the calculated energy of instability for a particular element.

The first method of calculation leads to an exact energy balance, and shows the source of the liberated energy. The second method of calculation involves less numerical calculation, and gives separately the energy from the ascending and the descending air.

TABLE 3

Pressure (millibars)		Energy released (joule/gr)	Mean (joule/gr)	Mean energy of layer (joule/gr)	Mean velocity (m/sec)
Initial	Final				
1,000	700	0.473	0.272		
700	1,000	0.072		0.222	21.1
975	725	0.293	0.173		
725	975	0.053		0.134	16.4
950	750	0.156	0.096		
750	950	0.036		0.069	11.8
925	775	0.063	0.042		
775	925	0.021		0.028	7.5
900	800	0.017	0.014		
800	900	0.010		0.009	4.3
875	825	0.0028	0.003		
825	875	0.0029		0.0014	1.7
850	850	0.0	0.000		

APPLICABILITY OF THE TWO METHODS OF EVALUATION

We shall now consider the problem of which of the processes in the atmosphere correspond to the different methods of evaluation by the tephigram.

The usual method emphasizes the dynamical processes which involve the ascent of a small isolated mass of air; it yields the energy for this mass, but tells nothing about its source. This procedure is appropriate when the stratification of the system is not changed by the displacement of the element; each mass that ascends must be replaced by a mass with the same temperature and humidity, or else enough heat must be supplied to the system to maintain the temperature distribution unaltered (e. g., by continuous radiation). Conditions are most appropriate for the application of this method of evaluation when the vertical equilibrium in the atmosphere is conditionally unstable, but the temperature gradient less than the dry adiabatic; then the equilibrium is stable with respect to downward motion, and the process is one of strong ascending motions over small areas and slow downward motions over larger areas (4). The energy released will come largely from the ascending elements.

With gradients greater than the dry adiabatic, account must always be taken, even in dry air, of the energy contributions from descending air (5); these can be taken directly from the tephigram, which, therefore, always gives a good indication of the intensity of convection.

The other method of using the tephigram takes into account the changes in the vertical equilibrium brought about by the displacements of air, and should be used whenever the mass of air which ascends is so large that it spreads out into a layer of appreciable thickness. The vertical temperature distribution is then changed, in the absence of a supply of external energy; and the air which subsequently ascends meets with a different environment from that encountered by the previous ascending elements. This method is of fundamental importance to the quantitative determination of the energy of instability for an entire body of air, a knowledge of the amount of such energy is very desirable, because it is a numerical measure of the importance of the body of air for energy transformations in the atmosphere. When the tephigram is used only to calculate energy of instability for a single isolated ascending element, and this is erroneously considered an index to the total available energy, it is easy to overestimate the latter, because in an unstable equilibrium not all the air may ascend to the upper limit of the unstable region and frequently a part of the released energy is taken up by the downward moving air.

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(2) Max Margules, Uber die Energie der Stürme, *Jahrbuch der k. k. Zentralanstalt für Meteorologie*, Jahrgange 1903, Anhang, Wien 1905; trans. in Cleveland Abbe, *Mechanics of the Earth's Atmosphere* (3d collection), Washington, 1910. See F. M. Exner, *Dynamische Meteorologie*, Kap. 7; D. Brunt, *Physical and Dynamical Meteorology*, chap. XV.

(3) Anfinn Refsdal. Der feuchtlabile Niederschlag. *Geofysisker Publ.* 5. Nr. 12. Oslo 1930.

(4) P. Raethjen. Die Böenfront als fortschreitende Umlagerungswelle. *Met. Zeit.*, 51, 9–17. 1934.

(5) D. Brunt. The Transformations of Energy in the Atmosphere. *Quarterly Journal of the Royal Meteorological Soc.* 59, 343–349. 1933.

SYNOPTIC DETERMINATION AND FORECASTING SIGNIFICANCE OF COLD FRONTS ALOFT [1]

By B. HOLZMAN [2]

[Soil Conservation Service, Section of Climatic and Physiographic Research, Washington, D. C., December 1936]

Cold-front and warm-front types of occlusions [3] are common on the synoptic chart, but frequently the latter have been confused with the cold-front types. In synoptic analyses the boundaries of the various air masses have all too frequently been considered only from the viewpoint of surface representation, with the result that upper air cold fronts, although occasionally recognized, have generally been held unique. The concept of an upper cold front is by no means new [4]; and recently Wexler [5] has presented a detailed analysis of a warm-front type of occlusion.

Cold fronts almost invariably become upper-air fronts as a result of warm-front occlusions, although conceivably they may occasionally be generated by fields of frontogenesis with an influence confined to air masses aloft. The recognition of the warm-front type of occlusion and the upper cold front is of paramount significance to meteorologists. The origin of precipitation that occurs throughout the Great Plains in winter may often be directly attributed to an upper cold-front invasion. A forecast of ceilings, cloud layers, thunderstorms, zones of turbulence and icing conditions based upon the recognition of an upper cold front will have distinctive features of immediate pertinency to aircraft travel.

[1] Presented at the meeting of the American Meteorological Society, Kansas City, Missouri, June 1936.

[2] Formerly meteorologist—American Airlines, Inc., Newark, New Jersey.

[3] Bjerknes, et. al., *Physikalische Hydrodynamik*, p. 719. Berlin, 1933.

[4] Bjerknes, J. and Solberg, H. Life cycle of cyclones and the polar front theory of atmospheric circulation. *Nordske Videnskaps-Akademi Geofysiske Publikasjoner* vol. 3, no. 1, 1922.

[5] Wexler, H. Analysis of a warm-front type occlusion. MONTHLY WEATHER REVIEW, vol. 63, pp. 213-221, July 1935.

Warm-front occlusions always occur when the advancing wedge of air is of lesser density than the wedge upon which it encroaches. Thus in winter when the continent is colder than adjacent bodies of water, warm-front types of occlusions are prevalent along the western coast; and in summer, such occlusions will exhibit themselves on the eastern coast. However, occlusions are not necessarily confined to coast lines; and warm-front occlusions can be recognized over any part of continental or maritime areas whenever the densities of the air masses involved are appropriately related.

Numerous upper cold fronts outlining invasions of P_M (Polar Maritime) air aloft have been noted throughout the Middle West; and although associated with no immediately apparent occlusion, the historic sequences nearly always indicate an origin from occluding cyclones either over the Pacific Ocean or along the western coast of the continent. After crossing the Rocky Mountains this type of upper cold front generally rides aloft over a dome of P_C (Polar Continental) air, and may cause a wave on the cold front of the surface air mass. As the wave develops and occlusion begins, the relative densities generally cause the new cyclone itself to proceed as a cold-front type of occlusion. However, it is possible for the wave to occlude in the warm front manner; and if this be the case, a rather complex situation of two upper cold fronts, one marking the invasion of P_M air that originally induced the wave on the surface air mass, and one arising from the occluding cyclone, can then be detected.

When extensive masses of fresh P_C air recurrently occupy the Great Plains area in winter, a wave that has no genetic relation to an upper front may develop on the Polar Front that usually extends through the Canadian provinces of Alberta or Saskatchewan. With the intensification of the cyclone and the subsequent occlusion process, an upper cold front, marking the advance of an old P_C air mass, occasionally can be found over the Dakotas and Nebraska. This is explained by the fact that Polar air advancing as a surface air mass from the Canadian provinces is sometimes of less density than the fresh P_C air lying to the southeast. It may appear very unlikely that Polar air occupying the central and eastern portions of the United States should have a greater density than air from Alberta or Saskatchewan; but it is to be recalled that the modification of an air mass depends upon its trajectory, and in a rapid advance of a dome of Polar air from high latitudes to the lower latitudes of the United States it is possible for an air mass to maintain sufficient density for a cyclone developed on its northwestern periphery to occlude in a warm front manner. This type of upper cold front will be encountered only in rare instances, however; the normal occlusion of these cyclones is of the cold-front type.

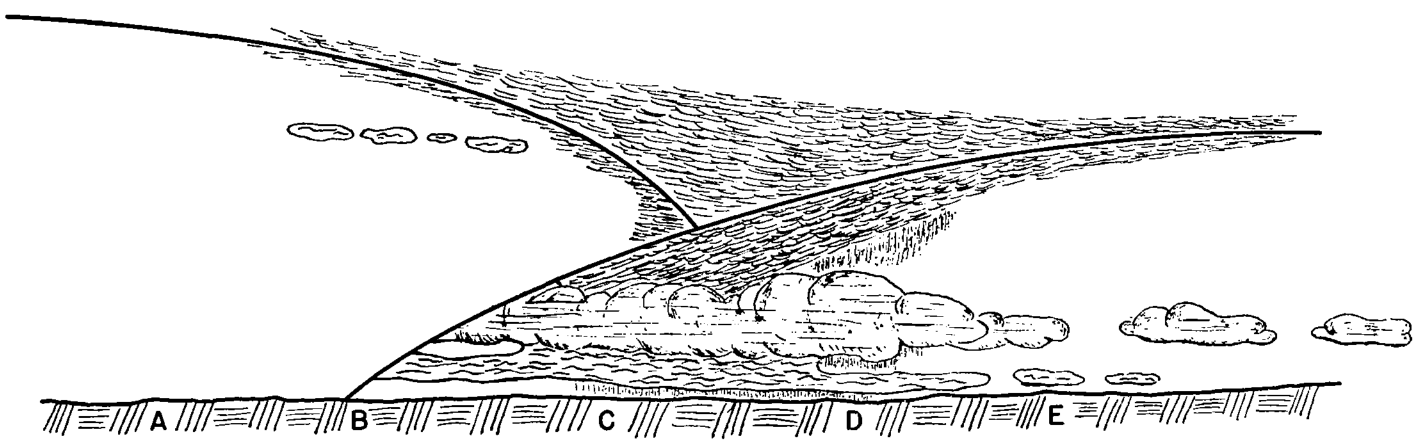


FIGURE 1.—Warm-front type of occlusion in winter.

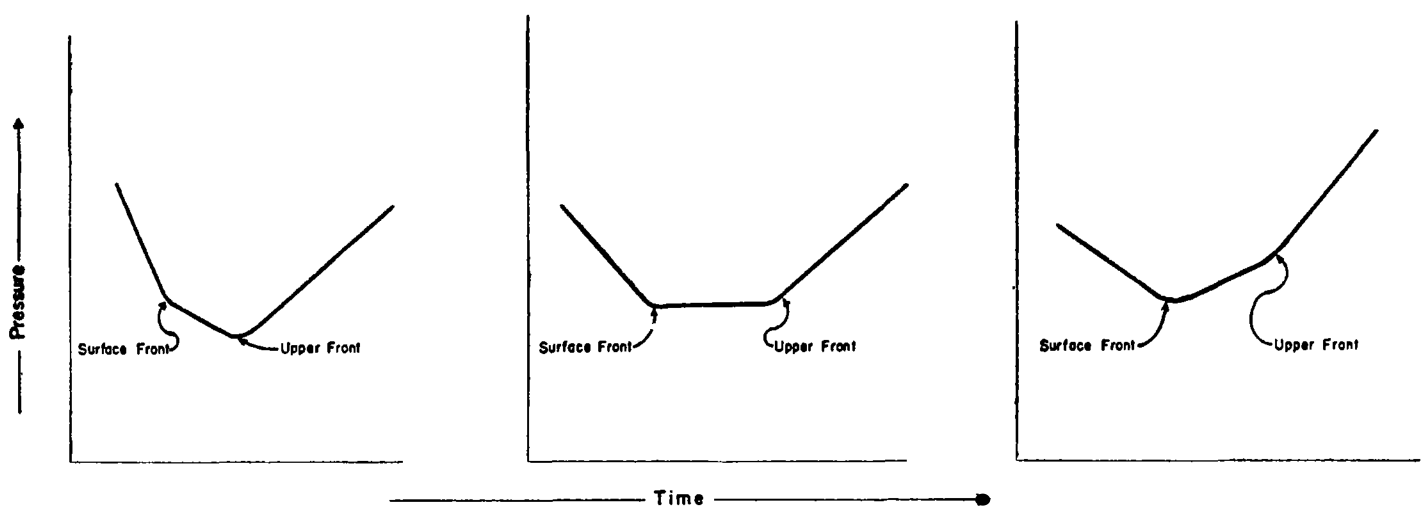


FIGURE 2.—Typical pressure traces during passage of an upper cold front with warm-front type of occlusion.

Willett [6] has called attention to the upper cold fronts that may exist between T_S (Tropical Superior) and T_G (Tropical Gulf) air masses. Either T_S or T_G may be the active air mass, depending upon which of the two air masses has the greater density. The development of the upper discontinuities between T_S and T_G does not originate from occluding cyclones as is generally the case for Polar air masses, but is instead probably caused by frontogenesis aloft brought about by properly oriented deformation fields. The reason is the fact that T_S is essentially an upper air mass, generally conceded to acquire its properties principally by subsidence in the upper levels of the atmosphere, and only infrequently reaches the surface. When T_S does appear at the surface, it usually has such high temperatures that it becomes the least dense of all air masses at these lower levels, and invariably forms the warm sector of a cyclone.

Upper cold fronts travel across the continent in a normal manner, comparable to surface discontinuities. In synoptic analyses the clues obtained from surface data for determination of upper fronts are generally not as clearly defined as the indications for surface fronts; but nevertheless, sufficient evidence frequently can be obtained from surface information, especially when used in conjunction with aerographic soundings, to recognize their presence. In the following paragraphs are enumerated a number of synoptic aids for the determination of warm front types of occlusions and upper cold fronts; they are not to be regarded as infallible rules, however, and the order of listing has no significance in respect to their relative importance.

Winds aloft.—Usually a well-marked discontinuity in the winds aloft separates the encroaching upper wedge from the air mass below. The winds in the surface air mass may be southwesterly, whereas aloft a vigorous shift to northwest will be encountered. In the various situations observed, this type of shift has most commonly accompanied the upper front. However, the discontinuity need not be indicated by a directional shift in wind; and many times a change in speed will be the only clue available. One is to be cautioned against attaching any particular significance to a mere change in direction of the winds aloft. In cases of over-running tropical air associated with a warm front, apparent directional discontinuities, actually in anticyclonic curvature of streamlines, are always encountered in the winds. As pointed out by Bjerknes [7] and others, a southwest current, during its ascent along a warm-front surface, may acquire considerable turning of its horizontal streamlines from the deflective effect of the earth's rotation; and aloft it will show as a northwest or north-northwest current.

Surface winds.—Surface winds are of little synoptic aid in locating an upper front. Since the advancing wedge travels aloft it usually cannot be expected to extend its influence to surface winds. Occasionally, because of the progressive modification of the surface wedge, the upper cold front works its way to the surface. In other instances the surface air behind the upper front, at the point where it first begins to ascend over the coldest surface air mass, happens to be colder than the surface wedge, and advances as a cold-front type of occlusion. In these cases a vigorous surface wind discontinuity accompanies the surface front.

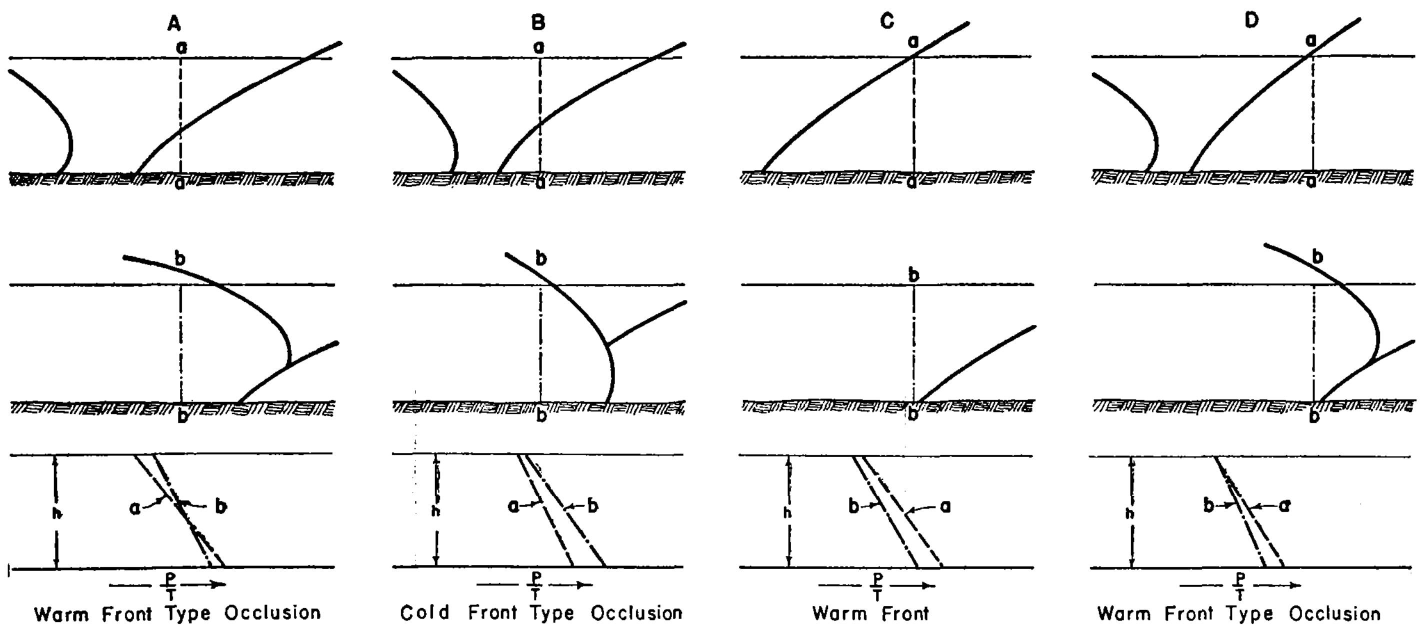


FIGURE 3.

However, when the surface boundary of the lower and passive wedge is near at hand, the distribution and character of surface wind directions and speeds frequently help to differentiate between the warm-front and cold-front types of occlusions. In the cold-front type of occlusion a well-marked wind shift, usually from a south or southwest to a northwest, will generally be encountered. The surface boundary in the warm-front type of occlusion will in contrast usually show a gradual shift from a southwest or west to a west-northwest or northwest, very similar to the shift that accompanies a warm front. Often a broad zone of winds having a slight southerly component shifting to a slight northerly component will mark the surface discontinuity of the passive wedge.

It should be pointed out that the location of the surface discontinuity in the warm-front type of occlusion frequently is of less significance in forecasting than the determination of the position of the upper cold front. Usually the chief importance of recognizing this surface

[6] Willett, H. C. Discussion and illustration of problems suggested by the analysis of atmospheric cross-sections. *Papers in Physical Oceanography and Meteorology Massachusetts Institute of Technology and Woods Hole Oceanographic Institution*, vol. 4, no. 2, July 1935.

[7] Bjerknes, J. Exploration de quelques perturbations atmosphériques à l'aide de sondages rapprochés dans le temps. *Norske Videnskaps-Akademi Geofysiske Publikasjoner*, vol. 9, no. 9, 1932.

boundary is to furnish indirect evidence of the presence of an upper cold front at some distance in advance of the shifting surface winds.

Pressure change characteristic.—The pressure change characteristic offers a very important clue to the presence of an upper front. The barometer trace during passage of a surface cold front will show falling, and then sharply rising, pressures; but the pressure change caused by the passage of an upper cold front is usually characterized by a lesser discontinuity—perhaps a slower rate of decrease either is not apparent or else has been left far behind the upper front, the barogram may exhibit only an ill-defined discontinuity, difficulty to distinguish from the normal diurnal pressure changes; but if a systematic linear arrangement of slight discontinuities in the pressure tendencies, unaccompanied by a surface wind shift, can be traced, this in itself is occasionally sufficient evidence to indicate the presence of an upper front.

Pressure trough.—In contrast to the generally distinct V-shaped isobars associated with a surface cold front, only

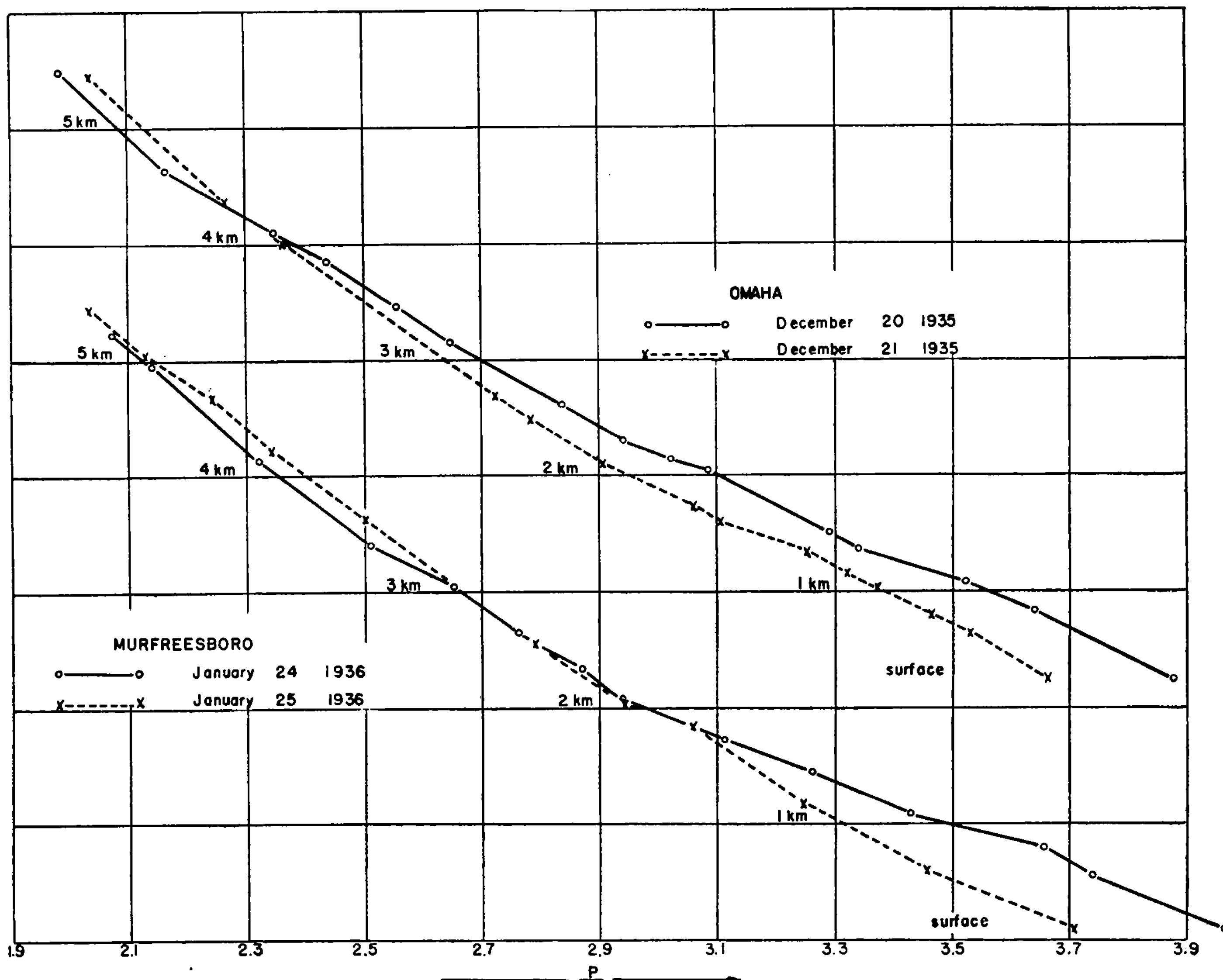


FIGURE 4.—Typical density-altitude curves during passages of upper cold fronts; P/T in mb/°A, altitude in km. The crossing of the curves indicates invasion by an air mass bounded by an upper cold front.

or only a slight rise in the barometer, followed by a steadily and rapidly rising pressure.

Thus in figure 1 the region CDE may have negative changes of from 4 to 6 hundredths of an inch in 3 hours. The region BC probably will exhibit negative changes of from 0 to 4 hundredths, since the advancing wedge aloft has the effect of compensating the falling pressures normally expected ahead of the surface front. The region AB is characterized by positive tendencies, generally 0 to 8 hundredths.

Typical pressure traces such as may be experienced at any one station are indicated in figure 2. Quite often, however, when the surface boundary of the lower wedge minor and poorly defined surface pressure throughs characterize upper cold fronts. A sharp discontinuity in the isobars is not always associated with surface fronts—not in cases of frontolysis, e. g. (*Physikalische Hydrodynamik*, p. 727)—and no undue significance should be given a broad or narrow trough of pressure with more or less continuous isobars.

Although an upper front may be evidenced at the surface by a broad pressure trough, aloft it may be accompanied by a pronounced low pressure, and the gradient will be such as to cause a very significant increase in the winds at these levels as the front approaches. However, in the case of the warm-front type of occlusion, a minor

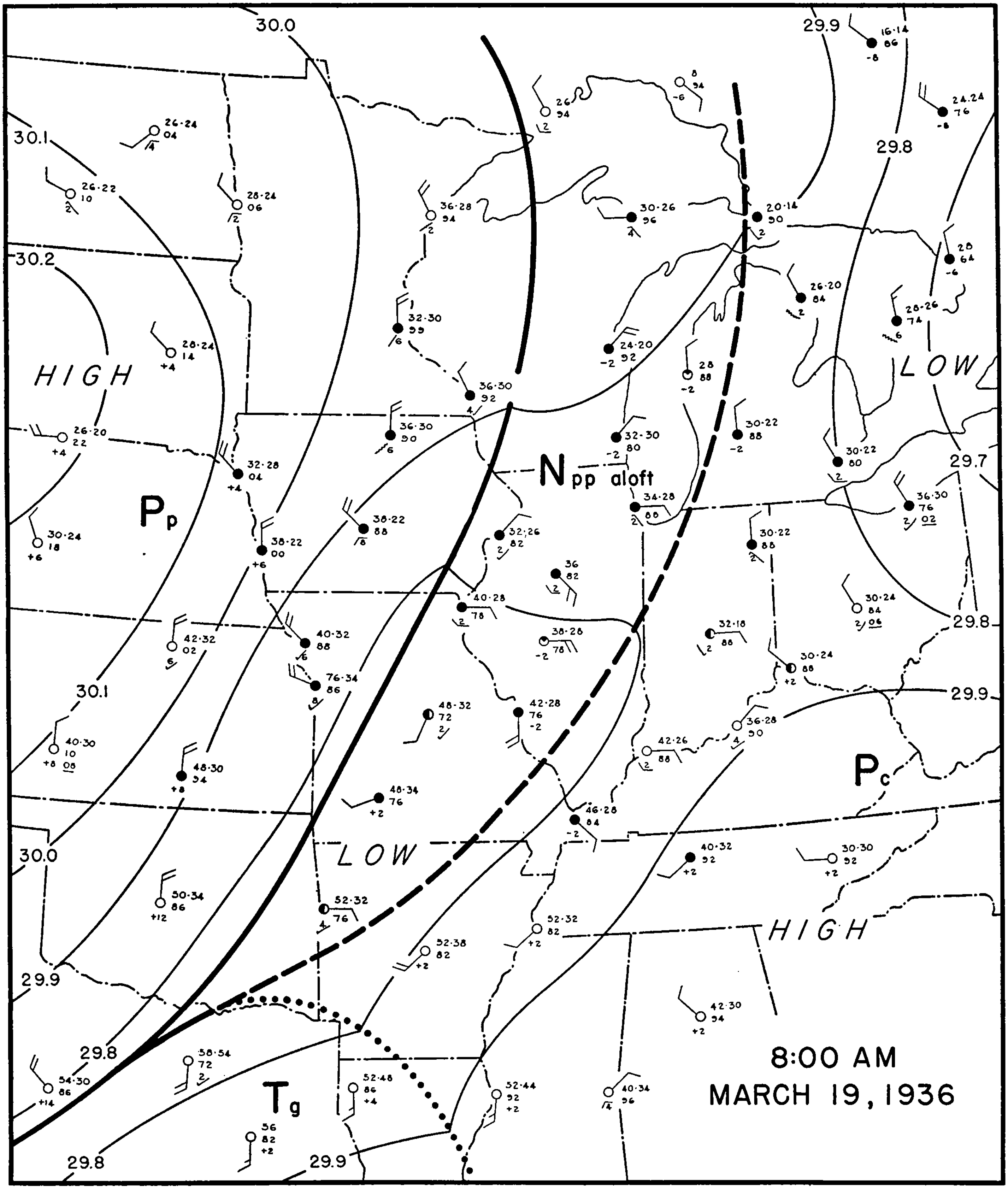

30.0
29.9
30.1
29.8
30.2
HIGH
LOW
29.7
Pp
Npp aloft
29.8
29.9
30.1
Pc
LOW
30.0
HIGH
29.9
29.8
Tg
29.8
29.9
8:00 AM
MARCH 19, 1936

FIGURE 5.

surface trough in advance of the trough that accompanies the surface front is generally significant, and is good evidence for the presence of an upper front. Isobars should be drawn very carefully, avoiding too great a smoothing, as the minor trough can easily be obscured. Frequently it will be helpful if the isobars are drawn before attempting to locate the frontal discontinuities.

Cloud types and precipitation.—A characteristic feature of the warm-front type of occlusion is the frequent absence of cloud forms during the initial occluding process. Usually a surface wind shift is indicated, and to all appearances it will seem to have all the properties of a cold front type of occlusion except for the fact that a zone of clear skies accompanies the shift. Unfortunately, this evidence in itself is not diagnostic, for many surface cold fronts similarly are attended by the lack of cloud forms. However, well in advance of the surface shift, as much as 100–500 miles, a zone of alto-cumulus or alto-stratus may lead one to suspect the presence of an upper cold front. When there has been no occlusion and there are no surface wind discontinuities, an anomalous belt of alto-cumulus may likewise indicate an upper cold front. Here again this evidence needs further substantiation, for a simple warm front may often show a zone of cloudiness separated from the surface wind discontinuity by a zone of clear skies.

Generally the most complex cloud systems that accompany warm-front type occlusions occur during winter. In the initial stage a belt of alto-cumulus or alto-stratus may be noticed in advance of the surface shift, and the upper front may likewise be present; but as the cold wedge proceeds aloft there is a sudden thickening of the alto-stratus, and within one or two hours without any evidence whatsoever from westward-lying stations a moderate snow condition may develop. A strato-cumulus layer generally will form beneath the lowering and thickening alto-stratus; and as precipitation continues, a low stratus deck eventually develops within the surface cold air mass, limiting ceilings to 500–1,500 feet. In the zone CD, figure 1, when the precipitation is at a maximum, the

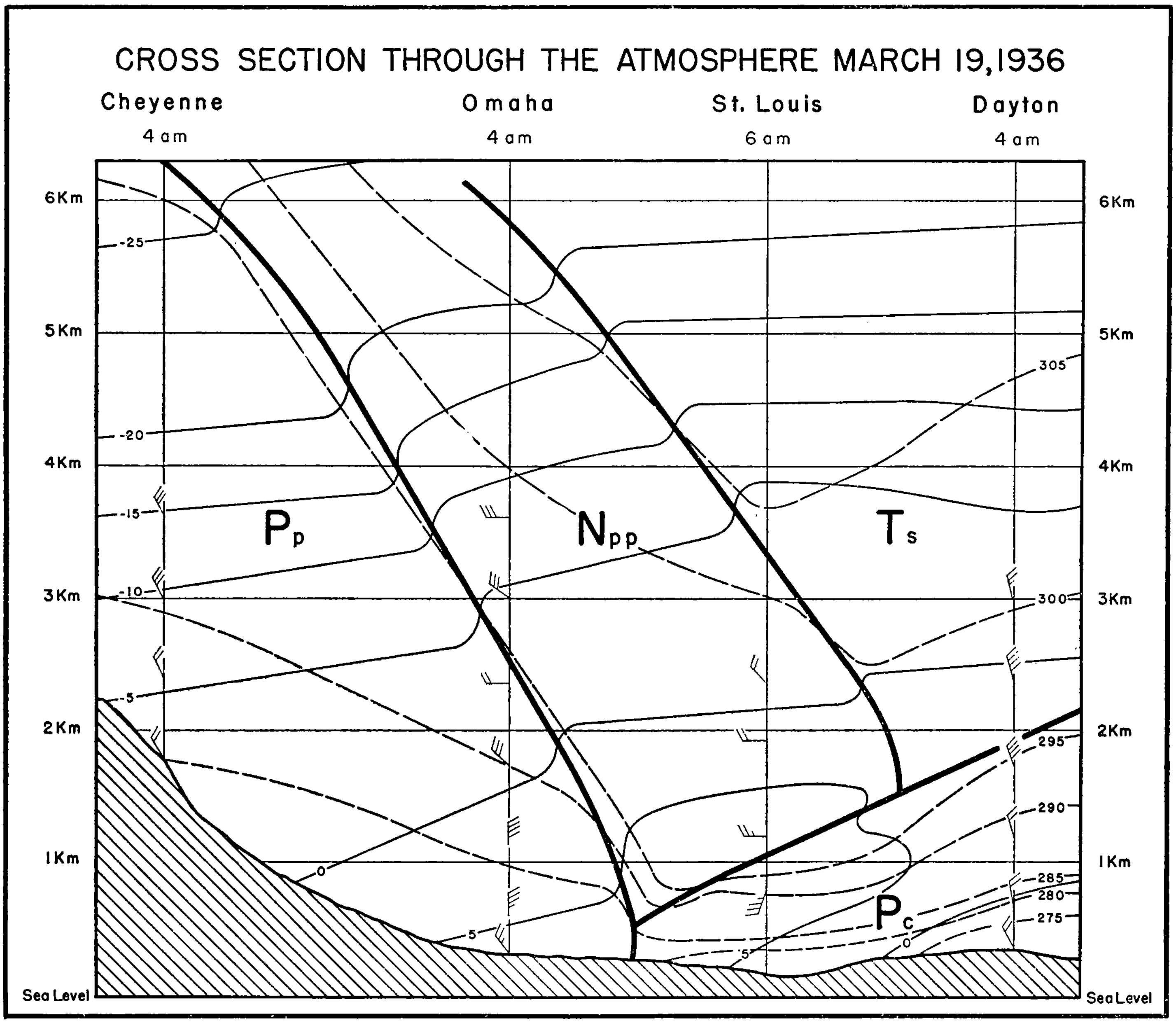


FIGURE 6.—Solenoidal distribution. The full lines are isotherms in °C.; the broken lines are lines of constant potential temperature or isentropic lines.

various cloud decks generally merge together into a thick cloud system. Thus an airplane flight made from E to A would, upon ascension, encounter first a low stratus condition near 500 to 800 feet with a top near 1,500, and second the strato-cumulus deck which may extend from 2,000 to 8,000 feet. Between E and D the flight could be made above the strato-cumulus. The upper alto-stratus would be steadily and rapidly thickening; and precipitation, if not encountered upon ascent from E, would most certainly be encountered above D where the clouds decks upper cold front, and will rarely occur in any season other than winter. Usually a zone of alto-cumulus with little or no precipitation will mark the advance of an upper cold front in spring and autumn. In summer a series of high level thunderstorms, caused by the release of the convective instability of the tropical air which the upper wedge most commonly displaces, or in a few cases caused by the release of the instability of the air in the upper advancing wedge itself, will serve to locate the boundary of the active air mass.

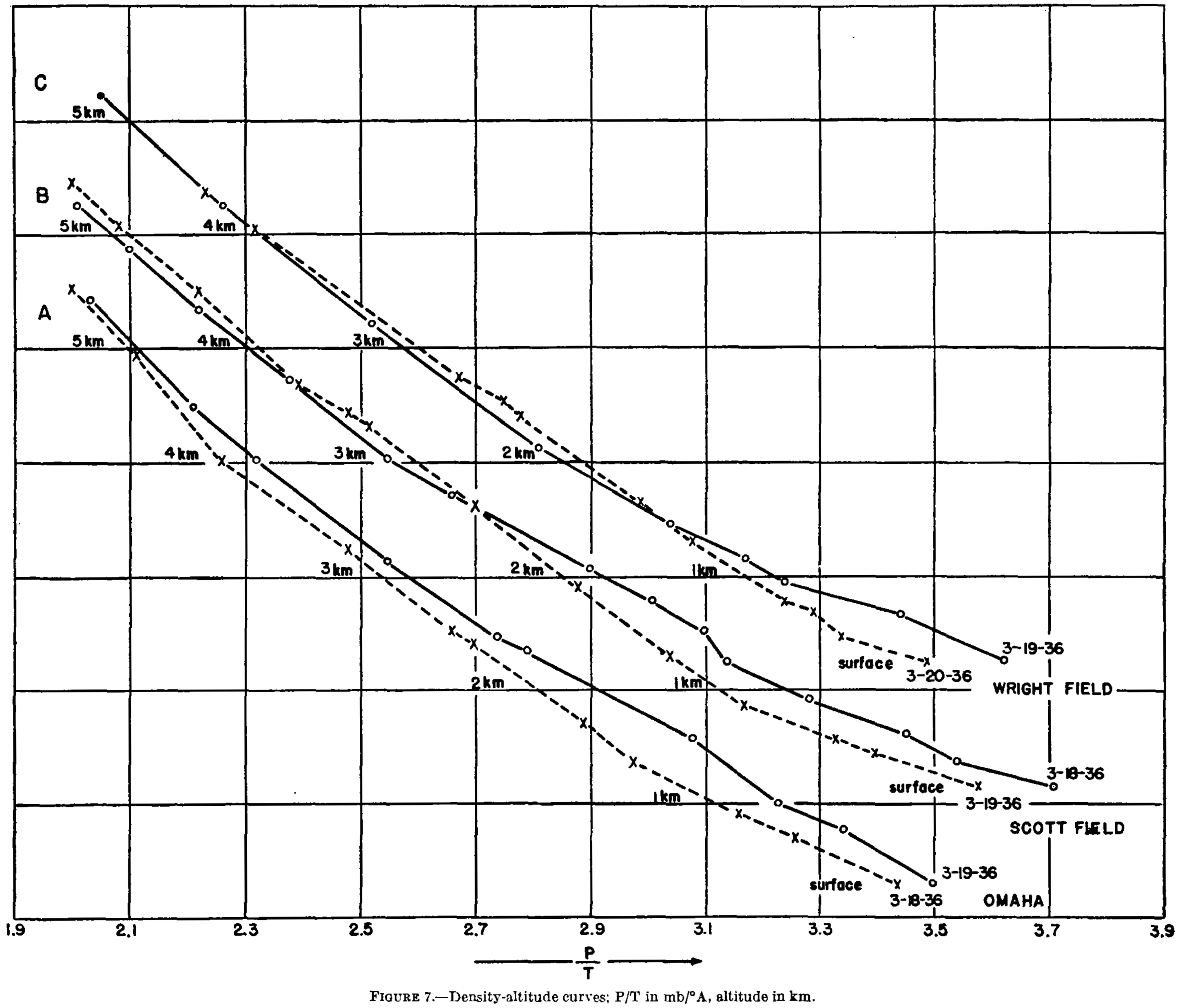


FIGURE 7.—Density-altitude curves; P/T in mb/°A, altitude in km.

begin to merge. The top of the entire cloud system between C and E would be extremely high for present passenger travel—it may exceed 17,000 or 18,000 feet. Between C and B, depending upon the altitude at which the flight is made, one may again expect to emerge between cloud layers, and the upper limit of the strato-cumulus will generally define the boundary of the surface wedge.

The situation just described represents probably the most complex of the cloud systems that accompany the

Surface temperatures.—To ascertain whether a warm front or cold front type of occlusion will take place, it is sometimes sufficient to compare the surface temperatures of the active and the passive air masses, and to presume that if the temperatures are high in the active air mass it will flow aloft; but this procedure should be used with reservation: The real reason an air mass ascends is because its density, level for level, is less than that of the wedge with which it comes in contact. Of course, within the narrow limits of the frontal zone the pressure is essentially the same in the cold and the warm mass, and the relative density is thus determined by temperature and to a slight extent also by the water vapor content. However, the distribution of meteorological stations does not allow a determination of density from temperatures alone, especially when comparisons for 12 or 24 hours are desirable. Likewise surface temperatures are easily influenced by insolation, radiation, evaporation, and condensation; and when employed for comparative purposes, in establishing the lesser or greater density of an air mass, should always be used in conjunction with the pressures.

$d\rho$, at the given level, produced by the increments in pressure and temperature, will be

$$d\rho = K\left[\frac{1}{30} - \frac{1}{30}\right] = 0.$$

The danger of comparing densities by consideration only of temperatures is amply illustrated by this example in which a 3° increase in temperature produces no change in density.

Density.—In the synoptic determination of upper fronts, the densities of the various air masses involved are of primary significance. An active air mass, the density of which at each level exceeds that of the mass with which it will come in contact, will of course preclude the possibility of a warm front type of occlusion. A P_p (Polar Pacific) air mass, with a density, level for level, less than that of a P_c air mass then overlying the central and eastern portions of the country, must necessarily continue its march aloft after crossing the Rocky Mountain chain.

The relation between density, pressure, temperature, and humidity, as derived from the equation of state for moist air, is

$$\rho = \frac{P}{R_d\,(1+0.604q)\,T},$$

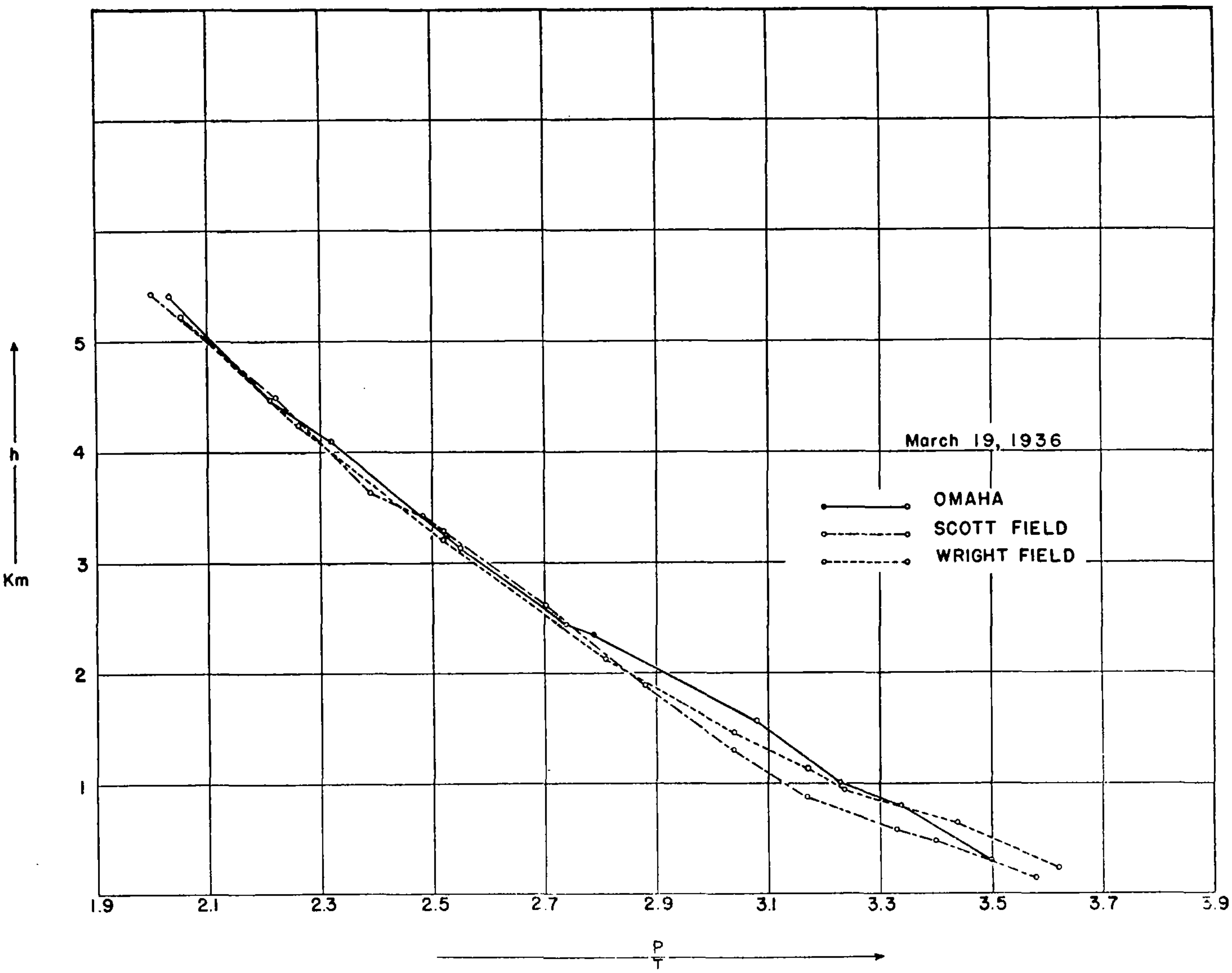


FIGURE 8.—Density-altitude curves; P/T in mb/°A, altitude in km.

The following illustration will serve to indicate the relative importance of changes in temperatures and pressures, and the effect of these changes upon density:

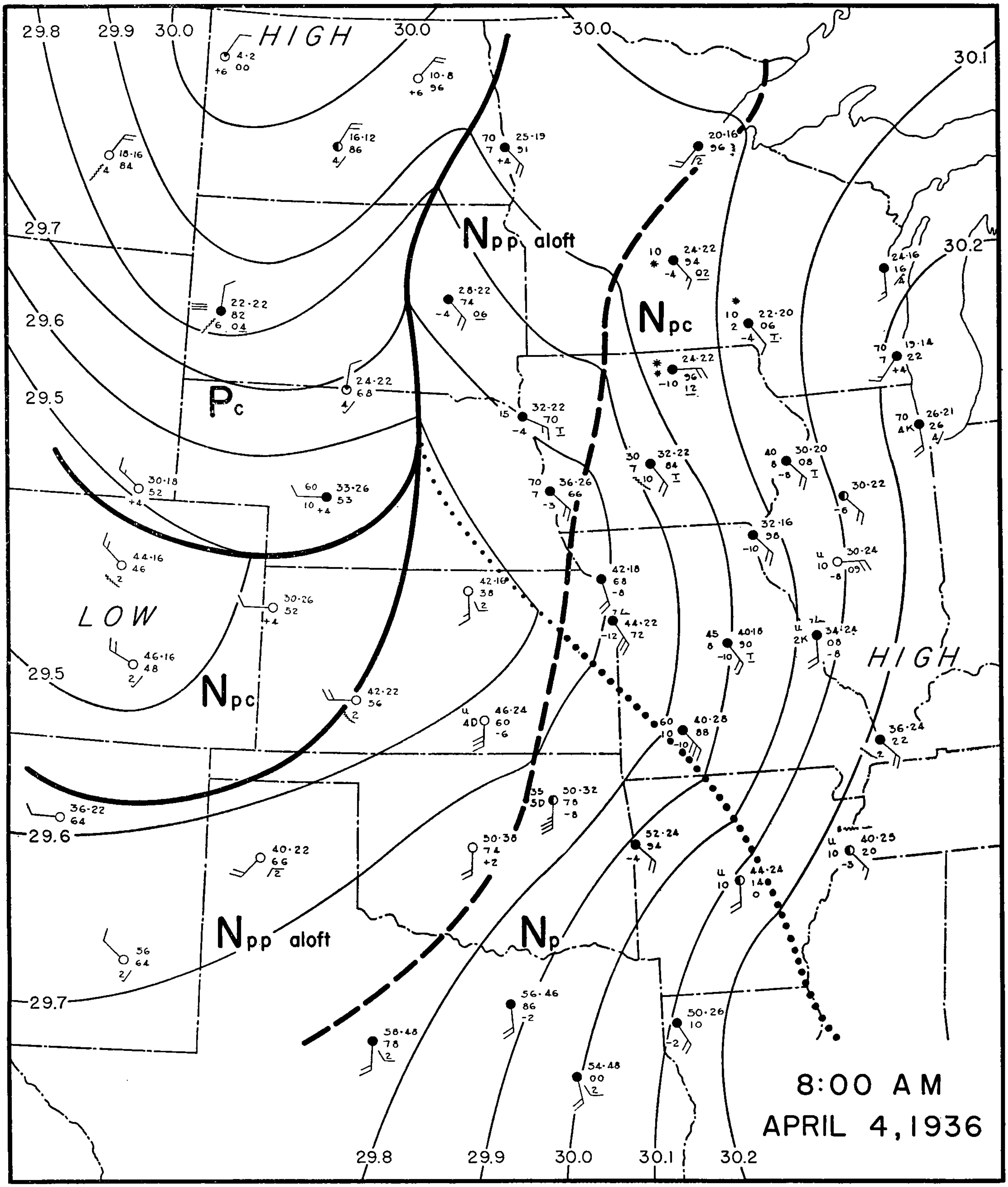
Since density, ρ, varies directly with pressure, P, and inversely with temperature, T, then

$$\rho = K\frac{P}{T}.$$

Differentiating,

$$d\rho = K\left[\frac{dP}{T} - \frac{P}{T^2}dT\right].$$

If the following values are assigned, $P=1,000$ millibars, $dP=+10$, $T=300°$ A., $dT=+3°$, the change in density,


29.8
29.9
30.0
HIGH
30.0
30.0
30.1
29.7
30.2
Npp aloft
Npc
29.6
29.5
Pc
LOW
29.5
Npc
HIGH
29.6
Npp aloft
Np
29.7
8:00 AM
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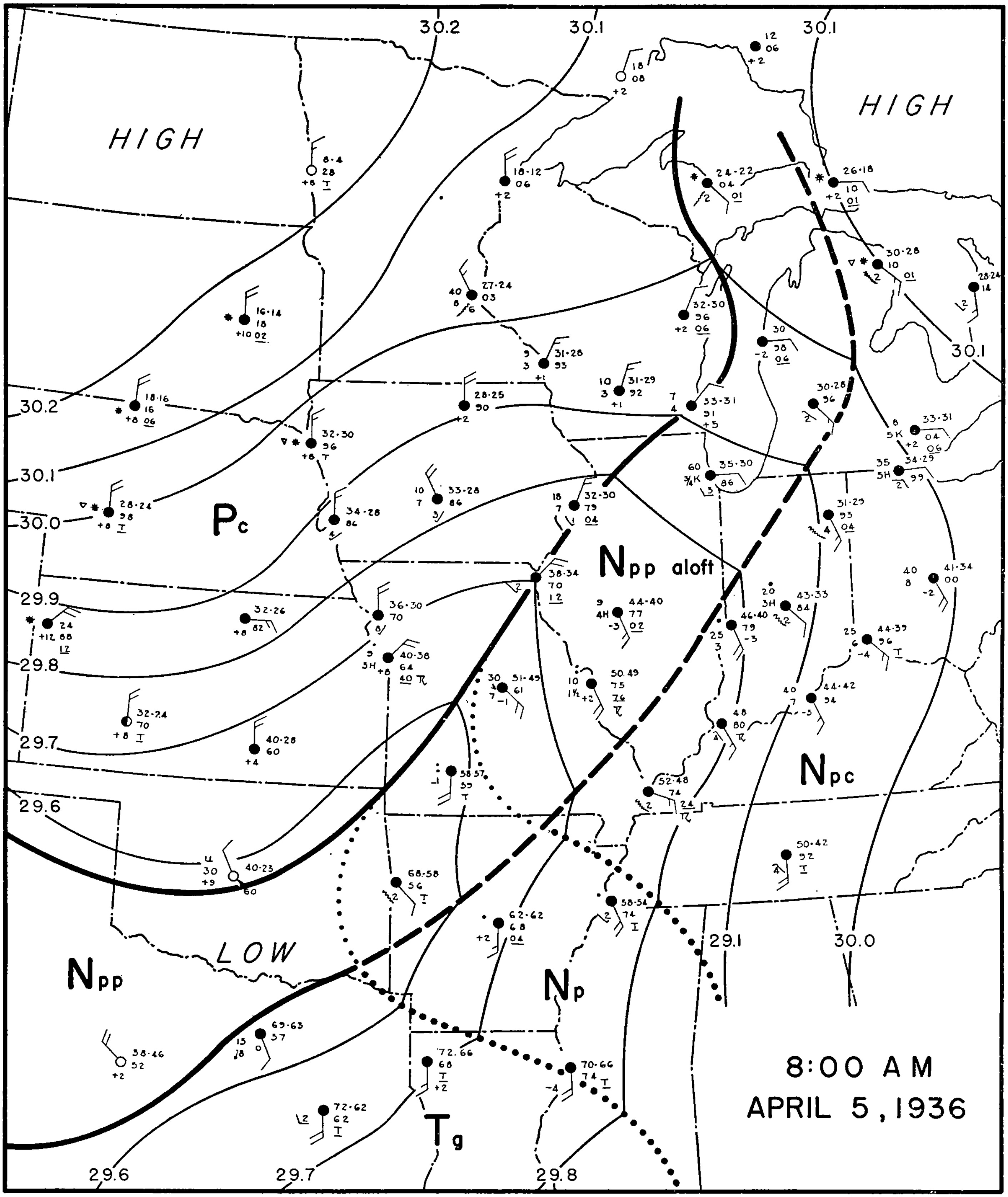
29.8
29.9
30.0
30.1
30.2

Figure 9.



HIGH
HIGH
30.2
30.1
30.1
30.0
29.9
29.8
29.7
29.6
Pc
Npp aloft
Npc
Npp
LOW
Np
Tg
29.6
29.7
29.8
29.1
30.0
8:00 AM
APRIL 5, 1936

FIGURE 10.

where ρ=density of humid air, P=pressure, R_d=gas constant for dry air, q=specific humidity, and T=temperature.

Virtual temperature, T', is defined by $T'=(1+0.604q)T$.

It can be shown that the error introduced by substituting T for T' is negligible. For P=1,000 millibars, T=20° C., and q=20 grams of water vapor per kilogram of air, only a 1 percent error would result from substituting T for T'.

Since the forecaster will be interested only in relative values of density, it will be sufficient to use the formula

$$\rho=K\frac{P}{T},$$

and compare the relative values of $\frac{P}{T}$. Figure 3 illustrates various density-elevation curves that might be expected in different synoptic situations.

One particularly interesting case is shown in figure 3A. Here the seemingly paradoxical condition of cold and dense air advancing aloft is indicated. The density-elevation curves for 2 consecutive days at the given station will cross each other and apparently substantiate the fact that denser air has made an invasion aloft. However, this apparent anomaly is easily explained; the displacement by the encroaching wedge has resulted in denser air only aloft, but this air still has a less density than the surface air mass upon which it rides. This singular crossing of the density curves is very significant, and offers positive evidence for the presence of an upper cold front.

Figure 4 shows observed cases of density curves when passages of upper cold fronts occurred. It should be emphasized that these are common occurrences.

T–θ solenoids.—When isothermal surfaces intersect isentropic or equal potential temperature surfaces in the atmosphere, parallelepipeds are formed analogous to the circulation solenoids [8] formed by the intersection of isobaric and isosteric surfaces. The work done in a cycle bounded by two adiabats and two isothermals is proportional to the area; and, therefore, regions in the atmosphere which have the greatest concentration of solenoids are zones of maximum available energy.

Bergeron [9] has shown how intersections of equiscalar surfaces may become concentrated in frontal zones by the action of frontogenesis or atmospheric deformation fields. Thus the discontinuity between a Tropical air mass and a Polar one will be defined by a concentration of T–θ solenoids in the frontal zone; and the transfer from potential to kinetic energy will be exhibited by a sinking of the colder air and a rising of the warmer air, maintaining a circulation such as will bring the ascendant of the potential temperature into coincidence with the temperature gradient.

Since normally T decreases, and θ increases, with altitude, the isothermal lines will ascend and the adiabatic lines will descend from the colder mass to the warmer one. The T–θ solenoidal distribution in a cross section of the atmosphere will determine the location of an upper front, or any discontinuity; and a measure of the potential energy of mass distribution in the system can be obtained at the same time.

Figure 6 shows a cross section of the atmosphere between Cheyenne and Dayton, on March 19, 1936. The isothermic and isentropic lines are drawn, and it can be seen that the greatest density of solenoids is confined to the active frontal zones.

The preceding enumeration of various synoptic aids for the determination of upper cold fronts—winds aloft and at the surface, pressure change characteristics, pressure troughs at the surface and aloft, types of clouds and precipitation, surface temperature distribution, density-altitude relations on successive days—is not to be interpreted to mean that any one of these to the exclusion of others is to be considered conclusive evidence for the presence of an upper front. Because of the complex relations that may arise from the juxtaposition and interaction of air masses, any one or even several meteorological factors characteristic of one situation may show great similarity to those associated with another situation of entirely different origin. For this reason it should be emphasized that all the conditions enumerated must be considered together, that any one or several indications may be necessary but not sufficient conditions to demonstrate the presence of an upper cold front, that all inductions must, of course, be consistent with the historic sequence of the meteorological situation.

Forecasting significance.—In late spring, summer, and autumn the weather phenomena resulting from upper cold fronts are relatively unimportant as far as airline transportation is concerned. Almost invariably one can forecast that all ceilings and visibilities will remain ample. Frequently a variable broken to overcast alto-cumulus with little or no precipitation will accompany the front. The surface visibilities will, of course, be somewhat impaired during any precipitation, but usually will range from 3 to 8 miles.

During summer and early autumn when the advancing upper wedge comes in contact with a T_M (Tropical Maritime) air mass characterized by conditional or convective instability, high level thunderstorms are usually developed. The mechanics of these high-level storms is not different from the case of a simple surface cold front coming in contact with a T_M mass and causing sufficient ascent to realize the potential instability of the Tropical current. It is quite possible that thunderstorms may develop in the advancing upper wedge itself, as described elsewhere, provided, of course, that the temperature and humidity structures are proper.

The cumulus clouds that accompany the high level thunderstorms have bases generally between eight to twelve thousand feet, with the maximum convective activity probably occurring well above 18,000 feet. These thunderstorms offer no difficulties to aircraft travel, as flight can be negotiated well below the cumulus clouds, and moderate turbulence with an occasional heavy shower are the only disagreeable elements to be expected.

The various cloud types, and the "between layer" flying possibilities have been described elsewhere for the winter case. (See fig. 1.) However, it is well to emphasize the suddenness with which precipitation can materialize in advance of the upper cold front. This is in sharp contrast with the generally clear sky condition that prevails at some distance behind the upper front. In the initial stages of the warm-front type of occlusion no indication of precipitation may be obtained from westward-lying stations, and a correct forecast can be made only from a recognition of the upper front.

Although a minor surface pressure trough generally accompanies the eastward march of the upper cold front, a very pronounced low pressure aloft may be associated with the front. The intensity of the pressure gradient aloft will in turn bring about a significant increase in the velocities of the winds aloft, and winds of 60 to 70 miles per hour between 9,000 and 15,000 feet may be found.

The weather resulting from an upper cold-front situation in winter occasionally presents a serious icing hazard

[8] Bjerknes, V.: Das dynamische Prinzip der Zirkulationsbewegungen in der Atmosphäre. *Meteorologische Zeitschrift*, p. 97 and 145, 1900; also p. 97, 1902.

[9] Bergeron, T.: Über die drei dimensional verknüpfende Wetteranalyse. *Norske Videnskaps-Akademi Geofysiske Publikasjoner*, vol. 5, no. 6, 1928.

to aircraft. This condition can best be illustrated by contrasting it with the icing hazards during a surface warm front situation. In the winter case of a simple warm front, where relatively warm moist southwesterly winds are advancing aloft over a wedge of very cold Polar air, the precipitation usually begins as snowfall. During this incipient stage, aircraft will experience no great difficulties other than the loss of power occasioned by the use of heat to prevent icing in the carburetor. As the warm front action continues, with the consequent modification of the Polar air to higher temperatures, a serious icing stage is reached when the precipitation from the alto-stratus begins as rain and on descent proceeds as a freezing rain. This hazardous stage may continue for from 8 to 12 hours, and by then the Polar wedge either has receded sufficiently or has become so modified that the temperature of precipitation is well above the freezing point. Moreover, in this warm front condition it is quite likely that in spite of the fact that the precipitation is freezing in the Polar wedge, a sufficient temperature inversion prevails aloft in the Tropical air for a rapid ascent through the Polar current to permit only a very slight accumulation of ice.

On the other hand the icing hazard that accompanies an upper cold front may cause considerable doubt as to the safety of navigation through the frontal zones. The advancing wedge aloft is generally warmer than the surface Polar mass, but will have only a small modifying effect upon the wedge below. This is because the air mass aloft is generally of Polar origin itself. It is also unlikely that any significant temperature inversion is present above the surface Polar current. In addition, an "on top flight" is excluded because of the extreme thickness of the alto-stratus that merges with the lower cloud systems in advance of the upper front. Once the temperature condition is such as to permit a mixed snow and rain to fall from the alto-stratus, the icing hazard can become indeed serious.

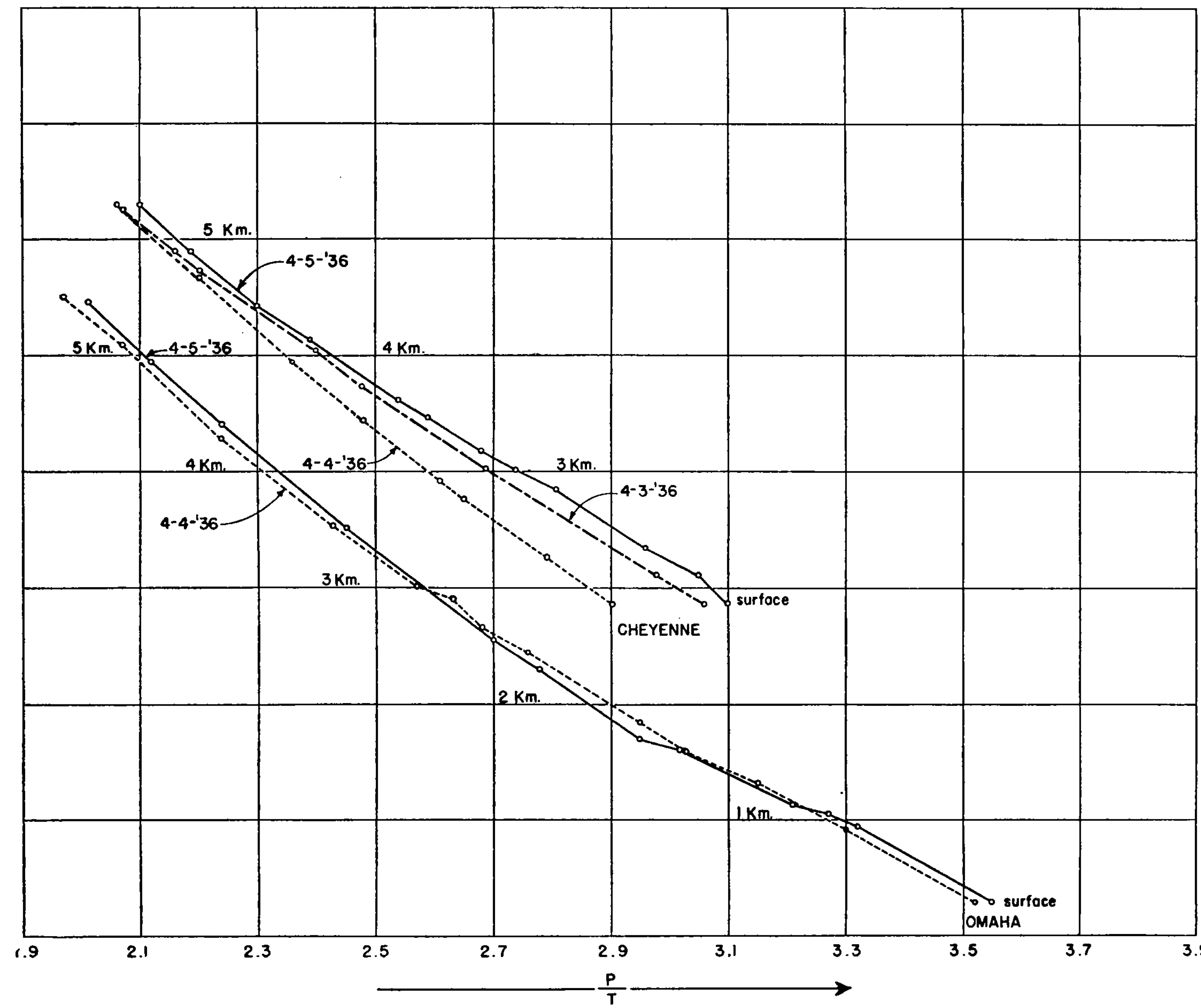


FIGURE 11.—Density-altitude curves; P/T in mb/°A, altitude in km.

When the upper wedge interacts with T_M air, icing conditions seem to be confined to the cloud system within the Tropical current. This conclusion is based upon evidence furnished by a number of pilots of American Airlines, Inc.

Three meteorological situations have been selected and are briefly described below. These synoptic examples have individual complexities and some analytical difficulties, but nevertheless are quite representative. In figures 5, 9, 10, and 12, in which the individual situations are represented, the solid line represents the cold front, the dotted line the warm front, the dashed line the cold front aloft, and the dot-dashed line the occluded front. The wind arrows fly with the wind and each bar indicates two units of wind force on the Beaufort scale. The meteorological observations are generally grouped so that the temperature and the dew-point are to the upper right of the station; pressure directly under the temperature; precipitation, if any, under the pressure; ceilings in hundreds of feet to the upper left; visibility directly under the ceiling; and pressure tendency below the station.

March 19, 1936.—The most frequent type of upper cold front appears as a P_P front aloft in the Middle West when the central and eastern portions of the country are occupied by fresh P_C air. An interesting situation of this type, illustrating both an upper cold front and a cold front type of occlusion, occurred on March 19, 1936. The surface conditions are represented in figure 5, and an east-west cross section through the atmosphere in figure 6.

An upper cold front, outlining the boundary of a transitional type of P_P air, is present between Scott Field and Wright Field, and is advancing over a shallow wedge of P_C air. A fresher surge of P_P air is indicated by the cold front between Omaha and Scott Field. This front is proceeding eastward and is displacing the shallow layer of return P_C air as a cold front type of occlusion, because the active P_P air mass is of the greater density.

The density relations for this synoptic situation completely verify the indicated conditions. Figure 7 shows the density curves for Omaha, Scott Field, and Wright Field. The air mass at Omaha on the 19th has a much greater density, level for level, than the air column that was present there on the 18th. This necessarily indicates a surface invasion by a Polar air mass, and is represented by the outbreak of fresh P_P air. The density curves for Scott Field on the 18th and 19th illustrate the singular crossing of the curves which is characteristic of the passage of an upper cold front. The upper cold front passed Wright Field between the 19th and 20th; and these curves, similarly, show the peculiar crossing.

The density relations for Omaha, Scott Field, and Wright Field on the 19th are illustrated in figure 8. It can be seen that in the lower levels the Omaha curve shows a denser mass of air than the curve for Wright Field;

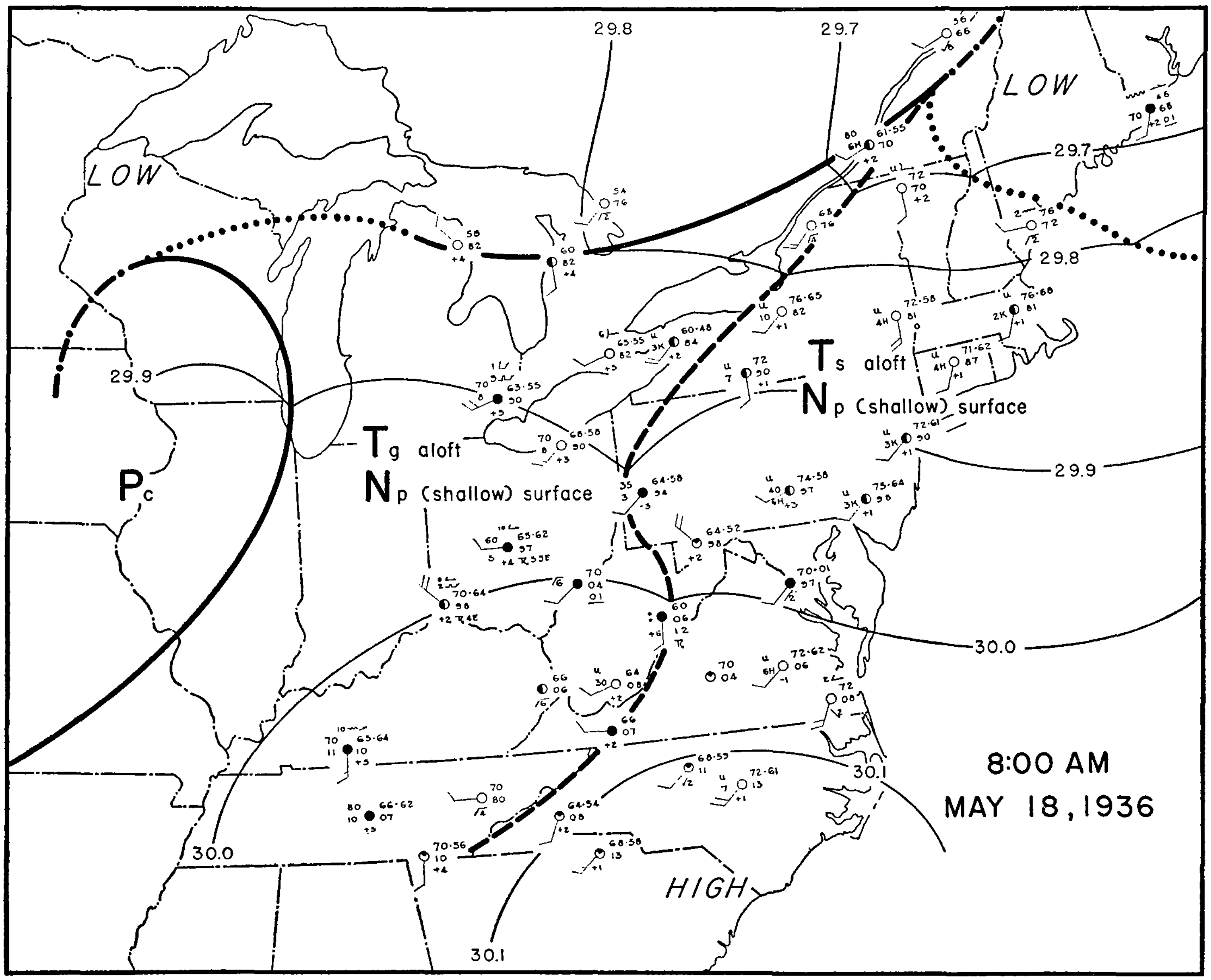


FIGURE 12.

and one of them must pass through the St. Louis area as a surface invasion. However, the air at Omaha below 800 meters is less dense than at the corresponding levels of the Wright Field curve, and thus indicates a possibility for the active P_P mass to occlude in the warm front manner by the time the air mass has invaded the Dayton area; but this possibility has to be substantiated by data at some later stage, for it is more than likely that at the time the P_P air is ready to invade the Dayton area, the dense layer of P_C air may have become sufficiently modified to be actually less dense than the advancing P_P air, and thus preclude the possibility of a warm front type of occlusion. The lower levels at Scott Field have a less density than the corresponding levels at Wright Field. This immediately eliminates the possibility of any surface cold front advancing into the Dayton area from the St. Louis area; and necessarily implies that as long as the indicated density relations prevail at these two stations, all air mass invasions must occur aloft.

No significant weather phenomena resulted from the upper cold front on the 19th; but on the 20th, a good deal of precipitation occurred, although the situation was then complicated by the advance of the cold front type of occlusion.

April 4 and 5, 1936.—Figures 9 and 10 show the 8 a. m. synoptic situations for April 4 and 5, 1936. On the 4th an upper cold front, marking the advance of N_{PP} (Modified Polar Pacific) air aloft over a dense wedge of P_C air, is oriented in a north-northeast to south-southwest direction through the Middle West. The front is particularly well-defined by the pronounced pressure change discontinuity that extends along the length of the front. To the east of the upper front, drops of 8 to 12 hundredths in 3 hours prevail; but immediately to the west of the front, drops of only 2 to 6 hundredths are generally found. A cold front marking a surface outbreak of fresh P_C air is present through the Dakotas and Nebraska, and it is interesting to note that no precipitation is taking place along the wind shift. However, in advance of the upper cold front, snow has developed throughout Wisconsin and Iowa and a rapid lowering of the ceilings has taken place.

On the 5th the upper front had advanced eastward, then extending through Michigan, Indiana, Illinois, Missouri, and Arkansas. The P_C cold front had actively

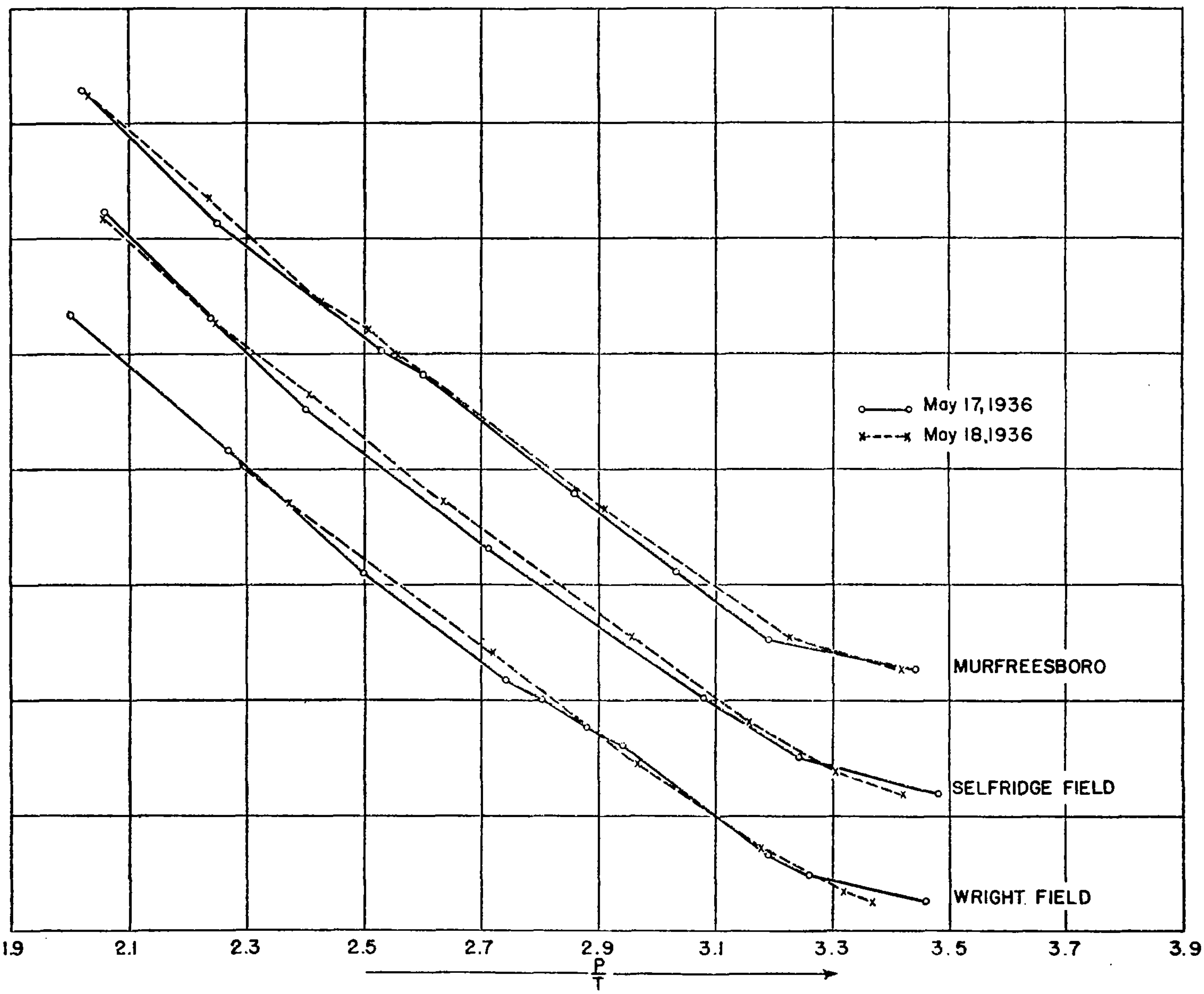


FIGURE 13.—Density-altitude curves; P/T in mb/°A, altitude in km.

advanced southeastward, and numerous snow squalls occurred within the air mass.

The density relations for Cheyenne and Omaha are illustrated in figure 11. The soundings at Scott Field, which would have been particularly interesting for this situation, were unfortunately not made, because of adverse flying conditions. However, the density curves for Cheyenne indicate less dense air on the 4th than had occupied the station on the 3rd. Some indication of the advance of the P_c air aloft is given by the fact that the slopes of the curves on the 3rd and 4th are such that the intersection occurs near the 5 km level. The hypothetical picture in figure 3D best illustrates these density relations. A very deep current of P_c air invaded Cheyenne on the 5th, and the density curve for that day shows the the greatest density, level for level, of the 3 days.

The density relations for Omaha on the 4th and 5th are especially significant. Denser air below 1,100 meters on the 5th indicates the depth of the P_c current. Between 1,100 and 3,000 meters the current becomes less dense than the air that prevailed at these levels on the 4th. Above 3,000 meters denser air on the 5th again prevails, compared with the corresponding levels on the 4th. This crossing of the density curves aloft is peculiar to the passage of the upper cold front and justifies the conclusion as to its presence.

May 18, 1936.—This situation was brought to the writer's attention by Warren Vine of American Airlines, who, flying from Murfreesboro to Washington between the hours of 1 p. m. to 5 p. m., encountered "a line of high level thunderstorms over the mountains." The line of storms advanced regularly eastward with a velocity comparable to that of the winds aloft. The bases of the cumulus clouds were generally above 8,000 feet, and lower clouds were encountered only during showers.

The synoptic situation is represented in figure 12. An upper cold front is present and virtually parallels the Appalachian chain. The interesting feature about this situation is that the upper front marks the advance of T_G air as a cold front. This condition frequently obtains when T_G air comes in contact with T_S air. The Maritime air is riding aloft over a very shallow thickness of highly modified P_c air, and is displacing T_S air that prevails aloft over the narrow wedge of old P_c air. During the day the air masses to the east of the upper cold front became considerably heated, and as the T_G air invaded the region a very unstable condition was produced. High-level thunderstorms developed during the afternoon with the advance of the upper front, and continued to accompany the front as it passed off the coastal regions during the evening. The storms developed in the advancing T_G air, as the T_S air was much too dry to produce any thunderstorm activity.

Figure 13 shows the density relations on May 17 and May 18 for Selfridge Field, Wright Field, and Murfreesboro. The curves are not as distinctive as one might desire; but the fact that all three stations show the advance of slightly denser air aloft, compared with that which prevailed at the same levels on the 17th, furnishes significant evidence of an upper cold front. The very shallow wedge of old P_c air is shown on the curves for the Selfridge Field and Wright Field soundings. At approximately 500 meters the curves intersect each other, indicating that below this level the advancing air on the 18th was less dense than the air on the 17th.

For all practical purposes the T_G cold front in this case may be considered as a surface front; but it is to be pointed out that surface information does not clearly define the front, and this example is a good illustration of the applicability of aerographic soundings to synoptic analysis.

ACKNOWLEDGMENTS

The writer wishes to acknowledge his indebtedness to American Airlines, Inc., under whose employment this study was begun; to Warren Vine, John Pricer, Walter Hunter, and many other pilots of American Airlines, Inc., whose helpful observations furnished data to analyze difficult and complex situations involving upper cold fronts; to A. B. Bowman, N. D. Garrow, and W. E. Pereira, meteorologists of American Airlines, for their kind assistance in the calculations and plotting of soundings and preparation of the synoptic charts; to H. R. Byers, S. Lichtblau, and H. Wexler, of the Meteorological Research Division, U. S. Weather Bureau, for their helpful discussions and kind cooperation. He is especially grateful to Dr. Byers for invaluable criticisms.

UPPER-AIR COLD FRONTS IN NORTH AMERICA

By STEPHEN LICHTBLAU

[Weather Bureau, Washington, December 1936]

Fronts aloft have long been recognized, but until recently very little attention has been given to them. In the United States much of the weather, especially in the colder months, is governed by such fronts as well as by surface fronts. Although as many different types of fronts may exist aloft as at the surface, we find that of the three types of fronts—namely, cold, warm, and occluded—only the cold front has much significance aloft, and it is by far the easiest to locate. Warm fronts aloft may occasionally be located when they are accompanied by well defined synoptic phenomena; but usually the meteorological elements, with the exception of precipitation, indicate gradual changes rather than the abrupt changes found with the passage of cold fronts aloft.

Occluded fronts are identified as such from their past history, if possible, or with the aid of airplane soundings; the soundings should show a trough of warm air in advance of the cold front aloft. However, many of the fronts designated as cold fronts aloft may in reality be occluded fronts aloft, since in many cases the history of such fronts moving eastward across the Pacific, where few reports are available, is quite vague. Furthermore, if there is a trough of warm air associated with the cold front aloft, it may neither be apparent in cloud and precipitation forms nor fall within the network of airplane sounding stations; but occluded fronts aloft are in most cases so high that no significant error will ordinarily accrue if such fronts are designated as cold fronts aloft. The following discussion is therefore limited to upper air cold fronts.

FORMATION

Cold fronts aloft may in most cases be traced back to surface occlusions of the warm front type. One exception occurs with frontogenesis aloft above a shallow polar current, usually of continental origin. The considerations for frontogenesis are as applicable aloft as they are on the surface.[1] Another exception of a more complicated nature occurs as a development in the advance portion of a deep polar current, in the form of a steepening of the slope of the polar wedge at some distance behind the

[1] Petterssen, Sverre: Contribution to the theory of Frontogenesis, Geofysiske Publikasjoner, vol. XI, no. 6.