isobars; they need not be circular—their shape is quite immaterial.

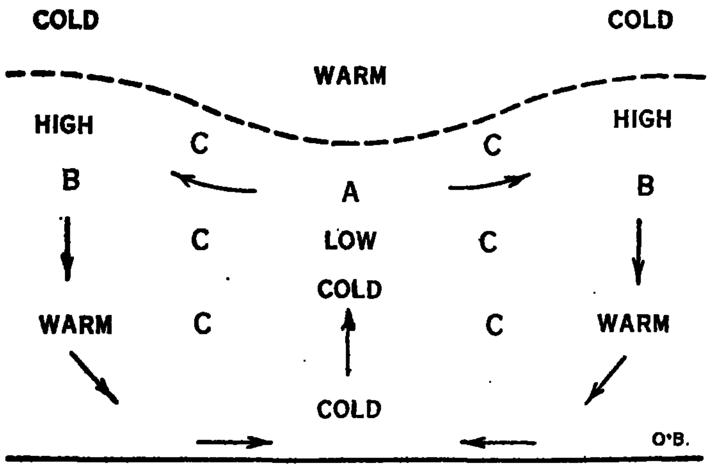

FIG. 2.—A conventional vertical section through a LOW.

Now, suppose that the inception of the system is brought about by a decrease of pressure in the region A and that the decrease is brought about by the strengthening of the winds in the region CC. In my previous paper [8] it was shown how, in the Northern Hemisphere, a wind had the low pressure on its left hand; hence the wind at C must be taken as blowing at right angles to the paper, away from the eye on the right-hand and toward it on the left. The result is a lower pressure at A than at B, and the natural tendency is for air to flow from B to A. In the middle regions the direct way is barred by the acceleration of the winds away from A, but in the diagram as drawn there is nothing to prevent air passing from B to A either above or below the region C. Consider the upper path first. The winds fall off in velocity in the stratosphere, as Mr. Cave and others have shown, so that there is no obstacle on account of their acceleration toward the right hand; but the stratosphere is so stable that any vertical current is strongly resisted, and probably very little air passes back above C from B to A. But we may probably take the stratosphere to consist of almost the same air, with very little interchange with the troposphere, and that being so it is naturally forced upward over B and drawn downward over A, with the result as regards the temperature that is shown. In figure 2 the position of its lower boundary is shown by the dotted line. The dynamical explanation therefore accounts for the very close connection between P_9 and H_c.

Now let us consider the lower path from B to A. It is probable that the air as it endeavors to reach A gets turned to the right by the earth's rotation and simply extends the region C downward, and that this continues till C extends nearly to the earth. If we count C as the region in which the wind is parallel to the isobars it can not quite reach the earth, because the friction, including what has very aptly been called "convectional friction" prevents the actual surface wind from being as strong as the gradient wind. Its acceleration outward can not balance the pressure gradient, and the surface wind, as is well known, blows inward at an angle of 20° or 30° with the isobars. Air can therefore pass from B to A by going first downward under B, then moving inward slowly—the friction of the surface prevents any rapid movement—and then rising under A. This process explains the curious distribution of temperature that is found both above and below.

[8] MONTHLY WEATHER REVIEW, November, 1915, 43: 552.

Thus all the close relationships between pressure and temperature that have been discovered, probably all that exist, can be explained on simple dynamic principles if we start with the supposition that the disturbance begins at 8 or 9 kilometers and then spreads downward, producing the surface phenomena that we know so well.

How the upper winds that encircle a certain region come into existence, strengthen themselves, or die away, is not clear; neither is the process which secures a sort of rough equilibrium between the pressure gradients and the winds, but the strongest winds are certainly prevalent in the upper half of the troposphere. However a low pressure is produced, it certainly is not due to the high temperature of the air above it; that is to say, it is not a convectional effect produced by the juxtaposition of hot and cold air.

THE PLANETARY SYSTEM OF CONVECTION.

By WM. R. BLAIR, Professor of Meteorology.

[Dated: Weather Bureau, Washington, May 11, 1916.]

Unequal heating of the air over a given area resulting from topography, from the distribution of land and water and of vegetation, or from a combination of these gives rise to local systems of convection. Other local systems are more or less mechanically caused. A current of air, relatively heavy when compared with air at the same level, undergoes change of speed and cross section, especially in its lower levels, in order to adapt itself to the topography of the bottom—solid, liquid, or aerial—over which it flows. These changes in rate and cross section are accompanied by changes in temperature, pressure, and by more or less change in direction of air movement. The changes may be small, but a study of many of these indicates that every gust of wind has all the attributes of a full-fledged system of convection and differs from other systems primarily in extent and duration only. Other systems of convection, the diurnal system and the planetary system, owe their existence to unequal heating, but in these cases the unequal heating is directly related to the relative positions of the earth and sun. The high and low pressure areas that move from west to east in the middle latitudes are apparently directly related to the planetary system of convection and will be considered again later.

Probably Ferrel more than any other has contributed to our comprehension of the planetary system of convection. Some of the principles formulated by him in connection with his study of this system are still considered as fundamental as ever. The law of equal areas, when we consider with it cross section and air density in the case of an air current, and the law of deflection to the right of air or other material in motion, because of the earth's rotation, are still to be given primary consideration. Since these studies by Ferrel were made many new data have been obtained. Observations have been made at higher latitudes and at higher levels than were then attainable. The abundance and range of these observations seem to justify a sort of reconstruction of the Ferrel conception of the planetary circulation. This conception has been generally accepted and is still found in the textbooks. It is well founded, but, reconstructed, it seems to be more complex than as first conceived.

The free-air observations available for the purpose of this paper are distributed about as follows: In tropical latitudes observations to considerable heights have been made in the Dutch East Indies and in Africa; about latitude 40° N. in the United States; from 40° to 60° N.

many excellent observations have been made in Europe and in Canada; for higher latitudes the observations made in Greenland, Spitzbergen, and in the Antarctic Continent have been used. While many data are thus available, many have been obtained in recent years that are not available, because they are not yet published or have not yet reached us. Only data published in sufficient detail to permit of their intercomparison with reference to the subject in hand have been used. These data, from whatever source, fit together remarkably well and the facts stated in the first part of this paper seem to be well substantiated, all available observations considered.

Observations in the upper tropical and lower middle latitudes would fill a rather wide gap and be of great assistance in any consideration of the general circulation. If, in addition to these, observations to great altitudes could be obtained at very high latitudes, the meridional distribution would be fairly complete. Observations in which the speed and direction of air movement, in addition to air temperature, pressure, and humidity, are obtained for all levels are especially valuable.

In the review of observations which follows, more space is given to the observations at high levels and high latitudes than to surface observations in the middle and lower latitudes, not that these are of more importance to the conception of the planetary system of circulation as a whole, but because they are the newer and less familiar data to be considered.

OBSERVATIONS OF AIR MOVEMENT.

In the series of free-balloon ascensions made at Fort Omaha in July, 1914,[1] there were three cases in which the balloon was followed with two theodolites to heights of 20 kilometers or above. In each of these cases the balloon in its ascent experienced differently directed winds for the first few kilometers above the earth's surface. Above this stratum it passed through a steady westerly wind with maximum velocity at the 12 to 15 kilometer levels. Between the 16 and 17 kilometer levels the balloons passed from the westerly wind into an easterly wind which increased with altitude from low to high velocity.

In looking over previous records three other ascensions are found in which the balloons were followed with one theodolite to the 20-kilometer level or above. Two of these three were made in July, 1913, at Avalon, Santa Catalina Island, Cal. The third was made in September, 1910, at Huron, S. Dak. The two July ascensions show practically the same phenomena at high levels above Avalon as are shown above Fort Omaha by the ascensions of July, 1914. In the ascension at Huron, made farther north and later in the year, the balloon did not experience the upper easterly wind, although it was observed to a height of 26.8 kilometers. At this height the wind was still westerly, but its velocity was low, 1.1 meters per second.

Of the six ascensions, the balloon in that of July 9, 1914, was observed to the greatest height, 31.6 kilometers. At this height the easterly wind had a speed of 19 meters per second. A noticeable fact in connection with this ascension is the persistence of the north component in the air movement to the highest levels at which observation was made. Figure 1 shows the horizontal projections of the paths taken by the balloons in the six ascensions to which reference has been made. It will be noted that, in each of the five cases showing an easterly wind above the 17-kilometer level, the north or south component prevailing in the westerly wind below the 16-kilometer level persists in the upper easterly wind. This north or south component does not necessarily obtain in the surface or variable wind stratum. The north or south components have maximum values in the upper westerly and in the upper easterly winds. Their values may be zero in the comparatively quiet air between these two currents.

Reviewing the free-air data obtained by other observatories, especially those obtained at great altitudes, it is found that in higher latitudes the upper easterly wind has not yet been observed. The balloons sent up in the higher latitudes have passed through the upper westerly winds into the region of comparatively quiet air. The upper easterly wind has been observed in the lower latitudes, but here it is found immediately above the upper westerly wind. The region of quiet air between these two currents, which has been found in the middle and higher latitudes, is very shallow, if it may be said to exist at all, over the Tropics. Over the Tropics the upper westerly winds are found at about 20 kilometers above sea level and are approximately 5 kilometers in depth. Above them the wind is easterly. The upper limit of the easterly wind has not been reached in the lower latitudes, but a maximum velocity of 40 meters per second has been observed at the 29.5-kilometer level, the velocity at the 30.5-kilometer level being at the same time 34 meters per second. The upper westerly wind is found to begin at lower levels and to be deeper in the middle and higher latitudes than over the Tropics. From a depth of 4 or 5 kilometers over the Tropics this current increases to a depth of 10 or 12 kilometers at 35°–40° north latitude. Observations of its depth at very high latitudes are not yet available.

Below the upper westerly winds in the Tropics are found in the order of their height: The trade winds, extending from the earth's surface to a height of 3 to 5 kilometers; the antitrades, extending from the 3–5-kilometer up to the 15–17-kilometer levels; the upper trades, lying between the antitrades and the upper westerly wind.

In the upper tropical and lower middle latitudes and between the antitrade and upper trade winds is found a region of comparatively quiet air similar to that found between the upper westerly and the upper easterly winds, but not so extensive. The observations upon which this statement is based are those on the movement of upper clouds in the United States south of about 35° north latitude. The motion of these clouds is indifferent in the summer months. When motion is evident it is as likely to be from the east or south as it is to be from the west or north. In the winter months the upper clouds over this territory move decidedly and from a westerly direction. This is taken as indicating that this region of light winds or calms moves north and south with the sun. Unfortunately no aerial soundings have been made in the southern United States nor have the cloud altitudes been observed together with the cloud movement. The extent and velocity of the easterly winds just above the comparatively calm region at about the cirrus level in these latitudes has not therefore been directly observed. East winds at the 10-kilometer level have, however, been observed as far north as Omaha and Indianapolis, but only occasionally.

Below the upper westerly wind in the middle latitudes is found a stratum in which differently directed winds blow. The resultant air movement in this stratum, as

[1] The results of this series of balloon ascensions will appear in this REVIEW, May, 1916.

observed at Mount Weather, Va., is from the west at rates varying with altitude from 3.5 meters per second near the earth's surface to 19.7 meters per second at the 4-kilometer level. Two maxima of wind frequency are found at the earth's surface. These are southeast and west-northwest to northwest. These two maxima converge toward the west with altitude, being south and vail below the upper westerly wind. The easterly winds resulting from this anticyclonic condition are shallow, usually less than 1 kilometer in depth. The polar anticyclonic conditions are better developed in the cold than in the warm half of the year and, because of uniformity of surface about the South Pole, seem to be better developed there than about the North Pole.

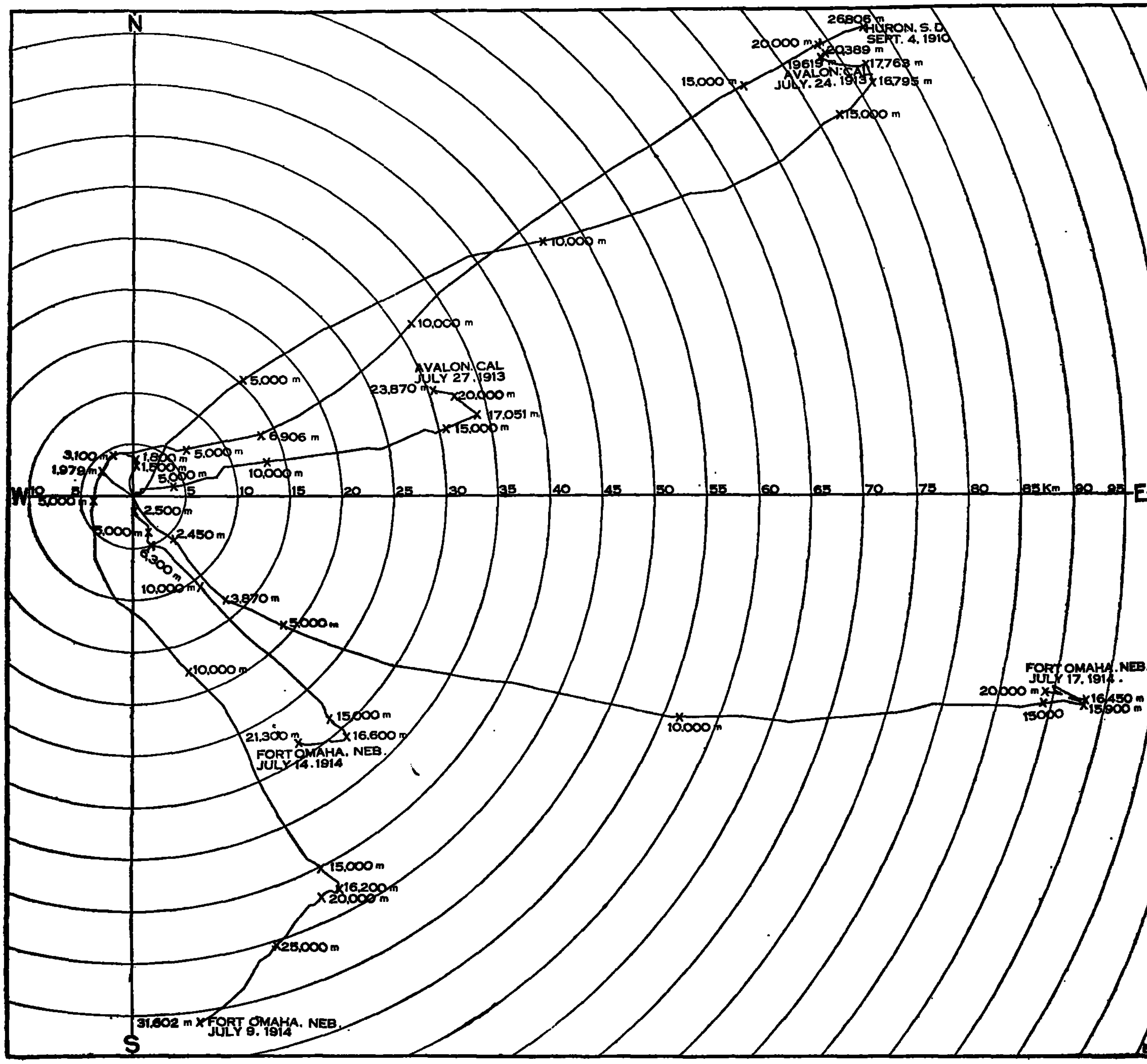

Fig. 1.—Horizontal projection of sounding balloon paths.

west-northwest to northwest at the 1-kilometer level, and southwest and west-northwest at the 2-kilometer level. But one maximum of wind frequency, from west to west-northwest, is found at the 3- and 4-kilometer levels. In the polar regions, bounded by small circles at approximately 60° north and south from the thermal equator, an anticyclonic condition about the poles tends to prevail below the upper westerly wind.

OBSERVATIONS OF TEMPERATURE.

Many observations of the temperature-altitude relation have been made at Mount Weather by means of kites and captive balloons and in the middle and far West of the United States by means of sounding balloons. As shown by these observations, this relation varies greatly from time to time in the lower 2 or 3 kilometers of the atmosphere, is fairly uniform and constant from the 3 to the 11 or 12-kilometer level, has a small value from the 11 or 12 to the 15 or 16-kilometer level, is negative [2] from the 15 or 16 kilometer level to the 28-kilometer level, is still negative, but of decidedly smaller value, from the 28 to the 32-kilometer levels. The value of the relation in the lowest stratum above defined may be anything from more than the adiabatic rate to a strongly inverted condition; in the second stratum about 6.5°C. per kilometer; in the third, 1°C. per kilometer or less; in the fourth, −1.7°C. per kilometer; and in the fifth, −0.3°C. per kilometer. This relation is fairly well shown in figure 2, which represents a mean of three observations, each to a height of more than 30 kilometers above sea level. The three observations considered were all made in the summer half of the year: One at Huron, S. Dak., September 1, 1910; one at Avalon, Cal., July 30, 1913; and one at Fort Omaha, Nebr., July 9, 1914. They should be considered as characteristic of the position they occupy with reference to the position of the thermal equator rather than as characteristic of their position on the earth's surface, although the latter consideration enters to some extent. With this curve of figure 2 as a basis the chief seasonal, latitude, and other variations in the relation it represents, may be briefly stated. Diurnal variations of temperature which affect the slope of the curve in its lower part will not be considered here.[3]

In the middle latitudes marked seasonal variations occur in the lowest of the strata above defined. During the warm half of the year the temperature in this region falls somewhat irregularly with altitude, always at less than the adiabatic rate in the mean, but sometimes exceeding this rate for brief periods of time. In the winter months an inversion of temperature with the maximum temperature at about the 1-kilometer level is shown in the mean, although there are times when inverted temperature conditions do not obtain. In the second stratum above defined the slope of the curve remains about the same throughout the year, but the bounding planes of this stratum change position. The lower boundary is somewhat lower in the winter than in the summer months and the upper boundary is considerably lower, from 2 to 3 kilometers. In the third stratum the change from summer to winter consists chiefly in the decided lowering of the lower boundary just mentioned. The upper boundary of this stratum—i. e., the surface of minimum temperature—seems to rise slightly, when observations made in this country are considered. In the fourth stratum the rise of temperature with altitude seems to be not nearly so rapid in the winter as in the summer months. But 0.3°C. per kilometer is shown by the observations in the United States. The fifth stratum has not been observed in the winter months. In these middle latitudes the temperature in the surface of minimum temperature is some 2 or 3 degrees (C.) higher in the winter than in the summer months.

To some extent the seasonal variations may be thought of as variations with latitude, or in distance from the thermal equator. There is evidence that from the latitude of the thermal equator to about 40° north of it the surface of minimum temperature is found at lower levels and is warmer with increasing latitude, while from

[2] According to the convention adopted by the International Commission for Scientific Aeronautics the temperature-altitude relation is positive when temperature decreases with altitude, negative when temperature increases with altitude.

[3] The diurnal system of convection has been treated in the Bulletin of the Mount Weather Observatory, Washington, 1913, v. 6, pt. 5.

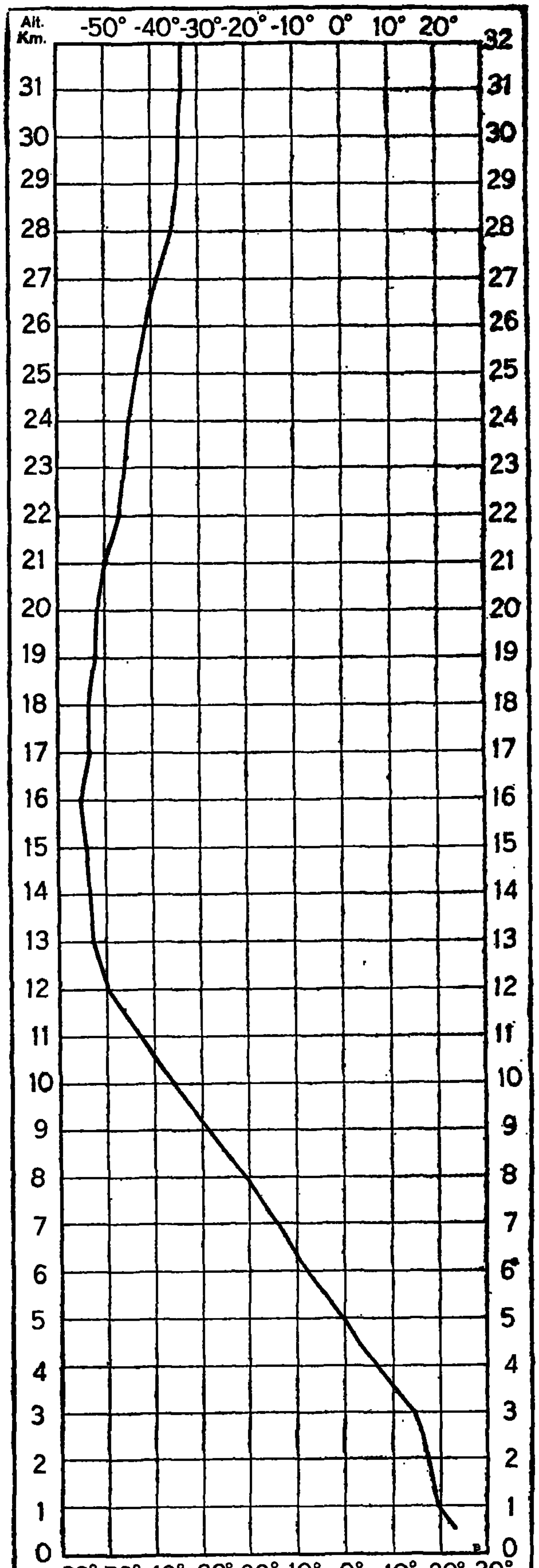

FIG. 2.—Mean of temperature-altitude relations observed in three high ascensions.

the middle latitudes north this surface rises and is colder with increasing latitude. The mean decrease in temperature with altitude in the tropical regions is approximately 6° C. per kilometer from the earth's surface up to the region of the upper westerly winds. This same type of temperature-altitude relation obtains in the middle latitudes in the second stratum above defined, but the rate of decrease tends to increase with latitude.

In the southerly wind that passes between the center of a high pressure area and the center of the succeeding low pressure area, and above it up to about the surface of minimum temperature, the air is warmer than it is in and above the northerly current that passes between the center of a low pressure area and the center of the succeeding high pressure area. At the surface of minimum temperature, or a little below, the temperature above these two air currents is the same. Above this surface the air over the southerly surface wind—i. e., above falling air pressure at the earth's surface—is colder than the air over the northerly surface wind—i. e., above rising air pressure at the earth's surface.

OBSERVATIONS OF AIR PRESSURE.

The pressure distribution over the earth's surface is such as to fit the observed winds. Leaving out of consideration for the present the influence of land and water surface, there tends to be a belt of low pressure at the thermal equator, a belt of high pressure on either side of this about 30° to the north and to the south, a belt of low pressure again at about 60° north and one at about 60° south of the thermal equator, a center of relatively high pressure at each of the poles. In middle latitudes the east and west trend of the isobars, found when means for a long period are taken, can hardly be said to exist at the earth's surface at any time, especially in the Northern Hemisphere. Instead, a series of closed isobars indicating areas of low and of high pressure obtain. It is found, however, that these closed isobars begin to open up a short distance above the earth's surface. Those about a low pressure area open on the north side, as a rule, while those about a high pressure area open on the south side. The tendency seems to be for the isobars to open up to the left of and on a line at right angles to the direction of motion of the low, to the right of and on a line at right angles to the direction of motion of the high. Closed isobars above the 3-kilometer level seem to be of infrequent occurrence.

CONCERNING THE OBSERVATIONS IN GENERAL.

All of the above observations are closely related. The surface stratum in middle latitudes, in which the temperature-altitude relation is very variable, is the stratum of differently directed winds. The more permanent currents which have been explored up to and including the upper westerly wind seem everywhere to be accompanied by fairly characteristic temperature conditions. In them the temperature-altitude relation has a value between 5° and 7° C. per kilometer. The surface of minimum temperature is found near the upper boundary of the upper westerly wind. Observations indicate the approach to a surface of maximum temperature located in or above the upper easterly current. Based upon the observations that have been made, a statement to the effect that such a surface of maximum temperature exists can not be definitely made. The upper easterly wind has been, to a very limited extent only, explored by means of self-recording instruments. Above the heights reached by means of sounding balloons, the only means of free air observation have been furnished by the luminous meteor trains which often persist long enough after the passage of the meteor to enable an observer to determine their altitude and movement. As nearly as may be estimated from the few observations of this sort available the easterly wind may extend to about the 60-kilometer level. Above this the drift seems to be from a westerly direction again.

In figure 3 an attempt has been made to fit together all the above observations and to represent a meridional section of the planetary system of convection so far as it has been observed. The dashed line in this figure indicates the limits within which observations have been made.

GENERAL CONSIDERATIONS.

In considering this scheme of air movement and its relation to the pressure, temperature, and moisture distribution in the atmosphere there are a few more or less fundamental facts and laws that one needs to have in mind. These need only be stated since they are generally accepted.

1. The earth is the chief source of atmospheric heat, especially in the lower strata of the atmosphere. This heat is transferred from the earth to the air by conduction and by radiation. It is distributed in the atmosphere by convection and by radiation.

2. The absorption of solar radiation, while relatively inconsiderable in the lower strata of the atmosphere, may be a relatively important source of heat in the upper strata. In this connection it is of interest to note that in the lower latitudes some considerable part of the atmosphere is always in the earth's shadow. A rough calculation shows that at 524 kilometers above the poles the sun is always shining; that at 30 kilometers above the poles the sun shines seven months of the year instead of six as at the poles themselves.

3. The chief cause of convection is a sufficient amount of unequal heating of air masses so located that the colder air mass is at the same or higher levels than the warmer. It is also conceivable that air may change level from causes entirely mechanical, e. g., it would tend to be thrown outward from a rotating air mass and would be changing level if outward, or some component of outward, were upward.

4. Air is heated by radiation it absorbs. It is not heated by transmitted radiation. In other words, the heating of air by radiation is inversely proportional to its diathermance. The moisture of the air is the constituent that more than any other absorbs terrestrial and solar radiation, consequently a dry air mass is likely to be relatively cool and a moist air mass relatively warm, regardless of the relative height of these masses above the earth's surface. Further, air above a stratum of moist air receives less terrestrial radiation and air below it less solar radiation than air similarly located with reference to a stratum of dry air.

5. The amount of moisture that may be contained in any air mass is directly related to the air temperature. This fact is especially useful in thinking of moisture distribution in the lower atmosphere. According to Stoney's conception of the gravitational sorting of the constituent gases of the atmosphere, the constituent, water vapor, will, above a certain level, increase with altitude, relatively to the heavier constituents, nitrogen and oxygen. This law is especially important in thinking of moisture distribution in the upper atmosphere. To a certain ex-

tent it may be said that air temperature determines the moisture content of the lower atmosphere, while moisture content determines the air temperature of the upper atmosphere.

6. In both direction and rate, the flow of air on any "equigravic"[4] surface bears a definite relation to the lines in which this surface cuts isobaric surfaces. The direction of flow in the northern hemisphere tends to be along the isobars from left to right as one goes directly from high to low pressure, but opposite to this in the southern hemisphere. The rate of flow is inversely proportional to the distance between the isobars, or proportional to the pressure gradient.

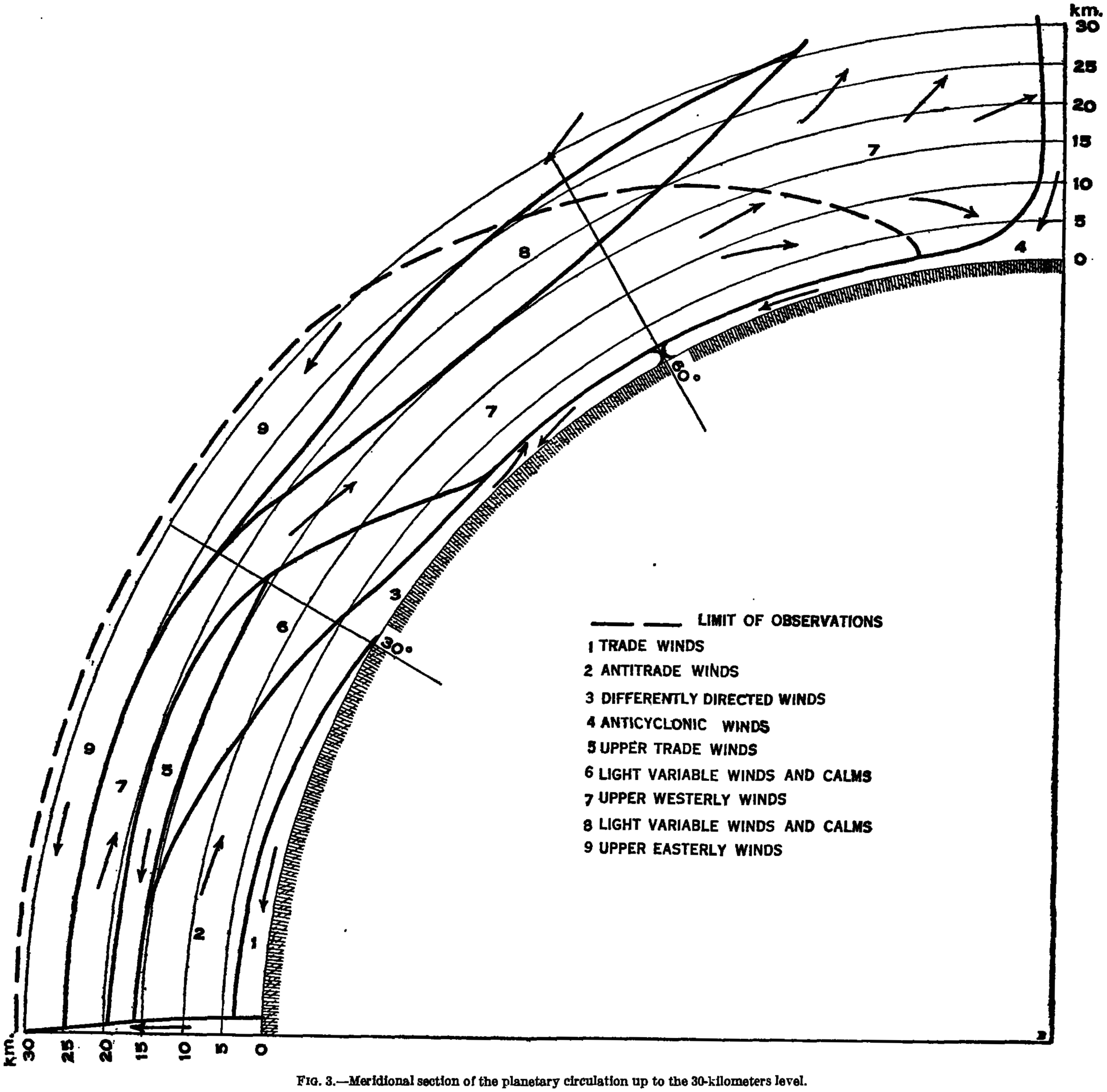

FIG. 3.—Meridional section of the planetary circulation up to the 30-kilometers level.

7. Barring change in its constitution, the potential temperature of an air mass tends to remain constant. Level, rate of flow, pressure, and temperature all vary in such ways as to take care of the topography and other characteristics of the bottom over which the air mass moves if it be moving, and to take care of warming or cooling by contact or by absorption and radiation,

[4] No entirely satisfactory name for the unit of gravity potential used in dynamic meteorology has yet been found. The value of this unit of potential is 10^5 ergs. The author suggests that the unit be called the "grav," pronounced as is the first syllable of gravity, that lines of equal gravity potential be called "equigravs," and that surfaces of equal gravity potential be called "equigravic surfaces." Since "g" is the abbreviation for the force of gravity and, in the C. G. S. system, for gram, it seems advisable to use "gv" as the abbreviation for "grav." This suggestion is put on trial above and following.—W. R. B.

whether it be moving or not. The "bottom" may be the earth's surface or it may be an aerial bottom. This is why a wind may become gusty. Since they are caused chiefly by the nature and topography of the bottom over which the current in which they occur flows, gusts are usually aperiodic.

8. The poles are about 22 kilometers nearer the center of the earth than is the earth's surface at the Equator. The difference between the sea-level value of gravity at the Equator and at the poles is 5.19 dynes. Of this, 3.35 is accounted for by the rotation of the earth and 1.84 by change of level. According to the law of change in gravity with height in general use, a change of 1.84 in the value of gravity would occur in about 6 kilometers altitude and a change of 5.19 in about 17 kilometers altitude. "Equigravic surfaces" do not depart much from hypsometric surfaces. Assuming that they coincide at latitude 45°, "equigravic surfaces" are below the hypsometric surfaces at lower latitudes and above them at higher latitudes. Actual departures at the 30-kilometer level are less than 100 meters.

THE GENERAL CIRCULATION OF THE ATMOSPHERE.

Isobars and isotherms which tend to run with the parallels of latitude are considerably distorted because of the peculiar distribution of land and water areas on the earth's surface. The more permanent belts of high and of low pressure are more or less broken up on this account and the circulation of the air considerably influenced. The number and distribution of free-air soundings do not at present warrant a detailed discussion of these influences from the experimental point of view. Only the more general features of this circulation, shown in figure 3, will now be considered. While it is likely that the system is less disturbed in the southern than in the northern hemisphere, because of the more uniform nature of the earth's surface, it is only necessary to consider here the region between the latitude upon which the sun's rays fall vertically and the North Pole. A suitable change in wind direction will usually be sufficient to make the discussion applicable to the region between the thermal equator and the South Pole.

Air in contact with that part of the earth's surface upon which the sun's rays fall vertically becomes relatively warm and is replaced by air moving in from the north and from the south of it. This gives rise to the trade winds at the earth's surface. These winds are north because of the unequal heating and east because, in their initial stages, at least, they progress over more and more rapidly moving surface as they move southward. These winds also acquire an upward component because the air in them receives more and more heat and moisture from the increasingly warm surface over which it moves. In its ascent the air of this current gains in density relative to the air at the same levels to the north of it, with the result that "equigravic" and isobaric surfaces coincide when the potential value at the former is from 3 to 6 "kilogravs," depending on season and distance from the thermal equator. Above the transition surface the isobaric surfaces cut the "equigravic" surfaces from below instead of from above as at lower levels, and the upward moving east wind acquires a component of motion from the south. As the southeast wind of these higher levels approaches higher latitudes it turns to the right, finally acquiring a component of motion from the west. The air of the trade winds in rising loses some of its moisture by precipitation. The air of the antitrade winds at higher altitudes is therefore differently constituted, having less moisture than the trades. This difference in constitution is of course small in the portions of these currents lying close together and more pronounced with distance from their common boundary plane. As a result of this change in constitution the transformation above described, up to the point where the component of motion from the south sets in, is not reversible. The drier air of the antitrades can not all have returned to the earth's surface by the time the northern limit of the trade wind has been reached. Its adiabatic rate of heating and cooling is greater than that of the moister air of the current below it. This difference in adiabatic rates for the dry and for the moist airs of these two strata, while always appreciable, becomes pronounced when condensation begins in the latter. It effectively limits the return to lower levels of the drier air of the antitrades, with the result that this air is for the time relatively heavy when compared with the air below it, especially so in the upper part of the antitrades. With this relation existing between the air in the trade and antitrade winds, it follows that air in the lower levels of the antitrade wind will begin returning to the trade wind in its upper levels as the former pursues its northerly course over the latter, and the air in the antitrade wind will have a downward component in its motion. This downward component brings the antitrades to the surface at latitude about 30° north of the thermal equator, from which point that portion of the air in them that has not been able to return to the trades continues north over the earth's surface—a warm, dry, southwest wind in the lower latitudes, but rapidly acquiring moisture in its progress toward higher latitudes.[5] Its relative density thus decreases with increasing latitude, and an upward component of motion is introduced. The air of the antitrades has apparently all left the earth's surface by the time latitude 60° north of the thermal equator has been reached. It does not rise far before the pressure gradient is reversed, as has been described in the transition between the trade and antitrade winds. The return of some of this air to the surface farther south, as well as the flow of air from the polar high pressure area through the rather broken belt of low pressure at latitude 60° north of the thermal equator, complicates the surface wind system of the middle latitudes. When these northerly winds meet the southerly antitrades, the latter either rise over them or pass them, with the result that to the left of the passing currents, as one faces the direction of flow, an area of low pressure is formed, while to the right is an area of high pressure. Retarded by surface friction, these surface currents can not flow in the direction of the isobars, but have a considerable component down the pressure slope. They do not therefore tend to mix across the maximum of air pressure on their right, but do tend to flow together or mix across the minimum of air pressure on their left. Part of the warm, usually moister, southerly current is forced up at this meeting, and more or less precipitation occurs.

The aperiodic undulations of surface air pressure thus set up move around the earth in the middle latitudes with about the speed and direction of the westerly wind at the 3-to-5-kilometers level. They have greater frequency and intensity in the winter months when the polar high pressure area is well developed than in the summer. The closed isobars about these maxima and

[5] The process by which the air of the trade winds passes (differently constituted in an important respect) into the air of the antitrade winds and the resulting lack of direct reversibility of the process has been described somewhat in detail because it is a typical process and one often found operating in the lower moist stratum of the atmosphere.

minima of surface air pressure begin to disappear a few hundred meters above the earth's surface, or with the decrease in the effect of friction between the earth's surface and the air. At 2 or 3 kilometers above the surface the isobars are no longer closed. Above these levels the trend of the isobars is along the parallels and the pressure slope is toward the north.

Tropical hurricanes probably have an origin somewhat similar to the less intense, larger low-pressure areas of the middle latitudes, except that in the Tropics the oppositely directed winds are in part at least of local origin. However it originates, the tropical hurricane, like the larger disturbances of the middle latitudes, moves with the air in the stratum just above the surface stratum in which it forms. In the case of the hurricane this upper current is the antitrade wind. In the case of the cyclones and anticyclones of middle latitudes the upper current is the upper westerly wind.

Above the antitrade winds of the lower latitudes the slope of the pressure gradient is again reversed. At these levels the air under which the antitrade winds descend in their northward journey is dense, relative to the air south of it, and an easterly wind with a component down the pressure slope is maintained. Because of the similarity in direction of these winds to the trade winds they have been called the upper trades. It is conceivable that in the northern part of the stratum occupied by these easterly winds the air will have a downward component. This component, together with heat it will receive from the earth's surface and from the air of lower levels, will affect the density of the air of the upper trades so that the downward component will disappear and, as it moves still farther south, an upward component will obtain. The upper trades are supplied with air by such return from the antitrades and air from the polar high pressure area as does not come down to the earth's surface and return to lower latitudes by way of the trade winds.

The downward component of air motion in the southern part of the stratum occupied by the antitrade wind and in the northern part of the stratum occupied by the upper trade wind has the effect of inclosing between these two strata, in the lower middle and upper tropical latitudes, a stratum of air in which there is no very well defined movement. This region of light winds and calms has been thought to accompany directly the high pressure observed at the earth's surface in the horse latitudes, but its area is more extensive than the high-pressure belt and besides the fairly steady antitrades pass under it, flowing under the influence of a pressure gradient sloping to the north, while above it the upper trades are moving under the influence of a pressure gradient sloping to the south. This transition stratum between the antitrades and upper trades has little or no depth in the lower tropical latitudes where the currents are both easterly, one with a small north and the other with a small south component. It is possible that some air from the upper trades may return to the antitrades before the former reach the thermal equator.

The increase in density of the air of the upper trades brought about by the upward component in its motion toward the thermal equator again gives rise to a reversal of the pressure gradient and a westerly current with a small south component obtains in the levels immediately above the stratum occupied by the upper trades. The upper westerly wind behaves in many respects like the antitrade wind and the somewhat detailed description of what happens to the air in its progress from the trade wind stratum into and through the antitrade stratum need not be repeated. The upper westerly wind differs from the antitrade wind in that the former does not at any time flow over the earth's surface. The air of the westerly wind is cold, dry, and, compared with the air at lower levels, relatively dense. It has a downward component of motion as it passes into higher latitude, as a result of which it undergoes adiabatic heating and appropriate changes in volume and density. In the lower latitudes air from the upper westerly wind is probably supplied to the upper trade wind over which it flows. The air that continues to higher latitudes forms a deeper current as it moves north in accord with the law that the area of its cross section times its density shall remain constant. This deepening of the current is not sufficient to keep its upper limit at the same level, at least until middle latitudes are reached. There is some evidence that the upper level rises from middle to higher latitudes. This being the case, there should be a position somewhere in the middle latitudes at which the surface of minimum temperature, located in the upper part of the upper westerly wind, will pass through a maximum, this maximum being coincident, or nearly so, with the lowest level reached by the surface.

In their journey northward the upper westerlies acquire some moisture from the air below them, especially in their lower levels. This, together with the fact that in the higher latitudes the air of the surface stratum contains less moisture than that at lower latitudes, tends to make the constitution of the airs in these two strata more nearly alike at the higher than at the lower latitudes. The direct result of this increasing similarity is the nearer approach to the earth's surface of the upper westerly wind in the higher latitudes. The shallow anticyclonic winds of the polar high-pressure area seem to be supplied with air on the poleward side by the upper westerly wind. The surface winds here tend to be easterly with a component of motion from the north. The air of these winds heats adiabatically as it moves from higher inland surfaces to sea level. Some of it thus heated leaves the earth's surface at latitude about 60° north of the thermal equator and some moves on to lower latitudes, where the result of its meeting with the antitrades has already been noted. The upper westerly wind is observed within a kilometer of the earth's surface at points 70° to 80° north and south latitudes.

The presence at relatively high levels of the stratum of dense air, found in the upper westerlies, has the effect of producing turbulence or turbulent convection in the stratum of air below it. In the middle latitudes turbulence occurs in the lower 2 to 5 kilometers of the atmosphere. Turbulence is likely to prevail at the lower boundary of any air mass occupying a level relatively high for its density, regardless of the position of such air mass in the atmosphere. Doubtless the antitrades contribute in this way to the intensity of tropical cyclones after the passing of differently directed currents in the stratum below has given rise to them.

The air under which the upper westerly current descends as it moves to higher latitudes will at some level above the latter become relatively dense when compared with the air south of it. A pressure gradient sloping to the south will be established in these upper levels and an easterly current with a component down the pressure slope maintained. The gradual deepening of the upper westerlies as they approach the poles, together with the diminution of the central force, g×cos. lat., has the effect of forcing air in the upper levels of the current to great altitudes. As a result of its being forced up, this air becomes dense relative to the air south of it and augments to some extent the easterly current prevailing at these higher levels. Observations to sufficient height in these high latitudes are lacking, but it seems that the forces operating here must result in the return at higher levels of a small part, at least, of the air carried northward by the upper westerlies. As has been pointed out above, the tendency of the air in this current is downward, but its high rate of adiabatic heating in descent, when compared with adiabatic rates of heating and cooling in the air below it, limits its return southward on its underside until extremely high latitudes are reached. Here the other forces mentioned tend to some extent to operate against the return at lower levels.

A stratum of comparatively quiet air, similar to that inclosed between the anti and upper trades, only of much greater extent, will be inclosed between the upper limit of the upper westerlies and the lower limit of the upper easterlies. The vertical extent of this stratum decreases toward its southern limits. As observed in the Tropics, the upper easterly wind passes immediately over the upper westerly wind. At this point of contact, probably in the lower middle or upper tropical latitudes, a return of air from the upper to the lower of these two currents takes place, sufficient to balance the interchange of air between them over the polar regions.

It should be noted that the supply of air from the upper westerly to the upper easterly wind in the polar regions, while it may take the form of a deep current there, will be a very shallow layer of air when distributed over the larger area covered by the easterly current as it goes south. The depth of the upper easterlies observed in the tropical regions, 6½ kilometers, indicates a very deep current in higher latitudes.

It appears from the above considerations that air over the thermal equator is, on the whole, rising at all levels so far explored and descending at higher latitudes. The rate of vertical motion must be exceedingly slow, since the upward or downward components of motion are required to carry the air only a few kilometers in the same time that the horizontal components carry it thousands of kilometers. The ratio of the vertical to the horizontal components of motion in the lower strata is less than in the higher. The latter currents travel more uniformly and to much greater distances than the former.

The general north and south movement of the whole system of winds above described may be caused by an aperiodic variation in the amount of solar energy reaching the earth's surface in the tropical low-pressure belt. The formation of a cloud cover in this region results from active heating of the earth's surface. This cloud cover reflects more than half the solar radiation incident upon it, with the result that the cover may, partially at least, disappear, allowing the earth's surface to be heated again, and so on. Such a variation would have the effect of varying the amount of solar energy used in the tropical low-pressure belt and of varying the width and position of the belt itself, thus increasing and decreasing the north-south component of the whole circulatory system.

Whatever its cause, this general north and south movement of the atmosphere up to the highest levels explored is peculiar in that the change in rate of meridional motion from the time of its greatest northward to the time of its greatest southward speed is rather gradual, this period being from 4 to 10 days. The change from greatest southward to greatest northward motion occupies a comparatively short time.

Some years ago Mr. E. H. Bowie called the writer's attention to the fact that the low-pressure areas enter and cross the United States in series. The first low-pressure area in such a series will enter the country well to the north and pursue a course eastward over the northern States, the second enters somewhat farther south, and so on. The last low-pressure area of the series may enter the extreme Southwest and pass along the Gulf and Atlantic coasts, although the series do not always carry as far south as this. The series follow each other in close succession. The relation between these series of low-pressure areas and the general meridional movement of the atmosphere seems to be quite direct. The fact that the low-pressure areas of any series pursue more nearly the same path across the North Atlantic than they have pursued across the continent seems to indicate that the change in position of the thermal equator occurs mostly over land areas. It is possible that the meridional motion found over the continental area is compensated by a meridional motion in the opposite direction of the oceans.

TEMPERATURE AND PRESSURE DISTRIBUTION.

The general features of the temperature and pressure distribution, especially in so far as they give rise to the circulatory system just described, have already been considered. It is the intention of this part of the paper to consider peculiarities in the distribution of these elements that have been observed in certain regions of the atmosphere.

The surface of minimum temperature near the upper limit of the upper westerly current has been of great interest to meteorologists since its discovery about 20 years ago. Many observations of it by means of sounding balloons have been made, but unfortunately these observations are not so well distributed as could be desired. The great majority of them have been in middle and upper middle latitudes. A remarkable feature of this surface of minimum temperature, as observed in the middle latitudes, is the large variation in its temperature from day to day. Based largely upon these observations of temperature variation, variations in air pressure have been found to exist. All of these changes in the region of minimum temperature are found closely related to the changes in the same elements observed at and near the earth's surface, as low and high pressure areas pass.

This relation is so close that some have gone so far as to look to the stratum of minimum temperature for the cause of the low and high pressure areas.[6] It is conceivable that gustiness of the upper westerly wind could cause variations in the air pressure at the earth's surface similar to those observed, but if this be the order of cause and effect the succession of high and low pressure areas would not be confined to the middle latitudes, since the upper westerly wind is observed at all latitudes. Moreover, it would be difficult to assign a cause for such gustiness in the upper westerly current. In the writer's opinion the high and low pressure areas are brought about by the passing of differently directed currents as described above, and the rough aerial bottom, owing to this cause, over which the upper westerlies must pass in the middle latitudes, accounts for their gustiness. Some contribution to the intensity of the disturbances thus

[6] *Shaw, W. N.* Principia Atmospherica: A study of the circulation of the atmosphere, Proc., Roy. Soc. of Edinburgh, v. 34, pt. 1, no. 9. *Reprinted* in this REVIEW, April, 1914; there particularly see p. 203.

caused in the lower stratum may be directly attributed to the overlying of the relatively dense stratum of air. This effect will be similar to that produced by the air of the antitrades, in the case of tropical cyclones, but it will be less pronounced in the case of these large area disturbances. If this be the correct interpretation of the phenomena observed in the middle latitudes, observations in higher and lower latitudes where surface winds are steadier than in the belt traversed by the areas of high and low pressure should show less gustiness, or none at all, in the upper westerly current.

It is only because the upper westerlies rest heavily on the bottom over which they flow that they find it necessary thus to adapt themselves to all its irregularities. The air in them is, as has been pointed out above, relatively dense for the level it occupies because of its dryness when compared with the air below it. It is for this reason that this gustiness does not occur in levels above the upper westerlies. It has been pointed out by those who seek the cause of the surface areas of high and of low pressure in the coldest part of the upper westerly current that the amplitude of the temperature and pressure variations here are even greater than at any level below. This is to be expected, because the temperature changes accompanying a given expansion or contraction of dry air are decidedly greater than those accompanying the same expansion or contraction of moist air, and, since values of the pressure-altitude relation are deduced largely from consideration of the temperature variation and not independently, the variations of pressure in these levels appear greater than they really are when compared with the variations of pressure at lower levels.

This interaction between the airs belonging to the surface and to the upper westerly winds doubtless plays an important part in the determination of the forward movement of the high or low pressure area over the earth's surface. These areas, it has been noted, seem to have the speed and direction of the air movement at the 3 to 5-kilometers level. The same may be said about the interaction between the airs of the trades and antitrades in the case of tropical cyclones. These cyclones, while in the tropical belt, seem to travel with the speed and direction of the antitrades.

Some work by the writer on the gustiness of surface winds is in progress, and an illustration of this may be of interest here. Figure 4 illustrates the changes of speed and direction of air movement and of pressure during the hour 8 to 9 a. m., February 4, 1916, as recorded at the Weather Bureau Observatory, Washington, D. C. The wind gusts during this hour are selected because of their regularity and of the low velocity of the wind in which they occur. Their regularity enables one to follow the changes more easily. By selecting a wind of low velocity, errors, owing to the inside exposure of the barometer, may be neglected in comparison with the effects being observed. Unfortunately, the only record of temperature available is of small scale, and the beginning and ending of the hour can not be closely located except by inference from the other records. The records by the wind vane, pressure-tube anemometer, and compensated mercurial barograph are all large scale and capable of fairly accurate reproduction.

It has been pointed out above that the air of the upper westerly wind is dry and dense when compared with the air below it, especially in the lower latitudes. The same may be said of the air in this current when compared with the air above it. Now, while this air mass holds a position somewhat higher in the air because of its dryness than its density entitles it to, it does not much affect the passing in of solar radiation and the passing out of terrestrial radiation. It has also been pointed out that the air of the upper westerly wind becomes more and more like the airs above and below it as it journeys northward. The only effect of this relationship between the air of the upper westerly current and the airs of the strata immediately above and below it is a rather decided minimum in the value of the temperature-altitude relation in the lower latitudes, this minimum being less pronounced with increasing latitude. It follows that above the surface of minimum temperature, found in the upper westerly current, the air temperature increases with altitude. This increase is

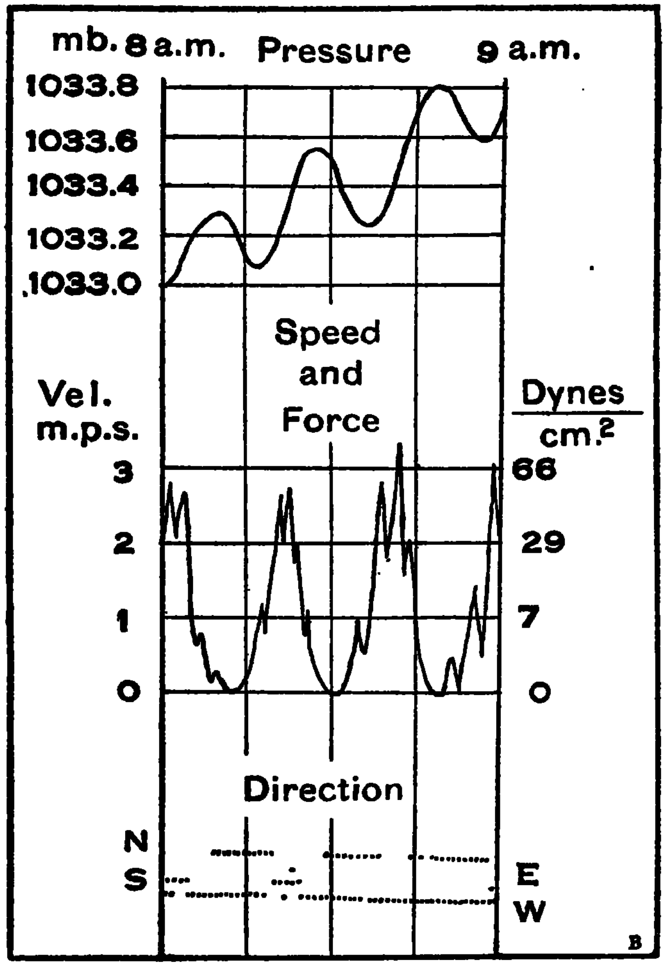

FIG. 4.—Relation between speed, force, pressure, and direction in wind gusts.

more rapid in the lower latitudes than in the higher and more rapid in the summer than in the winter months, so far as observations go. That terrestrial radiation is still effective at these high altitudes is shown by the difference in temperature here, owing to the difference in the screening effects of relatively dry and moist masses of air at levels below the surface of minimum temperature. Observations confirm the conclusion that the upper westerly wind is dry, when compared with air at lower levels. That the air of this current is dry, relative to the air above it, is also a matter of observation. It may be argued that, since the H_2O molecule is considerably lighter than that of nitrogen or of oxygen, the decrease in all three constituents with altitude will result in an increasing proportion of water vapor in the air with altitude up to a certain height. This limiting height can not be definitely determined, because air temperatures in these very high levels are not known. It is probable that it occurs below the 100-kilometer level. Observations indicate that of the total solar energy absorbed by the air from two-thirds to three-fourths is absorbed by the water vapor of the air. In view of the probability that at no great height above the surface of minimum temperature the moisture content of the air is a greater percentage of the whole air mass than at any lower level, solar heating of the air in these upper levels is likely to become relatively important. Especially is this true when we consider that at these levels there is available for absorption something over twice the amount of solar radiation available in the stratum of air lying on the earth's surface.

The density of the water vapor of the air doubtless varies over the surface of minimum temperature, increasing and decreasing with the temperature of the surface. Since the temperature of the surface of minimum temperature increases with increasing latitude, at least for some distance north and south of the Equator, then, by the law of gravitational sorting of the constituent gases of the atmosphere, the air of these upper levels above the higher latitudes will be moister than air of the same levels over the thermal equator. Taking this moisture distribution into consideration and assuming that somewhere beyond the 30-kilometer level a stratum exists in which the absorption of solar radiation by the water vapor of the air is the chief factor in the determination of the air temperature, the thermal belt will no longer be found above the Equator, but about one or the other of the poles, since air above the poles will receive the greater amount of direct insolation. These considerations point to a maximum of temperature with altitude probably somewhere below the level of greatest relative moisture content in the atmosphere, depending on where the combined heating effect of solar and terrestrial radiation is at a maximum. But they also point to a probable circulation of the air in the upper atmosphere with reference to the poleward thermal belts. It is possible that in high latitudes something of this influence is already felt in the extreme upper regions of the upper westerly current.

The location of the poleward thermal belts will be determined by the relative amount of absorbing constituents present in the air and by the heating effects of solar and of terrestrial radiation. Solar heating tends to take the thermal belt poleward, but a maximum of terrestrial radiation is available in these upper strata at a latitude determined by the potential of the earth's surface as a radiator and by the diathermance of the intervening strata of air. The earth's potential as a radiator decreases with latitude, while the diathermance of the intervening air increases with latitude. It is probable, therefore, that the influence of terrestrial radiation on the position of the poleward thermal belts will be to keep them away from the poles, especially in their lower levels. The belts should approach the poles with increasing altitude. Observations for determining, qualitatively at least, the relative importance of solar and terrestrial heating of the air at different levels are in progress, but considerable time will be needed for their completion. At best they will be limited as to latitude.

It should be stated that, on the assumption of a uniform horizontal distribution of absorbing constituents in these very high levels and entirely independent of the relative importance of solar and terrestrial radiation as sources of heat, relatively warm belts would exist around the poles at a latitude determined by the diathermance of the lower strata of air and the earth's potential as a radiator. These belts would owe their existence to the relatively greater amount of terrestrial radiation available for absorption at their latitudes than at any other latitude. For the same reason a minimum of temperature, or a relatively cold belt, would be found over the thermal equator where the screening effect of the lower strata of air is greatest. This reversal in the positions of the hot and cold belts, in the very high levels referred to, would be analogous to the reversal, in point of time, of the positions of the diurnal maximum and minimum of temperature which is found above the 1.5-kilometer level and would have a similar cause. As pointed out, the distribution of absorbing constituents and the possible relative importance of solar heating of the air in these high levels tend to strengthen the horizontal temperature gradients which must exist, as well as the circulation accompanying them.

The consideration of this subject indicates the necessity for a better distribution of the high level observations before final conclusions can be drawn. It also points out the great value of observations of air movement at all levels. There is need of a system of observations extending as far to the north and to the south as possible along one or more meridians.

SUMMARY.

1. This paper makes no attempt directly to show that the distribution of temperature in the atmosphere is in keeping with the fact that, in the long run, incoming and outgoing radiation balance each other. Recognizing this law, it attempts to show how the general circulation of the atmosphere is maintained and the influence of this circulatory system on the distribution of temperature and pressure in any particular part of the atmosphere.

2. Many of the atmospheric phenomena peculiar to given locations and seasons are not altogether of local origin, but are related more or less directly to the planetary system of convection. Among these phenomena may be mentioned: (1) The more decided minimum in the value of the temperature-altitude relation over middle latitudes in the summer than in the winter; (2) the variations in the temperature and the position of the surface of minimum temperature with latitude and, in the middle latitudes, with the passing over the earth's surface of high and low pressure areas; (3) the cyclonic and anticyclonic disturbances of the middle latitudes and to some extent the tropical cyclones.

3. The chief cause of nonreversibility of adiabatic transformations in the free air seems to be the change of constitution which takes place in the air during the transformation. The absorption and radiation of heat by the air mass under consideration enters to a greater or less extent, depending on the time occupied by the transformation and the amount of air in the mass, but this relation between the time and amount of air concerned in the transformation is usually such that the effect of absorption and radiation by the air is small.

4. The temperature conditions above the surface of minimum temperature are considered and some tentative conclusions, based on the distribution of atmospheric constituents, and on the relative heating effects at these high levels of solar and of terrestrial radiation, are drawn.

5. While turbulence or turbulent convection is found to be more active in some regions of the atmosphere than in others, convective circulation of the atmosphere obtains throughout the explored regions and doubtless for many kilometers above.