ALTITUDES OF THE BASES OF LOWER CLOUDS AS DETERMINED FROM KITE AND BALLOON OBSERVATIONS.[1]

551.576 : 629.132.1

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SYNOPSIS.

The altitudes at which kites and pilot balloons disappeared into bases of clouds on 5,500 occasions at United States Weather Bureau stations in the United States east of the Rocky Mountains are plotted in the form of frequency diagrams. When grouped together without regard to the name given by the observer, these observations show but one altitude of maximum frequency, at 350 to 400 meters above the ground, the same as for stratus clouds. The bases of strato-cumulus were most frequently at 750 to 1,050 meters above the ground; and those of cumulus between 1,000 and 1,700 meters. No difference was found between the northern and the southern groups of stations.—*C. F. B.*

It is primarily the purpose of this paper to present graphically, with a brief discussion, the results of some special studies made by the writer on the altitudes of maximum frequency of cloud bases, as determined largely from kite flights and pilot balloon ascensions.

LEVELS OF MAXIMUM AND MINIMUM CLOUDINESS.

According to the international system of cloud classification, and from a great many measurements of the heights of the different forms, certain average and limiting heights of each type have been found,[2] and these average altitudes have been grouped into five levels of maximum cloudiness. H. H. Clayton,[3] in his studies of cloud heights at Blue Hill Observatory, gives the following as average altitudes for these five levels: Stratus, 500 meters; cumulus, 1,600 meters; alto-cumulus, 3,800 meters; cirro-cumulus, 6,600 meters; cirrus, 8,900 meters. Nimbus is included with the stratus, strato-cumulus with the cumulus, strato-cumulus with the alto-cumulus, cumulo-nimbus base with cumulus and top with cirrus, and cirro-stratus with cirro-cumulus and cirrus.

Humphreys[4] states that "When the frequency of clouds is tabulated with reference to elevation, maxima and minima are found with the layers to which they obtain growing thicker with decrease of latitude." In the same work he discusses five principal levels of maximum cloudiness together with the four intervening regions and the isothermal region beyond, of minimum condensation.

These levels of maximum condensation are fog level, from the surface to an altitude of seldom more than 100 to 200 meters; cumulus level, foul weather type, commonly 1 to 2 kilometers above the surface; cumulus level, fair weather type [alto-cumulus] 3.5 to 4 kilometers above the surface; cirro-stratus level, at about 8 kilometers; and the cirrus level, average elevation in middle latitudes about 10 kilometers.

Regions of minimum condensation are scud region, between the fog level and the lower or foul weather cumulus level; the intercumulus region, from 2.5 to 3.5 kilometers; the alto-stratus region, from 4.5 to 6.0 kilometers; the intercirrus region, from 8.5 to 9.5 kilometers; and the isothermal region, beyond an altitude of about 11 kilometers in middle latitudes.

CLOUD DEPTH OR THICKNESS.

While there have been a great many measurements of cloud heights by various methods, the greater portion of such measurements have been to determine the height of the cloud base. While it is known that the thickness of clouds varies from the 8 or 10 kilometers of the most towering cumulo-nimbus, usually associated with a violent hail storm, down to that of a vanishingly thin cirrus, systematic measurements of cloud thickness have not been numerous, owing to the difficulty with existing methods.

Although the ideal conditions of no vertical air currents probably seldom obtain, it is believed that in temperate latitudes during all seasons, except the hottest hours during summer days when excessive local heating over land surfaces gives rise to strong vertical circulation, the vertical components of the atmospheric circulation will be relatively small in comparison with its general horizontal components; and, under such average conditions the foregoing ascensional rate formula may be generally depended upon to give values to an accuracy of about 5 per cent.

Unfortunately, for the present study, vertical currents usually do accompany clouds of all types, and are predominant in connection with the cumulus type. This will give rise to strong local convectional circulation, which is liable to introduce very large errors when the ascensional rate formula is used in calculating altitudes of such clouds from single theodolite observations on pilot balloons. On the average, however, from a long series of observations, the mean values so deduced for altitudes free from strong vertical currents must be somewhere near the actual values.

Altitudes from the disappearance of kites.—Of the two general methods for determining altitudes by means of kite flights, only the method of simultaneous theodolite readings of the angular altitude of the kite and the length of wire out at the moment of its disappearance in cloud base is used in actual computations, according to the equation, $H=s\ (\sin\ \phi)$, where H represents the cloud height, s the length of wire out, and ϕ the angular altitude of the kite. From this computed value of H, which is theoretically too high, 2 per cent is deducted.

The "hypsometric" formula could be used by observing carefully the exact moment at which the cloud disappears and computing the pressure and its corresponding altitude at a point on the pressure trace on the kite meteorograph sheet corresponding exactly to the same time. But since it frequently happens that an error of a minute or more is introduced in the clock time-rate, it follows that the general accuracy of the results obtained in this way would be no greater, but probably less, than that attained by the other method hereinbefore discussed.

Altitudes from the disappearance of pilot balloons.—By means of the "ascensional-rate" formula,[5] $r=71\left(\frac{l^3}{L^2}\right)^{.208}$ where r represents ascensional rate in meters per minute, l the free lift, and L the total lift, the altitude can readily be determined directly from the formula, or from curves and tables made up from this formula. The product of the ascensional rate thus obtained and the minutes elapsing between the time of the balloon's release and that of its disappearance in the cloud base gives the altitude of the cloud base in meters. As previously explained, the accuracy attained by single theodolite observations of pilot balloons and computations thereof

[1] Presented before the American Meteorological Society, Washington, D. C., Apr. 22, 1920.
[2] See table reprinted in Mo. Weather Rev., Sept., 1920, 48: 511.
[3] Discussion of the cloud obsrevations. *Ann. Astr. Obs. Harvard Coll.* 1896, vol. 30, pt. 4, pp. 271-500, 18 plates. Ref. to p. 341.
[4] Physics of the air. *Jour. Franklin Inst.*, 1918, pp. 643-646.

[5] Cf. Mo. Weather Rev., Apr., 1919, 47: 210-225, and Dec., 1920, 48: 692-697.

from the ascensional-rate formula is not considered nearly so great as that from kite observations. It must be remembered, however, in using a computed rate of ascent for pilot-balloon altitudes that there must be no vertical component to the atmospheric currents through which the balloon passes, and that for the formula used in the United States,[5] the balloon must be of the 6 or 9 inch spherical type.

DISCUSSION AND INTERPRETATION OF DATA.

A collection and systematic study of over 6,000 individual measurements of the altitudes of cloud bases from such kite and balloon observations as were obtainable at seven kite aerological stations and over twenty pilot-balloon stations located in various latitudes and longitudes throughout the United States east of the Rockies, some of short record and other extending over a period of more than five years, thus representing all seasons and all the varying conditions of wind, etc., have been made by the writer, and the results of such study are presented graphically in figures 1 to 8, inclusive, in this article.

In the scheme followed in plotting these data, the ordinates represent altitudes of the cloud bases and the abscissas represent the frequency, or number, of cloud bases observed at each altitude. It may be remarked that the altitudes can be accurately represented only to the nearest 50 meters. But this perhaps is a trifling discrepancy as compared with possible errors due to the best methods of measurement now in vogue, since it often happens that a kite or balloon is observed for some time after it actually reaches the lower portions of the cloud before it completely vanishes from sight. This would of course introduce an additional error. From a great many observations, however, during all conditions of weather that would permit such observations, it is quite probable that many of those irregular errors would balance one another in the long run, and the summation of the final results of such observations would be fairly representative of average conditions.

Various schemes of grouping these data have been adopted, some in accordance with long established principles of grouping according to special types of clouds, seasons, and latitudes; while, again, other methods have been adopted quite different from the customary treatment of such data. But the primary object of all these studies is to ascertain whether several regions, or levels, of maximum and of minimum cloud frequency, or condensation, really *do* exist, as usually accepted, or *do not* exist, as contended in 1918 by C. F. Brooks from unpublished observations made in Texas;[6] and, if so, how many such distinctive levels there are, and what their average altitudes are. With this object in view some of the accompanying cloud charts were made by combining certain typical forms and omitting others, while others were made by utterly disregarding forms or types and charting all cloud forms together. The one shows in a general way whether there exist levels of maximum frequency for each particular group, and, if so, the average altitude of each; the other shows whether there be actual regions of maximum frequency of condensation, or cloud formation, for all forms regardless of type. This latter method appeals to the writer as the most logical one to determine whether there are in reality such regions of maximum and minimum frequency of condensation as have been assumed; for, if there be such regions, it is obvious, as the terms suggest, that all "condensations," regardless of the name given to the cloud formed, must be given equal weight. If we fail to give equal weight to all types, then we are not finding the regions of maximum or of minimum frequency of condensation in general, but merely the levels of maximum frequency for each particular cloud type under consideration. It is quite evident, therefore, that with any principle of cloud classification according to *form* and *altitude* we should expect to find certain levels of maximum frequency corresponding to the mean altitude obtained for each type or group; e. g., if we divide the number twelve into four successive parts of three units each and let these represent certain cloud forms classified according to altitude, we should very logically expect to find four separate values, each representing the mean of all the observed altitudes within their respective zones, and these average values would then most certainly appear as levels of maximum condensation; while the intervening regions, because less frequented by any one particular type, though possibly frequented by even a greater number of all types due to the overlapping, so to speak, of the characteristic types of adjacent vertical regions, would, nevertheless, according to such system of grouping be considered regions of minimum condensation. The crux of the problem really centers about the question of whether there is sufficient overlapping of the different types, peculiar to different altitudes, to compensate for the deficiencies on either side of the average level of each type, or what the effect of such overlapping of the different types.

THE CLOUD CHARTS.

Figure 1.—This figure represents the altitude at which each stratus or alto-stratus base was observed, at all seasons and all stations regardless of geographical location. The reason for adopting this particular scheme of grouping stratus with alto-stratus clouds should be obvious when we consider the striking similarity in the general appearance of these two cloud forms, and the common occurrence of different observers calling the same cloud different names. As a rule the stratus appears the denser of the two because it is nearer the observer and therefore intercepts more light, direct or scattered, from the sky. Moreover, it is quite probable that each type is formed essentially by the same processes. Evidently, then, the fundamental distinction between these two types is primarily one of altitude; and, since the estimation of altitude is always attended with considerable uncertainty, even by one skilled in cloud observations, it is not at all surprising to find unskilled observers recording stratus for clouds whose bases are afterward found to be 2,500 meters, and alto-stratus for clouds whose bases are below 1,000 meters. The International Meteorological Conference adopted the altitude of 1,000 meters as the line of demarcation separating these two types.

From an examination of this figure it will readily be seen that up to an altitude of 200 meters the frequency increases rapidly; gradually from 200 to 400 meters; then decreases quite rapidly to about 650 meters; somewhat gradually from 650 to 1,600 meters; then somewhat slowly and more or less irregularly up to the upper limits at which they have been observed. But while there appears to be no doubt as to the existence of a region of maximum frequency somewhere below 500 meters, with a rapid decrease above that level, the amount of available data is insufficient to justify any definite conclusions as to the rate of decrease above 1,600

[5] Cf. MO. WEATHER REV., Apr., 1919, 47: 210-225, and Dec., 1920, 48: 692-697.
[6] In manuscript lectures, Signal Corps School of Meteorology, July, 1918.

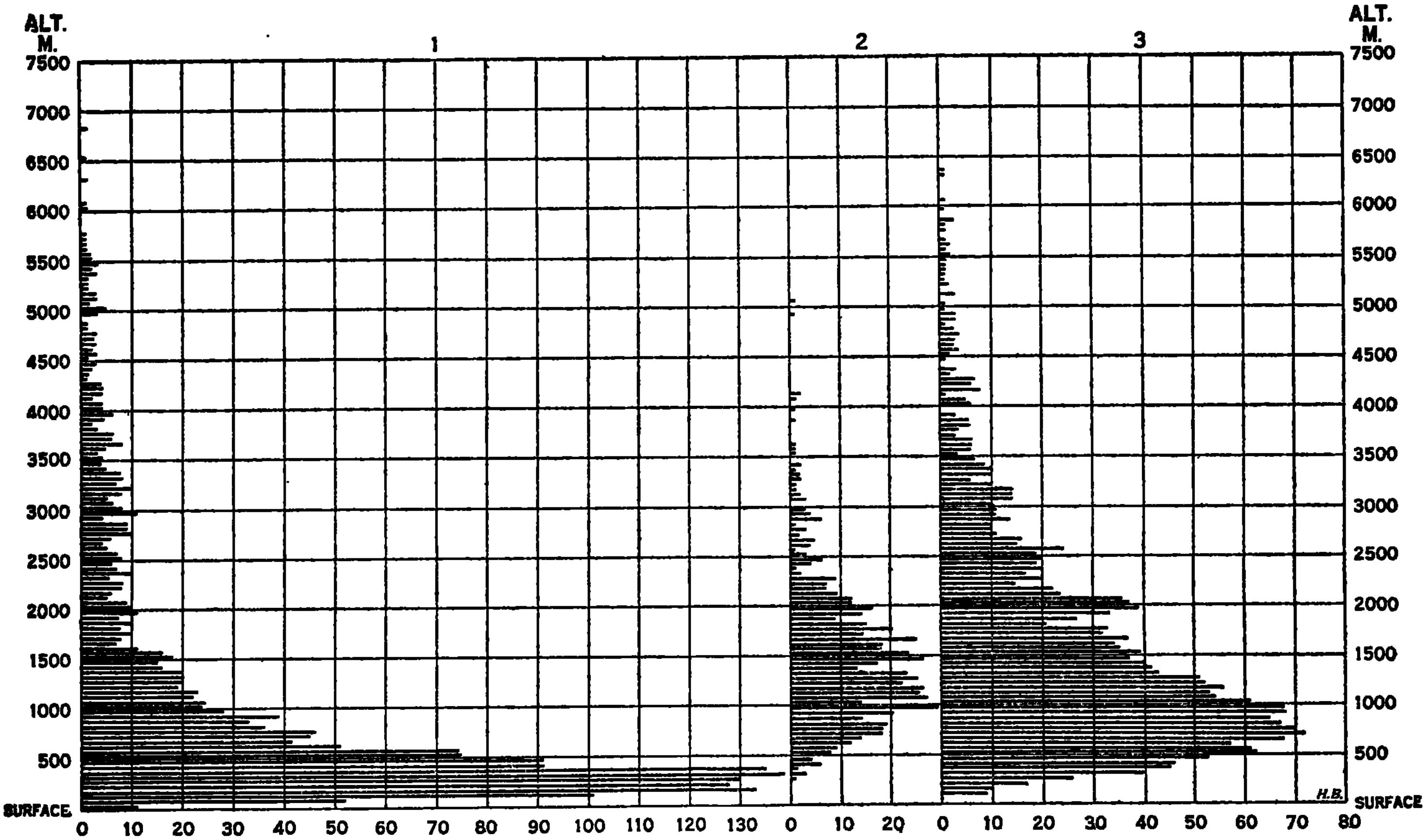
meters, or of the existence of alternate regions of secondary maximum or minimum condensation above this level. It is hoped that with future observations sufficient data of a more complete nature may be gathered to justify further conclusions in this regard.

The most salient feature brought out by figure 1 is that clouds of this type form at all altitudes from the surface to some high, upper limit, over 7 kilometers as shown here, and that any attempt to separate them according to altitude must therefore be impossible since such system of subclassifying them must necessarily be an arbitrary one.

Figure 2.—Since the cumulus and cumulo-nimbus types are quite distinct from all other cloud types, both in general form and appearance as well as in the causes and processes of their formation, they are therefore classified separately from their combination groups for charting. As before, in the case of the stratus and alto-stratus, all observations were grouped together in charting, regardless of season or of geographic location. As should most naturally be expected, the average "condensation level" at which these clouds are formed most frequently is found to be somewhat higher than that of the stratus type, ranging somewhere between 1,000 and 1,700 meters, with the slope of the frequency curve gradual above and below this level of maximum frequency. This feature agrees quite closely with the corresponding theoretical region that others have defined as a "level of maximum condensation."

Except in rare cases, where the cumulo-nimbus builds up massive, towering thunder heads, these clouds are found to exist principally below altitudes of 2,500 meters and almost entirely below 3,500 meters, the season being a chief determining factor, since relative humidity is dependent upon temperature for any given mass of air, and the temperature in turn is conditioned by seasonal changes. The methods of formation of both the cumulus and cumulo-nimbus are identical, due chiefly though not entirely to thermal convection.

Figure 3.—For the same reason that stratus and alto-stratus types were grouped together in figure 1, strato-cumulus and alto-cumulus types are grouped together in figure 3, including all observations during all seasons and in all geographic localities. The essential features that were brought out in figure 1 also appear in figure 3, viz, the rapid slope with increasing altitude to about 500 meters, followed by a gradual slope to a maximum somewhere between 750 and 1,050 meters, by a fairly moderate slope of 4,000 meters, and a gentle slope above. The salient feature of this chart, distinguishing it from figures 1 and 2, is that the region of maximum cloud frequency, or condensation, lies midway between those of the stratus and the cumulus types, as might logically be expected of the strato-cumulus type, as its name suggests. It thus appears that the theoretical region of minimum condensation between the stratus and the lower, or "foul weather," cumulus regions of maximum frequency is partly or quite wholly filled in by the blending or combination of these two types, and the hypothetical intervening region of minimum condensation between the stratus and cumulus levels has in reality no existence. Furthermore, the figure brings out quite clearly the fact that no intermediate gap due to minimum condensation exists between the so-called strato-cumulus and alto-cumulus



Frequency of cloud bases at different altitudes as determined from kite and balloon ascensions (all seasons, northern and southern stations):

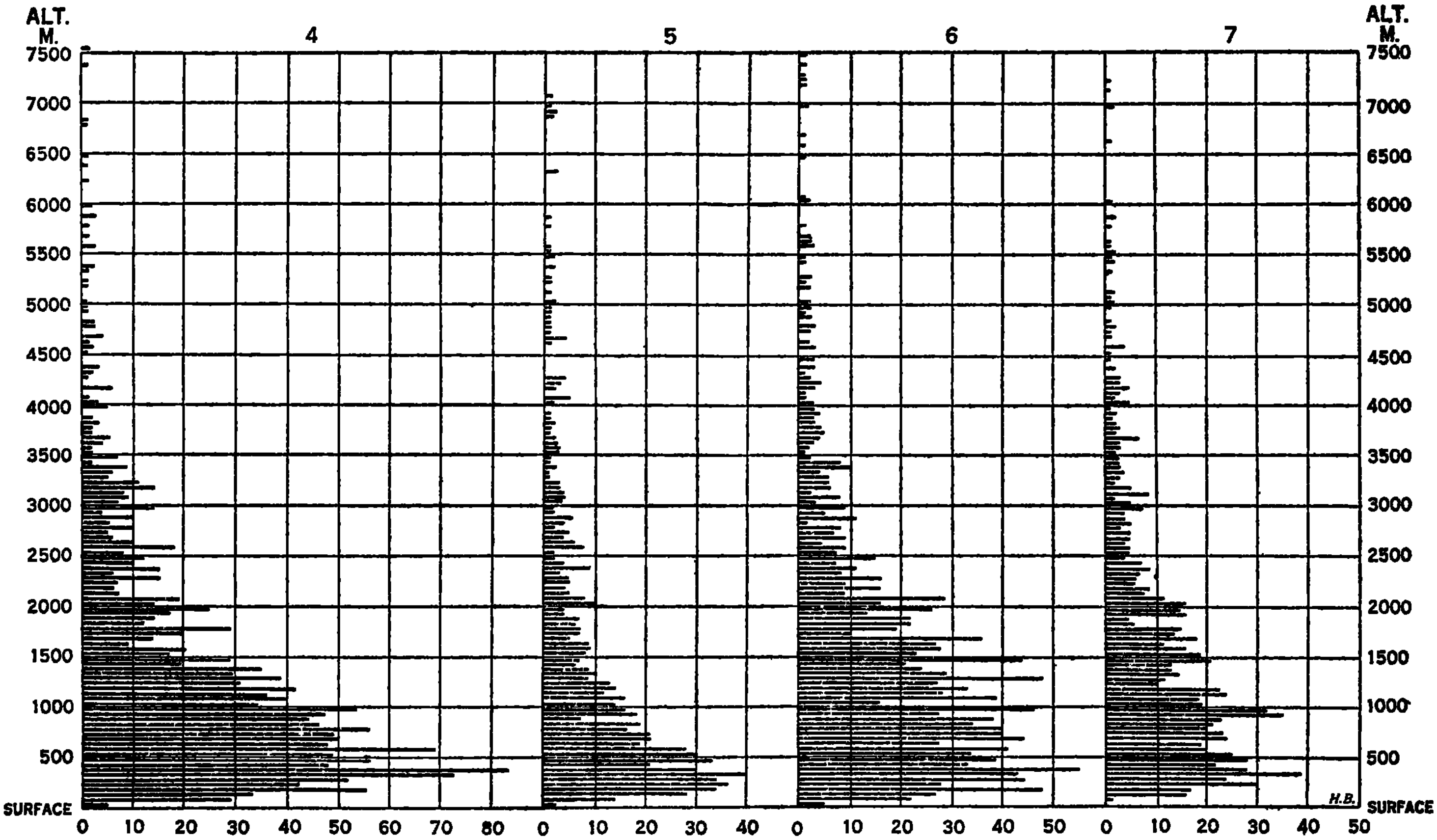
FIG. 1.—Stratus and alto-stratus. FIG. 2.—Cumulus and cumulo-nimbus. FIG. 3.—Strato-cumulus and alto-cumulus. (Ordinates represent altitudes in meters; abscissae, number of clouds observed.)

forms. This last feature would seem to indicate that the customary distinction between these two forms or types of cloud is based entirely on altitude, and therefore is arbitrarily made. It is a well-known optical principle, due to perspective, that the farther away any object is from the observation point the smaller it appears; hence, the alto-cumulus type, peculiar to fair weather and consequently higher altitudes, should appear smaller, as they do, and due to different relative distribution of light, they would appear more or less lighter and their blending of light and shadow more pronounced. These, indeed, are the chief distinguishing features between the alto-cumulus and the strato-cumulus types. It is not at all surprising, therefore, to find one observer calling a particular cloud A. Cu., and another calling the same cloud St. Cu., if we only bear in mind that different people estimate relative magnitudes as based upon apparent distance in a way to cause slight differences in the apparent diameter of the moon or other distant objects. In fact there is no sharp line of demarcation to distinguish the A. Cu. from the St. Cu. type, and the one gradually blends imperceptibly into the other type.

Figure 4.—Since the three preceding figures show different regions of maximum frequency corresponding to the different type forms, the question of there being regions of maximum frequency of condensation with alternate regions of minimum condensation when all the cloud types are considered simultaneously naturally enough presents itself for consideration. And if such theoretical regions do actually exist, at what average heights. Since it is also desirable to consider the varying influences of latitudinal and seasonal variation, it was decided to group all types with due regard to seasonal and latitudinal conditions. Accordingly, figure 6 represents such a grouping for all cloud forms observed during the winter half year at northern stations in the United States. This chart brings out the characteristic features of the foregoing charts, the level of maximum frequency being at an altitude of about 400 meters, corresponding to that of the most prevalent type of the season—the stratus. A notable difference, however, is to be observed in the more gradual slope of the chart in figure 4 above the level of maximum frequency. And again, this is exactly as might have been expected, since the strato-cumulus level of maximum frequency, a type common to the winter season, lies just above that of the stratus level.

Figure 5.—Precisely the same principle was followed in plotting this chart as in the preparation of figure 4, except that figure 5 consists of observations from stations in the southern latitudes of the United States, fewer in number and covering a somewhat shorter period of time. Although the number of observations from southern stations is comparatively small, the chart fails to show any increase in the average altitude of clouds with decrease in latitude, as is thought to be the case with the higher or cirrus types. While it is a generally accepted fact that, as observations have shown, the average height of clouds of the cirrus type increases with decrease in latitude, and also with the warm season, it does not necessarily follow that the same variation applies to the height of the lower clouds; furthermore, a comparison of figures 4 and 5 indicates quite conclusively that the same variation does not hold.

Figure 6.—Figure 6 follows the same scheme of grouping as figure 4, including all types for northern stations; but differs from figure 4 in that it includes



Frequency of cloud bases (all types) at different altitudes as determined from kite and balloon ascensions; winter (October to March, inclusive), summer (April to September, inclusive):

FIG. 4.—Northern stations. FIG. 5.—Southern stations. FIG. 6.—Northern stations. FIG. 7.—Southern stations. (Ordinates represent altitudes in meters; abscissae, number of clouds observed.)

only such observations as were made during the summer half-year. In contradistinction to the chart in figure 4, figure 6 shows a region of practically uniform frequency from 200 to 1,700 meters. This result is specially significant in that it indicates quite clearly that *the prevalence of the stratus, cumulus, and strato-cumulus types is about equal during the warmer season.*

is operative mainly during summer, over land surfaces at least. And lastly, the strato-cumulus type follows from the formation of the other types.

Figure 7.—In figure 7 the same principle was followed as in figure 6, plotting all cloud types observed during the summer season, but using only those data collected from southern stations. It is interesting to note that

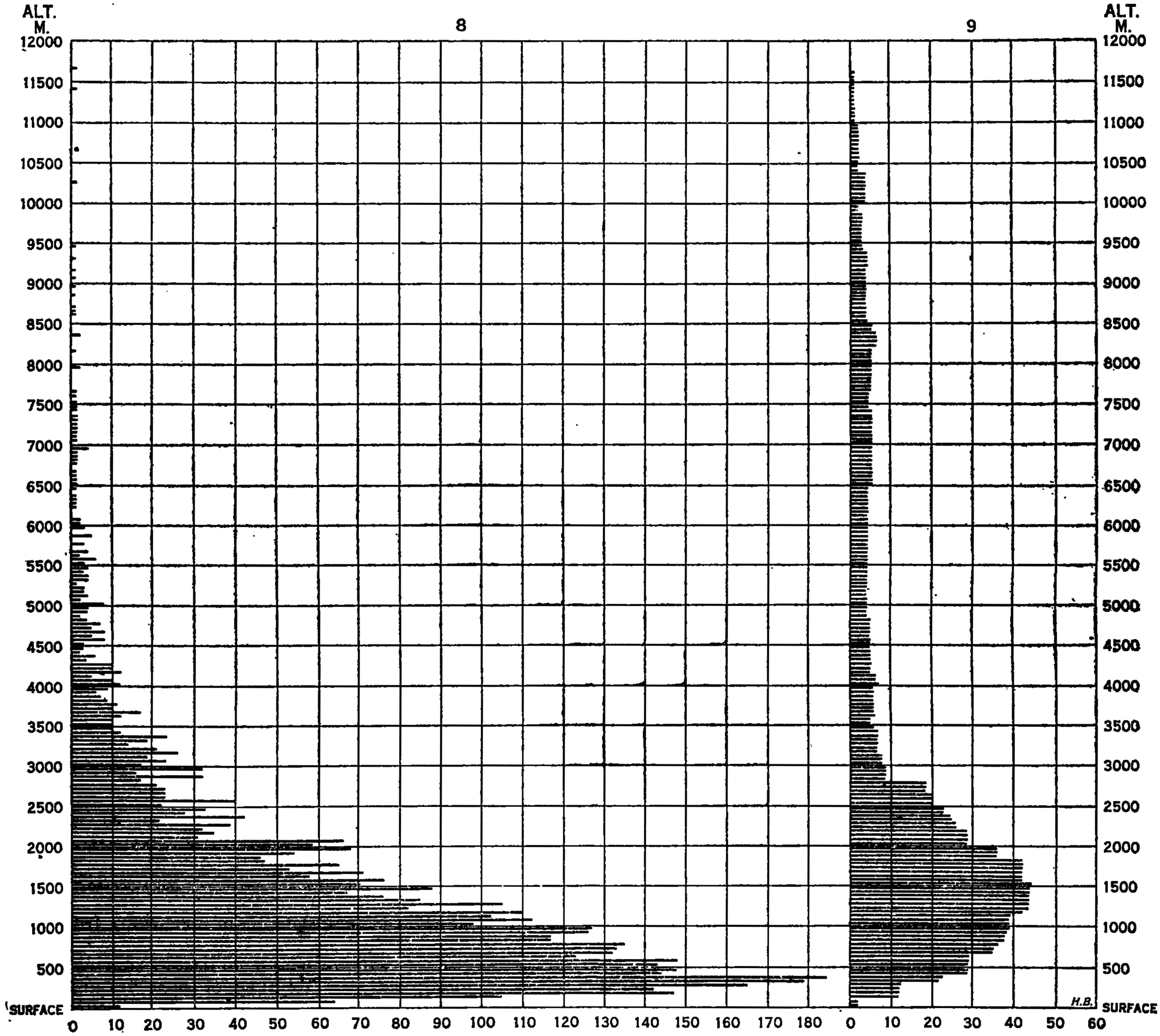


FIG. 8.—Frequency of cloud bases at different altitudes as determined from kite and balloon ascensions: all types of clouds, all seasons, northern and southern stations.
FIG. 9.—Frequency of clouds, as determined from double theodolite and other methods of observation, at Berlin, Upsala, Storlien and Blue Hill, for all types of clouds and all seasons. (Clayton, *loc. cit.*, p. 334.) (Ordinates represent altitudes in meters; abscissae, number of clouds observed.)

That this last condition is a perfectly reasonable inference is evident when we consider that the same processes that are supposed to be the chief processes of formation of the lower or stratus type are operative in summer as well as in winter, though perhaps to a somewhat less degree; while, on the other hand, the process peculiar to the formation of the purely cumulus type

the general features brought out by each chart are almost identical. Both show a deep stratum of practically uniform frequency between the limits of 200 and 1,700 meters, a comparatively rapid slope from 1,700 to 2,500 meters, and a gradual slope beyond 2,500 meters. As in figure 6, figure 7 also shows a comparatively equal frequency of the lower cloud forms. Another noteworthy and interesting feature is the fact that a comparison of figures 6 and 7 as of 5 and 6, shows no increase in the average height of maximum frequency with decrease in latitude. Comparison of figures 4, 5, 6, and 7 shows that the level of maximum frequency of the lowest cloud type occurs at about 350 to 400 meters above the surface, regardless of season or latitude, and that the same disregard to season or to latitude applies equally to the higher St. Cu. and Cu. types

Figure 8.—On this is charted over 5,500 observations of all cloud types during all seasons, and at widely distributed stations representing all latitudes and longitudes throughout that portion of the United States east of the Rockies. This chart is the nearest answer yet possible from existing data to the question of the average actual distribution of levels of maximum or minimum frequency of condensation. A cursory examination will show quite distinctly a level of maximum frequency in this group of observations, corresponding to the stratus level, at 350 to 400 meters. The more gradual slope above this level is due to the fewer cumuli and their higher levels. It might therefore seem from this that there actually exists only one level of maximum frequency of condensation, corresponding to that of maximum frequency of the stratus cloud base, and that, consequently, the regions on either side are regions of decreasing cloudiness, or condensation.

Figure 9.—This chart represents a departure from the other cloud charts in that the data made use of in constructing figure 9 were gathered from observations partly from European stations, grouped regardless of cloud type, season, or geographic location, as in figure 8; but, unlike figures 1 to 8, they show only mean values between small, though arbitrarily selected limits. These data, however, as used by Clayton in his cloud studies,[7] show substantially the same general features as figure 8, with the single exceptions that the level of maximum frequency is somewhat higher than that shown by figure 8, and owing to the far greater number of observations of higher clouds (in the cirrus region), there appears to be a region of maximum frequency somewhere within the limits of 6,500 and 8,500 meters. Thus far, then, this chart agrees more closely with the theoretical regions of maximum and minimum condensation to which numerous references have been made. But even this fails to indicate two regions of maxima corresponding to the so-called "foul-weather" and "fair-weather" cumuli, with the consequent "intercumulus" region of minimum condensation.

CONCLUSION.

It must be admitted that the theoretical distribution of maximum and minimum condensation in the main seems logical and, in spite of *frequency* alone not showing them (frequency × amount of cloudiness), which has not been considered here, would probably prove its correctness.

From a cursory inspection of the foregoing cloud charts and a hasty consideration of the interpretation thereof, one might arrive at the conclusion that such charts furnish conclusive evidence that only one appreciable region of maximum frequency of condensation actually exists in the upper air, and that the region on either side is one of decreasing condensation. Indeed, this view seems quite tenable. But, in the light of the meager data available, and of our very inadequate methods of procuring thorough and reliable observations at all altitudes simultaneously and in all conditions of weather, such a conclusion may not be considered as final. There are many substantial reasons which compel us to suspend judgment for the present at least, and to await future development of new and more complete methods of cloud measurement:

(1) Our measurements of clouds refer mainly to their bases. Few measurements of cloud thickness or of cloud density have been made, owing to lack of convenient methods. Since, therefore, our present knowledge of these interesting conditions is extremely meager, and since, too, the level of maximum density would not necessarily be at the cloud base, the association of cloud base and "level of maximum condensation" is unwarranted and most likely erroneous; for a complete observation would include thickness or depth of clouds in order to locate the regions of maximum condensation.

(2) Kite flights never reach into the cirrus levels, and not very frequently do they penetrate the higher alto-stratus and alto-cumulus levels. Practically all our observations of these higher cloud forms have been made with balloons, and it is not very frequently that a pilot balloon can be followed till it reaches these higher (cirrus) regions. So these handicaps to the measurement of all the higher cloud forms prevailing at the time of observation would tend to show a minimized prevalence of upper clouds as compared with the lower types.

(3) As is self-evident, when the sky is overcast with lower clouds the kite and pilot balloon methods of measurement fail to enable us to observe the higher forms simultaneously with the lower, or to ascertain whether there exist simultaneously alternate intermediate regions of relatively dry air between the upper and lower cloud strata.

(4) It is obvious that our cloud charts as they now stand do not prove or disprove conclusively that more than one region of maximum condensation exists; nor can we hope to get much nearer our goal until some more satisfactory method is inaugurated for observing all clouds regularly and simultaneously, that happen to exist at the specified times of such observations, which should be sufficiently distributed equally to include all types. We can only draw our own personal inferences from what we have before us, and this is left to the reader. They do, however, seem to justify the conclusion that at least one, and possibly two, regions of maximum *frequency* of condensation exist.

Moreover, the observations seem to establish the fact quite conclusively that neither latitude nor season produces any appreciable change in the average altitude of the lower clouds, as is supposed to be the case with the higher clouds.

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THE VERTICAL EXTENT OF CLOUD LAYERS.[1]

By W. PEPPLER.

[Abstracted from *Meteorologische Zeitschrift*, January, 1921, pp. 18–21.]

This paper is a continuation of the discussion of measurements upon clouds at Lindenberg, covering a period of 11 years of observations with kites and captive bal-

[7] *Ibid.*, p. 334.

[1] *Die vertikale Erstreckung der Wolkenschichten und die Wolkenlagen über Lindenberg.*