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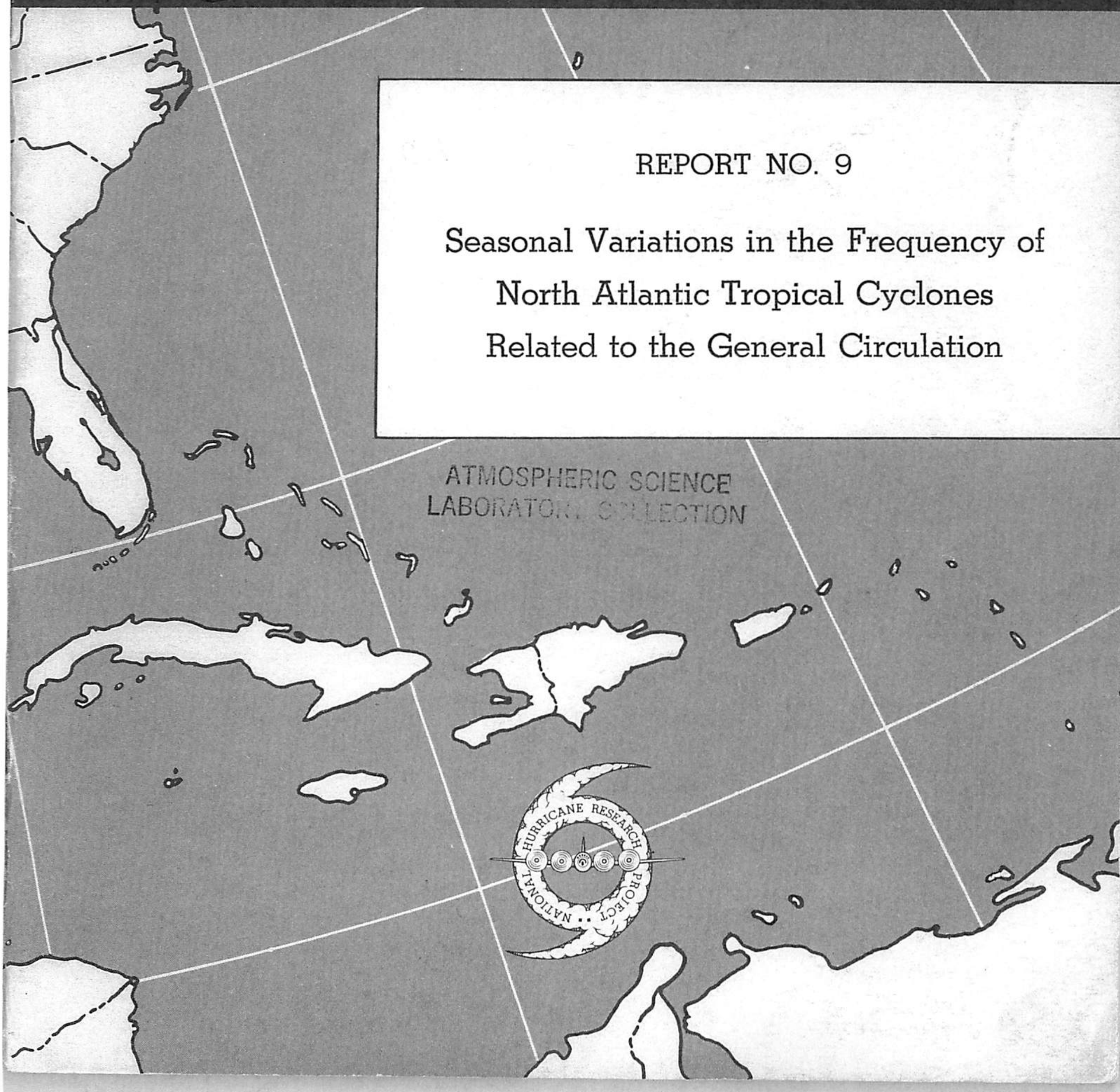

REPORT NO. 9

Seasonal Variations in the Frequency of North Atlantic Tropical Cyclones Related to the General Circulation

U. S. DEPARTMENT OF COMMERCE
Sinclair Weeks, Secretary
WEATHER BUREAU
F. W. Reichelderfer, Chief

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Emanuel M. Ballenzweig
Extended Forecast Section, U. S. Weather Bureau

Washington, D. C.
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NATIONAL HURRICANE RESEARCH PROJECT REPORTS

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Commerce-Weather Bureau, Washington, D. C.

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SEASONAL VARIATIONS IN THE FREQUENCY OF NORTH ATLANTIC TROPICAL CYCLONES RELATED TO THE GENERAL CIRCULATION

Emanuel M. Ballenzweig
Extended Forecast Section, U. S. Weather Bureau, Washington, D. C.

ABSTRACT

Tropical cyclone frequencies in the North Atlantic and along the coastal areas bordering on its western perimeter are related to mean patterns of the general circulation of the order of a season. In some hurricane seasons certain regions are relatively free of tropical cyclones while other areas become unusually vulnerable. The planetary waves vary in form and position from one hurricane season to another and it is demonstrated by means of composite charts that these varying circulation patterns form the framework for steering tropical cyclones after their generation and also play a role in determining their formation. Interrelationships between the tropical storm frequencies in the different geographical areas are discussed and the patterns favoring tropical cyclone penetration into the various areas compared. The significance of the results is presented and it is concluded that it may be possible to predict areas of greater or lesser vulnerability to tropical cyclones during a given circulation regime.

1. INTRODUCTION

The increased incidence of hurricane devastation in the heavily populated and industrialized northeastern section of the United States has aroused considerable public interest and has spurred a tremendous amount of study on the hurricane problem. The encouraging results of a recent study by Namias [1] on the relation of tropical storm penetration into New England to the general circulation inspired this current investigation of seasonal variations in the incidence of North Atlantic tropical cyclones in various areas.

This study is based on the observation that in some hurricane seasons certain regions are relatively free of tropical cyclones while other areas become unusually vulnerable. The planetary waves, which come to light by averaging mid-tropospheric charts for intervals of a season, vary in form and position from one hurricane season to another; and it will be demonstrated by means of composite charts in this and subsequent reports that these varying circulation patterns form the framework for steering tropical storms after they are generated and also play a role in determining their genesis. These variations in the form, position, and intensity of planetary waves can conveniently be studied by means of the deviations from normal of the height of a mid-tropospheric pressure surface. Deviations of pressures from their mean

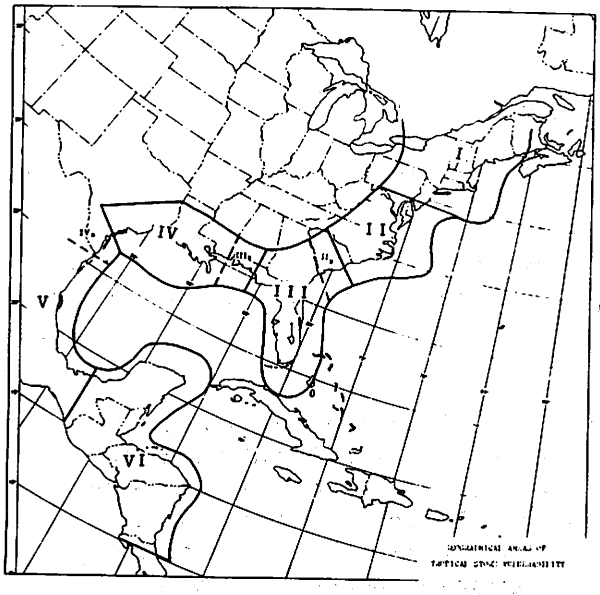

Figure 1. - Geographical areas of tropical storm vulnerability used in this study.

values become of increasing importance as the period of averaging increases and permanent seasonal features tend to dominate the circulation. These departures are especially useful in the upper air, where normal height varies greatly in both space and time and where the circulation usually assumes the form of open waves in a circumpolar current. The height anomaly, which appears to be a quasi-conservative property of the general circulation, readily converts these waves into individual vortices, helping the synoptician to assimilate information about variations in the general circulation.

2. PROCEDURE

For purposes of this study the principal hurricane months were considered to be August, September, and October because most North Atlantic hurricanes occur during these three months. Maps of the 700-mb. height and its anomaly for each of the seasons thus derived from 1933 to 1955 were constructed from data on punched cards in the Extended Forecast Section [1]. (Henceforth the word "season", if unqualified, refers to the three peak months considered.)

The tropical storm[1] tracks for this period were then studied. All tropical cyclones which persisted as closed circulations and showed translation for at least a 24-hour period were included in this research. These storms were all traced back as far as possible, often to their source in an easterly wave or along the intertropical convergence zone, and followed until they lost their identity as individual circulations.

Geographical areas of vulnerability were then designed on an empirical basis (fig. 1). The seaward boundaries (from New England to Texas) have been delineated in such a fashion that no storm (in the past 50 years) that traveled outside the boundaries affected the coastal stations with either strong winds, heavy precipitation, or unusually high tides. Because of scant data, the seaward boundaries of the Mexican and Central American areas could not be

1 The terms "tropical storm", "tropical cyclone", etc. used here do not conform to the interagency definitions used by the U. S. Weather Bureau. Of all the cyclones included in this study (see table 1) 87 percent are known to have attained tropical storm intensity (>34kt.) as defined by the U. S. Weather Bureau (60 percent of these tropical storms reached hurricane intensity); the remaining 13 percent were of indeterminate intensity.

defined in the same manner; they were therefore based on the lateral seaward extent of the other areas, taking into account the small size of storms in low latitudes, and the fact that many storms are first spawned near these coasts. In setting up the internal boundaries between the areas the following considerations were employed: Capes Cod and Hatteras should be centers of areas, as they project out to sea and are prone to be affected by tropical storms; the Florida peninsula should be a major portion of an area; one boundary should exist west of Yucatan, as many storms recurve in that area. Boundaries were drawn, wherever possible, in areas of minimum frequency of storms crossing the coastline.

Six areas were defined by these considerations. Area I includes New England, New York, Pennsylvania, and most of New Jersey; Area II, the southern tip of New Jersey, Maryland, Delaware, Virginia, and the Carolinas; III, most of South Carolina, Georgia, Florida, and Alabama; IV, the western edge of Florida, western Alabama, Mississippi, Louisiana, and Texas; V, extreme southeastern Texas, most of Mexico (except for Yucatan); and VI, Yucatan and Central America. There are three buffer zones each about 100 miles wide between Areas II and III, III and IV, and IV and V. These are areas where history has shown that the occurrence of a storm constitutes a threat to the areas on either side of the zone.

On the basis of the tropical cyclone tracks the frequencies of cyclones entering each of the geographical areas were tabulated for the seasons (August - October) 1933-1955 (table 1). A storm entering a buffer zone was counted in both adjacent areas. The column marked "total" shows the frequency of tropical cyclones occurring in the entire North Atlantic region. This includes all storms striking Areas I through VI as well as those passing out to sea without entering any of these areas. It should also be realized in comparing the numbers in the different columns that the same storm may penetrate more than one area (see table 3, p. 27). Seasons of maximum occurrence (dashed shading) and those of minimum occurrence (dotted shading) were selected for each of the six areas and for the North Atlantic. Mean 700-mb. height anomalies for the specially derived season of each of these groups of years have been computed and the resulting composite charts drawn to see if there are any important differences between maximum and minimum threat years in each area.

3. TROPICAL STORM ACTIVITY RELATED TO THE GENERAL CIRCULATION

In this section will be shown and discussed: composite charts of 700-mb. height anomaly for seasons of maximum occurrence of tropical storms in each area; composite charts for seasons of minimum occurrence; the differences between these two contrasting regimes as shown by wind speed profiles; the differences between the anomaly patterns of maximum and minimum seasons in each area (henceforth called max-minus-min charts); and an example of two charts showing the percentage frequency of positive or negative signs of the anomalies for a selected case.

The max-minus-min charts are shown for two reasons. In the first place, they quickly show the portions of the pair of composite charts in which the main height differences lie, so that the differences between the two contrast-

Table 1. - Tropical storm frequency by area for each season (August-October)

YEAR	I	II	III	IV	V	VI	TOTAL
1933	2	3	5	1	5	4	16
1934	2	3	2	2	1	1	11
1935	1	1	3	0	1	2	6
1936	3	2	3	4	4	3	13
1937	2	3	4	3	0	1	9
1938	2	2	1	3	1	3	8
1939	1	1	1	1	0	2	5
1940	1	2	2	2	0	3	9
1941	0	2	3	2	1	1	6
1942	1	1	0	2	1	3	10
1943	3	3	1	1	0	2	10
1944	3	3	3	1	3	4	10
1945	1	1	2	2	1	2	8
1946	0	2	3	0	1	1	4
1947	0	3	5	4	2	1	11
1948	0	2	5	1	0	2	9
1949	1	2	2	4	1	1	15
1950	2	2	4	3	2	2	18
1951	0	1	1	0	2	2	10
1952	1	1	2	0	0	0	6
1953	3	4	5	2	0	2	12
1954	3	3	1	1	2	1	8
1955	3	4	2	2	3	2	14
TOTAL	35	51	60	41	31	45	228
MEAN	1.5	2.2	2.6	1.8	1.4	2.0	9.9

ing circulation regimes are graphically available. Secondly, the series of 700-mb. charts from 1933 to the present is not of uniform accuracy and their completion involved estimations which will not be detailed here (some of the estimations are described in [1 and 2]); the max-minus-min charts are an attempt to remove part of the possible inconsistencies in the analysis. Of course, the extent to which this removes the inconsistencies depends on the relative number of charts in the masimum and minimum categories selected prior to and subsequent to the various changes in the procedure of constructing the series of mean 700-mb. charts.

The North Atlantic Region

Composite charts of the departures from normal of the 700-mb. surface for the 5 seasons of maximum and the 5 seasons of minimum tropical cyclone formation in the entire North Atlantic are shown in figures 2 and 3 respectively. One can see fairly large differences in many parts of the hemisphere (cf. figs. 2, 3, 4). Figure 5 shows the percentage of the 5 seasons that comprise figure 2 in which the anomaly has a given sign (either positive or negative). It is a rough measure of the homogeneity of the anomaly pattern and it appears that the sign of the anomaly is very consistent in the vicinity of the anomaly centers. Figure 6 is the same type of study with reference to the data of figure 3, and shows similar results. Since the degree of congruity of sign is equally high for anomalies on the contrasting charts, it is implied that they have some statistical significance. This is supported by synoptic and physical evidence.

Perhaps the most significant difference is the position and size of the positive anomaly area in the Atlantic. In the seasons of maximum frequency it is extensive, centered at 40°N. latitude and stretching from the Atlantic coast of North America to the Atlantic coast of Europe; while in the seasons of minimum frequency it is much less extensive and is centered at 30°N. The more northerly position of the positive anomalies in the seasons of maximum number of storms is associated with an extensive area in the Tropics with heights below normal (figs. 2 and 4), and it is known that tropical storms usually form in areas where pressures are already below normal. There is another important difference: In the seasons of maximum frequency there is a well-organized cell of below normal heights south of Iceland, while in the seasons of minimum frequency there is a cell of negative anomalies over Great Britain and Scandinavia and another cell over the northeastern United States, two factors associated with depression of the westerlies southward over the Atlantic.

The consequence of these anomalous contours on the wind field can be seen in figure 7 which depicts the zonal geostrophic wind speed profiles at 700 mb. averaged between 100°W. and 0° longitude for the same groups of years that comprise figures 2 and 3. The average for the years of maximum frequency is represented by the solid curve, that for the years of minimum frequency by the dashed curve. The more northerly position of the westerlies in the seasons of maximum frequency is apparent. Also apparent is the fact that the westerlies on the average were not as strong through a wide zone south of 47°N. in the years of maximum frequency (cf. fig. 4). A small northward shift in the easterlies is indicated in those years. This picture of the westerlies being

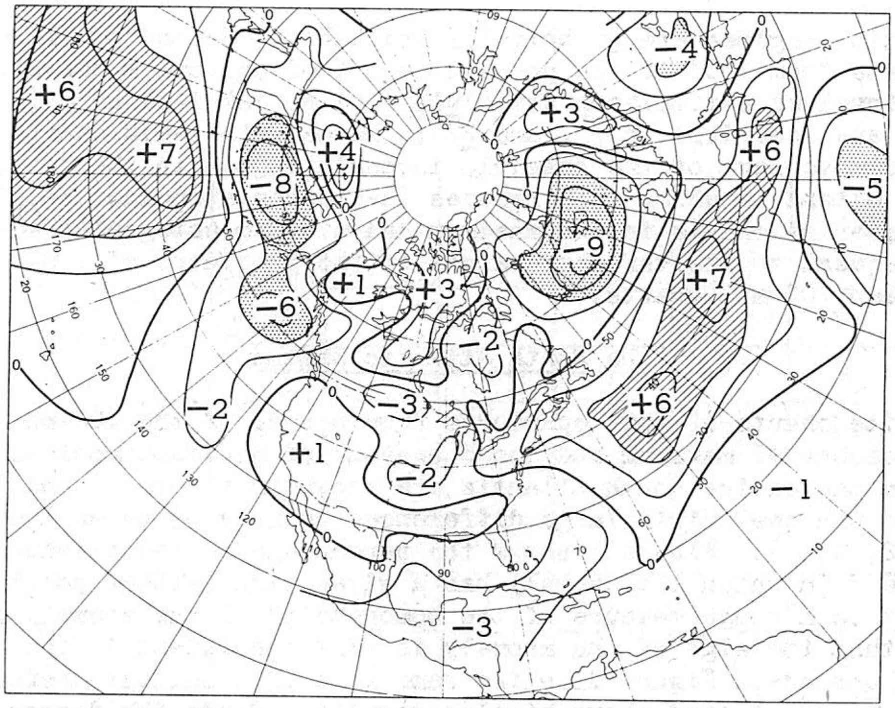

Figure 2. - Composite chart of the average departures from normal (in tens of feet) of 700-mb. heights for the 5 seasons (August-October) of maximum tropical cyclone incidence in the North Atlantic. Areas of positive anomaly ≥ 40 ft. are hatched, those of negative anomaly ≥ 40 ft. are dotted.

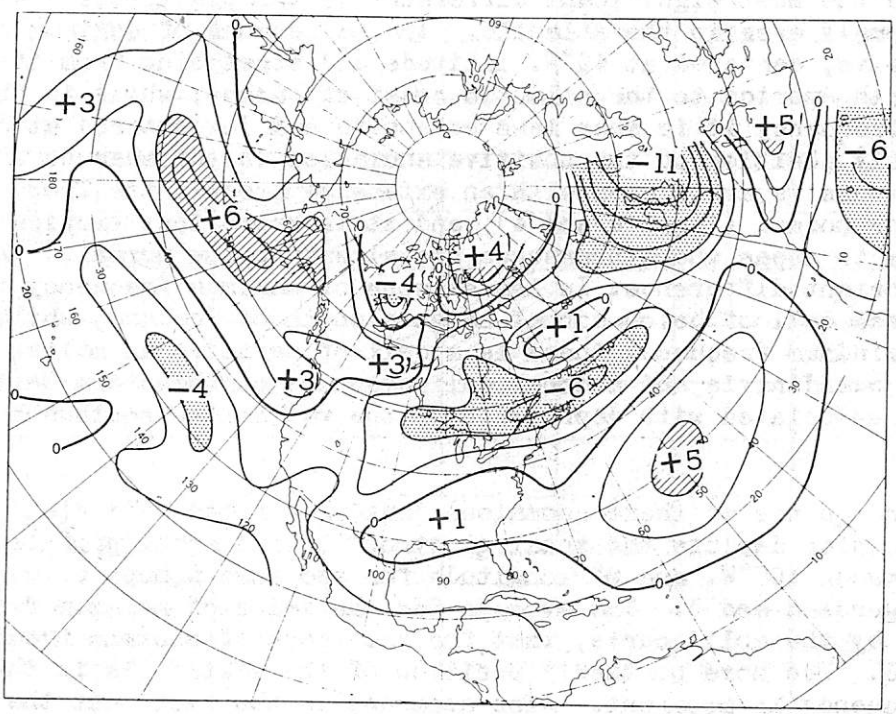

Figure 3. - Composite chart of the average departures from normal (in tens of feet) of 700-mb. heights for those 5 seasons of minimum tropical cyclone incidence in the North Atlantic.

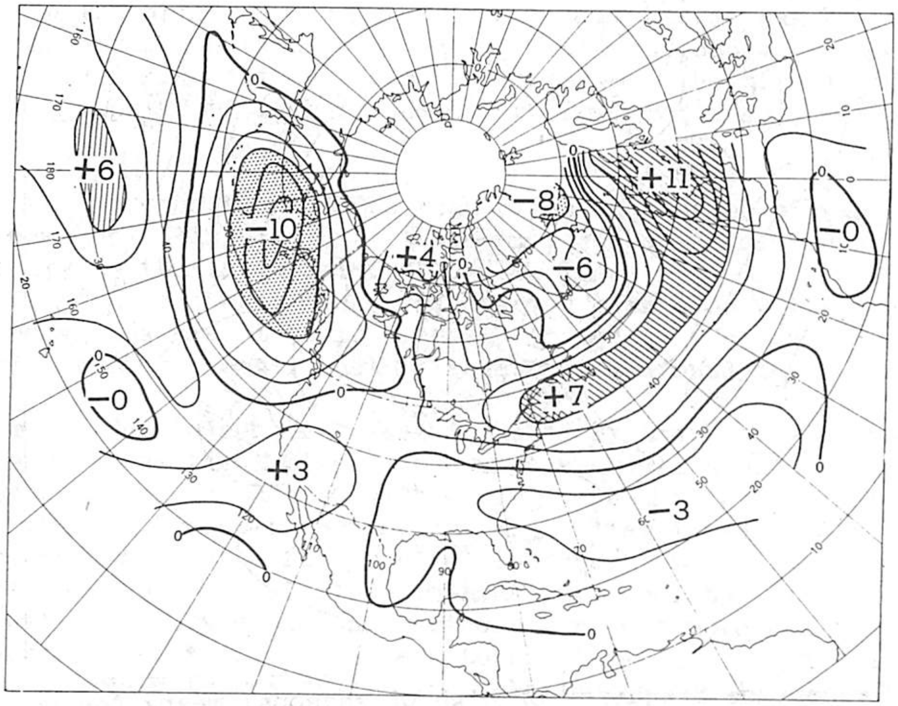

Figure 4. - Max-minus-min chart showing the height differences (in tens of ft.) between figure 2 and figure 3. Areas of positive height difference ≥ 60 ft. are hatched, those of negative height difference ≥ 60 ft. are dotted.

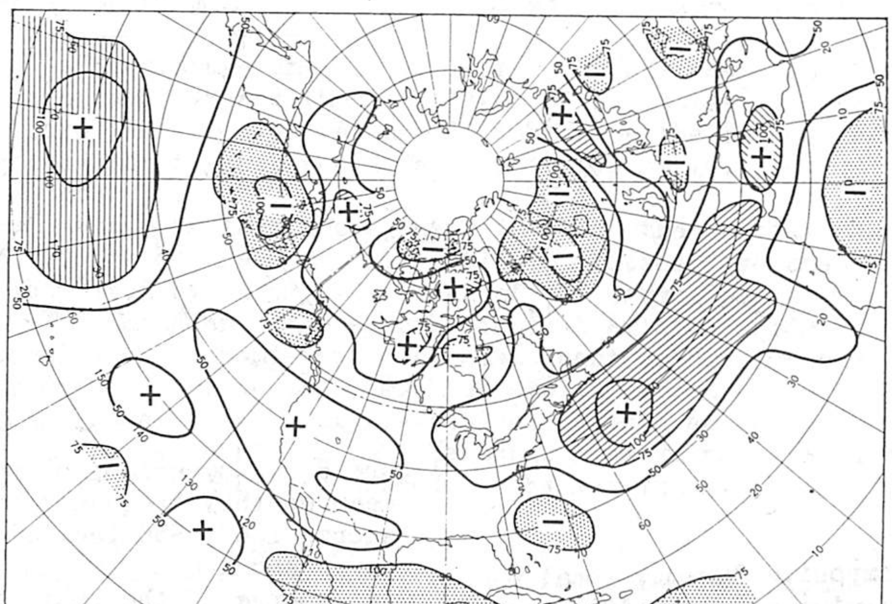

Figure 5. - Precentage frequency of sign of seasonal means for the 5 seasons of maximum tropical cyclone incidence in the entire North Atlantic. Hatched areas are positive in at least 75 percent of the seasons, dotted areas are negative in at least 75 percent of the seasons.

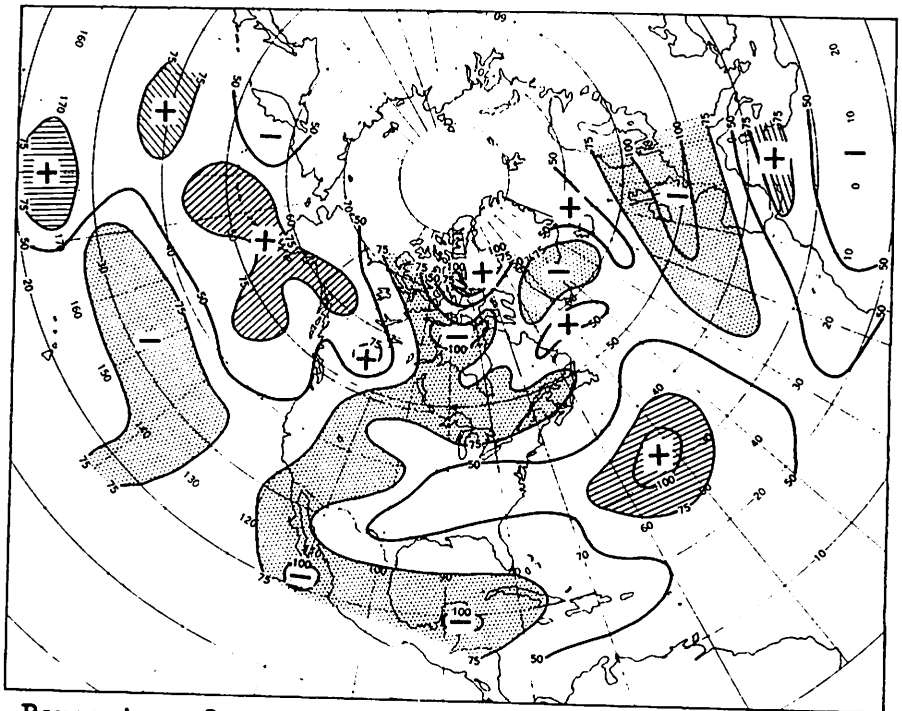

Figure 6. - Percentage frequency of sign of seasonal means for the 5 seasons of minimum tropical cyclone incidence in the entire North Atlantic.

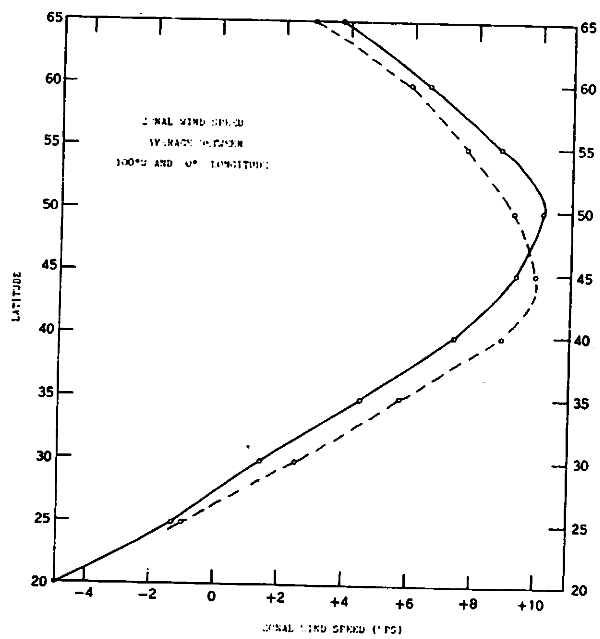

Figure 7. - Composite 700-mb. zonal geostrophic wind speed profiles averaged between 0° and 100°W. for the seasons of maximum tropical storm incidence in the North Atlantic (solid curve) and seasons of minimum occurrence (dashed). Note suggestion of a displacement of the axis of maximum westerlies in the seasons of minimum frequency.

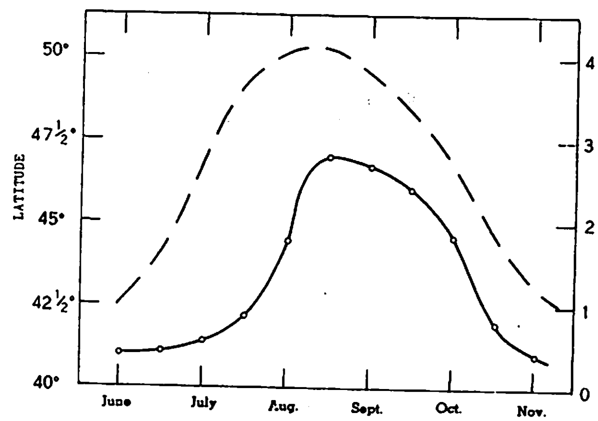

Figure 8. - Comparison of the curve of mean monthly frequency of tropical storms 1887-1956 (solid) and the curve showing a portion of the annual course of the latitudinal position of the axis of maximum westerlies at 700 mb. averaged around the Hemisphere (dashed). Note the similarity in the positions of the two peaks.

farther north in periods of maximum formation of storms has been often suspected but never demonstrated for a large number of cases. A good example has been provided recently by the contrast between the circulations of August 1955 and 1956, months of high frequency and low frequency , respectively, in the Atlantic [3].

The northerly position of the westerlies in seasons of frequent occurrence is what one might anticipate from the normal seasonal relationship of tropical storm activity to the latitude of the westerlies (fig. 8); i.e., the greatest number of tropical cyclones (the solid curve) occurs near the time of the year when the westerlies are at their highest latitude. (The dashed curve is the normal latitude of the zonal westerlies averaged around the hemisphere [4].)

This may be explained, at least in part, by the following pertinent physical factors. In the first place, in summer and fall a northerly displacement of the westerlies is associated with a similar shift in the subtropical anticyclones. The zone of deep subtropical easterlies is shunted north, and, in effect, the area favorable for tropical cyclone formation is enlarged. Besides, such a distribution of zonal winds is usually associated with the shearing of planetary wave trains wherein the northern portions move eastward more rapidly than the southern portions which tend to fracture and, if they extend into the easterlies, become retrogressive. The relative motion is often associated with the deployment and cutting off of pools of cold mid-tropospheric air in the Tropics and subtropics. Namias [5] believes that both the cold air aloft and the injection of a broad field of cyclonic vorticity (at the base of an originally longitudinally extensive trough) are highly favorable to the growth of cyclonic vortices of many scales - including, of course, the hurricane.

<u>Area I</u> - The average anomaly field for the six cases in which three tropical storms entered Area I (northeastern United States) in each season is shown in figure 9. The average anomaly field for the five seasons when no tropical storms threatened Area I is seen in figure 10.

Figure 9 suggests that those years in which the coastal regions of northeastern United States are most vulnerable to tropical cyclones show a tendency to be characterized by an amplification of the normal planetary wave pattern (fig. 12). The Canadian ridge and the central Atlantic ridge are both stronger than normal and the semi-permanent east coast trough, between the two ridges is slightly deeper than normal. Such an amplification favors the northward motion of east coast storms, extra-tropical as well as tropical, making the projecting land areas north of Cape Hatteras more vulnerable than usual. This amplification is even more pronounced on the max-minus-min chart (fig. 11).

In the Atlantic in the seasons of minimum threat, a deep and extensive negative anomaly replaces the positive one found in the maximum threat years, and a net positive anomaly exists over eastern United States. Both of these features are unfavorable to northward steering by the Atlantic subtropical anticyclone.

When superimposed upon the normal pattern (fig. 12), the net result of the mean anomalies of minimum threat years is a wave pattern of less amplitude than normal, particularly so compared to the mean of maximum threat years.

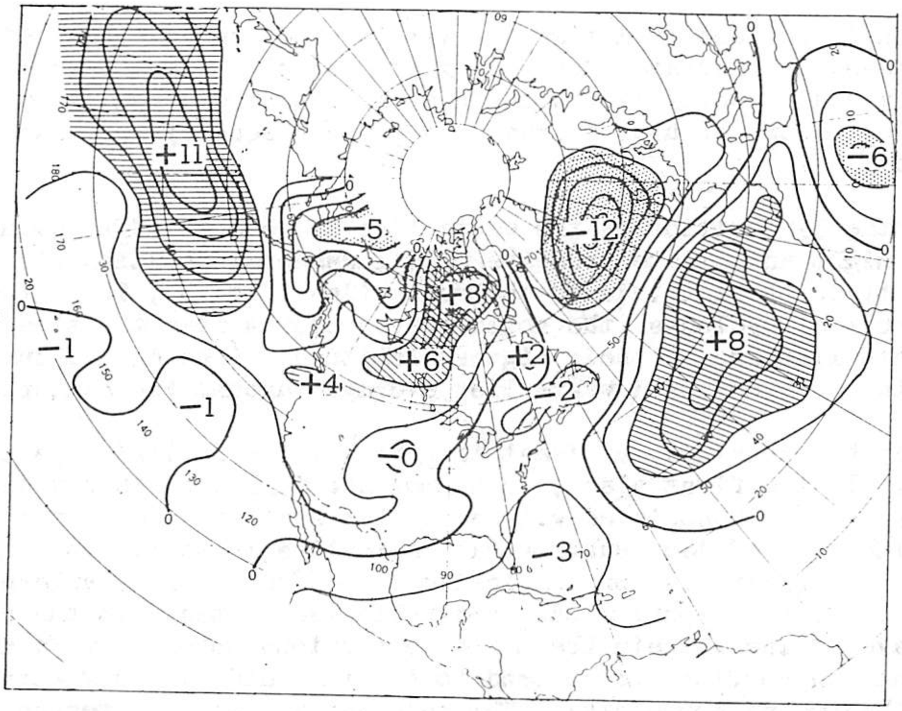

Figure 9. - Composite chart of the average departures from normal (in tens of feet) of 700-mb. heights for the 6 seasons of maximum tropical cyclone incidence in Area I, northeastern United States.

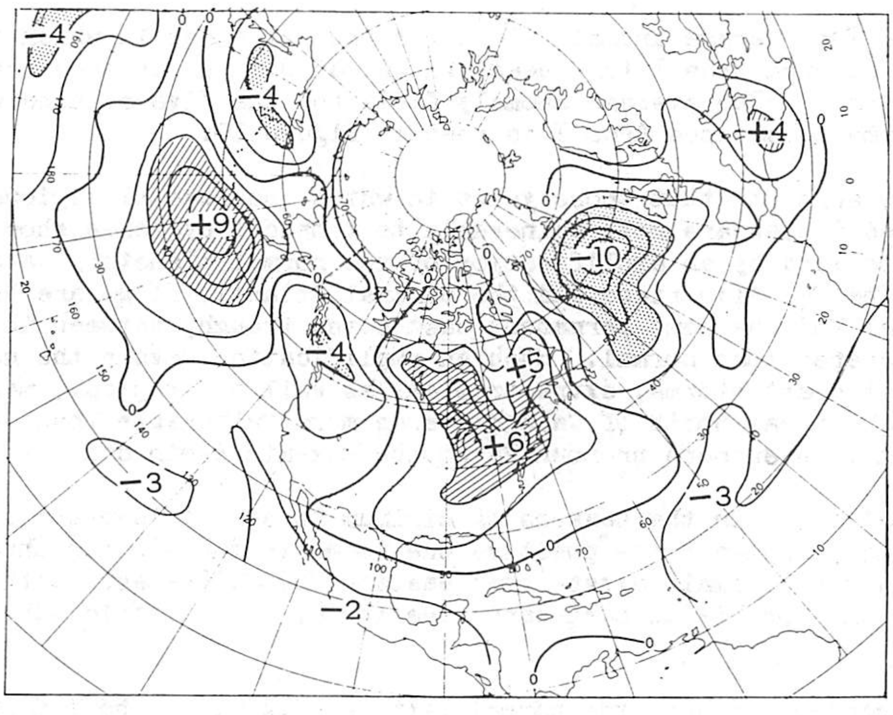

Figure 10. - Composite chart of the average departures from normal (in tens of feet) of 700-mb. heights for the 5 seasons of minimum tropical cyclone incidence in Area I.

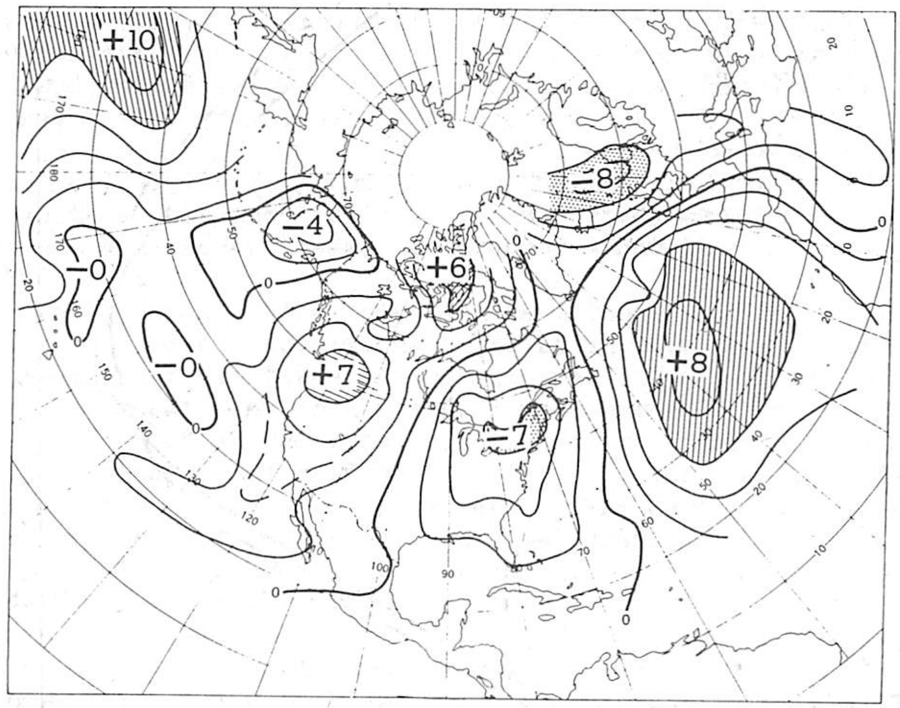

Figure 11. - Max-minus-min chart for Area I, showing the height difference(in tens of feet) between the composite charts of figures 9 and 10.

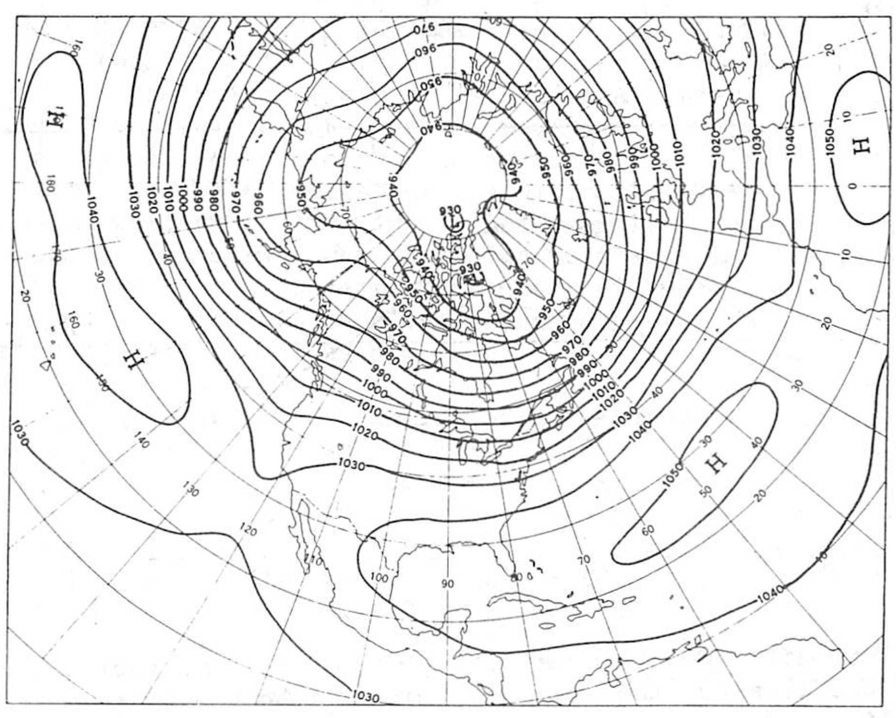

Figure 12. - Normal 700-mb. chart for the specially derived season (August - October). Labeled in tens of feet.

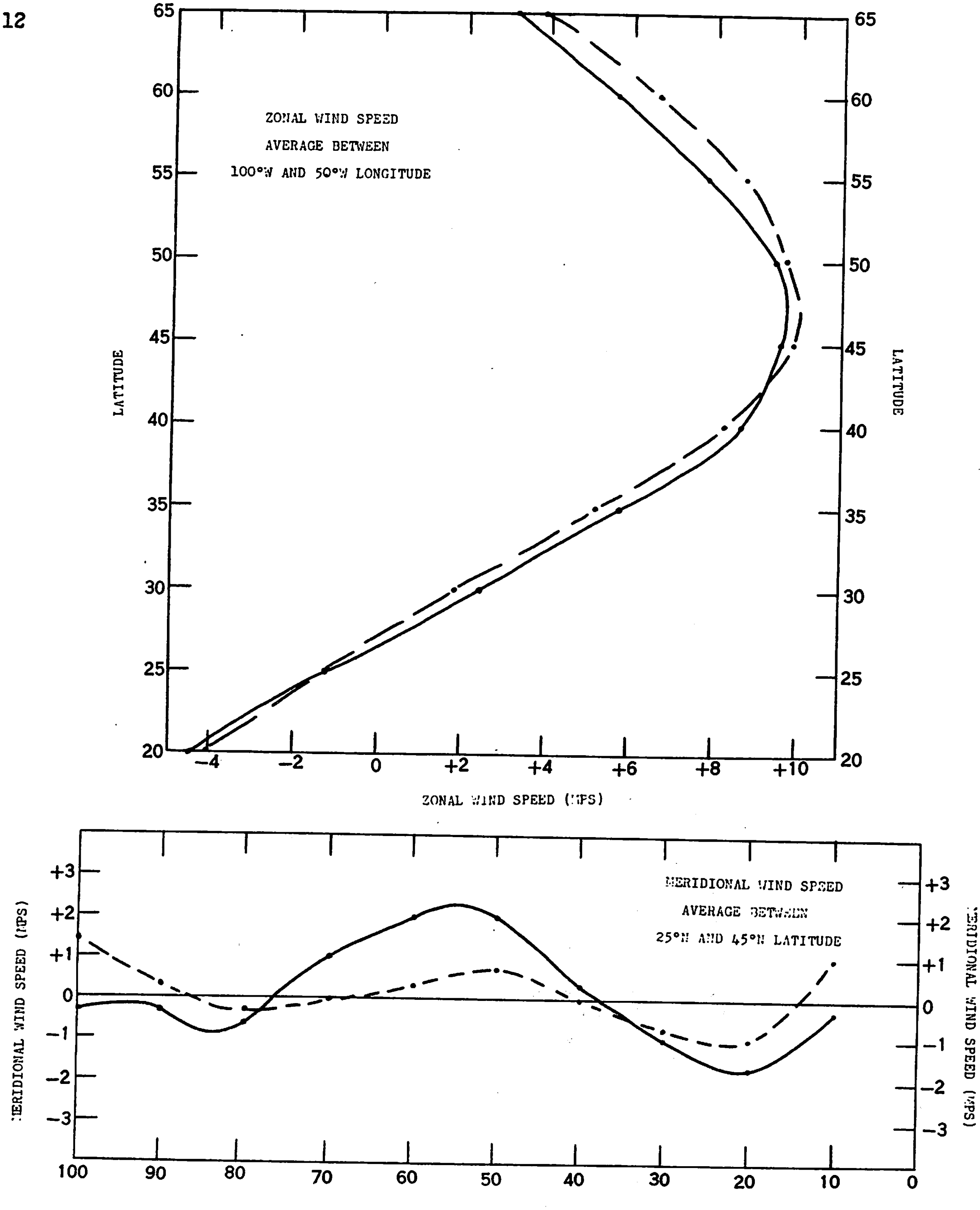

Figure 13. - Composite 700-mb. zonal (top) and meridional (bottom) geostrophic wind speed profiles for the seasons of maximum tropical storm incidence in Area I (solid curve) and minimum occurrence (dashed curve). Zonal winds are averaged between 50° and 100°W. longitude; meridional winds between 25° and 45°N. latitude. Northerly winds are negative, southerly, positive; the troughs and ridges are where the wind direction changes and hence the meridional wind speed is zero.

This effect of a flatter than normal planetary wave pattern over North America and adjacent waters provides for more eastward steering of many captured disturbances. Due to the large positive anomalies over New England, some tropical storms may be forced inland to the south.

The study by Namias [1] for the New England area indicated essentially the same results as obtained for Area I. His study was for a slightly different area and a different season (September - November).

Figure 13 illustrates the zonal and meridional wind speed profiles associated with the anomalous conditions. The zonal wind speed profiles (which in this case, and for all the areas of vulnerability, are averaged between 100°W. and 50°W. longitude) do not differ much between seasons of maximum and minimum penetration of storms into Area I. On the other hand, the meridional profiles shown in the lower half of the figure differ considerably. In seasons of maximum occurrence of tropical storms the east coast trough is some 5° to 10° farther to the west than in minimal seasons and the profile displays more amplitude. The stronger southerly component of flow implied from the anomaly fields of figure 11 is very evident in figure 13.

Area II - Figures 14 and 15 are the composite 700-mb. height anomaly fields for the 9 seasons of maximum and the 6 seasons of minimum tropical cyclone penetration into Area II, the mid-Atlantic coast. Again, interesting differences appear between the two charts over large areas of the Hemisphere (see figs. 14, 15, and 16). The most immediately apparent differences are in the positions and orientations of the anomaly trough and ridge in the eastern United States and the mid-Atlantic. The anomalous flow off the east coast of the United States in the seasons of maximum frequency is in a direction that would favor storm penetration into Area II. In the seasons of few storms, there exists an anomaly ridge in the Gulf of Alaska and along the North Pacific coastal region of the United States. The physical interconnection between a ridge and its downstream trough favors a negative area over the Great Lakes when there is a positive area along the North Pacific coast of the United States and Canada. This has been demonstrated empirically by Martin [6] who made a study of the probability of the sign of the anomaly (positive or negative) in other areas of the Hemisphere when the sign of the anomaly in given key areas is known. The southwest-northeast orientation of the anomaly trough centered over Ontario tends to inhibit tropical storms from entering Area II due to the southwesterly offshore anomalous component.

Figure 17 shows the zonal and meridional geostrophic wind speed profiles associated with the Area II classification. In contrast with Area I where the difference lay in the meridional component, it appears that zonal wind speed differences are more important for determining the vulnerability of Area II. The westerly maximum is about 15° of latitude farther north in the years of maximum frequency, and the westerlies are weaker south of 50°N. latitude than they are in the seasons of minimum frequency. These weaker westerlies may be the effect of including some easterly winds which occasionally migrated farther north than normal and helped steer tropical storms toward the mid-Atlantic coast of the United States.

Area III - Figures 18 and 19 focus our attention on Area III, the southeastern United States, where we again find important differences in the anomaly patterns for the 6 seasons of maximum contrasted with the 6 seasons of minimum frequency of tropical cyclones (figs. 18, 19, and 20).

In the seasons of maximum frequency there is a positive anomaly area north of the Great Lakes which, in conjunction with an Atlantic ridge displaced far to the north (evidenced by the positive anomalies), is associated with a wide band of anomalous easterly flow in the Atlantic which can aid the steering of tropical storms toward Area III. The anomalous easterly flow is especially marked in the max-minus-min chart (fig. 20) which also points up the importance of the height anomalies in the Great Lakes. This anomalous positive area over the Great Lakes is probably associated in part with energy propagation from the upstream anomaly trough in the Gulf of Alaska. The seasons of minimum tropical storm penetration into Area III are characterized by a negative anomaly area replacing the positive one over the Great Lakes. This is related physically and statistically [6] with the upstream anomaly ridge in northwestern Canada, the downstream anomaly ridge in the Atlantic, and other features shown in figure 19. This results in an offshore northerly anomalous wind component, tending to make tropical storm penetration into Area III less likely.

Figure 21 shows zonal and meridional geostrophic wind speed profiles of maximum and minimum seasons in Area III. Again, the meridional profiles show little difference, while the differences between the zonal wind speed profiles seem more pronounced than in either Areas I or II. In the seasons of maximum

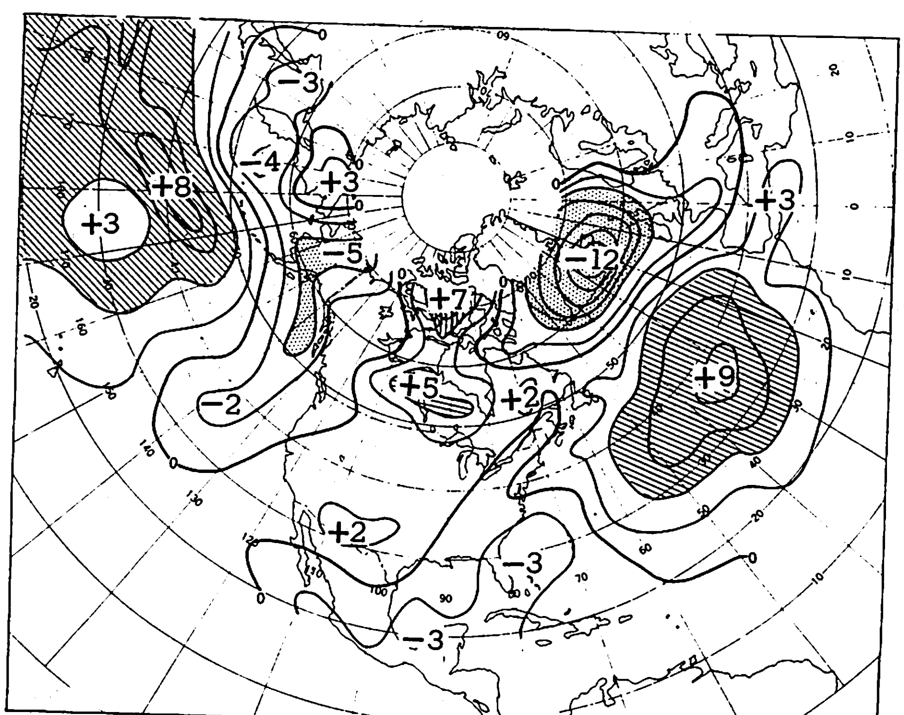

Figure 14. - Composite chart of the average departures from normal (in tens of feet) of 700-mb. heights for the 9 seasons of maximum tropical cyclone incidence in Area II, the mid-Atlantic coast of the United States.

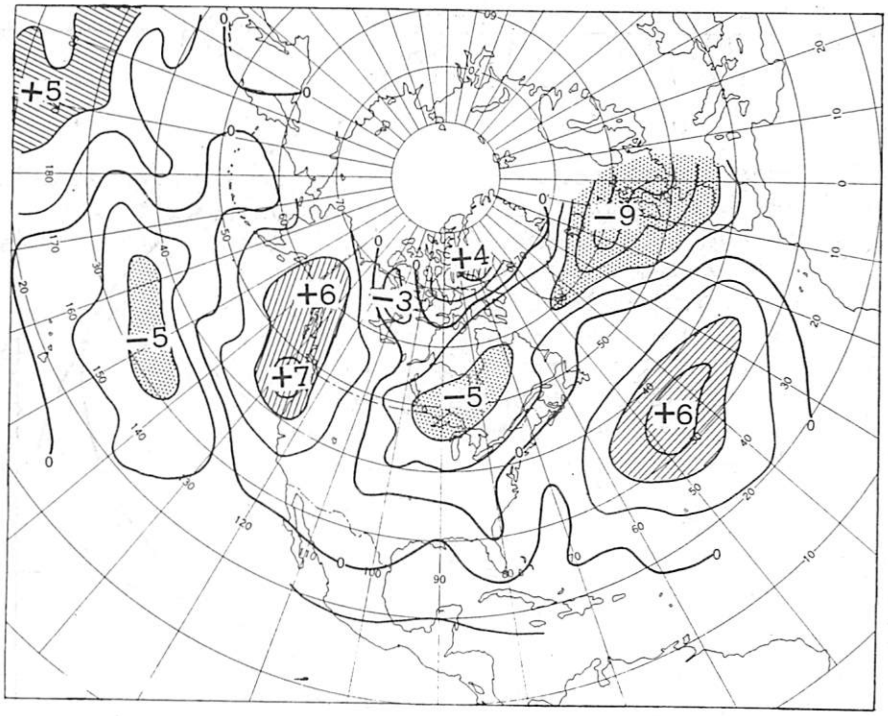

Figure 15. - Composite chart of the average departures from normal (in tens of feet) of 700-mb. heights for the 6 seasons of minimum tropical cyclone incidence in Area II.

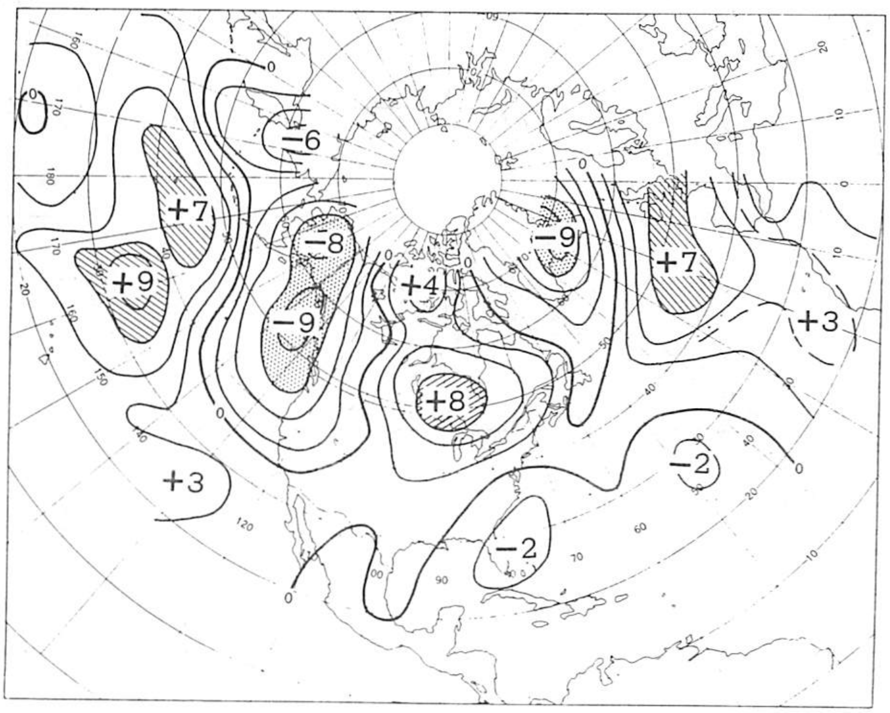

Figure 16. - Max-minus-min chart for Area II showing the height difference (in tens of feet) between the composite charts of figures 14 and 15.

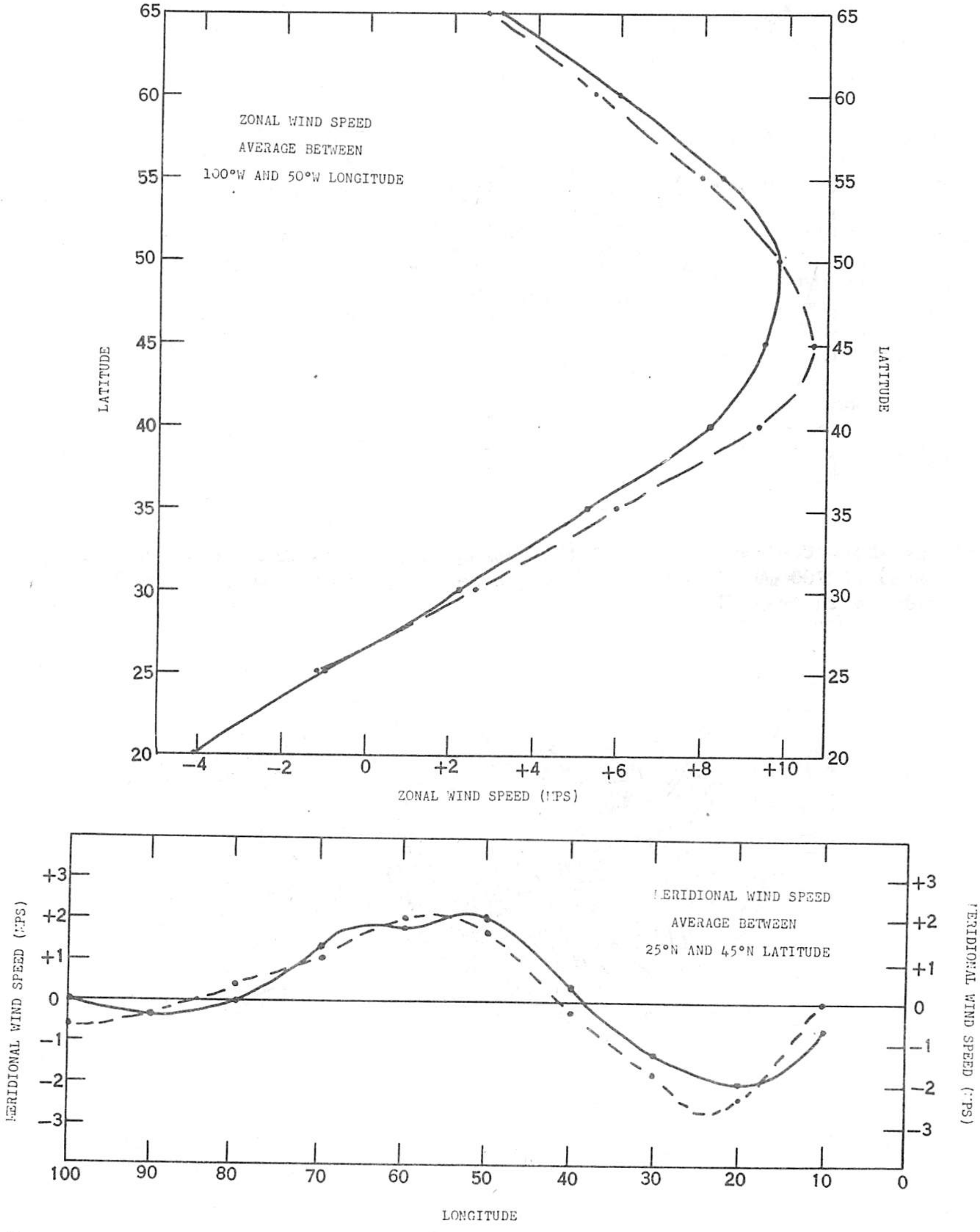

Figure 17. - Composite 700-mb. zonal and meridional geostrophic wind speed profiles for seasons of maximum and minimum tropical storm incidence in Area II.

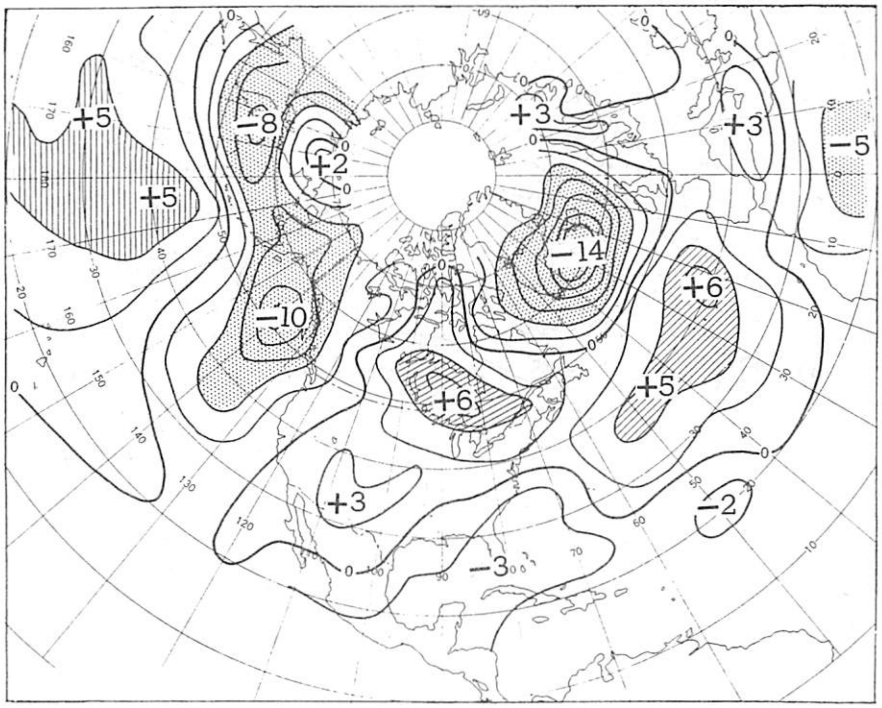

Figure 18. - Composite chart of the average departures from normal (in tens of feet) of 700-mb. heights for the 6 seasons of maximum tropical cyclone incidence in Area III, the southeastern United States.

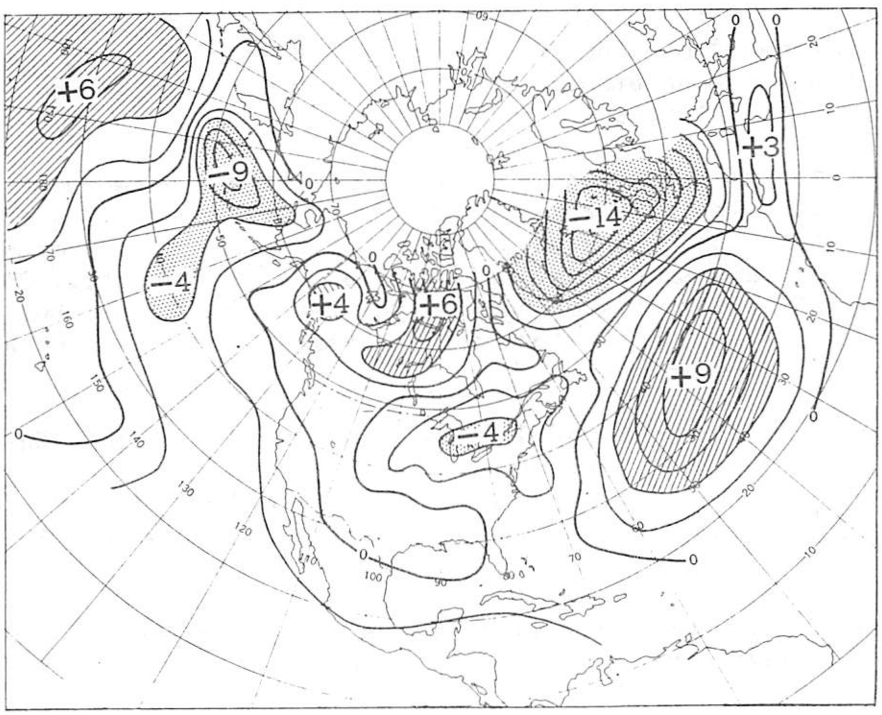

Figure 19. - Composite chart of the average departures from normal (in tens of feet) of 700-mb. heights for the 6 seasons of minimum tropical cyclone incidence in Area III.

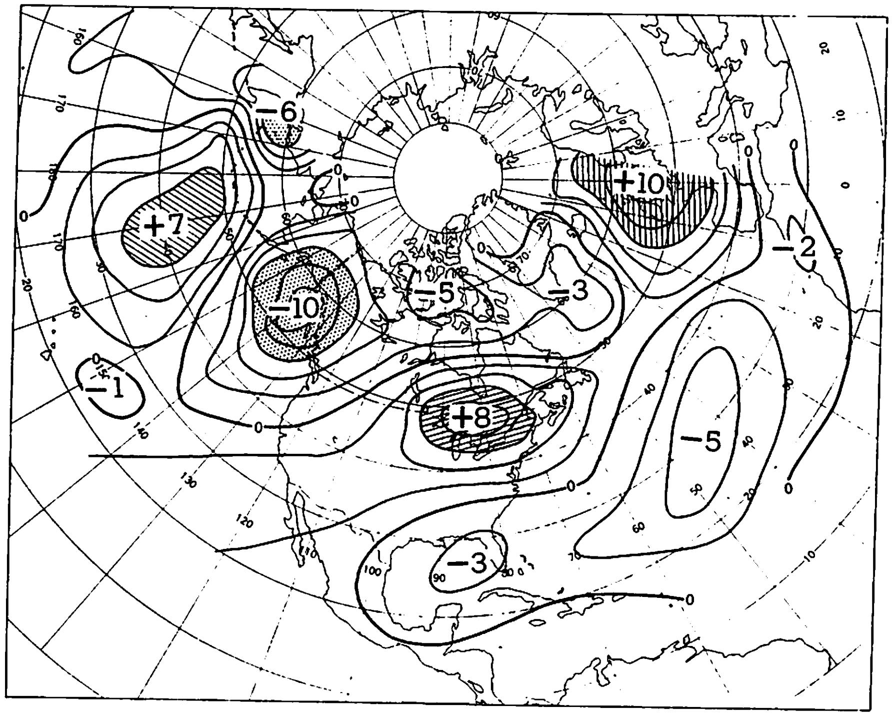

Figure 20. - Max-minus-min chart for Area III showing the height difference (in tens of feet) between the composite charts of figures 18 and 19.

frequency the peak of the westerlies is about 10° of latitude farther north than in the seasons of minimum frequency. In seasons of maximum frequency the westerlies are not as strong as in the seasons of minimum occurrence in a band south of 47°N. latitude (cf. fig. 20).

Area IV - The composite anomaly pattern for the 6 seasons of maximum tropical storm penetration into Area IV, the north Gulf coast (fig. 22), is markedly different from the composite anomaly pattern for the 4 seasons of minimum occurrence in the same area (fig. 23). These differences (fig. 24) are not necessarily a reflection of a change in the steering current, but seem to indicate a change in the circulation regime favorable for tropical storm formation in the Gulf of Mexico.

Any storm that forms in the Gulf is a threat to the north Gulf coast. This is evidenced by the observations that 63 percent of all the tropical storms that form in the Gulf enter Area IV [9]; and that the frequency of tropical storm penetration into Area IV has a correlation of 0.79 with the frequency of formation in the Gulf of Mexico.

Mr. Conner[1] of the Weather Bureau Office in New Orleans has indicated that a tip-off to the development of tropical storms in the Gulf of Mexico is a

1 Personal communication

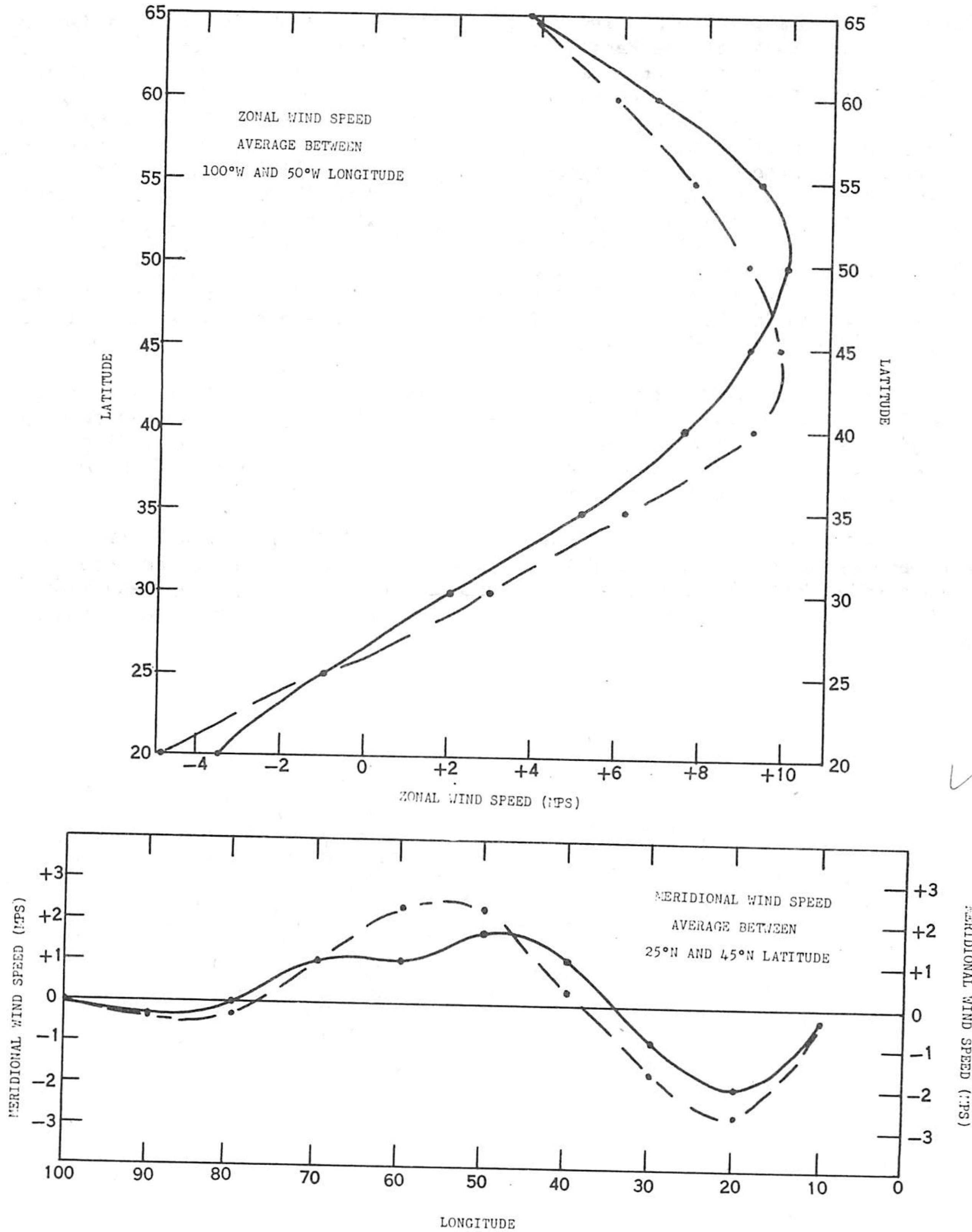

Figure 21. - Composite 700-mb. zonal and meridional geostrophic wind speed profiles for seasons of maximum and minimum tropical storm incidence in Area III.

deeper than normal trough in the eastern Pacific. This tendency for a deeper than normal trough off the Pacific coast of the United States is shown in the seasons of maximum occurrence of tropical storms in Area IV (fig. 22) and is especially well-marked on the max-minus-min chart (fig. 24). This feature also appears in those seasons of maximum formation in the Gulf, but since the anomaly pattern of those seasons is practically identical to that for maximum occurrence in Area IV, it is not reproduced in this study. (It will be discussed by this author in a forthcoming article in which formation of tropical storms in various areas in relation to the general circulation is discussed [7].) The positive height anomalies across the northern border of the United States (fig. 22) are possibly a reflection of the presence of a continental anticyclone during a part of these seasons, its northerly position related to storm formation in the Gulf. The positive anomalies are supported by the vorticity flux from the Gulf of Alaska area.

In the seasons when few storms enter Area IV (fig. 23) the 700-mb. height anomalies are positive in the Gulf of Alaska and Aleutian area and an anomaly trough exists along the northern border of the United States. According to Conner's statement given above, this should result in few storms forming in the Gulf of Mexico, and hence few storms affecting Area IV.

<u>Area V</u> - In the composite charts (figs. 25 and 26) for Area V, the coastal area bordering on the western Gulf of Mexico, once again differences are apparent (fig. 27). Most of these dissimilarities, though, are in areas remote from Area V. In the immediate vicinity of this area the heights vary little and the data are poor.

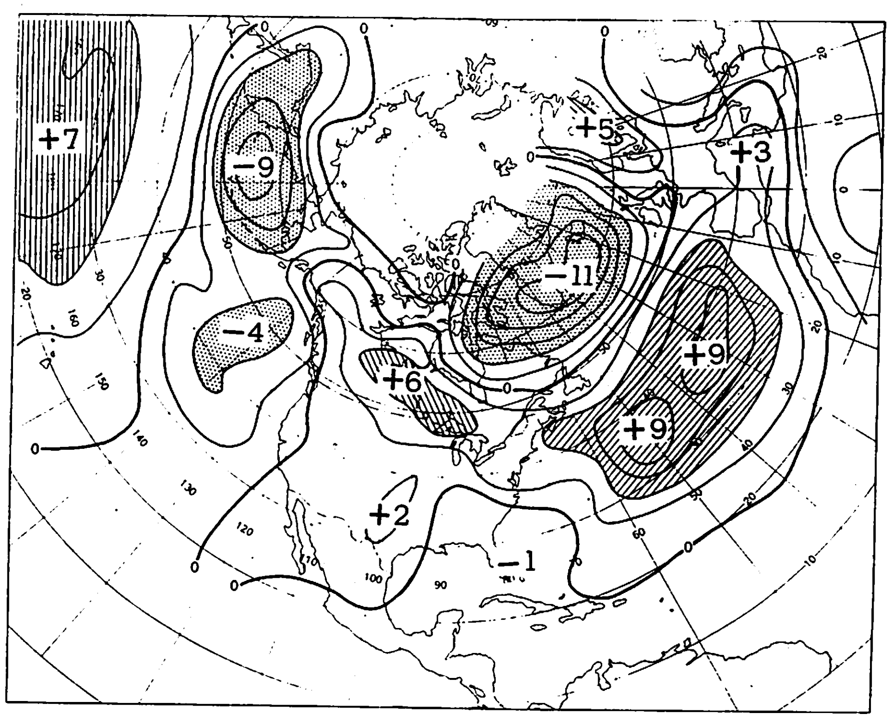

Figure 22. - Composite chart of the average departures from normal (in tens of feet) of 700-mb. heights for the 6 seasons of maximum tropical cyclone incidence in Area IV, the north Gulf coast of the United States.

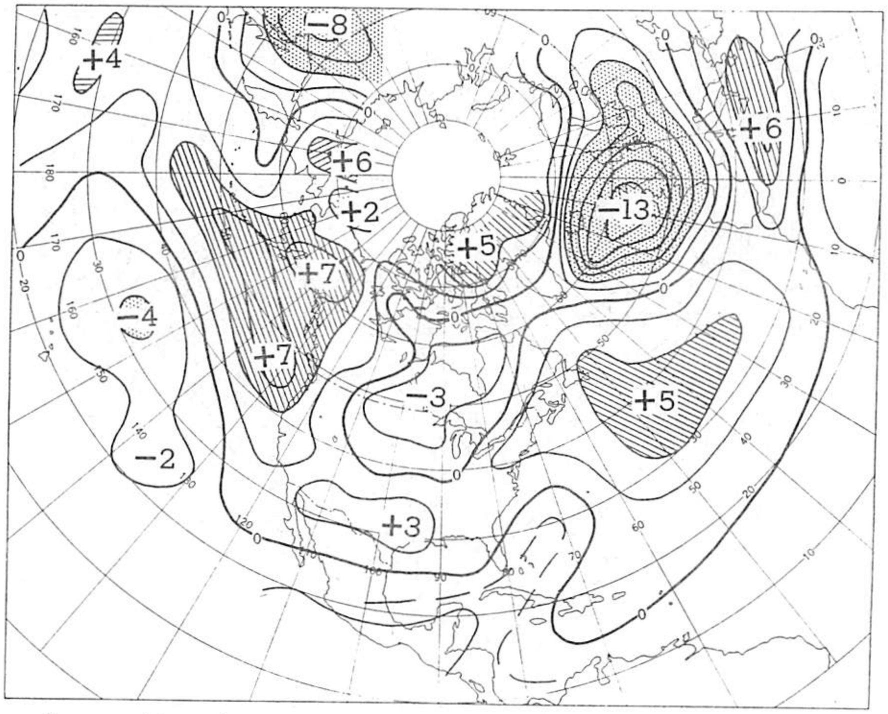

Figure 23. - Composite chart of the average departures from normal (in tens of feet) of 700-mb. heights for the 4 seasons of minimum tropical cyclone incidence in Area IV.

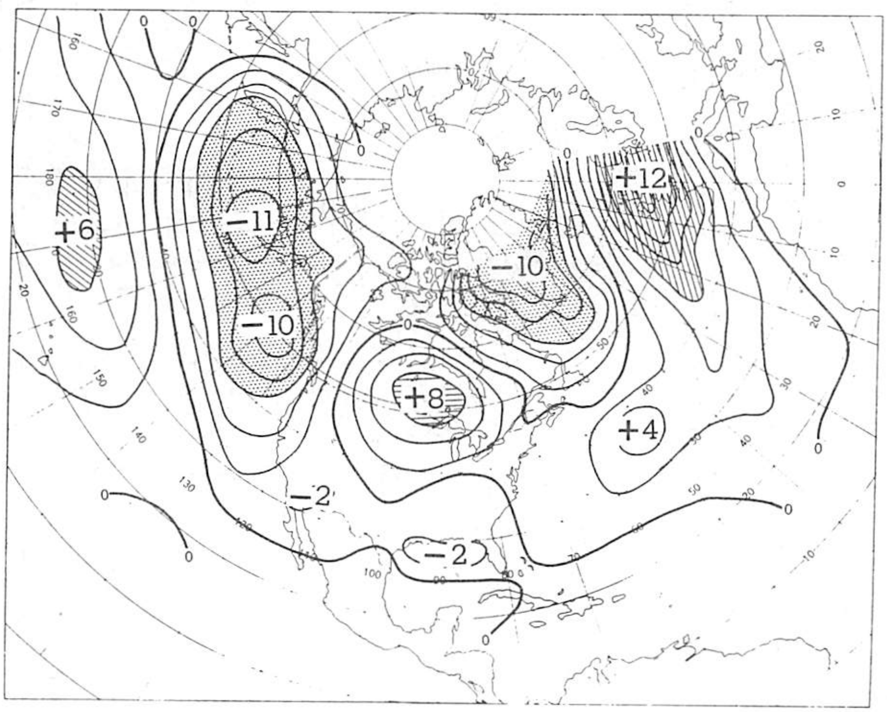

Figure 24. - Max-minus-min chart for Area IV showing the height difference (in tens of feet) between the composite charts of figures 22 and 23.

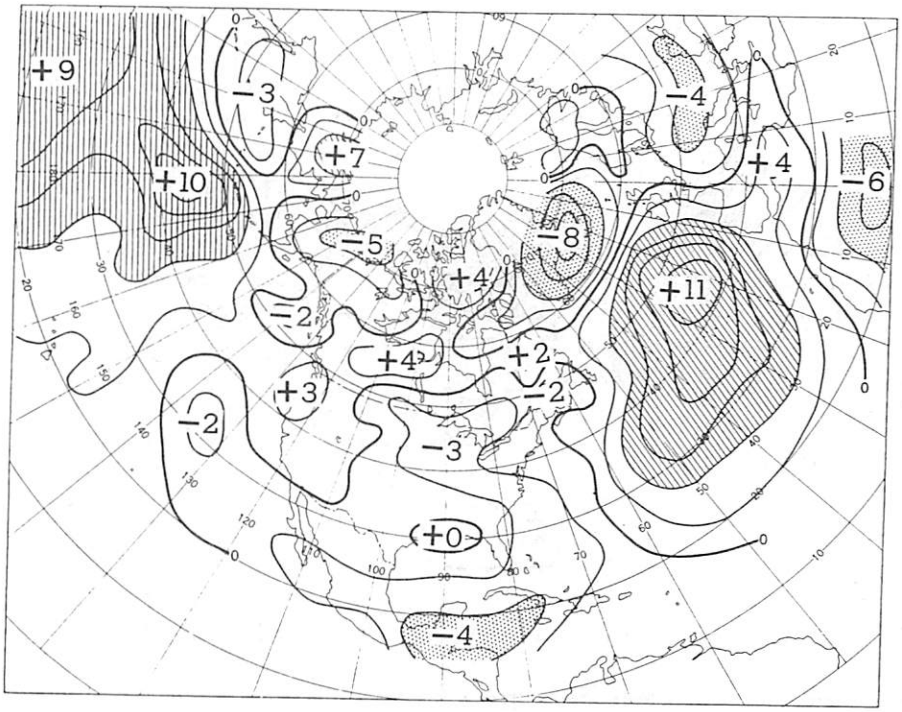

Figure 25. - Composite chart of the average departures from normal (in tens of feet) of 700-mb. heights for the four seasons of maximum tropical cyclone incidence in Area V, the west Gulf coast of Mexico.

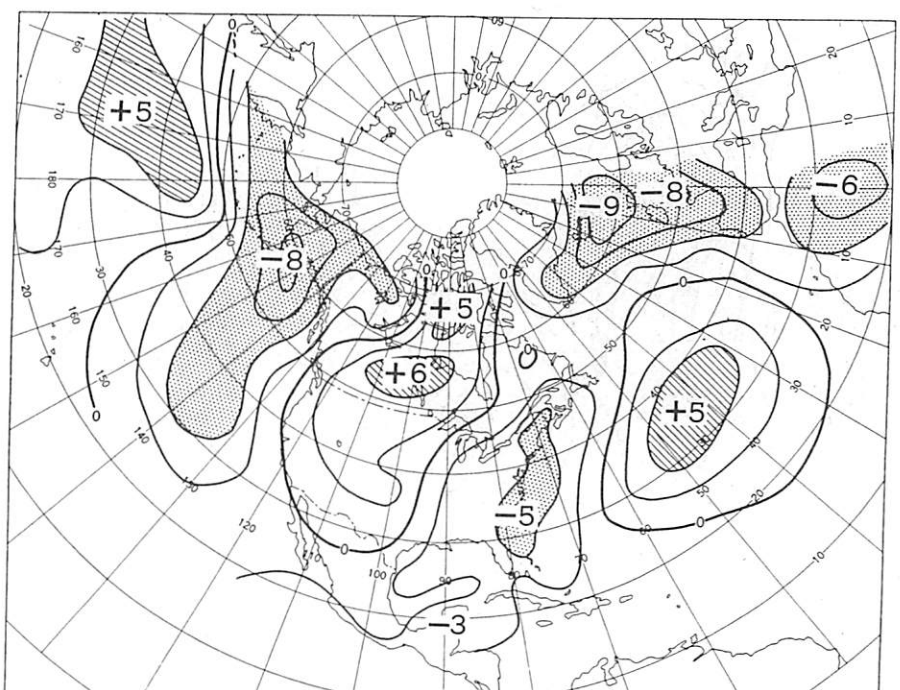

Figure 26. - Composite chart of the average departures from normal (in tens of feet) of 700-mb. heights for the 7 seasons of minimum tropical cyclone incidence in Area V.

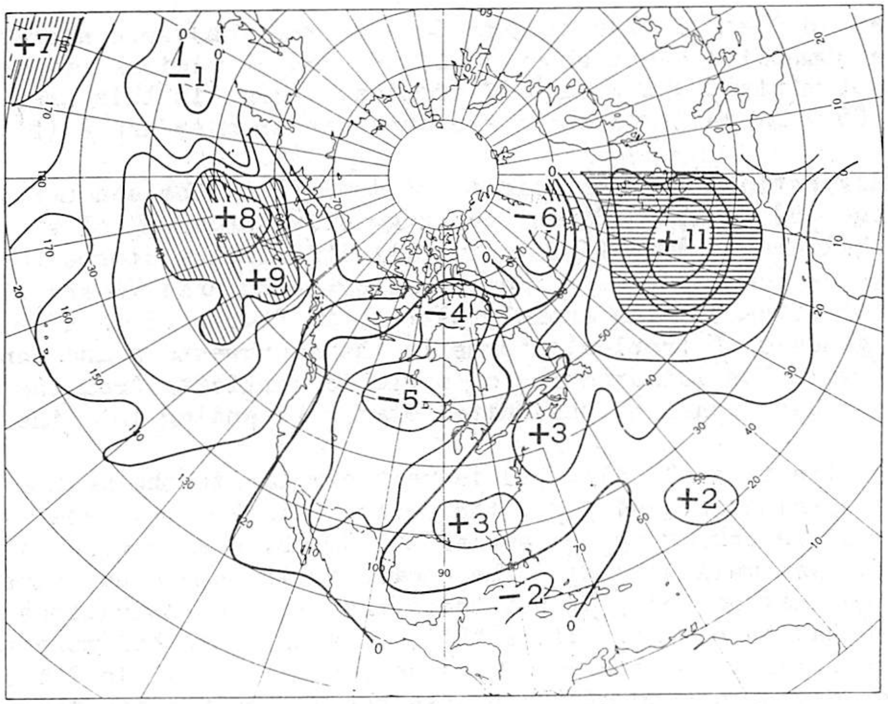

Figure 27. - Max-minus-min chart for Area V showing the height difference (in tens of feet) between the composite charts of figures 25 and 26.

The most striking features of the composite map for the 4 seasons of maximum occurrence of tropical storms (fig. 25) are the extensive area covered by above normal 700-mb. heights in the central Pacific and the huge anomaly ridge in the eastern half of the North Atlantic. (The area in the Pacific is associated with consistent positive anomalies south of 40°N. latitude and positive anomalies in the entire Atlantic ridge are highly consonant.) The negative anomaly pattern in the vicinity of Yucatan is suggestive of a steering current that would enhance the probability of a storm entering Area V, but these below normal heights are also a feature of the minimal seasons. One possible reason for the indefiniteness of this composite is the fact that no tropical storms entered Area V in the month of October of any of the 4 seasons of maximum occurrence. This may imply that a season is too long a mean for arriving at a representative pattern favoring storm penetration in that area.

The 7 seasons of minimum frequency in this area present a composite picture (fig. 26) that could inhibit tropical storm penetration in Area V. The anomalous flow is largely meridional: an anomaly trough in the Gulf of Alaska oriented north-south, an anomaly ridge in the vicinity of the Rockies, and an anomaly trough along the east coast of the United States. This pattern is easily understood physically, and the resultant anomalous northerly flow across Area V makes storm penetration into that area unlikely.

<u>Area VI</u> - Anomaly fields for the 6 seasons when three or more tropical

storms occurred in Area VI (Yucatan and Central America) were averaged, resulting in the composite chart shown in figure 28. A similar map prepared for the 8 seasons of minimal occurrence of tropical storms in this area is presented in figure 29. Large differences are apparent in many areas (fig. 30).

The anomaly pattern in the vicinity of Area VI in the seasons of maximum occurrence (fig. 28) is ill-defined, but suggestive of tropical storm penetration into that area. Area VI is primarily affected by storms forming in the Caribbean area (60 percent of the storms entering Area VI are first detected in the Caribbean). The anomaly pattern in figure 28 is also a pattern favorable for genesis of tropical storms in the southwestern and central Caribbean [7] with the introduction of cyclonic vorticity from the anomaly trough along the east coast of the United States extending into the Tropics.

This composite picture (fig. 28) is very similar to the mean anomaly pattern for the period 1933-44 [8], the period when 700-mb. data were scarce and the data used in preparing the series of 700-mb. charts were largely based on various estimations [2]. The anomalies in some areas have changed remarkably since that period [8] but there are certain indications that these changes are secular in nature. Since 1944, no season has had more than two tropical storms in Area VI; the mean for the period 1933-44 in 2.4 storms per season contrasted with a mean of 1.4 storms per season for the period 1945-56. Figure 28 is also similar to figure 9, the average anomaly pattern for the seasons of maximum frequency in Area I. Area I, also, shows a decline in storm frequency from 1.8 per season in the earlier period to 1.2 in the latter (see table 1, p. 4).

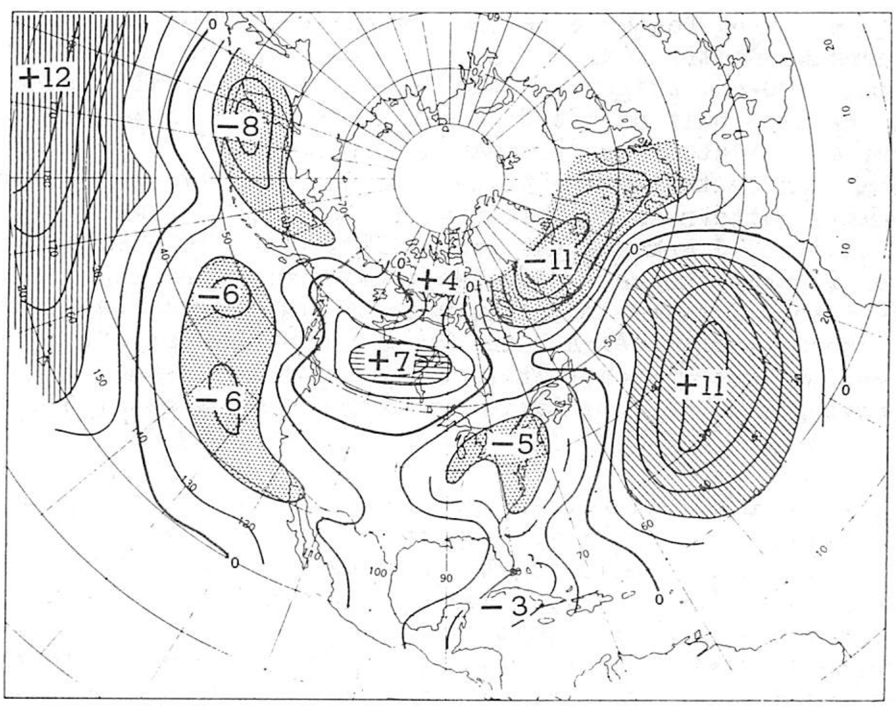

Figure 28. - Composite chart of the average departures from normal (in tens of feet) of 700-mb. heights for the 6 seasons of maximum tropical cyclone incidence in Area VI, Yucatan and Central America.

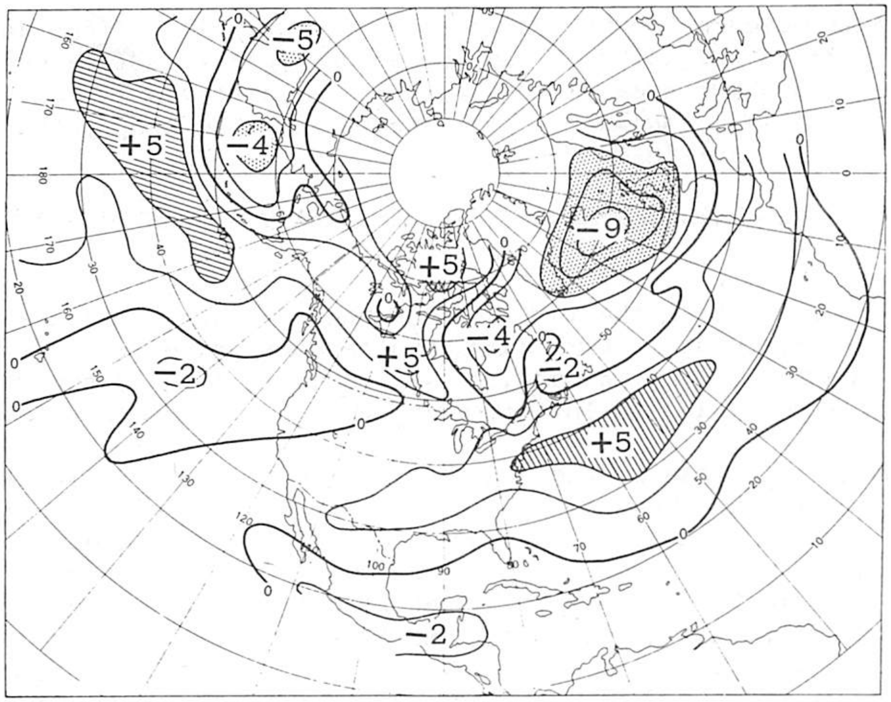

Figure 29. - Composite chart of the average departures from normal (in tens of feet) of 700-mb. heights for the 8 seasons of minimum tropical cyclone incidence in Area VI.

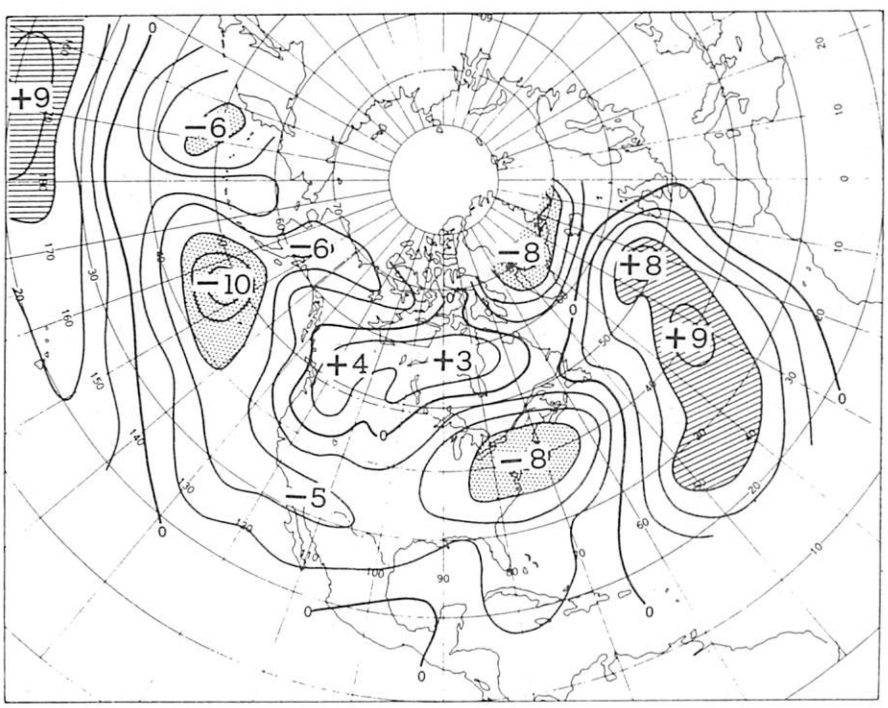

Figure 30. - Max-minus-min chart for Area VI showing the height difference (in tens of feet) between the composite charts of figures 28 and 29.

The anomaly pattern for those 8 seasons unfavorable to tropical storm penetration into Area VI (fig. 29) is one where the storms might be encouraged to re-curve before reaching Area VI and/or take a more northerly route affecting Areas II, III, and IV. Checking table 1 shows that the mean of these 8 seasons is slightly above normal in those areas.

4. INTERRELATIONSHIPS BETWEEN THE VULNERABILITY OF THE GEOGRAPHICAL AREAS

It was pointed out in the introduction that certain areas are relatively free of tropical cyclones in some hurricane seasons while other areas become unusually vulnerable. This is readily seen in table 1 where the frequencies of tropical cyclone incidence in each area in each season are presented.

On the basis of table 1, the correlation coefficients interrelating tropical storm activity in the various areas were computed and are shown in table 2.

Table 2. - Correlation coefficients interrelating tropical storm activity in the various areas

	II	III	IV	V	VI	Total
I	0.61	-0.06	0.18	0.32	0.34	0.42
II	- -	0.41	0.27	0.25	0.06	0.43
III	- -	- -	0.19	0.20	0.02	0.32
IV	- -	- -	- -	0.15	0.03	0.52
V	- -	- -	- -	- -	0.50	0.55
VI	- -	- -	- -	- -	- -	0.32

The magnitude of some of these correlations is a reflection of the percentage of tropical storms in each area that is common to other areas. These percentages are shown in table 3 and have the following interpretation: The figures shown in the third to eighth column of each row are the percentages of the total number of storms shown in the second column; e.g., the 89 percent in row I, column II indicates that 89 percent of the 35 storms which entered Area I were mutual to Area II; and the 61 percent in row II, column I shows that 61 percent of the 51 storms that entered Area II were also incident in Area I.

The high correlations between Areas I and II, II and III, and V and VI are a reflection of the fact that many of the storms entering one of these areas tend to move into the adjacent area.

<u>Area II Maximal Seasons</u> - Some of these interrelations appear in similarities among the composite charts also. The composite for the seasons of maximal incidence of tropical cyclones in Area II (fig. 14) consists of nine seasons, five of which were maximal seasons in Area I, and three of the remaining four were maximal in Area III. Figure 14 therefore resembles the other two composites (figs. 9 and 18) in some respects.

<u>Minimal Seasons in Area II and Area III</u> - A far more striking similarity

Table 3. - Percentage of tropical storms in each area which are shared with the other areas

Area	Number of storms	Percentage shared I	II	III	IV	V	VI
I	35	- -	89	40	3	0	0
II	51	61	- -	53	4	0	0
III	60	23	45	- -	28	3	17
IV	41	2	5	41	- -	15	27
V	31	0	0	6	19	- -	52
VI	45	7	7	22	24	36	- -

exists between the charts for the seasons of minimum tropical storm frequencies in Areas II and III (figs. 15 and 19) and also between the max-minus-min charts for those two areas (figs. 16 and 20) which indicate that similar conditions inhibit tropical storm incidence in these adjacent areas.

Inverse Relationship Between Areas I and III - Another interesting relationship is that between Areas I (northeastern United States) and III (southeastern United States). The correlation coefficient between these two areas is an insignificantly low value but a study of the composite charts indicates a much stronger inverse relationship between storm frequencies in these areas. The composite chart for the seasons when no tropical storms threatened the northeastern coast (fig. 10) has a general likeness to the composite chart for the seasons when four or more tropical cyclones entered the southeastern United States (fig. 18). The most significant feature in common is the area of positive height anomalies in the northeastern sector of the United States, a feature that tends to act as a bulwark against the penetration of cyclones into the northeastern sector of the United States and at the same time produces eastward anomalous flow encouraging cyclones to move into areas to the south (namely, Areas II and III). The antithetical relationship between storm incidence in the Northeast and that in the Southeast is demonstrated in table 4.

Table 4. - Mean departure from normal storm frequencies (See table 1.)

	Area I		Area III	
	Maximal seasons	Minimal seasons	Maximal seasons	Minimal seasons
Area I	+1.5	-1.5	±0	+0.2
Area III	-o.1	+0.8	+2.1	-1.8

Interrelations Between Area VI and Other Areas - It was pointed out in a previous section that the composite chart for the seasons of minimal frequency of tropical storms in Area VI is one which should result in a more than average number of storms in Areas II, III, and IV. This is reflected in the negligible correlations between each of these areas and Area VI. Even though no storms that occur in Area VI ever reach Area I, these two areas have one of the higher correlations on table 2, almost high enough to be of significance. It was shown earlier that the composite charts for the seasons of maximum incidence in each of these areas are similar. Since this similarity is not due to the same storms entering each area there must be a different reason. A possible answer is that this correlation, taken together with the similarity between the composites, is due to a certain preferred cyclone track seen in many years (e.g., 1944, fig. 31). This is a double-pronged track - one part traveling west into Mexico and another recurving into the mid-Atlantic and north Atlantic States [4].

5. SIGNIFICANCE OF THE RESULTS

The significance of the differences between the various pairs of composite charts has not been subjected to rigorous statistical testing. But, as seen in the figures accompanying this text, the sign of many of the anomaly centers on the chart of maximum frequency for a particular area is the reverse of the sign for the chart of minimum frequency; and other interesting differences exist between these charts.

Furthermore, a test has been made of the frequency of positive or negative signs of the anomalies on each mean chart and the major anomaly areas were found to have consistent signs for all individual seasons which comprise the mean. (An example of these frequency charts has been shown in figs. 5 and 6.) It was suggested in section 3 that since the degree of uniformity of sign is equally high for anomalies on each of the contrasting charts, the differences have some statistical significance. It was further pointed out in section 3 that these anomaly patterns are supported by synoptic evidence and physical reasoning.

These charts show interesting differences between maximum and minimum threat years in all areas studied. The inclusion of a large number of daily charts in each of these mean charts makes it unlikely that the anomaly pattern is materially affected by tropical storms of these years, which, after all, occur on a small number of days and occupy a relatively small portion of the map. As Namias [9] has pointed out, "...one of the chief functions of mean charts is precisely the smoothing out of certain undesirable features such as the smaller-scale eddies which move rapidly through the basic large-scale and slowly evolving pattern."

This contention is borne out by the following example (figs. 32, 33, and 34). Figure 32 is a chart of 700-mb. height anomalies for the hurricane season 1947. This was a season when 5 tropical storms entered Area III, posing a threat to the Florida area. The anomaly pattern for this season bears a fair resemblance to the composite chart for those years of maximum tropical storm penetration into Area III (cf. fig. 18). The chart for the 1947 season

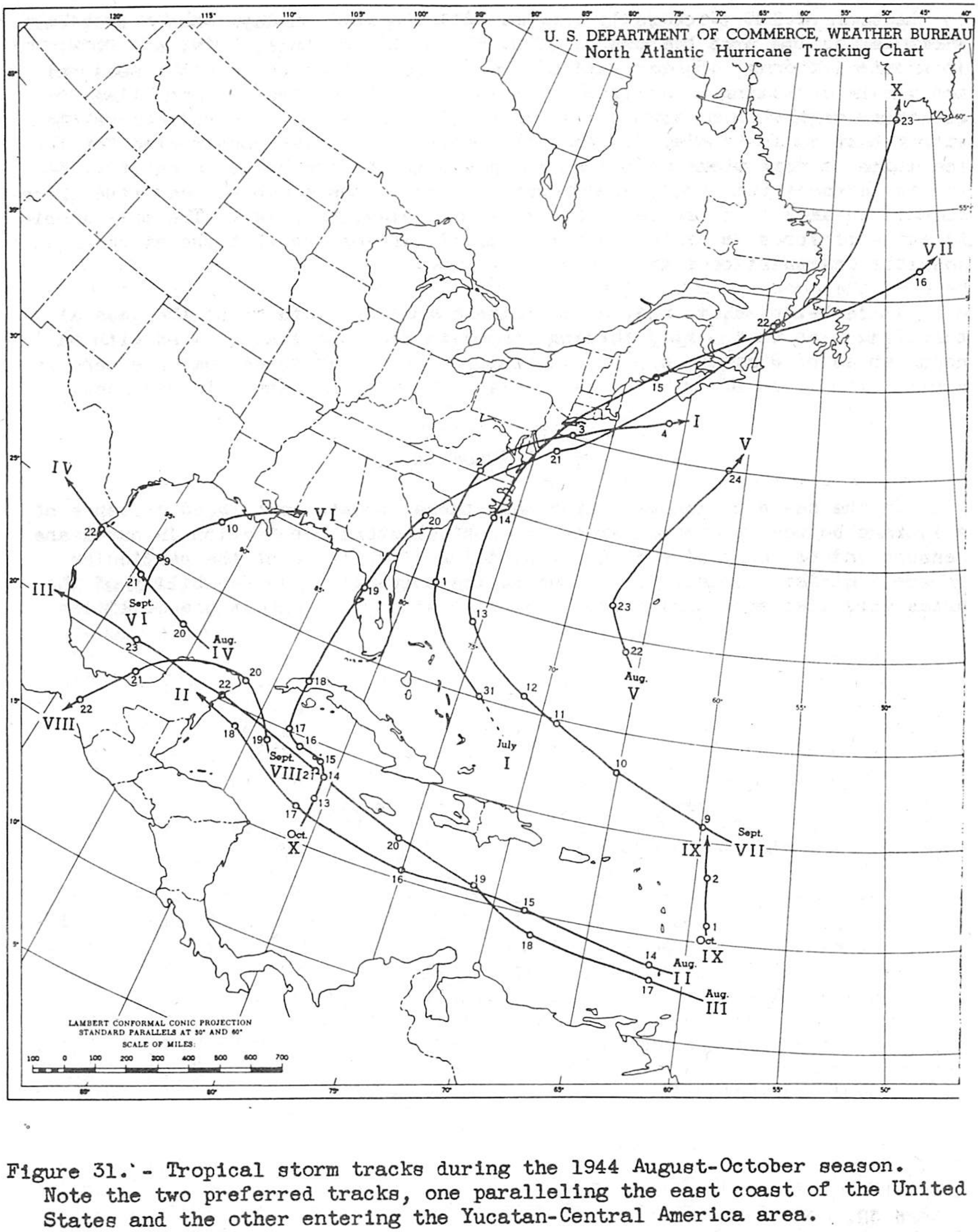

Figure 31. - Tropical storm tracks during the 1944 August-October season. Note the two preferred tracks, one paralleling the east coast of the United States and the other entering the Yucatan-Central America area.

is the mean of 180 twice-daily charts. All the data on days when a tropical storm was in the area bounded by 20°N. and 35°N. latitude, 70°W. and 90°W. longitude (23 days, 46 observation times) were subtracted from the seasonal mean. The resulting chart (fig. 33), the mean 700-mb. height anomalies for all those days when no tropical storm was in that area, is highly correlated with the chart for the entire season. Another chart was constructed for the remaining 23 days when a tropical storm was in the prescribed area (fig. 34) and the anomaly pattern is again very similar to the seasonal mean (and therefore also similar to the chart for non-tropical-storm days). The only significant difference is in the key area itself, indicating that the storm affects the local circulation pattern only.

It is believed, therefore, that the anomalous features of the general circulation shown in the preceding composite charts are associated with basic recurrences of similar large-scale features, and that these features tend to control the paths of the tropical vortices as well as other disturbances.

6. CONCLUSION

On the basis of the data examined, there appears to be good evidence of a linkage between preferred areas of tropical storm penetration in hurricane seasons and the character of the prevailing circulation of the particular season. Striking interrelations among the comparative vulnerability of the areas were also shown. This is noteworthy since it opens up possibilities

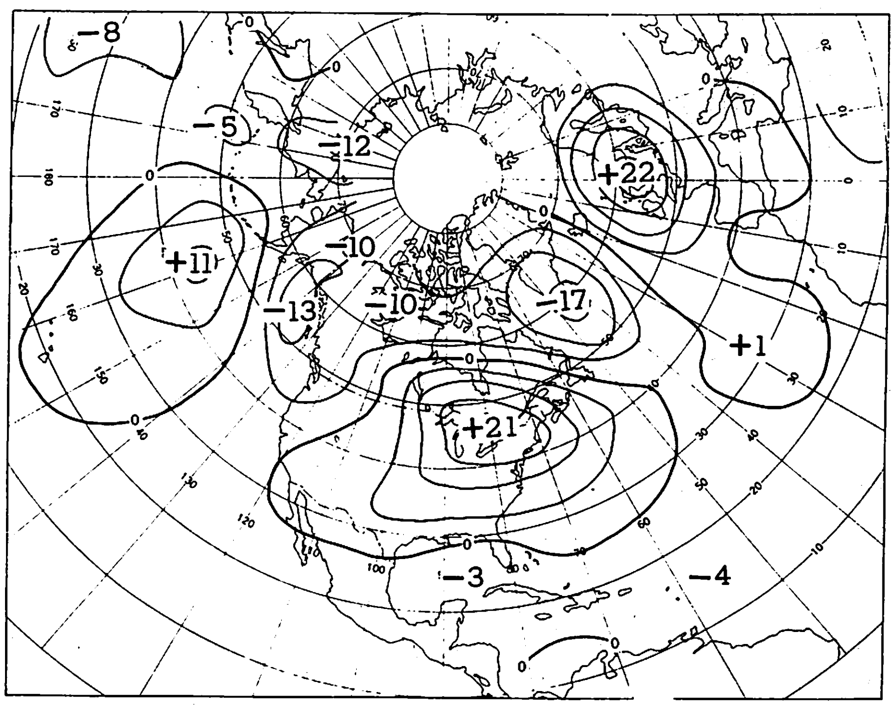

Figure 32. - Mean 700-mb. height departures from normal (in tens of feet) for the season (August, September, October) of 1947, a season when 5 tropical storms entered Area III.

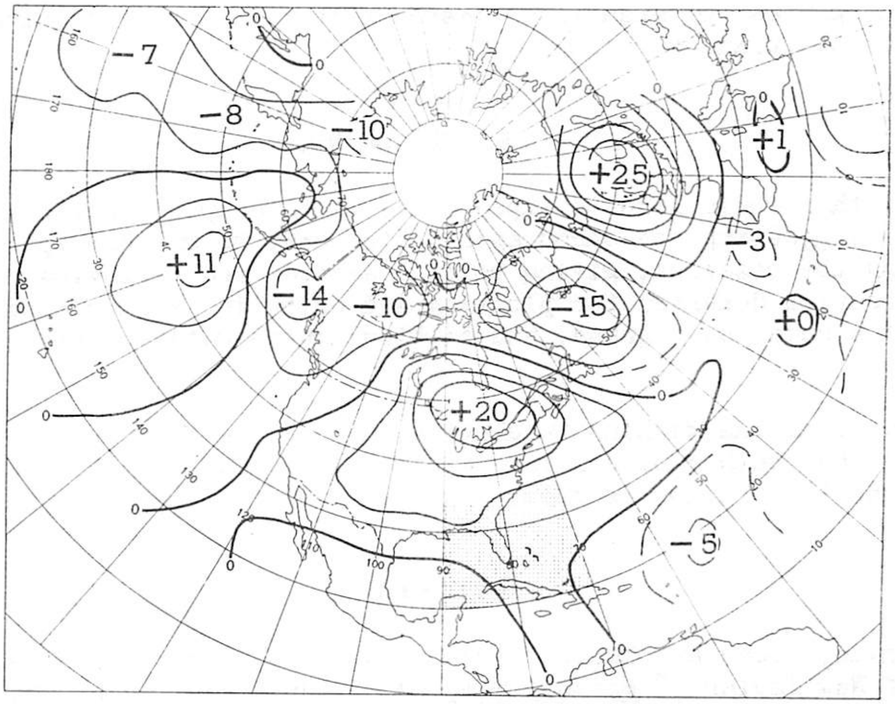

Figure 33. - Average 700-mb. height departures from normal (in tens of feet) for the days when no tropical storms occurred in the shaded area during the hurricane season of 1947.

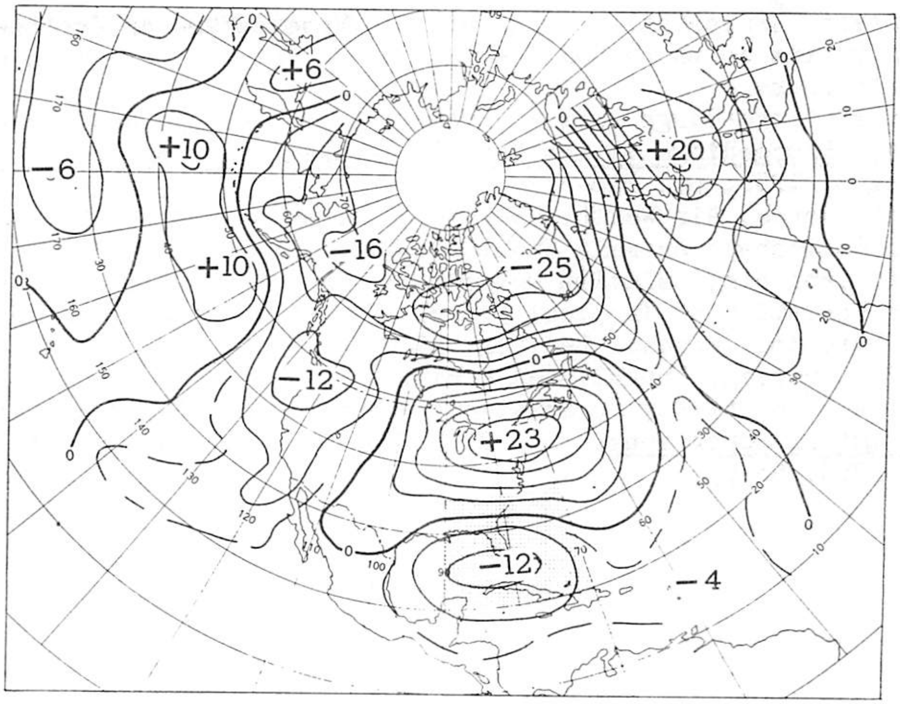

Figure 34. - Average 700-mb. height departures from normal (in tens of feet) for the days when there was at least one tropical storm in the shaded area during the hurricane season of 1947.

of predicting areas of greater or lesser vulnerability to tropical storms during a given circulation regime.

ACKNOWLEDGMENTS

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