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PRELIMINARY STEPS IN THE MAKING OF FREE-AIR PRESSURE AND WIND CHARTS.[1]

By C. LeRoy Meisinger.

[Weather Bureau, Washington, D. C., March 29, 1920.]

SYNOPSIS.

The most accurate forecasts of winds at moderate elevations over wide areas can be made only when we have isobaric and wind charts for those levels. One of the most important steps in the making of such charts is the securing of accurate data on the mean temperature of the air column between the station and a given level in the free air. To this end, such information, obtained by kites at Mount Weather, Va., Drexel, Nebr., and Ellendale, N. Dak., has been classified by months for each of the eight recorded wind directions at the surface. The surface wind direction has been used as an index to determine whether such local phenomena can be used as a guide to conditions aloft. The final values which were obtained from a study of the data represent the differences in degrees, centigrade, between the mean temperature of the air column and the surface temperature. It was found, in general, that in winter, with southerly winds, the air column has a higher mean temperature than the surface; that in summer, with northerly winds, the air column has a temperature below that of the surface. These effects are due, primarily, to the seasonal variation of surface temperature. The amplitude of the values was much greater at the inland stations, Ellendale and Drexel, than at Mount Weather, near the coast. Aside from the geographical contrasts, the difference between the surface temperature and that of the air column to a height of 1 or 2 kilometers depends, so far as the surface factor is concerned, mostly on the season; and, so far as the temperatures aloft are involved, upon the wind direction.

A statistical study of the errors which may be carried into the reductions of pressure to levels in the free air as a result of the errors in the temperature argument, leads to the gratifying result that the values by which the surface temperature is corrected to obtained the mean temperature of the air column, will not, in general, be in error by more than 1.5° C., which, even with long air columns, is not sufficiently large to produce large errors in the pressure. For air columns 1,000 meters in length, when the conditions are, for example, $\theta=0°$ C., and B_0 (station pressure)=1,000 mb., the study shows that the probable variation of a given value in temperature units will yield a probable variation in pressure units of about ±0.5 mb.; and, under the same conditions, with a 2,000-meter air column about ±1.3 mb. These errors are very small indeed, and give considerable promise to this type of pressure reduction.

INTRODUCTION.

When Torricelli, in 1643, by his classic experiment,[2] demonstrated that the weight of a given air column is equaled by the weight of a column of mercury of equal cross-section and about 760 millimeters in length, he opened a field of meteorological investigation of such vast extent that even to-day it has not been fully explored. In fact, there are many problems requiring a more satisfactory solution. One of these problems concerns itself with the growing necessity for forecasts of winds aloft for the use of aviation. This problem, emphasized, as it was, by the war, has, with the cessation of hostilities, lost none of its importance, for it is a matter of common comment that the skies are filling with the hum of aerial commercial traffic. The increasing demands for accurate forecasting of conditions aloft necessitate a closer study of these conditions, and an application of what is known, both theoretically and empirically. It is unfortunate, however, that the supply of kite and sounding-balloon data upon which our knowledge rests is, as yet, somewhat limited. While, in general, such forecasting can be done with a certain degree of success by means of the present sea-level isobaric maps supplemented by current aerological data, it is a recognized truth that the promise of best forecasting of winds aloft over wide areas can be found in pressure charts of the same approximate level for which it is desired to forecast.

Not only will the production of accurate maps for upper levels be of value in forecasting for aerial activities, but they will also hold forth the alluring possibility of the solution of one of the long-recognized difficulties in barometry. In 1900 Prof. Bigelow said,[3] concerning this problem:

> The primary practical difficulty in forming station reduction tables for pressure on a plateau or otherwise elevated region consists in determining the mean temperature of the air column to be substituted for the plateau itself, where an observation of temperature can be made only upon the surface of the ground, and the corresponding sea-level temperature can only be indirectly inferred. If the plateau temperature does not agree with that of a free-air column at the same elevation, in what ratio does it differ from it, and how is the difference to be obtained in any exact way that will not be the result of conjecture merely? If the temperature gradients in the free-air can be found by balloon and kite ascensions, or by measurements on cloud heights and by computations on the physical processes involved, how are the corresponding gradients to be found within the plateau itself?

These questions have not been answered, and it is certain that the temperature argument at present employed, i. e., the mean of the current and the preceding 12-hour temperature, often introduces errors in the sea-level reduction, especially where the so-called air column is especially long.

As indicated in the remarks of Prof. Bigelow, the heart of the problem lies in the determination of the mean temperature of the air column, not only in the case where the air column is imaginary, as in sea-level reduction, but also when it is real, as in reduction to levels in the free-air. Realizing this, the scope of this paper is only such as to treat of temperature in relation to pressure reductions in America,[4] through the observations of free-air temperatures by kites and sounding balloons.

THE VALUE OF FREE-AIR PRESSURE CHARTS.

Gradient, or geostrophic winds.—The value of upper air-pressure maps as aids to aviation depends upon the relation between the horizontal air movement and the hori-

[1] Presented in two papers before the American Meteorological Society at St. Louis, Dec. 30, 1919, and at Washington, Apr. 22, 1920.

[2] Hellmann, G.: Neudrucke von Schriften und Karten über Meteorologie und Erdmagnetismus No. 7: *Evangelista Torricelli: Esperienza dell' Argento Vivo.* pp. (1)-(6); and No. 2: *Blaise Pascal: Récit de la Grande Expérience de l'Equilibre des Liqueurs. See also* Zum 250-jährigen Jubiläum des Barometers, *Meteorologische Zeitschrift*, Dec., 1894, pp. 445-450.

[3] Bigelow, Frank H: Report on the barometry of the United States, Canada, and the West Indies. *Report of the Chief of the Weather Bureau*, vol. 2, 1900-1901, p. 25.

[4] The reductions, which were made by Bigelow in the work cited above, employed temperature gradients which were obtained mostly in Europe by manned balloons, temperature distribution in the lowest 5 kilometers of cyclones and anticyclones," and which are not strictly applicable to conditions in the United States. (*See Vertical temperature distribution in the lowest 5 kilometers of cyclones and anticyclones.*" Willis Ray Gregg. Monthly Weather Review, Sept., 1919, 47; 647-649.)

zontal pressure gradient which produces such movement. It is well known that the surface wind, where it is not influenced too strongly by the terrain, blows at a certain angle across the isobars. This is to be attributed to the rotation of the earth combined with the friction or resistance to the air stream moving over its surface. As we attain even moderate elevations, however, the effect of surface friction is largely eliminated, and the deflection of the air stream by the earth's rotation and the curvature of the isobars are the dominating factors. It is found that at such heights the wind blows practically parallel to the isobars of a given level. This is true, in general, as high as 500 meters, with respect to the sea-level isobars. It should be borne in mind, however, that, strictly, the conduct of the wind at a given level is subject to the pressure distribution at that level. This wind, leaving surface friction out of consideration, is called the gradient, or geostrophic, wind, and may be defined as the wind in which equilibrium is maintained between the pull of gravity down the pressure slope, the deflective tendency due to the earth's rotation, and the centrifugal tendency due to the curvature of the wind path; and its velocity may be computed from the formulæ given by Dr. Humphreys:[5]

$$v=\sqrt{\frac{r}{\rho}\frac{dp}{dn}+(r\omega \sin \phi)^2}-r\omega \sin \phi, \text{ for cyclones;}$$

$$v=r\omega \sin \phi-\sqrt{(r\omega \sin \phi)^2-\frac{r}{\rho}\frac{dp}{dn}}, \text{ for anticyclones;}$$

and,

$$v=\frac{\frac{dp}{dn}}{2\,\omega\rho \sin \phi}, \text{ for straight isobars;}$$

in which v is the velocity, $\frac{dp}{dn}$ is the difference in pressure per unit horizontal distance normal to the isobars; $r=r_1 \sec \alpha$, in which r_1 is the radius of curvature of the wind path, and α is the angular radius of the circle upon which the air is moving, measured from the center of the earth; ρ is the density of the air, ω is the angle through which the earth turns in a second, and ϕ is the latitude of the place.

The agreement between computed and observed velocities of the wind aloft has often been noted. A good example is to be found in a recent note by Mr. Gregg,[6] in which he computes a wind velocity at 2,500 meters above sea-level of 23 meters per second, a value which agreed within 2 or 3 meters per second with those obtained by many pilot balloon stations in the eastern United States on the days in question. Another example of this relation is given in the flight of free-balloons from Fort Omaha, Nebr., at nearly constant elevations.[7] The first example is one in which the computed wind is obtained from isobars for the 2,500-meter level, whereas the second shows the agreement, up to almost 1 kilometer, where the velocity was computed from the sea-level isobars. It is obvious that were there no surface friction, the surface wind would attain gradient velocity, and this is more nearly the case over the ocean than over the land.

Forecasting for aviation.—Now, recognizing the close agreement which obtains between theory and observation, it is apparent that if accurate charts of the pressure aloft can be made, it will not only be possible to tell with almost mathematical accuracy what winds are blowing at the time, but also, after some experience, to forecast what changes are to be expected. This is the point of practical contact with forecasting for aviation.

General forecasting.—The contact with the general forecasting of weather is not at once so obvious, and the scheme of free-air pressure charts, in combination with surface weather, is one whose practical utility must be established by experience. This is true especially in the eastern United States, where the average elevation of the land above sea level is not very great. In the West, it appears to be a simple and direct step toward accurately representing the pressure distribution. But this is an old problem and its satisfactory solution must follow a careful and painstaking study. It is believed, however, that these charts will lead in the proper direction for the following reasons:

1st. Reduction planes, say at 1 or 2 kilometers above sea-level, will materially shorten the distance through which pressure must be reduced. It can be seen from the accompanying map (fig. 1) that over the eastern part of the United States the air columns would average about 700 and 1,700 meters in length, respectively, whereas an area half as large as that east of the Mississippi has an elevation of more than a kilometer and a half, and in this area the length of the air column would average about 500 meters to either plane. It will be shown later that considerable errors could exist in the mean temperature of so short an air column without materially affecting the reductions through it.

2nd. Abnormal temperatures, due to chinooks, or other less pronounced causes, introduce considerable error in sea-level reductions[8], whereas a reduction to a free-air plane, as will be shown later, will yield a more truthful representation of facts.

3rd. There is a certain uneasiness in using the temperature argument employed at present, because it does not represent in any real sense that which is implied by θ in the Laplacian formula, namely, *the mean temperature of the air column between the station and a point in the same vertical located in the reduction plane.* When the reduction is to sea-level *there obviously is no air column* and the value substituted is only an arbitrary one, which, under ordinary conditions, happens to suffice. Free-air charts, on the other hand, do have an air column that is real and observable if means are provided for its observation.

THE NATURE OF THE INVESTIGATION.

Wind direction as an index to temperatures aloft.—From the beginning, the idea of practicability has been kept in mind. It seems desirable to discover some means of reduction of such simplicity and directness that its application will not be difficult. Again, it is desirable to find a method which will relate the temperatures aloft to some observable surface phenomenon. Of all surface phenomena, the one which is most likely to affect temperature, either aloft or at the surface, is wind direction. Will it not be possible from a suitable study of the data to note the wind direction at the surface and the current surface temperature, and, from the time of day and year, tell what correction must be applied to this surface temperature to yield the mean temperature of the air column? It is the answer to this question which it is the immediate purpose of this paper to seek.

[5] Humphreys, William J.: The physics of the air. *Journal of the Franklin Institute*, Nov., 1917, pp. 668–669.

[6] Gregg, Willis Ray: Note on high free-air wind velocities observed December 16 and 17, 1919. MONTHLY WEATHER REVIEW, Dec., 1919, 47: 853–854.

[7] Meisinger, C. LeRoy: The constant elevation free-balloon flights from Fort Omaha. MONTHLY WEATHER REVIEW, Aug., 1919, 47: 535–538

[8] Hallenbeck, Cleve: The influence of abnormal temperature conditions on the sea-level pressure reductions. (Unpublished.) "The writer * * * has observed 'chinook' rises in temperature that lowered the sea-level pressure 0.13 to 0.20 inch, all without affecting the station pressure."

Aerological observations in the United States.—In June, 1907, the United States Weather Bureau began making aerological observations at Mount Weather, Va. This was continued for a period of five years, during which time numerous kite and captive balloon ascensions were made for observing conditions aloft. Late in 1915 kite observations were begun at Drexel, Nebr., and since that time flights have been made there almost daily. Still later other stations were established at Ellendale, N. Dak., Broken Arrow, Okla., Groesbeck, Tex., Royal Center, Ind., and Leesburg, Ga. The data from all of these stations have been published [9] and are being published as rapidly as funds will permit. The three stations having the most complete data were selected and investigated, namely, Mount Weather, Drexel, and Ellendale. From these three stations records of over 3,000 kite flights have been examined.

The selection of reduction levels.—The question of the selection of reduction levels is an important one, and is, doubtless, one which experience must decide. At the outset, however, there are two considerations which will assist in their tentative selection: First, the level must be sufficiently elevated to be unaffected by topography; and, second, it must be near enough to the surface to represent the pressure distribution which is, at the moment, controlling the surface weather. The elevations of such levels, therefore, depends largely upon the elevation of the surface they are to cover—in other words, upon the general topography of the United States. Fig. 1 shows the general elevations of the United States, with the area above and below each succeeding 500-meter level from sea level to 2 kilometers. The western part of the United States is quite high, many points lying far above the 2-kilometer level. It is thought best, therefore, to investigate temperatures between the surface and the two levels, 1 and 2 kilometers above sea level, respectively.

The elevations of the stations investigated are:

	Meters above M. S. L.
Mount Weather, Va.	526
Drexel, Nebr.	396
Ellendale, N. Dak.	444

The first of these stations is located on the Blue Ridge and is situated upon a mountain top, with a valley on either side; the last two are in the open plains region and are well exposed to winds from every direction.

Briefly, then, the procedure of the investigation was as follows: The observed mean temperatures of the air column between the 1 and 2 kilometer levels were tabulated from kite records. The differences between these values and the current surface temperatures were obtained. These differences were then classified by wind directions and months. It must be emphasized that the values to be discussed in this paper are not mean temperatures of the air column, but are *the differences between the mean temperature of the air column and the current surface temperature under certain conditions of wind direction and season.*

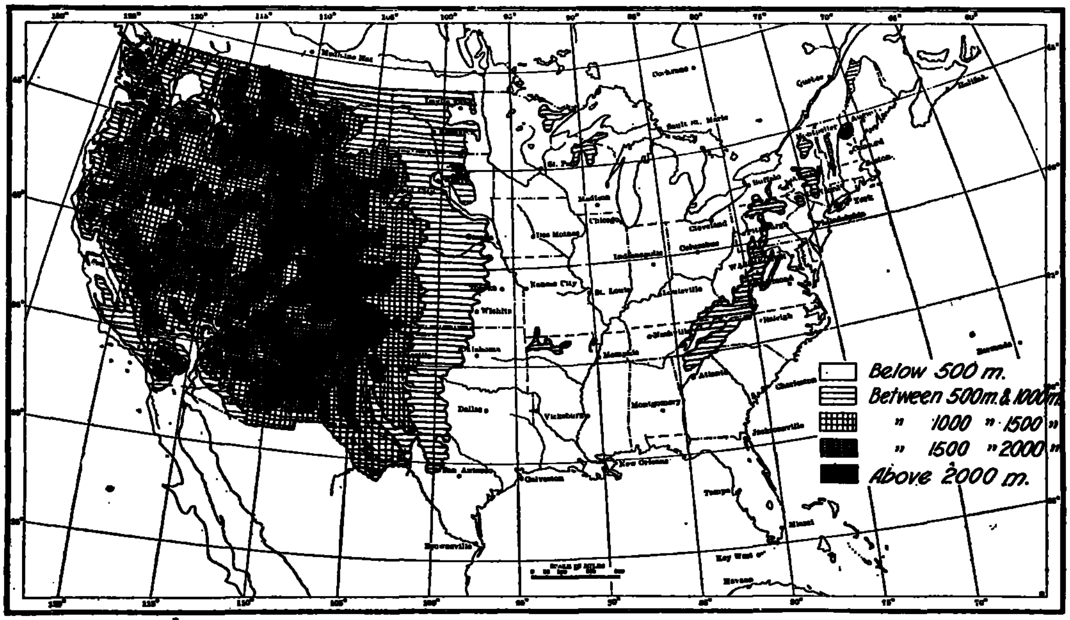


FIG. 1.—Elevations of different portions of the United States above sea-level.

It should further be noted that the kite flights from which these data were obtained were made in the forenoons, and that the average time of the middle of the flights is about 8 a. m. This is because most of the flights at aerological stations are made during the mornings, thus leaving insufficient information from those few which are made in the afternoons. Thus, the values we shall obtain are applicable only to morning conditions, approximately corresponding to the time of regular station observations.

TEMPERATURES AT THE SURFACE AND ALOFT.

The factors affecting temperature.—Temperatures at the surface and aloft may be said to be subject principally to six factors, namely:

1. Wind direction.
2. Seasonal variation.
3. Geographical location.
4. Diurnal variation.
5. State of weather.
6. Character of surface.

[9] Mount Weather: *Bulletin of the Mount Weather Observatory*, vols. 1-6, 1908-1913.
Drexel, Nebr.: MONTHLY WEATHER REVIEW SUPPLEMENTS Nos. 3, 5, 7, 8, 10, 11, 12, 13, 14.
Ellendale, N. Dak.: MONTHLY WEATHER REVIEW SUPPLEMENTS Nos. 12, 13, 14.
Broken Arrow, Okla., and Royal Center, Ind.: MONTHLY WEATHER REVIEW SUPPLEMENTS Nos. 14 and 15.
Groesbeck, Tex., and Leesburg, Ga.: MONTHLY WEATHER REVIEW SUPPLEMENT No. 15.

Winds aloft and surface winds may be affected in greater or less degree by each of these factors, and these relations and interrelations will be discussed. It is possible at the outset, however, to eliminate the last three factors from consideration in this discussion. While it is obvious that temperatures may vary considerably, especially at the surface, during the daily period, such variation is not important in this discussion, since all observations were made at practically the same time of day at all stations. Second, the conditions of the cloudiness of the sky may exert a less marked influence upon temperatures; but, in this work, all the observations have been lumped together, whether made in clear, partly cloudy, or cloudy sky; hence the averages represent the means of conditions with all degrees of cloudiness. Finally, the character of the surface need not be considered, since all the observations have been made over land surfaces which are, in the main, of the same character. The only exception is that in the case of Mount Weather, whose mountain location was taken into consideration, as will be shown. This leaves the first three factors to be considered.

Wind direction.—First of all, let us consider the effect of wind direction on temperatures at the surface. The

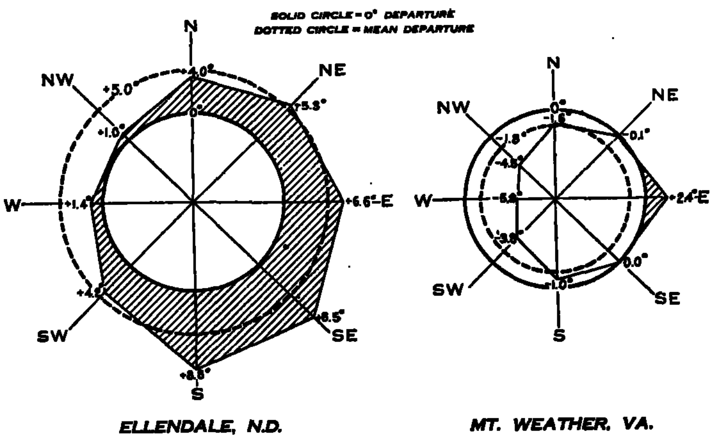


FIG. 2.—Temperature differences between air column (surface to 2,000 meters above sea-level) and surface (°C.), by wind directions for Ellendale and Mount Weather, in January.

air next to the ground is dependent to a large degree upon the temperature of the surface itself. If it be warm, as in summer, and the wind becomes northerly, and the air of relatively low temperature transported to regions where the earth is very warm, it is well known that the wind must be persistent in order to affect to any considerable degree the temperature of the region; for the high temperature of the earth will warm the air [10] as it progresses southward. There are many familiar examples of southerly winds in winter, blowing out of very warm regions and losing their identity as warm winds after blowing over cold ground or snow-covered surface for some distance. True, if the winds are of high velocity and persist for a considerable time, they will have a telling effect upon surface temperature. This, of course, does not refer to such abnormal local effects as chinooks, in which winds with a temperature far higher than that of the surface, owing to dynamic heating, suddenly swoop down upon a locality, often with sufficient effectiveness to melt and evaporate entirely a considerable depth of snow without leaving so much as a muddy surface;[11] nor are we referring to cases in which a very warm layer of air may be overriding a cold one in waves in such a manner that the troughs of the waves may occasionally intersect the surface, and produce for a short time a change of wind direction and an abnormally high temperature. We have reference, rather, to the normal varying circulation about the ordinary veering and backing of winds as the result of the passage of HIGHS and LOWS.

But what of the temperatures aloft? They are not subject to the effects of radiation and absorption of the earth's surface to the same degree as are surface temperatures. The frictional turbulence of the lower layers does not play so conspicuous a part in the determination of temperatures aloft. They are dependent upon the temperature of the region from which the air is being transported. If from the south in winter, an upper current may retain its identity as a warm one over others many degrees colder. As an example of this, one may note the upper air phenomena which accompanied the recent sleet storms in eastern United States.[12] Here, the southerly component produced a temperature above freezing in the upper air over land that was considerably below freezing; indeed, in one case, rain fell upon a surface where the air temperature was as low as —11° C. Again, along the Atlantic coast, in winter, an east or southeast wind may transport warm air from the Gulf stream or from the warmer waters of the Atlantic, but the effect is most marked aloft. Or, in the plains States, winds which have their origin in the chinooks of the Rocky Mountains, may, after striking the surface, rebound, as it were, and flow out over the cold air blanket of the Middle West, producing upper-air temperatures much higher than those at the surface.[13] These points seem to indicate that the temperatures of the upper air are to a great degree dependent upon wind direction.

Let us now compare the effects of different wind directions upon temperatures at the surface and aloft, using data which were obtained from kite flights. Figure 2 shows the difference between the mean temperature of the air column (surface to 2,000 meters) and the surface temperature at Ellendale with various wind directions in January. The solid circle is the origin or locus where the mean temperature of the air column equals the surface temperature. The actual values are measured from this circle along radii which represent wind directions, and, if positive, are measured outward; if negative, inward. A study of this diagram will show several features of interest which will be pointed out from time to time. But the significant point in the present connection is that westerly or northwesterly winds produced aloft the lowest temperatures relative to those at the surface, while southerly or southeasterly winds produced aloft the highest temperatures relative to those at the surface. The fact that all the values for January at Ellendale are positive will be brought out later in the discussion. Figure 2, which gives, in the same manner, the data for Mount Weather for January, shows the same effect, except that, owing to its coastal location, westerly winds produce lowest temperatures aloft rela-

[10] Martin, Howard H.: The relation of winds to temperature in Central Ohio. MONTHLY WEATHER REVIEW, February, 1920, 48: 85–86.

[11] Mr. Herbert Lyman, at Helena, Mont., has observed a snow cover of 10 inches disappear over night, leaving a dry surface the following morning. *See also*, Mark W. Harrington: The chinook winds. *American Meteorological Journal*, vol. 3, pp. 520–521, 1887.

[12] Meisinger, C. LeRoy: The precipitation of sleet and the formation of glaze in eastern United States, with remarks on forecasting. MONTHLY WEATHER REVIEW, Feb., 1920, 48: 73–80.

[13] Bavendick, F. J.: Blizzards and chinooks of North Dakota plains. MONTHLY WEATHER REVIEW, Feb., 1920. 48: 82–83.

tive to the surface, while easterly winds, blowing off the ocean, produce highest relative temperatures aloft.

It is necessary to digress, for a moment, to mention that, owing to the mountain-top location of Mount Weather, the surface temperatures employed are those of the nearest Weather Bureau station in the valley, namely, Washington, D. C., about 40 miles southeast of the mountain. In determining the mean temperature of the air column, the mean was taken between the Washington surface and the Mount Weather surface, which gave a good value for the mean temperature of the lowest 500 meters. Above Mount Weather the kite results are used and these are averaged with the previously determined value for the lowest 500 meters. Hence, in the strictest sense, these are the mean temperatures above Washington, D. C., although if this fact is borne in mind, there should be no confusion in referring to Mount Weather data.

Figure 3 shows the same effects as were pointed out above, but to a much smaller degree, the reason being that the seasonal effect is of so much greater amplitude that the effect of wind direction is nearly obliterated in summer. Figure 4, however, brings together the data for all the stations for the whole year and contrasts the effect of two opposing winds upon the difference between the mean temperature of the air column and the surface temperature. Let us, in considering this diagram, try to neglect the annual march of these temperature differences and think only of the comparison between the two wind directions for a given station. First, consider Ellendale: With a southeast wind we find nearly all the ordinates are positive in sign indicating that the mean temperature of the air column is greater than the surface temperature. With a northwest wind most of the ordinates are negative. For Drexel, the mean ordinate is somewhat less than that of Ellendale, but has the same general characteristics, namely, that its mean ordinate for a southeast wind is greater by several degrees than the mean ordinate with a northwest wind. Similarly, for Mount Weather all values are negative for both winds, the southeast giving a mean ordinate approximately 3° C. higher than the northwest.

Seasonal variation.—Considering next the effect of seasonal change of temperature upon the surface and upper levels, we know from experience that the seasonal amplitude of the temperature march is large. We have only to reflect upon the contrast between the blistering days of midsummer and the raw, biting blasts of midwinter, to convince ourselves of the truth of this statement. Aloft, on the other hand, the amplitude is not so great. An excellent illustration of this is given by Mr. Gregg for Drexel, Nebr.[14] He shows in a diagram the annual march of temperature at the surface and at levels in the free air. At the surface we find a variation of 36° C., from a minimum of −9° C. in mid-January to +27° C. in mid-July. At 1 kilometer above sea level the values extend from a minimum of −8° C. in January to +22° C. in July, or a range of 30° C. At 2 kilometers the range is from −7° C. to +16° C., or a range of 23° C. This shows that as one ascends and frees oneself from the surface influence, the amplitude of seasonal variation becomes smaller and smaller.

With these facts in mind, we can consider our diagrams in the light of seasonal variation. Turning again to figure 2. For Ellendale, located in the heart of the continent and in a northerly latitude, we know that not only is the annual march of temperature of great amplitude, but also that the tendency is for extremely cold winters. The diagram shows that all wind directions give a temperature aloft which is higher than that at the surface. In July (fig. 3) we find that the temperatures aloft are lower than at the surface. But we know that the annual range aloft is less than at the surface. Hence we must attribute the great difference between the values with a given wind direction in January and July to the seasonal range of surface temperature. The same is true at Mount Weather (figs. 2 and 3). In January we find the values much higher than the corresponding values in July. The reason, of course, is that we have superimposed upon a widely varying range of surface temperatures a lesser range aloft.

For the entire year, we see from figure 4 that for all stations there is a decided maximum in winter and a minimum in summer, indicating that in summer the air aloft at Ellendale and Drexel tends to have, with southerly winds, large positive values and in winter small negative values; with northerly winds in winter small positive values, and in summer moderately large negative values.

For Mount Weather the mean temperature of the air column tends to become equal to, or slightly higher than, the surface temperature in winter, with rather large negative differences in summer with southerly winds, and with northerly winds to have a more uniform negative difference throughout the year.

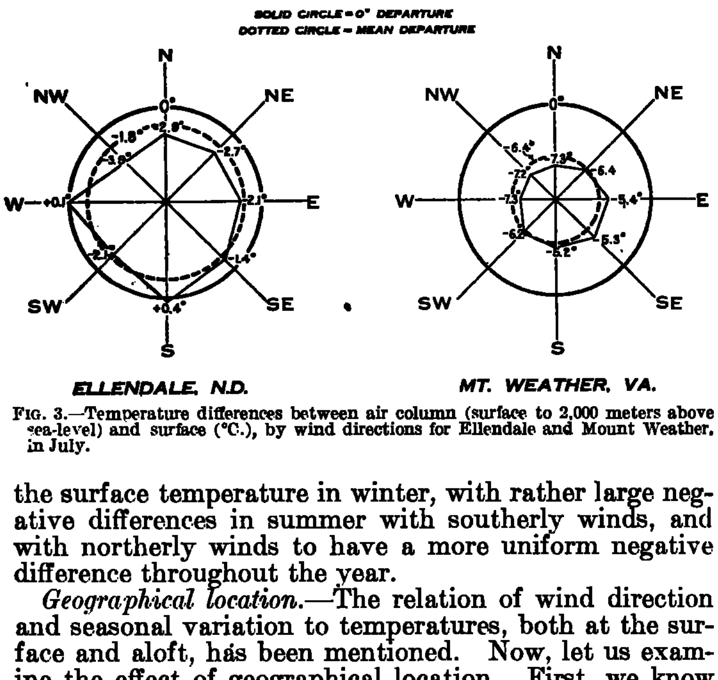


FIG. 3.—Temperature differences between air column (surface to 2,000 meters above sea-level) and surface (°C.), by wind directions for Ellendale and Mount Weather, in July.

Geographical location.—The relation of wind direction and seasonal variation to temperatures, both at the surface and aloft, has been mentioned. Now, let us examine the effect of geographical location. First, we know that inland locations, as characterized by Ellendale and Drexel, have greater extremes of temperature than those coastal stations of which Mount Weather is an example. This is due, of course, to the location with respect to the ocean with its moderating influence. Land, being a better absorber and radiator of heat than water, will heat up more rapidly in summer and cool more rapidly in winter than will the ocean. By way of comparison with the value of surface temperature and temperatures in the free air, similar to that of Drexel, we have for Mount Weather[15] a maximum mean surface temperature of 23° C. and a mean minimum of −1° C., a range of 24° C. At 1,000 meters above sea level we have a mean maximum of 19° C. and a mean minimum of −2° C., a range of 21° C.; and at 2,000 meters there is a mean maximum

[14] Gregg, Willis Ray. Average free-air conditions as observed by means of kites at Drexel Aerological Station, Nebr., during the period November, 1915, to December 1918, inclusive. MONTHLY WEATHER REVIEW, January, 1920, 48: 1-11.

[15] Blair, William R.: Summary of the free-air data obtained at Mount Weather for the five years, July 1, 1907, to June 30, 1912. *Bulletin of the Mount Weather Observatory*, vol. 6, 1913, p. 179.

of about 13° C., and a mean minimum of about −4° C., giving a range of 17° C. In Table 1 these values are contrasted with those of Drexel.

TABLE 1.

Station.	Surface.			1 kilometer.			2 kilometers.		
	Max.	Min.	Range.	Max.	Min.	Range.	Max.	Min.	Range.
	°C.	°C.	°C.	°C.	°C.	°C.	°C.	°C.	°C.
Drexel, Nebr.	27	−9	36	22	−8	30	16	−7	23
(Washington, D. C.)	(30)	(−3)	(33)						
Mount Weather	23	−1	24	19	−2	21	13	−4	17

Thus, comparing inland and coastal temperatures for the surface, we find that the inland surface experiences the larger range; in this case, 3° C. larger; aloft, also, there is a smaller range of temperature near the coast than inland, the differences from the table being, for the 1-kilometer level, 9 °C., and for the 2-kilometer level, 6 °C.

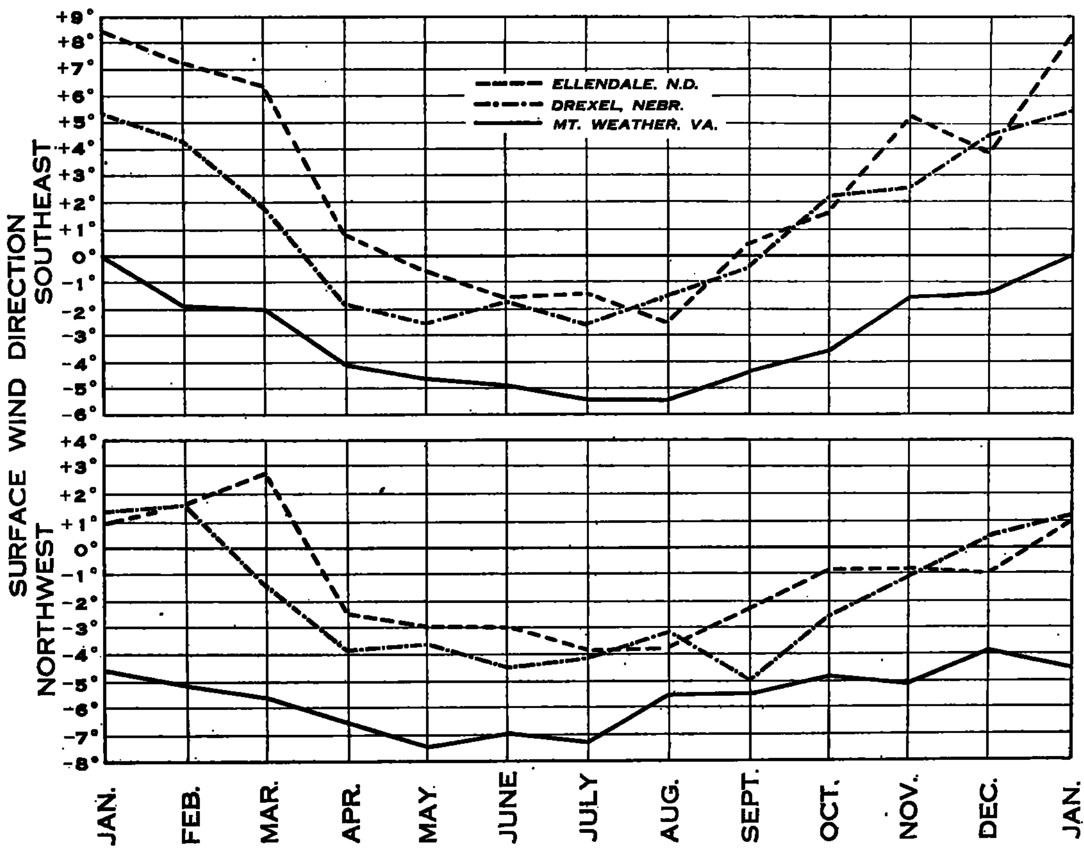


FIG. 4.—Temperature differences between air column (surface to 2,000 meters above sea level) and surface (°C.), for Ellendale, Drexel, and Mount Weather, for southeast and northwest winds, throughout the year.

Referring again to figure 4, we see that the inland stations are those of greatest amplitude. The curve for Mount Weather is relatively flat. This means that the temperature differences at the surface, attributable to the geographical distribution of the stations is reflected in the temperatures aloft, but to a less marked extent.

Summary of the effects of the factors.—An effort has been made in the foregoing discussion to separate the individual factors from the complex or operative factors in each diagram. But this is difficult, especially where all the factors are simultaneously operative. And in reality each of the diagrams has shown the total or resultant effect of the three factors we have treated above, wind direction, seasonal variation, and geographical location. It is now well to consider the results as we find them in combination. First, concerning surface temperatures, it should be said that they are influenced primarily by seasonal variation and geographical location. Next, temperatures aloft are influenced chiefly by wind direction, but do not respond to seasonal variation or geographical location as easily or completely as do these at the surface. What is the result of this combination?

It means that for winter, at inland stations, there is a strong tendency for air warmer than that at the surface to be present aloft with all directions of surface wind (fig. 2). For summer, at inland stations, there is a strong tendency for air cooler than that at the surface to be present aloft, with all directions of surface wind (fig. 2). For winter, at coastal stations, there is a tendency when the station is on the east coast, for warmer air aloft with east winds, and for cooler air aloft with west winds. For summer, at coastal stations, there is a tendency for cooler air aloft from all directions.

To bring all the information toegther, six diagrams have been prepared which show for each month and for each surface wind direction, the difference between the mean temperature of the air column and the surface temperature for that place, from the surface to 1 kilometer above sea level, and from the surface to 2 kilometers above sea level, respectively. Figures 5 and 6 give this information for Mount Weather; figures 7 and 8 for Drexel, and figures 9 and 10 for Ellendale. The main features of these isopleths are fairly obvious, and have really been pointed out in the foregoing discussion. For instance, all the diagrams show a maximum in winter with southerly winds, except in figure 6, where the maximum occurs with an easterly wind, because of the warm air from the ocean. As we proceed to the inland stations, the amplitude, indicated by the crowding of the isotherms, increases, until for Ellendale (fig. 10) the winter maximum gives a temperature of the air column between the surface and the 2 kilometers level 9° C. higher than the surface temperature. These curves have been smoothed but very little. In each case the 0° departure lines have been drawn heavier than the others.

An example of the use of the isopleths.—To be certain that the full value of the isopleths is understood, an example is given: Suppose that at Ellendale on the morning of April 15 we have a surface wind from the west and a temperature of 10° C. What is the mean temperature of the air column between the surface and the 2-kilometer level? Looking at figure 10, we find the point on the chart corresponding to April 15 along the axis of abscissæ, and "west" on the axis of ordinates, and the value of that point obtained by interpolating between the isotherms is −2.2° C. This means that to find the mean temperature of the air column we must subtract

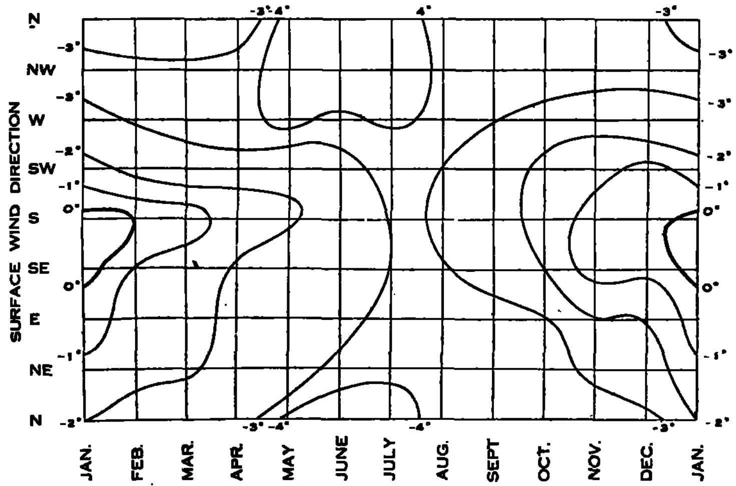


FIG. 5.—Temperature differences between air column (surface to 1,000 meters above sea-level) and surface (°C.), for the eight recorded wind directions throughout the year at Mount Weather, Va.

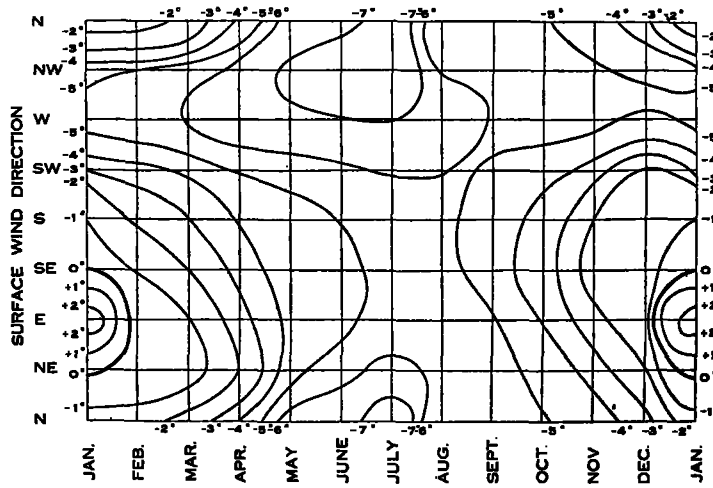


FIG. 6.—Temperature differences between air column (surface to 2,000 meters above sea-level) and surface (°C.), for the eight recorded wind directions throughout the year at Mount Weather, Va.

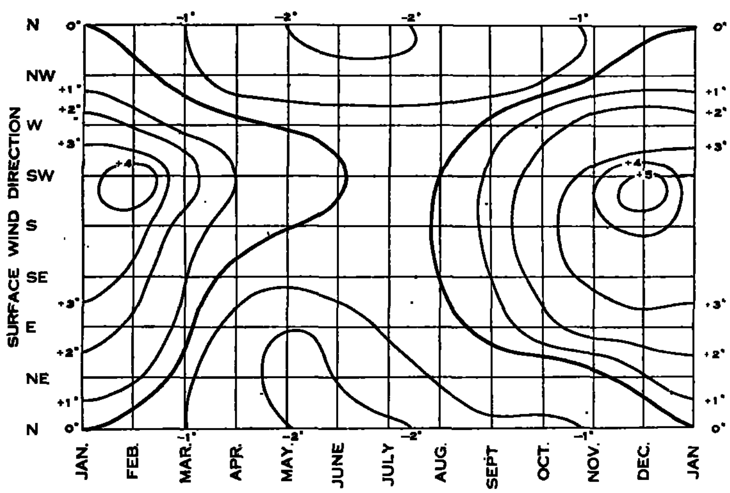


FIG. 7.—Temperature differences between air column (surface to 1,000 meters above sea-level) and surface (°C.), for the eight recorded wind directions throughout the year at Drexel, Nebr.

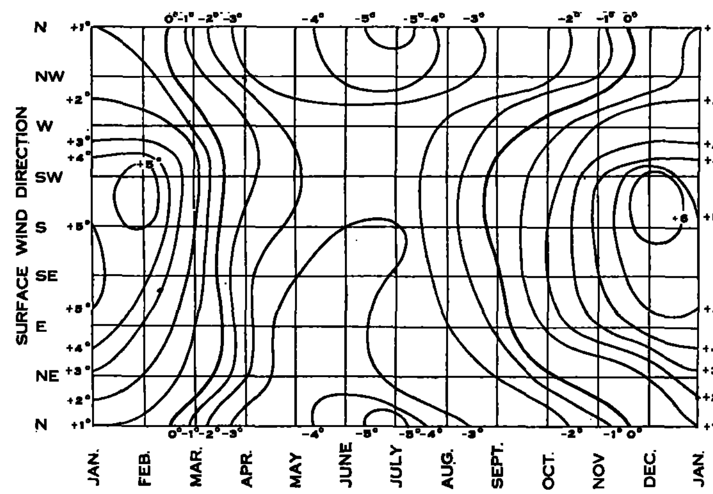


FIG. 8.—Temperature differences between air column (surface to 2,000 meters above sea-level) and surface (°C.), for the eight recorded wind directions throughout the year at Drexel, Nebr.

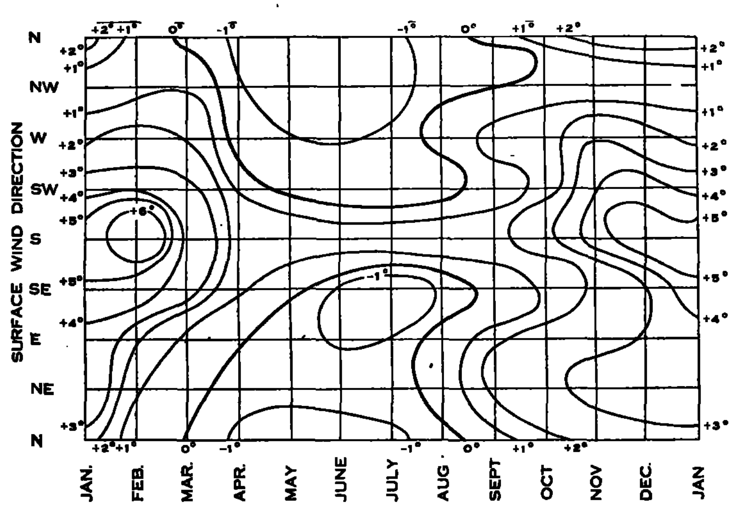


FIG. 9.—Temperature differences between air column (surface to 1,000 meters above sea-level) and surface (°C.), for the eight recorded wind directions throughout the year at Ellendale, N. Dak.

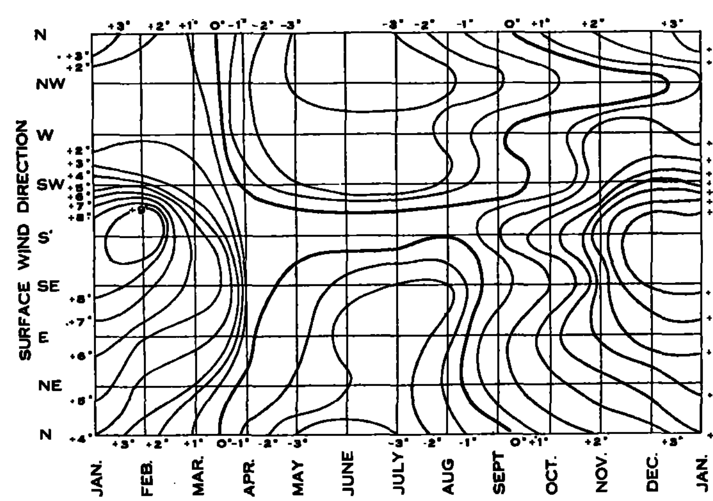


FIG. 10.—Temperature differences between air column (surface to 2,000 meters above sea-level) and surface (°C.), for the eight recorded wind directions throughout the year at Ellendale, N. Dak.

2.2° C. from the current surface temperature, which would give 7.8° C. If the wind had been southeast on the same date, 0.1° C. should have been added to the current surface temperature, giving 10.1° C., the mean temperature of the air column.

But the reader may say that these data are only for three points in the whole of the United States, and may ask, How will it be possible to apply such corrections to surface temperatures in all parts of the country? The only answer that can well be given is that until more kite stations are established the problem can not be brought to a satisfactory completion. True, there are other stations which have not been investigated in this paper. But the reason is that the remaining kite stations do not have long enough records to permit of the use of averages obtained from their data. However, after more stations are established, and investigated, it will be possible to draw maps showing lines of equal departure for various wind directions and months throughout the country, and such maps will make possible the construction of temperature tables for any station.

THE ACCURACY OF THE VALUES.

It is necessary, before any attempt is made to apply these values to the actual construction of maps of the pressure at levels in the free air, to know with what accuracy they have been determined. To do this, the familiar statistical methods have been used in treating the data. First, the departures of the individual observations from the mean were classified in the same manner as the means themselves, i. e., by months and wind directions. The object of this procedure was to determine whether or not the values from which the isopleths were drawn are homogeneous. Unfortunately, the number of observations from which each of the individual means was obtained is too small safely to employ statistically. If we can demonstrate the homogeneity of the whole mass of data from which a given isopleth was drawn, we can treat the mass statistically with safety, since the observations will then amount to several hundred.

In other words, to be very specific, suppose we have a certain group of, say, 30 observations. We obtain the mean and tabulate the difference between this mean and the 30 individual observations. The mean will represent one of the points on the isopleth, but since 30 is usually too small a number to treat statistically, we seem to be in need either of more observations or some method for combining this group of 30 with other groups (and there are 95 other similar groups represented in the diagram, some containing more and some less observations than the number indicated above). The former course is not possible, since this study already makes use of all available data from the stations in question. The latter is the only feasible plan.

One of the fundamental ideas of statistics is that the values must be homogeneous. The question for us to answer is, What is the criterion of homogeneity? If we can establish with certainty the fact that several hundred observations are homogeneous, we shall be entirely justified in combining them. It can be reasoned that if we have residuals in one small set which have certain characteristics, as, for example, the same general magnitude or equal range of variation, and if we can show that the residuals in other similar small sets have the same characteristics, it will be safe to say that if there had been as many observations in each individual set as the total when they are all combined, the result for each set would be the same as is the result for the entire total now.

The test for homogeneity.—For the sake of dealing with as many residuals as possible, let us select, in order to test the homogeneity of the observations, those groups which have the largest number of observations, and see how one group compares with another in various parts of the isopleth with respect to the mean residual. If there is little difference, we may be justified in treating the whole mass as homogeneous. Within these tables, for convenience, the square of the mean residual has been entered.

TABLE 2.—*Mount Weather, Va. 1,000 meters.*

Month.	N.	NE.	E.	SE.	S.	SW.	W.	NW.	Mean.	$\sqrt{\text{Mean}}$.
January	8.44								8.44	2.9 } 2.9
Do					8.31				8.31	2.9
April					4.96				4.96	2.2 } 1.9
Do								2.99	2.99	1.7
May						6.96			6.96	2.6
June		3.56							3.56	1.9 } 1.6
Do							1.64		1.64	1.3
July						0.91			0.91	0.9
August		1.39							1.39	1.2
September	2.36								2.36	1.5
October								1.69	1.69	1.3
November						3.94			3.94	2.0
December							4.81		4.81	2.2
Mean	5.40	2.47			6.63	3.94	3.22	2.34		
$\sqrt{\text{Mean}}$	2.3	1.7			2.6	1.9	1.9	1.6		1.9

TABLE 3.—*Mount Weather, Va. 2,000 meters.*

Month.	N.	NE.	E.	SE.	S.	SW.	W.	NW.	Mean.	$\sqrt{\text{Mean}}$.
January			15.97		11.06				13.51	3.7
February								20.04	20.04	4.5
March	10.69			5.97					8.33	2.9
April		5.85			6.11				5.98	2.4
May						17.83			17.83	4.2
June							3.39		3.39	1.8
July										
August		3.13							3.13	1.8
September	3.20								3.20	1.8
October								5.02	5.02	2.2
November						9.19			9.19	3.1
December					5.75		15.89		10.82	3.3
Mean	6.94	4.49	15.97	5.97	7.64	13.51	9.64	12.53		
$\sqrt{\text{Mean}}$	2.6	2.1	4.0	2.4	2.7	3.7	3.1	3.5		2.9

TABLE 4.—*Drexel, Nebr. 1,000 meters.*

Month.	N.	NE.	E.	SE.	S.	SW.	W.	NW.	Mean.	$\sqrt{\text{Mean}}$.
January	11.67	2.75				9.46		7.25	7.78	2.8
February					7.22				7.22	2.7
March			2.28	7.22					4.75	2.2
April		1.68					8.49		5.08	2.2
May										
June										
July										
August				3.43		10.99			6.71	2.6
September					3.28		18.46		10.87	3.3
October	3.22								3.22	1.8
November										
December								2.74	2.74	1.6
Mean	7.44	2.22	2.28	5.33	5.25	9.72	13.47	4.99		
$\sqrt{\text{Mean}}$	2.7	1.5	1.5	2.3	2.3	3.1	3.7	2.2		2.4

TABLE 5.—*Drexel, Nebr. 2,000 meters.*

Month.	N.	NE.	E.	SE.	S.	SW.	W.	NW.	Mean.	$\sqrt{\text{Mean}}$.
January		1.90			5.06	13.48			6.81	2.6
February							12.46	10.38	11.42	3.4
March			4.26						4.26	2.1
April	5.59	4.20		5.22					7.50	2.7
May										
June										
July				6.93	2.78		1.92		5.81	2.4
August		4.89				15.23			10.06	3.2
September										
October		0.62							0.62	0.8
November										
December					7.89			6.02	6.95	2.6
Mean	5.59	2.90	4.26	6.07	7.86	14.35	7.19	8.20		
$\sqrt{\text{Mean}}$	2.4	1.7	2.1	2.5	2.8	3.8	2.7	2.9		2.5

TABLE 6.—*Ellendale, N. Dak. 1,000 meters.*

Month.	N.	NE.	E.	SE.	S.	SW.	W.	NW.	Mean.	$\sqrt{\text{Mean}}$.
January							7.35	4.55	5.95	2.4
February	1.82								1.82	1.3
March					9.27	2.05			5.66	2.4
April										
May										
June										
July								4.11	4.11	2.0
August		2.92							2.92	1.7
September	1.76								1.76	1.3
October							1.07		1.07	1.0
November										
December					20.35				20.35	4.5
Mean	1.79	2.92			14.81	2.05	4.21	4.33		
$\sqrt{\text{Mean}}$	1.3	1.7			3.8	1.4	2.1	2.1		2.1

TABLE 7.—*Ellendale, N. Dak. 2,000 meters.*

Month.	N.	NE.	E.	SE.	S.	SW.	W.	NW.	Mean.	$\sqrt{\text{Mean}}$.
January							8.69	6.67	7.68	2.8
February										
March	8.73				10.90	1.68			7.10	2.7
April										
May										
June										
July										
August		7.65		7.82					7.73	2.8
September	3.93								3.93	2.0
October							1.99	6.22	4.10	2.0
November						30.12			30.12	5.5
December										
Mean	6.33	7.65		7.82	10.90	15.90	5.34	6.44		
$\sqrt{\text{Mean}}$	2.5	2.7		2.8	3.3	4.0	2.3	2.5		2.9

In these tables are presented, classified by wind directions horizontally and by months vertically, the values of the mean square residuals for certain months and wind directions; in other words, the mean square residuals of the values of the corresponding points in the isopleths. These have been selected rather indiscriminately except that values founded upon the largest number of observations have been given preference. The mean of the mean square residuals and its square root are tabulated both horizontally and vertically, so that one can get an idea of the value of the mean residual for all wind directions for different months, or for an individual wind direction for the whole year. In the lower right-hand corner appears for comparison with the other tables the value of the mean of the mean residuals.

A perusal of these tables will convince one that there are no systematic variations in the values of errors throughout the year or with various wind directions. To make this clearer, the following condensed table brings together the maximum and minimum values of these means, together with the mean for each table:

TABLE 8.—*Summary of data on the distribution of errors.*

	Maximum.	Minimum.	Range.	Mean for table.
	°C.	°C.	°C.	°C.
Mount Weather, 1 kilometer	2.9	0.9	2.0	1.9
Mount Weather, 2 kilometers	4.5	1.8	2.7	2.9
Drexel, Nebr., 1 kilometer	3.7	1.5	2.2	2.4
Drexel, Nebr., 2 kilometer	3.4	0.8	2.6	2.5
Ellendale, N. Dak., 1 kilometer	4.5	1.0	3.5	2.1
Ellendale, N. Dak., 2 kilometers	5.5	2.0	3.5	2.[illegible]

We are not so much concerned with the comparison between tables as between values within the tables themselves, and not so much with the fact that particularly large or small values occur within the table, provided they occur irregularly. This can be judged best by looking at the tables directly, remembering that the individual tabulated values are the mean squares of the residuals and not the mean residuals themselves. Such an examination reveals the fact that the values are unsystematically distributed. For example, consider Table 4. Here we find the largest tabulated value is 18.46 for a west wind in September; the second largest value is for a north wind in January, closely followed by a southwest wind in August. The smallest value is for a northeast wind in April, the next larger is for an east wind in March, but a northwest wind in December gives a value almost as small. In Table 5, the largest values are to be found for a southwest wind in January and August, a fact which would seem to rule out seasonal factors. The smallest values occur for a northeast wind in January and a west wind in July, and for a northeast wind in October. Moreover, the range between the maximum and minimum values shown in Table 8 is small, being greatest for Ellendale and least for Drexel, which would appear to rule out geographical location as a factor of influence. Therefore, it appears that the errors are not systematic; and that they are indiscriminately scattered throughout the isopleths in such a manner that they may be considered as accidental. At any rate, if one were willing to admit the slightest effect of external influences in the distribution of the magnitudes of the residuals, it is plainly seen that such effects must be so small as to be hidden by the accidental variation.

Frequency histograms.—Having shown that the observations in a given isopleth are homogeneous, we can now proceed to discuss the data statistically. Frequency histograms have been drawn showing the number of observations having residuals of various magnitudes grouped in classes of whole degrees, as, for example, $-0.5°$ to $0.5°$, $0.5°$ to $1.5°$, $1.5°$ to $2.5°$, etc., and similarly in the negative direction. The histograms are presented herewith in figures 11 to 13, which show the residuals grouped symmetrically about the y-axis. This apparently indicates that the residuals obey the normal error distribution, and therefore the normal curve of error will best fit the data. These curves, computed for each of the six groups of data, are drawn from the equations appearing upon the diagrams.

The normal curve of error.—The equation for this type of curve, commonly known as the normal curve of error, is of the form:

$$y = \frac{h}{\sqrt{\pi}} e^{-h^2x^2}$$

or, in logarithmic form,

$$\log y = \log \frac{h}{\sqrt{\pi}} - h^2x^2 \log e$$

in which y is the probability of the occurrence of a given value of x, π and e are the well-known constants, and h is the *measure of precision* or index of the flatness of the frequency curve, and depends for its value upon the data under consideration. The value of h is given by the relation:

$$h = \sqrt{\frac{n}{2\Sigma x^2}}$$

in which n is the number of observations and Σx^2 the sum of the squares of the residuals.

The standard deviation.—It is also of interest to know the value of the standard deviation, which is defined [16] as "those values of the departure which locate the points

[16] Marvin, Charles F.: Elementary notes on least squares, the theory of statistics and correlation, for meteorology and agriculture. MONTHLY WEATHER REVIEW, October, 1916, 44: 551-569.

on a frequency curve where the curvature changes from convex to concave—that is, points of inflection," or[17] "the square root of the arithmetic mean of the squares of all deviations, deviations being measured from the arithmetic mean of the observations," and, stated in the mathematical form, is

$$\sigma=\sqrt{\frac{\Sigma x^2}{n}}$$

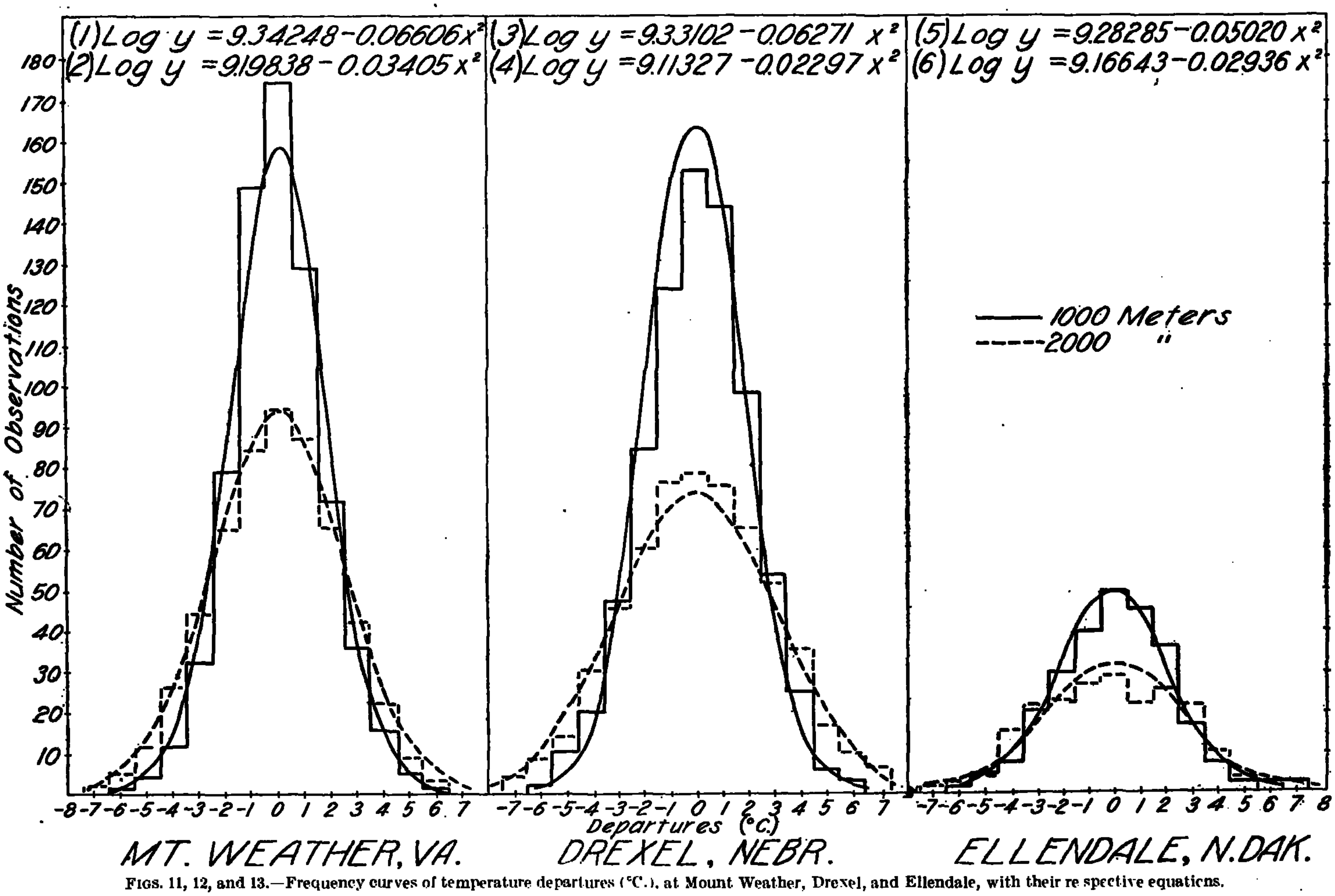
The probable variation.[18]—The probable variation of a given value from the mean is obtained from the relation

$$E=0.6745\sigma$$

Equations for the frequency curves.—Having thus determined the values of the constant h, which, for the normal curve of error, is the only constant which must be determined, we can superimpose upon the histograms the curves represented by the equations derived from the data themselves. (See figs. 11, 12, and 13.)

THE HYPSOMETRIC FORMULA.

Laplace[19] has provided us with the well-known hypsometric formula, which has been so frequently and thoroughly discussed that nothing will be added by its presentation here in its complete and amplified form.[20]



FIGS. 11, 12, and 13.—Frequency curves of temperature departures (°C.), at Mount Weather, Drexel, and Ellendale, with their respective equations.

and this will be used later in showing how small are the errors obtained by this method in determining the mean temperature of the air column.

To this end the values of n, Σx^2, h, σ, and E have been tabulated.

TABLE 9.—*Statistical data for frequency curves.*

	n	Σx^2	h	σ	E
				°C.	
Mount Weather, Va., 1 kilometer	720	2312.66	0.39	1.8	1.2
Mount Weather, Va., 2 kilometers	588	3705.77	0.28	2.5	1.6
Drexel, Nebr., 1 kilometer	785	3689.85	0.38	2.1	1.4
Drexel, Nebr., 2 kilometers	571	5443.81	0.23	3.1	2.0
Ellendale, N. Dak., 1 kilometer	255	1101.46	0.31	2.2	1.4
Ellendale, N. Dak., 2 kilometers	210	1593.25	0.26	2.7	1.8

[17] Yule, G. Udny: An introduction to the theory of statistics. London, 1916, p. 134.

[18] Prof. Marvin points out that while this expression is mathematically identical with "probable error," the latter refers to measurements *of a fixed quantity*, whereas the former more aptly refers to the changing values *of a variable quantity*.

A briefer statement of this equation is given by Prof. Kimball,[21] as follows:

$$\text{Log } B=\log B_0-\frac{Z}{18400\ [1+0.00367\ (\theta+0.378\ \frac{e}{b}/0.00367)]}$$

in which B is the reduced pressure in millibars at the upper level; B_0, the pressure as observed, in millibars; Z, the length of the air column, in meters; θ, the mean temperature of the air column, in degrees centigrade; $\frac{e}{b}$ is the ratio of the vapor pressure to the pressure of dry air at 0° C., in metric units. It has been shown[22] that

[19] *Mécanique Céleste*, Liv. X, Chap. IV.

[20] For a statement of the amplified and complete formula of Laplace with its constants, see *Smithsonian Meteorological Tables, Fourth Revised Edition*, Washington, 1918, pp. xxxix–xli.

[21] Kimball, Herbert H.: On the relations of atmospheric pressure, temperature, and density to altitude. MONTHLY WEATHER REVIEW, 47: 156–158, 1919.

[22] Humphreys, Wm. J.: Physics of the air. *Journal of the Franklin Institute*, Sept., 1917, p. 386.

the error introduced into the reduced pressure by an error of 1 mm. in the value of e in an air column whose length is as great as 3 kilometers is very slight indeed; hence it will be unnecessary in this connection to consider the term containing e. Thus, omitting this term, our equation becomes:

$$\text{Log } B = \log B_0 - \frac{Z}{18400\ (1+0.00367\ \theta)}$$

The purpose of introducing the hypsometric formula at this point is to determine what effect errors of various magnitudes in the value of θ will have under various conditions of surface pressure, with various lengths of air column, and with θ itself at various reasonable points on the scale. Therefore, with values of Z varying by 500 meter intervals from the surface to 2,000 meters, with values of B_0 at 986.6 mb. (740 mm.), 1,013.3 mb. (760 mm.), and 1,039.9 mb. (780 mm.), and with values of θ at $-20°$ C., 0° C., and 20° C., the error in B has been computed when $d\theta$, or the error in measuring θ, varies by intervals of 1° C. up to 5°. This is shown graphically in figure 14. The abscissæ represent values of Z in meters, and the ordinates are errors in B in millibars. The various conditions of pressure and temperature are shown by the respective curves. It is seen at once that of the varying conditions surface barometric pressure has the least effect upon B, and that variations because of high or low values of θ are more marked. This information is presented in detail in Table 10.

TABLE 10.

B_0		θ	$d\theta$																			
mb.	mm.	°C.	1° C.				2° C.				3° C.				4° C.				5° C.			
Length of air column (m.)			500	1,000	1,500	2,000	500	1,000	1,500	2,000	500	1,000	1,500	2,000	500	1,000	1,500	2,000	500	1,000	1,500	2,000
			mb.	*mb.*	*mb.*	*mb.*	*mb.*	*mb.*	*mb.*	*mb.*	*mb.*	*mb.*	*mb.*	*mb.*	*mb.*	*mb.*	*mb.*	*mb.*	*mb.*	*mb.*	*mb.*	*mb.*
986.6	740	−20	0.25	0.46	0.63	0.30	0.50	0.93	1.29	1.60	0.75	1.39	1.95	2.39	1.02	1.86	2.58	3.23	1.25	2.31	3.24	4.06
		0	0.21	0.40	0.55	0.69	0.43	0.80	1.11	1.38	0.65	1.20	1.70	2.07	0.83	1.60	2.24	2.79	1.09	2.00	2.80	3.59
		+20	0.18	0.34	0.49	0.61	0.37	0.70	0.99	1.22	0.55	1.05	1.48	1.83	0.75	1.40	1.98	2.48	0.94	1.76	2.36	3.13
1,013.3	760	−20	0.27	0.47	0.67	0.81	0.51	0.95	1.34	1.63	0.77	1.43	2.00	2.43	0.03	1.91	2.67	3.31	1.27	2.38	3.33	4.16
		0	0.22	0.42	0.57	0.73	0.45	0.83	1.14	1.43	0.67	1.25	1.74	2.16	0.87	1.64	2.31	2.88	1.11	2.06	2.88	3.63
		+20	0.18	0.35	0.50	0.63	0.37	0.71	1.03	1.29	0.55	1.07	1.54	1.91	0.75	1.44	2.04	2.59	0.95	1.80	2.50	3.25
1,039.9	780	−20	0.27	0.49	0.70	0.82	0.53	0.98	1.39	1.67	0.80	1.47	2.10	2.50	1.06	1.96	2.77	3.40	1.31	2.46	3.43	4.26
		0	0.23	0.43	0.58	0.75	0.46	0.86	1.18	1.50	0.70	1.30	1.79	2.26	0.91	1.70	2.36	2.99	1.14	2.11	2.96	3.73
		+20	0.18	0.37	0.53	0.65	0.38	0.74	1.06	1.35	0.57	1.11	1.60	2.00	0.77	1.48	2.11	2.69	0.98	1.86	1.30	3.39

The reader may well point out that sea-level reductions in mountainous regions have been treated chiefly, showing that the long imaginary air columns and abnormal temperatures may combine to introduce large errors, and that this has been compared to long air columns in reducing to upper levels from data secured in eastern United States. What of the errors of reduction to sea-level in eastern United States, where the imaginary air column is short, averaging about 300 or 400 meters? Such comparisons are resolved into two divisions:

(1) *Short air columns:* Reduction to upper levels in the plateau region compared with reduction to sea-level in eastern United States.

(2) *Long air columns:* Reduction to sea-level in plateau region compared with reduction to upper levels in eastern United States.

Since the basic formula by which these pressures are reduced is the same in each case, the comparative value of the two methods (in so far as we may dare to compare them in this early state of upper air reductions) must lie in the relative merits of the temperature determination. It is not within the province of this paper to assume a critical attitude toward the present reductions; it is rather to assume such an attitude toward the method of upper air reductions and measure their accuracy, if comparisons may be resorted to, in terms of results by the present methods. As has been mentioned before, the plan of upper-air reductions has in its favor the fact that the temperature argument is a real, observable quantity, whereas the sea-level argument is merely an arbitrary value derived from surface conditions, and it is apparent upon the face of the proposition that there are many conditions in which local phenomena may lead to values of temperature which will give erroneous pressure values at sea level, even with relatively short air columns. Summing up the relative merits in this rather superficial manner (the only manner possible until it is within our ability to construct the maps of the upper air) it appears that (1) reduction through short air columns to sea level or to upper levels may be of approximately equal accuracy, since the error can not be very large in either case; (2) reduction through long air columns seems to be very satisfactory in the case of upper-air reduction, and, in many cases, to be very questionable in sea-level reductions; and (3) the importance of the location of the plateau region with respect to the paths of pressure areas across the country, and the fact that the plateau region is so extensive, render point (2) so important as to make worth while any attempt to improve such reduction.

In studying figure 14, it is found that in reducing to a level in the free-air an error of 5° C. in the mean temperature of the air column 2 kilometers in length will result in an error of about 4 mb. in the reduced pressure. In the case of Drexel, where the value of h is lowest, i. e., where the frequency curve is the flattest, for the 2-kilometer air column, the chance that an error of this magnitude will occur is 1:4; but, at the same station for the 1-kilometer level the chance of a 5° C. error is 1:34. For the 2-kilometer level at Mount Weather the chance of a 5° C. error is 1:8, but for the 1-kilometer level it is 1:40. It is obvious that for the longer air column, the chance of large errors is much greater than for the shorter. But this is not discouraging, for a glance at the table to be given shortly, will show how generally small will be these errors, as based upon the probable variation.

Having determined the probable variations of the mean temperature of the air column from those from which the isopleths have been drawn, and also the amount of error subsequently introduced by air columns of various lengths, it will be of interest to see how these probable variations will affect the reduced pressure at the upper levels. Basing our values upon figure 14 and Table 10,

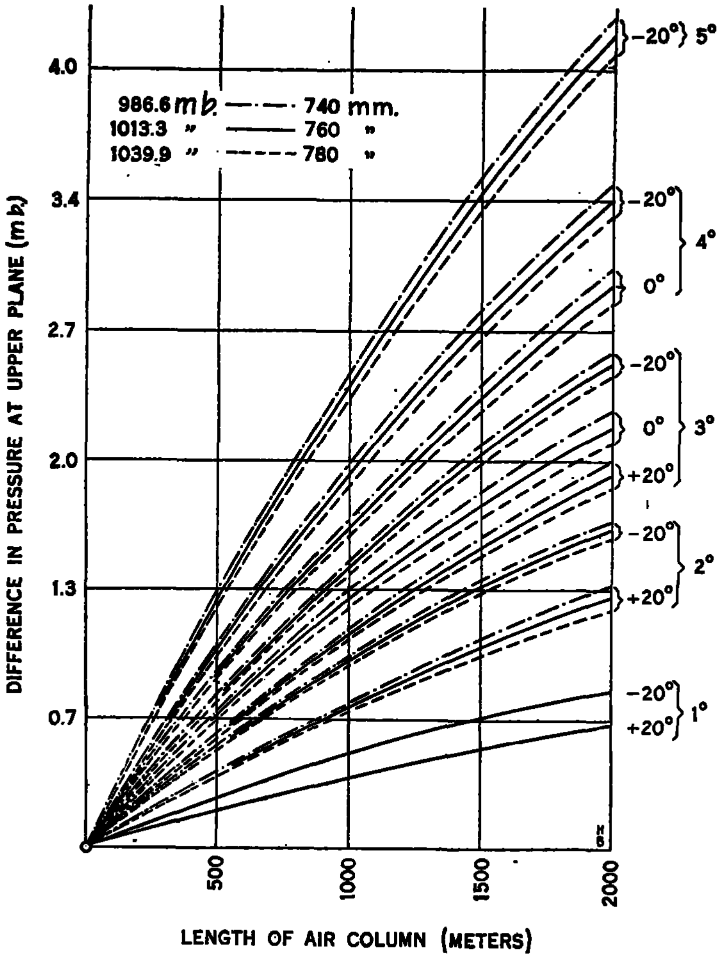


FIG. 14.—Pressure differences with various lengths of air column, corresponding to various errors in the mean temperature of the column with varying conditions of surface pressure and temperature.

let us obtain the pressure error due to the specific probable variations. A brief table will show this:

TABLE 11.—*Pressure errors due to errors in θ, under standard conditions.*

Station.	E	Length of air column.	
		1,000 meters.	2,000 meters.
	°C.	mb.	mb.
Mount Weather, Va.	1.2	0.49	
	1.6		1.15
Drexel, Nebr.	1.4	0.58	
	2.0		1.43
Ellendale, N. Dak.	1.4	0.58	
	1.8		1.29

These values appear to be very satisfactory. If we assume that the average elevation of the eastern half of the United States is 300 meters, the length of the air column in reducing to the upper level will average 1,700 meters, which will decrease the error shown above. In the mountain districts of the West, the error will decrease as the elevations become greater, and, if we can only obtain aerological information equivalent to that from the three eastern stations we have studied, it seems that upper-air reductions will be most reliable in the region where the sea-level reductions are the least reliable.

To show the practicability of this scheme, let us give an example of its use. Suppose the observer at Drexel (selected because we have data from that station) proposes to reduce his pressure to the level, 1 kilometer above sea level. At the time of observation, on the morning of September 1, he has a surface temperature of 10° C., and the wind direction is northwest. We find from figure 7 that, at that time, the correction to his surface temperature to obtain the mean temperature of the air column is −1.2° C., which, when applied, gives him the air column temperature of 8.8° C. Suppose that his corrected station barometric pressure is 970 mb., he will be able to tell from his tables that the pressure reduced through the air column 604 meters in length (Drexel's altitude is 396 meters) will be 901.6 mb. We know statistically that this observation will have a probable variation of less than 0.4 mb., which is certainly within satisfactory limits of accuracy.

CONCLUSION.

As was stated in the beginning, this paper can not pretend to do more than penetrate the most superficial stratum of this great and important problem. As one progresses through the various steps of its most elementary aspects, new vistas are opening on every hand—vistas that are attractive and inviting, and withal necessary to explore before one can be positive in his survey of the field. Here have been dealt with only the temperature argument and its relation to pressure reductions, and that for only three stations. One can not speak with finality until the upper air over the entire broad reaches of the United States has been penetrated by kites or other means in a score or more of places, and until their meteorographs have brought to earth thousands of records of the conditions aloft. Of this, one is certain: That for the stations investigated the plan reveals itself in an orderly simplicity not suspected at the beginning. Why should it not for the stations yet to be studied? Is it too much to see in this study the nucleus of a method of pressure reductions and a step toward forecasting for aviation with greater accuracy and even toward solving the nettling problem of plateau barometry?

By way of summary, let us review the steps that have been followed to attain the results of this paper:

1. We assumed fundamentally that surface wind direction is a reliable criterion of temperatures aloft, at least within the lower 2 kilometers of the atmosphere.[23]

> Observations at Mount Weather, Va., Drexel, Nebr., and Ellendale, N. Dak., show that temperatures at the surface and aloft are subject to three principal controls—wind direction, geographical location, and seasonal variation. The last two affect temperatures at the surface and aloft in a nearly parallel manner, while wind direction produces a more marked effect upon temperatures aloft than at the surface.

2. There is an orderly and well-marked progression of differences between the mean temperature of the air column and surface temperature in different months and with different wind directions which can be utilized to obtain the mean temperature of the air column when the correction to be applied is known.

[23] While this assumption has been shown to be justified in America (see footnote 3) the work of Mr. W. H. Dines in Europe leads to the conclusion that such a relation is not to be relied upon. See The characteristics of the free atmosphere, *Geophysical Memoirs, No. 13*, Meteorological Office, London, 1919, pp. 47-76. Abstract by W. R. Gregg in MONTHLY WEATHER REVIEW, Sept., 1919, pp. 644-647.

3. The probable variation of the values is conveniently small.

4. The probable variation when converted into units of pressure, gives an accuracy of reduction which is very satisfactory, even for long air columns.

ACKNOWLEDGMENTS.

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TEMPERATURES VERSUS PRESSURES AS DETERMINANTS OF WINDS ALOFT.[1]

By W. R. GREGG, WEATHER BUREAU.

[Author's Abstract.]

From theoretical considerations a certain definite relation is expected to exist between the pressure gradient indicated on synoptic weather maps and the wind at a short distance, some four or five hundred meters, above the surface. Observations with kites and balloons show that this relation does exist, when averages are considered, but that wide variations are frequently found in individual cases. These variations are due partly to incorrect sea-level pressure reductions, partly to too much smoothing of the isobars, but principally to departures of horizontal temperature distribution from normal conditions. If, for example, there is a steep latitudinal temperature gradient, the free-air winds quickly depart from those indicated by the pressure gradient, and the principle of "gradient winds" breaks down. If, on the other hand, there is little temperature change over extended areas, the free-air winds conform very closely to the surface pressure distribution and indeed under these conditions anticyclones and cyclones are found to continue as such to great altitudes. The first type is most frequently found in winter and the second in summer, but occasionally in other seasons; in all cases it is the temperature distribution that is the controlling factor. Two illustrations are given: One shows the conditions on December 17, 1919, when a very steep south to north temperature gradient produced over the entire country, east of the Rocky Mountains, free-air west-northwesterly winds, quite at variance in many sections with the surface pressure distribution. (A note on this appeared in the MONTHLY WEATHER REVIEW, Dec. 1919, **47**: 853–854.) The other illustration shows the conditions on March 23, 1920, when absence of any marked latitudinal temperature gradient resulted in free-air winds closely following the surface isobars to heights of 4 to 8 kilometers.

Studies based upon observations in Europe indicate that anticyclones are warmer than cyclones at all levels in the troposphere. In the United States the reverse condition has been found. The reason for this difference is not that different processes are in operation, but that in Europe the effects of purely dynamic heating and cooling are more pronounced than are those due to the importation of cold and warm air by winds with a northerly or southerly component, whereas the reverse is true in the United States. The free-air pressure gradients resulting from changes in air density due to these currents of warm and cold air are decidedly different from those at sea-level and show that LOWS bend backward with altitude to the northwest and HIGHS to the southwest. Hence, in the upper levels winds with a northerly component (usually northwesterly) blow across the surface HIGHS, and winds with a southerly component (usually southwesterly) across the surface LOWS. These are average conditions. Variations from them are of course produced by variations in surface and free-air temperatures from the normal. A careful study of these temperature variations gives valuable aid not only in forecasting free-air winds, but also in predicting the movements of cyclones and anticyclones, and therefore the accompanying changes in surface conditions.

[1] Presented before American Meteorological Society, Washington, D. C., Apr. 22, 1920.

DETECTION OF STORMS AND THEIR TRAVEL BY RADIO EQUIPMENT.

By Lieut. (j. g.) C. N. KEYSER.

[Navy Department, Washington, D. C., June 18, 1920.]

The perfection of radio apparatus for securing compass bearings by ships and aircraft paves the way for the development of a new phase of meteorological forecasting. The question of static has been the subject of considerable investigation by those interested in radio transmission as well as those interested primarily in meteorology and meteorological prognostication. Those interested in radio attacked the problem, first, in respect to its elimination from the field of radio transmission as a whole, and later, when this failed, in respect to the elimination of this interference from the radio receiver itself. The first problem resolved itself into finding out during what periods, in what particular localities, and under what conditions static disturbances prevented or hindered the receipt of radio messages, in order that times of transmission and locations for stations might be determined upon to eliminate this difficulty. These attempts at eliminating static did not prove successful. As a result the next attempt was made to eliminate static interference from the receiving set itself, and in this much greater progress has been made. The latest developments in radio receiving equipment have been successful in damping considerably, if not entirely eliminating, the interference from static disturbances.

The problem, from the meteorologist's standpoint, is not to devise means of eliminating static from radio receiving, but to associate the various types and intensities of static with the approach, movement, and intensity of local and general electrical storm, and of forecasting the approach of the same. The advent of aviation, more especially of "lighter-than-air" craft has made the forecasting of this type of storm of vital importance.

The matter of detecting storms in their travel by the use of radio equipment is still in its experimental stage and is as yet an open field for the experimenter as well as the amateur meteorological and radio enthusiast to enter. The time will probably come when storm detectors will be a part of the regular equipment of all meteorological stations, and when the reporting of static will be