CYCLOGENESIS IN THE ATLANTIC COASTAL REGION OF THE UNITED STATES [1]

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ABSTRACT

Cyclones originating in the Atlantic coastal region of the United States are classified into two types, and the characteristics of each type as determined from a study of 208 cyclones over a period of ten years are discussed. Methods of detecting cyclogenesis in its early stages are described and illustrated with an example.

CONTENTS

1. Introduction

Forecasting the development of cyclones and their associated weather is always a difficult problem; and in some parts of the world, such as the Atlantic coastal region of the United States, cyclogenesis is so rapid that it may transform an apparently innocuous weather situation into a severe cyclonic storm within the forecast period. It is to the advantage of the forecaster in the Atlantic coastal region to be well informed on the characteristics of cyclones that originate there. Meteorologists familiar with the region are acquainted with most of the cyclone characteristics in a general way, but their knowledge is gained through daily experience and may be sketchy, unorganized, and inordinately influenced by individual cases where the forecast failed. For greatest usefulness the characteristics must be established objectively from a long series of weather maps.

Cyclogenesis is complex and cannot be forecasted satisfactorily by empirical means alone. The major cause of failure in forecasting the formation and development of new cyclones is undoubtedly the lack of sure knowledge of the physical processes involved. An objective summary of the characteristics of east-coast cyclones should therefore not be limited to the establishment of empirical forecasting guides. It should have also the important and far-reaching aim of establishing a basis for theoretical studies of the causes of cyclogenesis.

The ten-year period from 1929 to 1939 was selected for a detailed study of the characteristics of cyclones that originate in the Atlantic coastal region. The precise boundaries of the region to be studied are shown in Figure 6, and were determined somewhat arbitrarily to include most of the United States east of the Appalachian Mountains and to extend about 1000 km eastward out to sea. Only the months from October through April, when cyclogenesis is more frequent and intense, were considered.

Statistical data that might be used as a background for theoretical studies or as guides in forecasting were derived from the characteristics of the 208 cyclones originating during the period selected. The sources of data were principally the historical series of daily northern-hemisphere sea-level maps published by the United States Weather Bureau, the daily weather map of the United States published each day by the Weather Bureau in Washington, the monthly summaries of cyclone tracks in the *Monthly Weather Review*, and an incomplete series of 3-km charts supplied by the Weather Bureau. It cannot be stated that any consecutive ten-year period is representative of weather conditions for all time, as some elements in some localities will deviate significantly from their long-period average; thus the characteristics

[1] From the report of a research project conducted jointly by the U. S. Weather Bureau and New York University.

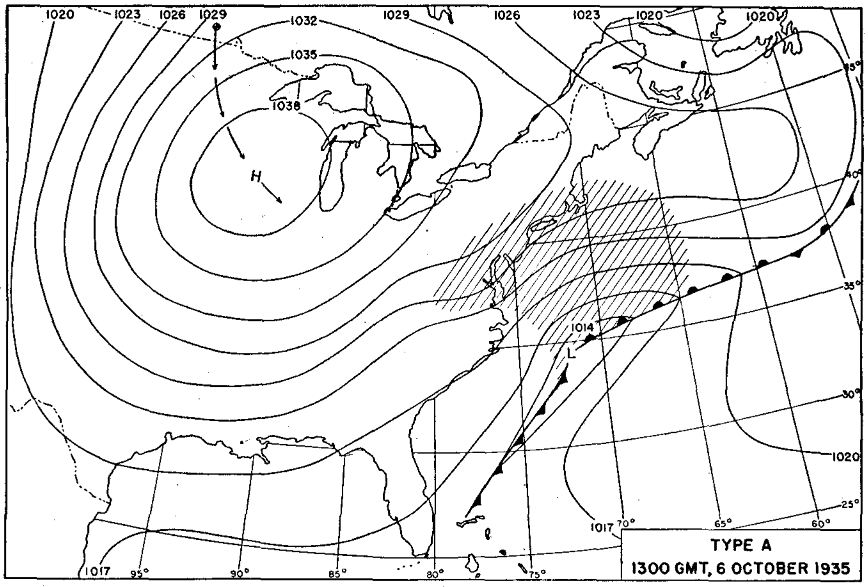

FIG. 1. Example of type-A cyclone at time of origin. Fronts are indicated by the conventional symbols; areas where precipitation is occurring are covered by hatching, whether the precipitation is intermittent or continuous; the lines are isobars labeled in millibars; and 24-hourly positions of pressure centers are marked by a cross enclosed in a circle.

summarized here are representative only to the extent that the period from which they were determined is representative.

Because of the characteristic rapidity of cyclogenesis in this region, it is necessary to detect cyclogenesis at its inception or as soon thereafter as possible. Following the presentation of statistical data there is a discussion of the premonitory signs of cyclogenesis, together with an example showing how cyclogenesis can be discovered and located at an early stage.

2. Types of cyclones

Two distinct types of cyclogenesis can be recognized in the Atlantic coastal region of the United States. Their distinguishing features are observed principally in the fields of motion and pressure and in the frontal pattern on the surface weather map at the time the new cyclone originates. The characteristics of each type are usually quite apparent although differing in details from case to case. It has been found in this study that when the surface map does not exhibit the characteristics of one of the two types a new cyclone is highly unlikely to form in the region.

Type A.—Type A appears as a cyclone wave along the front of a cold outbreak. This type of cyclogenesis is not peculiar to the Atlantic coastal region or even to east coasts in general. It is a common occurrence in regions where cold outbreaks occur frequently, but it is most often observed along east coasts in the colder part of the year. At the time of origin of a type-A cyclone in the Atlantic coastal region the characteristic features of the surface weather map are:

1. A cold anticyclone covering most of the United States east of the Rocky Mountains.

2. A cold, continental airmass flowing off the continent.

3. A current of warm, maritime air from a southerly or southeasterly direction in the western Atlantic, associated with a more or less well developed warm anticyclone and opposed to the offshore flow of cold air.

4. A retardation of a portion of the cold front in such a way that the front is distorted into a wave form.

5. A spreading of middle clouds and precipitation over the retarded portion of the cold wedge.

Type-A cyclones generally originate over the ocean and move in a northeasterly direction so that in many cases they do not have much effect on the weather of coastal stations. A typical example selected from the period of study is shown in Figures 1 and 2.

Type B.—Type B originates near the coast line to the southeast of an older cyclone. Its point of origin is along the warm front, or what appears to be the warm front, of the older storm. There is some reason to believe that this type is not as common in other parts of the world and owes its frequency to the peculiar topography of the east coast of North America. It is not often recognized elsewhere and not always recognized in this region. In many cases detailed study of a close network of observations is necessary to identify type B; consequently the historical northern hemisphere maps, having been analyzed from an open network, sometimes do not distinguish between the primary cyclone and the secondary that forms near it. The characteristics of type B are:

1. An occluding or occluded primary cyclone in the region of the Great Lakes, nearly stationary or moving northeastward.

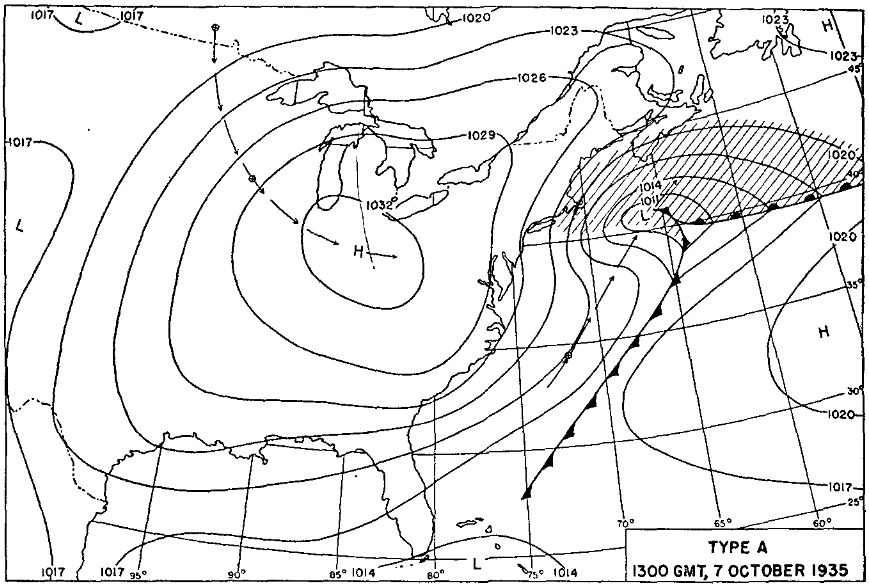

FIG. 2. Example of type-A cyclone 24 hours after origin.

2. A shallow wedge of cold continental air and associated pressure wedge, lying between the Appalachian Mountains and the Gulf Stream, the wedge line oriented southwestward from a cold anticyclone centered in eastern Canada or over the Grand Banks and crossing the 45th parallel near longitude 68° W. The shallow, cold airmass is sluggish and tends to remain along the coast during cyclogenesis.

3. A warm, maritime airmass flowing northward against the sluggish cold wedge, creating and maintaining a frontal discontinuity between the two airmasses.

4. A spreading of middle clouds and precipitation over the cold wedge, partially separated from the cloud and precipitation area of the primary cyclone.

5. A local area of falling pressure dissociated from the isallobaric minimum preceding the primary cyclone, but associated with the front of the cold wedge in the region where the airmass contrast and the convergence are greatest. The cyclone forms in this area.

As this cyclone type originates near the coast line and usually moves northeastward it affects the coastal weather much more frequently than does type A. A typical example is shown in Figures 3 and 4. On the first map the wedge line is evident along the New England coast; it extends southwestward to South Carolina and in the north it curves eastward and then southeastward into the anticyclone centered near 42° N, 55° W. Sometimes the anticyclone is centered over Canada, but in every case the cold wedge lies along the coast. Another type-B example is shown at its time of origin in Figure 17; note that the northern extension of the wedge line curves westward in this case.

In Figure 3 the secondary cyclone is forming on the warm front of the primary cyclone. The frontal structure is commonly interpreted in this manner. In many cases, however, the secondary originates on a new front that is not connected with the primary system, as in the example of Figures 15–17.

Sometimes the cold wedge is very narrow and the secondary appears to originate at the peak of the warm sector of the primary cyclone. In every such case during the period of study a closer examination showed that the secondary cyclone was forming east of the warm-sector peak. If the cold wedge between the warm-sector peak and the new cyclone is so narrow that it does not manifest itself definitely in the available pressure reports, it can be detected in the surface wind field. An isobaric analysis that is based on both winds and pressures will generally require that the new pressure minimum be located east of the point where the primary cold and warm fronts join.

Intermediate type.—In rare cases the features of type B appear soon after a cold outbreak, the primary cyclone being somewhat west or southwest of its customary position near the Great Lakes and still in the early stages of its development. A new cyclone forming along the coast in these circumstances may be classified as either type A or type B. The best distinguishing feature is then the nature of the front along the coast; if it is still identifiable as the forward edge of the preceding cold outbreak, the cyclone is better classified as type A, but, if the original cold front has disappeared or moved out into the Atlantic while a new front forms along the coast, the cyclone is type B.

Type-A and type-B regimes.—It is sometimes possible to anticipate the type of cyclogenesis two or

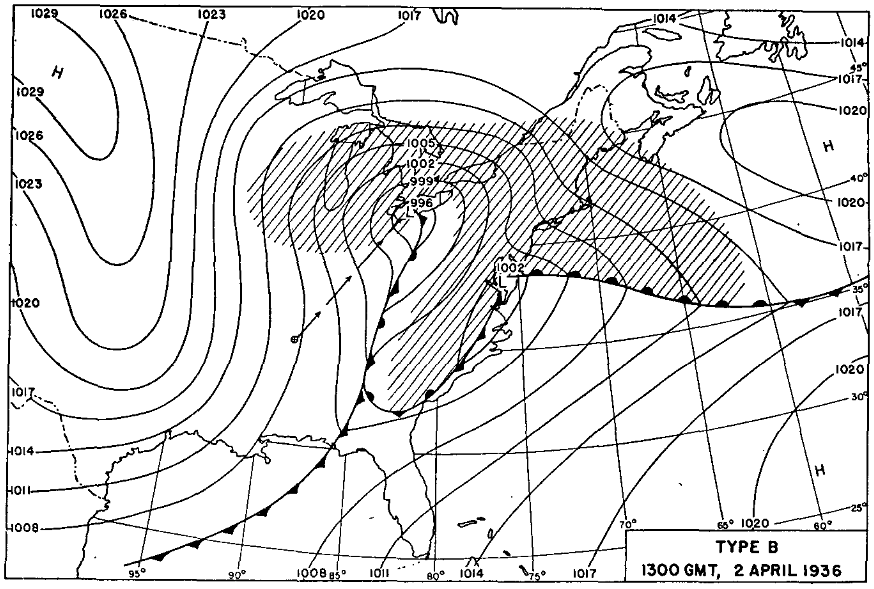

FIG. 3. Example of type-B cyclone at time of origin.

three days in advance on the basis of the characteristic features, although there is no assurance that cyclogenesis will take place. The characteristic features of a type may be considered a description of a weather regime. When the east-coast weather does not conform to either type, a trend toward a regime of type A or B may be noted. If the trend seems reliable and not transitory, the forecaster can estimate the length of time required for a cyclogenetic regime to set in, and in view of the type of regime he can locate the approximate region where cyclogenesis may occur.

Four types of east-coast cyclones are described in an unpublished manuscript, "New England coastal storms," by L. T. Rodgers, Weather Bureau Airport Station, Boston. Rodgers' four types, although defined independently of this study, represent subdivisions of the two described here. The conditions favorable for cyclogenesis near the Atlantic coast have been discussed briefly by Austin [1], whose two cyclogenetic types are very similar to types A and B as defined here.

3. Characteristics of east-coast cyclones

A number of characteristics of the cyclones forming in the east-coast region can be studied statistically. The statistics cannot be used objectively by a forecaster faced with a particular weather situation, which may deviate widely from the normal; but they are useful for two purposes: as background knowledge for the forecaster, serving him in the same way that climatological summaries do, and as a factual groundwork on which to base theoretical studies of cyclogenesis. The pure statistics are not entirely sufficient for either purpose; both require the careful, detailed investigation of a number of individual cyclones.

Monthly frequency.—The average number of cases of both types of cyclogenesis and of types A and B individually, as determined from the ten-year period of study, is shown for each month from October through April in Figure 5. It will be noted that the frequency of type A is greatest in November, dropping to a minimum in January, and rising to a secondary maximum in March. Although the months from May through September were not studied, it is probably safe to say that the frequency is somewhat lower in those months than in November or March.

Type B rises to a maximum frequency in January, drops to a minimum in February, and then rises to a secondary maximum in March. The February minimum is not caused solely by the smaller number of days in February as compared with January and March, as this would account for a reduction of only 9 per cent or 0.2 case per month,[2] whereas February has 0.8 fewer than January and 0.7 fewer than March. It may simply be an accident of the short period of study, ten years not being a sufficiently long period to determine the normal monthly frequency.

On the other hand the February minimum of type-B cyclones may be a real minimum. It is supported by the fact that along the path frequented by type-B cyclones, following the coast from Norfolk to Eastport, most of the weather stations have secondary maxima of average daily precipitation in January and March with a slight minimum in February. The precipitation averages are based on forty years of record; hence the correlation of storm frequency with average daily precipitation confirms the February

[2] Average number of days in February, 28.25; in January and March, 31; $(31 - 28.25)/31 = 0.09$. Average number of cyclones in January and March, 2.45; $0.09 \times 2.45 = 0.2$.

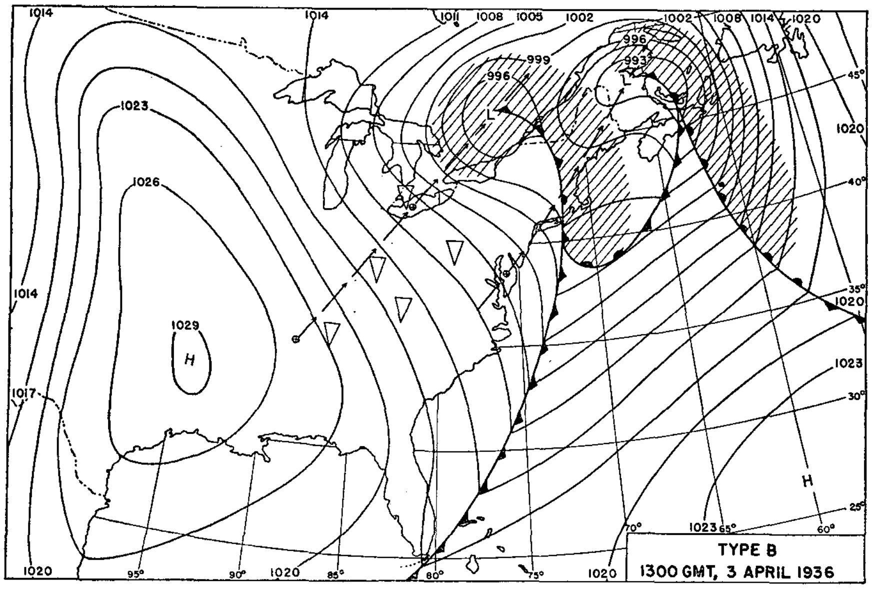

FIG. 4. Example of type-B cyclone 24 hours after origin.

minimum. Moreover, February is the coldest month in the Atlantic coastal region and the mean boundary between cold continental air and warm maritime air is farthest south then, possibly too far south for a favorable combination of airmass contrast and topography. The secondary winter maximum of average daily precipitation at stations south of Norfolk occurs in February, and on the average more storms originate in the eastern Gulf of Mexico in February than in any other month [2]. Finally, the selection of latitude 30° N as the southern boundary of the region of study (see Fig. 6) may have been unwise; the possibility exists that a significant number of type-B storms originated south of that boundary in February.

The number of cases of cyclones forming in a region similar to the region used in this study, but not having exactly the same boundaries, was determined by Bowie and Weightman [2] for a twenty-year period from 1892 to 1912. Dividing their monthly totals for the "south-Atlantic" type by 20, one obtains the frequencies shown in Table 1. The south-Atlantic type includes both types A and B so that

TABLE 1. Monthly frequency of "south-Atlantic" cyclones.

October	0.50	January	0.40
November	0.85	February	0.20
December	0.35	March	0.30
		April	0.60

these frequencies can be compared with the upper line in Figure 5. The most striking difference is the smaller frequency found by Bowie and Weightman. It is not clear from their discussion what the cause of the difference may be. Perhaps type-B cyclones were not classified as separate storms when they originated close to their primary; and many cases of type A, which forms most frequently over the Gulf Stream, may have been overlooked due to lack of data.

The deviation of individual years from the ten-year average frequency can be seen in Table 2. For example, during the four years 1930 through 1933 no cyclones of type B occurred in January, the month of highest frequency in the averages. As another example, the seasons of 1929–30 and 1933–34 had each a total of twenty cyclones, approximately equal to the ten-year average (20.8); but there were 50 per cent more cases of type A than type B, whereas in the whole ten-year period there were about 50 per cent more of type B than of type A.

Geographical frequency.—In tracking a cyclone and in studying the distribution of elements about it, the point of minimum pressure is commonly taken

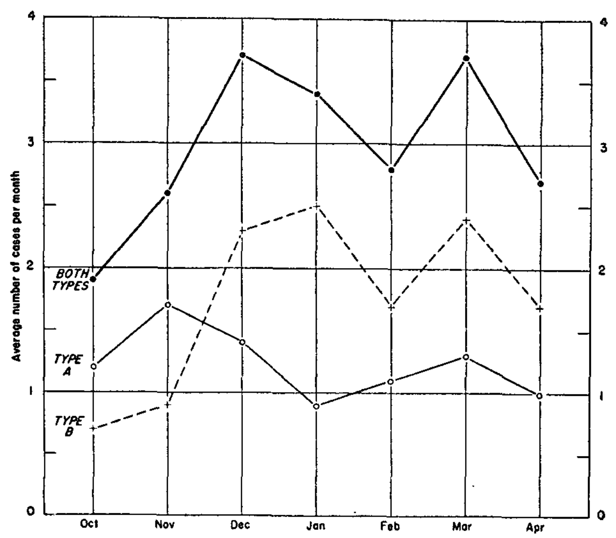

FIG. 5. Average monthly frequency of cyclones originating in the Atlantic coastal region.

TABLE 2. Number of cases of cyclogenesis in each month of period of study.

Month	October		November		December		January		February		March		April		Total		
Type	A	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B	Both types
1929–30	0	0	5	1	1	4	1	0	2	0	2	1	1	2	12	8	20
1930–31	0	1	2	2	2	1	0	0	1	1	1	2	0	0	6	7	13
1931–32	1	1	0	1	0	3	0	0	0	2	1	0	1	0	3	7	10
1932–33	2	1	1	1	1	1	1	0	3	1	0	3	2	2	10	9	19
1933–34	1	1	0	2	2	2	2	1	0	0	5	0	2	2	12	8	20
1934–35	1	3	1	1	3	4	0	5	1	2	0	5	2	3	8	23	31
1935–36	2	0	3	0	2	4	1	4	0	3	1	3	0	2	9	16	25
1936–37	2	0	2	0	0	0	2	5	0	6	1	3	0	2	7	16	23
1937–38	2	0	1	0	2	0	2	3	3	0	2	3	0	1	12	7	19
1938–39	1	0	2	1	1	4	0	7	1	2	0	4	2	3	7	21	28
Total	12	7	17	9	14	23	9	25	11	17	13	24	10	17	86	122	208
Both types	19		26		37		34		28		37		27				

as the center. The cyclones discussed here have been considered to originate at the time and place where a minimum point first appears in the pressure field. A dense network of stations and frequent reports of pressure, neither of which was available in this investigation, would be needed to detect a pressure minimum precisely at its inception. Three sources of data, the once-daily Washington maps, the once-daily northern hemisphere maps, and the monthly summaries of cyclone tracks in the *Monthly Weather Review*, were used to determine the time and point of origin. The latter source shows twice-daily positions of cyclones, so that by consideration of the phenomena accompanying cyclogenesis it was possible to fix the time of beginning within 12 hours. The average error of timing can therefore be estimated at 6 hours. Because the majority of east-coast cyclones move slowly during the first few hours of their history, the error of timing results in only a small error in position.

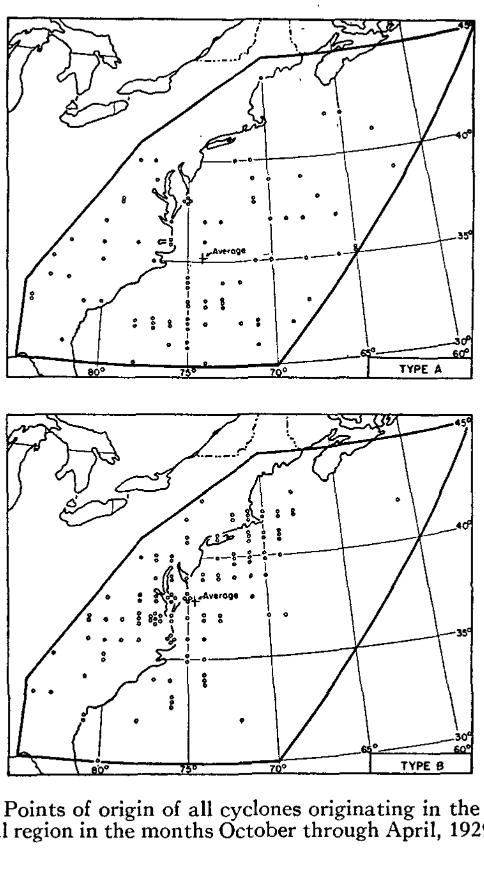

FIG. 6. Points of origin of all cyclones originating in the Atlantic coastal region in the months October through April, 1929–1939.

The point of origin of each of the 208 cyclones is shown in Figure 6. Either type of cyclone may form almost anywhere in the region of study, but a tendency toward concentration in certain areas is apparent. To bring out this tendency, Figure 6 was analyzed according to the number of cyclones originating in overlapping areas with dimensions 3 latitude degrees by 3 longitude degrees. The results are shown in Figure 7; here the favored areas of formation of each cyclone type are clearly revealed. A similar diagram has been constructed by Petterssen [3] without distinction between types of cyclones.

Type A most frequently forms slightly east of the temperature axis of the Gulf Stream near latitude 32° N. There is some indication that the land area east of the Appalachians and the water area north of the axis of the Gulf Stream, where it swings eastward, are also favored areas for this type of cyclogenesis. Type B shows two concentrations, the primary one near Norfolk and the other south of Cape Cod. The line AA′ has been drawn perpendicular to the axis of high frequency to subdivide the region of study into two regions that can be examined separately.

Displacement of cyclones during the first 24 hours.—The direction and distance of movement of each cyclone during the first day of its existence were determined as accurately as possible by reference to all of the three sources cited. These data define a vector starting at the point of origin and ending at the position of the pressure minimum 24 hours later, the time interval being either 1300 to 1300 GMT, or 0100 to 0100 GMT.

A simple average of the cyclone movement is apt to be misleading for it does not show the rather large variations from cyclone to cyclone. Figure 8 is an analysis that discloses the most significant features.

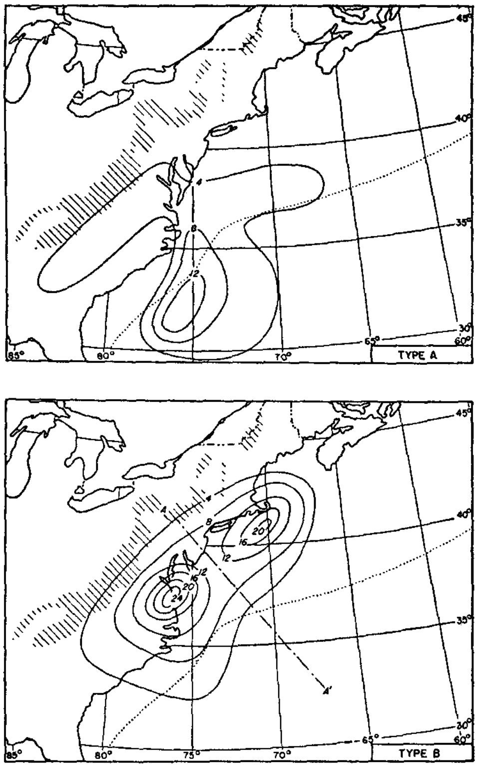

FIG. 7. Number of cyclones originating in areas bounded by meridians and parallels 3 degrees apart in the months October through April, 1929–1939. The hatching covers areas where the earth's surface is more than 1500 feet above sea level, and the dotted line is the locus of maximum sea-surface temperature at each latitude in winter.

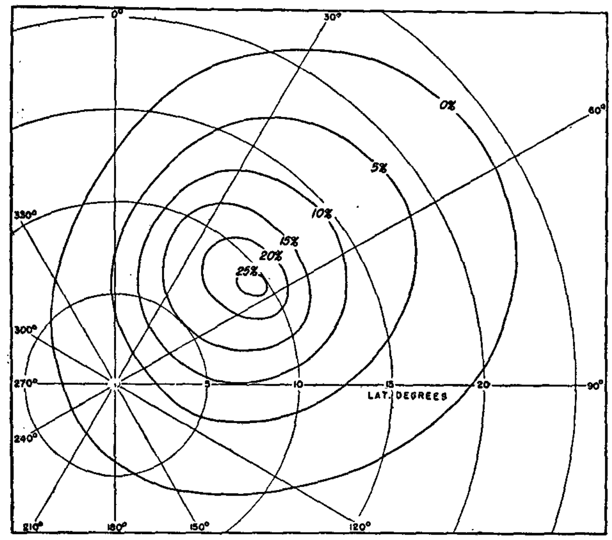

FIG. 8. Movement of cyclones during the first 24 hours. The direction toward which cyclones move is indicated in degrees east of north, and the distance is indicated in latitude degrees. The value of an isopleth at any point represents the percentage frequency of cyclones whose movement vector was equivalent to a vector starting at the origin and ending within a distance of 3 latitude degrees of the corresponding point. Both cyclone types are included in this analysis, regardless of the month or of the point of origin.

The isopleth value can be interpreted as a probability that the 24-hour trajectory of any cyclone starting at the center of the polar diagram will end somewhere within 3 latitude degrees of the corresponding point.

The most frequent 24-hour displacement is toward 55° east of north for a distance of 9.5 latitude degrees (660 miles), but this modal vector has a probability only a little greater than 25 per cent. A forecast based solely on the modal vector would generally be unsatisfactory; it would have only one chance in four of verifying within a distance of 3 latitude degrees. As no obvious variation of movement with type, region, or month was discovered in the data, Figure 8 includes all new cyclones in the period of study.

Deepening of cyclones during the first 24 hours.—The change of central pressure during the first 24 hours was computed for the 138 cyclones originating at 1300, the sources of data being inadequate to obtain the 24-hour deepening of cyclones originating at 0100. The pressure changes have been divided into class intervals of 3 mb centered at +9, +6, +3, 0, −3, −6, · · ·, and the percentage frequency in each interval is shown for each cyclone type in Figure 9. The modal frequency for type A is at −6 mb and for type B at −9 mb; but, as in the case of cyclone movement, the frequencies, 23 and 19 per cent, do not indicate a great enough chance of verification for a forecast based solely on the most probable rate of deepening.

In Figure 10 the percentage frequency is shown for each type by 3-mb class intervals of central pressure

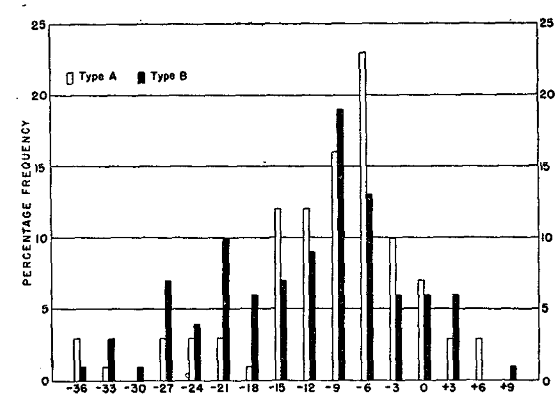

FIG. 9. Deepening of cyclones during the first 24 hours.

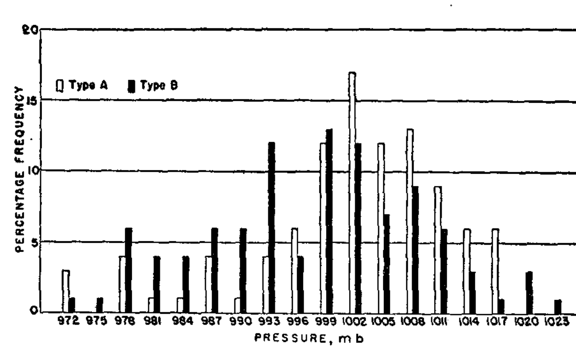

FIG. 10. Central pressure of cyclones at end of the first 24 hours.

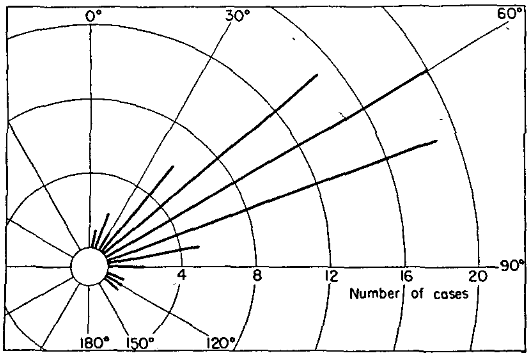

FIG. 11. Orientation of 3-km isobar at time and point of origin, in degrees east of north with lower pressure to the left of the vector. The length of a radial line represents the number of cases observed out of a total of 74.

at the end of the first day. This graph is a summary of the same cases represented in Figure 9. The most frequent central pressure of type-A cyclones after 24 hours is 1002 mb and of type-B cyclones 999 mb. The modal frequencies, 17 and 13 per cent, are small and the range of observed central pressures, 972 to 1023 mb, is great.

Isobar direction at 3 km at time and point of origin.—It was noted early in the investigation of east-coast storms that the isobars at the 3-km level almost invariably indicate a wind direction from south of west in the area of cyclogenesis when a new cyclone of either type forms on the east coast. To summarize statistically the isobar orientation, 3-km charts representing about half of the period of study were obtained from the Weather Bureau. These were available for 32 months, in which 46 type-A and 64 type-B cyclones were observed, or 110 in all. The observation time for the 3-km charts was sometimes 0900 and sometimes 1200 GMT, so the isobar direction has been summarized only for cyclones whose time of origin was 1300. Elimination of the 0100 cyclones, and two 1300 cyclones where the upper isobar was curved too sharply for a representative direction to be obtained, left 74 cases to be summarized.

The number of cases of cyclogenesis for each 10-degree interval of isobar direction is shown in Figure 11. In 54 cases, or 73 per cent of the total, the 3-km isobar at the time and point of origin was oriented between 45° and 75° east of north. In only three cases was the wind direction, as indicated by the isobar, from north of west. The normal 3-km isobar direction in the east-coast region for the period from October through April is about 95° [4]. There were too few observations of wind on the 3-km charts for an analysis of the actual wind direction to be made.

Relation between 3-km isobar direction and cyclone trajectory.—The difference between the 3-km isobar direction at the time and point of origin and the direction of the subsequent 24-hour trajectory of the cyclone is illustrated in Figure 12. The most frequent deviation is 20° to the left of the isobar, and the correlation coefficient between initial isobar direction and orientation of the subsequent trajectory is 0.42.

If any real relation exists between the upper isobar and the path followed by a storm, the mean isobar direction over the storm center for the 24-hour period should have a higher correlation with the path than does the initial isobar direction. For the 74 cases illustrated in Figure 12 the isobar direction was determined from the 3-km charts at the location of the center after 24 hours, and a simple average was made of the initial and final directions. In addition 32 cases of storms originating at 0100 GMT were included, the 3-km isobar direction being taken from the upper-level chart at the location of the storm after 12 hours. The correlation coefficient between mean isobar direction, or isobar direction in the middle of the period, and the orientation of the cyclone trajectory was found to be 0.63 for the 106 cases available, and the most frequent deviation of path from isobar was between +5° and −5°.

The value of the correlation coefficients is undoubtedly affected strongly by random errors such as personal errors of analysis of the surface and upper-level charts, and by systematic errors such as are introduced by the simplifying assumptions made in extrapolating pressure from the sea surface up to 3 km. An examination of the charts has shown that a much higher correlation could be obtained by subjective correction of both types of error, but it would then be impossible to determine how much of the correlation was real and how much due to personal bias.

The relation between storm trajectory and upper-level flow might best be tested by using actually observed winds; but again, as in the study of air flow and cyclogenesis, there were not enough observed winds for the relation to be examined.

Location of primary cyclone at time of type-B cyclogenesis.—The most important distinguishing feature

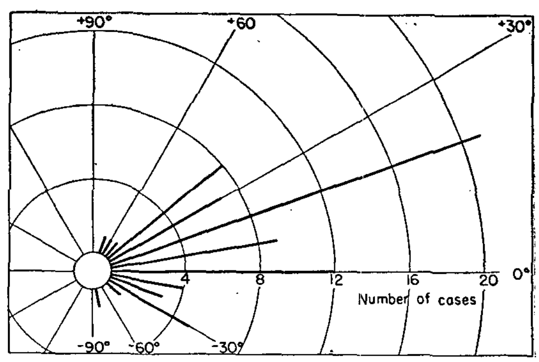

FIG. 12. Deviation of 24-hour cyclone track from initial isobar direction at 3 km. A positive angle indicates that the cyclone trajectory deviated to the left (toward lower pressure), and for each angle of deviation the number of observed cases is represented by the length of the radial line.

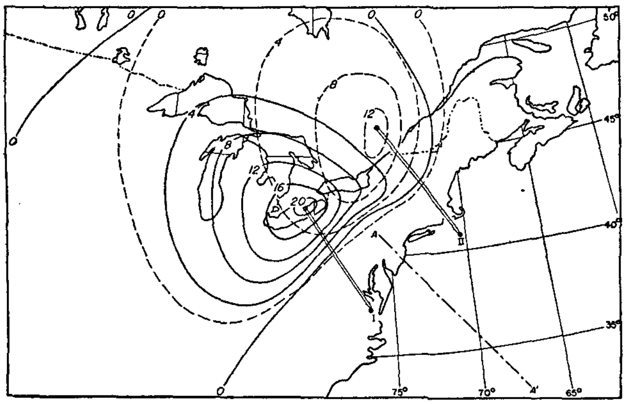

FIG. 13. Frequency of location of primary cyclone in areas bounded by meridians and parallels 5 degrees apart, at time of origin of type-B secondaries. Separate analysis for secondaries originating northeast and southwest of line AA′ from Fig. 7. The endpoints of vectors I and II are the corresponding maximum points of Fig. 7 (lower).

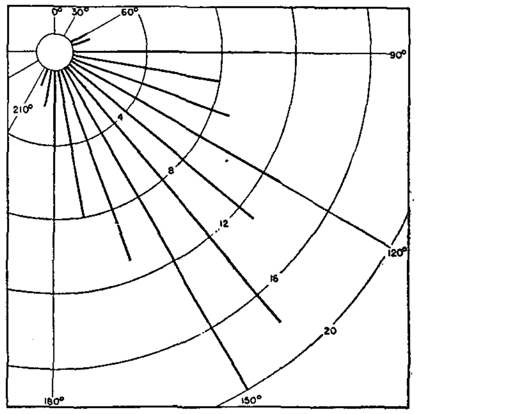

FIG. 14. Bearing of secondary from primary cyclone at time of origin. Each radial line represents the number of occurrences within a 10-degree sector. Total number of cases, 121.

between type-A and type-B cyclones is the presence of an older cyclone in the eastern half of the United States. The location of the primary cyclone at the time of origin of the secondary was determined for all of the 122 cases of type B except for the one case where it was indeterminate. The two sets of isopleths in Figure 13 show the distribution of primaries for the two regions of secondary cyclone origin. The presence of a primary cyclone evidently is not an extraneous feature of type-B cyclogenesis; for, if it were, the isopleths of Figure 13 would not show such a markedly systematic organization. For the region of origin southwest of AA′ the primary cyclone is most frequently located over Lake Erie at the time of origin of its secondary, and for the region northeast of AA′ it is located just north of Ottawa. The orientation of vectors I and II is approximately 150° or slightly east of south-southeast.

The orientation of the type-B cyclone from its primary at the time of origin was measured for each of the 121 cases, and the number of cases found for each angle is shown in Figure 14. The bearing of the secondary was measured at the primary center on a Lambert conformal conic projection, and thus it is not exactly a true bearing on the earth's surface. The secondaries originated almost exclusively in the southeast quadrant of the primary, 53 per cent originating along a line oriented within 20° of due southeast from the primary. The most frequent orientation is 150° or the same as was found by the different type of analysis shown in Figure 13.

Location of wedge line at time of cyclogenesis.—A cold, continental airmass plays an important role in both types of cyclogenesis. During the study of cases of cyclogenesis in the years 1929 to 1939 it was observed that the high-pressure center of the continental airmass is located somewhere in the United States east of the Rocky Mountains when type-A cyclones form and that its associated wedge line, oriented generally north-south, may be found at any longitude in that region. On the other hand, the northeast-southwest pressure ridge associated with the shallow wedge of cold air that is characteristic of type-B cyclogenesis was almost invariably located near the eastern coast line. To put these impressions on a more objective basis, the longitude of the wedge line of the continental high nearest the east coast was determined at the point where the wedge crossed the 45th parallel at the time of origin for all cyclones originating at 1300. As no 0100 maps were available, this analysis could not be made for cyclones originating at that time.

For type-A cyclones the wedge line was found to cross the 45th parallel between 108° W and 58° W with no tendency toward concentration at any longitude. For type-B cyclones the wedge line was found in a much more restricted zone, between 75° W and 62° W with a concentration at 70–66° W, as shown in Table 3. In a few cases no wedge line existed at the 45th parallel, but one could be found along the coast south of that latitude; in such cases its position at 45° N was determined by extrapolating the wedge line northward. The modal longitude of the wedge line for cyclones originating in the region northeast of line AA′ (Fig. 13) was not found to differ markedly from the modal longitude for those originating in the southwestern region.

TABLE 3. Longitude of cold-wedge line at latitude 45° at time of origin of type-B cyclones.

Longitude, °W	75	74	73	72	71	70	69	68	67	66	65	64	63	62	Total
Number of cases	1	3	3	1	5	9	10	5	11	8	5	4	1	1	67

Zonal index and cyclogenesis.—To examine the relation between cyclogenesis in the Atlantic coastal region and the large-scale, zonal circulation indices, there were obtained, from the Weather Bureau, values of the mean five-day index for the whole hemisphere covering 32 months, and values for the North Atlantic and North American divisions covering 13 months. Analysis of the data revealed no tendency for high or low values, or for rising or falling trends, either at the time of new cyclones or preceding their formation. Thus, no indication was found that the zonal index is closely related to cyclogenesis in the Atlantic coastal region.

4. Premonitory signs of cyclogenesis

Since new cyclones in the coastal region develop rapidly and may come to maturity within 24 hours, it is desirable that the inception of a cyclone be detected at the earliest possible moment.

Middle sky and weather.—One of the earliest signs of cyclogenesis is the spreading of middle clouds and precipitation over the coastal region. This phenomenon so consistently precedes the appearance of a pressure minimum that one is led to believe that the hydrometeors are closely related to the causes of cyclogenesis. The middle cloud sequence observed at a fixed location is of the typical warm-front type: first altocumulus translucidus (M_3 or M_5 in the international classification) or the mixed form of altocumulus and altostratus (M_7), then thicker clouds of the form altostratus opacus (M_2), and finally nimbostratus. The middle clouds may be hidden by turbulence stratocumulus at a lower level and may be preceded and accompanied by cirrostratus.

In type-A cyclogenesis the coastal region will have experienced a cold-front passage within the past day or two, and the appearance of the warm-front sequence of middle clouds is a significant premonition of the new development.

In type-B cyclogenesis the cloud sequence is not as certain an indication, because it would be expected on the approach of the primary cyclone. For this type it is necessary to examine the synoptic pattern of middle clouds; either there is a partial separation between the middle cloud systems of the primary and of the developing secondary in the coastal region, or the cloud system of the primary will spread over the region faster than the primary cyclone moves in that direction. The separation of cloud systems fails to be noticeable when the secondary develops close to the primary. In type B there will sometimes be found two precipitation areas, more or less distinct from one another: one associated with the primary cyclone and the other over the coastal region. Sometimes the separation of areas is not observed, but the precipitation spreads over the coastal region at a rate that would not be expected from the movement of the primary cyclone. Spreading of middle clouds and precipitation in this region is a sign that cyclogenesis has begun, but it does not guarantee that the process will continue until a separate cyclone has formed. In many cases the primary is too strong and the coastal cyclogenesis too weak to result in a new cyclone.

The field of pressure change.—The best indication that a pressure minimum is forming can be found in the pattern of the isallobars. Isallobars reflect the movement and development of pressure systems; the movement is evident from the successive pressure charts, but the development of a pressure system is more obscure and cannot be seen clearly unless the pressure and pressure-change charts are viewed together. A point or line of maximum pressure fall, not associated with a moving pressure center or trough, is a direct and indisputable sign that a new system has been forming during the period represented by the isallobars. A situation of this kind does not, of course, mean that a new system *will* form, but only that one has been forming.

Three-hour pressure changes are customarily plotted on the weather map and, for the purpose of forecasting, should be analyzed in the coastal region. Detailed analysis of these tendencies should contribute greatly to a successful forecast. To discover trends of a longer period that may be too indistinct to show in the 3-hour tendencies, 12-hour pressure changes can be computed from the reported pressures and analyzed on a separate chart. In a number of cases that were studied the 12-hour isallobars gave striking evidence of the formation of a new cyclone in situations where the analysis would not otherwise have revealed it clearly.

The process of cyclogenesis can proceed for several hours without the formation of a new pressure minimum; this depends on both the isallobaric gradient and the pressure gradient. To reverse the pressure gradient locally and thus produce a pressure minimum, a much greater local fall must occur where the isobars are closely packed than where they are widely separated. In type-B cyclogenesis, if the primary continues to deepen or to move toward the area of secondary cyclogenesis, there is less probability that the pressure fall associated with the secondary will reverse the pressure gradient and form a separate center of low pressure. It seems that some degree of cyclogenesis almost always occurs in the coastal region when the features of the surface weather map are characteristic of type B, but in many cases the gradients of pressure and pressure tendency are not favorable and the duration of cyclogenesis is insufficient for a separate center to form. Moderate to heavy precipitation that cannot be attributed to the normal weather pattern of the primary cyclone often occurs in the coastal region under these circumstances. Similarly there are many abortive cases of type-A cyclogenesis where

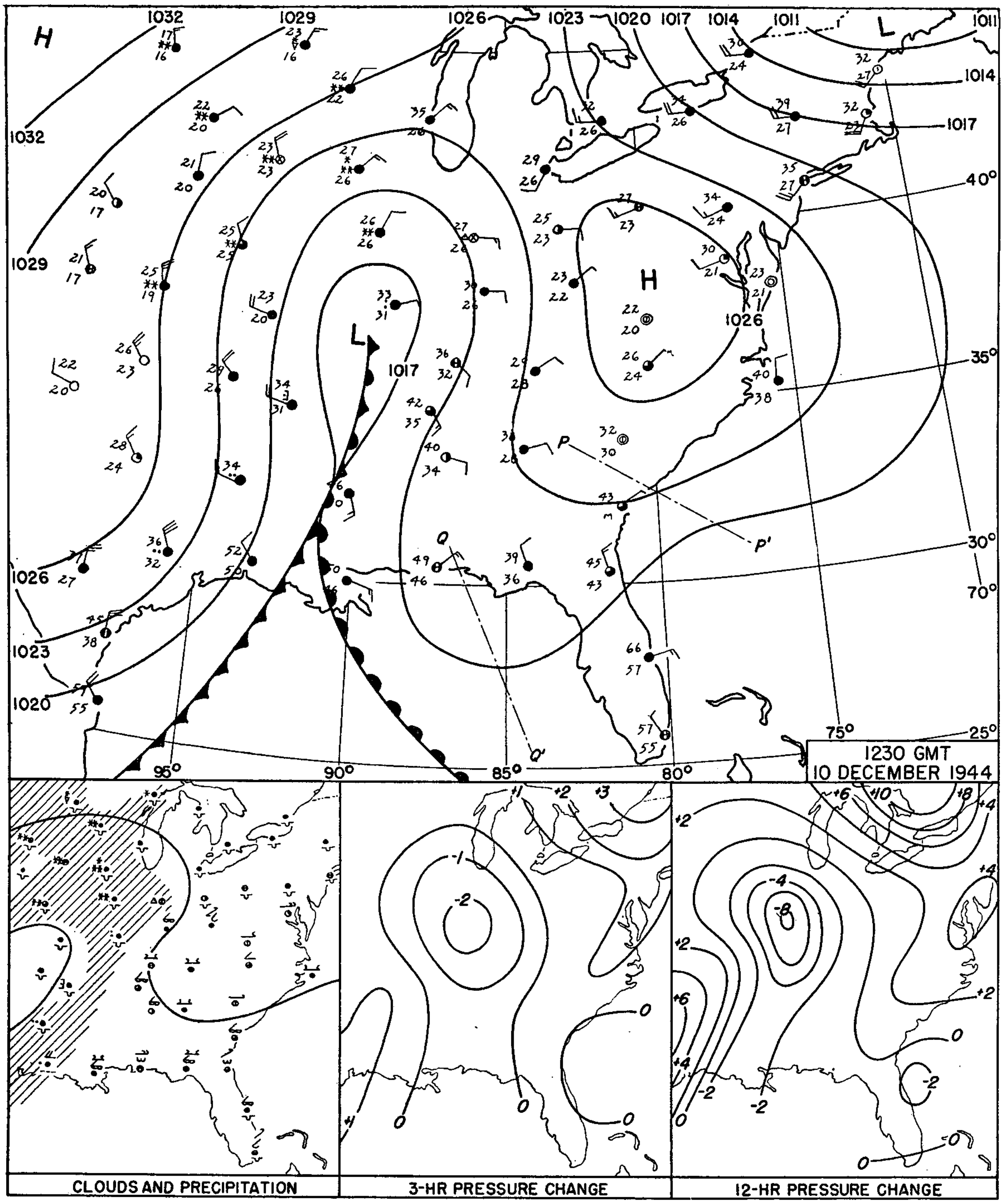

FIG. 15. Example of detection of cyclogenesis, first map.

cyclonic weather prevails in the absence of a clearly defined pressure minimum.

Example of detection of cyclogenesis.—A case of a type-B cyclone forming in the coastal region has been selected to illustrate the use of clouds, precipitation, and pressure changes in detecting cyclogenesis. At 1230 GMT, 10 December 1944 (Fig. 15), the outstanding feature of the surface weather map is an occluding cyclone centered in southeastern Missouri and moving north-northeastward toward the Great Lakes region. A cold wedge is settling down between the Appalachian Mountains and the Gulf Stream, the cold air drifting southwestward into Alabama, Georgia, and Florida. The wedge line intersects the 45th parallel at longitude 86° W and is moving eastward toward the longitude band, between 70° and 66° W, where it is most frequently situated at the time of origin of type-B cyclones (see Table 3).

The 3-km isobars at 0400 GMT (not shown) were mostly west-east over all the coastal region except

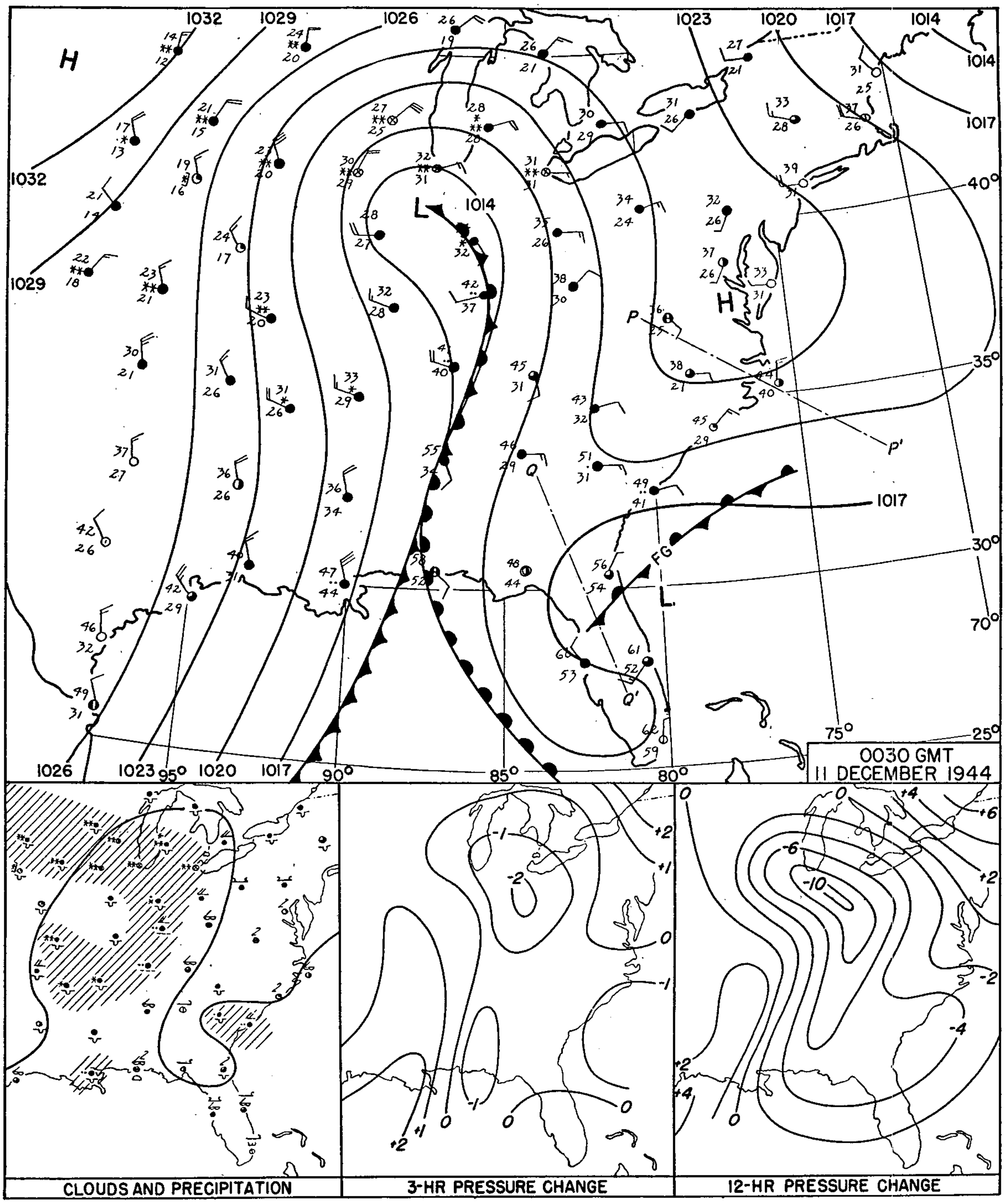

FIG. 16. Example of detection of cyclogenesis, second map.

Florida, where they were southwest-northeast and hence favorable for cyclogenesis (see Fig. 11). The weather situation is very nearly a typical, type-B regime with cyclogenesis most probable in the Florida region. It has been pointed out that, according to the analysis of the period 1929–1939, type-B secondaries almost invariably originate in the southeast quadrant of the primary with a probability of 53 per cent that the point of origin will be in the area between two lines radiating from the primary center and oriented 20° on either side of due southeast. The lines PP′ and QQ′ of Figure 15 and the following two figures have been drawn accordingly. In Figure 15 it is seen that Florida is within the area between the two lines, as well as within the area of favorable upper isobars. Individually, these two criteria do not carry much weight, but occurring together as in this case they may be significant.

The boundary of the middle cloud system has been drawn on the small chart of hydrometeors shown in

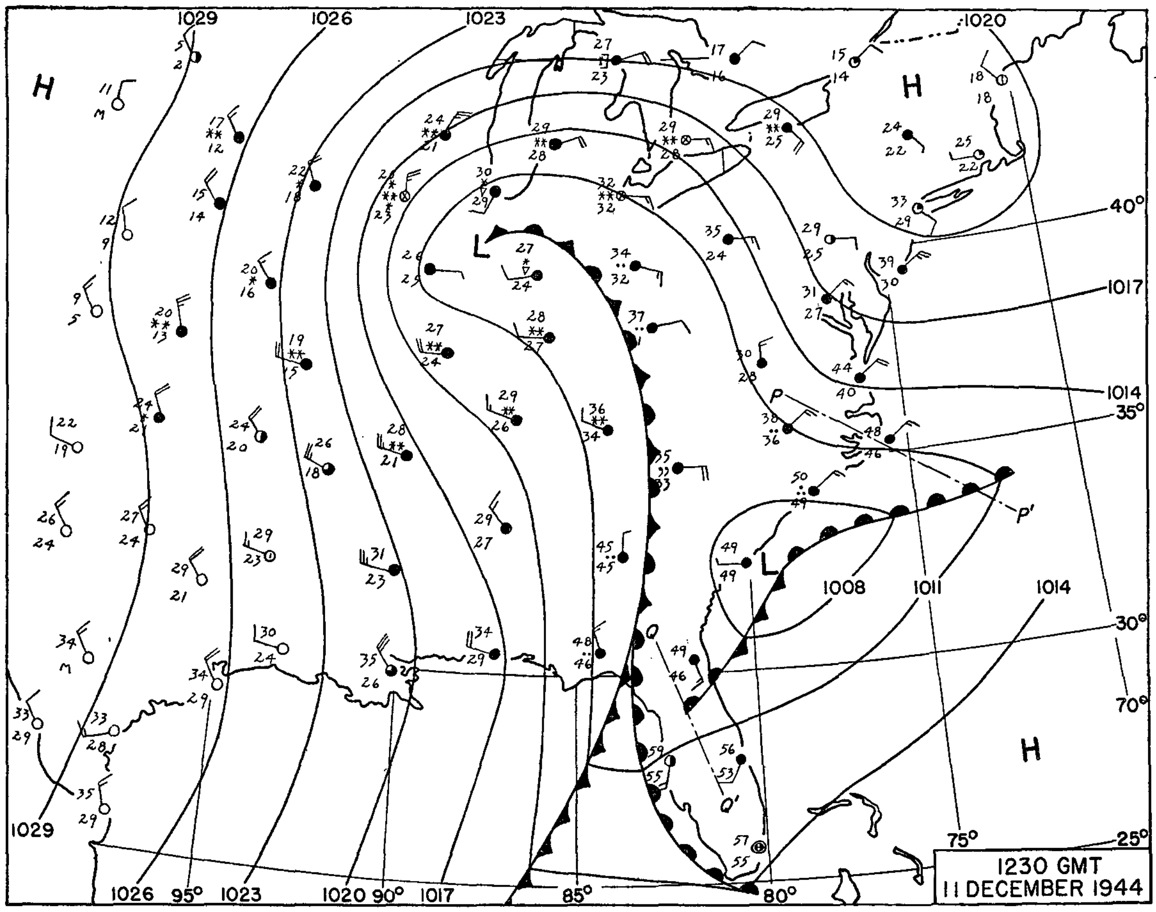

FIG. 17. Example of detection of cyclogenesis, third map.

the lower left-hand part of Figure 15. This boundary cannot be drawn with certainty where the middle clouds are obscured by a lower overcast; a careful analyst can, however, estimate its position rather accurately by judicious interpretation of cloud forms reported within such areas. In this case there is no doubt that a system of middle clouds, partially separated from the system of the primary cyclone, is spreading over the southeastern coastal region. As yet no separate area of precipitation has appeared.

The 3-hour pressure changes (lower center of Fig. 15) do not at this time give a positive indication that a new pressure minimum is forming. Zero change is reported at Savannah, Ga., and Melbourne, Fla., suggesting that there may be an area of slightly falling pressure east of Jacksonville. The significance of the zero changes is enhanced by the fact that in this region in December the pressure normally rises about 0.6 mb in the 3 hours preceding 1230 GMT. The best interpretation is that a pressure minimum may be forming east of Jacksonville.

The 12-hour pressure changes, representing a longer period and hence greater changes, may be expected to show the incipient pressure minimum more definitely, provided the trend has existed throughout the 12-hour period. The small chart in the lower right-hand part of Figure 15 shows isallobars for the 12-hour period preceding 1230 GMT. The sea-level pressure reported at Melbourne was 2.0 mb lower at the end than at the beginning of the period; on this basis a closed -2 isallobar has been drawn with the center of falling pressure located in the area where the 3-hour changes suggested an isallobaric low. The pressure would normally have risen about 0.6 mb over Florida in the 12 hours preceding 1230 GMT in December.

Twelve hours later, at 0030 GMT, 11 December (Fig. 16), a partial cyclonic circulation has appeared in the surface winds around Jacksonville, and the isobar for 1017 mb forms a trough in that area. As observations at sea are not available, it is not possible to determine whether there is a closed cyclonic circulation and a pressure minimum east of Jacksonville.

It seems certain at this time that a front is developing in a zone oriented roughly southwest-northeast just south of Jacksonville. The new front is not an extension of the frontal system of the primary cyclone but is developing in the cold air north of the original warm front. This development of a new front is rather common in type-B cyclones; the interpretation of cyclogenesis as occurring along the warm front of the primary cyclone, although having the advantage of simplicity, is in many cases less accurate. Certain signs bear out the analysis shown in this case: At Melbourne the wind shift from ENE to SW was accompanied by a fall of 5 F in the dew point, apparently because the air is now coming from the interior of Florida instead of directly from the sea, whereas, if the wind shift had marked the passage of the primary warm front, the dew point should have risen. In Florida south of the new front the dew points are in the range 52–58 F, which in this season and in this area is more representative of an incompletely modified cP airmass than of the mT air that should be found south of the main front. Finally, middle clouds of the pre-warm-front type, especially M_7, are still reported in Florida south of the zone of frontogenesis as they were 12 hours before.

The chart of hydrometeors in Figure 16 shows a sharper separation between the middle cloud systems of the old and the new cyclones than was observed on the preceding chart, and there is now an entirely separate zone of precipitation in the area of cyclogenesis. In the field of 3-hour pressure change an isallobar of -1 mb can be constructed on the southeast coast on the basis of a fall of 1.4 mb reported at Wilmington, S. C. The normal 3-hour change at this time at Wilmington is $+0.7$ mb. In the same general area the 12-hour isallobars swing far eastward from the trough of the primary cyclone, and the pressures at Savannah and Jacksonville are 5.0 mb lower than on the first map, as compared with a normal change of about -0.6 mb.

At 1230 GMT of 11 December (Fig. 17) the observations indicate rather definitely a closed 1008-mb isobar around a pressure minimum located near Wilmington. Three-hour pressure changes between -4 and -5 mb are reported by several stations north of the new low center. From this time on, the development of the cyclone is rapid and it begins to move northward in the general current of upper winds that have meanwhile been backing to south. In the succeeding 12 hours its central pressure fell from 1007 to 990 mb; the center moved at about 36 miles per hour to a point near Washington; and the primary center entirely disappeared, not through filling but as a result of the rapid deepening of the secondary.

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REFERENCES

1. Austin, J. M., 1941: Favorable conditions for cyclogenesis near the Atlantic coast. *Bull. Am. Meteor. Soc.*, 22, 270–271.
2. Bowie, E. H., and R. H. Weightman, 1914: Types of storms of the United States and their average movements. *Monthly Weather Rev.*, Supplement 1, 37 pp., 114 charts.
3. Petterssen, Sverre, 1941: Cyclogenesis over southeastern United States and the Atlantic coast. *Bull Am. Meteor. Soc.*, 22, 269–270.
4. U. S. Weather Bureau, 1944: Normal weather maps, northern hemisphere upper level. Washington, United States Weather Bureau, 72 charts.