhausted in the course of 5 years. It will not be reprinted, however, being rather out of date, owing to the advances that have been made since 1930 in weather forecasting and the developments in certain of its principles, largely through the availability of more pilot-balloon and airplane observations. The present work is an attempt to add these latest features to the older body of knowledge on weather forecasting.

This publication has been prepared primarily to serve the needs of those who have a working knowledge of meteorology and are beginning to make deductions from synoptic weather charts. It is

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[1] Italic numbers in parentheses refer to Literature Cited, p. 50.

not a complete treatment of the subject nor does it contain any new principles. It does, however, outline some of the more important considerations that should be borne in mind in making weather predictions from synoptic charts.

To make weather forecasts it is of course necessary to have at least a working knowledge of meteorology and the reading of one or more of the relatively recent works on the subject (*5*, *9*, *12*, *15*, *18*, *26*, *33*, *40*) is urged. It is assumed that the reader has available for his use working charts similar to the ones prepared at the district forecast centers, including the pilot-balloon and radiosonde observations.

Remarks concerning forecasting in the sections on the process of forecasting refer more particularly to conditions east of the Rocky Mountains.

Forecasting on the basis of a single station is defective, in that little definite information can be gained regarding the size, rate, and direction of movement of disturbances or of air masses and the fronts that attend them. Although, with the necessary knowledge and experience, very helpful results can be obtained from a careful analysis of local observations of pressure, temperature, winds, and clouds, nevertheless, far more definite and reliable forecasts can be made from meteorological reports from a well-organized network of stations.

Weather forecasting, born in empiricism, is steadily and surely developing along sound physical lines. The introduction of frontal methods, the later detailed analysis of the air masses, the more recent development of kinematical methods for forecasting the movements and intensities of fronts, HIGHS, LOWS, the isentropic charts, etc., are meteorological milestones along the path of progress. Perhaps ultimately forecasts will be made mathematically with complete or nearly complete elimination of the personal equation, but for some time to come the predictions must, in the words of A. H. R. Goldie, "continue to be a combination of physical reasoning with the practical experience of the synoptic charts."

BASIC OBSERVATIONAL DATA

SURFACE DATA

The Weather Bureau receives twice-daily surface observations by telegraph, radio, and cable taken at 7:30 a. m. and 7:30 p. m. (seventy-fifth meridian time) from a very complete network of stations covering the United States, Canada, Mexico, and Alaska, many stations in Europe, and some on the eastern coasts of Asia. In addition, two intermediate observations, from about 250 stations, taken at 1:30 a. m. and 1:30 p. m., are received over the teletype circuits at the airway forecast centers and the district forecast centers. The domestic and Canadian reports contain the following fundamental data: Barometric pressure reduced to sea level, current temperature, dew point, direction of the wind, weather, amount of sky covered, force of wind, precipitation, maximum and minimum temperature, barometric tendency, clouds, and certain other miscellaneous phenomena. During the season of West Indian hurricanes twice-daily reports are received from the West Indies, Mexico, and the eastern coasts of

Central America, and intermediate reports from most of these areas when a tropical storm is known to be in progress. Supplementing the land observations, vessel reports are received twice daily by radio throughout the year from areas off the Atlantic and Pacific coasts and in the Gulf of Mexico and the Caribbean Sea. During the hurricane season four reports at 6-hour intervals are received from vessels in the Gulf of Mexico and the Caribbean Sea, and selected ships transmit observations four times daily throughout the year. The number of vessels reporting four times daily will be increased due to the growing demands for transoceanic flying.

UPPER-AIR DATA

Pilot-balloon observations, giving velocities and directions of the wind at the surface, and at 2,000, 4,000, 6,000, 8,000, 10,000, 12,000, and 14,000 feet above sea level are received from about 100 stations of the Army, the Navy, and the Weather Bureau. About 10 such reports come from Canada, and it is hoped that others from that country will be added in the near future since these outpost stations are most important in detecting the presence and determining the velocity of the cold-air masses that affect the weather in our northern border States and in some cases are felt as far south as the Gulf. In addition, about 20 others are received from Mexico, Central America, Puerto Rico, Panama, Honolulu, and Alaska, and a few from ships at sea.

Observations of pressure, temperature, and humidity up to more than 5,000 meters are scheduled once daily from about 34 stations through cooperation of the Army and Navy with the Weather Bureau. The great majority are made by radiosonde, but a few are still made by airplane. Ultimately, it is hoped that these will be available twice daily.

DISTRIBUTION

Most of the surface observations are made available by telegraph to the district forecast centers at Albuquerque, Chicago, Denver, Jacksonville, Kansas City, New Orleans, San Francisco, and Washington. Selected reports are telegraphed to many of the other field stations. Reports received at San Francisco and Washington are broadcast by radio telegraph twice daily through the Naval radio stations at Mare Island and Arlington at 8:00 a. m. and 8:00 p. m., seventy-fifth meridian time. In addition, such broadcasts are made at 2 a. m. and 2 p. m. from Washington. A bulletin for marine interests containing land and ship reports, forecasts of winds off the coast, and giving the location and movement of severe storms is broadcast daily at 10 a. m. and 10 p. m. from Arlington (NAA) and Annapolis (NSS). In addition, about 120 Weather Bureau field offices print and disseminate the data in the form of maps and bulletins. Numerous daily papers publish in tabular form portions of the information, while some publish daily weather maps which are received by wire photo or are prepared at local Weather Bureau offices.

CHARTS AND GRAPHS

It is impracticable to enter all the data on a single chart if it is desired to draw lines of equal change for pressure, temperature, etc. As these lines of equal change of pressure in 12 hours and temperature in 24 hours have valuable significance they should be separated from the other data for the best results. Therefore, at the district forecast center at Washington, for example, three charts showing surface conditions are prepared and also others that indicate the state of the sky and conditions in the free air.

The Weather Map

The principal chart, frequently referred to as the "weather map," has entered on it for each station the barometric pressure, the barometric tendency, current temperature, direction and velocity of the wind, state of sky, the weather, the previous 6-hour precipitation, and in addition certain miscellaneous phenomena such as maximum wind velocity and direction, frosts, dew point, thunderstorms, fog, etc. Isobars are drawn in black for each 3.0 millibars (0.09 inch) of pressure and isotherms in blue for each 10° of temperature. The tracks of the LOWS and HIGHS are shown by broken, heavy black and red lines, respectively.

The fronts are indicated in the conventional manner, solid red for warm fronts and solid blue for cold fronts. In addition, purple is used for occluded fronts and broken red and broken blue lines for upper level warm and cold fronts. Frontogenesis is indicated by lines consisting of red dots for warm fronts and blue dots for cold fronts. The force of the wind is indicated by barbs and half barbs on the wind-direction shaft.

The Temperature Map

On this chart are shown the current temperature and the minimum temperature with morning reports and current temperature and maximum temperature with evening reports. Departures from normal and the 24-hour changes are also entered. Lines are drawn delimiting areas over which the 24-hour change has exceeded the so-called stationary limits, which are 10° F. in December, January, February, and March; 8° in April, May, October, and November; 6° in June, July, August, and September, and a line is drawn separating areas of rising from those of falling temperature. In addition, lines are drawn for zero departure from normal and also for departures of 10°, 20°, etc.

The Pressure-Change Map

The pressure at the observation and the amount and characteristic of the 3-hour tendency or change are charted and the 12-hour change computed after eliminating the diurnal variation. Lines are drawn in red for each 3.0 mb. (0.09 inch) of rising pressure in 12 hours, and in blue for each 3.0 mb. (0.09 inch) of falling pressure. In addition lines are drawn in green for each 1.5 mb. (0.045 inch) of rising and falling tendencies, etc., and black lines separate areas of rising from those of falling tendencies.

THE CLOUD MAP

The direction of the wind is shown by a black arrow, lower cloud by a blue, and upper cloud by a red arrow. The cloud amounts are indicated by appropriate shading in the station circle. Areas of cloudiness of $8/10$ or more are enclosed in green lines. Precipitation occurring at the time of observation is indicated by yellow shading. The type of cloud is indicated by the international symbols.

THE PILOT-BALLOON CHART

This chart really consists of eight small charts, all arranged on the same sheet. On each of these the data for a particular elevation above sea level are plotted, beginning with the surface and progressing through the 2,000-, 4,000-, 6,000-, 8,000-, 10,000-, 12,000-, and 14,000 foot levels—of course, only such thereof as are above the station level. Arrows show the wind direction and figures the velocity in miles per hour. In the margin of the sheet a table is provided for data at the maximum elevation. Very complete pictures of the wind structure of the cyclone and of the anticyclone are thus obtained.

In addition, on the 6,000,- 10,000-, and 14,000-foot charts the pressure is entered and isobars are drawn.

GRAPHS OF RADIOSONDE OBSERVATIONS

For some years pressure, temperatures, and relative humidities in the free air were obtained by means of kites, to which meteorographs were attached. In 1931 kites were replaced by airplanes, flights being made each morning under contracts by commercial fliers. More recently the airplane observations have been replaced by the radiometeorograph or radiosonde. At present, observations are scheduled each morning at 34 stations in the United States, including 26 by the Weather Bureau, 2 by the Army, and 6 by the Navy. These are graphed on sheets containing a number of small cross-section bases. On these bases the vertical temperature distribution is indicated by a line joining points plotted on the cross sections, the ordinates being pressures to the 0.288 power and the abscissae temperatures in degrees centigrade. At points where the temperature-lapse rate or relative humidity changes, the relative humidity and the specific humidity are entered; and elevations at which clouds and precipitation are encountered are indicated. Mention of these will be made in the section on air-mass analysis.

From the temperature, pressure, and humidity data in graphic form an isentropic chart is prepared each morning for a certain potential temperature surface which is changed with the season. On the isentropic chart data are entered and lines drawn for two series of pressures, the first indicating the pressure at the isentropic surface and the second the pressure to which a body of air would have to be reduced in order that it become saturated. Such a procedure has been described by Byers (*13*) and is found to be somewhat more convenient than plotting the height of the potential temperature surface and the specific humidity at the surface. Such charts are made available each morning to the forecaster for use in analyzing and studying the surface map. In addition, vertical cross sections, generally three in number, are prepared for his use. On these the temperature, the potential temperature, the relative humidity, and the specific humidity are entered for each significant level. On the cross sections lines of equal potential temperature are drawn and the fronts indicated in conventional colors.

MATTERS OF SPECIAL CONSIDERATION

When weather maps are studied it is essential to have in mind certain general and fundamental principles, a few of which are outlined here.

Seasonal

It will be recalled that there is a steady rise in the daily mean temperatures in the spring and a similar fall in the autumn. Observations which are simultaneous in the United States and Canada are taken in the eastern half of the country about 7:30 a. m. and 7:30 p. m., local time, while in the Pacific States the hours of local time are about 4:30 a. m. and 4:30 p. m. In the West, therefore, the morning current temperatures are quite close to but in most cases not so low as the minima, and the evening current temperatures quite close to but lower than the maxima. In the East, however, such is not the case. The minimum occurs in the spring and summer seasons several hours before the morning observation is made and there may be a difference of 6° to 16° F., especially in northern districts, between the minimum and the observation temperature. Similarly, in the northeastern United States during the fall and winter, the evening temperature is taken 3 or 4 hours after the maximum temperature occurs and, with the normally rapid fall toward sundown, the 8 p. m. temperature is in many instances much lower than the maximum.

Water temperatures must be considered in making forecasts of temperature, at least for coastal regions. On-shore winds reflect the temperature of the water off the coast, but in considering this effect it is necessary to have in mind whether it is daytime or nighttime, because, while the water temperatures are substantially constant, land temperatures normally vary considerably between day and night. While this is most pronounced in the warmer season it, nevertheless, must be considered during the cold season as well.

Thus, the water temperature off Boston, for example, during the month of January is 33° F., while the mean maximum temperature at Boston is 35° and the mean minimum 19°, and during July the water temperature is 60°, while the mean maximum at Boston is 80° and the mean minimum 63°. Charts showing the water temperatures for January, April, July, and October are given in figures 1 to 4. The temperatures for the Great Lakes purport to be corrected by Horton and Grunsky (*25*) to the mean for the day and are based on manuscript records 1874–86 furnished by N. B. Conger. The January Lake temperatures were omitted because of the uncertainties concerning effects from winds off the Lakes when the water is frozen. The water temperatures for the Atlantic, Pacific, and Gulf stations are taken from manuscript charts in the forecast map room at Washington. The observations in printed form cannot be located but are undoubtedly based on the water-temperature measurements made at coastal stations of the Weather Bureau under a regular observational program that was in effect for a number of years. A thorough survey has been made in the past several years by the Marine Division of water temperatures off our coasts and are available for distribution to Weather Bureau stations. The data given on these charts differ somewhat from data on the charts in this publication. This is due to the fact that observations on which the latter charts are based were made in harbors and not on the open ocean, as was done with observations in the Marine Division charts.

Convection effects are felt to greater heights in summer than in winter. In the former they are observed on the average up to 1,200 to 1,800 meters, while in winter convection extends only to an average height of 600 to 800 meters.

DIURNAL

On clear nights, with wind velocity less than 6 or 8 miles per hour—that is, when the return radiation to the earth is much less than the outgoing and turbulence is confined to a very shallow layer—the air becomes 4° to 8° F. or more (at times even much more) colder at the surface than at an elevation of 40 or 50 feet. Such distribution of temperature is known as an "inversion"; that is, an increase of temperature with increase of altitude instead of the usual decrease. Even on plains the so-called inversions occur. Conditions of this kind are accentuated by a snow cover and differences of as much as 15° or slightly more have been observed in some cases between the surface temperatures at stations only a short distance apart, due, in large measure, to air drainage. Observations at Weather Bureau offices on the tops of buildings in large cities during calm, clear nights show minimum temperatures higher than those in the suburbs, due largely to inversions. These differences often amount to 4° or 5°, and in some cases 10° to 15°, as before indicated. When winds of consequence prevail such differences are inconsequential, because mixing by turbulence prevents the formation of a marked inversion.

In considering the 12-hour pressure change and the 3-hour pressure tendencies, it is important to remember the amount of the diurnal variation in the different seasons for the different regions, and to note whether the weather is cloudy or clear, since the clouds tend to decrease the diurnal variations. In studying the tendencies it is essential to take into consideration the time of the maximum and minimum with respect to the time of obseravtion, as well as the state of the sky, and to make the necessary allowances for thunderstorm effects.

It is interesting in comparing the rainfall in the east Gulf States with that of the upper Mississippi Valley and the northern Plains States (*27*), to note that in the former the bulk of the precipitation, at least during the growing season (April to September), occurs during the daylight hours, due to convectional showers attending thunderstorms, while in the latter the greater part occurs during the nighttime. The latter phenomenon has never been satisfactorily explained but undoubtedly is associated with the nighttime cooling by radiation and the readjustment of the air masses, especially at higher levels, caused by the changes in density that bring about instability.

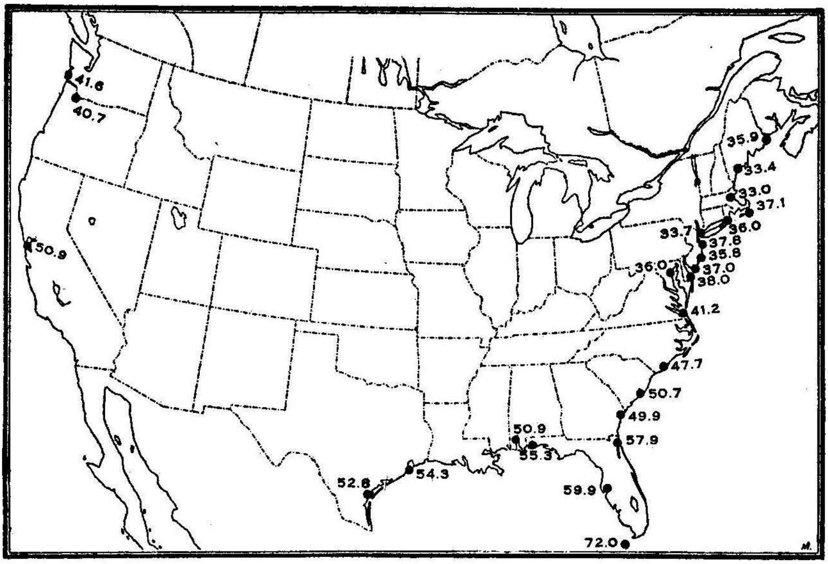

FIGURE 1.—Water temperatures, January.

With regard to wind, there is a decided tendency for it to increase as soon as convection extends to considerable heights, normally around noon, due to the wiping out of the surface temperature inversion, and to decrease shortly after active convection ceases. This increase is due to vertical convection of the air brought about by the heating of the surface of the earth by the solar rays, since it mingles the faster moving upper air with the slower, frictionally

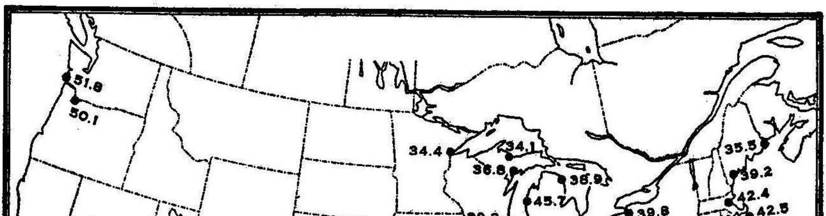

FIGURE 2.—Water temperatures, April.

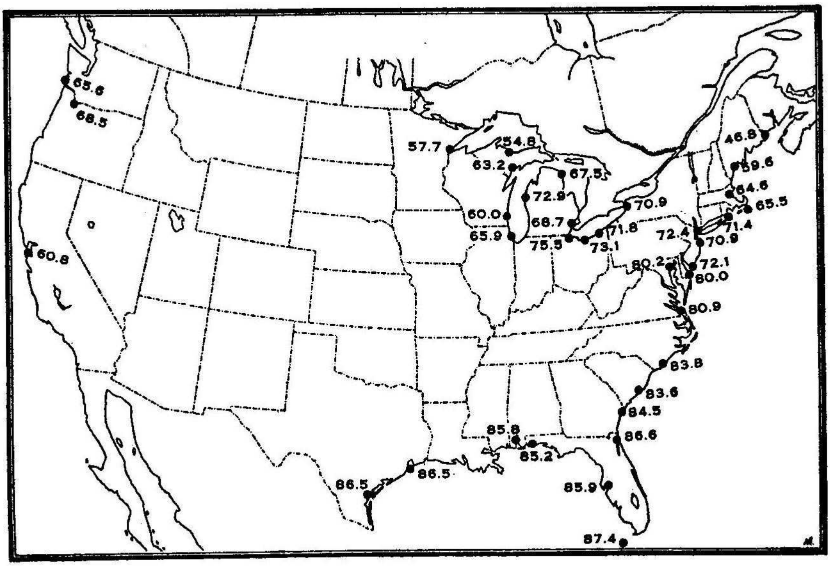

FIGURE 3.—Water temperatures, July.

controlled surface air, with the net result that surface velocities are increased and upper air velocities are decreased. The late-afternoon decrease of wind velocity is owing to the dominance of surface friction in the absence of convection. Furthermore, there are local characteristics of wind direction under slight barometric gradients which should not be overlooked. Especially is it important in temperature forecasting to consider the effect of the land and sea breezes

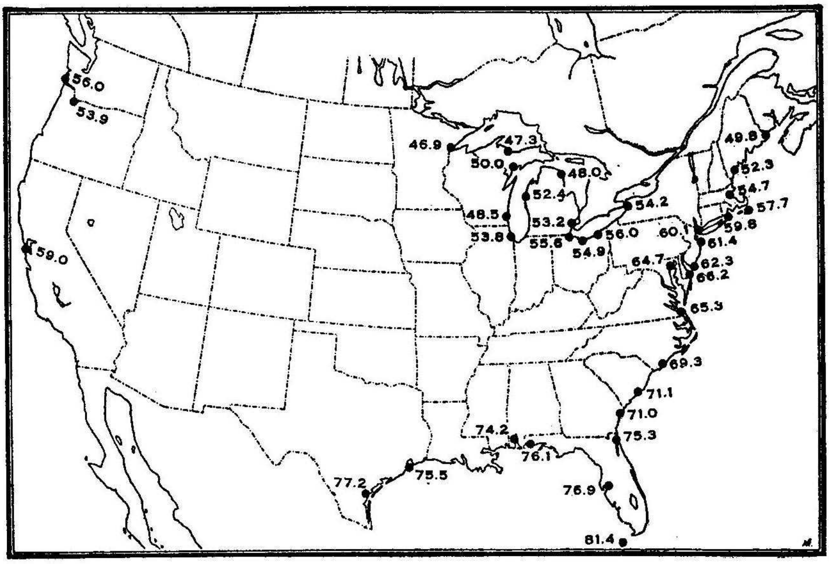

FIGURE 4.—Water temperatures, October.

and the land and lake breezes which occur during the prevalence of slight barometric gradients. It is often a difficult task to judge whether the slight barometric gradients will be sufficient to overcome the land- and sea-breeze tendency. Of course, when the barometric gradient is large, the land and sea breezes are entirely overcome, but the tendency remains, nevertheless, and causes the actual velocity to differ more or less from that indicated by the current barometric gradient.

There are also well-known diurnal effects on mountains and in valleys, up-slope winds prevailing during the day and down-slope winds at night.

TOPOGRAPHIC

Topography has an important effect when air drainage gives rise to pooling effects, as indicated by the fact that on clear nights the hollows or valleys become 10° or more colder than the surrounding higher ground.

Snow flurries in the northern Appalachians accompanying winds that are stronger than fresh are good examples of the effect of topography. The snow flurries, with fresh to strong winds on the windward shores of the Great Lakes, need a little explanation. The air current, while crossing the lake, picks up some moisture and, being unimpeded by appreciable surface friction, reaches the shore as a fresh to strong wind. Here the land, with its trees and other obstructions, retards the flow of air at the surface and thereby builds up a wedge of dense air from the ground that causes enough lifting to produce, especially when the surface is very cold, flurries and light falls of snow along the lake shore and even for some distance in the interior. Any hills or rises of the land tend to accentuate the wedge effect. It might be questioned whether much moisture is picked up in passing over the lake. That is answered by certain observations in April 1935, when considerable increases in the specific humidity of a crossing current were noted up to 1,000 meters. At times of strong winds snow flurries may be experienced considerable distances inland. Similar effects may also occur along the coast of any large body of water when the winds are of sufficient velocity and are blowing onshore, and may even give rise to thunderstorms along the Gulf and occasionally along the South Atlantic coasts.

Topography becomes quite important in the study of vertical cross sections. In drawing isobars it is advisable to consider the temperatures at elevated stations, since the pressures due to reduction to sea level may be out of step with surrounding stations by reason of the temperature arguments used in the reduction; too high if the local temperatures are abnormally low and too low if the local temperatures are abnormally high.

GENERAL

Cloudiness acts as a blanket in conserving the heat of the air in the layers near the surface. During the night it prevents the usual cooling by radiation, but if the cloud blanket is high it has but little effect. During the day even a high cloud blanket will prevent intense heating by the sun's rays.

Frosts form on clear and quiet nights when the temperature and humidity conditions are favorable, but they do not form when the sky is generally overcast nor when the wind is blowing with appreciable velocity. In the first instance, the cloud layer by its own radiation to the earth prevents marked surface cooling; while in the second, the wind causes mixing through turbulence and thereby distributes the loss of heat through a relatively large mass of air and correspondingly reduces the fall in temperature at the surface of the earth.

Fog of the radiation type is prevented when the wind velocities are more than 6 miles per hour, due to the turbulent mixing of the layers of the air near the surface with those next above and also when cloudiness prevails. It is well known that in air that remains absolutely calm, fog can only form in a thin layer, probably not more than a foot or two thick, immediately next to the ground.

Up-slope and down-slope winds are effective in producing temperature changes. It is well known that air moving up slope becomes cooled, due to adiabatic expansion, while air moving down slope becomes warmed through adiabatic compression. Such warming is illustrated by the chinook (foehn) winds of some of our western Mountain and Plain States, during the prevalence of which marked rises of temperature have been reported, amounting in some cases to 40° or more in an hour.

On the average there is somewhat greater deviation of the wind direction from the tangent to the isobar in the HIGH than in the LOW. The amount of incurvature at the surface in the LOW averages about 40° over land and about 30° over the ocean. At the gradient level, 500 meters over both land and water, the wind direction is approximately tangent to the isobars at that level. The wind velocity near the surface is about one-half the gradient value over land and about 60 percent to 70 percent over water.

To have even fairly general precipitation in a given region, it is necessary to have considerable moisture in the air over that area. This moisture may be imported directly from some large water body by the winds prevailing at and preceding that time. In regions bordering on the Gulf of Mexico and the Atlantic and Pacific Oceans the distance of the transport is small, but in the upper Mississippi Valley and northern Plains States the moisture is not transported in all cases directly from the water body. It is believed that for these far-inland regions some moisture is carried by relatively easy stages and by several separate steps from distant moisture sources. For example, moisture from the Gulf is precipitated over the northern Gulf States, then reevaporated and carried farther north one or more times before it finally reaches the upper Mississippi Valley, where it is again precipitated. Undoubtedly a large part of the moisture precipitated in the northern Plains States comes originally from the Gulf of Mexico and another considerable part over the mountains from the Pacific. Air-mass analysis shows that in the case of some of the lighter shower types precipitation occurs when air, identified by means of its characteristics and previous history, has come from the Pacific. It is believed, however, that the heavier falls of precipitation may be traced back directly or indirectly to the Gulf.

The Great Lakes, large though they be, are not sufficiently large to give to the air passing over them enough water vapor to cause more than light precipitation, except possibly very occasionally. The idea has been advanced that if the first LOW of a series is wet, that is, attended by general precipitation, the succeeding LOWS will be wet, and vice versa. Such a thought is undoubtedly linked up with the phenomena of reevaporation and reprecipitation or with maintenance of currents from main moisture sources. It is known that general rains do not fall in the middle Mississippi and the Ohio Valleys unless, for 24 to 48 hours preceding it, there are south or southwest moist winds from the Gulf in levels between the surface and 2 to 4 kilometers over the middle Gulf States and eastern Texas. This increase in moisture may be verified by the increase in humidity readings aloft from radiosonde observations at Oklahoma City and Nashville.

CYCLONES AND ANTICYCLONES

SURFACE STRUCTURE

The cyclones and anticyclones, or LOWS and HIGHS, shown on the weather map are systems of winds conforming to the pressure distribution. Anticyclones of the Northern Hemisphere are wind systems in which the surface air is directed spirally outward from the center, turning to the right or in the direction of the hands of a watch, face up. They are identical in location with the HIGHS, or high-pressure areas. The cyclones of the Northern Hemisphere are wind systems in which the surface air flows spirally inward toward the center, turning counterclockwise, and are identical in location with the LOWS, or low-pressure areas. In reality these wind systems are made up of cold and warm air masses. Roughly speaking, the eastern part of the HIGH and the western part of the LOW may be considered as one unit, and the western part of the HIGH and the eastern part of the LOW as another unit. In the first, surface temperatures are low or falling and the pressure rising, while in the latter, temperatures are high or rising and the pressure falling. A still better way of viewing these HIGHS and LOWS was emphasized about 20 years ago by the Norwegian school of meteorologists at Bergen, and is sometimes referred to as the frontal system. This system not only pictures the wind systems of the cyclones and anticyclones at the surface but in the vertical sense as well. In the following section this system will be described.

BAROMETRIC PATTERNS

The configuration of isobars on weather maps was discussed by Abercromby (*1*) as early as 1887. As his classification of HIGHS and LOWS was based on a study of barometric types experienced in the British Isles and western Europe where the climate is largely of a marine variety, it was decided to modify his types slightly, as was done on a former occasion (*30*) to conform to those of North America, where the weather is conspicuously continental.

From the viewpoint of barometric patterns, LOWS may be divided into three classes as follows: (1) The round LOW, (2) the trough type, and (3) the col, or saddle. The round LOW is the type in which the isobars are roughly circular, and is best exemplified in hurricanes, but even in these the isobars are not strictly circular except possibly very close to the center. In extratropical LOWS, isobars have a tendency to become roughly circular in the United States after a LOW has moved northward with a considerable increase in intensity and is in process of occlusion. Generally speaking, this class may be described more specifically as one in which most of the inner isobars are roughly circular. The trough type includes in our classification those of the V type, the inverted V, and the elliptical type. In the V type the central isobars, of which there are often several, may be more or less circular in the northern end of the trough, but the isobars next outward from the center have a V form. In such cases the HIGHS are generally situated to the west and to the east of the LOW center. In the inverted V type the isobars may be similarly described, except that the whole pressure field is inverted in a north and south sense, the HIGHS in such case being to the northwest and northeast of the LOW center. The elliptical type is one in which the isobars are oval, the major axis being to the minor axis in the ratio of 2 or more to 1. There may be a center in one end of the oval, or there may be a center in each end, with occasionally a third center in the middle. The outer isobars on the east and west sides frequently trend north and south and may be approximately straight. Such a system, with its several centers, does not retain its form for any length of time, because one of the centers deepens and the whole system changes shape, generally into the V type. The col, or saddle, is a system of isobars involving a LOW, generally of slight intensity, saddled by two HIGHS, one to the northwest and the other to the northeast of the LOW center, with relatively high pressure between them. It is sometimes the forerunner of the inverted V type.

HIGHS may be subdivided similarly into (1) the round, (2) the elliptical, and (3) the wedge type. The round HIGH is characterized by circular isobars and generally moves rapidly. The elliptical, or elongated, HIGH is the most common and needs no further comment except to state that the isobars are roughly elliptical. The wedge type consists of inverted V-shaped isobars, with occasionally a round isobar in the opening of the inverted V. In such cases LOWS are generally situated to the northeast and to the northwest of the HIGH center.

Thus far the cyclones and anticyclones have been discussed only from a pressure, temperature, and wind viewpoint, and that only at the surface, but in the following section their vertical structure will be taken up.

FRONTS

AIR MASSES

Masses of air that remain for some time over particular regions of considerable extent develop properties that are characteristic of the region, especially as regards temperature and moisture. Consider, for example, the Gulf of Mexico, where temperatures are high and the moisture content is large. A mass of air overlying such a region gradually acquires properties that are characterized by high temperatures and large moisture content, not only at and near the surface, but gradually in intermediate, and finally in upper levels, due mainly to convection. On the other hand, let us consider the region of northwestern Canada where, in the winter season, temperatures and humidities both are low. Such characteristics will be transmitted first to the lower layers by mixing, due to turbulence, and gradually to higher and higher levels until an equilibrium condition is finally reached. Some idea of the time required for the cooling to progress from the surface to higher levels is given in papers by Wexler (*46*, *47*).

With respect to the two masses, the Gulf air on the one hand and the continental Canadian air on the other, the characteristics are imparted more rapidly and to greater elevations in the former than in the latter, because convection extends to high levels over the Gulf on account of the more intense surface heating in the lower latitudes, and the obvious further fact that air moving from a cold to a warm region becomes increasingly unstable, while the reverse is true for air moving from a warm to a colder region.

The process of transmitting these characteristics to considerable elevations is slow, probably occupying several days over the warm Gulf and a week or more over the interior of northern Canada. A longer time is required to impart characteristic properties to air moving from the Tropics to polar regions than to air moving from polar to tropical regions.

The principal classes of air from a thermal standpoint are polar, or cold, and tropical, or warm. These are further subdivided on the general basis of moisture, being separated into two main classes, depending on whether the source is land and dry, or water and moist. The source regions, as they have been termed, are important in studying weather conditions. American air masses as classified by Willett (*48*) are listed in table 1, with the abbreviations commonly employed to designate them.

TABLE 1.—*Classification of American air masses, after Willett*

Source by latitude	Natural	Classification of local source regions	
		Local source region	General classification with symbols
Polar (P)	Continental	Alaska, Canada, the Arctic	Polar Candian, Pc.
		Modified in southern and central United States.	Neutralized polar Canadian, Npc.
	Maritime	North Pacific Ocean	Polar Pacific, Pp.
		Modified in central and western United States.	Neutralized polar Pacific, Npp.
		Colder portion of the North Atlantic Ocean.	Polar Atlantic, Pa.
		Modified over warmer portions of North Atlantic Ocean.	Neutralized polar Atlantic, Npa.
Tropical (T)	Continental	Southwestern United States and northern Mexico.	Tropical continental, Tc.
			Neutralized tropical continental, Ntc.
	Maritime	Gulf of Mexico and Caribbean Sea	Tropical Gulf, Tg.
		Modified over the United States or over the North Atlantic Ocean.	Neutralized tropical maritime, Ntm.; neutralized tropical Gulf, Ntg.
		Sargasso Sea, Middle Atlantic	Tropical Atlantic, Ta.
		Modified in United States or over the North Atlantic Ocean.	Neutralized tropical maritime, Ntm.; neutralized tropical Atlantic, Nta.
		Pacific	Tropical, dry (Sec-superieur)Ts.[1]

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[1] The tropical sec has been added to Willett's original classification, based on his more recent statement (*49*). It is tropical air probably of high altitude, Pacific origin, that, having crossed the Rockies, descends over the great central valleys. Such air has been identified on the Pacific coast at elevations as low as 500 m. Air of similar characteristics has been observed by others over the eastern part of the United States and western Europe and undoubtedly has its origin over the Atlantic.

Air masses that have acquired characteristic properties are designated by the name or abbreviation of the source region, even though they may have moved to some other region and acquired different thermal and moisture characteristics, especially in the lower layers. When their characteristics have become somewhat modified, their designations are changed by prefixing the letter N, indicating neutralized (transitional or modified). The boundary between air masses is called a "front," or "frontal surface." When one is speaking in terms of conditions in a horizontal plane, for example the earth's surface, the front is a line; but when considering three dimensional situations, the front, or discontinuity, is a surface.

A somewhat different classification of air masses was developed by Bergeron (*3*). His classification is a threefold one, (1) Whether the air is continental or maritime; (2), whether it is polar or tropical; and, (3), whether it is warmer or colder than the surface over which it passes. It will be seen, therefore, that his classification has a more general application and we have been using it recently in the Weather Bureau.

DISCONTINUITIES AND FRONTAL MODEL

The system of fronts, in its more complete aspect, was developed by the Norwegians under Bjerknes (*4*) during and immediately following the World War and, while certain features of the system have been modified, some of the main concepts remain practically the same up to the present time. A brief description of the system follows:

According to the Bjerknes system a cyclone consists of two essentially different air masses, figure 5 showing the distribution of the elements. While patterned quite closely after the conventional Bjerknes model, it differs therefrom in several respects in order to show better the wind structure of LOWS and HIGHS in this country, but the general principle is the same in both cases. In figure 5 the central section shows the surface distribution with a warm, moist current of south or southwest winds, indicated by the double arrows constituting the warm sector and with cold air at the rear and in front of the warm sector. The warm and cold air masses are separated by fairly distinct boundary surfaces, shown by the broken lines, which pass through the cyclone center and are called the "cold front" where cold air is replacing warm air, and the "warm front" where warm air is replacing cold air. Surfaces of discontinuity are inclined in the vertical always toward the cold side at an angle of slope with the surface of the earth of the order of 1 to 75 or 100 in the case of the cold front and of about 1 to 125 or 200 in the case of the warm front. In figures 5 and 7 the slopes of the warm fronts and the cold fronts are much exaggerated. If drawn to scale and with the vertical and horizontal proportions the same, the fronts would be nearly parallel to the base line representing the earth's surface and would be hardly distinguishable from it.

It will be further noted that the cold front (in the vertical) (figs. 5 and 7, *C*) is not represented by a straight line but has a blunt nose near the surface, due to the slowing up of the surface flow of air on account of frictional and turbulence effects. The top of the nose is, on the average, at an elevation of 1,000 to 2,000 meters, dependent on the temperature difference between the warm and cold sectors. The upper portion of figure 5 shows a vertical east-west section through the cyclone north of the center along line *AA* of the middle portion. Here the air at the surface is moving from an easterly or northerly quarter and is quite cold, as is most always found in the northern quadrants of a LOW. Aloft the wind is from the southwest and, being of tropical origin, is relatively warm and humid. It came originally from lower levels and low latitudes, having undergone a forced ascent over the cold wedge of surface air with the result that there is considerable cloudiness and precipitation, due to cooling by by expansion incident to ascent.

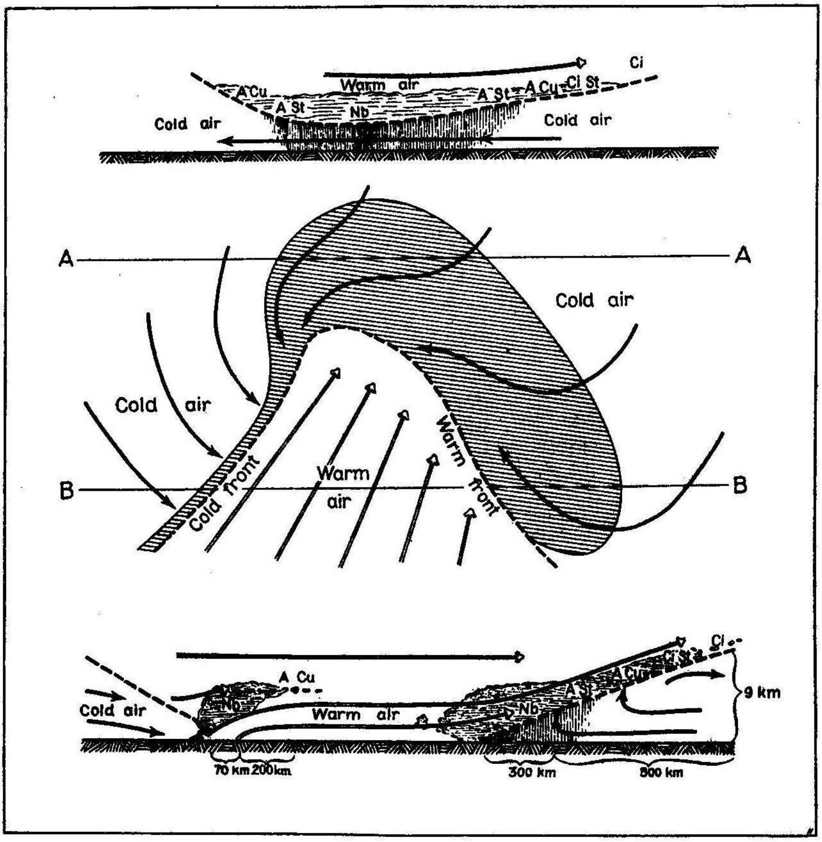


FIGURE 5.—Modified Bjerknes cyclone model.

The lower portion of figure 5 shows another verticle east-west section through the cyclone south of the center along the line *BB* of the middle portion. At the left are seen the cold polar surface winds from the west and northwest underrunning the warm, moist, tropical winds from the south and southwest, which latter persist aloft after the winds have changed to westerly at the surface. This underrunning results in forced ascent of warm, moist air from the south with resulting cloudiness and occasionally heavy and, as a rule, brief showers. This front is called the "cold front" and is generally identified with the squall line, or trough of the LOW. At the right of the section there is the relatively warm southwest winds aloft overrunning the colder surface air from the east, giving wide spread cloudiness and precipitation. In the central figure the line trending southeast from the LOW center shows the position of the warm front while the cold front extends southwestward from the center of lowest pressure. Between the warm front and the cold front, at and near which cloudiness and precipitation are in evidence, there is a region of warm air and relatively clear sky and sunshine, although cumulus clouds are to be expected, and at times scattered local showers because of conditions favorable to convection. It will be noted that a narrow band of showers is pictured along and immediately behind the cold front, which showers, however, are entirely absent in many cases.

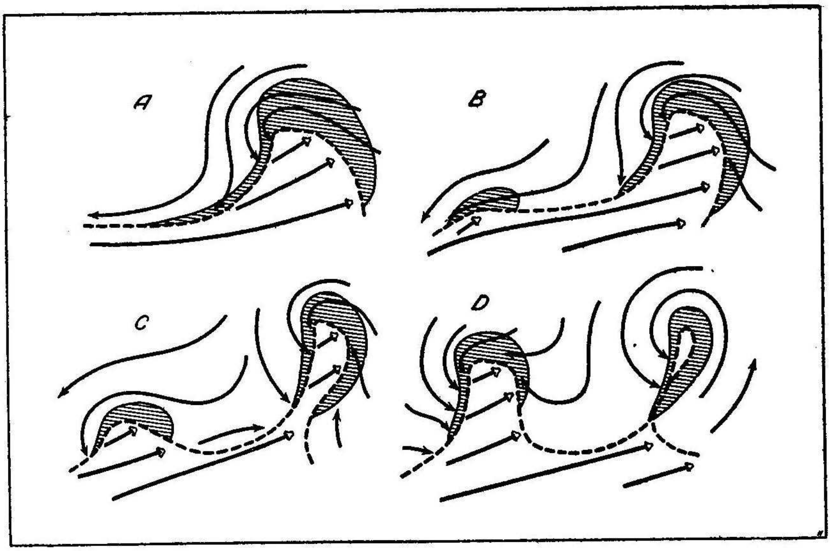


FIGURE 6.—Stages of cyclone life cycle.

At and immediately ahead of the warm front, on the other hand, the area over which the rain is falling more or less steadily is relatively broad, the rain being due to the upflow of the warm, moist south and southwest current over the cold, dense current from the east and southeast, which produces adiabatic cooling. It will be noted further that on the warm front, warm surface air is replacing cold and that on the cold front cold air is replacing warm. What may be a cold front today may, therefore, become a warm front tomorrow, and such occurs in certain cases. A stationary front is one along which there is neither replacement of warm air by cold, nor cold air by warm. Cyclones have a regular life history; they develop, increase in intensity for a while, and later occlude and die out. In the United States about 40 percent of the cyclones observed develop within its borders or over the waters immediately adjacent thereto. Cyclones frequently occur in families on lines and surfaces of discontinuities separating cold, polar air from warm, tropical air. The point where the development takes place is where a bend or wave develops in the line or surface of discontinuity (fig. 6, *B* and *C*), generally to the south or southwest of the anticyclone that follows the parent LOW. The family, or series, may consist of 2, 3, or even 4 individual LOWS, each one starting successively farther and farther to the south and east.

When the cold front advances more rapidly than the warm front, as is the case in most instances, they gradually get closer and closer together and finally meet, as indicated in figure 6, *D*. The south and southwest currents constituting the warm sector give place to the polar air at the surface at first, which gradually extends to greater and greater heights until the supply of warm, tropical air has been shut off completely. Such a process is called an "occlusion." Of the occlusions there are two types: One with a cold-front aspect, as indicated in figure 7, *A*, and another with the warm-front aspect, as

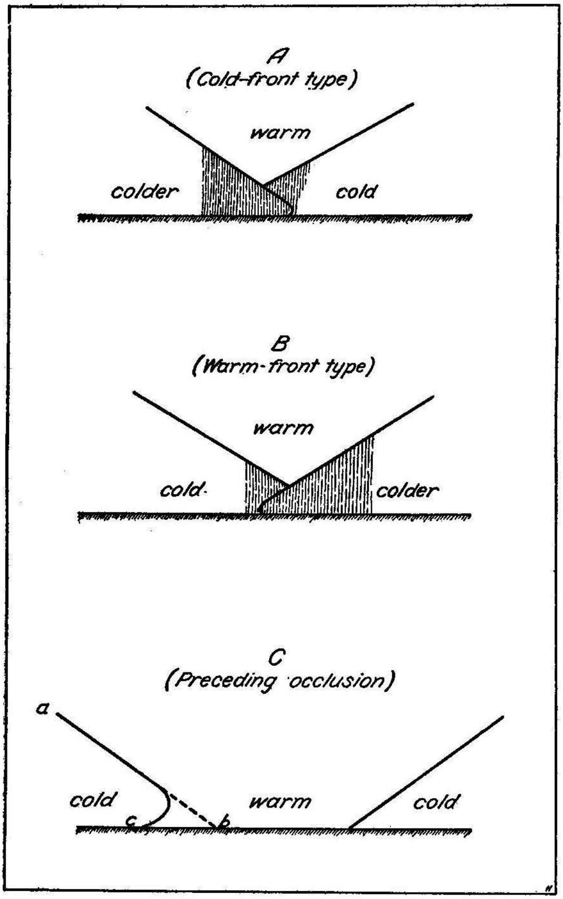


FIGURE 7.—Types of occlusions.

indicated in figure 7, *B*. In the former the precipitation occurs more on the cold-front side and in the latter mostly on the warm-front side. In the first the cold air to the west is colder than the cold air to the east, and in the latter the reverse is true. A variation of these types is known as the "back-bent" occlusion, some cases of it at least having been formerly viewed as a secondary cold front. Apparently the distinction between a secondary cold front, as distinguished from the back-bent occlusion, is that in the latter a valley or trough of warm air persists aloft, whereas in the former there is no warm sector aloft. Recently we are inclined to believe that the secondary cold fronts are often due to frontogenesis. Following occlusion a LOW generally decreases in intensity and the isobars tend to become more nearly circular. Regeneration or redevelopment takes place when a LOW increases in intensity after having first decreased. The term "frontogenesis" is used to mean the genesis, or birth, of a front and "cyclogenesis" the development of a disturbance on a front, while "frontolysis" indicates the dissipation of a front.

An examination of the pilot-balloon observations in connection with the surface weather maps gives a very good idea of the wind structure of LOWS and HIGHS, but actual temperature and humidity observations in the free air are necessary to get a definite idea of the more significant conditions pertaining to stability and precipitation processes. To accomplish this most effectively a large number of airplane flights is required. At present the schedule provides for only 34 radiosonde observations each morning to represent the whole United States. While a larger number is greatly to be desired, a good deal can be accomplished with the material available. The intensified methods of air-mass analysis, which were developed at Bergen and have been applied to conditions in this country by Rossby and Willett at the Massachusetts Institute of Technology, permit the identification of air masses through the conservative properties that characterize them largely by aid of the data from radio-sonde observations.

A number of rules or axioms regarding frontal considerations have been published from time to time. Recently a most complete list of them has been presented by Chromov (*14*) in Russian. An English translation was made by Schell (*39*). Rules are also given by Petterssen (*31*).

AIR-MASS ANALYSIS

The President's Science Advisory Board, in its report of November 13, 1933, referred to air-mass analysis as "an aid to forecasting " The assistance that can be obtained from it, added to the experience gained from the study of the weather maps, has proved a valuable adjunct in the forecast work. Forecasters of the Weather Bureau have used air-mass analysis increasingly ever since kite and pilot-balloon observations were available by telegraph.

Weather Bureau forecasters depend more and more on upper-air observations and analyses of the air masses. Byers (*12*, pp. *147–155*) has pointed out in his chapter on weather forecasting that—

> The ability to forecast weather accurately comes as much from experience as from study. The rules for prediction cannot be stated simply and it is extremely difficult to attain success in forecasting through formal study or instruction.

Later he says:

> In general, it may be stated that the second step in forecasting is the application of all of the forecaster's knowledge of meteorology, augmented by thermodynamic calculation to the problem at hand. * * * It is evident that much depends on the judgment of the forecaster in weighing the different contributing factors.

In fact, meteorologists and forecasters are a unit in advocating the application of mathematics and physical principles as far as possible to the problem of forecasting. It is proper to say, however, that while a great deal of progress has been made, much remains to be accomplished. At present the development of the analysis of the current map has made more progress than the forecasting of the future positions and characteristics of the air masses. It is expected, however, that more attention will be given to the latter.

Practical precepts gained from experience should, in fact, be preserved and every effort made to add to them, for it will be some time yet before the application of the air-mass analysis to actual forecasting is sufficiently developed to serve as the sole basis for making weather predictions. The greatest assistance from it is manifested in the shorter period forecasts (*11*), although its application to longer-period forecasts of 24 to 48 hours has been also amply demonstrated, and it is actually being used in some cases by the Norwegian Weather Service in weather outlooks several days in advance for fishermen.

Air-mass analysis may be defined as a careful study and analysis of preceding and present meteorological conditions over the region of observations, particularly as regards the temperature and moisture properties of the air, the frontal structure, and their bearing on stability.

Precipitation is brought about by the lifting of air and the adiabatic cooling resulting from it. This lifting may be accomplished in several different ways: (1) Due to frontal action, (2) by insolational heating leading to instability and thermal convection, (3) by topography, and (4) by convergence. All depend largely on the moisture content and the amount of cooling through lifting. That caused by topography is fixed as to place, while the other three may occur in any geographic location.

Air is said to be stable when it remains in or tends to return to its former position following displacement. If displacement results in a tendency to further movement away from its original position, the original condition is designated unstable. Neutral equilibrium is the condition under which air neither resists nor assists displacement. These three conditions are different for dry and saturated air. An idea of whether a mass of air is stable or unstable may be obtained by comparison of the lapse rate of temperature of the particluar air mass with the adiabatic lapse rate. For dry air, the latter is about 1° C. per 103 m., and is commonly called the dry adiabatic. The adiabatic lapse rate of saturated air is less than that of the dry air because liberation of the latent heat of condensation has the effect of lessening the rate of temperature decrease, due to expansion with increased altitude. Therefore, for dry air to be unstable the lapse rate must be greater than the dry adiabatic, and for saturated air the lapse rate must be greater than the saturation adiabatic. Under conditions of neutral equilibrium the actual lapse rate of dry air is the same as the dry adiabatic, and for saturated air the same as the saturation adiabatic. Another term that is often used in connection with air-mass analysis is "conditional instability," which is a condition of an air mass when the temperature lapse rate is between the dry and the saturation adiabatic, under which conditions it is stable for dry air and unstable for saturated air.

While temperature is helpful in identifying the source of an air mass, moisture content must also be considered, as well as changes in both of them due to exposure to the different conditions in the region to which the air mass has moved. Evaporation and condensation as applying to the moisture content and adiabatic changes as affecting temperature are the most important factors in changing the properties of air masses. In efforts to secure an index which will remain as constant as possible with change of height and resulting change of temperature, equivalent potential temperature has been used to represent temperature, and specific humidity has been employed to represent the moisture content. For detailed development of these indices the reader is referred to the work of Rossby (*35*) and to a series of papers in a more popular form by Namias (*29*). In brief, equivalent potential temperature may be defined as the temperature a particle of air would have if it were lifted pseudoadiabatically (approximately at the saturation adiabatic rate) until all its moisture had been removed, all the heat of condensation of water vapor being added to the air, and the sample of dry air then compressed to a pressure of 1,000 millibars (29.53 inches) Specific humidity is defined as the mass of water vapor per unit mass of moist air (grams of water vapor per gram of moist air). The Rossby diagram was devised to obtain the equivalent potential temperature, the ordinates of the diagram being the partial potential temperature (or the potential temperature of dry air) and the abscissae being the mixing ratio (or amount of moisture in grams per kilogram of dry air).

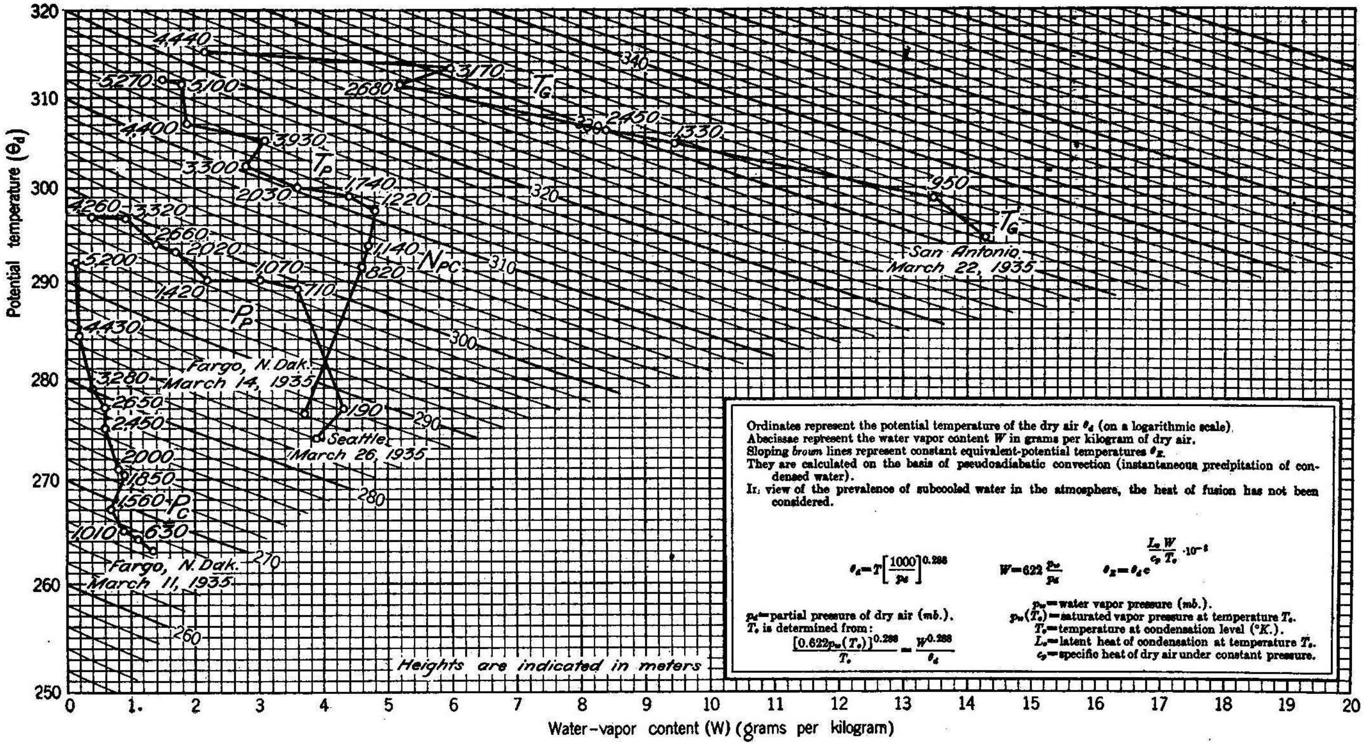
In actual practice, however, the potential temperature, which differs only slightly from the partial potential temperature, is used for the ordinate; and the specific humidity which is a very nearly equivalent quantity, is employed in place of the mixing ratio for the abscissa. Generally speaking, graphs showing the equivalent potential temperatures on a Rossby or similar diagram (fig. 8) are useful in determining the properties of an air mass and, inferentially, its origin. In brief, it is found that, when the curve or line connecting the points representing equivalent potential temperatures is nearly vertical on the left-hand side of the diagram where the specific humidity is small, the air is dry at all levels, cold at the surface, and warmer aloft. These properties are characteristic of polar continental air. (See the Fargo graph of March 11, 1935, in fig. 8.) When the curve is nearly horizontal, showing warm air at the surface and aloft and with high humidity at the surface decreasing with elevation, the characteristics are those of tropical ocean or tropical Gulf air. (See the San Antonio graph in fig. 8.)

In addition, cross sections of the United States, east and west and north and south, are prepared each day showing equivalent potential temperatures based on potential temperature and specific humidity to assist in analyzing the air masses in the vertical and to give a more precise idea of the slope of the surfaces of discontinuity (*50*, *51*). The adiabatic diagrams also are of considerable assistance.

The characteristics of American air masses have been discussed by Willett (*48*), and air masses in the Pacific States by Byers (*10*). It will be apparent how helpful it is to know how near a mass of air is to instability and how much lifting will be required to produce condensation, which can be obtained from the Refsdal or other similar diagrams. The characteristics of air masses may be brought out in a number of different ways by means of the data from radiosonde observations. In the current forecasting work at the Central Office adiabatic charts are plotted for each station. For a while charts showing the temperature lapse rate between 2,000 and 4,000 m. were prepared. All methods essayed so far have drawbacks. If individual stations are used, there are blind spots between them. If charts for different levels are employed, there are blind spots between levels. The consensus of opinion is that the better method is to plot by stations, supplemented by cross sections.

It was realized by Shaw (*41*) that air flow was not parallel to the earth's surface, but was along surfaces having what he called equal entropy, i. e., along isentropic surfaces or surfaces having the same potential temperature throughout. Studies made by Rossby (*35*, *36* *37*) and collaborators have further developed this idea and have utilized the isentropic surfaces on which flow patterns of particular moist and dry masses of air are traced from day to day. This they were able to do by identifying the particular masses or tongues by means of potential temperatures and specific humidities. Byers (*13*) has suggested the use of condensation pressures instead of specific humidities which can be correlated with the pressures at the isentropic surface, and from the difference between the two pressures the amount of lifting necessary to produce condensation can be easily obtained. At the Washington forecast center these isentropic charts are available to the forecaster each morning as a regular program and have been found of considerable help. They explain in some cases precipitation that is not explainable by the frontal analysis and constitute an added tool for investigating the physical processes of the weather (*44*).

An isentropic chart for March 29, 1939, on the 301° potential-temperature surface is reproduced in figure 9. The solid lines represent the pressures in millibars at the potential-temperature surface, while the broken lines indicate the pressure to which the air particles in the potential-temperature surface would have to be reduced in order that saturation take place. The hatched section represents the areas over which the condensation pressure is the same as the pressure at the isentropic surface. Moist and dry-tongue-flow patterns are shown by heavy arrows, M indicating moist and D indicating dry. Figure 10 gives a north-south vertical cross section from Sault Ste. Marie to Pensacola for March 29, 1939. In this figure the solid lines indicate potential temperatures, while the broken lines indicate specific humidities or grams of moisture per kilogram of moist air.



Ordinates represent the potential temperature of the dry air θ_d (on a logarithmic scale).
Abscissae represent the water vapor content W in grams per kilogram of dry air.
Sloping *brown* lines represent constant equivalent-potential temperatures θ_E.
They are calculated on the basis of pseudoadiabatic convection (instantaneous precipitation of condensed water).
In view of the prevalence of subcooled water in the atmosphere, the heat of fusion has not been considered.

$$\theta_d = T\left[\frac{1000}{p_d}\right]^{0.288} \qquad W = 622\,\frac{p_w}{p_d} \qquad \theta_E = \theta_d\, e^{\frac{L_c}{c_p}\frac{W}{T_c}\cdot 10^{-3}}$$

p_d = partial pressure of dry air (*mb.*).
T_c is determined from:

$$\frac{[0.622\,p_w(T_c)]^{0.288}}{T_c} = \frac{W^{0.288}}{\theta_d}$$

p_w = water vapor pressure (*mb.*).
$p_w(T_c)$ = saturated vapor pressure at temperature T_c.
T_c = temperature at condensation level (°*K.*).
L_c = latent heat of condensation at temperature T_c.
c_p = specific heat of dry air under constant pressure.

FIGURE 8.—Section of equivalent potential temperature diagram, after Rossby.

THE PROCESS OF FORECASTING

To maintain schedules, forecasts, synopses, etc., based on the 8 a. m. (seventy-fifth meridian time) observations must all be completed before 10 a. m.; that is, the receipt and plotting of the reports, the study of the maps, and the issuance of the forecasts, warnings, summaries, and bulletins must be completed within 2 hours of the time the observations are taken at the field stations.

Let us, therefore, view the problem of weather forecasting from synoptic charts on the basis that there are available the surface, pilot-balloon, and radiosonde observations. In other words, suppose the same situation exists that district forecasters of the Weather Bureau have had since the upper air data became available from 25 or more stations.

It will be well in the beginning to describe briefly the periods for which the district and State forecasts usually are made.

The forecasts for the States made at the district forecast centers, prepared on the basis of the 7:30 a. m. (seventy-fifth meridian time) observations are undoubtedly used more widely by industries and others than the forecasts issued on the 7:30 p. m. observations. They are for the periods tonight and tomorrow (naming the day of the week following the day of issue). Tonight covers the period between 7:30 p. m. of the current day and 7:30 a. m. of the following day, and tomorrow covers the period 7:30 a. m. to 7:30 p. m. of the following day. Therefore, the 12-hour precipitation found on the 7:30 a. m. map of the following day justifies a forecast of precipitation, or weather, for tonight; and 12-hour precipitation found on the 7:30 p. m. map of the following day verifies the period denominated tomorrow. Temperature is verified in a similar manner, with this variation—the temperature change in 24 hours ending tomorrow at 7:30 a. m. verifies the tonight period, and the 24-hour change on the 7:30 p. m. map of the following day verifies tomorrow. For the tonight period it is necessary to forecast only the temperature at 7:30 a. m. tomorrow, but for the tomorrow period the Bureau has to forecast not only what the temperature will be at 7:30 p. m. of the current day but also at 7:30 p. m. of the following day.

Forecasts based on the 7:30 a. m. map appear in the afternoon and evening papers, while those issued on the 7:30 p. m. maps, which are made for the 2 days following the day of issue, are the ones that appear in the morning papers.

An attempt will be made to follow in a rather general way the steps through which the forecaster goes in making his predictions. It should be clearly understood that, while comments are offered on the different steps, they do not pretend to be complete and are offered more in the way of suggestion.

DRAWING ISOBARS AND ISOTHERMS

The first thing a forecaster has to do on the map is to sketch the isobars. These are sketched on one part of the map while data are being entered by an assistant on another part. Therefore, when all the data have been entered, it requires only a few minutes to complete the isobars by joining up the portions that have been sketched in.

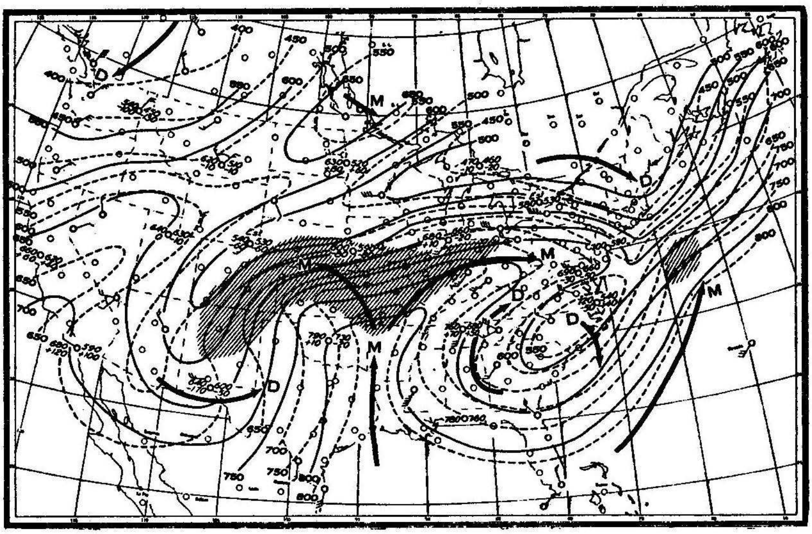


FIGURE 9.—Isentropic chart, March 29, 1939.

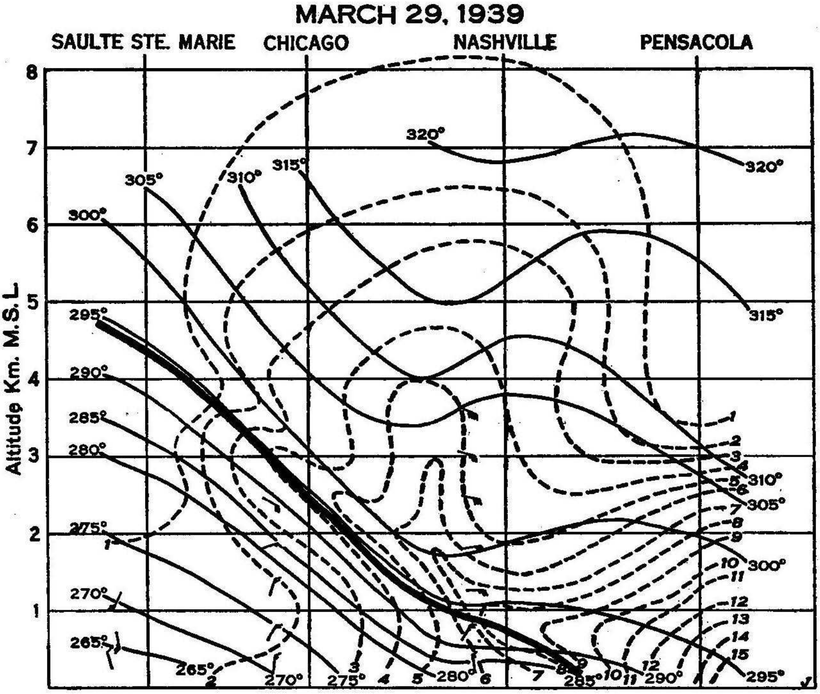


FIGURE 10.—Vertical cross section, March 29, 1939.

Locating Fronts and the Highs and Lows

After locating from the isobars the centers of HIGHS and LOWS, the well-marked cold and warm fronts are located. In general, cold fronts are much easier to identify and locate than the warm fronts. The former are located by considering (1) surface temperature discontinuities, (2) surface wind discontinuities, (3) pressure tendencies and characteristics, (4) dew-point discontinuities, (5) the type of clouds and the character of occurrence of precipitation from which frequently some assistance can be derived, and (6) from previous history. Where there are well-marked temperature and wind discontinuities, there is no difficulty in locating such a front, but, when there is little temperature difference between the usual warm sector and the cold air mass to the west, resort is had to the barometric tendencies (changes in the 3 hours preceding the observation) and other available aids. Steadily rising tendencies (increasing pressure) are characteristic of the cold front and the area immediately behind it, and the amounts are often quite marked. Further behind it the tendencies show rising characteristics, but are not so large in amount. It should be pointed out that in considering wind discontinuities at the cold front, colder air may be carried by winds from any westerly quarter, even southwest in some cases, although normally a southwest wind is a warm one. In a few cases on the New England coast southeast winds have brought in the cold air mass. The warm fronts are far more difficult, as a rule, to place, as has been pointed out in a previous article concerning American fronts (*38*). This is attributable to the thinness of the cold surface air of the shielding layer to the east and northeast of the surface warm front, which, as a result of turbulent mixing with the warmer layer of the overrunning warm sector aloft, encountered at only slight elevations, has its properties somewhat modified in temperature and dew point. Frequently, too, the wind discontinuity is poorly marked or is not in evidence at all. In such cases the occurrence of precipitation at the time of observation a short distance ahead of the surface warm front serves to place the front approximately. The tendencies are also decidedly helpful in that ahead of the warm front the tendencies show steadily falling pressure, while in the warm sector immediately back of the warm front the falls are much less in amount, and often stationary characteristics are reported.

A diagram that was developed in illustrating the reporting of tendency characteristics is given in figure 11. All the cases given are for upper fronts. The heavy dot near the foot of the broken vertical line represents the position of the observer at the ground at the time of observation, and the open circle represents the position of the observer 3 hours before the observation. The fronts are considered as moving from the left to the right, as fronts normally move from west to east, which gives just the reverse of the type of record seen on barograph trace sheets. It will be quite apparent from the diagram that somewhat different characteristics may attend the passage of the same type of fronts. For example: An upper cold front (case 5) may be preceded by "steadily falling" characteristics but may be followed by "falling, then falling more slowly," or "falling, then

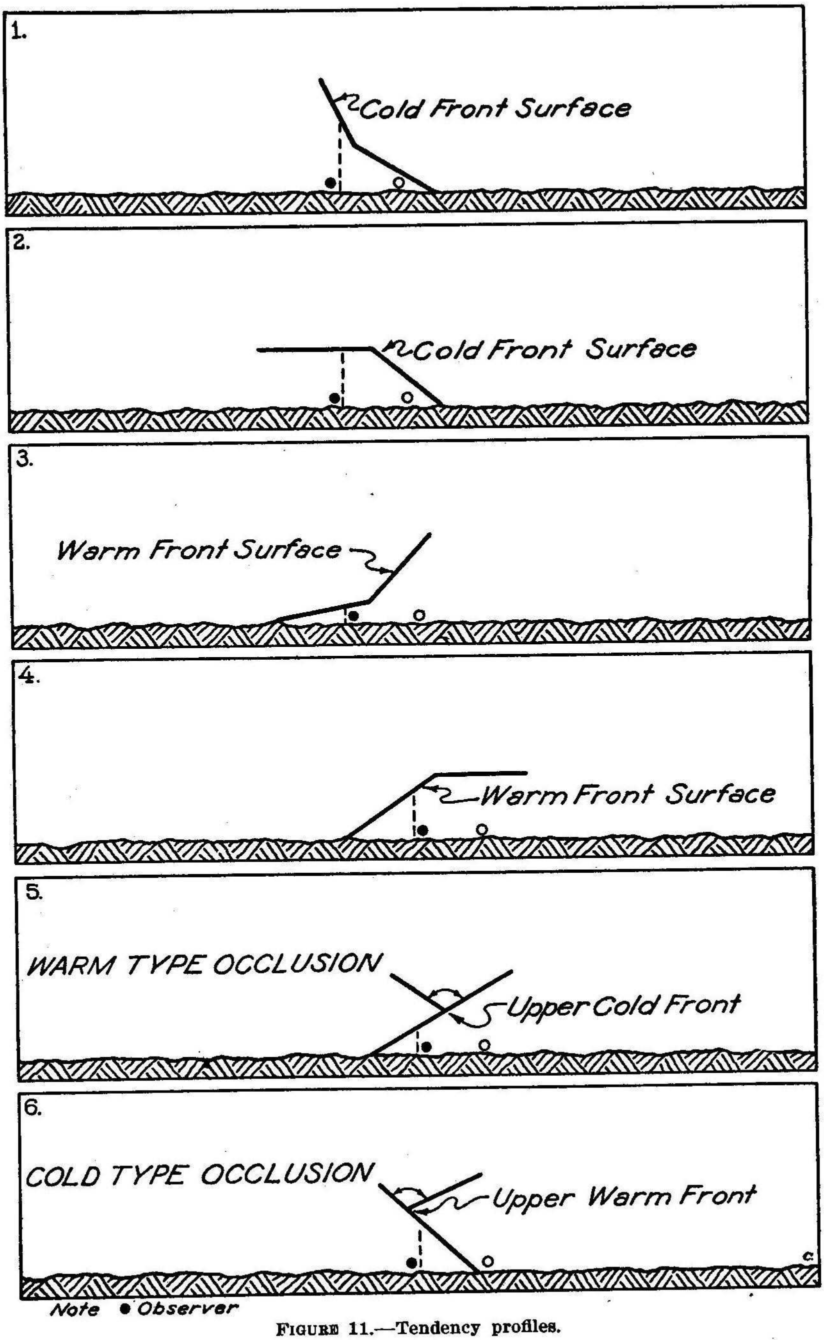


FIGURE 11.—Tendency profiles.

stationary" sometimes even by "falling, then rising," etc. The same remark is applicable to surface fronts; for example, a warm front passage may be preceded by "steadily falling" tendencies but may be followed either by "falling, then stationary" or "falling, then falling more slowly" when the station is near the front or may be followed by "slowly falling," "stationary," or even "slowly rising" tendencies when the station is some little distance behind the front. It is often noted that some distance ahead of the warm front tendencies change from "falling rapidly" to "falling less rapidly." This situation merely means a decrease in steepness of slope of the warm-front surface as shown in case 3. In such cases the active rain occurs ahead of the line where the characteristics change or under the steeper part of the slope; whereas, between the surface warm front and the upper warm front at which the steepening takes place there will be little, if any, active precipitation. This steepening of the front is also noticed in connection with cold fronts, as in case 1, and is frequently accompanied by brief showers.

In the Plains States, due to down-slope effects, the surface air coming from the west is often warmer than the air to the east and, instead of having a cold front, a warm front will ensue. Again, cold fronts in the Rocky Mountain region may disappear or become much less marked as the front moves east over the Plains States, due to down-slope warming action of the surface air. In summer, air near the surface coming from the Gulf is often found to be colder than the air in the interior. With elevation, however, the cold-surface front changes to a warm front.

A good idea of the existence of the warm front action aloft can be gained by noting the presence of alto-stratus clouds, and at higher levels the cirro-stratus and cirrus. The advance of the plus-minus line of 12-hour pressure change (separating an area of falling pressure to the west from an area of rising pressure to the east) is also helpful in identifying the presence of the warm front, as it frequently happens that the plus-minus line is associated with the existence of the warm front aloft. Dew points are often of considerable assistance in locating fronts. Low dew points are characteristic of continental air and high dew points of maritime air. Frequently the differences between the dew point and the current temperature will be found of assistance. The fronts are helpful at times in locating the position of the LOW center, especially in the LOWS where there is no well-marked warm sector and stations are not close together. Isobars are also of assistance in placing fronts when few reports are available, such as over the ocean. Even over the land the change of direction of isobars is of assistance in placing a front.

FORECASTING FUTURE POSITIONS OF FRONTS AND HIGH AND LOWS

After locating the fronts and the HIGHS and LOWS, the next step is to estimate their future movement. As a ground work for this step it will not be amiss to consider briefly the different types of LOWS and HIGHS and their seasonal variations in velocity. The average speed and direction of movement is dependent in considerable measure upon their types, which have been classified according to regions of origin or first appearance by Bowie and Weightman (*7*, *8*). The average 24-hour speed of the different types for the four seasons is given in table 2.

TABLE 2.—*Rate of movement in 24 hours in miles of lows and highs by types and seasons*

Type	Spring	Summer	Autumn	Winter	Year
			LOWS		
	Miles	*Miles*	*Miles*	*Miles*	*Miles*
Alberta	575	496	624	718	605
North Pacific	560	461	581	728	582
South Pacific	551	534	538	702	581
Northern Rocky Mountain	599	508	562	775	611
Colorado	559	516	609	686	592
Texas	623	477	512	735	587
East Gulf	525	412	498	728	541
South Atlantic	512	498	576	662	562
Central	600	474	554	693	580
All types	569	477	589	718	588
			HIGHS		
North Pacific	584	487	555	624	562
South Pacific	540	479	517	589	531
Alberta	540	505	569	584	550
Plateau and Rocky Mountain regions	583	477	545	631	559
Hudson Bay	465	403	433	500	450
All types	550	485	552	594	530

Values for the different seasons were obtained by averaging, without weighting for number of observations, the values for December, January, and February for the winter season; March, April, and May for spring, etc. Of course averages are only the most general guide and every case has to be considered by itself.

When the general eastward movement or drift is normal, i. e., when there is a fairly regular sequence of HIGHS and LOWS, a good index to the subsequent rate of movement is the previous 24-hour movement of the HIGH or LOW. If there is any question about the location of the centers from which to obtain the 24-hour movement, an excellent check can be obtained from the pressure-change chart by measuring the 24-hour movement of the maximum 12-hour-rise center and of the maximum 12-hour-fall center, the movement of the maximum-rise center being associated with the HIGHS and the maximum-fall center with the LOWS. The same principle may be applied to the movement of a trough, as at times the trough is moving faster in its northern than in its southern portion, or vice versa. It is helpful in many cases to trace in on the current map the position of the trough 12 and 24 hours preceding and also the axes of the HIGH. These cases of regularity of movement, which generally occur in the northern half of the country with little if any change in direction, are the simplest of the cases with which the forecaster has to deal, but it is the more complicated cases that cause concern and sometimes even chagrin. The more complicated cases generally involve change of direction and possibly change of rate of speed or the development of a new disturbance.

In forecasting the movement of cold fronts, the winds behind the front give a very good approximation of the speed of movement.

These winds should preferably be the winds at 500 meters elevation. In case these are not available, a speed approximately double that of the surface velocities may be used. Another index that has been found helpful is the geostrophic wind scale, which can be utilized for obtaining the gradient winds from the isobars. The use of such scale is more applicable to estimating cold-front movements, but may be utilized also in connection with warm fronts in cases when there is a well-developed warm sector. The scales used in actual practice are made of celluloid and are graduated to correspond to the projection employed on the base map. Also, they have to be adapted for different latitudes, as explained by Lichtblau (*28*). Lows, with well-developed warm sectors, have an instantaneous movement in the direction of the isobars in the warm sector and the distance moved is directly proportional to the wind speed in the warm sector, which is inversely proportional to the distance between the warm sector isobars.

A few general rules of an empirical character that have been found helpful in such situations follow:

Slowing up of the rate of movement of a LOW frequently presages change of direction. For instance, a LOW that has advanced southeastward through the southern Rocky Mountain region to Texas, with decreased speed, almost always turns to the northeastward and occasionally almost due north. Figure 12 showing map of December 4, 1925, illustrates this case. The change of direction following decrease in speed is as well marked in the case of tropical disturbances as in those of extratropical origin.

When there is a deep stagnant LOW over the Canadian Maritime Provinces and another LOW appears over Manitoba, there is decided probability that the Manitoba LOW will move southeastward until it reaches the Middle Atlantic States, and even sometimes the Caro-

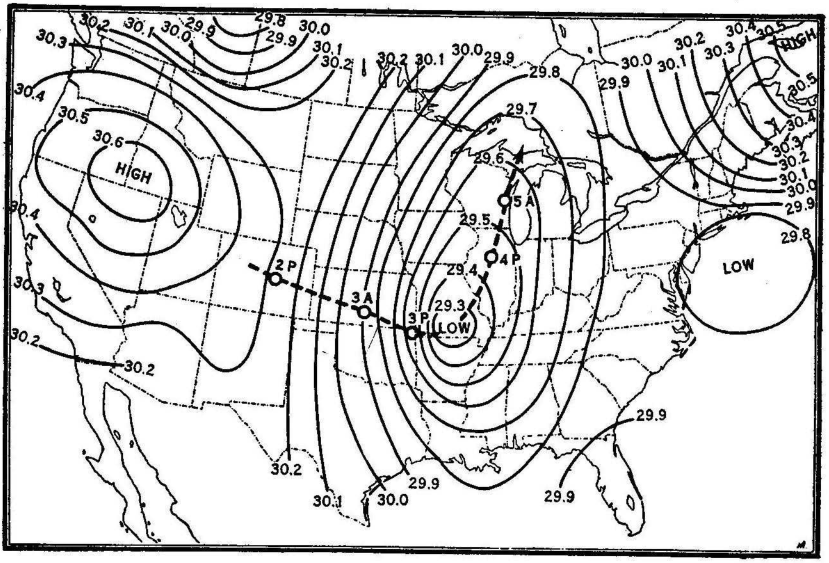


FIGURE 12.—Map of December 4, 1925, showing slowing up of movement presaging change of direction.

linas, without giving precipitation in the North Atlantic States. The map of February 7, 1926, shown in figure 13, is a case of this kind.

If the isobars of a LOW of the inverted V-type have a considerable extension of the point of the inverted V, there will either be a development of another center in the extension of the V or a very rapid movement of the center which is located in the southern or open end of the V. Figure 14 shows the map of February 16, 1925, which exemplifies this type.

When a secondary develops in the ordinary V-type of LOW, in most all cases the secondary will move very rapidly.

In the case of a LOW of the Alberta type, preceded by a HIGH that moves southeastward or south-southeastward from Hudson Bay to the Middle Atlantic States or the Carolinas, the LOW will have a marked acceleration of movement. Figure 15 shows map of February 14, 1934, which is of this type.

If the upper winds at the 2,000- to 4,000-meter levels, in connection with a LOW, back in its eastern half from southwest to south-southwest or to the south, and veer in its western half from northwest to north-northwest or to the north, there will be a very decided slowing up in its rate of movement, but as soon as the upper winds shift back to their original directions, the normal rate of progression will be resumed. (See maps of June 9–10, 1930, and December 16, 1930, available at any district forecast center and many Weather Bureau stations.)

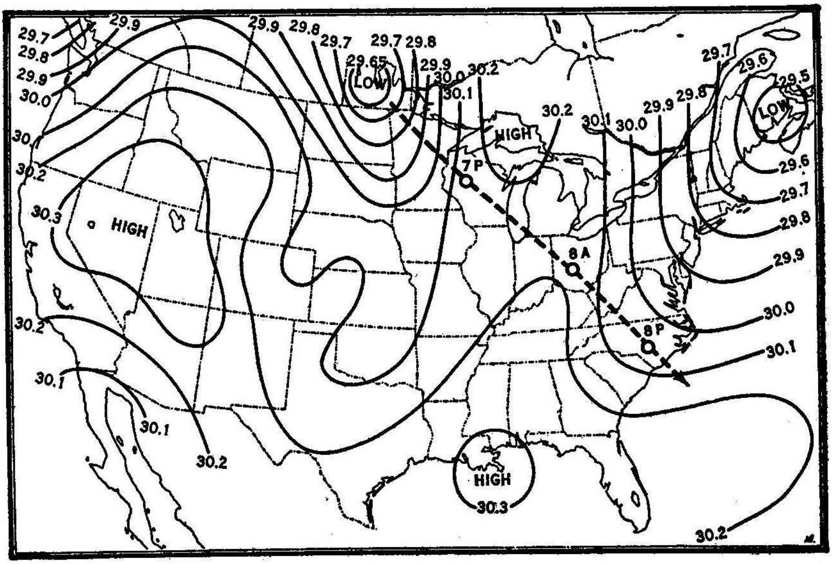


FIGURE 13.—Map of February 7, 1926, showing stagnant low over Canadian Northeast, following which low over Manitoba moves southeastward to the Carolinas.

If the isotherms are crowded in and to the north of a LOW center, the center will tend to move along the isotherms. This rule gives quite consistent results for the subsequent 12 hours, and in many cases for 24 hours. Garriott called the isotherms the "leading strings" of the LOW. Best results are obtained when the isotherms trend nearly east and west immediately north of the center of the LOW.

Consideration should be given to possible blocking effects. Blocked conditions occur most frequently and for longer periods in the spring of the year, due in most cases to the impeding effects of cold air masses that move southeastward from Hudson Bay or regions to the east of it and settle over the Canadian Maritime Provinces, where cold coastal waters prevail and tend to accentuate the coldness of the air and retard the movement of the HIGH. (See maps of April 21–28, 1916, and April 1–8, 1918.) Cases are also found in other seasons of the year. (See maps of June 1–9, 1919). Such blocking is not confined to the Canadian Maritime Provinces. In fact, as Garriott pointed out, slowing up of storm movement in the region of Iceland is followed 5 or 6 days later by slowing up of storm movement over Newfoundland. The retardation in the Newfoundland region may be felt as far west as the Mississippi Valley. It is believed that retardation in any part of the main storm track is reflected after a proper interval in a blocking to the westward along the main storm track. The above cases relate to entire blocking of movement. There are other cases of blocking that result in change of direction. For example, high-pressure areas over and off the Atlantic coast, having little if any eastward movement, cause disturbances coming from the west to be deflected to the northeast in both winter and summer, although the summer is more productive of such cases.

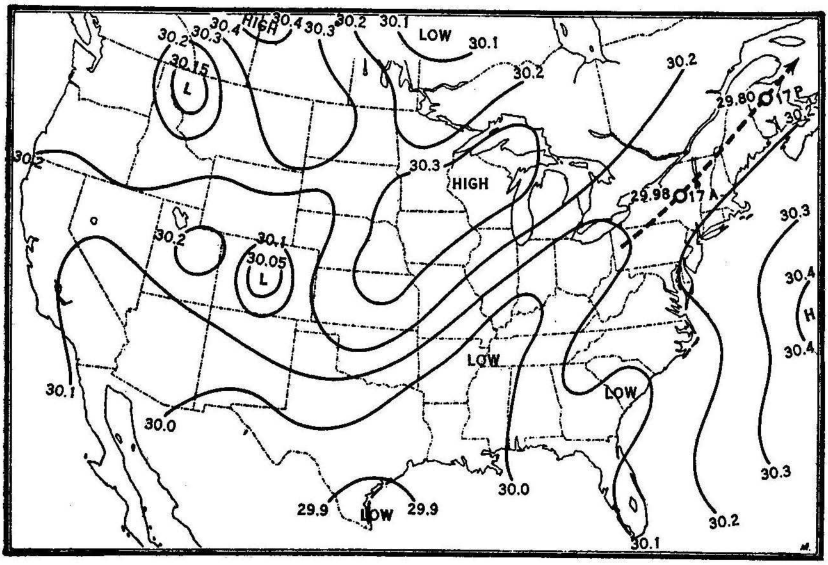


FIGURE 14.—Map of February 16 (p. m.), 1925, showing fast movement of new development in the invested V type.

Of course, if the high-pressure area off the south Atlantic coast is moving, the above does not hold. It is only when the high area is stationary, or nearly so. The reverse is also true. If there is a moving LOW off the South Atlantic coast, cold-air masses and high-pressure areas over the Lake region move rapidly southeastward; whereas, if the low-pressure area, or trough, is stationary off the

South Atlantic coast, changes to colder will take place only over middle and northern sections and will not be felt to the east Gulf coast, or the changes will be delayed.

A method developed by Petterssen, described in the next section, will be found very helpful in forecasting not only the movement of HIGHS and LOWS, but of fronts as well. Forecasting the future movement of fronts and centers will be found to be of vital importance when one attempts to forecast winds, temperatures, and precipitation.

FORECASTING THE DEVELOPMENT AND CHANGES IN INTENSITY OF FRONTS AND HIGHS AND LOWS

Forecasting the development of HIGHS and LOWS is a most important factor in determining future weather. Petterssen (*32*) utilizing the Norwegian concepts, has given some helpful indications of when to expect frontogenesis and cyclogenesis from a consideration of the wind and temperature fields. To get frontogenesis it is necessary to have a considerable horizontal temperature gradient and at the same time a wind field such that temperatures of marked contrast will be brought nearer together or, in other words, steepen the temperature gradient. The axis along which isotherms are being concentrated is referred to as the axis of dilatation, and the general field in which such concentration is taking place is referred to as the field of deformation.

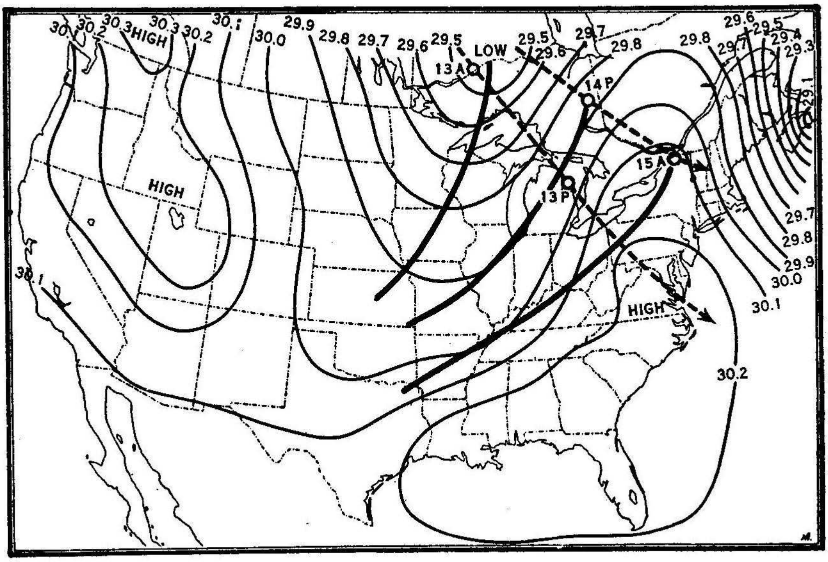


FIGURE 15.—Map of February 14, 1934, showing HIGH moving southeastward from Hudson Bay, followed by accelerated movement of LOW in the West. Heavy lines show subsequent positions of trough.

Forecasting the development of LOWS and HIGHS is quite a difficult task in many cases, but a few empirical precepts which have been found to be of aid will be given.

In most cases new LOWS or secondaries having a wave form develop along old occlusions of the trough of a previous LOW much in the same manner as indicated in figure 6.

The so-called "swinging-trough" type occurs with a **V** type of LOW in which the principal center is over the upper Mississippi Valley or upper Lake region and with its trough extending southward to the Gulf. The main center moves slowly northeastward or east-northeastward, while the southern part of the trough moves eastward faster than the northern part. In many cases a secondary develops in the southern end of the trough and, with rapidly increasing intensity moves northeastward. This is true when a wave forms on the cold front. If pressure at Bermuda is low; the secondary center will pass northeastward off the Atlantic coast, but if Bermuda pressure is high and stationary, the secondary center may cross the southern Appalachian range and move northeastward or north-northeastward over the Middle and North Atlantic States. The map of November 8, 1913 (fig. 16), shows a primary LOW over the upper Lakes with a trough extending southward to the east Gulf States without indications of a secondary center in the southern part of the trough. During the following 12 hours a secondary center developed over the north portion of the South Atlantic States with lowest pressure of 29.52 inches, which, during the next 12 hours, had advanced to northern Virginia with lowest pressure 29.12 inches, and during the following 12 hours to Lake Erie with lowest pressure 28.61 inches.

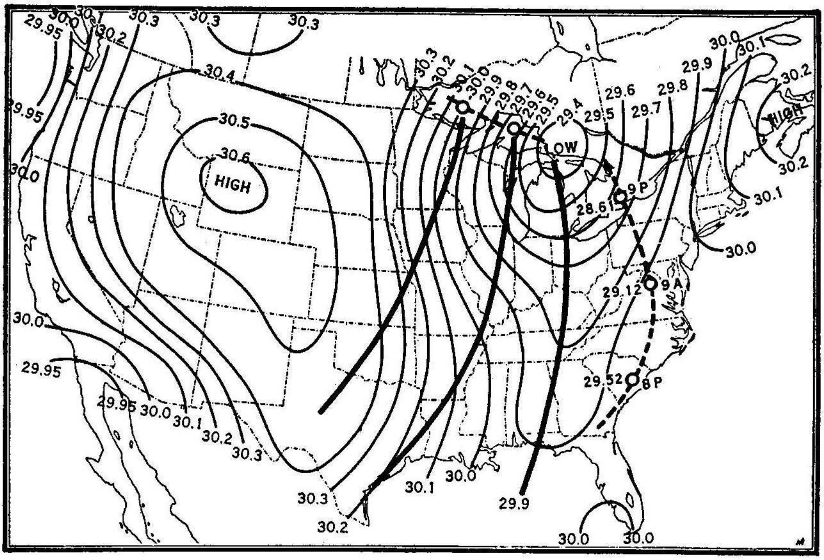


FIGURE 16.—Map of November 8, 1913, showing development of secondary in swinging-trough type. Heavy lines show previous positions of trough.

If the main northern center is moving north-northeastward, the secondary may develop over the middle or east Gulf States and move northeastward up the Ohio Valley. (See maps of November 21, 1924, and January 20, 1910.) The best evidence so far found as to the formation of such a secondary disturbance is an incipient cyclonic circulation of the wind or a localized 12-hour pressure fall in the southern end of the trough. If both occur, the secondary will quite surely develop. The formation of a wave is the earliest symptom and the pressure fall is next. The primary LOW which is in the process of occlusion begins to lose intensity in most cases shortly after the secondary develops, filling up gradually after the secondary reaches a full stage of activity. In a few cases both primary and secondary increase in intensity, but later the primary decreases and the secondary increases further. The best development takes place when the primary moves rather slowly. With primaries of northern origin when the movement is slightly southeast instead of east, the development of the secondary is marked. (See maps of February 7–8, 1903, and December 18, 1904.

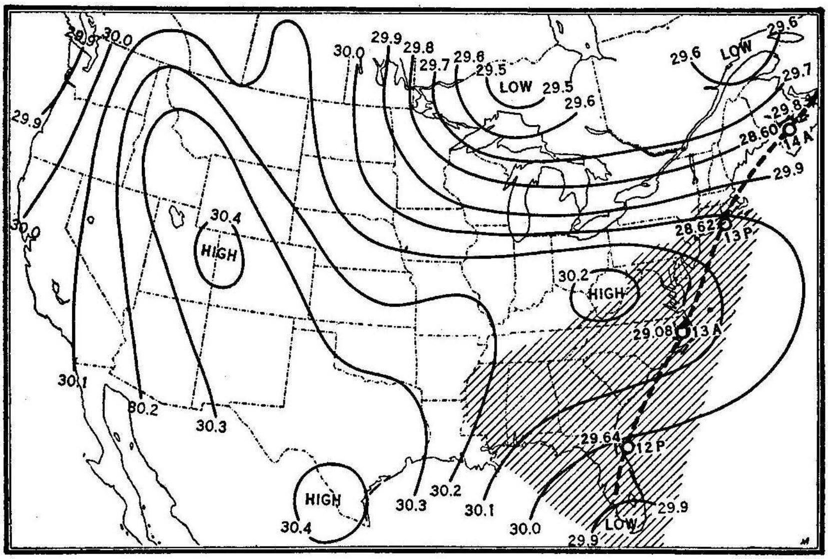


FIGURE 17.—Map of November 12, 1904, showing "neck-of-high" type. Hatching shows precipitation in following 24 hours.

The most frequent examples of the "neck-of-high" type occur with the main body of the HIGH over the Rocky Mountain region, the Plains States, and the interior of the west Gulf States, with a neck extending eastward into the Ohio Valley. The neck breaks off and the head moves eastward, leaving the main body of the HIGH over the Rocky Mountains and Plains States, and a LOW develops in the middle and east Gulf or South Atlantic States that increases rapidly in intensity and moves northeastward, attended by general rains and snows and often by storm winds. Figure 17 shows the map of November 12, 1904, which is followed by a rapid development of a LOW over Florida, which moved north-northeastward with unusually rapid decrease of pressure at the center, attaining a minimum of 28.62 inches near Long Island by the evening of the 13th.

This type may be found in a number of different positions. Occasionally the main body of the HIGH will be over the Plains States and west Gulf States, with the neck extending northeastward through the

Ohio Valley. In this case the neck moves northeastward and the LOW develops in the east Gulf or South Atlantic States, more likely the latter, and moves northward or northeastward with attendant general precipitation. Again the main body of the HIGH may be over the Ohio Valley and east Gulf and South Atlantic States with the neck extending northeastward to Newfoundland. In this case the neck will move northeastward and the LOW will develop over the Middle Atlantic States. (See maps of November 12–13, 1904, and November 27–28, 1912.) Another interesting and rather unusual case was one in which the main body of the HIGH was over the Canadian Northwest with the neck extending to Lake Superior. The neck broke off and a rapid development took place over Lake Michigan and moved northeastward with increased intensity. (See maps of February 16–17, 1929, also maps of November 13, 1908, November 27, 1912, December 20, 1908, December 22, 1912, April 1–3, 1915, February 9, 1927, April 18, 1922, March 14, 1911, and March 8, 1905.)

It is apparent that when a secondary develops in either of the two types just mentioned, i. e., the "swinging-trough" and the "neck-of-high," it has a very definite frontal interpretation. In both cases the front on which the wave forms has been deformed by greater rises of pressure behind and ahead of the place where the wave forms, as compared to rises where the wave actually forms. In the case of the swinging-trough, the wave forms along the cold front; and in the case of the neck-of-high, along a stationary front.

When a well-marked LOW has passed up the Atlantic coast to the Canadian Northeast, close to the source of the polar air masses near the Canadian border, even though no HIGH is in evidence, one will develop in the rear of this LOW. In several such cases HIGHS have been known to build up over the Hudson Bay region from an initial pressure of 30.00 inches to 30.50 or more inches. (See maps of July 1–3, 1933, and October 14–15, 1934.)

The occlusion of the LOW is attended by the rising pressure in the trough of the LOW, and by this is meant that the pressure in the trough at the current observation, compared to what it was the previous observation in a similar part of the trough, has risen (allowing for diurnal variation). Sometimes the occlusion is confirmed by the fact that precipitation has decreased, and in some cases actually ceased, in or near the trough. Frequently also a decreasing angle between the winds immediately before the cold front and the winds immediately behind it is noted.

The term "occlusion," as applied to HIGHS, has been suggested by Humphreys to cover cases where the feeder current from the cold-source region fails and the HIGH produced by the cold current has been surrounded by warmer air. In such cases, the high decreases in intensity.

Shortly after occlusion, a LOW in most cases decreases in intensity, i. e. pressure rises at the center and the wind circulation and distribution of pressure become more symmetrical.

On the weather maps as they apply to eastern Canada are found a number of exceptions to the foregoing rule. If the secondary develops in the southern part of a V-shaped trough, the secondary will subsequently increase in intensity while the primary will decrease. Some writers speak of the two LOWS joining. However, based on numerous observations and careful study, it is quite apparent that two LOWS do not as a rule actually join but that one decreases and the other increases. The secondary of February 28–March 1, 1914, is shown in Weather Forecasting in the United States (*24, pp. 224–226*), together with pressure-change charts at 4-hour intervals. These charts show quite clearly that the two centers did not join, and the same condition is true in many other cases of two LOWS that might seem to join.

HIGHS decrease in central pressure frequently as they move southwards and the feeder of cold north winds is cut off. Further, the mass of cold air constituting the dome of the HIGH spreads out, the dome flattens, and the horizontal extent of the high area increases. HIGHS that decrease after the polar current is cut off may again increase or be reinforced, due to a reestablishment of a new feeder current of fresh polar air. Again HIGHS may increase, due either to an increase in the wind velocities or to a decrease of temperature in the polar supply current. HIGHS have a tendency to increase in spring and summer in passing over the Great Lakes or over New England waters, both of which are colder than the land. Pacific HIGHS, unless they are reinforced, seldom bring temperature changes of consequence to eastern sections. In fact, true Pacific HIGHS always decrease in intensity as they pass eastward. Alberta HIGHS, in contrast, bring decided changes to colder over middle and eastern sections.

FORECASTING WEATHER CONDITIONS

After carefully analyzing our weather situation, a position has now been reached where forecasts can be made of the winds and, based on the transport of air by the winds, the resulting temperature changes, except insofar as they may be modified by precipitation which, of course, has the most marked effects during the warmer season, and sunshine which is effective both in winter and summer.

WINDS

It is apparent that the forecasting of wind direction and, in a measure, the force is dependent upon ability to accurately predict the movement of the HIGH and LOW systems and the discontinuities attending them. Wind velocity is roughly proportional to the barometric gradient; popularly speaking, the closeness of the isobars. Wind speeds in the free air at the so-called "gradient level" (500 m.) are considerably greater than at the surface over land—due to friction, particularly at night, owing to the absence of convection. During the day, when convection is active, surface winds tend to increase, although they do not attain the velocities of the gradient level. Over the water, differences between the surface and the gradient level are much less than over the land. Gold (*17*) and others have pointed out that anticyclonic winds will be stronger for the same barometric gradient than cyclonic winds. Increasing LOWS cause increasing winds, and vice versa. Occasionally blows reach strong or even gale force on the southern side of an anticyclone, even when no LOW is in evidence, especially along the middle and south Atlantic coasts. Such blows have been termed "line blows," probably because there is little shifting of the wind direction during the blow as contrasted with cyclonic storm winds.

TEMPERATURE

The forecasting of temperature is dependent largely on ability to accurately forecast the winds. It is almost axiomatic that, if the air is warm at 8 a. m. today with southerly winds, and the wind may be expected to shift to a westerly or northwesterly quarter during the following 24 hours, falling temperature should be forecast for tomorrow morning.

In other words, if we are in the warm sector this morning and expect the cold front to pass in the next 24 hours, colder for tomorrow morning should be forecast. In the case in which it is moderately warm this morning but is expected to be considerably warmer this afternoon, to be followed by the passage of the cold front late tonight, the question is whether the cooling off, due to the passage of the cold front, will be sufficient to offset the warming that is to take place this afternoon, so that the temperature tomorrow morning will be lower than it is this morning. All sorts of variations of these cases occur owing to the position of the station with respect to the fronts, the rate of movement of the system, and how much higher or lower the temperatures are at the station compared to those in the region to the west of it, from which air will be transported. If the differences in temperature are large, the temperature change will be large, etc. Thus far the problem has been considered from the point of view of a single station.

Forecasting for a State or larger region must be thought of in terms of areas rather than stations. As an aid in making such forecasts it has been noted that, during times of normal eastward movement of the LOWS and HIGHS, the 12-hour pressure fall of 0.10 inch or more on last night's map corresponds in its general features with the 24-hour temperature fall on tomorrow morning's map. In other words, if the area of negative 12-hour pressure change of 0.10 inch or more on last night's map (7:30 p. m.), was over the Ohio Valley, for example, it will be found that the area of the 24-hour temperature fall on tomorrow morning's map will be over the same region, and also that the 12-hour pressure fall on this morning's map corresponds in a general way, with the 24-hour temperature change on tomorrow night's map.

When the speed of eastward movements of LOWS and HIGHS is quite large, the 12-hour pressure fall on this morning's map will correspond with the 24-hour temperature change on tomorrow morning's map. Modification has to be made in the opposite sense when the general eastward drift is quite slow. While it is not desired to suggest such methods be used too strictly, they, nevertheless, serve as an excellent general guide.

When transport of air alone is to be considered, it is a good rule not to forecast colder farther southward than the area of 12-hour pressure fall of 0.10 inch or more. This principle is also useful in dealing with cold waves. It is a common saying, and one having a good deal of virtue, but of course not without exceptions, that unless a well-developed LOW passes over an area no real marked change to colder will follow. Of course there is often the complicating consideration of onshore and offshore winds, precipitation, cloudiness, and diurnal effects.

Forecasting minimum temperatures depends largely on the ability to forecast the transport of air, but also considerably on foreknowledge of radiation effects. First it is necessary to determine what the trajectory or path of the air will be in the following 24 hours and, in reality, work backwards to the point or region from which the air over the station tomorrow morning will have come. If the pressure distribution is such that the air will come from a point 500 miles to the northwest, then the minimum temperatures at that point may be taken this morning as an approximation of the minimum for the next morning at the station. If to the west 600 miles or to the north 400 miles, then the lowest temperature of the appropriate region is used accordingly as a general guide. If the winds are high locally one should count mainly on the transport of air and not any on radiation because turbulence will prevent an inversion layer; but, if winds during the latter part of the night will be light, then one should count considerably less on transport and more largely on radiation. Again, if the sky is to be cloudy with light winds during the night one should count little on radiation, and vice versa. If winds are expected from a large water body, one should depend mainly on transport and little on radiation—except, perhaps, along the Great Lakes when they are frozen over. A key station, that is, some station generally to the west or north from which the air is expected to be transported, may be employed to advantage under these different types to give a general indication of tomorrow morning's minimum. For example, in forecasting for Washington during the colder season when northwest winds are expected to prevail, the temperature at Cincinnati on the current morning and at Pittsburgh on the current evening afford useful guides as to the minmum at Washington the following morning. When winds other than northwest are expected, other key stations have to be employed. Assistance in selecting key stations and making correction allowances for the individual morning may be gained through a consideration of the pressure gradients between certain pairs of stations, as pointed out by Tannehill in unpublished manuscript, which latter are usually, but not always, selected in the region from which the air is expected to be transported.

Formulas based on temperature and humidity readings at the local station in the afternoon or early evening are employed in the West to calculate the minimum of the following morning (*42*).

Later rules, taking into consideration pressure gradients, were developed by Floyd Young in Pacific States but unfortunately have not been published.

Maximum temperatures generally become gradually higher day after day as long as a station remains in the warm sector, and of course get radically higher as the air at the station changes from a cold mass to a warmer mass. It is noted also that, other things considered, temperatures rise rapidly during the afternoon if the pressure begins to fall rapidly, which may be interpreted as an indication of the passing from a cold-air mass to a warm one either at the surface or aloft, or both.

The amount the temperature will rise during the day depends largely on the temperature aloft at the morning observation, provided, of course, that no air of different temperature is transported over the station. The elevation up to which the temperature aloft is to be considered is the level to which convection will reach, and is higher in summer (1,200 to 1,800 m.) than in winter (600 to 800 m.). The process of heating by the sun's action, which takes place beginning at the surface, is illustrated in figure 18. The vertical temperature distribution over Washington, D. C., at 7:47 a. m., March 13, 1930, is shown by the solid line in the figure. The volume of air heated between 7:47 a. m. and 10:15 a. m. is proportional to the area of the triangle ABB′. During this interval of 2 hours and 28 minutes the temperature rose at the surface from 42° to 57° F., or at the rate of 1° per 10 minutes. The rise of 10° from 57° to 67° during the interval 10:15 a. m. to 1:00 p. m. was at the rate of 1° per 16½ minutes, the rise of 5° from 67° to 72° during the interval 1:00 p. m. to 3:00 p. m. was at the rate of 1° per 24 minutes, and the rise of 1° between 3:00 p. m. and 4:30 p. m. occupied about 90 minutes. The rise became progressively slower as the column of air to be heated increased. Above the point *E* in the figure, very little heating, if any, took place because any further surface heating would only have been possible if a mass of air of great vertical extent had been heated.

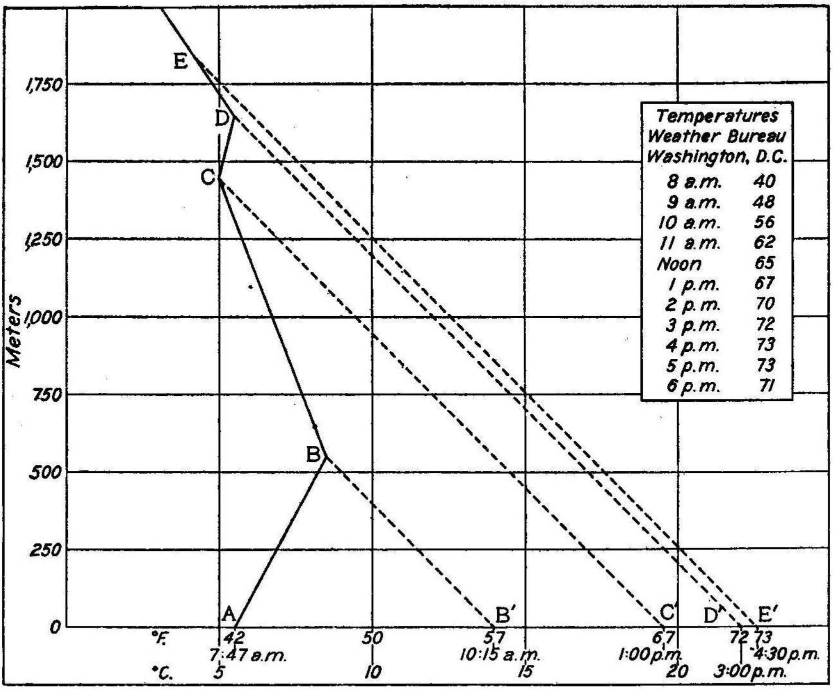


FIGURE 18.—Vertical temperature distribution at Naval Air Station, Anacostia, D. C., March 13, 1930, as related to occurrence of maximum temperatures.

PRECIPITATION

The forecasting of winds and temperature is less difficult than that of precipitation. This difference is reflected in the forecast verification figures which, on the average, show that verification of temperature is 1 to 6 percent higher than that of precipitation. This is due to the fact that, if the wind systems can be forecast, the temperatures are a logical consequence and can be forecast quite accurately. In forecasting precipitation, however, even if the pressure systems and the winds can be forecast, it is not possible in some cases to tell whether precipitation will occur, and even if it does it may be quite scattered and spotty. It is necessary to envisage as well as possible from the observational material on hand the frontal action and conditions of instability, but as yet this can only be done in a general way and then usually only in a qualitative sense. It is impossible at present to make any quantitative estimates of the frontal action except to indicate in a certain limited number of cases that the precipitation will be heavy or light. Deductions made as to frontal action, even in a qualitative way, concerning precipitation can only be made in a part of the cases and in the others one has to depend on experience to round out the qualitative deductions or to decide what is to be substituted for them.

When pressure conditions are quite flat and no fronts are near, the amount of local heating, as indicated by the maximum temperature, necessary to produce instability and thunderstorms, can be obtained from a diagram based on the local radiosonde observation. In case fronts are involved, the amount of lifting sufficient to produce condensation can also be obtained from such diagrams as well as from the isentropic chart.

If precipitation has already begun on the current map and it is necessary merely to extend the area forward with the proper timing or to specify when the precipitation will end, the problem is not so difficult as if it is required to forecast not only its beginning but its subsequent spread or, in some case, to say that there will be none at all. For the more general types of precipitation it is necessary to know whether there is a major flow of air in intermediate or higher levels from the region of some important water body, such as the Gulf, or ocean. If this condition does not exist, the resulting precipitation will be light, except possibly at individual stations in connection with thunderstorms, and then quite scattered. For example, in forecasting general precipitation in the Ohio Valley, the pilot-ballon observations at 1 to 3 km. above sea level are examined to determine whether there have been winds from the Gulf, i. e., from the south or southwest, for a time and with a velocity sufficient to transport moist air from the Gulf. The moisture conditions will be reflected in the humidities at Oklahoma City, Shreveport, and Nashville, as shown by the airplane observations at 1 to 3 km.

Better still, considerable assistance is obtained from the isentropic charts on which are located the dry and moist tongues of air, together with winds at the isentropic surface. From these it is possible to obtain a picture of the regions in which a moist-tongue of air is flowing up isentropic surfaces and how much lifting will be required to produce condensation. Of course, for forecasting it is necessary to forecast not only the flow of air in the moist tongue but also the future topography of the isentropic surface; otherwise, it would not be known whether the flow of the moist-tongue air was up or down slope and, as a result, whether the relative humidity was decreasing or increasing. Specifically, condensation-pressure lines have to intersect equal topography lines to get condensation. In spite of uncertainties attending the estimates or calculations, forecasters who have used these charts consider them a valuable aid (*44*).

Downslope west winds have a tendency to be dry east of the Appalachians, while the upslope west winds on the west slope of the Appalachians, after the trough has passed, have a tendency to be accompanied by light rain or snow, depending on the temperature. East winds are upslope for the upland region on the eastern side of the Appalachians and are often accompanied by precipitation. On the eastern slope of the Rockies, west winds are downslope and are most always dry, while east winds are upslope and attended frequently by precipitation. The same type of effects is experienced in the North Pacific States. The Coast Range first takes its rainfall toll of the westerly upslope winds, and as the still moist air continues eastward the western slopes of the Cascades nearly finish up the process of extracting moisture from the air, so that after it arrives at the Divide the amounts of precipitation are quite small. On the eastern side of the Divide, as a consequence precipitation, which is influenced by downslope effects, is small indeed. Nevertheless, sufficient moisture is transported over the Rockies to cause precipitation in the Plains States, the upper Mississippi Valley, and occasionally in the Ohio Valley and the Lake region.

Lows are apt to be wet if they have a well-developed warm sector; also if there is a localized 12-hour pressure fall or wind circulation in the southern part of the trough. Rain, sleet, or snow (not due to orographic effects) back of the cold front indicates the persistence of the warm, moist current from the south or southwest aloft.

Ordinarily, as soon as the trough of a LOW passes and the winds shift to west, the precipitation ceases. In the case of a slow-moving LOW that is increasing rapidly in intensity and the center of which is still near the station, precipitation continues. In such cases the moist, warm air from the warm sector is carried all the way around to the north of the LOW center. This condition has also been noted in cases of LOWS that move north or north-northeast to the Lake region with greatly increased intensity, in which case they are in process of occlusion.

Whether there will be rain or snow depends on the temperature, and when that is within a degree or two of the freezing point it is extremely difficult to say which it will be. Another very difficult condition is the forecasting of sleet (or frozen rain) and ice-storm conditions (rain falling and freezing on the ground, and objects attached to it.) Both are the result of warm-front action. The temperature of the ground and the air near the ground is and has been below freezing, while the air above where the precipitation is occurring is above freezing, with the result that the precipitation begins as rain. The two cases are quite similar but with the difference that the layer of cold air near the ground is thin in the case of ice-storm conditions, while in the case of sleet the cold layer of air near the ground is sufficiently thick to freeze the rain drops that pass through it before they reach the ground.

Two or three rules connected with barometric patterns are associated very directly with the development and spread of precipitation. Sometimes these are referred to briefly as (1) the pivoting **HIGH**, (2) the round HIGH, and (3) the neck of HIGH breaking off. These are helpful in diagnosing some map situations which are difficult on account of the rapidity of the action and, therefore, will be discussed briefly.

The pivoting HIGH may be described as follows: Anticyclones that make their first appearance in the Mackenzie Valley move southward and southeastward over Saskatchewan and Manitoba with an extension southward over the eastern slope of the Rocky Mountains and the Plains States, sometimes as far south as Oklahoma and northern Texas. The main center remains over Saskatchewan and Manitoba, while the southern extension or wedge swings to the eastward. This pivoting over Saskatchewan and Manitoba and the swinging eastward of the southern part of the axis in most all cases presages the development of a LOW in the Southwest and the rapid development of general rains over the Gulf States and rains or snows in the Ohio and middle Mississippi Valleys. This type has a number of variations, due to the location of the HIGH axis, but they all have similar subsequent behavior. (See maps of December 13, 1925, February 1–2, 1926, February 15, 1928, February 15, 1929, February 26, 1930, February 4 and 14, 1932, and October 29, 1925.) The last-mentioned map particularly illustrates this type and is reproduced in figure 19.

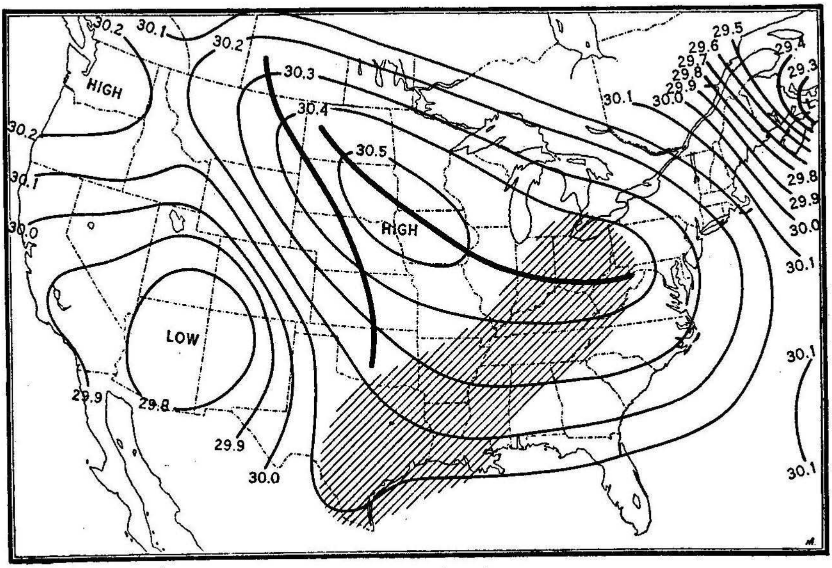


FIGURE 19.—Map of October 29, 1925, showing pivoting HIGH. Hatching shows precipitation in following 24 hours and heavy lines the previous and current positions of the HIGH axis.

With even a slight LOW over Texas, round or circular HIGHS that move north of east through the middle Mississippi Valley are most always followed by a rapid eastward and northeastward spread of general precipitation and an increase in intensity of the LOW. This is most marked when the center of maximum 12-hour pressure rise preceding the HIGH moves northeastward and a 12-hour pressure fall, even though slight, has appeared over Texas. When no LOW is in evidence over Texas or New Mexico, one very likely will develop when a HIGH of the above-mentioned type is present. (See map of December 19, 1928, which is reproduced in figure 20.) But with elongated HIGHS, preceding which the maximum 12-hour pressure-rise center moves northeastward, the rule does not hold. (See maps of February 11–12, 1930.)

The neck-of-high type has already been described (p. 35). As soon as the LOW develops, general precipitation attends it.

It is impossible in the scope of this publication to include a discussion of the special problems of forecasting in the Rocky Mountains and the Pacific States. In the former the topographic features affect the lower layers of the air so much that statements concerning forecasting east of the Rockies apply only in principle. In the Pacific States the weather is largely of a maritime type, affected greatly in the interior by topography, and there also remarks concerning the weather east of the Rocky Mountains apply only in a general way.

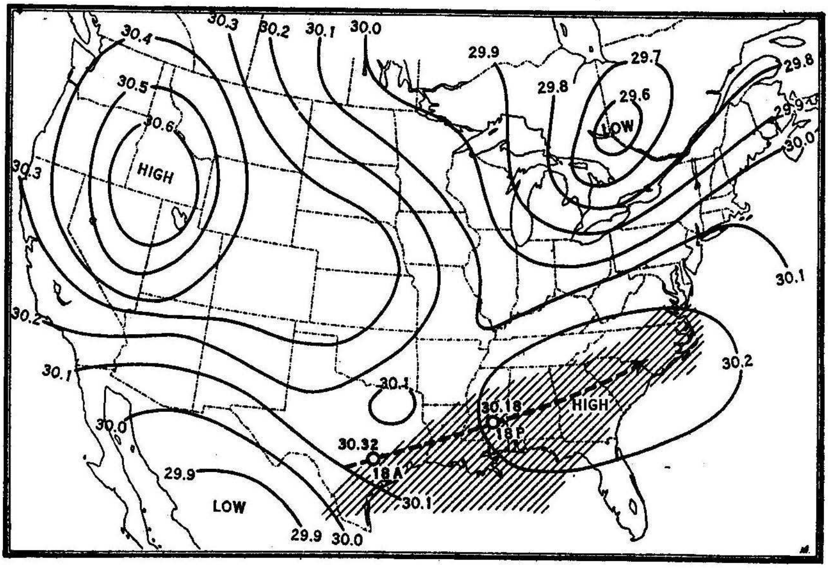


FIGURE 20.—Map of December 19, 1928, showing round HIGH. Hatching shows precipitation in following 24 hours.

MATHEMATICAL FORECASTING OF THE MOVEMENT OF HIGHS AND LOWS

Attempts have been made in the past to calculate the direction and speed of movement of LOWS by some more or less empirical process, involving simple mathematical calculations. Bowie's method (*6*), employing barometric gradients surrounding the LOW center, resolved into east-west and north-south components, and used in connection with a so-called "normal 24-hour movement," specially devised for the purpose, met with partial success but required some individual judgment in modifying the elements to be computed. The writer experimented a good deal some 15 or 20 years ago with temperature distribution as affecting or controlling the movement of LOWS by taking an average of the direction trend of the isotherms through and just north of the LOW center to represent the future direction and the temperature gradient at right angles to the isotherms as being inversely proportional to the future speed. The results were quite satisfactory for predicting the 12-hour movement but only fairly so for predicting the 24-hour one, even when the temperature gradient was large. They were not satisfactory for 24 hours when the temperature gradient was small, and the results were never published.

In 1915 Guilbert (*19*, *20*, *21*, *22*) presented three rules for forecasting the displacement of and variations at the center of high- and low-pressure areas. The method was based on a comparision of the actual winds with what was called the gradient wind, which was defined as a wind whose force was proportional to the barometric gradient. The application of these rules involves a comparision of wind velocities recorded by instruments exposed under varying conditions which makes them in many ways incomparable. The result has been that, while they were studied quite carefully in this country, they did not give good results apparently for the reasons indicated above.

A system of mathematical forecasting based on 7 dependent and 4 independent variables was developed and discussed by Richardson (*34*) but, owing to the time required for the computations, it was entirely impractible.

Angervo (*2*) in 1928 and Gião (*16*) in 1929 also contributed to the subject of forecasting the movement of pressure systems by means of physical and mathematical methods and some reference to their papers will be found in the work of Petterssen, to be mentioned next.

More recently a kinematical method developed by rigorous mathematics has been given to the forecasting world by Petterssen (*31, p. 5*). Happily this method, or at least a considerable part of it, at present is susceptible of practical application. In introducing his method the author, who was regularly engaged in forecast work, says:

> The physical analysis, naturally, forms the basis of rational weather forecasting. The step from the completed physical analysis to the forecast is, however, a difficult one. It is this step that the writer has endeavoured to facilitate in the present memoir. The leading idea is: to develop methods for evaluating the instantaneous velocity and acceleration of the various pressure formations, such as cyclones, anticyclones, troughs, wedges, fronts, etc. Furthermore, to evaluate the displacement and variation in intensity during the forecast period * * * Throughout, it has been a leading idea to express the forecasting equations in terms of pressure only, because atmospheric pressure is the only element for which no question of representativeness arises.

No attempt will be made to follow the development of the forecasting equations. However, it is proposed to outline very simply and briefly enough of the method to provide a working knowledge of the scheme for predicting the movement of LOW centers, HIGH centers, and trough lines, omitting the acceleration term and the discussion of the formula for obtaining the increase or decrease in intensity.

The author constructs coordinate axes through some point for which it is desired to calculate the movement.

In the case of a high- or low-pressure system, the axes are constructed through the center of the system in such a manner that they pass through the points of either maximum or minimum curvatures of the pressure profile or isobars. The axes may be either straight or curved, and need not be orthogonal. For purposes of simplification, an arbitrary unit of length is adopted. This unit should be chosen sufficiently large so that the tendencies (3-hour pressure changes) observed immediately behind the center are not affected by the pressure variations immediately preceding and following the passage of the center. As a general rule, it can be stated that the length unit should, if possible, be not smaller than 3° of latitude. The above considerations hold also in the case of a trough, front, or wedge, except that only one axis is needed for the computation of each point, which axis should be drawn most often at right angles to the trough line, front, or wedge.

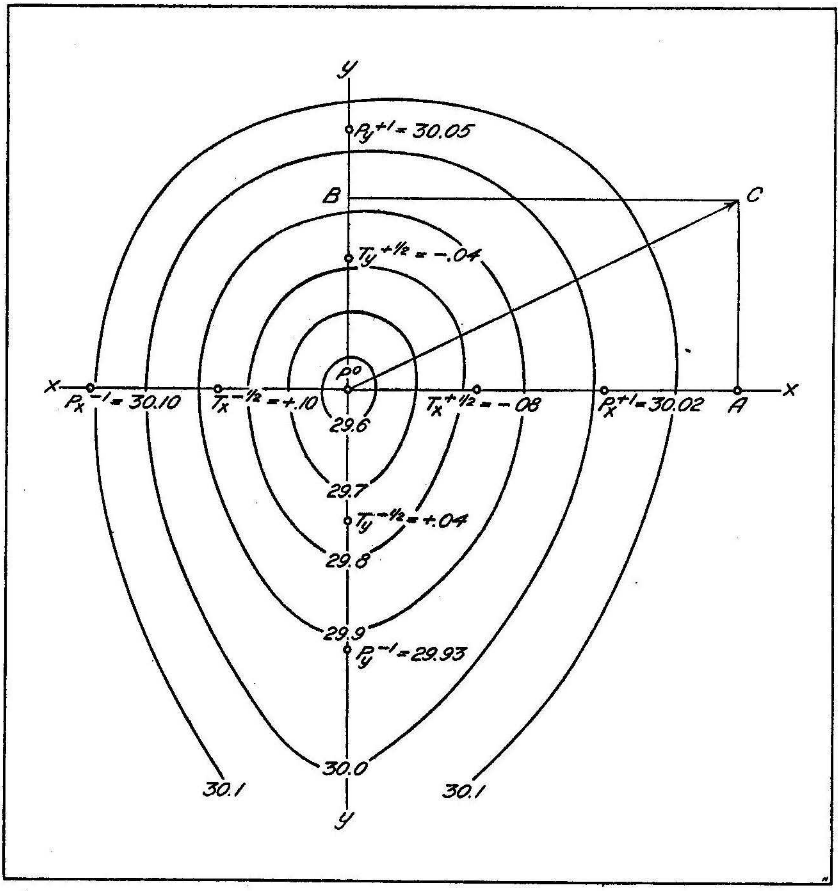


FIGURE 21.—Diagram, illustrating Petterssen's method of forecasting movement of a LOW.

In the illustration (fig. 21) the unit is selected equal to the line P_x^{-1} P^0 to the left of the Y axis and to P_x^{+1} P^0 to the right of the y axis. The units are further divided into half units by the points $T_x^{-\frac{1}{2}}$ and

$T_x^{+\frac{1}{2}}$. Similarly, units (not necessarily of the same length) are laid off on the y axis.

The equation for calculating the movement, m, of the point selected—in this case, the center of the LOW— is as follows:

$$m=-\left(\frac{T^{+\frac{1}{2}}\quad-\quad T^{-\frac{1}{2}}}{P^{+1}-2P^{0}+P^{-1}}\right)$$

in which $T^{+\frac{1}{2}}$ and $T^{-\frac{1}{2}}$ represent the amounts of the pressure tendency (or 3-hour pressure change) at the points indicated by $T_x^{+\frac{1}{2}}$ and $T_x^{-\frac{1}{2}}$ in the pressure system; and P^{+1}, P^{0}, and P^{-1} represent the actual pressures at the points P_x^{+1}, P^{0}, and P_x^{-1}. As the pressure tendencies are for 3 hours, the solution of the expression gives predicted movement in the succeeding 3 hours; hence, to obtain the movement for 12 or 24 hours, it is necessary to multiply by 4 or 8, respectively. The solution gives the result in terms of the unit adopted and along the x axis, to the right of the y axis if positive and to the left if negative. A similar computation is made along the y axis to determine the movement along that axis, above the x axis if positive and below the x axis if negative. The vector along the x axis and the vector along the y axis give the predicted components of motion.

The calculations are based on the behavior of the pressure at the instant of observation. If tendencies for the 3 hours immediately preceding the 3 hours for which the tendency is given in the telegraphic observations were available, it would be possible to improve the forecast as to predicted movement by taking into consideration the acceleration. To compute acceleration the author has added an acceleration term. Other formulas have also been developed by the author to calculate the change in intensity, i. e., the deepening or filling up of the center or of the trough and wedge.

Referring again to figure 21, in which the isobars are solid curved lines, let an attempt be made to calculate the movement of the center in 24 hours. First it will be necessary to calculate the movement along the x axis by using the formula and multiplying by 8 to obtain the 24-hour movement, as follows:

$$m_x=-\left(\frac{T_x^{+\frac{1}{2}}\quad-\quad T_x^{-\frac{1}{2}}}{P_x^{+1}-2P^{0}+P_x^{-1}}\right)8$$

$$T_x^{+\frac{1}{2}}=-0.08.\quad T_x^{-\frac{1}{2}}=+0.10$$

$$P_x^{+1}=30.02.\quad P^{0}=29.58.\quad P_x^{-1}=30.10$$

substituting the values in the formula, we have:

$$m_x=-\left(\frac{-0.08-0.10}{30.02-2(29.58)+30.10}\right)8=\frac{144}{96}=1\tfrac{1}{2}\text{ units approximately,}$$

which, being positive, is in a direction to the right of the y axis, along the x axis to the point A.

In a similar manner, the movement along the y axis may be computed. By substituting in the formula:

$$m_y=-\left(\frac{-0.04-0.04}{30.05-2(29.58)+29.93}\right)8=\frac{64}{82}=\tfrac{3}{4}\text{ units approximately,}$$

which, being positive, is above the x axis and along the y axis to the point B. The point A on the x axis is projected at right angles to the *x* axis, and the point *B* on the *y* axis is projected at right angles to the *y* axis. These projections intersect in the point *C*, which is the predicted position of the LOW center at the end of 24 hours.

In the absence of data from which to compute the acceleration term, certain rules have been developed by Petterssen to locate what he calls "neutral points" where the convection term vanishes. At these points the 3-hour pressure tendencies are an index of the rate of increase or decrease in the pressure system. For a round LOW the neutral point occurs at the center, and for a trough it occurs along the trough. It is also pointed out that if a 3-hour pressure tendency profile along the *x* axis through the pressure center (or trough) is prepared like in figure 22, then the cyclonic curvature of the tendency profile *AA* shows retardation and increasing strength (greater pressure gradients). The anticyclonic curvature of the tendency profile *BB* indicates acceleration and decreasing strength (smaller pressure gradients). If the tendency profile cuts the *x* axis ahead of the pressure center (plus tendencies at the center), like *AA* in figure 22, filling is indicated. If, however, the tendency profile cuts the *x* axis in the rear of the pressure center (minus tendencies at the center), like in *BB*, deepening is indicated. Similar profiles may be prepared along the *y* axis to obtain the *y* component of the accelerations. By combining the *x* and *y* components, indications of change in direction may be obtained.

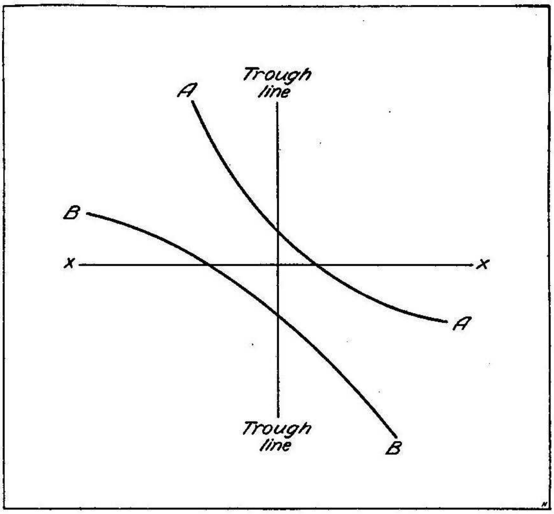


FIGURE 22.—Tendency profiles.

Similar conclusions may be drawn from the 3-hour tendency profiles in the HIGH. Cyclonic curvature of the profile is associated with acceleration and decreasing strength (decreasing gradients) and anticyclonic curvature with retardation and increasing strength (increasing barometric gradients). If the profile cuts the *x* axis ahead of the HIGH center (minus tendencies at the center), the pressure decreases at the center; if in the rear of the high center (plus tendencies at the center), increasing pressure at the center results. The rule applies also to wedges.

The curvature of the isobars at the rear of the cold front is also used in obtaining an idea of whether the movement of the front will be fast or slow, rapid movement being indicated when isobars are curved cyclonically and slow movement when curved anticyclonically. The opposite is true with respect to the curvature of the isobars in advance of the warm front with relation to the movement of the warm front.

In studying Petterssen's kinematical methods, Stevens (*43*) found a very slight modification was required for the deepening and filling of LOWS and HIGHS.

LONGER PERIOD FORECASTS

There is an insistent demand for an extension of weather predictions beyond the regular forecast period to serve business, commerce, and industry in planning their affairs. Probably the greatest demand is for forecasts several days to a week in advance, which the Weather Bureau has been meeting for some years by its Weekly Outlook, issued each Saturday. There is also a need for seasonal forecasts but, in spite of a great deal of research still being carried on by investigators in this country as well as abroad, no sufficiently reliable method has been developed to warrant their issue.

WEEKLY OUTLOOK

The outlooks, which cover the period Monday to Saturday, are based on the weather chart of the Northern Hemisphere, which is prepared twice daily. Ordinarily, meteorological events, even in the far borders of the regular field of observations for Saturday morning, covering the United States, Canada, and Alaska, have changed or moved beyond such field of observations by the following Thursday. Up to that point in the calendar of events the outlooks are fairly satisfactory. Reports west of Alaska are so meager, however, that for the last 2 days of the week, namely, Friday and Saturday, the results are not so satisfactory, because the forecaster has to call on his fund of experience to help him prevision what events may reasonably be expected to follow those which he can definitely see on the map. Most of the LOWS come through the Aleutian Island region from the coast of Japan, and between the Aleutians and Japan very little daily information is available. It will be recalled that disturbances that are in active being today, run a life cycle and, after occlusion, gradually disappear, followed by the development of new LOWS on old occluded fronts. Further it will be recalled that about 40 percent of the LOWS that affect the United States develop over or in the waters contiguous to our continent. Again, storms move in a variety of directions, may change their courses, may increase or decrease, and may accelerate or slow up. So it is readily apparent why the Weekly Outlooks are not more satisfactory than they are. Nevertheless, owing to the demand for them they have been continued.

SEASONAL FORECASTS

In conclusion, a word regarding seasonal forecasts may not be out of place. It seems quite apparent that predictions for several days or a week in advance cannot be as specific and definite as the forecasts for 36 and 48 hours ahead. The regions for which the forecasts are made should be larger and there should be more latitude regarding the timing of the events, in spite of the fact that they are both based on the daily synoptic charts and that the same general type of events is contemplated. When one comes, however, to forecasts for a season in advance, very different considerations are necessary. It is believed that everyone who has studied the problem will admit that, if and when such predictions become possible, they probably will not attempt to specify weather for particular days, nor will particular weather events be mentioned. On the other hand, they will specify whether the temperature and precipitation will be near, above, or below normal for a particular month or season; perhaps that the precipitation will be characterized by well-distributed rains or by heavy local showers, or that the extremes of temperature will be slight or great. A brief summary of some of the investigational work which has been done on long-range forecasting will be found in National Research Council Bulletin 79 (*30, pp. 267–275*), and in forthcoming Supplements of the Weather Review entitled "Preliminary Studies in Seasonal Weather Forecasting" (*45*) and "Reports on Critical Studies of Methods of Long-Range Weather Forecasting." The latter has just appeared as Monthly Weather Review Supplement No. 39.

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U. S. GOVERNMENT PRINTING OFFICE : 1943