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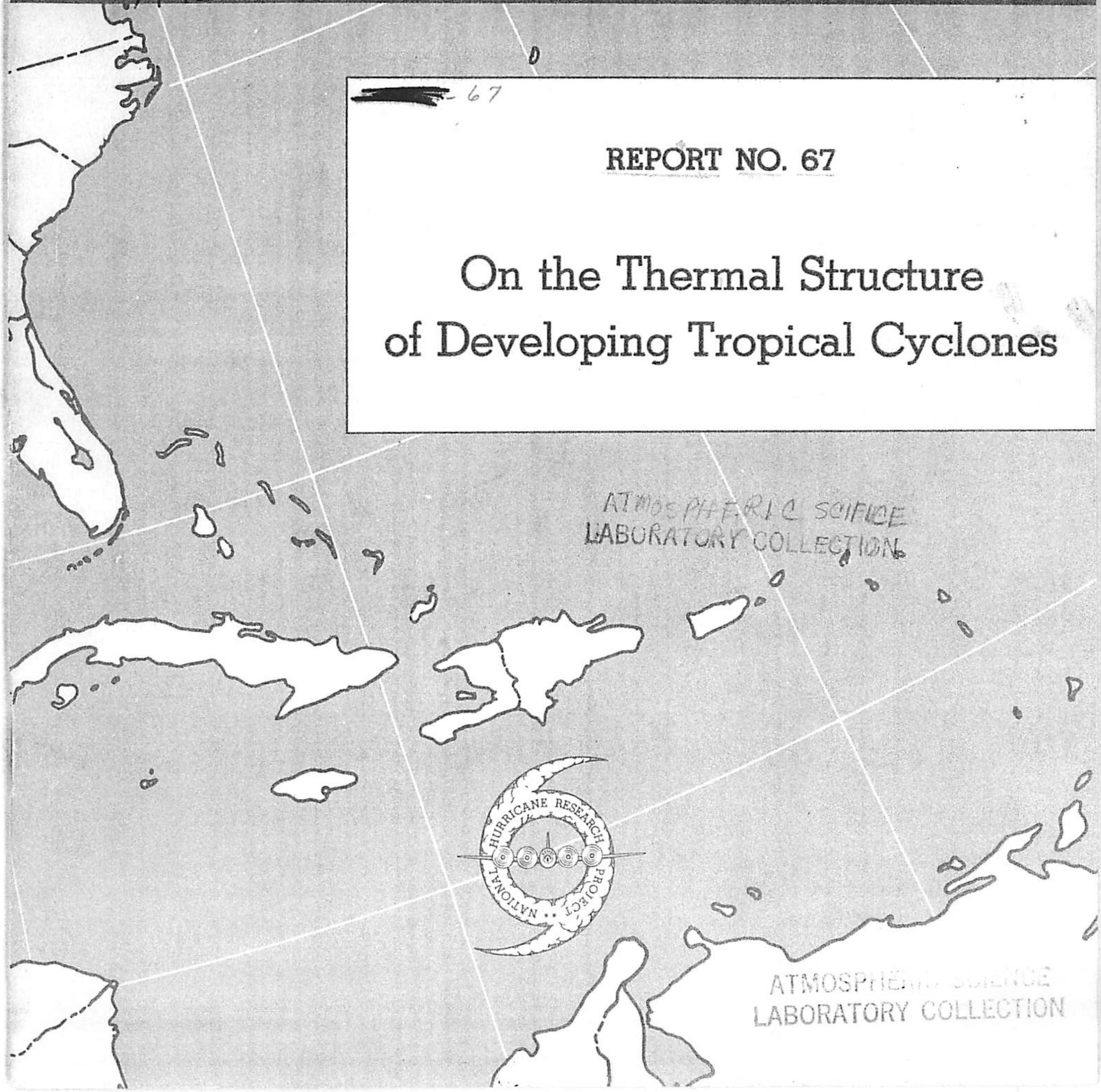

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REPORT NO. 67

On the Thermal Structure of Developing Tropical Cyclones

U. S. DEPARTMENT OF COMMERCE
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WEATHER BUREAU
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NATIONAL HURRICANE RESEARCH PROJECT

REPORT NO. 67

On the Thermal Structure of Developing Tropical Cyclones

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Project, Miami, Fla.

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NATIONAL HURRICANE RESEARCH PROJECT REPORTS

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ON THE THERMAL STRUCTURE OF DEVELOPING TROPICAL CYCLONES

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ABSTRACT

In an effort to determine the nature of the thermal field in the vicinity of developing tropical cyclones as distinguishable by use of data from the existing operational network, thickness charts were constructed for the West Indies area. The development of thirteen Atlantic storms was investigated, these being chosen from the population of 1958-1962 Atlantic storms by including only those favorably situated relative to the data network. To serve as a control group, nine disturbances which failed to develop were treated in the same manner. The method of analysis of the thickness charts is discussed. The thickness and shear patterns in the vicinity of the storms are described, and comparison made between developing and non-developing cases. Changes in the thickness pattern as development proceeds are discussed briefly. Several different thickness layers are compared and rated for their usefulness in delineating the above patterns. Finally, the operational utility of thickness charts as an aid in predicting cyclogenesis is evaluated.

1. INTRODUCTION

It is widely known that the ultimate product of the hurricane development process is a warm-core cyclone. The temperature excess over mean tropical conditions is greatest inside the eye wall in the upper troposphere, and the warm anomalies spread farthest from the eye in the upper troposphere. The cross-section presented by LaSeur [5] for hurricane Cleo, 1958, shows these features, and there is every reason to believe that this is a typical distribution. To be consistent with this thermal field, actual wind shears should have anticyclonic components, more marked in the upper than in the lower troposphere. That this is indeed observed is amply documented in the literature.

Our recent increased understanding of the structure of the mature hurricane is largely attributable to abundant data from research and reconnaissance aircraft. The incipient stages of the hurricane are less well observed, however. The same can be said for the more common disturbances of the Tropics. In both cases, models of thermal structure are far from definitive, and the nature of the evolutionary process by which the warm core of the hurricane develops is not clear. Since the expansion of the West Indies network in the mid 1950's, however, a number of tropical cyclones have formed in the region for which rawinsonde data appear to be adequate for at least a synoptic-scale discription of the development. The purpose of this report is to assemble and present recent observational data concerning the thermal structure of tropical cyclones in their nascent stages, to determine whether

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[1]Present affiliation Florida State University, Tallahassee, Fla. The research was initiated while the author was employed at the National Hurricane Research Project, Miami, and concluded while engaged in graduate study at Florida State University.

particular features appear consistently during or prior to development, and whether there are material differences from nondeveloping cases. Specifically, the operational usefulness of this information will be evaluated.

2. CASES SELECTED FOR ANALYSIS

All tropical cyclones which formed near the data network were considered for this study. If it was felt that enough rawinsonde data surrounded the incipient storm for reasonably definitive analysis of upper-level flow patterns, it was chosen for analysis. Usually, this meant that at least two quadrants had ample data, with peripheral data in another quadrant. This eliminated all storms deepening in data voids such as the Gulf of Mexico unless they were close to shore or unless peripheral data left little doubt of the main features of the situation. Of 42 named storms from 1958 through 1962, only 13 were considered to have passable data coverage.[2] Clearly, no storms which deepened in the low-latitude Atlantic Ocean, east of 60°W., are included, so any results here may not be applicable to deepening processes in this region.

It is important that any result obtained for developing cases be tested for predictive usefulness by examining "duds" in a similar manner. Therefore, a control group of situations was chosen where development appeared plausible but failed to materialize. Some of these are weak tropical storms that maintained status quo or weakened, and others are unnamed waves or vortices which did not deepen. A description of the cases chosen appears in Appendix 1. (Appendix 1 shows that there were six large and six small storms among the developing cases. "Size" refers to the time of initial intensification; several "small" storms covered large areas some time later. It is interesting to note that five of the six small storms developed rapidly, while all six large storms developed slowly. Since the two sets of storms differ so markedly in size and in rate of intensification, there is reason to suspect that the very nature of the intensification processes may be different. Colón [2] contrasted hurricanes in which the wind maximum first appears at large radius and moves gradually inward (example, Helene, 1958) with those which rapidly develop an eye structure, with the wind maximum concurrently appearing in the eye wall, at very small radius (example, Daisy, 1958). The important role which may be played by convective-scale processes in such rapid eye formation has been emphasized by LaSeur [5]).

In developing cases, three map times, 24 hours apart, were analyzed. For consistency, an effort was made to have the second and third times encompass the period of most rapid deepening. This is felt to be more suitable than the time the pressure or wind reached a certain arbitrary value, for we seek to investigate the deepening process, which is a combination of increasing wind, decreasing pressure, increasing low-level vorticity, and an increasing degree of organization of convective clouds, to name a few symptoms. This choice of map times allows two charts to be examined before the time of the

[2] The charts for Ella, 1962 were not available in time to be included in this report

most significant intensification, permitting meaningful comparison with the control group.

3. CHARTS ANALYZED AND ANALYSIS METHODS

Several thickness charts were considered as a means of depicting the thermal field. For almost all situations, the 700-300-mb. and 500-200-mb. thicknesses were analyzed, as interest centers on the upper troposphere. In a few cases, the 1000-500-mb. and 300-150-mb. thicknesses were also examined. Shears of observed winds through the layer were plotted alongside thickness values. Actual temperatures at given levels were not seriously considered for analysis, even though this would locate features of interest more precisely in the vertical than would a thickness analysis. There is considerable irregularity in a radiosonde temperature trace, making it likely that frequent unrepresentative values would appear, a supposition well supported by experience. The reported thickness between two well-separated isobaric surfaces is relatively free from this type of random error. This is not so for systematic errors, a point to be discussed further.

Thickness Values vs. Shear Winds

In the analysis of thickness charts, the philosophy was adopted that orientation of the thickness contours approximately along the direction of the shear wind deserved highest priority, constructing thickness gradients in accordance with the strength of shear winds deserved lesser priority, and the thickness values themselves the least. Thickness values were of course drawn for insofar as possible, but in cases of marked conflict with the indications of the shears, they were adjusted quite freely.

This procedure may be justified by the following argument. From 500-200 mb. a systematic radiosonde error of 1°C. gives a thickness error[3] of 85 ft. The great majority of thicknesses need not be adjusted by more than this to produce a satisfying analysis, and 1°C. is not an uncommon systematic error. In the West Indies Network, several different radiosonde systems are in use and it is probable that calibration is not completely consistent among them. But it is instructive simply to show an example of a thickness analysis in which no thickness data have been modified at all (fig. 1). The huge anticyclonic shear system centered in the Bahamas, although stronger, has changed little in the past 48 hours. Thus, the thermal wind should serve as a rough approximation to the observed shears in this case, since major large-scale accelerations are not present. Retention of the exact thickness values leads to the thermal winds shown in table 1 in comparison with probable actual shears. Even more important are the gross distortions in the main synoptic features. The strong NE-SW trough shown across the Caribbean is not even suggested by the shears. In several places, shears of 50 kt. must cross contours at almost right angles.

To claim that imbalances of this magnitude do not occasionally exist

[3] For the purposed of this discussion, "error" also refers to data which may be measured correctly by the instrument but are representative of a smaller scale than we can be concerned with, given the existing density of observing stations.

Table 1. - Probable and computed shears (500-200-mb. layer). Shears were computed from analysis assuming that all reported thickness values were correct.

Location	Computed Shear		Probable Shear	
Leeward Islands	N	240 kt.	N	40 kt.
Puerto Rico	N	15	N	45
Southwest Caribbean	WSW	65	ENE	15
16°N., 69°W.	WNW	45	NNE	30
Southeastern Georgia	E	30	SW	30
Mobile, Ala.	NW	15	NNW	50

would be highly imprudent. But it is hardly likely that they would appear throughout the analysis area. (The examples in table 1 were deliberately chosen so that the vicinity of the developing hurricane is not included.) A suggested analysis for this case is shown in figure 2. In arriving at this solution, only two thickness reports were modified by more than 85 ft. (1°C. mean temperature change).

This example is a rather typical one; most charts analyzed in the manner of figure 1 will share its undesirable features. Before accepting the suggested analysis procedure as reasonable, it is natural to inquire about the accuracy of the observed shears, which must have some characteristic error distribution of their own. Several arguments may be advanced to support the contention that the shears are relatively more reliable than the thickness values, but for these purposes, an appeal to experience may not be out of order. In contrast to thickness patterns alone, shear patterns tend to form reasonable synoptic-scale systems which show excellent continuity from day to day. That actual winds are relatively more reliable in the Tropics than contour heights is widely accepted among synoptic meteorologists. These factors, combined with reluctance to accept widespread, large acceleration fields, lead to the author's belief that thickness analysis in the Tropics must place more emphasis on drawing for shears than for the thickness values.

It is fully recognized that the problem of constructing accurate, independent analyses of the field of motion and the thermal field is a crucial one. It is also a complex one and far from solution at this time, especially in the Tropics. This report will not attempt to become involved in the problem of imbalances. By constraining the thermal field to be as closely balanced with the shear winds as possible, we are prevented from examining a number of problems. For example, we cannot determine whether the anticyclonic shear region above a developing low-level cyclone precedes or follows the development of the warm core when the analysis procedure does not allow one to exist without the other.

Parameters Measured from Thickness Charts

Examination of the thickness charts immediately revealed many interesting features. But because an objective means of comparing different situations and different thickness charts is desirable, certain quantitative measurements were carried out, although perhaps not completely justifiably in view of the analytical uncertainties. Almost without exception, a warm center appeared in the immediate vicinity of the storm. The thickness value here was tabulated for each case. Since it quickly became apparent that the thickness pattern was at least as important as the absolute value of the thickness, the geostrophic vorticity of the thermal wind was estimated. This is

$$\zeta_{T_g} = (g/f)(\nabla_p^2 H)_o$$

or, in finite difference form,

$$\zeta_{T_g} \approx (4g/fd^2)(\overline{H} - H_o)$$

where ζ_{T_g} is the geostrophic vorticity of the thermal wind at a given point, H_o the thickness at that point, and $\overline{H}$ a suitable space mean thickness at a distance d from the point. A radius of 5° of latitude was chosen for d, and the space mean determined by averaging thickness values at eight points equally spaced around the circle.[4] The same procedure was used to determine the mean anticyclonic shear component (NOT the mean absolute value of the shear) at the same radius. 5° was an arbitrary choice of radius which appeared appropriate in most cases. For very large or very small storms, different radii would be more suitable. This is quite an important issue in the measurement of the anticyclonic shear component, which should probably be measured at the first shear maximum radially outward from the warm center. For the (perhaps dubious) sake of objectivity, this was not done in this study.

4. RESULTS AND DISCUSSION

After the analysis of the various thickness charts, the parameters discussed in the preceding section were tabulated in Appendix 2. Counting both developing and control cases, a total of 95 thickness charts were used for the tabulations. Of those 95, no less than 93 charts showed a warm center or strong warm ridge in the immediate vicinity of the low-level disturbance in question. Both exceptions were charts for the storm which became hurricane Daisy, 1962, an interesting case which will be commented upon later.

[4] An inconsistency was inadvertently introduced into these tabulations. It was discovered that for the first seven developing cases, the 5° circle was centered at the point of greatest thickness in the immediate vicinity of the storm, and for all other cases the center is the (vorticity maximum of the) low-level disturbance. In many cases, however, those points turn out to coincide, and in most others the difference introduced does not appear to be significant enough to warrant recomputation.

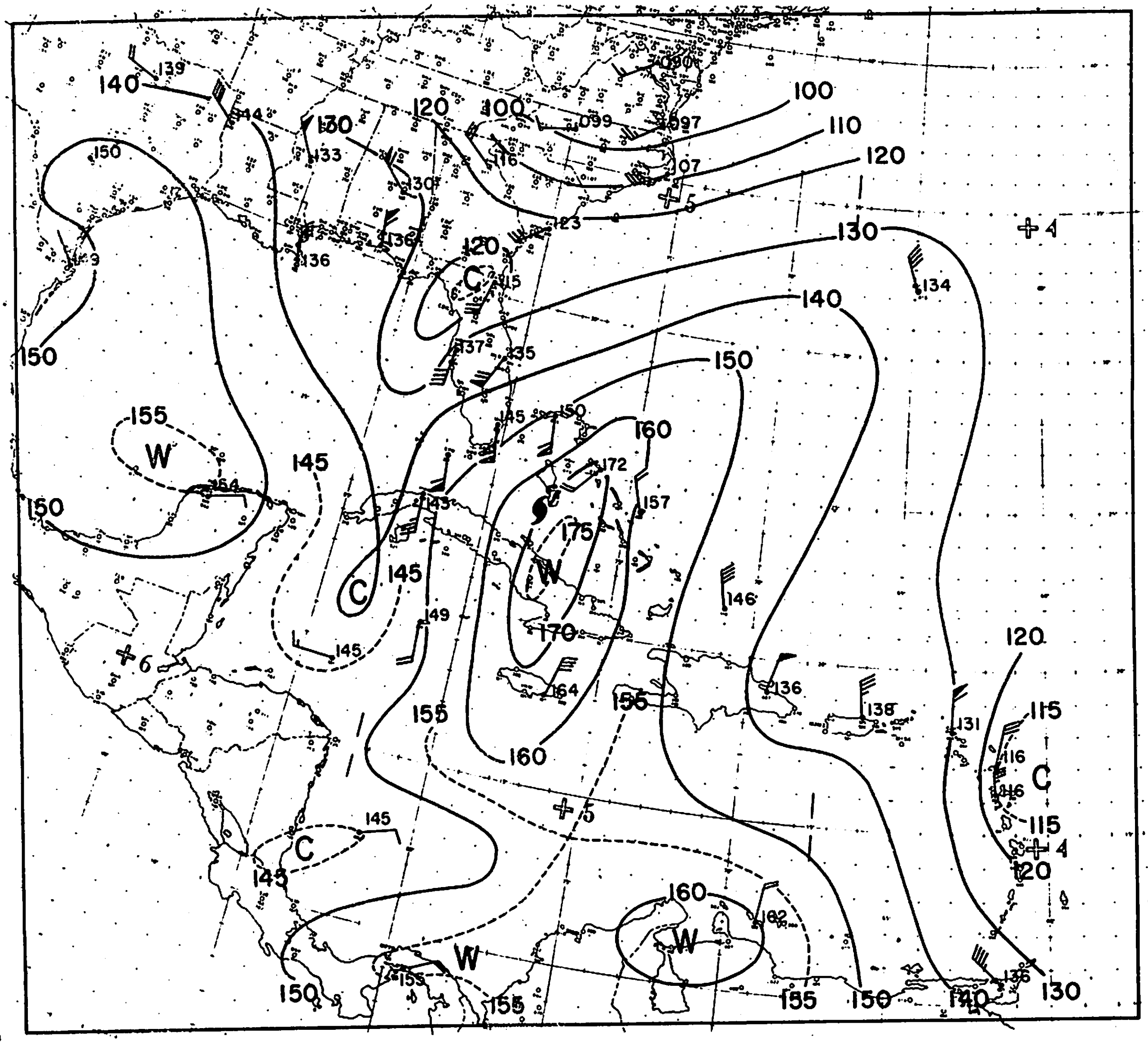

Figure 1. - 500-200-mb. thickness chart, 1200 GMT, October 6, 1958. The hurricane symbol ( ) marks the center of Janice, which has just attained hurricane force. Plotted at each station is the vertical shear of the horizontal wind from 500-200 mb. and the thickness value. First and last digits of thickness values are omitted. (140 = 21,400 ft., etc.) All thickness values were drawn for in this analysis.

If the thickness charts for Daisy, 1962, are omitted, 91 remain. Without exception, these charts show, in the immediate vicinity of the low-level disturbance, that H* is above the corresponding value for the mean tropical atmosphere, and ζ_{T_g} and $|\Delta V|_A$ are in the warm (anticyclonic) sense. (Symbols defined in table 2).

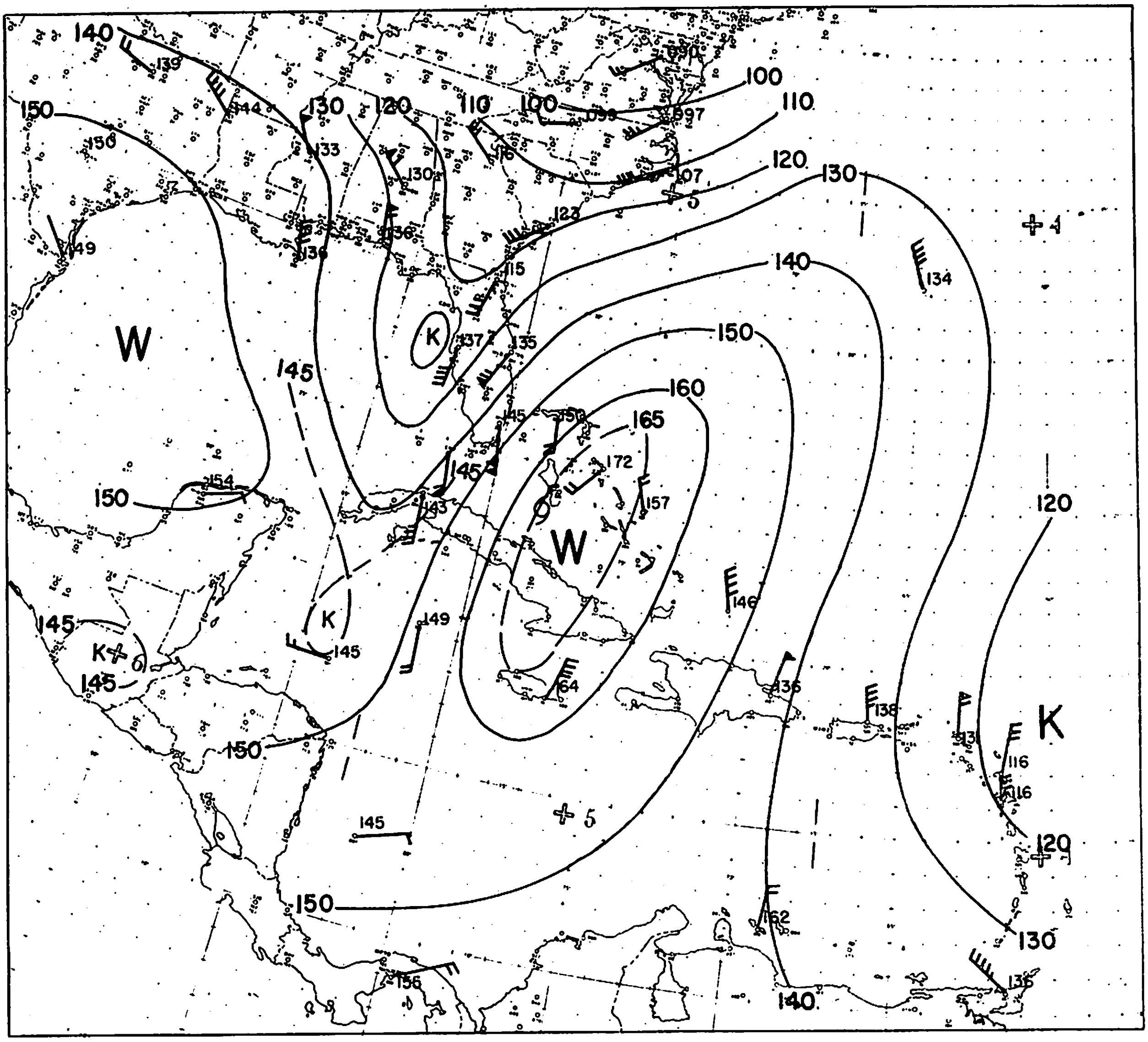

Figure 2. - Same as figure 1, except analyzed with higher priority given shears than thickness values.

Many authors have postulated the presence of anticyclonic flow in the upper troposphere above an incipient tropical cyclone (e.g. Riehl [6], Alaka [1], Yanai [7]). To the extent that this can come about only if the middle and upper troposphere over the disturbance is warmer than ambient conditions, the results here are consistent with earlier ideas. Indeed, the presence of a thermal ridge is a weaker condition than the existence of anticyclonic flow; it is quite possible for cyclonic vorticity to be present at 200 mb. in the same location as a 500-200-mb. thickness ridge so long as the 500-mb. vorticity is great enough.

Description of the Developing Cases

For convenience in the discussion, 500-200-mb. data for the 13 developing cases have been averaged and appear in table 2. The averaging process retains the time changes as the storm develops; the three columns are averages for the three map times analyzed for each storm. The thickness value in the warm region is well above the mean West Indies hurricane season value of 21,400 ft. (Jordan [4]) and changes very little as development proceeds. The other parameters, which are measures of the intensity rather than the absolute value of the warm region, show modest increases with time, mostly between the second and third map time, or concurrent with the storm's development.

Not all the individual storms have the characteristics of the mean picture just described. Frances, 1961, and the two 1962 storms show much weaker warm regions before intensification takes place. Gracie, 1959, has a warm region which is weakest just prior to intensification (although with a warm absolute value). But many of the variations may be due as much to faulty analysis as to physical reality, and as a rule, the mean picture seems to be fairly representative. The case of Hattie, 1961, is as typical as any. The 500-200-mb. charts for that storm are shown in figures 3-5.

Table 2. - Developing vs. nondeveloping cases. (500-200-mb. data.) The mean tropical atmosphere for the 500-200-mb. thickness is 21400 ft.

	H^* (ft.)	$-(\overline{H} - H_o)$ (ft.)	$-\zeta_{T_g}$ (10^{-5} sec.$^{-1}$)	$\overline{\lvert\Delta \mathbb{V}\rvert}_A$ (kt.)
Developing Cases: 13 storms for each map time.				
1st Map Time	21570	58	4.7	15
2d Map Time	21580	75	5.4	19
3d Map Time	21590	100	6.6	24
Nondeveloping Cases: 16 map times.				
Control Group	21530	52	3.7	11

H^* = thickness of the 500-200-mb. layer (highest value near low level disturbance).

$\overline{\lvert\Delta \mathbb{V}\rvert}_A$ = average anticyclonic wind shear for the 700-300 or 500-200-mb. layer. (See Appendix 2 for detailed explanation).

ζ_{T_g} = geostrophic vorticity of the thermal wind.

$\overline{H}$ = mean thickness 5° lat. for p_o, (8 values).

H_o = the thickness at p_o (center of the disturbance).

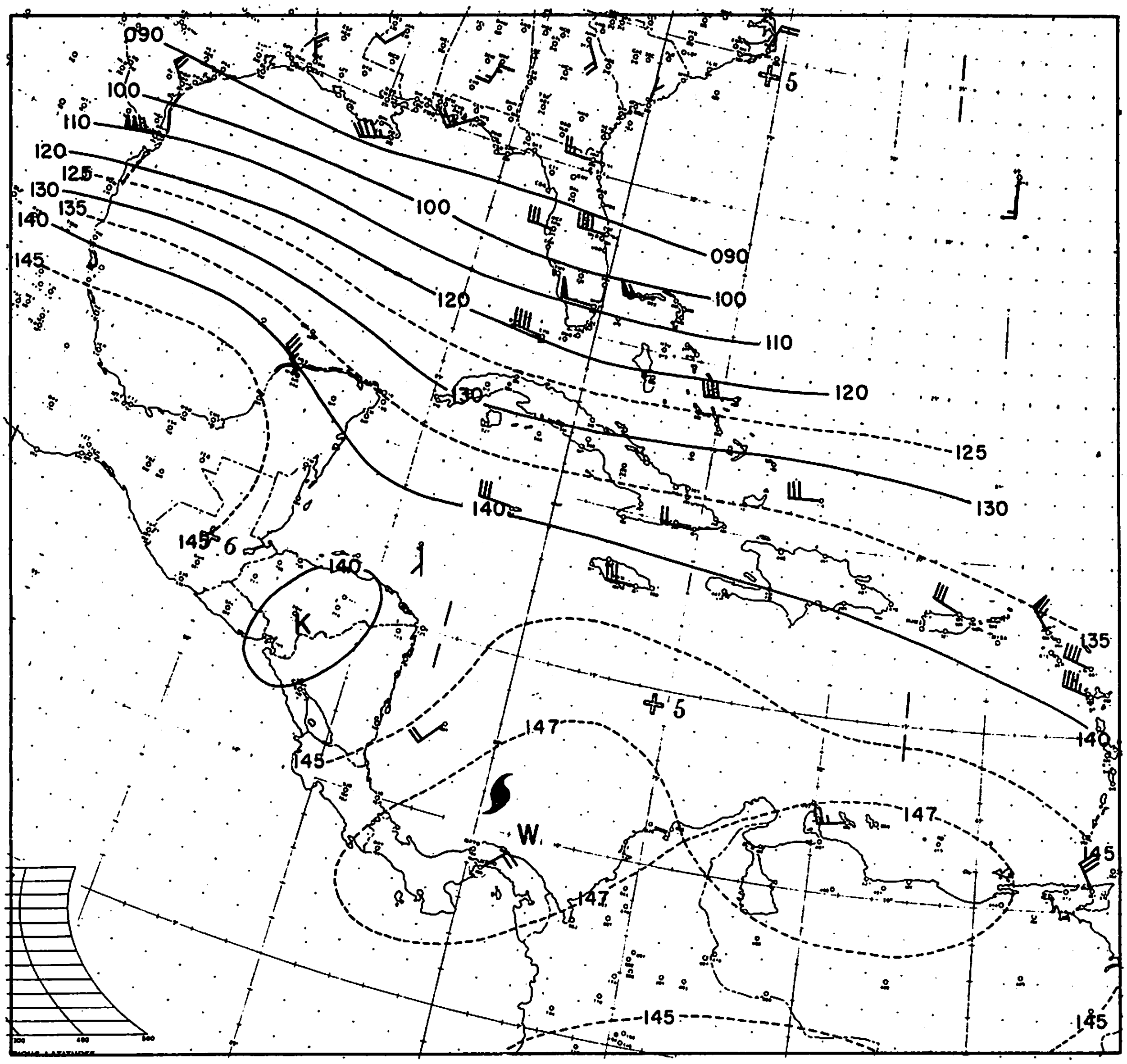

Figure 3. - 500-200-mb. thickness chart, 0000 GMT, October 26, 1961. The hurricane symbol marks the estimated location of the vorticity maximum of the low-level disturbance which later became Hattie. It is barely detectable at this time.

Developing vs. Nondeveloping Cases

A comparison of developing cases with the control group is made in table 2, in the mean. It shows that the upper troposphere is less warm and the warm region less intense in the control group. But here is where the averaging process has been misleading, for there is wide variation among the individual storms in the control group. No less than 8 of the 16 control cases have a warm region which is at least as intense as that of the average developing case 24 hours before rapid deepening starts. If the developing cases are considered at the second map time, when deepening is imminent, the difference is more significant, but even here, several of the control group approach

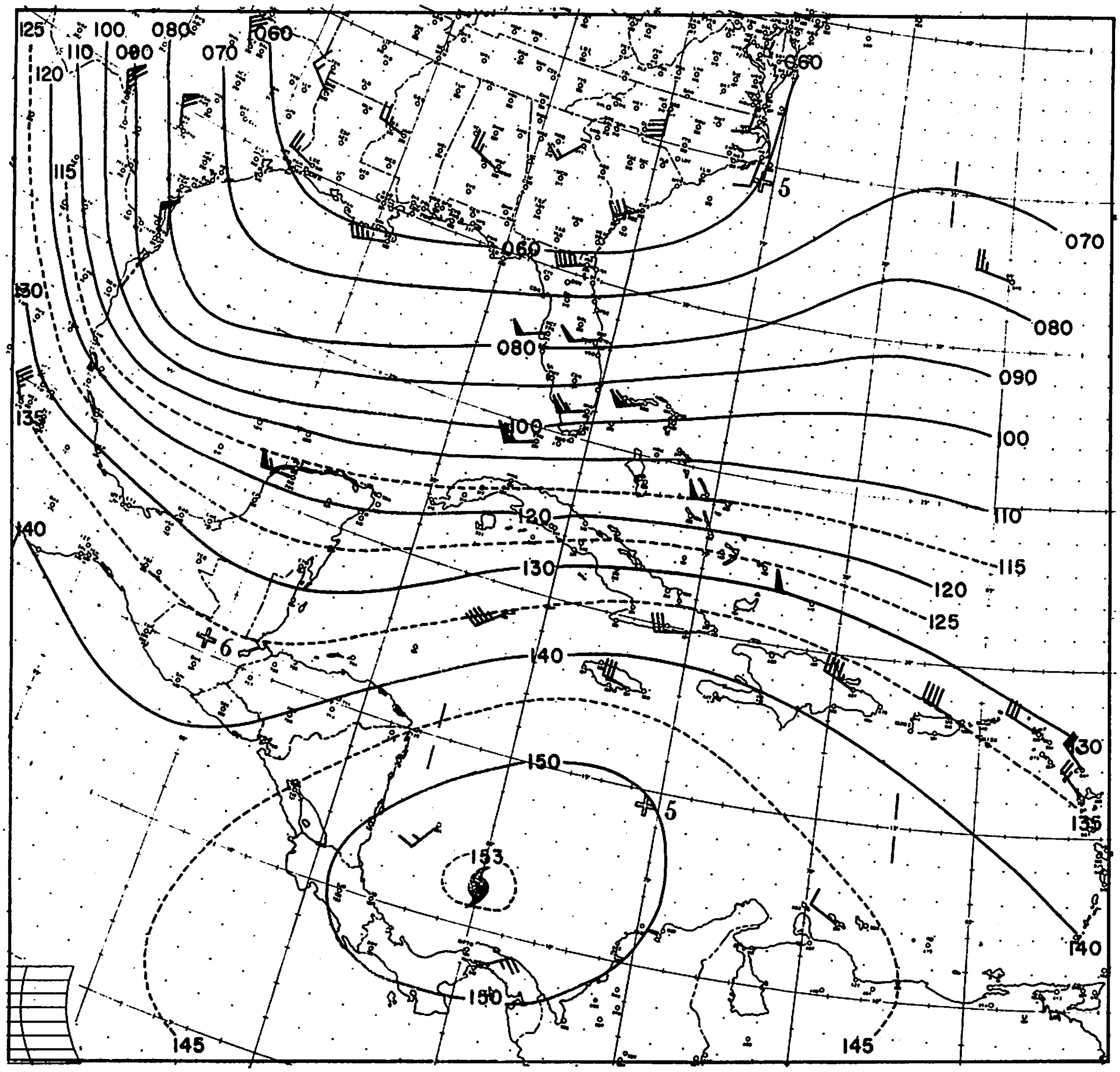

Figure 4. - 500-200-mb. thickness chart, 0000 GMT, October 27, 1961. The hurricane symbol marks the center of the tropical depression. Rapid intensification is about to begin.

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the average developing case. Of course, it would not be meaningful to consider the third map time, when the cyclogenesis has already taken place. There may be objections to including weak tropical storms in the control group, even though they maintained status quo or lost intensity. It turns out that the statistics for these storms are virtually identical with those of the control group as a whole.

Large vs. Small Storms

In view of the fact that about half the developing cases were large storms which deepened slowly and the other half small storms most of which deepened rapidly, it seemed reasonable to look for differences in the thermal structure on the synoptic scale. Omitting Ella and Daisy from the sample, the former because it was too far east for measurement on the first day, the latter

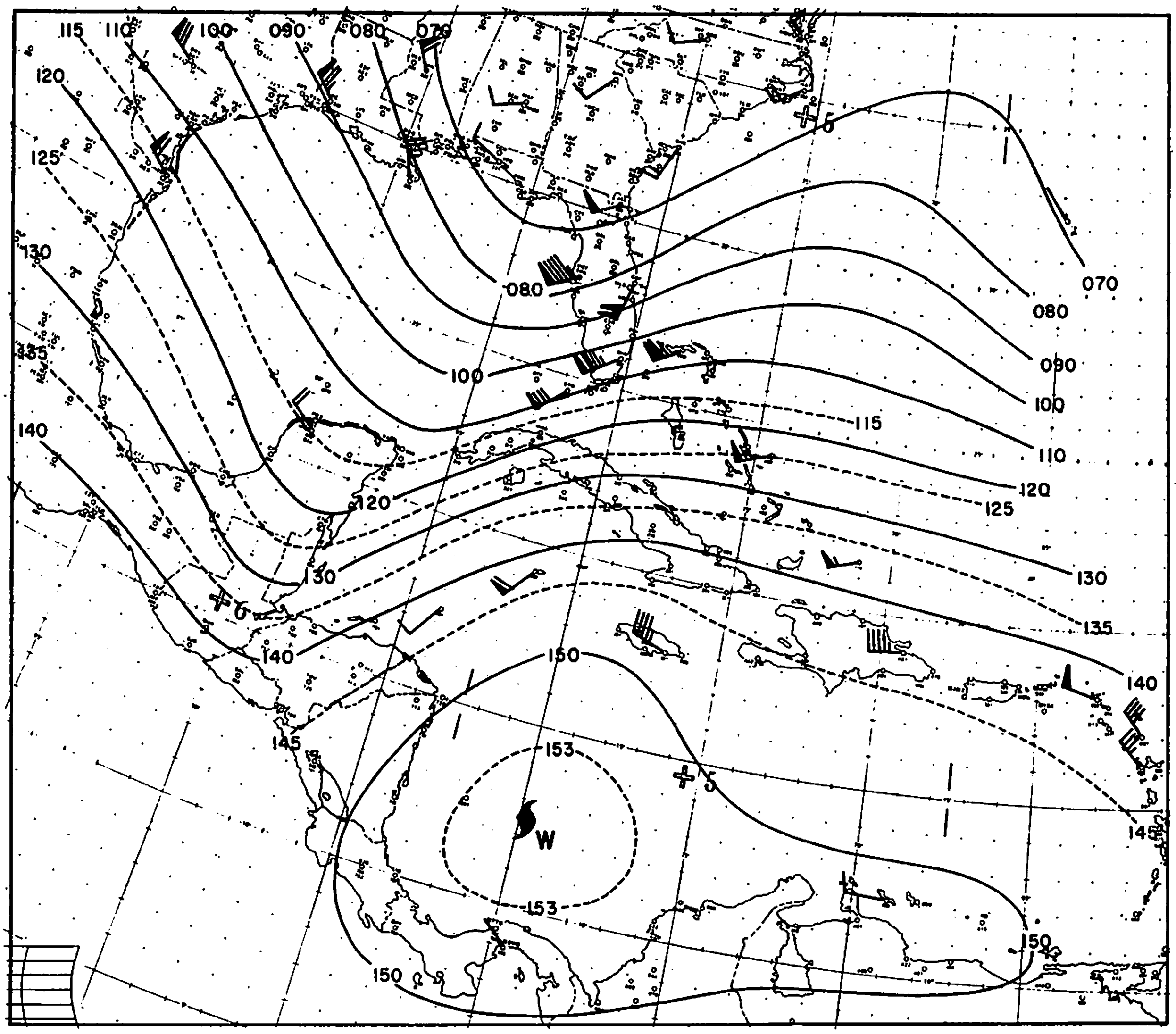

Figure 5. - 500-200-mb. thickness chart, 0000 GMT, October 28, 1961. Hurricane symbol marks the center of Hattie. The storm is still intensifying rapidly, has just reached hurricane force, and will shortly have winds of 110 kt.

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because it seemed to be a special case, five large storms and five small storms remain. These are compared in table 3. The thickness values are significantly greater for the large storms. But the intensity of the warm region is only slightly greater than that of the small storms.

Comparison of Different Thickness Charts

1. 700-300 mb. vs. 500-200 mb. For most of the developing cases and for the majority of the control group, 700-300 and 500-200-mb. charts were analyzed for the same map times, permitting a direct comparison. The appropriate tabulations for individual storms are in Appendix 2. These data have been averaged as described above, and the mean data are compared in table 4. The 500-200-mb. warm regions have central thickness values which are above

Table 3. - Large vs. small developing storms. (500-200-mb. data.) Mean tropical atmosphere, 500-200 mb. thickness is 21,400 ft. For definition of symbols see table 2.

	H* (ft.)	$-(\overline{H}-H_o)$ (ft.)	$-\zeta_{T_g}$ (10^{-5} sec.$^{-1}$)	$\overline{\lvert\Delta \mathbf{V}\rvert}_A$ (kt.)
5 Large Storms:				
1st Map Time	21610	72	5.7	20
2d Map Time	21620	86	6.0	21
3d Map Time	21650	114	7.4	27
5 Small Storms:				
1st Map Time	21520	68	5.5	15
2d Map Time	21550	76	5.9	17
3d Map Time	21560	94	6.3	27

the mean tropical values by a greater amount than those of the 700-300-mb. warm regions, and also have slightly greater intensity. The difference between the two charts is perhaps greater as development proceeds than it is at the first map time.

The difference between the two charts in describing the control group does not appear significant. Overall, there is slightly more difference shown between the developing cases and the control group on the 500-200-mb. than on the 700-300-mb. chart. For diagnostic or predictive value, then, the 500-200-mb. chart is to be slightly preferred. Another point in its favor is that it is an easier chart to analyze, because synoptic features are usually more distinct and gradients larger than on other charts considered. The existence of two primary regimes of flow in the Tropics has often been pointed out, and the high-level regime is usually centered near the 200-mb. level. The favorable characteristics of the 500-200-mb. chart are probably attributable to this fact. In summary, the 500-200-mb. chart is believed to be of slightly greater operational usefulness than the 700-300-mb. chart.

2. <u>The 1000-500-mb. chart</u>. This thickness chart did not show consistent patterns of warmth in the vicinity of the storms. One of the difficulties of this chart is that the appropriate interval over which to compute the shear is not clear. While this would be no problem in, say, the 850-500-mb. chart, any low-level shear determination in the vicinity of tropical storms will be the relatively small vector difference between two large and imperfectly measured values (low balloon elevation angles are probable). Tropical storms

Table 4. - 700-300-mb. and 500-200-mb. charts compared. Mean tropical atmosphere for 700-300-mb. thickness is 21,350 ft.; for 500-200-mb. thickness, 21,400 ft. For definition of symbols see table 2.

	H^* (ft.)	$-(\overline{H} - H_o)$ (ft.)	$-\zeta_{T_g}$ (10^{-5} sec.$^{-1}$)	$\overline{\lvert\Delta V\rvert}_A$ (kt.)
Developing Cases: 11 storms for each map time.				
700-300 mb.:				
1st Map Time	21480	65	5.4	15
2d Map Time	21490	64	4.7	16
3d Map Time	21500	86	5.8	19
500-200 mb.:				
1st Map Time	21570	69	5.7	17
2d Map Time	21590	80	5.8	22
3d Map Time	21610	100	6.8	26
Nondeveloping Cases: 9 map times.				
700-300 mb. Control Group	21470	58	4.1	9
500-200-mb. Control Group	21550	59	4.2	12

aside, the gradients on this chart are generally weak. All things considered, this is a most difficult chart to analyze correctly.

3. The 300-1500-mb. chart. This chart was investigated, and proved very interesting, although time did not permit a systematic evaluation. This layer encompasses most of the outflow region of tropical storms, without extending high enough to become involved with serious tropopause complications. A priori, it might be expected to reveal significant changes in cyclogenetic situations. Indeed, this layer showed the largest 24-hour changes of any studied. Its disadvantages are relatively weak gradients, reduced data coverage, and apparently reduced data accuracy; factors which make analysis quite difficult.

It is believed, though, that such high-level layers deserve further study as a means of representing the upper tropospheric thermal field.

Shears of Mean Layer Winds vs. Shears of Conventional Winds

Several times during the analysis of each chart, a shear was encountered which appeared questionable. These charts were not prepared under operational pressures, so time was available to check the soundings. In the great majority of the cases of questionable shears, the wind at either 500 mb. or 200 mb. was not representative of the winds just above and below. In many cases, a transmission error or a computational error was involved, and in some other cases, the wind was probably real. Whatever the cause of the report, however, a more reasonable and satisfying analysis of the thickness chart almost always results if the shear is determined as the vector difference between two winds, each of which represents a fairly deep layer centered at its level.

Colón and Zipser [3] have discussed the use of the "mean layer wind", which is determined by the balloon displacement over a deeper layer than that used for the standard short-time wind. The mean layer winds are computed on an operational basis at stations throughout the Caribbean region for 3000-10,000 ft., 17,000-23,000 ft., and 37,000-42,000 ft. It seemed reasonable to experiment with the 500-200-mb. thickness chart using for shears the vector difference between the second and third mean layer winds in place of the 500-mb. and 200-mb. winds. The result was a more satisfying set of shears which displayed improved time and space continuity. While the necessity of checking the soundings was not eliminated, the time consumed in so doing was reduced.

When the shear of mean layer winds is used, there may be a bias toward its having a systematically smaller magnitude than the shear of the 500 and 200-mb. winds. It is not clear to what extent this is true and to what extent it needs to be considered when analyzing the charts.

5. COMMENTS ON THE OPERATIONAL USEFULNESS OF THE 500-200-MB. THICKNESS CHART

In compiling the statistics tabulated in Appendix 2, a circle of 5° radius was arbitrarily chosen for the purpose of obtaining an objective measure of the intensity of the warm regions. It is believed that this is unnecessary and in a few cases even undesirable in an operational situation. The important question is whether an appreciably warm region is physically present above the storm, not whether it is detectable by some specific arbitrary process. In an individual case, it may be apparent at a glance that a 5° circle is a poor choice. For example, the warm region connected with Alma was rather close to a cold trough just to the west. Figure 6 shows how using a 5° radius affected the shear determination on August 28, by including cyclonic values which clearly do not represent the true physical structure of the storm area. Casual examination correctly reveals that the warm region is quite intense, with strong anticyclonic shear in all quadrants.

One possible approach to the situation would be first to analyze the 500-200-mb. thickness chart, giving the observed shears their due weight. Select the location where cyclogenesis appears most possible. This might be the point of maximum cyclonic vorticity of the low-level wind, or the cyclonic singular

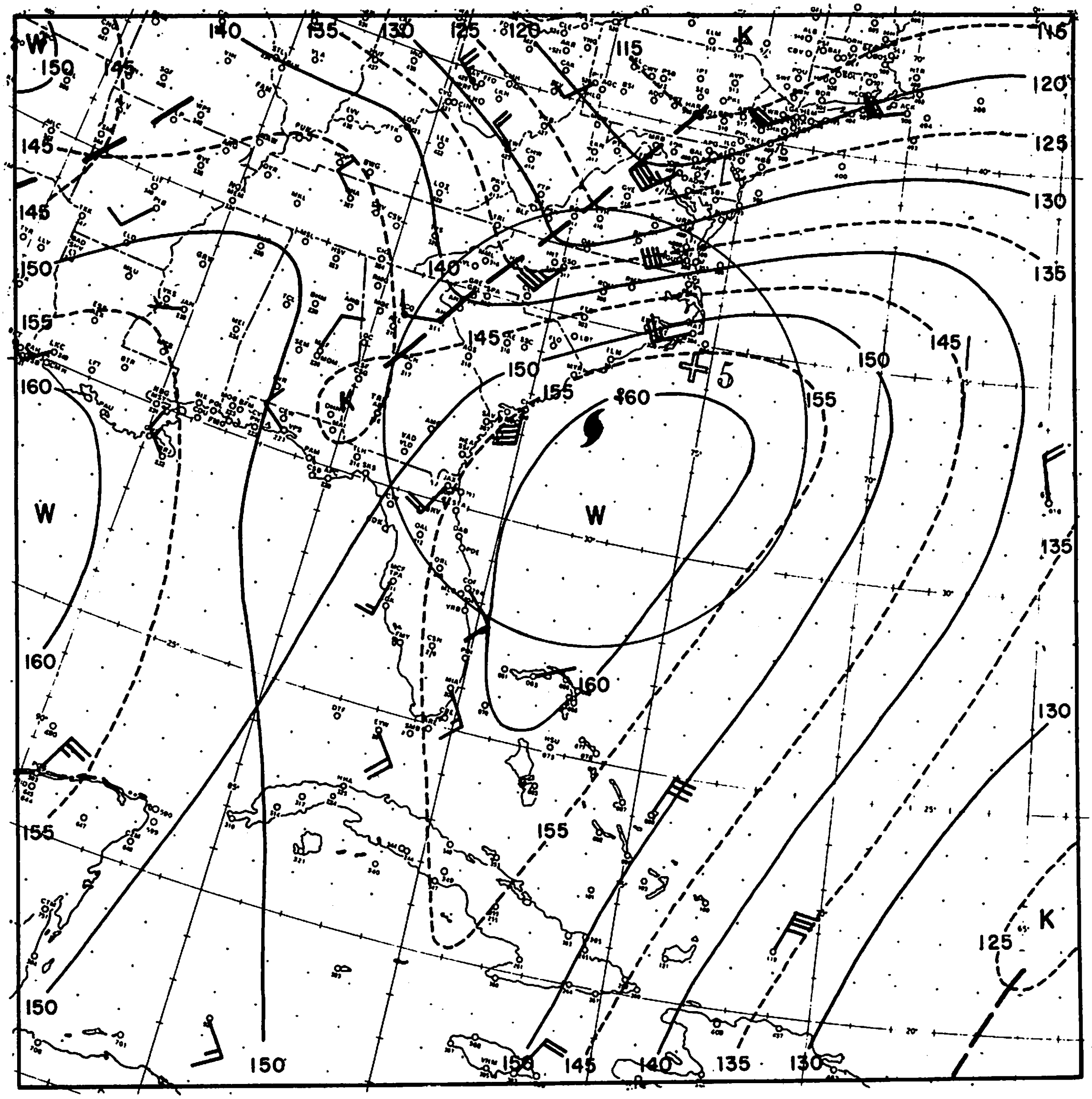

Figure 6. - 500-200-mb. thickness chart, 0000 GMT, August 28, 1962. Hurricane symbol marks the center of Alma, whose maximum winds are about 60 kt. at this time. Note that the 5° radius circle crosses the cold trough over the eastern Appalachian Mountains.

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point of a depression. <u>If</u> there is any ambiguity in selection of the point from low-level considerations only, it is suggested that it be chosen as close to the anticyclonic thermal vorticity maximum on the 500-200-mb. chart as is reasonable. (This is probably where the 5° circle used in this study should have been centered.)

Having chosen the point, the greatest thickness in its immediate vicinity can be noted and compared with those in this report. The intensity can be determined quite well by inspection, looking primarily at the strength of the anticyclonic shear circulation about the point. If the point is in a flat warm region, however, the existence of a strong shear circulation at a large distance is not pertinent unless the disturbance being considered is also very large.

Turning to the interpretation of the chart, it is apparent that the existence of a warm region over a storm does not guarantee its intensification. Far from it; many disturbances in the nondeveloping control group were associated with warm regions of at least moderate intensity. Evidently, warmth is not a sufficient condition. It does, however, appear to be a necessary condition.

One could also say necessary <u>prior</u> condition, prior meaning at least 24 hours in advance, if it were not for the case of Daisy, 1962, whose thickness charts are shown in figures 7-10. In all other storms, a warm region was present 24 hours prior to intensification, while in Daisy the warming may have preceded the intensification only by a short time. The statement has to be qualified, because the sparse data coverage does not permit an analysis that the author is willing to defend too strongly. One conclusion is inescapable, however. Even if Daisy were warm before October 3, this warmth became much more pronounced on that day, for the evidences of warming appeared at the island stations as the storm was moving away from them. Data from NHRP research aircraft from 1700-2300 GMT on October 2 (550 mb.) do not show the storm to be warmer than its environment at that time.

The cases studied here seem to support the following tentative conclusions:

(a). If a suspicious disturbance is found to be cold, or to be associated with a warm region of only minimal strength, the conditions for appreciable tropical cyclogenesis probably do not exist, and probably will not exist for at least 24 hours.

(b). If a small suspicious disturbance is found to be warm, and the warm region above minimal intensity, the forecast problem is as great as ever. For the data here show that many such disturbances never deepen at all, while rapid, even "explosive" deepening may begin in a matter of hours in other cases. While the presence of a warm region of above average intensity, or one which has undergone a recent increase in intensity, has to be considered a favorable factor for cyclogenesis, it has not yet been demonstrated that this is sufficient cause to forecast such.

(c). If a large suspicious disturbance is found to be warm, and the warm region above minimal intensity, there is perhaps slightly more to go on. It appears that a fairly large moderately intense warm region, with fairly high central thickness value, is favorable for development. (Daisy is a shattering exception !). In any case, no large storm deepened rapidly, but this is information which did not come from analysis of thickness charts.

(d) If the storm in question is far enough away from the warm center to be in strong shear (as shown on the 500-200-mb. chart), only slow intensification is likely even if other factors are favorable. It does not seem necessary for development that the warm center <u>coincide</u> with the disturbance, however.

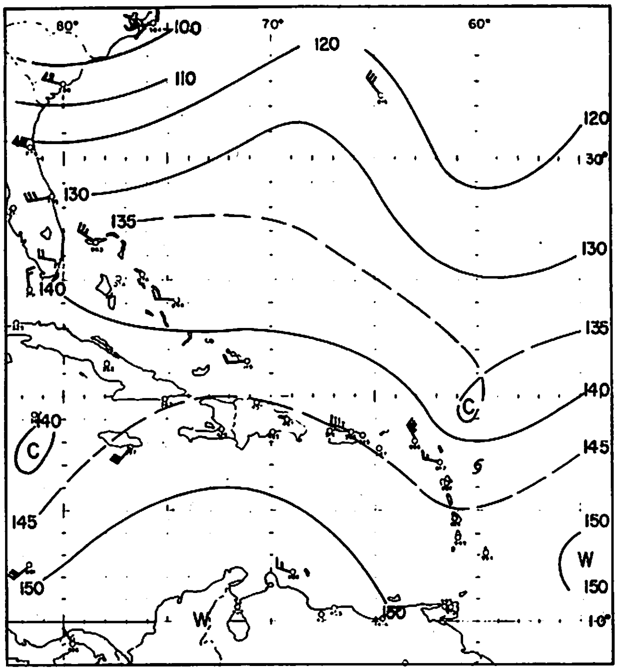

Figure 7. - 500-200-mb. thickness chart, 0000 GMT, October 1, 1962. Hurricane symbol marks the center of Daisy, with maximum winds about 35 kt.

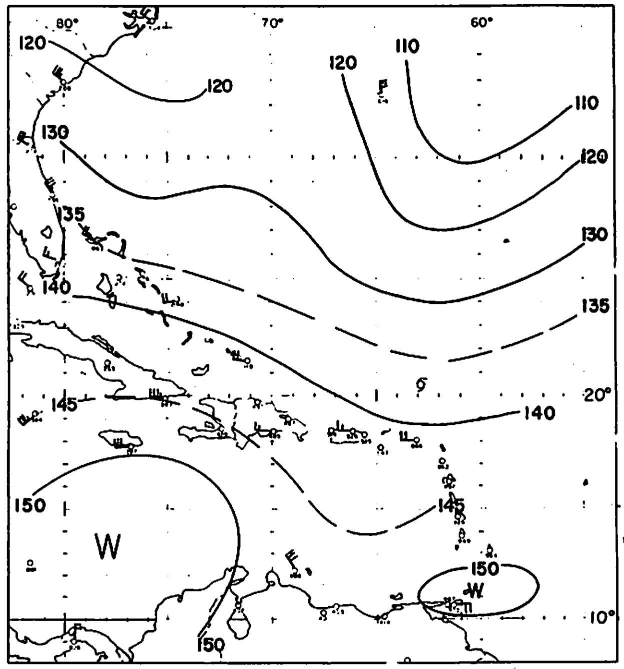

Figure 8. - 500-200-mb. thickness chart, 0000 GMT, October 2, 1962. Hurricane symbol marks the center of Daisy, with maximum winds about 35 kt.

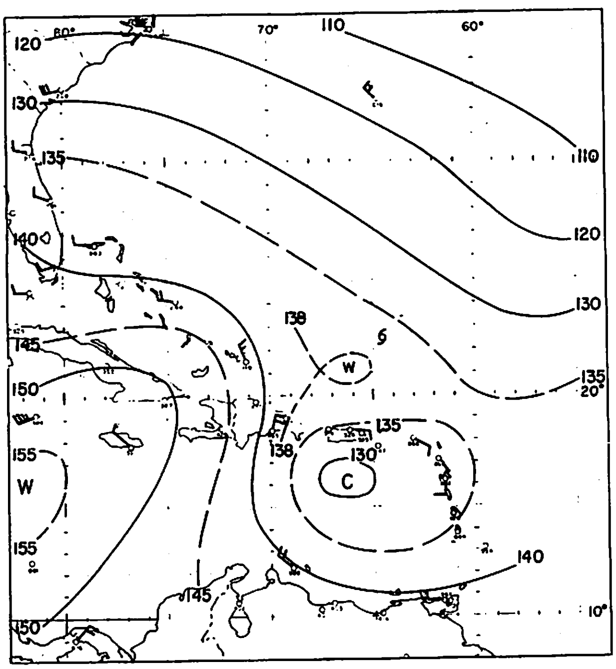

Figure 9. - 500-200-mb. thickness chart, 0000 GMT, October 3, 1962. Hurricane symbol marks the center of Daisy, with maximum winds about 40 kt.

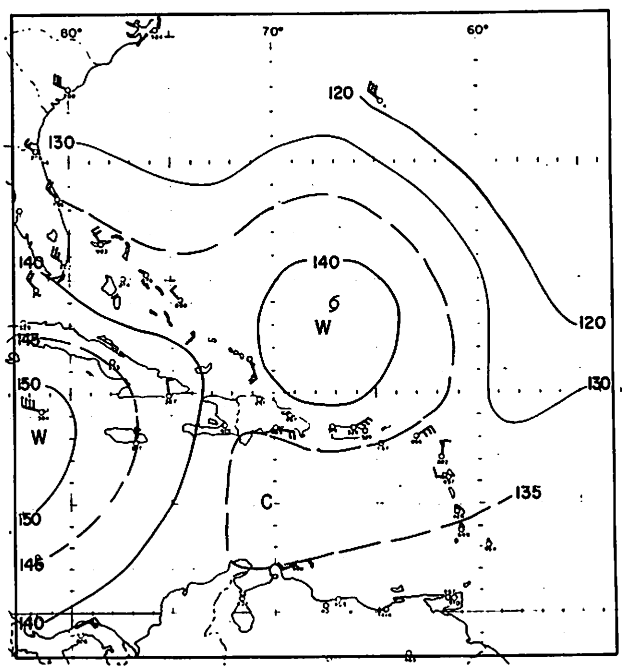

Figure 10. - 500-200-mb. thickness chart, 0000 GMT, October 4, 1962. The symbol marks the center of Daisy, with maximum winds of about 55 kt. The storm will become a hurricane during this day.

As the disturbance is followed from day to day, and the thickness chart examined concurrently, the situation often arises where it appears that the disturbance is about to enter a cold region. This might be considered to be a sign that deepening will not take place. But in the author's experience, a frequent occurrence has been that the warmth of the disturbance overwhelms the cold region, or that the cold region moves at the same speed as the disturbance and always stays ahead of it. It should be kept in mind that the presence of cold air adjacent to the warm region increases the anticyclonic shear and thermal vorticity of the warm region. In a few cases, deepening occurred at just that time when a cold trough deepened to the west of the storm, or moved into that region from middle latitudes. In the latter case, it may be possible to forecast that the trough will remain west of the storm, remain strong, and move little. If so, two alternatives are suggested by this study. The storm may continue westward and lose intensity when it enters the cold region, or, more likely, the storm may turn northward, remain warm, and perhaps intensify as it does so.

It may be in order to show an example of a situation where the findings of this report might have been useful. The second case in the control group is tropical storm Florence, 1960. On September 19, 0000 GMT, Florence, with maximum winds reported at 45 kt., was located just southwest of Grand Turk Island, about 60 mi. from a location occupied by the destructive hurricane Donna less than 12 days previously. Continuation of past motion would have placed the storm in the western Bahamas in 24 hours, approaching the south Florida coast. The forecast of its intensity in the next 24 hours was therefore a highly critical and sensitive problem. The thickness chart for this case, figure 11, shows that while a small warm region exists over the storm, it is of very minimal intensity. (Note Appendix 2.) A forecast of little or no deepening in 24 hours might be made on this basis. Twelve hours from this map time, the storm had not only failed to deepen, but lost intensity to such an extent that a Navy reconnaissance aircraft could not find a center. (The actual forecasts in this case were excellent; and the author is not implying that he would have the courage to issue a "no deepening" forecast in a similar situation even were he armed with the results of this study at the time.)

6. SUMMARIZING STATEMENTS

Of the four thickness charts considered, the 500-200-mb. chart appears to be the most useful in defining the thermal field in the vicinity of developing tropical cyclones, with the 700-300-mb. chart a close second. The use of mean layer winds can be recommended as being mildly superior to the reported 500-mb. and 200-mb. winds in defining the appropriate shear through the layer. The shears must be weighted more heavily than the reported thickness values in analysis.

The existence of a warm region of greater than minimal intensity in the upper troposphere over the immediate vicinity of a surface disturbance is a favorable but not sufficient condition for tropical cyclogenesis. With the glaring exception of Daisy, 1962, all developing cases in this sample were associated with such warm regions at least 24 hr. prior to the most significant intensification. This fact is made less useful to the forecaster by the

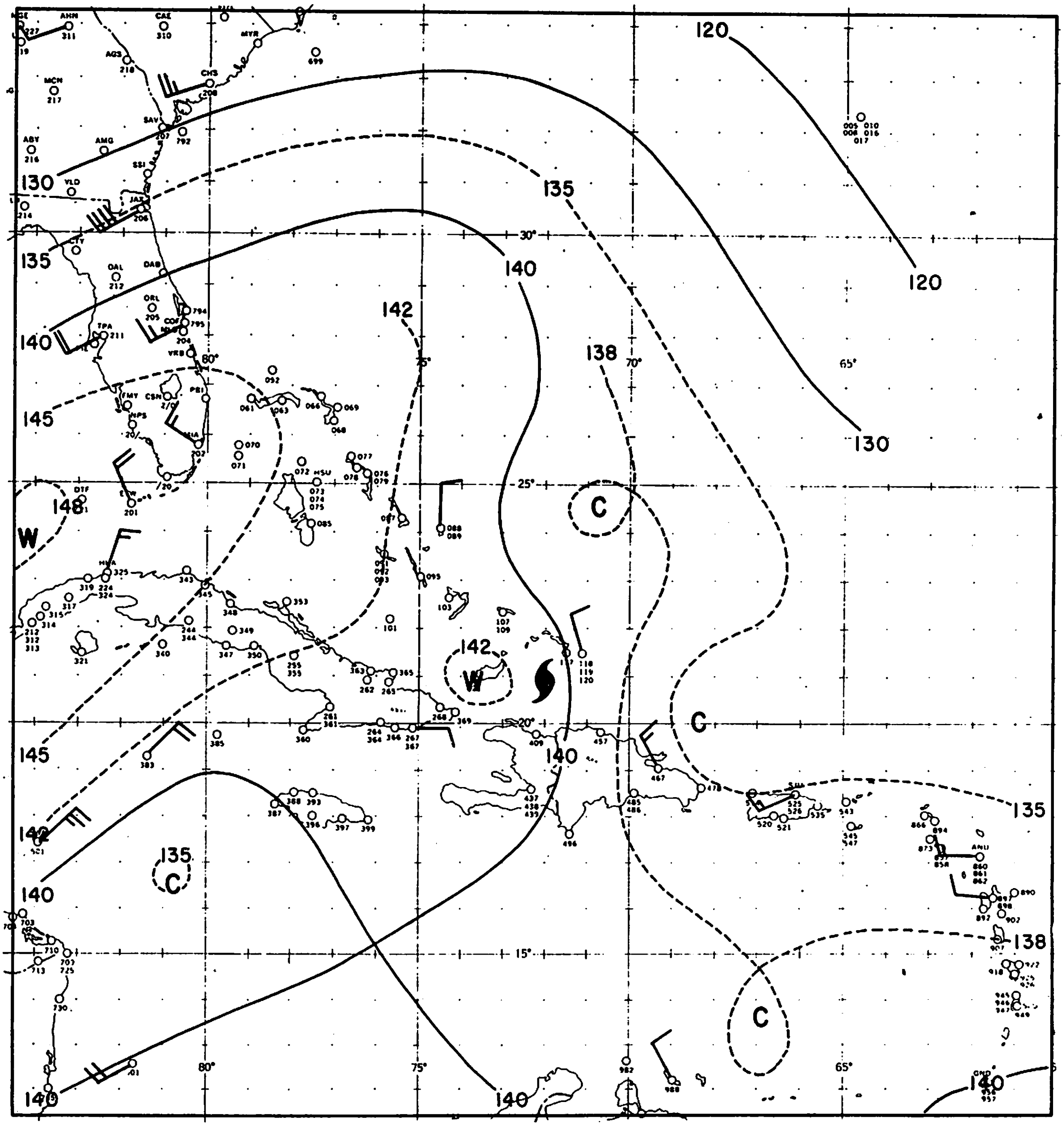

Figure 11. - 500-200-mb. thickness chart, 0000 GMT, September 19, 1960. The symbol marks the center of Florence, with maximum winds of about 45 kt. at this time.

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finding that all nondeveloping cases except Daisy were also in warm regions, but in some cases these were minimal.

As a rule, significant time changes in the strength of the warm regions were not observed in the 24 hr. prior to the most significant cyclogenesis.

More frequently, the cyclogenesis itself was accompanied by intensification of the warm region.

It is emphasized that the scope of this study is confined to features discernable from the existing synoptic network under semi-operational conditions. Nothing can be said about the convective and meso-scale thermal and wind patterns that may exist. The very nature of the available data, and the analysis techniques adopted because of the limitations of the data, preclude any discussion of the imbalances that are certain to exist in any developing situation.

ACKNOWLEDGMENTS

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Appendix 1 — Characteristics of Storm Studied

A. Developing Cases

Identification	Size (extent) during developing stages	Rate of development	Characteristics of wind increase* during most rapid development	24-hour period of most rapid development begins
Ella, 1958	small	rapid	25-65 kt in 24 hr	12Z 8/30/58
Janice, 1958	large	mod. slow	38-65 kt in 24 hr 30-65 kt in 33 hr	12Z 10/5/56
Debra, 1959	small	rapid	30-65 kt in 20 hr	00Z 7/24/59
Gracie, 1959	small	very rapid	25-75 kt in 24 hr	00Z 9/22/59
Judith, 1959	large	slow**	30-50 kt in 24 hr	00Z 10/17/59
Brenda, 1960	large	slow	30-45 kt in 24 hr	00Z 7/26/60
Ethel, 1960	small	very rapid	25-140 kt in 24 hr	00Z 9/14/60
Carla, 1961	large	slow	30-65 kt in 60 hr	slow, steady development begins near 00Z 9/4/61
Frances, 1961	small	mod. slow	50-76 kt in 24 hr	12Z 10/3/61
Gerda, 1961	large	slow	35-55 kt in 24 hr	00Z 10/19/61
Hattie, 1961	small	rapid	40-65 kt in 24 hr 50-110 kt in 24 hr	00Z 10/27/61
Alma, 1962	medium	slow	40-60 kt in 24 hr	12Z 8/27/62
Daisy, 1962	large	slow	40-55 kt in 24 hr	00Z 10/3/62

B. Control Group

Bahamas Wave	Small wave was intensifying until 12Z, 9/17/60, after which it weakened in Western Bahamas.
Florence, 1960	Remained at same intensity for 12 hr prior to 00Z, 9/19/60, then weakened from 45-25 kt in next 12 hr
Gulf Wave	Very short deepening of wave in Gulf of Mexico prior to 12Z, 8/18/61, then weakened in West Gulf.
Florida Vortex	Small vortex failed to deepen either east or west of Florida peninsula, which it crossed on 8/29/61, 03-12Z.
Isle of Pines Vortex	Very slight deepening of system until 12Z, 8/30/61, then weakened west of Isle of Pines.
Frances, 1961	No appreciable change in intensity for 48 hr after 12Z, 10/1/61. (about 45 kt)
Gerda, 1961	No appreciable change in intensity for 24 hr after 12Z, 10/17/61. (about 35 kt)
Alma, 1962	No appreciable change in intensity for 48 hr after 12Z, 8/24/62. (about 30 kt)
Daisy, 1962	No appreciable change in intensity for 36 hr after 00Z, 10/1/62. (about 40 kt)

* Author's estimate, based on study of available observations.
** Superimposed upon this large envelope, slow intensification, a small eye formed rapidly late on Oct. 17 with winds to 65 kt, then dissipated rapidly. (See LaSeur [5] for discussion of this case.)

Appendix 2 — Parameters Measured from Thickness Charts

A. Developing Cases

Identification	Chart time	H* (ft)	$-(\bar{H}-H_o)$ (ft)	$-\zeta_{T_g}$ ($10^{-5}sec^{-1}$)	$\lvert\Delta V\rvert_A$ (kt)	H* (ft)	$-(\bar{H}-H_c)$ (ft)	$-\zeta_{T_g}$ ($10^{-5}sec^{-1}$)	$\lvert\Delta V\rvert_A$ (kt)
		500-200 mb data				700-300 mb data			
Ella, 1958	12Z Aug 29*	...	...	...	...	...	...	...	...
	12Z Aug 30	21600	50	4.6	21	21460	40	3.7	12
	12Z Aug 31	21570	60	5.5	26	21500	50	4.6	13
Janice, 1958	12Z Oct 4	21610	80	7.3	23	21470	80	7.3	17
	12Z Oct 5	21610	110	8.6	20	21450	100	7.8	18
	12Z Oct 6	21690	170	11.6	35	21450	100	6.8	23
Debra, 1959	00Z Jul 23	21550	70	4.2	25	21470+	70	4.2	18
	00Z Jul 24	21620	100	5.7	25	21510	90	5.1	23
	00Z Jul 25	21630	120	6.6	38	21500	110	6.0	31
Gracie, 1959	00Z Sept 21	21520	110	8.6	18	21460	80	7.3	17
	00Z Sept 22	21560	50	3.7	15	21470	70	5.2	17
	00Z Sept 23	21550	110	7.5	24	21470	110	7.5	17
Judith, 1959	00Z Oct 16	21630	60	4.5	17	21550	60	4.5	11
	00Z Oct 17	21630	70	4.8	23	21620	70	4.8	18
	00Z Oct 18	21630	70	4.2	22	21580	60	3.6	15
Brenda, 1960	00Z Jul 27	21590	110	6.7	22	21470	40	2.4	11
	00Z Jul 28	21650	120	6.8	29	21510	90	5.1	20
	00Z Jul 29	21690	120	6.4	29	21580	150	8.0	28
Ethel, 1960	00Z Sept 13	21620	90	6.7	15	21500	90	6.7	16
	00Z Sept 14	21610	110	7.5	18	21460	60	5.0	14
	00Z Sept 15	21580	100	6.3	27	21450	70	4.4	13
Carla, 1961	12Z Sept 3	21540	40	5.0	20	21500	20	2.5	17
	12Z Sept 4	21590	40	4.4	21	21480	10	1.1	13
	12Z Sept 5	21650	80	7.6	29	21580	60	5.7	22
Frances, 1961	12Z Oct 2	21430	40	3.9	3	21370	50	4.8	8
	12Z Oct 3	21460	70	5.7	9	21410	50	4.1	10
	12Z Oct 4	21500	100	6.5	20	21430	80	5.2	14
Gerda, 1961	00Z Oct 18	21670	70	5.0	16	21590	120	8.5	20
	00Z Oct 19	21620	90	5.5	10	21530	100	6.1	15
	12Z Oct 19**	21610	130	7.1	22	21500	150	8.2	16
Hattie, 1961	00Z Oct 26	21490	30	4.2	13	21450	40	5.6	15
	00Z Oct 27	21530	50	7.0	19	21460	20	2.8	12
	00Z Oct 28	21550	40	4.7	27	21450	30	3.6	16
Alma, 1962	00Z Aug 26	21570	10	0.7	6	...	...	...	...
	00Z Aug 27	21610	80	4.5	10	...	...	...	...
	00Z Aug 28	21620	120	5.9	13	...	...	...	...
Daisy, 1962	00Z Oct 2	None	0	0.0	-2	...	...	...	...
	00Z Oct 3	21380	30	2.0	4	...	...	...	...
	00Z Oct 4	21450	80	5.2	19	...	...	...	...

Appendix 2—contd

B. Control Group

Identification	Chart time	H^* (ft)	$-(\bar{H}-H_o)$ (ft)	$-\zeta_{T_g}$ ($10^{-5}sec^{-1}$)	$\overline{\lvert\Delta V\rvert_A}$ (kt)	H^* (ft)	$-(\bar{H}-H_o)$ (ft)	$-\zeta_{T_g}$ ($10^{-5}sec^{-1}$)	$\overline{\lvert\Delta V\rvert_A}$ (kt)
		500-200 mb data				700-300 mb data			
Bahamas Wave	12Z Sept 17	21560	80	4.9	17	...	...	...	...
Florence, 1960	12Z Sept 18	21430	60	4.5	7	...	...	...	...
	00Z Sept 19	21420	20	1.5	3	...	...	...	...
Gulf Wave	00Z Aug 16	21530	50	3.3	10	21460	40	2.6	10
	00Z Aug 17	21500	20	1.2	9	21470	40	2.4	12
	00Z Aug 18	21600	90	5.1	18	21520	50	2.8	14
Florida Vortex	12Z Aug 28	21520	60	3.6	16	...	...	...	...
	12Z Aug 29	21560	60	3.4	17	21500	80	4.5	12
Isle of Pines Vortex	12Z Aug 29	21570	70	5.2	15	21470	30	2.2	5
	12Z Aug 30	21580	70	5.0	15	21510	60	4.3	7
Frances, 1961	12Z Oct 1	21460	70	6.4	8	21360	50	4.6	6
	00Z Oct 2	21450	40	3.6	6	21340	50	4.6	3
Gerda, 1961	12Z Oct 17	21670	60	4.5	10	21570	120	8.9	16
Alma, 1962	00Z Aug 24	21520	60	4.9	16	...	...	...	...
	00Z Aug 25	21540	50	3.7	8	...	...	...	...
Daisy, 1962	00Z Oct 1	None	-20	-1.8	-4	...	...	...	...

Explanation of symbols:

* Storm too far East for quantitative description.

** Storm too far North for quantitative description at 00Z Oct 20.

H^* Highest thickness value in immediate vicinity of low-level disturbance.

H_o Thickness value at a point p_o located over the low-level disturbance

$\bar{H}$ Mean thickness value at a distance 5° latitude from p_o, determined by averaging 8 points equally spaced along the circumference of a circle of radius 5° latitude centered at p_o.

ζ_{T_g} Vorticity of the thermal wind at p_o, determined geostrophically from $(\bar{H}-H_o)$.

$\overline{\lvert\Delta V\rvert_A}$ At each of the 8 points on the 5° latitude circle described above, the observed wind shear through the (700-300 mb or 500-200 mb) layer is ΔV. This vector is resolved into radial and tangential components with respect to p_o, the tangential component being considered positive when anticyclonic. This $\lvert\Delta V\rvert_A$ is averaged for the 8 points to yield $\overline{\lvert\Delta V\rvert_A}$