SUMMER AIR MASS INSTABILITY

AND ITS SYNOPTIC REPRESENTATION

by

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I. INTRODUCTION

There is a type of phenomenon that occurs in Nature which may be described abstractly as a surge from an unstable state to a more stable state, a process which tends always to achieve a minimization of the potential energy of the system undergoing the "surge reaction". It is possible to interpret all spontaneous activity in Nature in terms of such surges towards stability, and such an interpretation has long been placed on a class of meteorological disturbances usually referred to as "instability phenomena". During the summer months, when cyclonic activity and frontal passages are characteristically weak and infrequent, such instability phenomena assume major importance in determining the nature of the weather experienced over most of the United States; for "the weather" of that season consists principally of the air-mass thundershower and its precursor, the cumulus cloud of deep convection, each of which may be interpreted as a means to Nature's end of attaining a stable state of minimum potential energy in every system, a state which is never completely achieved in the atmosphere because of the diurnally recurrent accretions of potential energy resulting from insolational heating at the surface.

In the system which commands the attention of the weather forecaster it is the potential energy of atmospheric mass distribution in the earth's gravitational field that must be studied if the times and places of occurrence of these surge processes (convective phenomena) are to be predicted. The necessary information concerning the mass distribution in a vertical column of the atmosphere at a given time and place is obtainable from the pressure, temperature, and humidity observations made throughout that column by means of a sounding balloon; so it is to the results of such observations that the forecaster turns in attempting to discern regions whose air-mass instability suggests most strongly the imminence of convective activity. The solution to the summer forecast problem being so dependent on the problem of ascertaining the state of stability of the free atmosphere and the nature of its moisture distribution, it becomes necessary to utilize to the utmost the upper air data afforded by the present network of radiosonde stations. Although no truly new information can be obtained by altering the <u>mode of representation</u> of this valuable aerological data, nevertheless the efficiency with which pertinent information is conveyed to the mind of the forecaster depends greatly on the method of presentation. The conventional plot of an individual sounding on an adiabatic chart is most effective only as long as a small area is to be studied. When stability and humidity conditions must be known for an extensive area of operations then a station-by-station study of the upper air data is a rather primitive method of trying to obtain a clear picture of the stability and humidity fields over the entire forecast area and more effective means of correlating this information must be devised.

This paper describes some investigations conducted in an attempt to develop and evaluate more effective modes of representation of this upper-air data so important in forecasting summer convective phenomena, and comments on several problems that arose in the course of the interpretation of the results of the statistical evaluation.

II. REPRESENTATION OF THE STABILITY-HUMIDITY FIELDS OF THE ATMOSPHERE.

1. The stability and humidity fields of the lower troposphere are of critical importance in determining the distribution of air-mass convective activity, so

it is for these fields that some effective and convenient method of representation is to be found.

Consideration of the manner in which convective cells are generated leads to the conlcusion that it is the layer from about 3-4,000 ft. up to about 15,000 ft. that must be analysed most carefully for its cloud-forming potentialities. At lower levels daytime surface heating and frictional effects tend to make all observations non-representative; at heights above 15,000 ft. the stability-humidity field will have but little to do with occurrence or non-occurrence of convective disturbances.

Briefly the method of representing the stability-humidity field of such a layer is as follows: First some numerical measure of the stability of the atmospheric column at each sounding station is decided upon (e.g., difference in temperature between top and bottom of the layer), this number is computed for each station, plotted on a base map, and finally, isolines of this number are drawn to delineate regions of significant stability or instability. Secondly, a measure of the prevailing humidity in the same layer is selected (e.g., average relative humidity) computed, plotted on the same map, and isolines of this quantity are drawn. Standards for "stable" and "unstable" regions are expressed in terms of the previously determined measure of stability, and standards for "moist" and "dry" areas are expressed in terms of the previously determined measure of prevailing humidity. According to these standards each point of the map must lie in some one of the four types of areas described by the four possible combinations of the stability and humidity types, i.e., moist-unstable, moist-stable, dry-unstable, or dry-stable; or it may lie in a neutral zone with reference to these standards if provision is made for such an area. By assigning a different color to each of these four types and coloring them on the plotted and analysed stability chart, the fields of stability and humidity are very clearly presented for study by the forecaster.

2. The first type of stability chart developed may be plotted directly from radiosonde reports as transmitted in the present (1945) teletype code. Selection of the 5-10,000 ft. layer as the stratum whose stability-humidity field is to be represented permits this procedure. The stability of the layer is considered as given by the difference in temperature between the top and bottom of the layer; the prevailing humidity by the average of all relative humidities reported in that layer. A similar chart for the layer 10-15,000 ft. is also readily plotted, and taken together, these two layers constitute a stratum whose stability-humidity characteristics should be of critical importance in determining the occurrence or non-occurrence of convective activity.

Although some such integrated measure of stability as results from a layer-by-layer computation of the circulation acceleration[1] would appear desirable, it can be shown that the circulation acceleration in any given layer depends only on the temperatures at the boundaries of that layer and is independent of the manner in which the lapse rate may vary within that layer.

The establishment of numerical standards is a somewhat arbitrary matter. The best standard to which a given lapse rate may be referred for purposes of evaluating its stability is the moist adiabatic lapse rate and this varies with the temperature, becoming greater for decreasing temperature. When stability is to be measured as a difference in temperature between two height levels, it will be seen that any fixed standards of stability will be appropriate only within a small temperature range. The value of the moist adiabatic lapse rate for a reasonable temperature range (at middle latitudes in summer) was found to be $8^{o}C./5000$ ft. Selecting lapse rates $2^{o}C./5000$ ft. on each side of this value as boundaries, regions with lapse rates in excess of $10^{o}C./5000$ ft. were designated as "unstable" regions, those with lapse rates less than $6^{o}C./5000$ ft. were designated as "stable" regions, while those with lapse rates between $6^{o}C.$ and $10^{o}C.$ were considered as having "neutral" stability for the purposes of this study. The boundary between "moist" and "dry" regions was taken as the isoline of 60% relative humidity because experience has shown that saturation may exist in regions whose radiosondes record relative humidities as low as 60%. The same standards may be applied to the higher layer at 10-15,000 ft.

A stability chart constructed according to the method just described provides a graphic representation of the areal distribution of two important variables affecting summer air-mass weather. It is easily plotted from the current radiosonde reports, and its analysis, rather than being a matter of lengthy interpretation, is a matter of mechanically drawing isolines*. Its value as a forecasting tool will depend on the extent of agreement between its areas of instability and high moisture content and the areas wherein convective activity is actually observed during the 12-18 hr. period following the time of the upper air observations represented by the stability chart. Part III of this paper is devoted to a statistical investigation of the "extent of agreement" for this first type of stability chart.

The use of an <u>average</u> relative humidity may be questioned in view of the possibility that the average would not distinguish between the case of a constant relative humidity and the case of a steadily varying relative humidity

* Such a chart may be plotted for the entire United States for a 5000 ft. layer in about thirty minutes; analysis requires about forty to fifty minutes.

whereas the two cases may have quite different implications as to the likelihood of convective activity. This difficulty has been obviated by the incorporation of an additional element into the station model of a second type of stability chart to be described below.

The method of averaging all the reported humidities in the layer may give a distorted value in the event that there are several significant points reported for levels separated by small vertical distance in one portion of the layer, with a single significant point of quite different humidity at some distance from these clustered points. This difficulty could be avoided only by using judgment in forming the average during plotting.

The advantage of great simplicity characteristic of this first chart, which may be called the "Delta-T" chart (because it is the difference in temperature between two levels that constitutes the measure of stability), is coupled with several limitations. For, in the interests of facility of plotting, the nature of the chart is to a considerable extent dictated by the form of the present radiosonde code--the layer represented must be bounded by the so-called "standard levels" at 5000 ft. intervals, and the stability measure is most conveniently expressed in terms of the difference in temperatures between these same levels. Since the 5000 ft. level is very near the earth's surface over a large part of the western United States, the 5-10,000 ft. stability and humidity will necessarily be strongly affected by surface influences in that region. And as previously pointed out, any fixed standard of stability will be appropriate only within a small temperature range when a temperature difference is used as the measure of stability. To overcome these limitations a more elaborate chart has been developed and this will now be described.

3. Whereas the first chart is plotted directly from radiosonde reports, the form of the second is such that it may be plotted only after an adiabatic chart has been plotted for each sounding, because of the different method of selecting the layer being studied and of evaluating the stability for that layer. Instead of considering a layer whose base and top are always at a fixed height above sea level, the layer of air whose base is everywhere 100 mbs. above the ground surface and whose top is everywhere 300 mbs. above the ground is studied. At stations near sea level this 200-mb.-thick layer will extend from about 3000 ft. to about 10,000 ft. above sea level.

To determine from the plotted sounding the stability of this 200 mb. layer, the following procedure is employed: Starting at the point on the lapse rate 100 mbs. above the surface, follow the moist adiabat through that point up to the level 300 mb. above the surface and read off the difference between the actual temperature and the temperatures on the aforementioned moist adiabat at the level P_0-300 mbs. For lapse rates greater than the moist adiabatic, it will be seen that this difference will be negative, for lapse rates less than the moist adiabatic it will be positive, so this difference may be considered to be a measure of the positive or negative stability of the layer. In accordance with the previous standards, but now in a more general fashion, "stable" layers were required to exhibit a departure from the moist adiabatic lapse rate greater than +2°C; "unstable" layers must have a departure of less than -2°C. Because on this second chart stability is measured as a departure from the moist adiabat, it may be conveniently called the "Gamma-M" chart.

The prevailing humidity in the layer being studied is, as before, taken as the average relative humidity in the layer; and the boundary between "moist" and "dry" regions may again be taken as the isoline of 60% relative humidity. As already recognized, the average relative humidity alone may be a misleading measure of the moisture distribution in the case of a rapidly varying (usually, decreasing with height) humidity. Information as to this vertical gradient of humidity is especially useful at stations where frontal rather than intra-air-mass weather is anticipated, because the stability with respect to forced lifting as at a front, i.e., the "convective stability", is dependent on this vertical gradient of humidity. In order to provide such information the lapse rate of potential pseudo wet-bulb temperature between the levels P_o-100 mbs. and P_o-300 mbs. may be read off the plotted sounding and entered on the station model.

In addition, two other elements are included in the data plotted for each station in order to aid the forecaster in determining the likelihood of thunderstorm development. The first is the pressure in tens of mbs. at the -5°C. level, included to give a measure of the height to which convective currents must penetrate in order that a cumulus congestus cloud may be transformed into a cumulonimbus. However, since there is no definite temperature level for such transformation, this figure is to be regarded as only giving an approximation to the actual cumulonimbus threshold. The other element in the station model is the stability (defined as before in terms of departure from Gamma-M) between the level P_o-300 mbs. and the level of the -5°C. isotherm. Taken together, these five elements present in concise form valuable information as to the stability of the atmospheric column and the probability of occurrence of thunderstorms. A stability chart plotted according to this station model represents an abstraction from a large number of soundings of the upper air data essential to a summer forecast. A station model and legend are given with Fig. 1

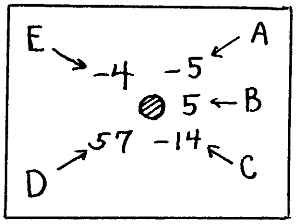

Fig. 1
Station model for the Gamma-M chart.

A = Difference between actual temperature at P_0-300 mbs. and temperature obtained by going up the moist adiabat from P_0-100 mbs. (Stability)

B = Average of all relative humidities reported in the layer between P_0-300 mbs. and P_0-100 mbs. (Prevailing Humidity)

C = Difference in potential wet-bulb temperature between P_0-100 mbs. and P_0-300 mbs. (Convective Stability)

D = Pressure (tens of mbs.) at the -5°C. level. (Cumulonimbus Threshold)

E = Difference in temperature between -5°C. and temperature obtained by going along the moist adiabat from the point on the actual lapse rate at P_0-300 mbs. up to the level of the -5°C. isotherm. (High-level Stability)

III. STATISTICAL EVALUATION OF THE DELTA-T CHART.

1. Although a stability chart would be of some interest even if it did no more than reveal certain aspects of the thermal structure and moisture distribution of the atmosphere, nevertheless the chart is suggested as a forecasting aid and it becomes desirable to evaluate quantitatively its utility as such. Remembering that the stability chart consists of a number of area-types (e.g., moist-unstable, dry-stable, etc.) and that there will be, on the surface maps, areas of certain weather types (e.g., areas of thunderstorms, areas of completely clear skies, etc.), the research problem here may be generalized to the form: Find various sets of properties that will define such areas (S-areas) on the stability chart as will be in complete coincidence with areas of various weather types (W-areas) as found on the surface maps during the forecast period. If such sets of properties could be determined for each of the several weather types then, by definition, these weather areas could be forecast with complete accuracy. Now it will not be expected that any set of S-properties can be assembled to produce such 100% coincidence with W-areas, but, given any trial set, it follows that its prognostic value may be weighed by determining the degree of coincidence between the S-area so defined and the corresponding W-area. That, then, is what will be done below with the relatively simple set of properties (temperature difference and average relative humidity) introduced to define the S-areas of the Delta-T chart.

It remains to define the W-areas. Although a large number of weather-types might be defined, only one has been considered for the purposes of this statistical investigation--namely, that of "significant convective activity". An area will herein be regarded as exhibiting "significant convective activity" when all stations within that area report greater than 4-tenths coverage (Code 4 N_h in the 1942 U.S.W.B. Weather Code) of cumulus congestus, or report thundershowers within the past three hours. The surface maps for the forecast period may be analysed for such W-areas by enclosing with a smooth curve all stations meeting these requirements and shading in the resulting convective areas.

The degree of coincidence between these convective areas and the four S-areas of the Delta-T chart is to be evaluated. Because there is no well-established statistical approach to this problem, a function that may be called the "congruity" has been devised for this study. The manner in which the congruity, designated as "C", measures the degree of coincidence of S- on W-areas will be seen from the simplified case illustrated in Fig. 2.

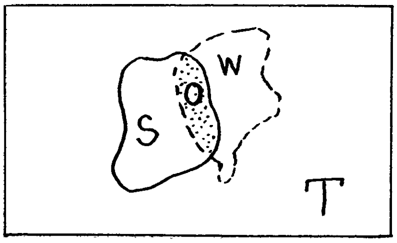

Fig. 2.

S = Total area of a given stability type. (Enclosed in solid curve.)

W = Total area of a given weather type--here convective cloudiness. (Enclosed in dashed curve.)

O = Overlap area of S on W. (Stippled area.)

C = Congruity $= \sqrt{O/W \times O/S} = \sqrt{O^2/WS}$

It is evident that:

(1) When there is complete coincidence of W on S, C = 1.0.

(2) When there is no overlap of W on S, C = 0.0.

(3) When there is partial coincidence of W on S, 0.0 C 1.0.

It is evident that the congruity resembles the coefficient of correlation in its extreme values and in its qualitative meaning, each being a measure of the degree of relation between two variables.

Before adjudging the significance of any measure of relationship such as the congruity it is necessary to determine what part, if any, of the observed relationship may be due to mere chance. The degree of relationship as indicated by the statistical measure must, of course, differ appreciably from that which would be expected from probability considerations, in order for the measure to be regarded as significant. In the case of the congruity of S- and W-areas this means that before one may attribute any significant prognostic power to an S-area, it must be known by how much the observed overlap of S on W differs from the overlap to be expected due to mere chance. It is to be noted that this difference may be <u>either</u> positive or negative. As an example, the observed overlap of convective areas on dry-stable areas must be <u>less</u> than the computed probable area of overlap; for otherwise the hypothesis underlying the stability chart is in one point contradicted--it being presupposed that dry and stable areas should be noticeably free from marked convective action. The manner in which these <u>probable</u> areas of overlap between S- and W-areas have been computed will be indicated briefly with reference to the idealized case already illustrated in Fig. 2.

Let the total area (of the rectangle in the case illustrated, but of the map in the actual practice, be T units, the area of convective activity be W units, and the given stability area (of any one type, as moist-unstable) be S units. If a point is selected at random from anywhere within the area, T, then:

(1) W/T = Probability that the point will fall within area W.

(2) S/T = Probability that the point will fall within area S.

(3) $W/T \times S/T$ = Probability that the point will fall within both area W and area S, i.e., probability that it will lie in an overlap area.

If this last figure gives the probability that any random point will lie in an overlap area, then the product of this probability and the total area within which the area may fall gives the probable area of overlap:

(4) $W/T \times S/T \times T = WS/T$ = Probable area of overlap due to mere chance.

If A_o = Observed area of overlap between a given S-area and W-area, and

A_e = Expected area of overlap due to chance, then A_o/A_e may be taken as a measure of the role played by chance in producing the observed overlap. If A_o/A_e approaches unity for any given S-area then that area has no prognostic significance but if A_o/A_e departs in either a positive or negative sense from unity, then there is something more than mere chance that is tending to produce the observed congruity (or lack of congruity as the case may be) so that the prognostic power of each area will vary as the departure from unity of its A_o/A_e ratio.

Finally, when the congruities and A_o/A_e-ratios have been computed, the statistical evaluation will be complete only after some test has been applied to determine the reliability of results obtained from a limited rather than unlimited sample, since only ten days were studied here. The Chi-square test for the reliability of the mean of a small sample[5] was applied to each of the mean A_o/A_e-ratios, using the formula:

$$\chi^2 = \frac{\Sigma(A_o - A_e)^2}{\Sigma\left[(A_o - A_e) - \frac{\Sigma(A_o - A_e)}{N}\right]^2} \quad N = \text{Number of cases (10)}$$

For a sample of ten cases, the number used here, the value of χ^2 is required by statistical theory to exceed 16.92 for the A_o/A_e-ratio to be regarded as a reliable measure of the ratio which would be obtained using an infinitely large number of cases[4].

The preceding discussion has presented a general method for obtaining and evaluating an areal correlation. The following section will outline the actual mechanics of applying this method to this investigation of stability-humidity fields in their relation to intra-air mass convective activity.

2. Because of the surface influences acting on the 5-10,000 ft. layer in the West, all measurements were restricted to that portion of the United States east of the 105th meridian. Also, because only intra-air-mass convective activity is under consideration here, no measurements were made in any region containing frontal surfaces regardless of whether those surfaces were within or without the layers represented by the stability charts. To illustrate, in Fig. 3 the stippled area, bounded in succession by coastline, 105th meridian, a cold front, a warm front, and an international boundary, represents the T-area, the total field available for the occurrence of W- and S-areas. Fronts were placed in such a way as to mark the position of maximum advance (during the 24-hr. "forecast period" associated with each stability chart) into the air-mass over the southeastern United States.

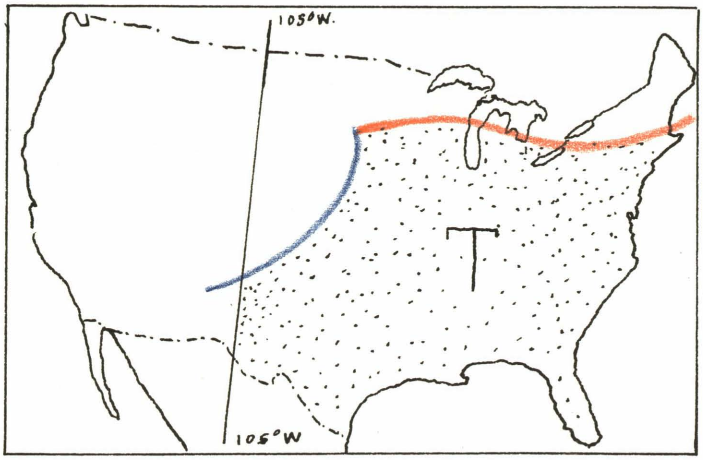

Fig. 3.

The total S-areas of each of the four S-types was measured planimetrically on each of four stability charts for each of ten days in June and August, 1944. These four charts were the 5-10,000 ft. and 10-15,000 ft. stability charts for 0400Z and 1600Z. The total W-areas on the 1830Z and 0030Z surface maps were similarly measured and all areas tabulated. Then, on a tracing table, overlap areas were discerned and measured for each of the four S-types using the eight possible combinations of four stability charts and two surface maps. These measurements provided the working data, and, when subjected to the statistical treatment described in the previous section, gave the results shown in Table I.

Table I.

Statistical Evaluation of the Delta-T Chart for Ten Days During June and August, 1944

(Figures are Averages for Ten Days.)

Surface Map Time		0400Z 5 - 10,000' MU	DU	MS	DS	10 - 15,000' MU	DU	MS	DS	1600Z 5 - 10,000' MU	DU	MS	DS	10 - 15,000' MU	DU	MS	DS
1830Z	Congruity	.39	.17	.00	.14	.17	.20	.00	00	.28	.26	.00	.20	.17	.20	.00	.00
	Std. Dev'n.	.33								.28							
	A_o/A_e	1.5	0.5	0.2	0.5	1.0	0.5	--	--	1.6	0.5	0.0		1.2	0.5	--	--
	χ^2	20.0	22.7	100.0	--	9.7	77.5	--	--	34.3	20.7	131.0		10.0	42.0	--	--
0030Z	Contruity	.36	.20	.00	.00	.20	.20	.00	.00	.28	.22	.00	.00	.14	.21	.00	.00
	Std. Dev'n.	.32								.33							
	A_o/A_e	1.9	0.8	0.9	0.4	0.5	0.7	--	--	2.1	0.8	0.5	0.4	1.0	0.5	--	--
	χ^2	23.3	13.9	10.0	17.0	13.7	15.9	--	--	4.7	10.1	10.8	100.0	13.0	19.9	--	--

MU = Moist-unstable

DU = Dry-unstable

MS = Moist-stable

DS = Dry-stable

It will be seen that the highest average congruities do occur, as would be anticipated, with the moist-unstable areas, but that even for these areas, the congruity is not large, ranging from 0.28 to 0.39. Furthermore, the standard deviations for these highest average congruities are nearly as large as the averages themselves, indicating considerable dispersion about the mean. Again, the A_o/A_e-ratios attest the relation of moist-unstable areas to areas of convective activity, for it is in these MU areas alone that the observed overlap is greater than that to be expected as a result of chance. The A_o/A_e-ratios indicate that there is about one-and-a-half to two times as much overlap as would occur by chance, with corresponding χ^2 values indicating significance in all cases but one (χ^2's in excess of 16.92 are to be regarded as indicating a reliable A_o/A_e-ratio for the number of cases emoloyed here.)

Table I shows that the dry-stable and dry-unstable areas of the chart may be used to forecast regions free from strong convective activity with considerable assurance, the congruities and A_o/A_e-ratios both being quite small for these areas. This is a useful relationship, for it makes it possible to forecast some, if not all, of the areas within which operations will not be hindered by air mass instability. That is, it appears to be easier to predict where convective activity won't occur than to say where it will occur.

Inspection of the congruities and A_o/A_e-ratios for the 10-15,000 ft. chart reveals only a slight relationship between convective activity and the high-level stability-humidity fields. This would suggest that, inasmuch as the convective cells which grow into air-mass thunderstorms are established in the lower layers of the atmosphere (ca. 3-5,000 ft.), it is in those lower layers, rather than aloft that one must seek the critical factors determining location of air-mass convective activity.

Perhaps the most surprising result indicated in Table I is the greater prognostic power of the 0400Z stability chart as compared with the 1600Z chart. Even when the 1830Z convective areas are concerned, the 0400Z stability-humidity pattern is more closely related to the congestus cloudiness than is the nearly-synoptic 1600Z stability-humidity pattern. The implication is that the early-morning, undisturbed field determines where convective cells may grow during the day and that by mid-afternoon the very convection itself has increased the stability of the atmosphere in such a way as to produce a poorer areal correlation between instability and cloudiness. This matter will be discussed at greater length in Part IV, in company with several other problems suggested by the results summarized in Table I.

IV. SOME RELATED PROBLEMS

1. Diurnal variations of stability. Because the afternoon is the time of maximum surface temperature, it might be expected that it would also be the time of maximum atmospheric instability atmosphere, yet measurements of the total areas of instability on the Delta-T chart at 0400Z and at 1600Z for ten days indicated that there is an average of 1.7 times as much unstable area in the early morning hours, as in the early afternoon. This average refers to the sum of both moist-unstable and dry-unstable areas, the first exhibiting a ratio of 1.6 between 0400Z unstable area and 1600Z unstable area, the second a ratio of 1.8. The amounts of convective cloudiness exhibits an afternoon maximum, there being 1.9 times as much area of congestus clouds at 1830Z (afternoon) as at 0030Z (evening) during the ten days studied here. Despite this inverse nature of the diurnal variations of instability and cloudiness, it is the 0400Z stability chart that has the greater prognostic power, as shown by Table I. This paradox of greatest cloudiness at time of maximum observed stability, raises the question of what factors combine to produce the observed diurnal variation of stability in the 5-10,000 ft. layer. Several hypotheses suggest themselves and must be considered:

(a) Instrument-error hypothesis. The first question that must be answered is the extent to which measurements may be distorted by instrumental errors. The normal variation of temperature with height is such that the radiosonde is usually moving into regions where the temperature is lower than that in the region through which it has just passed. Any lag of the temperature element would thus tend to give an observed temperature that was too high. Since the lag depends, among other things, on the ventilation, and since the effectiveness of ventilation is a function of air density[3], it is possible that the decreased air density at 10,000 ft. as compared with 5,000 ft. would increase the lag and yield a 10,000 ft. temperature that was larger than the true value thereby overestimating the stability of the layer. Calculations of this lag error, however, indicate that the error in observed 5-10,000 ft. temperature differences (stabilities) could not exceed 0.2°C., so it is reasonable to neglect this factor here. Furthermore, since the lapse rate of density does not vary extremely from night to day, this effect would not yield any diurnal variation of stability, so it appears justifiable to throw out instrument errors of this type as significant factors in producing the observed variation of stability.

(b) Stirring hypothesis. Since convective activity is a surge towards a more stable state, it might be expected that once convective cells with their attendant cloud forms were established, the atmosphere would already have undergone a decrease in its potential energy, so that its stability would be increased as a result of the stirring up of the convective action. This would imply that by afternoon (1600Z) there would be both greater cloudiness and lesser instability than there was in the early morning (0400Z). By comparing the changes of stability from 0400Z to 1600Z at stations where there was convective activity with stations where there was not convective activity, it might be possible to test this second hypothesis. This was done and the following results obtained:

Convective activity occuring at 1600Z (59 cases)

20% were more unstable at 1600Z than at 0400Z

61% were less unstable at 1600Z than at 0400Z

19% showed no change.

Convective activity not occuring at 1600Z (80 cases)

36% were more unstable at 1600Z than at 0400Z

47% were less unstable at 1600Z than at 0400Z

17% showed no change.

This gives no decisive answer, but does indicate a trend in the direction of increased afternoon stability at points where convective cells have already been established. Apparently, then, stirring may be one factor, but not a critical factor.

(c) Direct absorption or radiation in the free atmosphere. The 0400Z maximum in instability might be due to greater radiational cooling at the 10,000 ft. level than at the 5000 ft. level, a condition that would prevail when there was a marked vertical gradient of water vapor. The vertical variation in the amount of direct absorption of solar radiation during the day under conditions of decreasing humidity with height in the 5-10,000 ft. layer would, however, tend to increase the instability of the layer because of greater absorption in the lower vapor-rich levels.

In order to determine at which levels (5000 or 10,000 ft.) the more important temperature changes were acting to produce the observed diurnal variation of stability, sixteen stations were studied over a period of fifteen days with respect to these temperature changes. In order to avoid inclusion of any temperature changes accompanying frontal passages, analysed surface maps were checked and all stations whose upper level temperature changes might have been due to changes of air-mass on any particular day were thrown out for that day. The changes at top and bottom of the 5-10,000 ft. layer and also the stability (temperature difference) changes in the same layer were averaged over the 15 days for each station and the results tabulated in Table II.

Table II.

Intra-Air-Mass Variations of Temperature and Stability
(16 Stations for 15 Days

Station Number	0400Z 5000'	1600Z 10,000'	S	1600Z 5000'	0400Z 10,000'	S
240	+0.4	+1.1	-0.8	-0.4	-1.2	+0.8
327	-0.7	+0.4	-1.1	+0.5	-0.8	+1.4
219	+0.1	+1.8	-1.7	-0.3	-1.4	+1.2
208	+1.8	+2.2	-0.4	-0.9	-1.0	+0.1
405	+0.2	+1.7	-1.6	+0.1	-1.6	+1.7
202	+0.6	+1.8	-1.3	-0.4	-1.6	+0.8
265	-1.2	-0.4	-0.3	+1.2	+0.5	+0.7
434	+1.1	+0.5	+0.6	-0.8	-1.2	+0.4
409	+0.4	+1.6	-1.1	+0.8	-0.6	+1.4
303	+1.4	+1.1	+0.3	-1.3	-1.1	-0.1
353	0.0	+0.5	-0.5	0.0	-0.9	+0.9
253	-1.36	+0.1	-1.4	+1.5	+0.2	+1.2
308	-0.4	+0.3	-0.8	+0.7	-0.4	+1.1
534	+0.2	+1.1	-0.9	0.0	-0.3	+0.3
205	+0.9	+1.3	-0.4	-0.6	-0.6	0.0
250	-0.5	+0.8	-1.4	+0.7	-0.8	+1.5
Average	+0.2	+1.0	-0.8	0.0	-0.8	+0.8

It will be seen that the control of the diurnal stability variation seems definitely to be located at the <u>top</u> of the layer 5-10,000 ft.. From 0400Z to 1600Z, the 10,000 ft. level warms up, on an average, 1.0°C. whereas the 5000 ft. level warms up only about a sixth of a degree. From 1600Z to 0400Z, the upper level cools off about 0.8°C. against a very slight (less than 0.1°C.) warming at the 5000 ft. level. Table II reveals nothing as to the cause of the diurnal variation, but points definitely to the 10,000 ft. level as the region of critical importance. Final answers to these questions will not be sought here, but may be considered as suitable problems for further research.

2. Prediction of stability changes by means of an "advective tendency". When isotherms and streamlines are not parallel in a region, then the temperature at a fixed point in that region will change as a result of advection of air of different temperature. If, under the above conditinns, the pressure and temperature fields also vary with height, then it becomes possible to obtain different degrees of advective temperature change at various elevations--a condition that must lead to changes in lapse rate and, therefore, to changes in stability. The effect of advection upon the temperature of a fixed point in the free atmosphere may be deduced theoretically from the thermal wind relationships and an "advective tendency" may be devised to evaluate this effect quantitatively. Such an advective tendency, if it be computed as a three-hour tendency, would bear somewhat the same relationship to stability isolines as the conventional three-hour pressure tendency does to isobars. However, the advective tendency is but one component part of the total change of stability while the pressure tendency is the total effect of <u>all</u> components affecting that quantity.

It may be shown from the thermal wind relationship[2] that the time rate of change of temperature due to advection in the free atmosphere is given by

$$\frac{\partial T}{\partial t} = V_1 V_2 \sin\theta \sin \phi \left(\frac{2\omega}{g \Delta z} \cdot T \right)$$

where

T = Temperature (assumed constant along any vertical).

$\frac{\partial T}{\partial t}$ = Change of the temperature with time at a fixed point.

V_1 = Wind speed at the bottom of the layer in question.

V_2 = Wind speed at the top of the layer in question.

θ = Angle between V_1 and V_2 (angle of veering or backing).

ϕ = Latitude.

ω = Angular velocity of the earth.

Δz = Vertical thickness of the layer (constant).

g = acceleration of gravity

As long as a fixed thickness, Δz , is used, and assuming some fixed temperature for that layer, the factors in the parenthesis in (5) become constant and the advective temperature change, or "advective tendency", depends only on the wind speeds at the top and at the bottom, angle of veering or backing, and latitude. The sign of the change is governed by the sign of θ.

In order to evaluate advective tendencies quickly and easily, a slide rule was constructed with a scale for each of the four variables in (5), using a thickness of 2000 ft. and a temperature of 285°A. The scales were so constructed as to give the final answer directly in terms of degrees C. per three hours. By computing the tendency first for the bottom of the layer using the 5000 and 7000 ft. winds, and then for the top of the layer using the 8000 and 10,000 ft. winds, and finally, by adding these two tendencies algebraically, the advective effect on stability may be obtained for each station reporting pilot balloon observations.

By comparing the changes predicted by these tendencies with the <u>actual</u> changes in stability, the degree of dependency of the latter on the former has been determined. Tendencies computed from the four regular pilot balloon observations have been correlated with stability changes obtained from the two regular radiosonde observations. Two types of correlation coefficients have been employed. The first is the usual Pearsonian coefficient, r_p,

$$r_p = \frac{\Sigma(XY) - n\bar{X}\bar{Y}}{\sqrt{(\Sigma X^2 - n\bar{X}^2)(\Sigma Y^2 - n\bar{Y}^2)}}$$

where x and y are the variables being correlated, x and y the means of each, and n the total number of cases. The standard error, S.E., of the Pearsonian coefficient is obtained from

$$S.E. = \frac{1 - r_p^2}{\sqrt{n-1}}$$

It is usually considered that the correlation coefficient must be greater than three times as large as its own standard error to be regarded as reliable.

The second type of correlation used is the tetrachoric, which measures just the agreement in sign of changes of two variables[6]. When the advective tendency predicts an increase of stability, the actual change may be either an increase or a decrease and the number of cases of each may be designated as a and b respectively. Or if the advective tendency is negative, the actual change may again be either positive or negative, the frequencies being designated as c and d respectively. A frequency table of the form in Fig. 5

may be used to tabulate the data and the results introduced into the formula for the tetrachoric correlation coefficient.

Predicted \ Actual	+	-
+	a	b
-	c	d

Fig. 5

The results of the correlations of advective tendencies are given in Table III.

Table III.

Correlations of Advective Tendencies Against Actually Observed Stability Changes.

Pibal Time	Period of Change	Pearsonian r	Standard Error	Tetrachoric r	Number of Cases
0400Z	0400 to 1600	+0.10	0.10	+0.04	101
1000Z	0400 to 1600	+0.46	0.09	+0.50	76
1600Z	1600 to 0400	+0.16	0.11	+0.14	85
2200Z	1600 to 0400	+0.28	0.10	+0.18	80

It is apparent from Table III that advection is <u>not</u> a dominant factor in producing the stability changes observed in these data, for even the largest r_p is only 0.46, a value somewhat below the conventional limits of forecast significance. Even the tetrachoric coefficients are small, indicating that there is not much agreement even between the <u>signs</u> of the observed and predicted changes. When the tendencies for all four pibal runs are summed and correlated against the twenty-four hour stability changes (to avoid diurnal effects) it is seen that poor correlation still exists.

V. DISCUSSION OF SOME EXAMPLES OF THE DELTA-T AND GAMMA-M CHARTS.

In order to illustrate the above methods of representing stability and humidity fields, four Delta-T charts and one Gamma-M chart are given in Figs. 6-10. The relation between stability-humidity pattern on these charts and regions of convective activity may be seen by comparing the afternoon and evening convective areas drawn on the overlays ahead of each chart. The key to the coloring scheme for Figs. 6-10 is given on p. 34.

1. Delta-T chart for 0400Z June 4, 1944 (Fig. 6). The 5-10,000 ft. layer over the eastern United States south of Pennesylvania is fairly unstable, with greatest instability along the Appalachians. The center of this area is moist, the north and south flanks being dry. Referring to the convective pattern superposed on the overlays, it is seen that there is considerable convection indicated in this area at 1830Z (afternoon), with the moist center exhibiting the largest region of congestus clouds. By evening the activity had diminished greatly in area. Note that to the north, in the Great Lakes-St. Lawrence region, the marked stability revealed on the Delta-T chart is associated with freedom from convective action.

Further west a band of stable and dry air extends from Texas northwards into Iowa. At 1830Z, there is an extensive area in which congestus clouds are reported in Texas. The reason for the rather surprising existence of congestus clouds in such a dry and stable region was evident from San Antonio's afternoon sounding. There was a fairly steep lapse rate from the surface to about 6500 ft. with a strong inversion between 6500 ft. and 10,000 ft. The clouds, with bases at 2500 ft., extend up to 6500 ft. and were therefore reported as congestus. The discrepancy apparent here, it is to be noted, is the result of the verification technique employed rather than of a basic weakness of the chart, for a forecast of good flying weather in the Texas region based on the stability-humidity field would actually be correct, convective clouds limited to the layer below 6500 ft. being no serious hazard to operations. In other words, the standard of "significant convective activity" employed here may, at times, give a misleading measure of the prognostic power of the stability chart due to the wide variations in intensity of convective action that fall within the defined limits of "greater than code 4 coverage of cumulus congestus".

The Southwest exhibits great instability and dryness, a characteristic feature of nearly all stability charts investigated. Marked stability due to subsidence over the southern California coast is reflected in the crowding of the stability isolines in that region.

2. Delta-T chart for 1600Z June 4, 1944. (Fig. 7.) The most conspicuous change from the chart of 12 hrs. previous is the decrease in size of the unstable areas over the East and in the Rockies. From New York City to Cape Hatteras a stabilization has occurred as a result of the advance southwards of the cold front. Most of the cloudiness in Georgia and the Carolinas is frontal rather than air mass, but it is, nevertheless, associated with a definitely unstable 5-10,000 ft. layer.

The stable-dry tongue in Texas has now advanced into Louisiana and is larger in area. The inversion that produced this stability was apparently caused by warm dry air from the Plateau of Mexico being advected over more unstable and moist air sweeping in from the Gulf in the lower layers.

The effect of the subsidence inversion over Southern California does not appear on this afternoon chart, perhaps as a result of diurnal heating of the surface layers.

It is interesting to note the manner in which the moist and stable area is moving down from Canada behind the wave centered in Minnesota. Despite near-saturation humidities in the cool air, its stability (not entirely a result of frontal inversion) is too great to permit development of deep convection.

3. Delta-T chart for 0400Z June 5, 1944 (Fig. 8). In comparing the pattern on this chart with those of the two previous charts it will be seen that no marked reversal of pattern has occurred, but that, on the other hand, there is less than ideal continuity in the successive patterns. This lack of continuity exhibited here is found in almost all sequences studied. It does not appear feasible to attempt to forecast stability-humidity fields because too many factors tend to disrupt continuity; but this step is not intended, anyhow, inasmuch as the stability chart is, itself, a prognostic chart in the sense that it reveals the potentialities for future convective action.

The unstable region in the East is now confined to a narrow wedge in Alabama and Tennessee, but a new and rather extensive area has developed in the Great Lakes where there was quite stable air 24 hrs. earlier. A large area of convective clouds is found overlapping this unstable area, at 1830Z, decreasing by evening (0030Z).

The dry stable area of Texas has diminished as the unstable area of the Rockies spreads eastward. Note the 12 hr. change in area of the Rocky Mountain dry-unstable region that occurred between 1600Z on the 4th and 0400Z on the 5th. This is typical of the diurnal change of stability found during this study.

The moist-stable area in the northern Plains States hangs back despite the eastward motion of the wave and cold front, and is again an area free from convective activity throughout the day.

4. Delta-T and Gamma-M charts for July 8, 1944 (Figs. 9 and 10). These two figures are included for purposes of comparison of the stability-humidity fields as represented by the two methods described in this paper. The most obvious difference in the two patterns lies in the greater area represented as unstable according to the methods used in constructing the Gamma-M chart. Thus, in the Texas-Louisiana area, the Gamma-M chart shows that the actual lapse rate exceeds the moist-adiabatic lapse rate (which is small at the relatively high temperatures of the Gulf States) by 2°C./5000 ft., while the Delta-T chart only indicates neutral stability. This difference is partly due to the slight difference in layers represented by the two charts, but is chiefly a result of the different stability criteria employed with the two charts.

In the Rockies, both charts indicate dry and unstable layers, despite the fact that two different layers are represented by the two charts. This suggests that the characteristic dryness and instability of the region is not limited to the 5-10,000 ft. layer but extends to higher levels, since the Gamma-M chart in the Rockies represents a layer with top at about 15,000 ft.

SUMMARY

Two methods of representing the essential upper air data needed in forecasting air-mass convective activity over an extensive operations area have been proposed and their relative merits discussed. It is felt that the advantage of simplicity in plotting enjoyed by the Delta-T chart outweighs its disadvantages of having to use a somewhat crude standard of stability (temperature difference) and of measuring conditions in a layer subject to strong surface influences over the mountainous West. The Gamma-M chart, though more difficult to plot, is free from both of the disadvantages inherent in the Delta-T chart, and the additional data included in its station model give a much more complete description of the state of the lower troposphere than do the data of the Delta-T station model. It might be added that the disadvantage of having to plot adiabatic charts for all stations could be obviated by the inclusion in the regular radiosonde reports of two groups giving the data for each station in a form that could be plotted directly.

A quantitative evaluation of the prognostic power of the Delta-T chart revealed that though there is a significant relation between areas of convective action and areas of instability and high moisture content, yet this relation is not such as to permit a perfect forecast of the location of all convective regions on the basis of the stability charts. It appears that though stability and humidity are of critical importance in the occurrence of convective activity, three factors may tend to reduce the forecast effectiveness of the stability charts: (1) The radiosonde data is not sufficiently accurate to correctly describe actual stability and humidity conditions (lag errors, crude hygrometric measurements, etc.,), (2) The modes of representation investigated are not sufficiently descriptive of the <u>critical</u>

stability-humidity factors (other layers than those employed may be more closely related to occurrence of convective action) averages for deep layers may obscure important gradations within that layer, the criteria for stability and humidity which determine the final representation of the fields of these variables may be at fault) etc.(3) The prognostic power of the charts may be weakened by factors tending to produce short-time changes in the stability-humidity field that influence simultaneous developments of convective action (convergence, orographic effects, differential surface heating, etc.). It is felt, then, that any shortcomings in the prognostic significance of the charts described here does not reflect a lack of relation between stability-humidity characteristics of the atmospheric column and the potentialities of growth of convective cells, but rather that more refined methods of representation of these factors must be devised.

KEY TO STABILITY CHARTS
(Figs. 6 - 10)

Isolines:

Stability (black)

Humidity (red)

Closed curves on overlays:


Afternoon (1830Z) convective areas (black)


Evening (0030Z) convective areas (red)

Stability-humidity types:

R. H. \ ΔT	$>10^{\circ}$	$<6^{\circ}$
$>60\%$	moist-unstable	moist-stable
$<60\%$	dry-unstable	dry-stable

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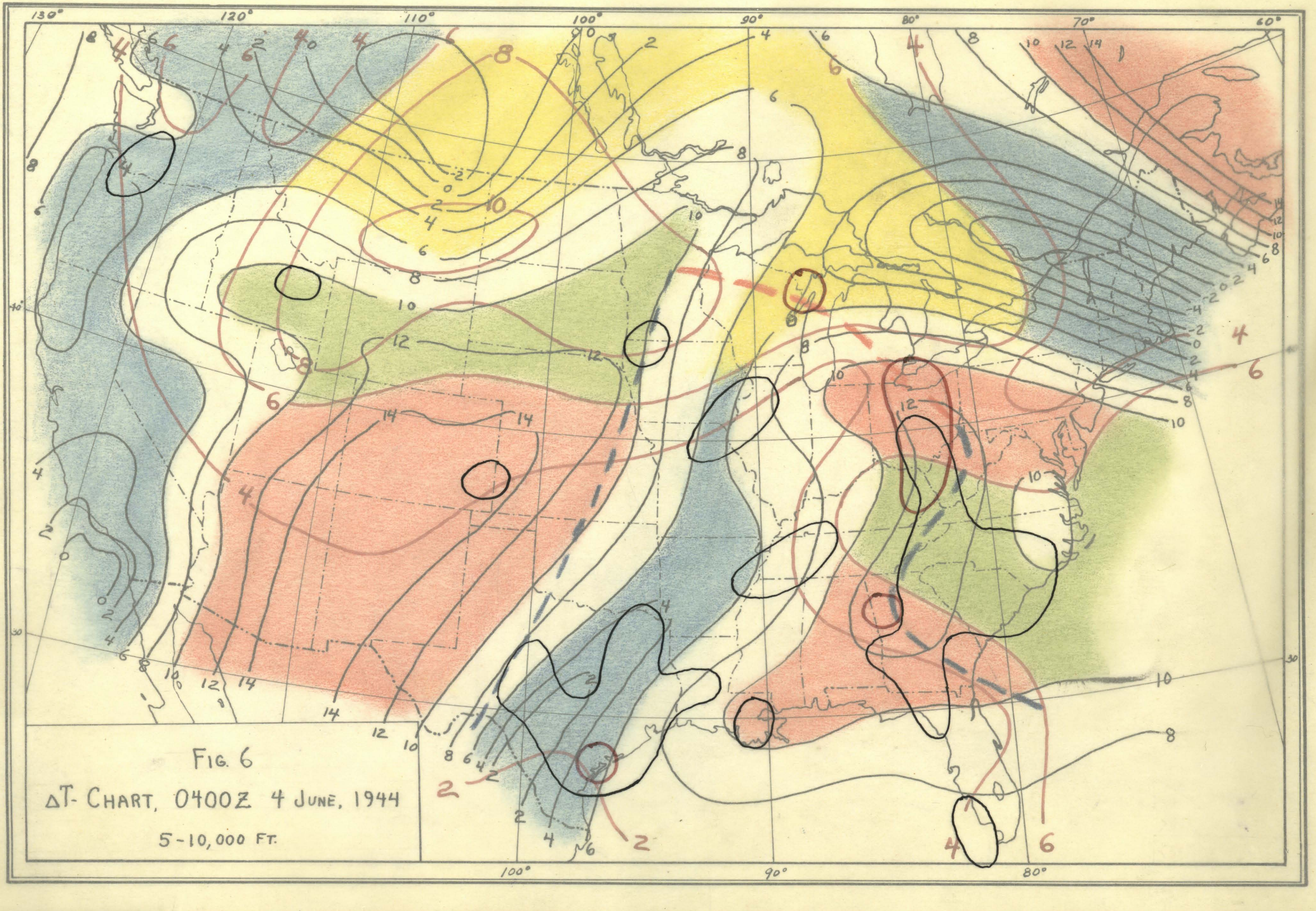

Fig. 6

ΔT- Chart, 0400Z 4 June, 1944

5-10,000 Ft.

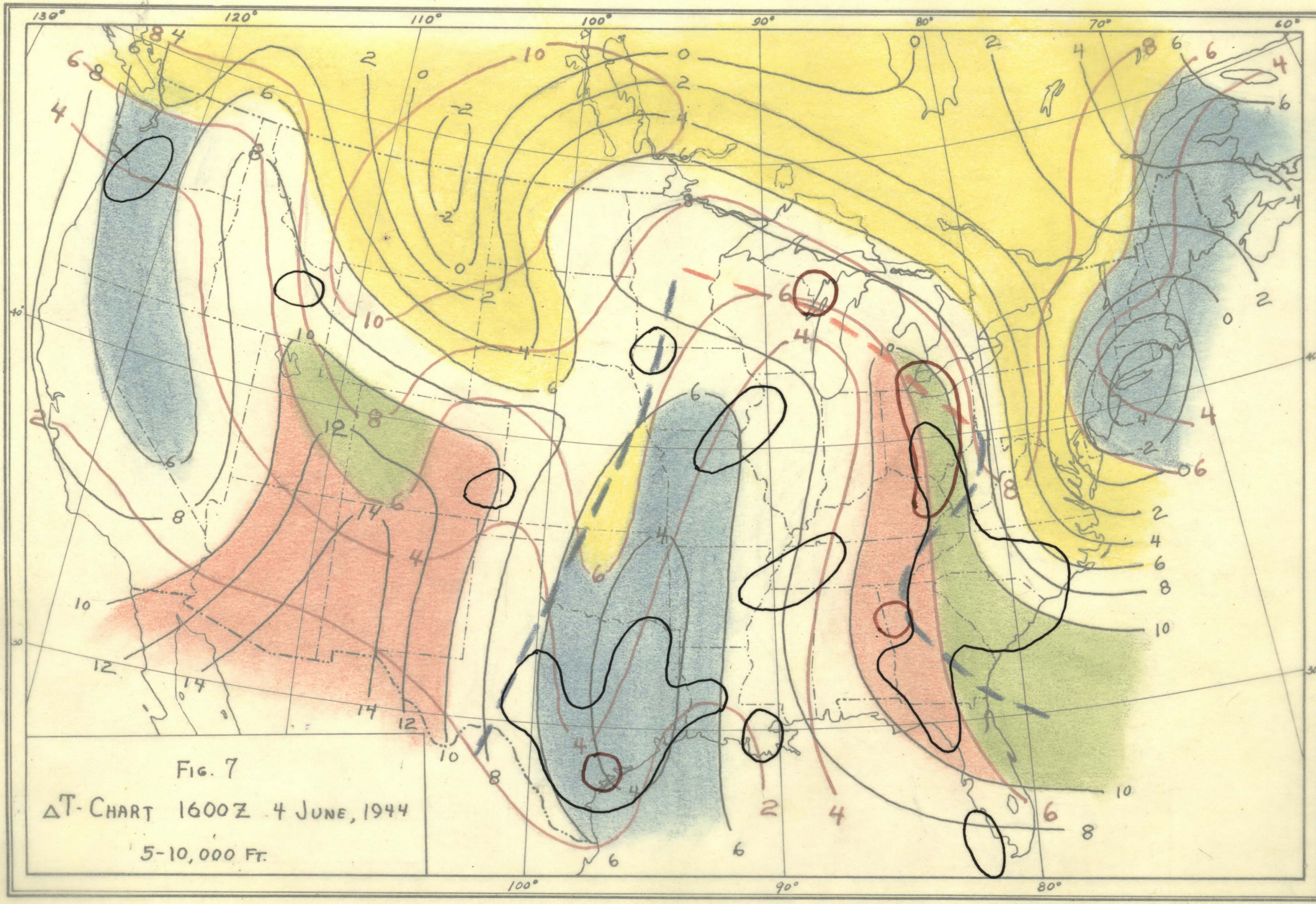

Fig. 7
ΔT-Chart 1600Z 4 June, 1944
5-10,000 Ft.

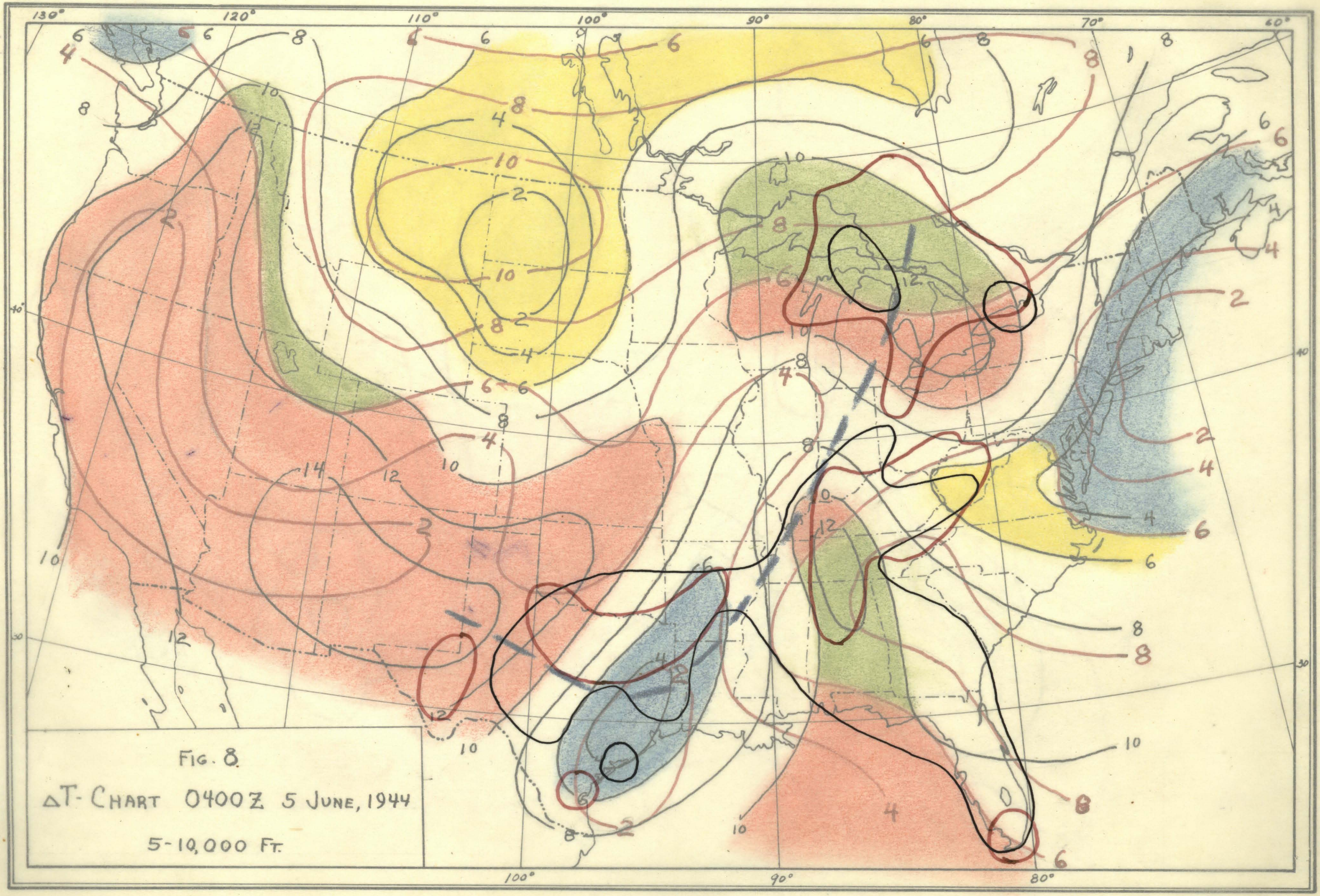

Fig. 8.

ΔT-Chart 0400Z 5 June, 1944

5-10,000 Ft.

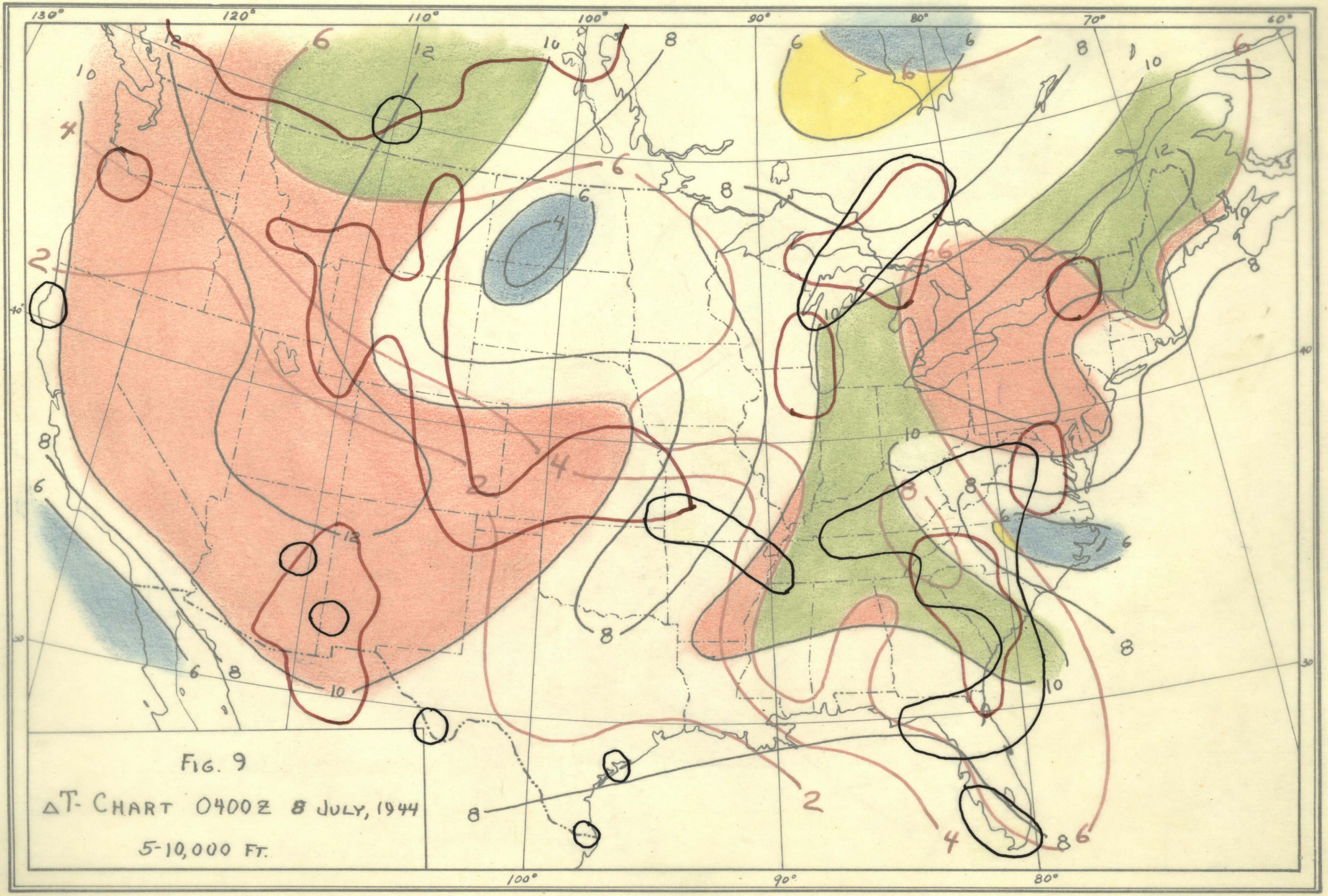

FIG. 9

ΔT- CHART 0400Z 8 JULY, 1944

5-10,000 FT.

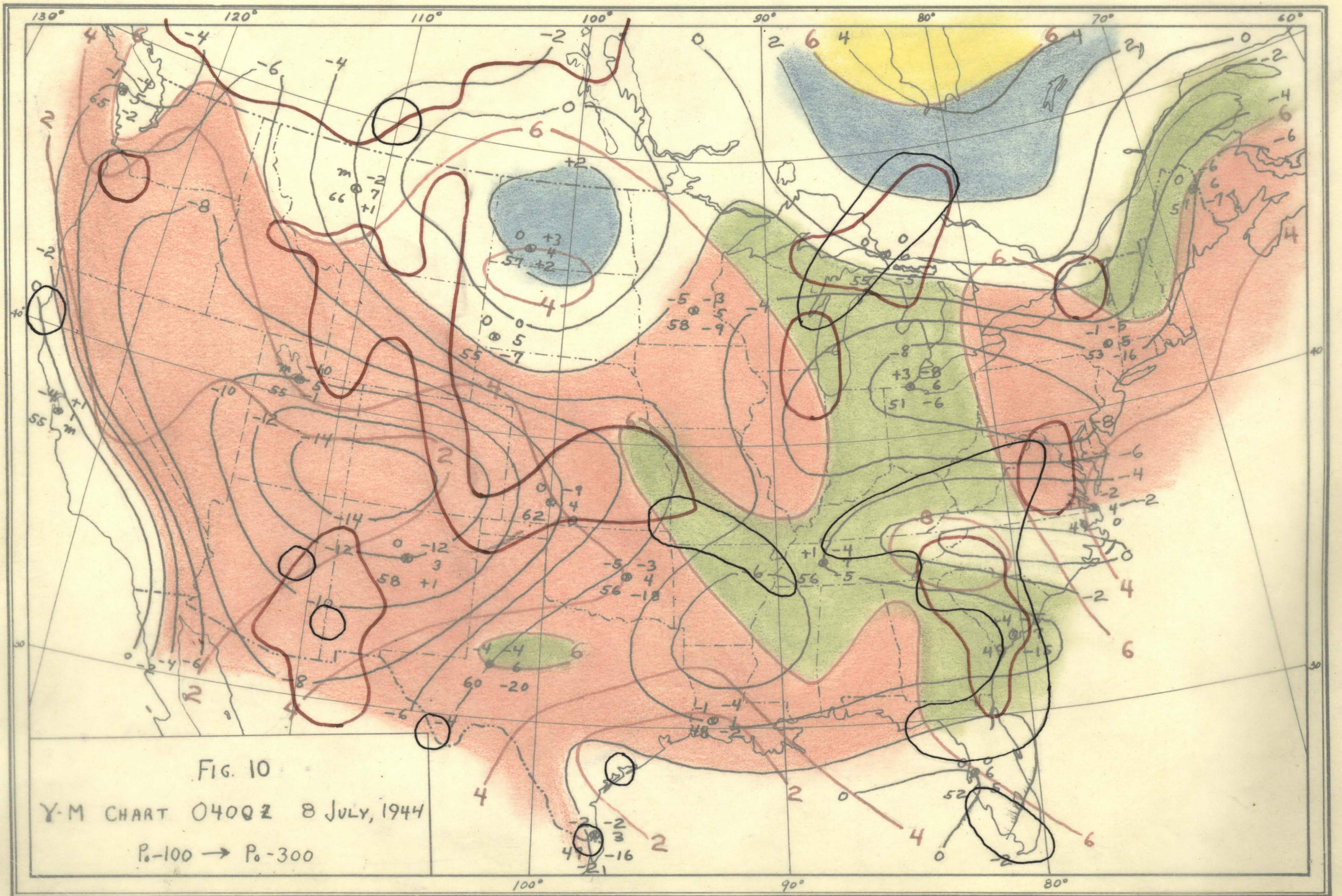

FIG. 10

Y-M CHART 0400Z 8 JULY, 1944

$P_o-100 \rightarrow P_o-300$