## THE LOCAL CIRCULATION OF THE ATMOSPHERE.

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In the November, 1915, number of this REVIEW[1] certain difficulties connected with the general circulation of the atmosphere and the distribution of temperature therein were pointed out. The local circulation, the passage of cyclones and anticyclones over a locality, with the accompanying changes of weather, ought also to be considered since the two subjects must be very closely interrelated.

The occurrence of a low barometer is so common that the difficulty of explaining it has perhaps been overlooked; also various explanations were put forward in the early days of meteorology which fuller knowledge has shown to be untenable. The commonly accepted view of 40 or 50 years ago was that the pressure of damp air was the cause of a depression; the greater probability of rain with a low barometer was as apparent then as now, and this, combined with the fact that water vapor has a lower specific gravity than air, supported the hypothesis.

But a fuller investigation has shown that the variations of the humidity can have but a very trifling effect on barometric pressure. For proof of this it will suffice to refer to Hann,[2] or to the fact that the British Meteorological Office entirely ignores the humidity in all questions involving the change of barometric pressure with change of height above sea level.

But while humidity has only a trifling effect upon the weight of the air there can be no doubt about the importance of the temperature, and a barometric reduction to sea level that ignored the temperature would be of little value. Can we then ascribe a low barometer to the warmth and hence the lightness of the overlying air? Ten years ago the answer would have been yes, but recent observations have shown that the air over a barometric depression is colder instead of warmer than usual, and over an anticyclonic region warmer instead of colder than usual. The point is a fundamental one. Observations show that the air over a cyclonic area is cold, the low pressure therefore is not due to lighter air and all our old theories which seemed so satisfactory and plausible have been upset. One's first feeling is to doubt the accuracy of the observations, and it is desirable to examine the evidence. There is no great difficulty; it is simply a matter of expense and a moderate amount of skill, in sending up a light meteorograph hanging from a small free balloon with a label attached offering a reward for the return of the meteorograph. The practice has been carried on systematically at many stations in Europe for 10 years at least, with the result that a thousand or perhaps more observations have been published giving the values of the temperature, and in many cases the humidity, from the ground upward to about 15 and in some cases to 20 km. (9–12 miles). The instruments used in the British Isles are different from those used on the Continent and the system of calibrating is different, but the results are practically identical. The British Isles are subject during the winter months, to a continual succession of deep depressions passing along their western coasts and they are in consequence a very suitable locality for the study of cyclones and anticyclones. The figures given in Table 1 below refer to the British Isles simply for this reason: Observations there at times of very low barometer, 29 inches or so, are more numerous than on the Continent, but were there no observations at all from England the Continental observations would amply suffice to show the coldness of the cyclone and the warmth of the anticyclone.

To show the contrast between the temperatures in a cyclone and in an anticyclone the following special cases are given from observations made at Pyrton Hill in 1910. Pyrton Hill is some 40 miles west-northwest of London.

TABLE 1.—*Vertical temperature distribution at Pyrton Hill, England, in a* HIGH *and a* LOW.

| Dates | Oct. 6, 1910. | Nov. 3, 1910. |
|---|---|---|
| Pressure, mean sea-level | 1029 mbar. (30.30 in.) | 979 mbar. (28.78 in) |
| ALTITUDE. | °C. | °C. |
| Ground | 16 | 5 |
| 1 km | 13 | −1 |
| 2 km | 12 | −4 |
| 3 km | 7 | −9 |
| 4 km | 0.5 | −15 |
| 5 km | − 5 | −24 |
| 6 km | −11.5 | −31 |
| 7 km | −18 | −39 |
| 8 km | −26 | −42 |
| 9 km | −34 | −42 |
| 10 km | −43 | −44 |
| 11 km | −52 | −43 |
| 12 km | −59 | −45 |
| 13 km | −66 | −45 |
| 14 km | −66 | −48 |
| 15 km | −66 | −50 |
| 16 km | ........ | −49 |

These are special instances though they follow the general rule, but they suffice to show that a low barometer is not caused by the warmth of the overlying air. On October 6, 1910, the high barometer had over it, up to 10 kilometers height, air with a mean temperature of −8° C., while on November 3 the corresponding mean over the very low barometer of 28.80 inches was −22°C., a value 25 degrees (F.) colder. Almost any pair of observations selected for showing a large difference in the barometric height will show the same characteristics, and it is almost a certainty that when the barometer is much below its mean value the temperature of the air from 1 kilometer up to 8 or 10 kilometers will be lower than usual. Every person who has worked up the European observations has come to this conclusion.

In Table 2[3] the most probable values of the temperature in the British Isles at times of low and of high barometer are given in the absolute, centigrade and Fahrenheit scales.

TABLE 2.—*Probable temperatures over the British Isles in a* HIGH *and in a* LOW.[3]

| Height. | | | Cyclone. | | | Anticyclone. | | | Difference. |
|---|---|---|---|---|---|---|---|---|---|
| *Kms.* | *Miles.* | *Ft.* | °*A.* | °*C.* | °*F.* | °*A.* | °*C.* | °*F.* | °*C.* |
| 1 | 0.62 | 3,300 | 276 | 3 | 37 | 279 | 6 | 43 | − 3 |
| 2 | 1.24 | 6,600 | 270 | − 3 | 27 | 276 | 3 | 37 | − 6 |
| 3 | 1.87 | 9,900 | 263 | −10 | 14 | 271 | − 2 | 28 | − 8 |
| 4 | 2.49 | 13,100 | 256 | −17 | 1 | 265 | − 8 | 18 | − 9 |
| 5 | 3.11 | 16,400 | 249 | −24 | −11 | 259 | −14 | 7 | −10 |
| 6 | 3.73 | 19,700 | 242 | −31 | −24 | 253 | −20 | − 4 | −11 |
| 7 | 4.35 | 23,000 | 234 | −39 | −38 | 246 | −27 | −17 | −12 |
| 8 | 4.97 | 26,300 | 228 | −45 | −49 | 238 | −35 | −31 | −10 |
| 9 | 5.59 | 29,600 | 226 | −47 | −53 | 231 | −42 | −44 | − 5 |
| 10 | 6.21 | 32,800 | 225 | −48 | −54 | 225 | −48 | −54 | 0 |
| 11 | 6.84 | 36,100 | 224 | −49 | −56 | 220 | −53 | −63 | 4 |
| 12 | 7.46 | 39,400 | 225 | −48 | −54 | 217 | −56 | −69 | 6 |
| 13 | 8.08 | 42,700 | 225 | −48 | −54 | 215 | −58 | −72 | 10 |
| 14 | 8.71 | 46,000 | 224 | −49 | −56 | 215 | −58 | −72 | 9 |
| Value of $H_o$. | | | 8.7 *km.* | | | 12.3 *km.* | | | 3.6 *km.* |

[1] MONTHLY WEATHER REVIEW, Nov., 1915, 43: 551–556.
[2] *Hann, J.* Lehrbuch der Meterologie, 2d edit., 1906, p. 612.

[3] This table is taken from the Journal of the Scottish Meteorological Society, 1914, 16, No. 31.

Now it is plain from these figures that we can not explain a low pressure area by the warmth and smaller density of the air above it. There must be, of course, a smaller mass of air above it, but the greater part of that mass has a lower temperature and therefore a higher density than usual. Just the same difficulty occurs in the question of the general circulation, for in the Southern Hemisphere over the latitude belts of 50°–60° S. the pressures are very low and the air temperature is also low. In both cases the explanation must be that the low pressures are due to dynamical causes and in the case of the cyclone the low temperature is probably also due to dynamical causes.

In the preceding paper it was shown that in consequence of the rise of potential temperature with increasing height the air would strongly resist any vertical motion. But if by any means the air were forced from a lower to a higher stratum, in its new position it would be found to be cold; and if forced into a lower stratum, it would be warm; using the terms "cold" and "warm" in the sense defined in the previous paper. For the air on coming under the decreased pressure of a higher stratum, if the motion is sufficiently rapid, will cool adiabatically at the rate—for short distances—of very nearly 1°C. per 100 meters and this gradient is in excess of the average rate of fall with increasing elevation. In reality the air's motion is usually slow, a few hundred feet an hour perhaps, and no doubt the cooling is not at the adiabatic rate for there is time for some warming up by means of radiation; still on the whole rising air will be cooled. Similarly falling air is warmed. But the tendency of cold air is to fall and of warm air to rise, and if the cold of a cyclone is produced by the upward motion of the air in the central parts that motion must be a forced one, forced, that is to say, by the pressure conditions.

There are only two ways in which air out of reach of contact with the ground can be warmed or cooled, and they are dynamic heating and cooling and radiation. It is true that heat may be imparted to the air by the latent heat of condensation, but we need not consider this point here because we have to account for the cold of the cyclone at the altitudes where rain is formed and the latent heat of condensation would account for warmth, but not for cold. We know for a fact that the air in a cyclonic area has a tendency to rise; it is proved by the inclination of the surface winds to the isobars and by the tendency to rain, since rain in any volume can only be caused by an ascending current; and we have the choice of two ways of accounting for the coldness of the rising air, one by dynamic cooling due to the rise which involves a pushing or sucking upward of the air, the other by radiation. If we accept the hypothesis of radiation, we must show that cyclonic conditions specially favor the loss of heat by radiation from the air at altitudes between 2 and 8 kilometers, and we must also explain why the air so cooled by radiation does not sink as one naturally would expect it to do.

Before discussing this point it will be well to see what happens at greater heights over the cyclone and over the anticyclone. Above some 10 kilometers the conditions of heat and cold are reversed. Thus at 7 kilometers (see Table 2) the cyclone is 12° C. colder than the anticyclone, but at 13 kilometers the conditions are reversed and it is 10° C. warmer. In a cyclone the fall of temperature with increasing height is very rapid in the lower strata, but it ceases at about 9 kilometers; in an anticyclone the fall per kilometer is not large to begin with, but it strengthens higher up and is continued to about 12 kilometers. In both cases the temperature gradient ceases suddenly at heights of about 9 to 12 kilometers. This is well shown in the two records given, and is a fixed rule with very few exceptions. The sudden cessation of the loss of temperature with height is not markedly shown in the mean values, because it does not always occur at the same height. This height is very commonly denoted by $H_c$ and its mean value is given at the foot of Table 2.

This sudden cessation was discussed by Teisserenc de Bort, the well-known French meteorologist, and he proposed to call the lower part of the atmosphere in which the fall of temperature is present, the "troposphere"; and the upper part in which the conditions are isothermal, or nearly so, in a vertical direction, the "stratosphere". There is no definite word to express the thickness of the troposphere $H_c$, but it would be convenient to have one. The temperature at the point where the gradient ceases, i. e., at the boundary between the troposphere and stratosphere may be denoted by $T_c$.

We have then to explain the following distinctions between a low-pressure and a high-pressure area:

(1) Low = a cold troposphere, a small value of $H_c$ and a high value of $T_c$.

(2) HIGH = a warm troposphere, a large value of $H_c$, and a low value of $T_c$.

It has been seen that we can explain the cold troposphere of the cyclone by means of a forced ascending current, and we can equally well explain the warm stratosphere (a high $T_c$) by a forced descent in the stratosphere. It will hardly do to say current, because the stratosphere is so stable for vertical displacement that no current can occur, but a bulge downward seems to form over a cyclone. Sir Napier Shaw has shown[4] that such a bulge will not alter the isothermal conditions, but will raise the temperature of the column by the same amount throughout.

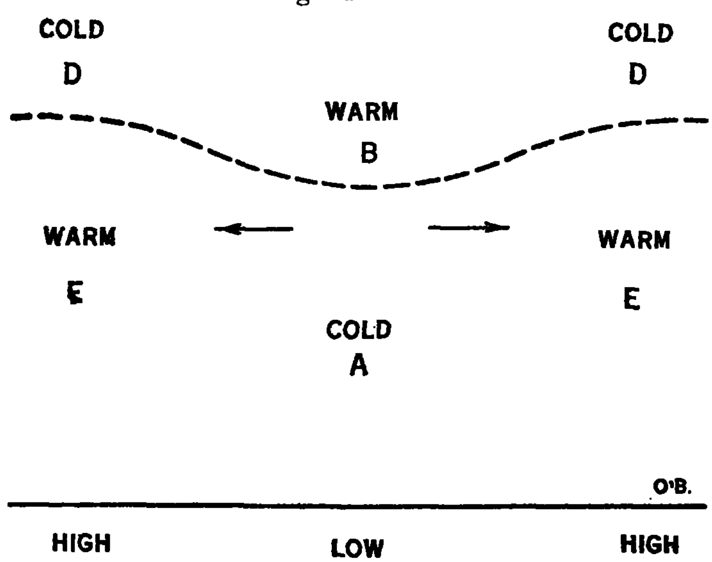


FIG. 1.—A vertical section through a LOW between two HIGHS.

Suppose the diagram, figure 1, to represent a vertical section through a low pressure placed between two anticyclones and remember that the horizontal and vertical scales are of necessity different in all such cases.

The terms "cold" and "warm" indicate departures from the average values for the height and are found almost without exception in every cyclone and anticyclone in which observations have been made. The

[4] *Shaw, W. N.* Note on the perturbations of the stratosphere. *In* The free atmosphere in the region of the British Isles. Meteorological Office, London, 1909. Publication No. 202. pp. 47–52.

temperatures close to the ground are uncertain, for they depend on the direction of the wind, on the time of day, and other things, but the indications in the diagram hold from 1 kilometer up to 20 kilometers, beyond which height we have practically no information. The dotted line denotes the boundary at which the fall of temperature with height ceases.

About three-quarters of the atmosphere is found below the dotted line and though the upper part over the LOW is warm the chief part, $A$, is cold; on the whole, therefore, the air is cold, and the explanation that a low pressure is caused by warmth fails utterly. The low pressure must be caused by the strength of the winds which encircle it and their tendency to draw the air away from the central parts, partly by their centrifugal action, but probably in temperate latitudes chiefly by their tendency to turn to the right on account of the rotation of the earth.

Now if the temperatures are due to dynamic causes they may be explained thus: We have seen that air that is being forced upward is cold and that air that is being forced downward is warm. If the winds are strongest at 8 or 9 kilometers, they will exert a sucking action away from the center at that height, as shown by the arrows; air will be drawn up in the region $A$ until its coldness and weight prevent any further rise; it will sink in the region $E$ until its warmth stops any further fall; the stratosphere will be drawn down under $B$ and raised under $D$, as we find it to be by actual observation. This will be more fully explained further on.

The alternative is to explain the temperatures by radiation, and I do not see how this can be done. In my previous paper the editor very kindly, by a footnote, called my attention to a paper by Prof. Humphreys which apparently contradicts my statement about the out-radiation in the Tropics. I failed to state the supposition that was in my mind that there was no supply or loss of heat save by radiation. With this supposition, which I certainly ought to have stated, my statement agrees precisely with one made by Prof. Humphreys in the same paper.

But I do not think that the out-radiation can be cut off by a veil of cirrus, for I very much doubt if the loss of heat by horizontal currents can be comparable to the loss by out-radiation when the district concerned is large, and in this case it is nearly half the surface of the earth (the belt 30° N.–30° S. comprises just half, taking the earth as a sphere). Also the amount of heat poured into the rainy equatorial belt by the condensation of vapor is very great, and it can hardly be dissipated by convection into the belts lying immediately north and south for the simple reason that these belts themselves are hotter rather than colder than the rainy belt.

If a veil of cirrus warmed the air below it and cooled the air above, we ought to find the cold region high up above the cirrus sheet of the cyclone and the warm region below it, but the opposite condition usually holds. Though cirrus cloud is not confined, at least in England, to areas of low pressure, it is certainly more common in such areas, for it is not at all frequent in anticyclones.

In the previous paper it was stated that the pressure at some 8 or 9 kilometers height (5½ miles) dominated all the other elements, and no account of our present knowledge of the local circulation can be at all complete without giving the grounds on which this statement is made. It is based on a statistical analysis of the European observations.

To attain to a complete knowledge of the local circulation we require to know the temperature, pressure, and humidity, also the velocity and direction of motion, of the air at each height, say in steps of 1 kilometer, over a considerable area. It is likely enough that there is some definite connection between some of these quantities, so that if two or three of them were known the rest might be known. The statistical method of correlation affords the means of ascertaining the nature of such connections, and it has been applied somewhat extensively to simultaneous pressures and temperatures of the air in a vertical direction, and to a less extent to the humidities and direction of motion. The following is a brief account of the results, some of which have been published [5] and some not.

As already stated, the pressure at 9 kilometers (in future for the sake of brevity denoted by $P_9$) seems to be the dominant factor—that is to say, that if $P_9$ is known, then the other pressures and temperatures are fairly well known. No other variable serves to give us so good a knowledge of the general conditions between 12 kilometers and 20 kilometers as this. If we knew that on a certain date the barometer at London stood at the low value of 29 inches, we should expect to find the temperature of the lower air column (from 1 to 9 kilometers) 8 degrees (C.) colder than usual and the thickness of the troposphere, $H_c$, 3 kilometers less than usual. These values would be guesses more or less, but it would be a practical certainty that both quantities would be below their average value. If, however, we knew the value of $P_9$ on that date, we could make a better guess at the temperature and at the value of $H_c$, because these quantities depend more on $P_9$ than on the surface value of the barometer.

It may be stated broadly that all the temperatures from 1 kilometer up to 20 kilometers, and probably much higher, are closely connected with $P_9$. The surface temperature is likely to be a little higher than usual when $P_9$ is high, but the connection is not a close one. The surface temperature seems to be dependent on the direction of the wind and other elements and is not closely correlated with any other quantity.

First, the $P_9$ is very closely connected with the temperature of the air in the column from 1 kilometer to 9 kilometers, the correlation coefficient, $r$, being nearly 0.90. The $P_9$ is calculated from the barometric reading at mean sea level and the mean temperarure from 0 to 9 kilometers, so that there must in any case be a close connection, but the actual connection is much closer than it would be if the temperature were purely fortuitous.

Secondly, the $P_9$ is closely connected with the thickness of the troposphere, $H_c$, the correlation reaching about $r=0.80$.

Thirdly, the mean temperature from 1 kilometer to 9 kilometers is of necessity highly correlated with the thickness of the troposphere, $H_c$, because both are closely connected with $P_9$. The correlation coefficient is about 0.75. The connection might be direct, but treating the figures by the method of partial correlation it appears that the connection is not a direct one, for if the influence of $P_9$ is excluded then there is no connection between the quantities.

It may be stated that a correlation coefficient is a numerical measure of the connection between two quantities; it must lie between +1 and −1. It gives the connection as it is shown by the given set of

[5] Meteorological Office No. 210b. Geophysical Memoir No. 2. Beiträge zur Physik der freien Atmosphäre. v. 5, pt. 4.

observations and is quite reliable when the number of observations on which it is based is large. A value of + 1.00 or − 1.00 shows perfect proportionality between the quantities, values of 0.70 or above show a close connection, and values below 0.25 or so are not significant. As a guide it may be said that the correlation coefficient between the closeness of the isobars and the strength of the wind is about 0.70.

The three instances given are the three closest connections that so far have been discovered between variable quantities in the upper air, but there are several others with correlation coefficients between 0.40 and 0.70. The fact is that the hopeless complexity that prevails at the surface is absent as soon as a height of a few thousand feet (1 km.) is reached. These connections are:

(1) Between $P_9$ and the surface pressure, $r=0.65$;
(2) Between $H_c$ and the surface pressure, $r=0.65$;
(3) Between $H_c$ and the temperature of the stratosphere, i. e., between $H_c$ and $T_c$, $r=-0.65$.
(4) Between the surface pressure and $T_c$, $r=-0.50$;
(5) Between the mean temperature 1 to 9 kilometers and the surface pressure, $r=0.45$;
(6) Between $P_9$ and $T_c$, $r=-0.45$.
(7) To these must be added a connection between the total amount of water vapor in the air and the mean temperature of the lower layers (0 to 5 km.), $r$ is about 0.65. This result is curious, for the anticyclone has from 1 to 5 kilometers a high temperature and a low relative humidity; the explanation is that warm air can hold so much more vapor than cold, that warm air even when dry in an anticyclone carries more water than the wet cold air of a cyclone.[6]

That the air in summer notwithstanding its dryness contains far more moisture than in winter is well known to most meteorologists.

It hardly seems likely that there are many more close connections in the atmosphere beyond those enumerated above, but there are a few other weak connections with correlation coefficients of 0.20 to 0.30 that may be stated. The temperature near the surface is colder with a north or northeast wind, but the effect does not extend to beyond 4 or 5 kilometers. The value of $H_c$ is lower with a barometric gradient favorable for north winds. The value of $H_c$ is lower when the barometer has been rising for 12 hours than when it has been falling. Perhaps these last two statements represent the same phenomena, for a rising barometer generally accompanies a northerly gradient. They are fairly well established, but the effect is not large and it is just possible that they are due to a large casual error.

There are also three negative results that must be stated. Save at low levels the direction and strength of the wind has no effect upon the temperature. The value of $H_c$ is not directly influenced either by the temperature or by the total water content of the lower air column.

Each of the above results is based on the statistical treatment of at least 200 observations, so that it is fairly reliable and we are able to draw a fairly accurate picture of the changes that are in progress in the upper air as a HIGH or LOW passes. As the pressure falls the air temperature from about 1 up to 9 or 10 kilometers becomes colder, the pressure up to the same height decreases by about the same amount as at the ground. Above 12 kilometers the temperature rises and a downward bulge of the stratosphere is formed which with a really deep depression may reach down to within 8 or even 7 kilometers of the ground.

In this upper part of the atmosphere the defect of pressure tails off rapidly not only in actual magnitude but as a percentage of the whole, until at 20 kilometers or a little over, equality of pressure between cyclones and anticyclones seems to be reached. It is at about this height that equality between the pressure over England and over the Equator is found.

The converse occurs with a high barometer. As previously stated we have the choice of two ways for explaining the peculiar distribution of temperature and the change of $H_c$, for the value of $H_c$—the thickness of the troposphere—is an essential part of this distribution, since it measures the height to which the fall of temperature with height extends. The view that $H_c$, so far as its variation between high and low pressure areas is concerned, is dependent on radiation seems to me quite untenable for the following reasons:

The out-radiation on which it is said to depend must itself be dependent on the temperature and radiative power of the lower strata. The radiative power undoubtedly varies with the amount of water vapor, but the statistical investigation shows that neither the temperature nor the water vapor of the air has the slightest effect upon $H_c$. Therefore $H_c$ can not be dependent on radiation. Still stronger, perhaps, is the following argument. Changes in temperature of 10 degrees (C.) may occur in 24 hours, and such changes can not be due to radiation because if the whole solar heat received per day were devoted to warming up the atmosphere it could only warm it about three degrees (C.). Radiation is therefore incapable of changing $H_c$ as rapidly as it is known to change under the changing pressure conditions.

On the other hand if we suppose that changes of pressure at about 9 kilometers height, i. e., changes in $P_9$, are the cause of the phenomena, there is no difficulty about explaining the other changes. Changes of temperature that are adiabatic occur simultaneously with the changes of volume which produce them and are in accordance with the formula

$$\delta T/T=0.29\,\delta P/P, \qquad (1)$$

where $T$ is the temperature on the absolute scale and $P$ is the pressure. If, therefore, we accept the change of pressure, the rapid change of temperature is readily explained.

The temperature changes are produced in two ways—one by the simple change of pressure of the air without change of height; the other by changes of height produced by the pressure distribution and the consequent change of pressure. Substituting the average value of $T$ and $P$ at an altitude of 9 kilometers, the equation (1) becomes

$$\delta T=0.22\ \delta P,$$

where $\delta T$ is expressed in centigrade degrees and $\delta P$ in millibars. The observations give just the same relationship between changes of pressure and temperature, and the inference is that there is no systematic ascent or descent of air at this height.[7] Below this height, that is to say, in the troposphere, the change of temperature is in excess of the value given by the formula; and above in the stratosphere, it is of the opposite sign; but how this may be brought about has already been explained.

It remains to show how these vertical motions may be produced. Let us take the conventional section through a cyclone presented in figure 2, remembering, however, that it can not be drawn to scale on any moderate sized piece of paper. Also there need be no symmetry about the horizontal section or plan; all that is necessary is that the low pressure should be inclosed by a set of closed

[6] Some quantitative measurements here would be interesting; also a consideration of clouds and depths of moist air.—C. A. jr.

[7] *Shaw, Sir Napier*, in Jour. Scott. met'l soc., No. 30, 16: 177.

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

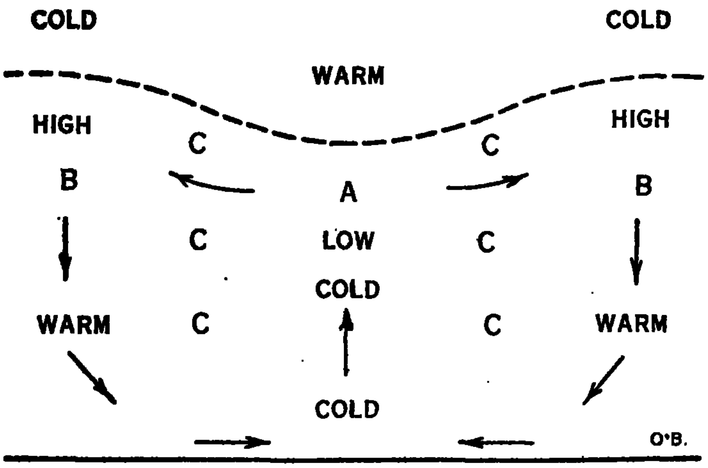


FIG. 2.—A conventional vertical section through a LOW.

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.

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## 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.