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AN ANALYSIS OF BAROTROPIC FORECAST ERRORS IN CASES OF RAPID SEA LEVEL CYCLOGENESIS[1]

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ABSTRACT

The 24-hour 500-mb. barotropic forecasts prepared by the Joint Numerical Weather Prediction Unit (JNWPU) have been investigated in 30 cases of rapid sea level cyclogenesis. Composite error maps are presented for the region of cyclogenesis. The 500-mb. errors are found to be significantly larger when the solenoidal field at that level is strong than when it is weak.

1. INTRODUCTION

It is well known that due to the assumption of conservation of absolute vorticity inherent in the barotropic model, it cannot forecast a change in absolute vorticity following the motion (i.e., development) at the 500-mb. level. The purpose of this study is to determine the character of the 500-mb. forecast errors in the vicinity of rapidly deepening sea level cyclones.

There appear to be two classes of cyclogenesis—those in which cyclogenesis at sea level is accompanied by deepening at upper levels, and those in which it is not. In the latter cases, simple superposition of the upper-level trough on a low-level warm tongue results in sea level cyclogenesis, while in the former cases, deepening of the upper-level trough plays the major role in the development of the sea level cyclone. Part of the purpose of this research is to determine whether there are really two distinct classes of cyclogenesis and whether the errors of barotropic forecasts may be anticipated if cyclogenesis is anticipated.

It would seem that if there are two classes of cyclogenesis, the 500-mb. barotropic forecasts may be better for the cases that are initially "quasi-barotropic" at 500 mb. (weak solenoidal field or none at all) than for the cases where the 500-mb. level is baroclinic (strong solenoidal field). This hypothesis is tested in this study.

Although barotropic forecast errors have been analyzed in the past (Staff Members, JNWPU [9, 10]; Cressman and Hubert [4]; Bristor [1]; Gates [5]; Gates et al. [6]) they have not been studied for a *group* of situations where rapid cyclogenesis was occurring over a particular area. (There have been some studies of individual cases; e.g., Charney and Phillips [2], and Charney [3].)

Error fields are constructed relative to the sea level cyclone position at the final time (24 hours after the initial time), and composite maps of the observed and forecast height changes as well as the error fields are presented.

2. DATA AND METHODS OF ANALYSIS

Weather maps on file in the Department of Meteorology and Oceanography at New York University covering the period 1956–1959 were examined to determine when and where cases of rapid cyclogenesis occurred. Rapid cyclogenesis is defined here as a deepening of 20 mb. or more in a 24-hour period. This applies both to a cyclone that has just formed, and to one that already exists but has not yet (previously) deepened the amount required by the above definition. The geographical area for the origin of these

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cases extends from longitude 100° W. eastward to longitude 60° W., and south of 50° N. latitude. These definitions resulted in a selection of 30 cases. The number of cases was limited due to the fact that rapid deepening at the surface is not a very frequent occurrence and that barotropic forecasts have been available for only the past three years. Table 1 gives the dates for the selected cases.

A track for each cyclone center was drawn on a Lambert conformal conic projection with standard parallels at 25.0° N. and 48.5° N. 500-mb. charts for the initial time and for 24 hours after the initial time were plotted and analyzed. (These two time periods will be referred to hereafter as 00 hours and 00+24 hours respectively.) These analyses were checked against the analyses obtained from the National Weather Analysis Center (NAWAC) and any obvious discrepancies were eliminated. A square grid of 196 points was constructed with intersection points 2° of latitude apart as measured on the Lambert conformal projection at the standard parallels. A graphical 24-hour, 500-mb. height change analysis was carried out for each of the 30 cases by placing the center of the grid over the center of the surface cyclone at 00+24 hours. The grid was oriented parallel to the path of the cyclone during the 6 hours ending at 00+24 hours, and the 00 hour and the 00+24-hour maps were superimposed on each other to obtain the graphical height change analysis. The JNWP barotropic forecast was transferred to the Lambert map projection and 24-hour height changes were determined over the same area as the observed changes.

Composite observed and forecast charts were constructed for the 30 cases. In order to determine the height change errors due to the barotropic forecast, the observed composite 500-mb. height change chart was subtracted from the barotropic forecast height change chart. In this manner composite error changes were constructed for the 30 cases.

As noted earlier, the cases occurred during the period 1956 through 1959. During that time three improvements were introduced into the barotropic model: (1) the use of the balance equation (Shuman [8]) beginning on April 20, 1956, (2) enlargement of the grid on October 30, 1957, and (3) elimination during the summer of 1958 of the error due to spurious retrogression of very long atmospheric waves. This latter error probably did not affect the 24-hour barotropic forecasts significantly, especially in the areas under study in this research (Wolff [11]). The effect of the other two improvements will be discussed in section 3.

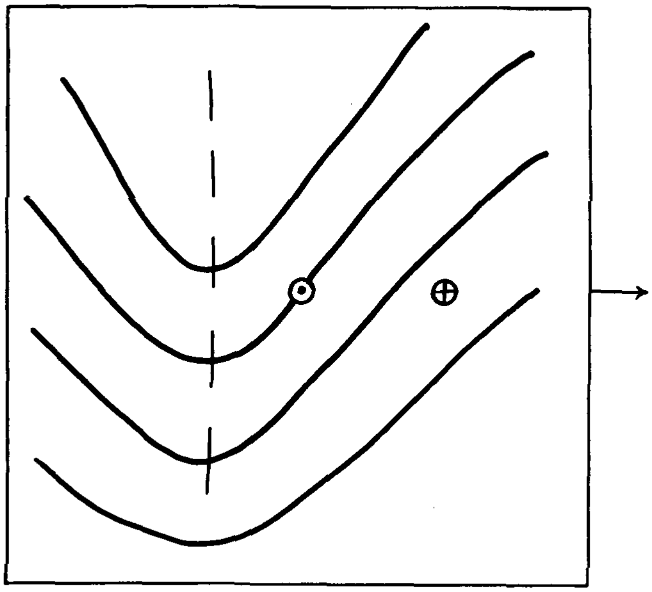

FIGURE 1.—Schematic illustration of method used to determine area in which solenoids at 500 mb. are counted. Circle with cross indicates cyclone center. Arrow is perpendicular to 500-mb. trough line. Circle with dot is center of square.

TABLE 1.—*Dates of cases of rapid cyclogenesis*

Time (GMT)	Date	Time (GMT)	Date
15	February 24–25, 1956	12	November 28–29, 1958
15	November 20–21, 1956	12	December 3–4, 1958
15	March 8–9, 1957	00	December 11–12, 1958
15	April 8–9, 1957	12	December 21–22, 1958
12	June 28–29, 1957	12	January 2–3, 1959
12	November 7–8, 1957	12	January 4–5, 1959
12	November 18–19, 1957	00	January 9–10, 1959
12	November 30–December 1, 1957	00	January 16–17, 1959
12	December 10–11, 1957	12	January 16–17, 1959
12	January 7–8, 1958	12	January 21–22, 1959
12	February 13–14, 1958	12	January 25–26, 1959
12	February 15–16, 1958	12	January 30–31, 1959
12	March 19–20, 1958	12	February 18–19, 1959
12	March 31–April 1, 1958	12	March 12–13, 1959
12	November 17–18, 1958	12	April 14–15, 1959

An effort was made to separate the cases into two groups on the basis of the intensity of the solenoidal field at 00 hours. This was done to test the hypothesis that the barotropic forecast errors may be larger in cases where the atmosphere is initially baroclinic than where it is barotropic.

On a constant pressure chart the number of solenoids is represented by the number of quadrangles formed by isotherms and contours of geopotential height (Saucier [7]). For the purpose of determining the number of solenoids in a given area, 2½° C. isotherms and 100-foot contours were drawn on the NAWAC 500-mb. charts. The following procedure was then used to count solenoids. A square 30° of latitude along each of its sides was constructed. The square was placed on the Lambert map as shown in figure 1, with the 500-mb. trough line parallel to two sides of the square and the cyclone position centered in the right half of the square.

The area obtained from the Lambert conformal projection was then transferred to the NAWAC 500-mb. analysis for each case, and the solenoids were counted. The area is somewhat distorted due to the fact that the NAWAC chart is a polar stereographic projection.

The counting of solenoids did not result in a sharp delineation between the quasi-barotropic and the baroclinic cases. The range of solenoids was from 0 to 77. The 500-mb. level was quasi-barotropic (zero solenoids) in only one of the cases, and therefore the separation of cases was based on the *number* of solenoids. The 30 cases

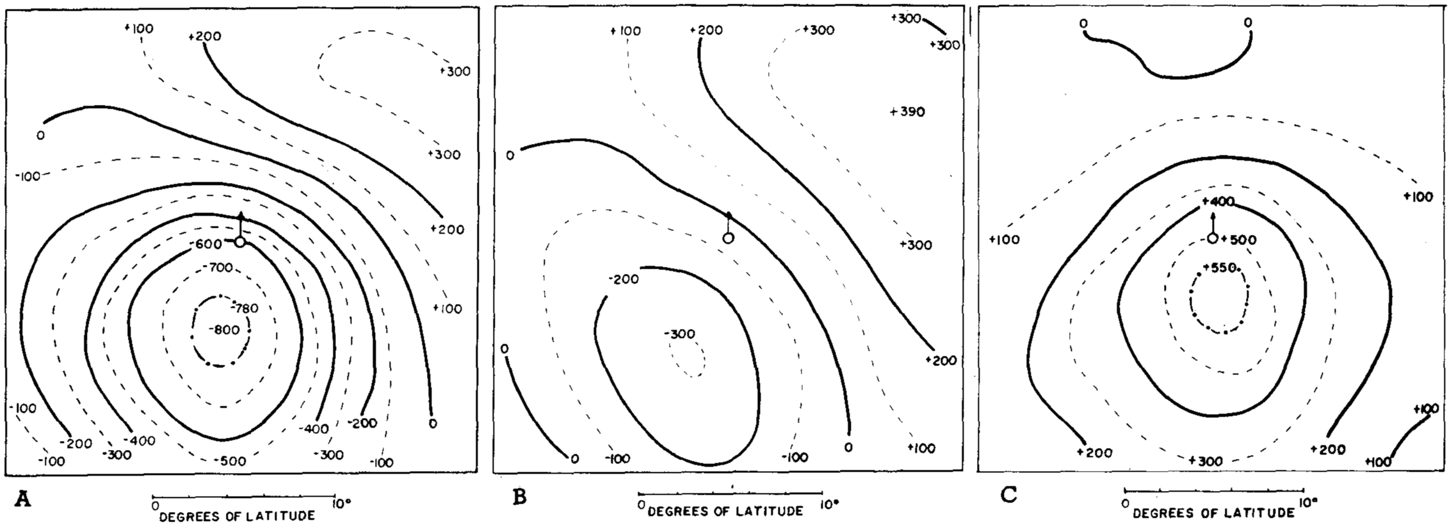

Figure 2.—Composite 500-mb. 24-hour height changes and forecast errors (30 cases), (A) observed, (B) barotropically forecast, oriented according to the path of the sea level cyclone center (open circle) during the 6 hours ending at 00+24 hours, (C) composite 500-mb. forecast height change error (forecast minus observed). Units are in geopotential feet (gp. ft.).

were tabulated in order of increasing number of solenoids in order to arrive at an equal number of cases for the "quasi-barotropic" ("weakly baroclinic" would be a more correct description) and the baroclinic cases. (To avoid confusion between "weakly baroclinic" and "baroclinic" cases, the term "quasi-barotropic" (with quotes) will be retained when referring to the "weakly baroclinic" cases.) The median of the 30 cases was used as the separation criterion. This resulted in designating as baroclinic those cases in which the number of solenoids was 20 or greater, and as "quasi-barotropic" those cases having less than 20 solenoids.

Composite 500-mb. observed and forecast height change maps were constructed for the "quasi-barotropic" and baroclinic cases separately.

3. RESULTS

Figure 2A illustrates the pattern of *observed* 24-hour height changes for all 30 cases and figure 2B represents the composite 500-mb. 24-hour height changes from the *barotropic forecasts* for all 30 cases. The center of maximum height decrease is only slightly (about 100 n. mi.) to the left and to the rear of the area on the observed composite chart. The magnitude of the decrease, however, is two and a half times greater on the observed composite.

Figure 2C shows the forecast minus the observed height change, and demonstrates the error field for the 30 cases. The error is in the form of a vortex with the largest error to the rear of the sea level cyclone. This maximum error is of the order of 580 feet. It may be noted that the area covered by an error of 200 feet or greater is roughly circular—about 1200 n. mi. in diameter—and is centered about 150–200 n. mi. to the rear of the surface cyclone. In the area of the grid not affected by the rapidly deepening sea level cyclones the errors are small, implying that the atmosphere is close to being quasi-barotropic.

Perhaps the forecaster involved with barotropic prognostic charts would be aided by some knowledge of the standard deviation of the error over the cyclone center and over the region of largest error. The standard deviation, to the nearest 10 feet, for the four grid points surrounding the cyclone center (representing roughly 60 n. mi. radius around the cyclone) averaged 260 feet. As can be seen in figure 2C the error in this area is about 500 feet. In the region of maximum error represented by the grid points near and within the maximum error contour of 550 feet, the average standard deviation was only 200 feet.

It might be argued that the large composite error could be due to randomness. Therefore, the significance of the error was tested using the Student's "t" test on the grid points comprising the two areas mentioned above. The error was found to be significant at less than the 1 percent level; i.e., very significant in these areas.

Composite observed, barotropic forecast, and error charts (not shown) were constructed for the 25 cases after the balance equation was introduced and the grid was enlarged. These showed that there was little difference in the error field from that of the composite error chart for the 30 cases (the composite errors for the 25 cases were actually somewhat larger). The fact that the elimination of the five cases before the improvements were used operationally in the model did not result in better forecasts is not really surprising. The use of balanced winds successfully suppresses spurious anticyclogenesis, but would not be expected to improve the barotropic forecasts in the region to the rear of rapidly deepening sea level cyclones. As far as enlargement of the grid is concerned, this has served to produce better barotropic forecasts (Staff Members, JNWPU [9,10]) but apparently none of the five cases

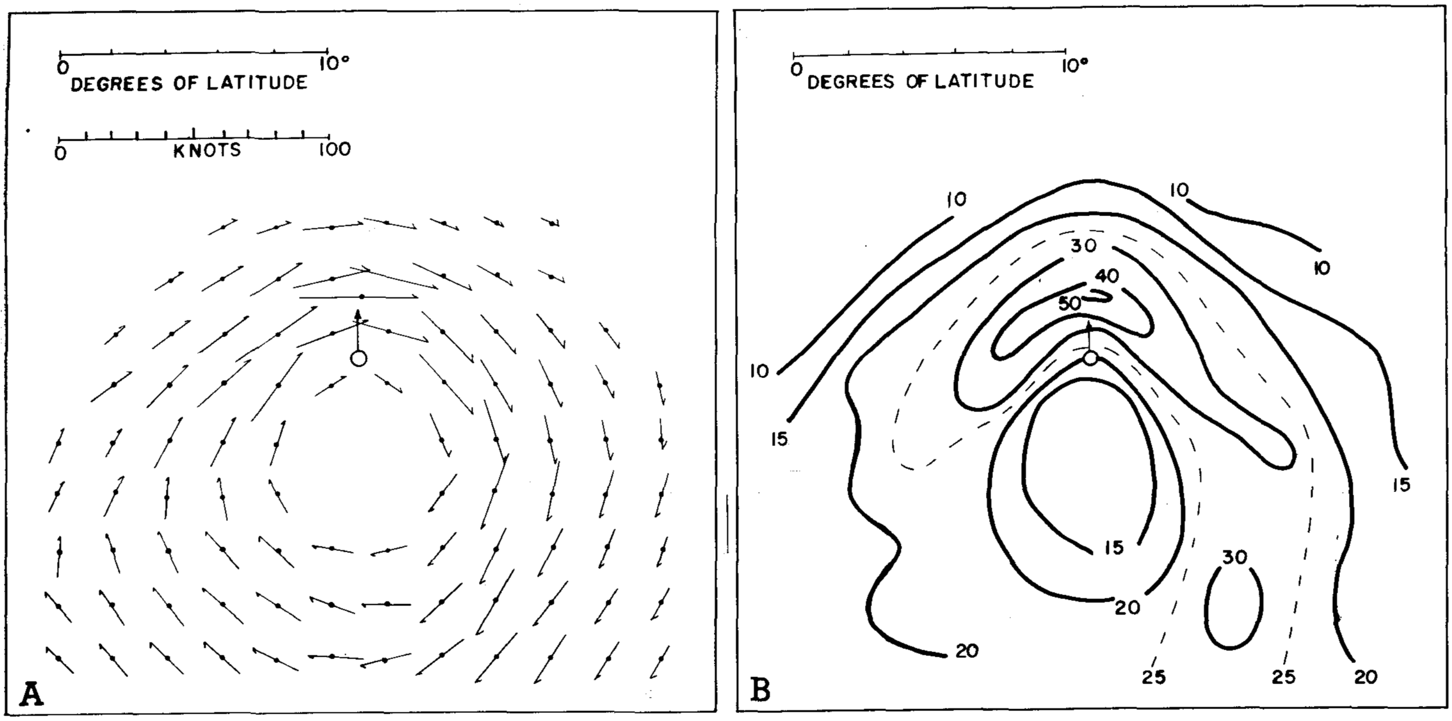

Figure 3.—(A) Composite vector wind error of the geostrophic wind (30 cases). (B) Analysis of magnitudes of vectors in (A) oriented same as figure 2.

in this study before the enlargement was sufficiently close to the boundaries of the grid to be affected by errors due to the boundary conditions imposed. Using the result that the improvements introduced in the barotropic model failed to make any real difference in the errors found in the region of cyclogenesis, the analysis of the errors and the conclusions drawn from this analysis will be based on all 30 cases.

500-mb. barotropic forecast error of the geostrophic wind.—The error in the geostropic wind is determined from the gradient of the height errors and may be obtained by applying a geostropic wind scale to the contours of the height errors.

Figure 3A illustrates the magnitude of the error for points around the cyclone center. In the portion of the figure that is devoid of errors the error of the geostrophic wind was less than 10 knots. The direction of the vectors shows the error field to be an anticyclone vortex, meaning that the cyclonic vortex was underforecast. This follows from the definition of the composite 500-mb. height error adopted in this paper, i.e., forecast minus observed equals error.

In figure 3B is shown the analysis of the vector magnitudes from figure 3A. Whereas the largest height error is to the rear of the sea level low center, the largest geostrophic wind error is about 100–150 n. mi. ahead of the sea level low center and is of the order of 50 knots. In general, as figure 3B indicates, the semicircle to the right of the sea level cyclone path has a somewhat greater wind error than that to the left of the cyclone center. The area covered by an error of 25 knots or greater is surrounded by the dashed line in figure 3B, and is rather extensive.

Baroclinic vs "quasi-barotropic" composites.—Figures 4 and 5 represent the observed and forecast 24-hour 500-mb. height changes and the error charts (forecast minus observed) for the 15 baroclinic and 15 "quasi-barotropic" cases respectively. In comparing the two observed height change charts, one notes that the 15 "quasi-barotropic" cases show an average height decrease that is about 200 feet less in absolute magnitude than that of the baroclinic cases. Other differences apparent in the observed height change charts for the two types of cases are: (1) the maximum height decrease is found closer to the sea level cyclone center on the composite for the "quasi-barotropic" cases, and (2) the −500-foot height change contour is found in the same approximate location on all sides of the cyclone center in both types of cases except to the rear, where the −500-foot contour extends about 250 n. mi. farther to the rear of the storm in the baroclinic cases. The forecast composite charts for the two types of cases (figs. 4B and 5B) are seen to be alike.

The maximum error for the "quasi-barotropic" cases (fig. 5C) is about 150 feet smaller in absolute magnitude than that for the baroclinic cases (fig. 4C), but it is concentrated over a smaller area. This maximum error (for the "quasi-barotropic" cases) lies about 250 n. mi. closer to the cyclone center, and it is directly to the rear of it in both cases.

A chart showing the difference between the two error charts is presented in figure 6. It is seen then that the average difference in the vicinity of the cylcone center is almost negligible. The maximum difference is centered about 500 n. mi. to the rear of the surface low center. The dashed line in figure 6 represents the 400-foot error

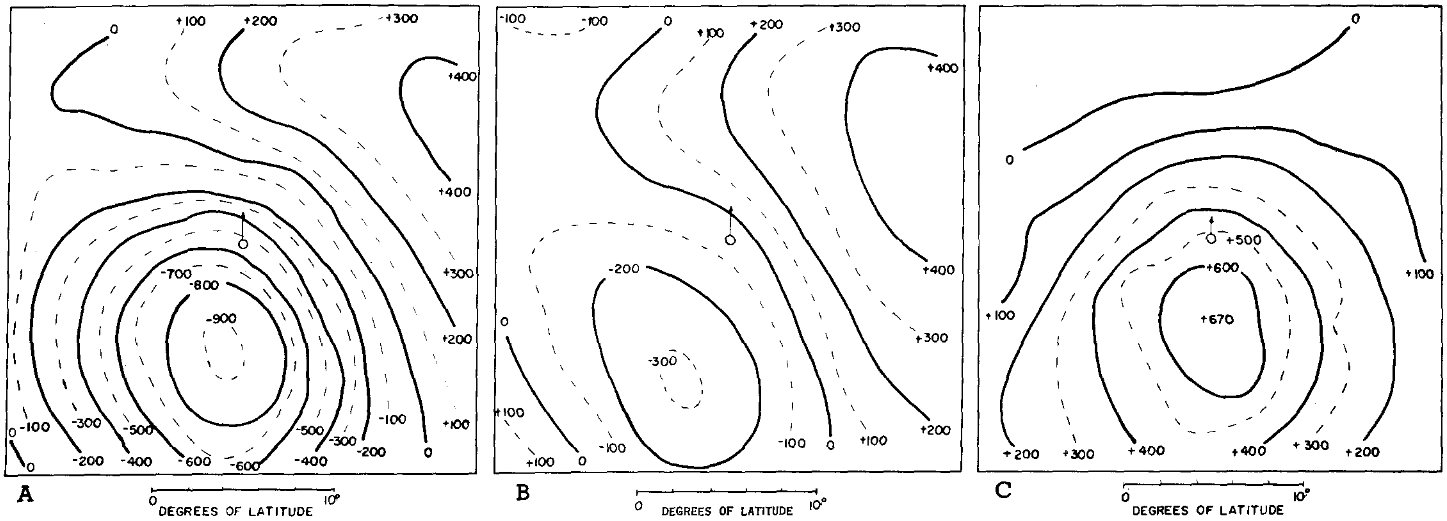

Figure 4.—Composite 500-mb. 24-hour height changes (15 baroclinic cases), (A) observed, (B) barotropically forecast, (C) composite 500-mb. height change error (forecast minus observed). Oriented same as figure 2. (Units in gp. ft.).

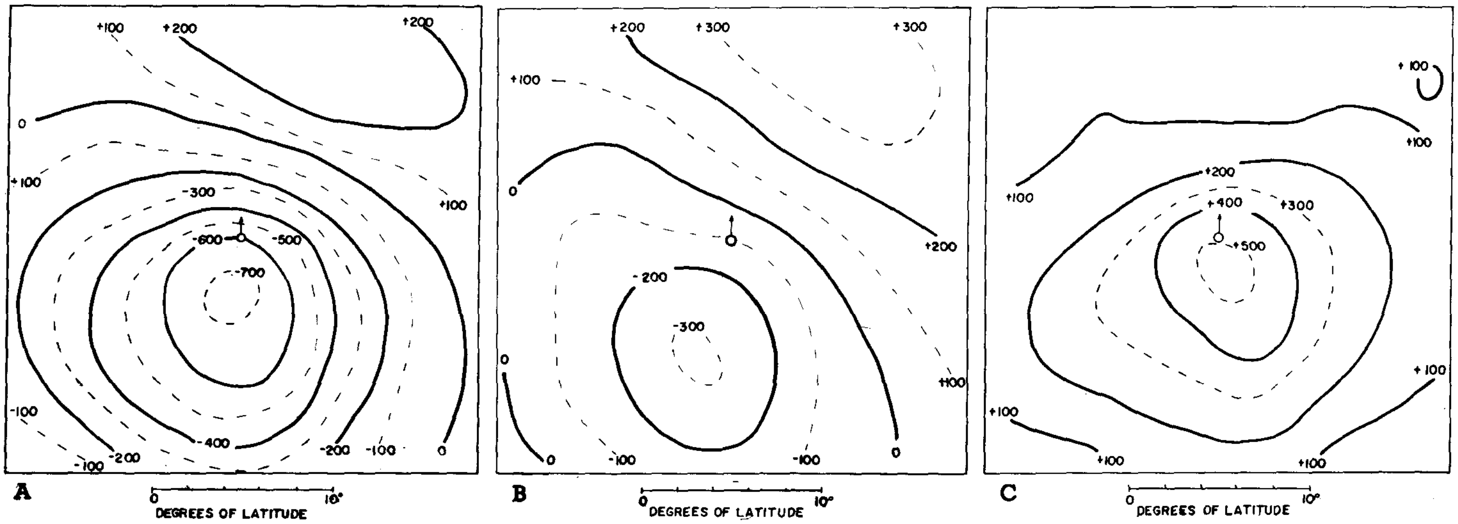

Figure 5.—Same as for figure 4 but for 15 "quasi-barotropic" cases. (Units in gp. ft.).

contour on the composite error chart for the 30 cases (fig. 2C). At the grid points lying within this area the Student's "t" test was applied to determine whether the difference between the forecasts was statistically significant. Of those tested, the seven grid points surrounded by the dot-dash line were found to be significant at the 5 percent level. This area is approximately a circle roughly 350 n. mi. in diameter. Four of the seven grid points were significant at the 2 percent level and two points were significant at the 1 percent level. These two points are indicated with checks on the figure.

In view of the fact that the composite barotropic forecasts are similar for both the "quasi-barotropic" and baroclinic cases, it is obvious that the difference in the composite observed height change charts for the two types of cases accounts for the difference in the composite height change error charts. The apparent inference here is that there are significant differences between the two types of cases over a relatively small part of the area covered by the grid. It must be kept in mind, however, that the separation of cases into the two types was not as sharp as one would have desired.

4. SUMMARY AND CONCLUSIONS

The composite height change charts for the 30 cases of cyclogenesis studied indicate that the barotropic forecasts predicted the area of maximum height decrease in approximately the right location, but the magnitude of the maximum decrease was observed to be two and a half times greater than forecast. The entire area of decrease was larger than forecast. This was due to the failure of the barotropic forecasts to predict the deepening of the trough.

The composite error chart for the 30 cases shows the error to be in the shape of a circular vortex and the maximum error to be of the order of 550–600 feet. It appears that the barotropic forecast error at 500 mb. represents a failure to forecast the development of a

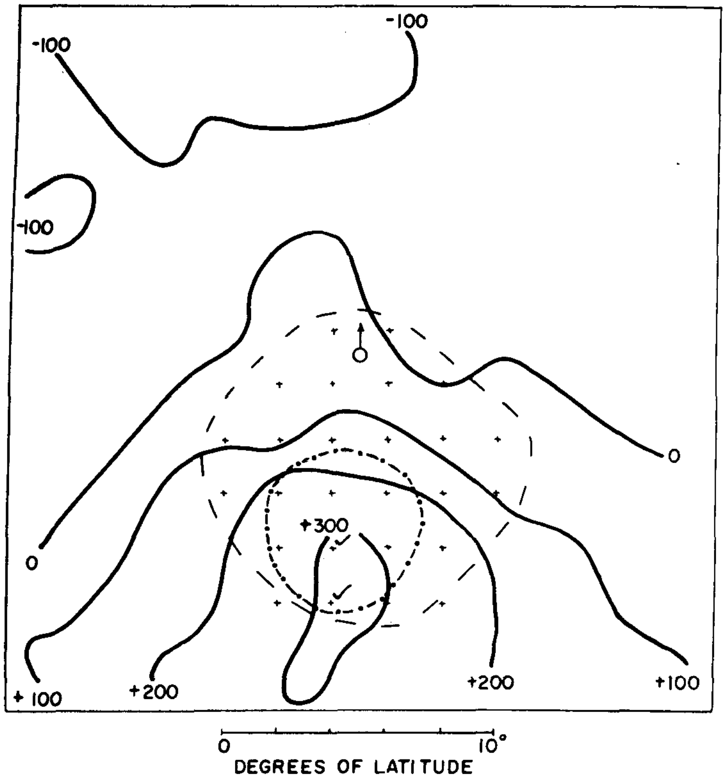

FIGURE 6.—Composite 500-mb. baroclinic height change error minus composite "quasi-barotropic" height change error. Oriented same as figure 2. (Units in gp. ft.) (See text for explanation of broken and dash-dot lines.)

cyclonic vortex at that level. The superposition of this vortex on the 500-mb. flow pattern distorts the latter into the shape of the observed pronounced trough. At the surface, where the basic flow is weak, the superposed vortex appears as a cyclone.

The composite observed 500-mb. height change chart for the "quasi-barotropic" cases shows both the magnitude and the area of the height changes to be smaller than for the baroclinic cases. The barotropic forecasts are similar for both types of cases. The composite error charts for the baroclinic and "quasi-barotropic" cases, therefore, show essentially the differences in the observed composite height change charts.

A chart showing the difference between the two types of cases indicated that the difference was statistically significant in a region to the rear of the sea level cyclone center.

The results presented above do not clearly resolve the question of whether there are really two distinct classes of cyclogenesis. The composite of cases studied indicates that although there is a region in the area of cyclogenesis where the error for the "quasi-barotropic" cases is significantly less than that for the baroclinic cases, the error charts for the "quasi-barotropic" cases themselves contain a large positive error. This implies that the rapid deepening of a surface cyclone may be independent of the degree of baroclinicity at 500 mb.

The barotropic forecast error of the geostrophic wind was determined for the 30 cases and the maximum error was found to lie some distance ahead of the sea level cyclone, and to be of the order of 50 knots.

On the whole, in the 30 cases examined, the barotropic forecasts appear to be satisfactory in areas not influenced by deepening cyclones at sea level. They are, as might be expected, unsatisfactory in areas of rapid sea level cyclogenesis whether the atmosphere be initially "quasi-barotropic" or baroclinic at 500 mb.

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