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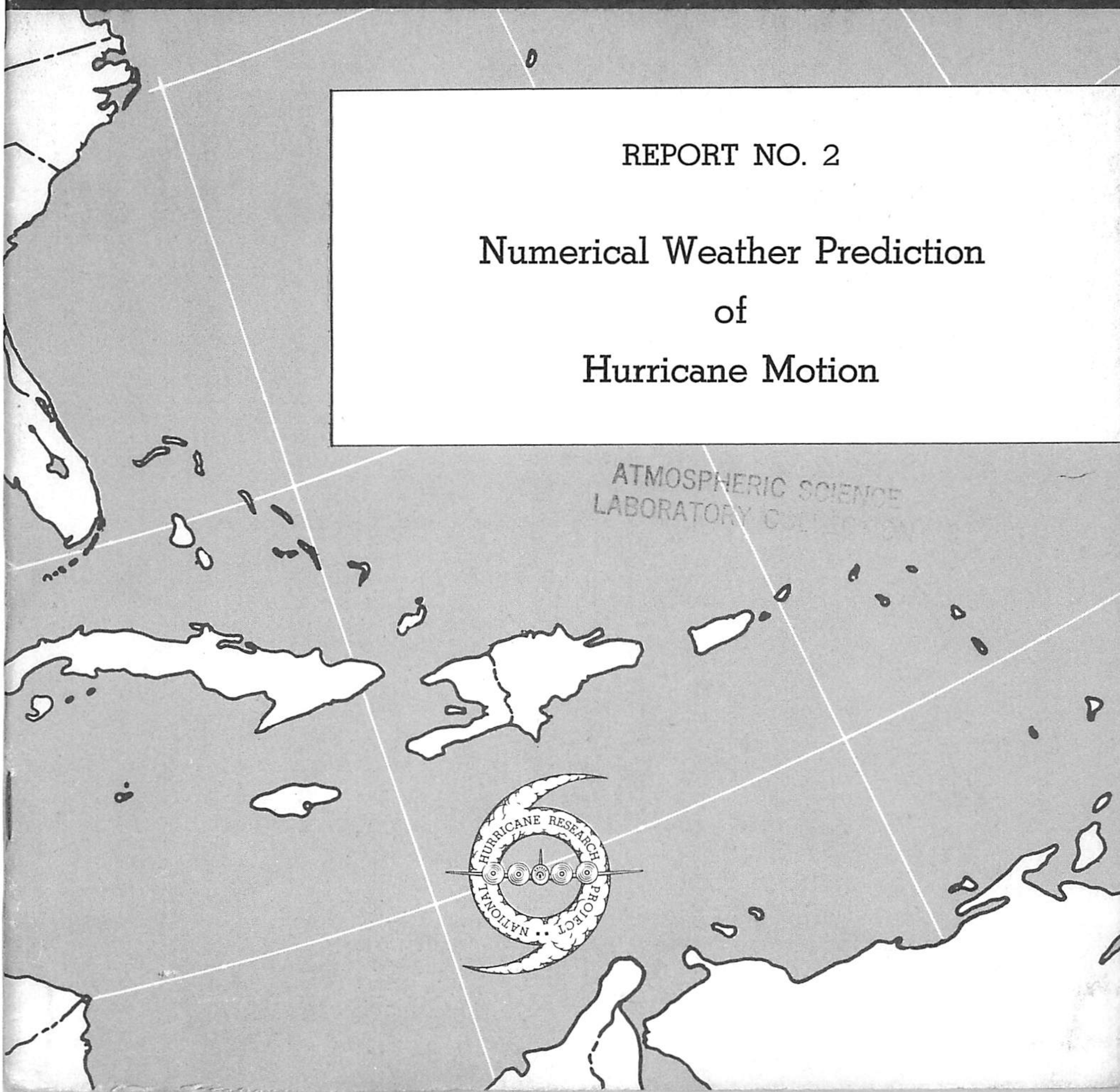

REPORT NO. 2

Numerical Weather Prediction of Hurricane Motion

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

NATIONAL HURRICANE RESEARCH PROJECT

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Numerical Weather Prediction of Hurricane Motion

Prepared by
Lester F. Hubert
Office of Meteorological Research, U. S. Weather Bureau, Washington, D. C.

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Commerce-Weather Bureau, Washington, D. C.

NUMERICAL WEATHER PREDICTION OF HURRICANE MOTION

Lester F. Hubert

Office of Meteorological Research, U. S. Weather Bureau, Washington, D. C.

INTRODUCTION

The 500-mb. prognostic maps produced by the Joint Numerical Weather Prediction Unit (JNWP) will contain forecasts of hurricane motion whenever a hurricane Low appears on the initial map. Forecast offices responsible for issuing official warnings will therefore routinely have numerical predictions of storm motion which will sometimes differ from forecasts made by other methods but they will have no background of experience with numerical predictions on which to base an evaluation.

The forecaster will be anxious to use all supplementary information available when he must make a critical forecast but he may be reluctant to use the results of a method which he knows was not designed specifically for small systems in the Tropics. In order to provide the rudiments of such a background, fourteen independent numerical forecasts were made on seven hurricanes and the results are reported at this time to be available before the beginning of the 1956 hurricane season.

NUMERICAL MODEL AND DATA USED

The standard barotropic model developed by JNWP was used to obtain prognostic 500-mb. maps for 24-hour, 48-hour, and 72-hour forecast periods. The input data (initial 500-mb. map) were read from the 500-mb. analyses shown in Table I-A. The area considered in the barotropic model is shown in figure 1. The baroclinic model was not used for two reasons. First the barotropic model produces forecasts for periods greater than 36 hours which are superior to the baroclinic model and second the additional work required to prepare input data for three levels (required by the baroclinic model) did not appear justified in view of the time and staff available for this project.

With the exception of the 1954 maps, the original manuscript 500-mb. maps prepared by the Northern Hemisphere Historical Unit were used as the initial analysis since those analyses were in a form convenient for this purpose and were prepared on a maximum amount of data. The 1954 maps were not available from this source so the manuscript maps prepared by the Air Force Analysis Center at Andrews Air Force Base were obtained and photographed. Reproduction was necessary because the original maps were too fragile to withstand the handling necessary. Wherever the gradients were flat, additional contours were drawn with proper regard for thermal consistency and time continuity but no significant reanalyses were made.

In addition to the forecasts made specifically for this project, the hurricane forecasts made by JNWP during the 1955 season have been included in this analysis (Table I-B). Both barotropic and baroclinic models were used during part of the 1955 season and the results of the baroclinic forecasts are also summarized. It should be borne in mind that these forecasts are not strictly comparable to the barotropic forecasts as a group, because several baroclinic forecasts were made on three similar situations while the barotropic predictions have been made on a wide variety of synoptic conditions.

Selection of the storms and forecast days for this study was based on the following considerations:

1. The large majority were storms that affected the continental United States - i.e., the type of situation that poses a critical forecast problem. The only exceptions were ABLE 1951 which moved southwestward threatening Florida and then looped southward into the Atlantic and JIG 1951 which also looped toward the mainland but did not enter land.

2. The storm paths had to remain well inside the grid boundaries which are shown in figure 1. This restriction eliminated Gulf of Mexico storms and hurricanes while they were located east of Puerto Rico. It would have been possible to rotate the grid so that the area east and northeast of Puerto Rico fell well inside the forecast area since the model is not affected by a change of longitude. The gain in ocean area, however, would be offset in part by the decrease of data density.

3. Forecast days were chosen so that one forecast would be made when the storm was distant from the coast in order to test the utility of the 72-hour forecasts for early warning. A second forecast date was chosen to test the accuracy of the 24-hour

TABLE I - Hurricane Forecasts

Storm designation	Forecast time-date (GMT)	Map of Actual Path and Forecast Positions	Source of initial data	Numerical model	Forecast + Index No.
A - Forecasts prepared specifically for this experiment					
ABLE 1951	1500 May 17	Fig. 2	No.Hemis.Hist. Map	Barotropic	1
	20	2	"	"	2
JIG 1951	Oct 16	3-A	"	"	3
	18	3-B	"	"	4
ABLE 1952	Aug 27	4	"	"	5
	29	4	"	"	6
BARBARA 1953	11	5-A	"	"	7
	13	5-B	"	"	8
CAROL 1953	Sept 5	6	"	"	9
	6	6	"	"	10
CAROL 1954	0300 Aug 28	7	USAF Analysis Center	"	11
	29	7	Andrews AFB	"	12
HAZEL 1954	Oct 14	8	"	"	13
	15	8	"	"	14
B - Experimental operational forecasts prepared by JNWP in 1955 season					
CONNIE 1955	1500 Aug 11	Fig. 9	JNWP operational map	Barotropic	15
	12	9	"	"	16
	8	None	"	Baroclinic	17
	9	"	"	"	18
	10	"	"	"	19
	11	"	"	"	20
	12	"	"	"	21
DIANE 1955	0300 Aug 15	10	"	Barotropic	22
	16	10	"	"	23
	1500 16	None	"	Baroclinic	24
	17	"	"	"	25
	18	"	"	"	26
IONE 1955	0300 Aug 15	Fig. 11-A	"	Barotropic	27
	16	None	"	"	28
	17	Fig. 11-B	"	"	29
	1500 17	None	"	Baroclinic	30
	18	"	"	"	31
	19	"	"	"	32

+ These index numbers are to identify the forecast on figures 12 through 28.

forecast when the storm was about to accelerate and/or enter the coast.

METHOD OF FORECAST ANALYSIS

From each initial map one 24-hour, one 48-hour, and one 72-hour prognostic 500-mb. map was made, but it is possible to interpret the maps in different ways to obtain slightly different motion forecasts. The following five interpretation methods were used:

1. The height minimum on each prognostic chart was located by drawing intermediate contours to get the best interpolated position for the Low. Prognostic charts normally are printed out each 24 hours, and the positions of the low at 24, 48, and 72 hours were connected with a smooth curve for a path forecast.

2. Method No. 1 was used to obtain the forecast positions and these positions were then corrected for an "initial error", which is defined as the vector distance between the actual storm position on the initial map and the apparent position of the low center that results from a reanalysis of the initial map using data at the grid points only; an error due to the large grid spacing and the asymmetry of the height field about the storm. This is discussed below.

3. The 24-hour, 48-hour, and 72-hour prognostic positions of the center of maximum vorticity may be interpreted to be the hurricane center forecast positions. Although the vorticity field is not explicitly shown on the prognostic charts there is considerable advantage in obtaining it (either by hand computation or modifying the code so a print-out of the vorticity is obtained) for the following reason. Small-scale perturbations frequently disappear from the prognostic height field after eight or ten time steps because of two characteristics of the model. First a smoothing is performed at each iteration which quickly suppresses the small systems. Second the mechanics of recovering the height field from the vorticity field is such that closed Lows and Highs disappear long before the vorticity maxima are smoothed, the vorticity centers being contained in gradient of lateral shear. Therefore if positions of the vorticity maxima are used, forecasts for longer periods are derived. The gain is illustrated by the fact that only four of the fourteen forecasts made show a hurricane Low on the 48-hour prognostic chart, but the vorticity maxima were apparent on eleven of the fourteen.

4. Method No. 3 was used to obtain prognostic positions and these positions were then corrected for the "initial error".

5. The numerically forecast wind field was averaged over a region several times the area under direct influence of the storm circulation and a trajectory forecast made with that mean wind. It seemed profitable to investigate this approach because frequently even the vorticity maximum did not appear on the 72-hour forecast while the trajectory method provides a full 72-hour forecast for every situation.

The area over which the geostrophic wind was averaged for this purpose was ten degrees of latitude by fifteen degrees of longitude centered on the storm at the initial time and moving with the computed trajectory. Details of this method are described in the discussion of forecast error.

SUMMARIES OF FIVE INTERPRETATION METHODS

Each of the five methods discussed above has been used, where possible, to obtain 24-, 48-, and 72-hour forecasts from fourteen independent numerical forecasts. Methods No. 1 and 2 yielded only a few 72-hour forecasts for reasons already discussed. In addition a few barotropic and a few baroclinic forecasts made by JNWP during the 1955 season have been used in connection with methods No. 1, 2, and 5.

The vector distances between each forecast position and the actual storm position have been computed and summarized in figures 12 through 28. Each figure shows the results of one type of forecast for a given forecast period, i.e., all 24-hour forecasts produced by method No. 1 are shown on figure 12, all 48-hour forecasts by use of that method are shown in figure 13, etc. Each "X" on the polar diagrams represents a forecast for the particular storm and initial time, identified in Table I and plotted in a coordinate system which is centered on the actual hurricane position, oriented in the direction of mean storm motion[1]. The center of each polar diagram therefore represents the actual position of the hurricane whose motion during the forecast period is toward the top of the figure.

Also shown on each polar diagram is the center of gravity of the forecast positions and the vector standard deviation about that point (σ_R).

Table II lists the information of figures 12 through 28. For example the first line shows that Method No. 1 yielded a dispersion of forecast errors of 139 n. mi. with the center of gravity of those fore-

[1] Direction of mean motion is determined by the orientation of a straight line on a mercator map connecting the positions of the storm at beginning and end of the forecast period.

TABLE II - Summary of Forecast Errors

Method of Fcst. Interpretation	Forecast Period (hours)	Vector from actual position to mean fcst. position (C.G.) Length (Mean fcst error-n.mi.	Direction to C. G.	Vector standard Deviation (σ_R) (n.mi.)	Number of cases
		A - Barotropic forecasts			
1. 500-mb. low	24	140	180°	139	16
	48	260	181	200	8
	72	290	237	--	3
2. 500-mb. low (corrected)	24	145	176	126	15
	48	280	184	204	7
	72	330	235	--	3
3. Vorticity max.	24	170	175	173	14
	48	260	184	228	11
	72	190	236	--	3
4. Vorticity max. (corrected)	24	195	173	149	14
	48	280	186	220	11
	72	285	212	--	3
5. Trajectory	24	140	160	170	18
	48	140	146	440	16
	72	180	75	--	7
		B - Baroclinic forecasts+			
1. 500-mb. low	24	108	205°	124	10
5. Trajectory	24	50	194	126	7

+ Baroclinic forecasts were not made for 48 or 72 hours.

casts lying 140 n. mi. behind (180°) the actual hurricane position. This means the average error was an insufficient displacement by 140 n. mi. in 24 hours and the standard vector deviation of all forecasts by this method was 139 n. mi.

It should be borne in mind that although five different methods of forecast interpretation have been employed, the methods are not independent and the similarity between various results reflects the fact that they are all based on the same basic forecast. It must also be pointed out that the number of independent forecasts is small so that any derived statistics contain a large degree of uncertainty. The number of 72-hour forecasts is so small that no dispersions have been computed.

The actual tracks of the hurricanes used in this study are shown in figures 2 through 11 along with forecast positions obtained by one method only. All five methods were used in connection with the seven storms 1951 through 1954 but the vorticity maximum centers were not analyzed for the 1955 storms. Figures 2 through 8 show forecast positions obtained by locating the vorticity maxima on each prognostic map, correcting the initial error, and connecting the corrected positions with a smooth curve. Figures 9 through 11 show the corrected positions of the 500-mb. Low (Method No. 2).

It would be possible to obtain a complete path forecast by any of the five methods by procuring a print-out of the pertinent information at each time iteration. For this study however, only 24-hour positions were obtained so the details of the path should be considered as estimates and not the result of numerical forecasts. The only exception is the trajectory method (Method No. 5) where linear interpolation was employed to obtain maps for each 12-hour period.

If the reader is interested in examining the result of any particular forecast not shown in figures 2 through 11 he may do so by laying off a straight line connecting the hurricane positions at the beginning and end of the forecast period involved, orienting a polar diagram on that line with its center at the hurricane position at the end of the period and transferring the position for the forecast from the appropriate polar diagram[2].

DISCUSSION OF FORECAST RESULTS

Dispersion of the individual forecasts is caused in part by failure of the forecast model, partly by erroneous input data, and partly by the difficulty in operating on a small feature with data at large grid spacing. The information made available by this investigation is not sufficient to provide a separation of the sources of error, but if we make the reasonable assumption that the errors in input data and the errors in interpretation of the prognostic maps produce errors that are random, any strong tendency of the model to produce a bias should be evident.

Such a bias does appear and is an important result-the barotropic model underestimates the motion. A certain amount of under-forecasting is to be expected because of the truncation error involved in finite difference computation and this is discussed below.

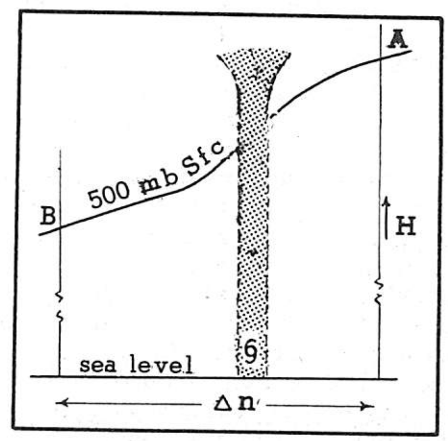
The second bias one might expect is a consistent deviation either toward high pressure or low pressure. This would be revealed by the vector which connects the origin of the polar diagrams and center of gravity deviating markedly from 180° or 360°. If such a bias exists it is not sufficiently strong to show up in this study, for Table II shows no significant deviation from 180°. (The number of 72-hour forecasts is too small to be considered in this comparison).

Another item of interest is whether the errors normal to the actual path are significantly different from the error along the path. If there were a significant difference the pattern of forecast positions on each polar diagram would be elliptical rather than circular. This was investigated by testing the 24-hour and 48-hour forecast patterns for significant ellipticity with the statistic suggested by Mauchly[3].

None of the distributions was significantly elliptical at the 5 percent level, therefore if there exists a bias toward greater error along the path or normal to it, it is too small to be evident here.

SOURCES OF FORECAST ERROR

Truncation errors. - The dominant feature of the barotropic model applied to hurricane motion forecast is the tendency to under-forecast which, as mentioned above, is due in part to truncation error made in computing the first derivative of the height field. This is illustrated by the sketch which represents the 500-mb. profile along the gradient. If the height gradient in the vicinity of the hurricane is computed by the finite difference method, viz. assuming that $\frac{\partial H}{\partial n} = \frac{H_A - H_B}{\Delta n}$, it is obvious that the geostrophic wind in the hurricane's vicinity will be underestimated.



2 The difference in direction of the mean motion and the difference of distance introduced by transposing a vector determined on a mercator projection map (on which the polar diagrams are based) to a polar stereographic map projection is small compared to the uncertainty in locating the hurricane positions with the large grid spacing.

3 For a circular distribution $L_e = 1$ and if elliptical $L_e < 1$ where:

$$L_e = \frac{2\sigma_x\sigma_y}{\sqrt{\frac{1 - r_{xy}^2}{\sigma_x^2 + \sigma_y^2}}}$$

and the probability of obtaining a given L_e from a circular distribution is $L_e^{(N-1)}$. J. W. Mauchly, "A Significant Test for Ellipticity in the Harmonic Dial", Terr. Magn. Atmos. Elect., Washington, D. C., vol. 45, 1940, p. 145.

In order to compensate for this effect, an empirical correction has been incorporated into the model that has the effect of multiplying all geostrophic wind speeds by a factor of 1.3, which provides the best correction for the motion of planetary waves of mid-latitudes - the systems for which this model was devised. Evidently it is not the proper correction for small-scale systems like the hurricane and the difference is most likely due to the difference in scale because the truncation error increases as the scale decreases. Furthermore a comparison of the actual hurricane speed with the forecast speed suggests a constant correction would not be satisfactory. This particular aspect is discussed in connection with figure 29 in the section "Inadequacies of the Model".

At first glance it would appear that the trajectory computation (Method No. 5) would forecast the same hurricane motion as was indicated by the 500-mb. Low because the numerical model moves the vorticity patterns in the direction of and proportional to the geostrophic wind. One of the reasons for investigating the trajectory method, and the reason the results are slightly different, is as follows:

In the barotropic model the vorticity is computed at each grid point and advected with the geostrophic wind at that point (plus the empirical correction). The geostrophic wind is computed from the height difference between points on either side of that central point, i.e. over a space of two grid lengths. Because the hurricane vorticity is such a small feature and concentrated essentially at one grid point, the forecast motion is controlled mainly by the gradient over an area of two by two grid lengths, centered on the storm, and this height difference is frequently small because of the closed circular contours about the storm. Consequently one would expect the movement to be underforecast (assuming the motion is roughly equal to the 500-mb. flow in which it is embedded).

If, however, the immediate vicinity of the storm were weighted less heavily and the net geostrophic wind computed from the height gradient over distances of more than two grid lengths the velocity so computed might reflect more accurately the mean motion of the storm's environment.

The area of 10 degrees latitude and 15 degrees longitude used in the trajectory computations is about 60 percent larger than an area two by two grid lenghts for storms at 30° N. A larger area was not used because the borders of anything much larger tend to reach across small troughs and ridges on the 500-mb. map and the purpose here was to consider the middle-scale features. A grid of this size was also used by Riehl and Haggard for a similar purpose[4].

Ideally the trajectory should be computed from a movable grid at each time step, viz. at two-hour intervals throughout the forecast period, because the height field is predicted by the barotropic model in two-hour increments. For example a two-hour trajectory would be computed on the $t_0 + 2$ hr map and the grid moved by that distance for the next step so the grid would always be centered at the forecast position of the hurricane. For the purpose of this experiment, trajectories were computed in 12-hour steps. The maps for each 12 hours were obtained by linear interpolation of the numerical prognostic maps. Components of the mean geostrophic wind were obtained by computing the average height difference between the lowest and highest latitude and longitude of the grid on the initial map and all prognostic maps in the following manner: (a) A 6-hour displacement was computed on the t_0 map; that distance laid off from the initial hurricane position and transferred to the t_{12} map. (b) A 12-hour displacement was computed from the t_{12} map with the grid centered at the $t_0 + 6$ hr position, and the new endpoint transferred to the t_{24} map, and so on until the 72-hour prognostic map was used for the final 6-hour computation. The point bisecting the trajectory leg computed on the t_{24} map represents the 24-hour forecast position, etc. The trajectories thus computed were about the same as would have been obtained had maps for shorter time steps been available, because the 500-mb. patterns moved slowly and changed in a regular fashion.

This method also suffers from truncation error and apparently to about the same degree as the other methods since the center of gravity of trajectory forecasts is almost exactly the same as that of Method No. 1. The larger dispersion of forecasts by trajectories suggests that the extraneous effect introduced by considering the larger area may have done more harm than good.

Errors due to large grid spacing. The grid spacing at 25° to 30° latitude is about 260 n. mi. and a feature of the height field as small as a hurricane cannot be uniquely located from data at those grid points because the height field is asymmetrical. Obviously if the height field were known to be symmetrical to a distance of two or three grid points in all directions from the center, the Low's position could be located very accurately. Like-

[4] H. Riehl, and W. Haggard, Second Research Report Task 12, "Prediction of Tropical Cyclone Tracks", U. S. Navy, Bur. of Aero., Project AROWA (TED-UNL-MA-501), 1955.

wise if the grid spacing were very short - say the average diameter of the eye - asymmetry would have little effect on the ability of the height field to delineate the position.

Neither of these conditions exists, however, and in addition, some asymmetry is injected subjectively by the analyst on the basis of theory, e.g., showing a tighter gradient to the right of the storm's path. An estimate of the position error can be made by comparing the storm's position shown on the analyzed map with the apparent position obtained by reanalyzing the same map from data at grid points only. Presumably the hurricane positions shown on the original 500-mb. maps are accurate because they have been fixed by reconnaissance aircraft and have been adjusted by an after-the-fact analysis.

The mean initial position error that resulted from reanalyzing grid data with linear interpolation was 80 n. mi., and it was 70 n. mi. when the interpolation was made in a subjective manner considering the change of gradient around the hurricane. It appears reasonable to believe that all methods of interpreting the prognostic map, with the possible exception of the trajectory method, have about this same uncertainty.

Grid spacing for the baroclinic model is just half that of the barotropic model. The gain in accuracy is reflected by the fact that the mean position error (based on ten initial maps used by JNWP in making baroclinic forecasts of three 1955 hurricanes) was only 25 n. mi.

Inadequacy of the barotropic model and 500-mb. data. The barotropic model cannot include the influence of a hurricane on its environment, and thereby on its own motion; therefore any such influence will not be forecast by the model. For example upper-level anticyclogenesis frequently appears to the right of a hurricane path which may well be the direct result of high-level warming produced by the hurricane - an effect that would not be forecast by the barotropic model in current use. Neither would the baroclinic model take this particular effect into account because the latter was designed to incorporate the effect of cold Lows (the mid-latitude cyclones) rather than the warm-core hurricane.

Because the hurricane motion forecast by the numerical model is largely controlled by an area of two by two grid points, it is obvious that small analysis errors will have a large effect on the forecast. Unfortunately these storms must be forecast when they are in regions of poor data and there is little doubt that part of the forecast error in this study may be attributed to erroneous input data.

In order to examine the tendency of the model to under-forecast hurricane displacement, the actual hurricane speeds were compared to the forecast speeds of the vorticity maxima for 24-hour and 48-hour forecast periods. Making the assumption that the actual storm speed is proportional to the 500-mb. geostrophic wind, the average ratio (R) of "actual speed/forecast speed" would indicate the empirical correction that might be applied to produce the best speed forecasts. The individual values of this ratio have a large scatter as can be seen from figure 29. The values of R are plotted on the vertical (log scale) axis and have a range from 0.65 to 11.5. Intuitively it does not seem reasonable that a range of one order of magnitude could be attributed to truncation error entirely. Examination of the initial 500-mb. maps and the prognostic charts suggests a partial explanation that involves the data density. In those situations where the hurricane lies in a very large low pressure area - about the size of a small mid-latitude cyclone - the forecast motion is slow because it is controlled by the gradient across a quasi-circular Low. Further, if this Low is distant from a trough moving at higher latitudes, the cyclone will be forecast to remain stationary and the prognostic charts will show the Low - therefore the hurricane, to have almost no motion. In some cases the hurricane actually moves along the periphery of the larger-scale Low with speeds up to 10 to 12 knots and the ratio of actual to forecast speed is of the order of 10. Two examples of this are illustrated by hurricanes ABLE 1952 and BARBARA 1953 and are represented by the points in the upper left portions of figure 29 A and B.

On the other hand there are cases when a hurricane embedded in the large Low does not move along the periphery and in those cases the numerical forecast of small motion is correct. It is quite likely that such storms move in response to details that cannot be detected on the 500-mb. analysis prepared with our present network of data, therefore these are details that would not be included by decreasing the grid spacing or eliminating the truncation error.

Now if all forecasts that involve a large 500-mb. Low are omitted from figure 29 - the points to the left of, say, 3 kt. are eliminated - the remaining points then appear to fall along a line of positive slope. This suggests that, eliminating the uncertainty due to the large cyclone, the forecast error may be a function of speed and therefore a function of the gradient and a constant correction for truncation may not be a satisfactory compensation.

Unreasonable anticyclogenesis is sometimes forecast by the numerical models. Although this is not a serious problem with the barotropic model, it did occur in varying degrees in about half of the fourteen forecasts. An unsuccessful attempt was made to relate the anticyclone "blow-up" cases to the largest errors of motion forecast. If there is any such relationship it was obscured by other factors and in addition it is possible that excessive anticyclogenesis compensated a part of the truncation error by over-forecasting the gradient.

Boundary errors. Figure 1 shows the tropical boundaries of the forecast area cutting across regions that are important to the hurricane forecast regions. Mass transport across the boundaries will bring with it vorticity, thereby influencing the subsequent patterns in a manner that cannot be forecast by the model. This does not always introduce a forecast error however, because the model specifies no time changes at the boundary. Any vorticity which exists on the boundary at initial time will be maintained so only the changes are neglected. The geostrophic components at the Gulf and Atlantic boundaries were computed for each forecast map in order to see if changes in this component were related to forecast error. No association was evident, but it must be borne in mind that this is a very crude manner of searching for possible boundary effects and a more refined investigation is planned.

APPLICATION OF RESULTS

The statistics derived from this experiment should be used to evaluate future forecasts in a qualitative manner only because:

a. The total number of independent forecasts is small.

b. The initial analyses used in operational JNWP forecasts may be somewhat better than those used here because of improved reconnaissance data.

c. The grid spacing and the barotropic model will be altered before the beginning of the 1956 hurricane season.

In connection with the latter point, the changes should result in improvement of hurricane motion forecasts because the grid length, therefore the truncation error, will be reduced. In addition the model itself will be improved in a manner that should improve forecasts especially in the subtropics. It is hoped that a few cases used in this study can be re-run with the new barotropic model for purposes of comparison.

In addition to applying the new barotropic model, further research on these particular cases is planned and if useful results are obtained they will be communicated to interested forecast offices.

ACKNOWLEDGMENTS

The experiment which is reported here would not have been completed soon enough for the 1956 hurricane season without the assistance of several other offices in the Weather Bureau in the time-consuming task of reading the initial 500-mb. maps. The help of the Weather Bureau Office at the Washington National Airport, the Extended Forecast Section, and the National Weather Analysis Center is gratefully acknowledged. The exacting work of preparing and checking the punched cards used as input decks for the electronic computer was done by the Machine Tabulation Unit of the Meteorological Statistics Section of the Weather Bureau.

The help of Dr. George Cressman, Director of JNWP, in reviewing this report, and the advice and suggestions provided by Dr. Cressman and the staff at JNWP are also acknowledged with thanks.

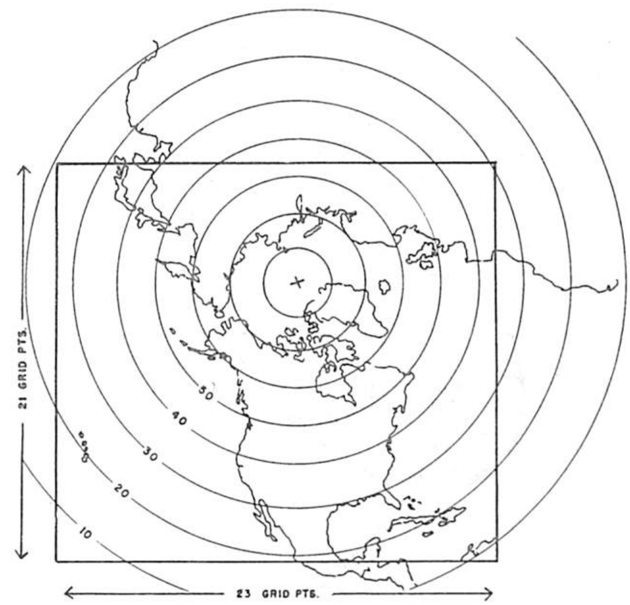


Fig 1. Forecast area of JNWP barotropic model

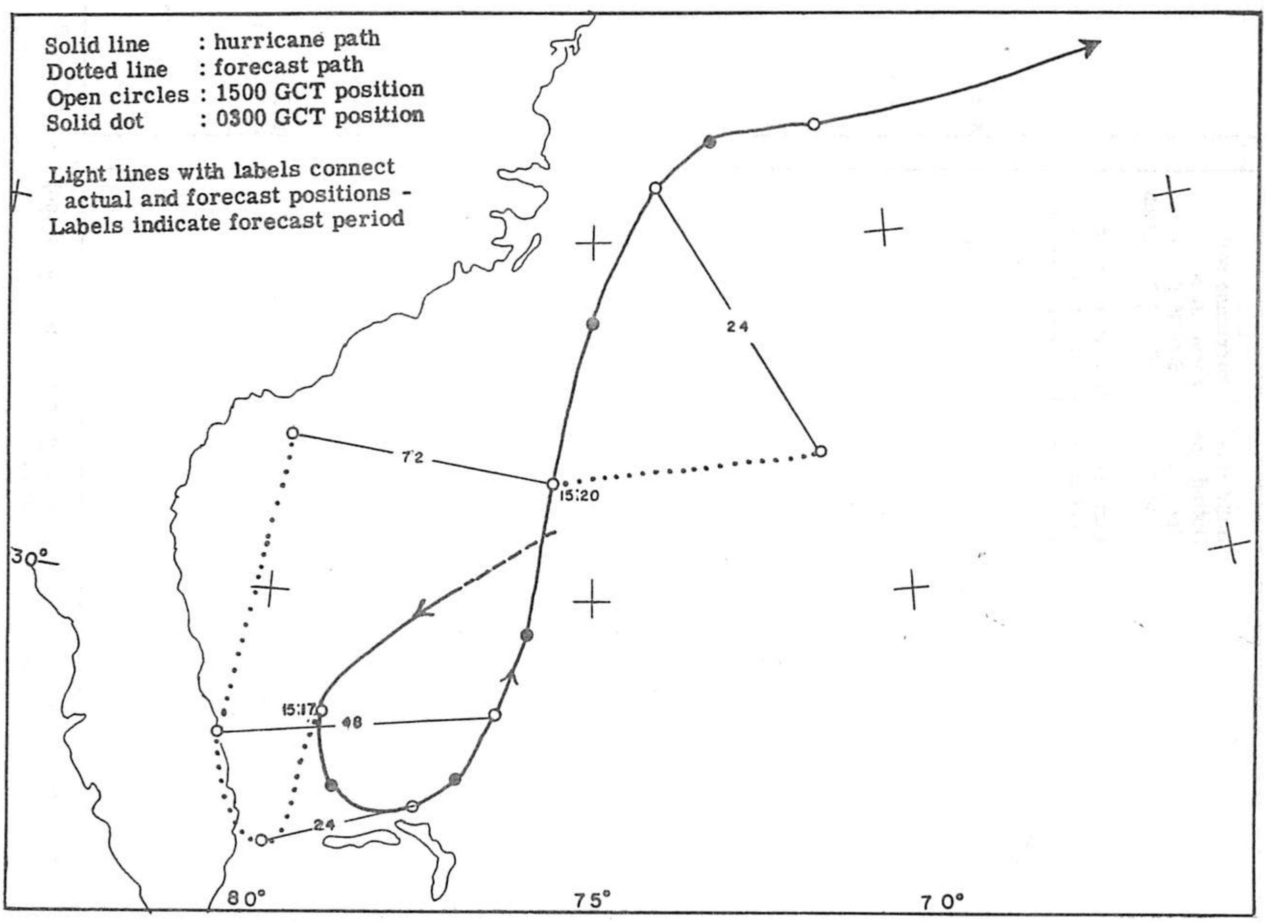


FIG. 2. ABLE 1951 Barotropic forecast of vorticity maximum (corrected) from 1500 GCT 17 May and 20 May.

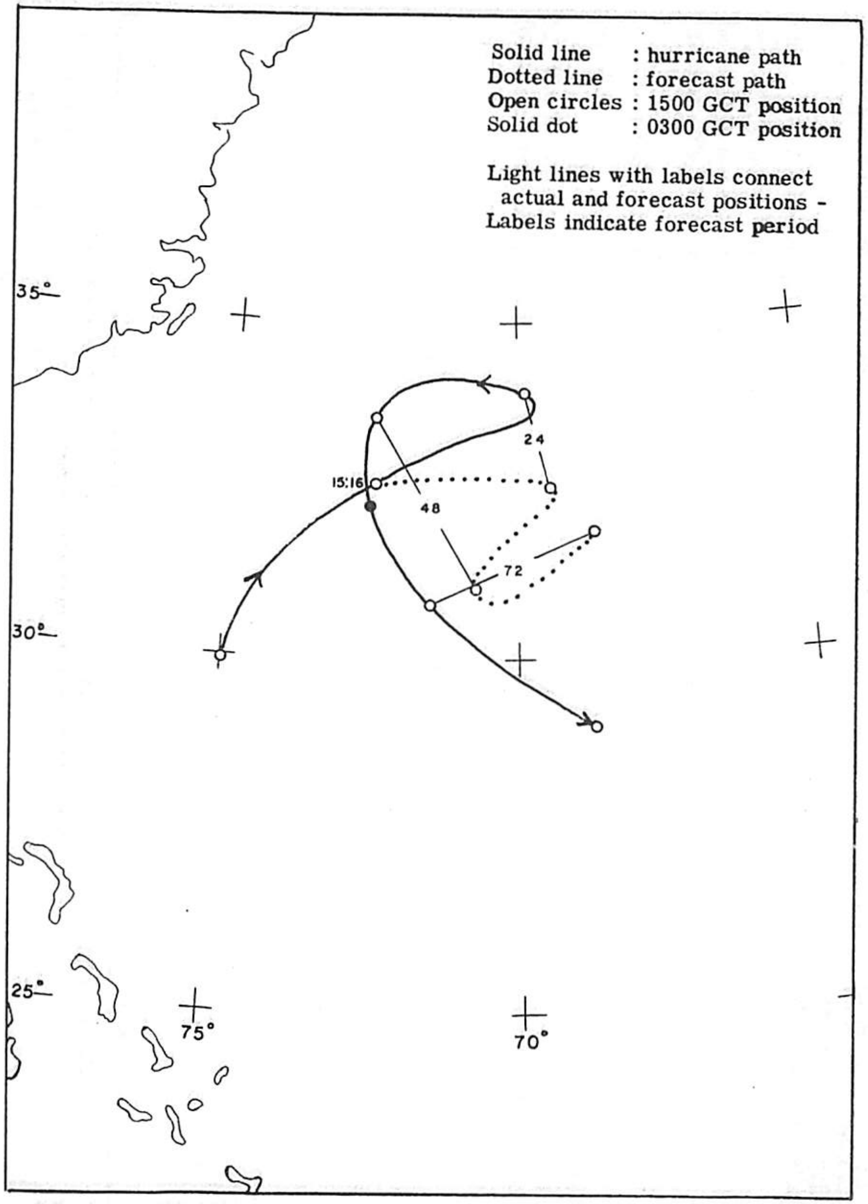


FIG. 3-A. JIG 1951 Barotropic forecast of vorticity maximum (corrected) from 1500 GCT 16 October.

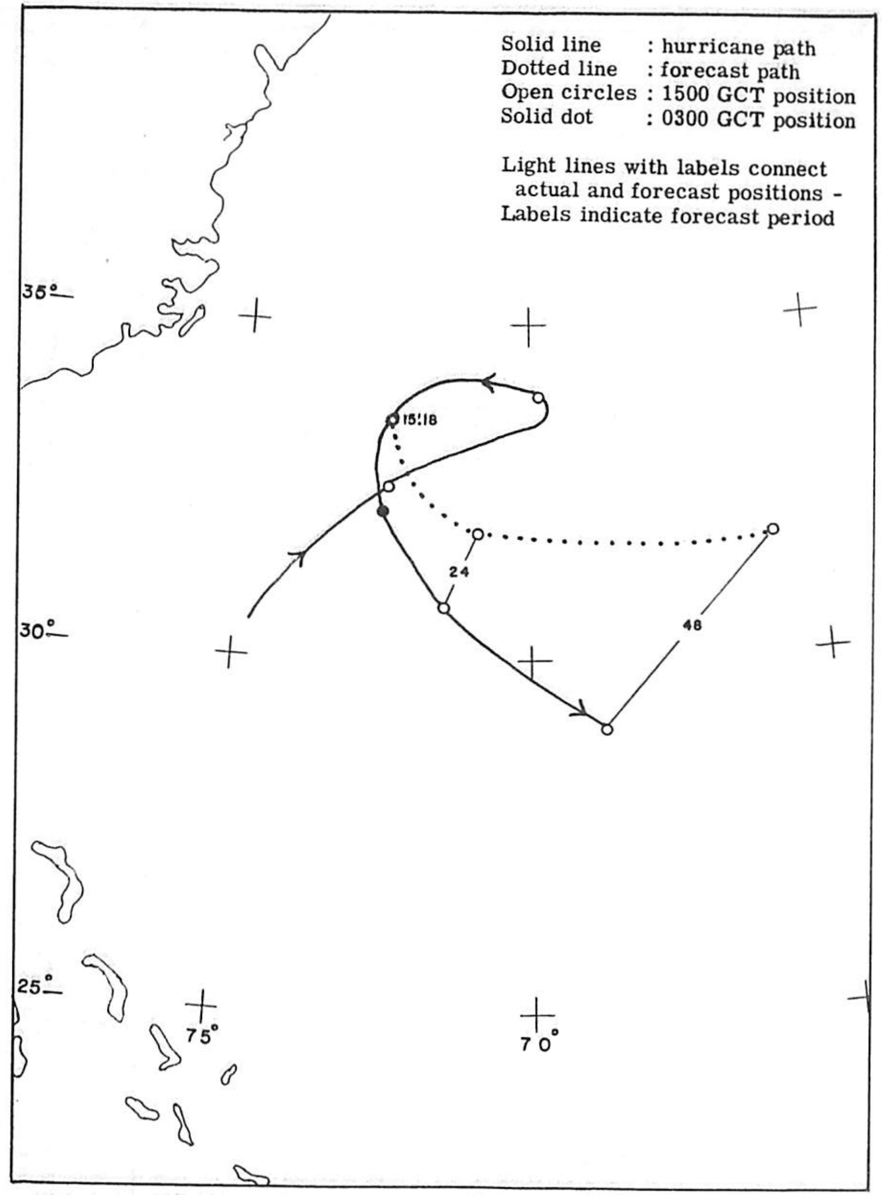


FIG. 3-B. JIG 1951 Barotropic forecast of vorticity maximum (corrected) from 1500 GCT 18 October.

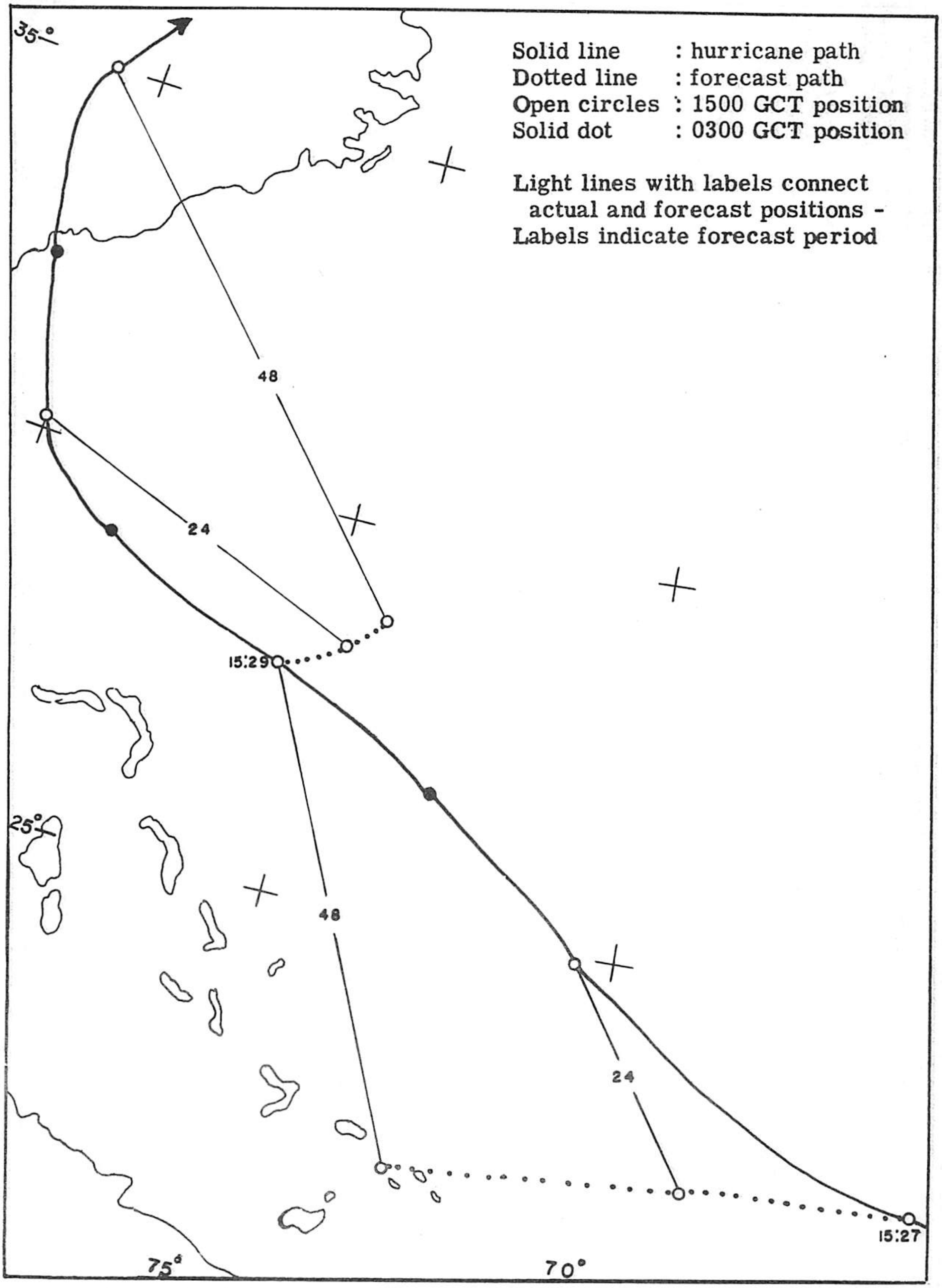


FIG. 4 ABLE 1952 Barotropic forecast of vorticity maximum (corrected) from 1500 GCT 27 August and 29 August.

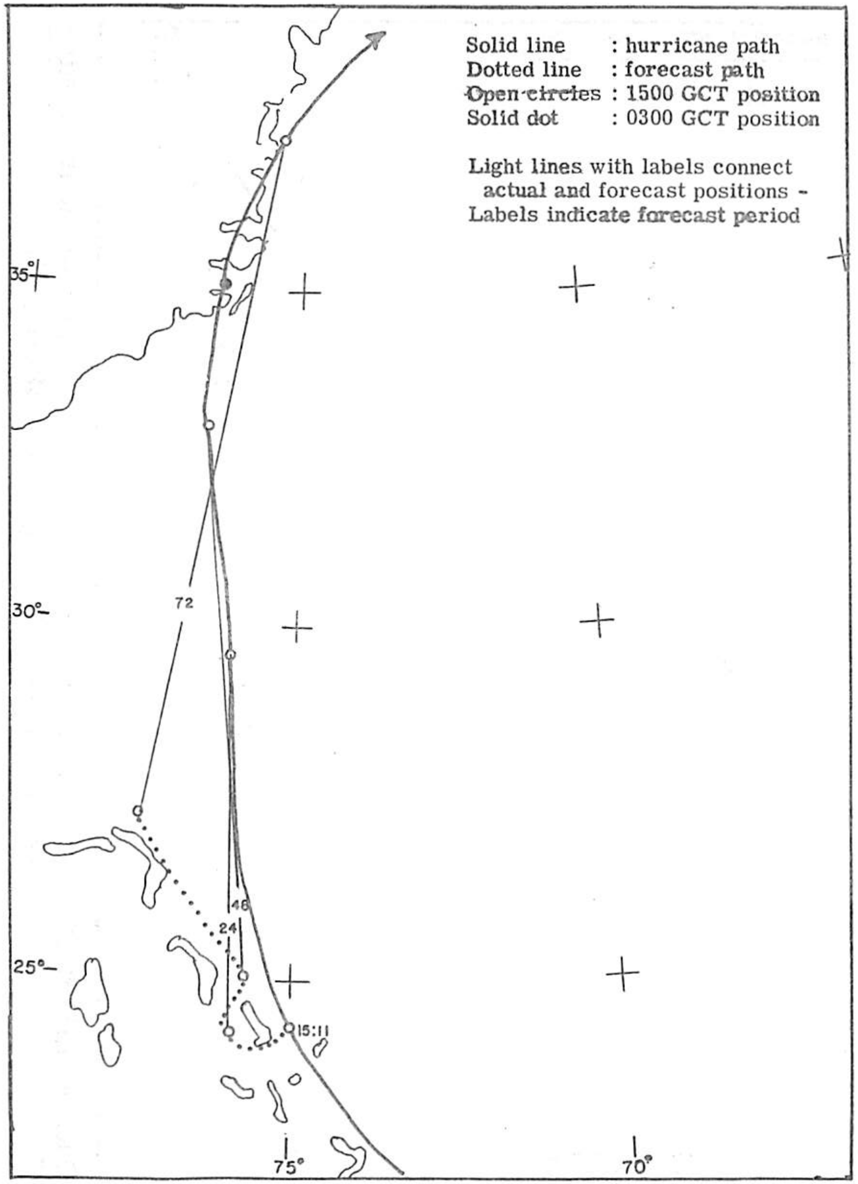


FIG. 5-A. BARBARA 1953 Barotropic forecast of vorticity maximum (corrected) from 1500 GCT 11 August.

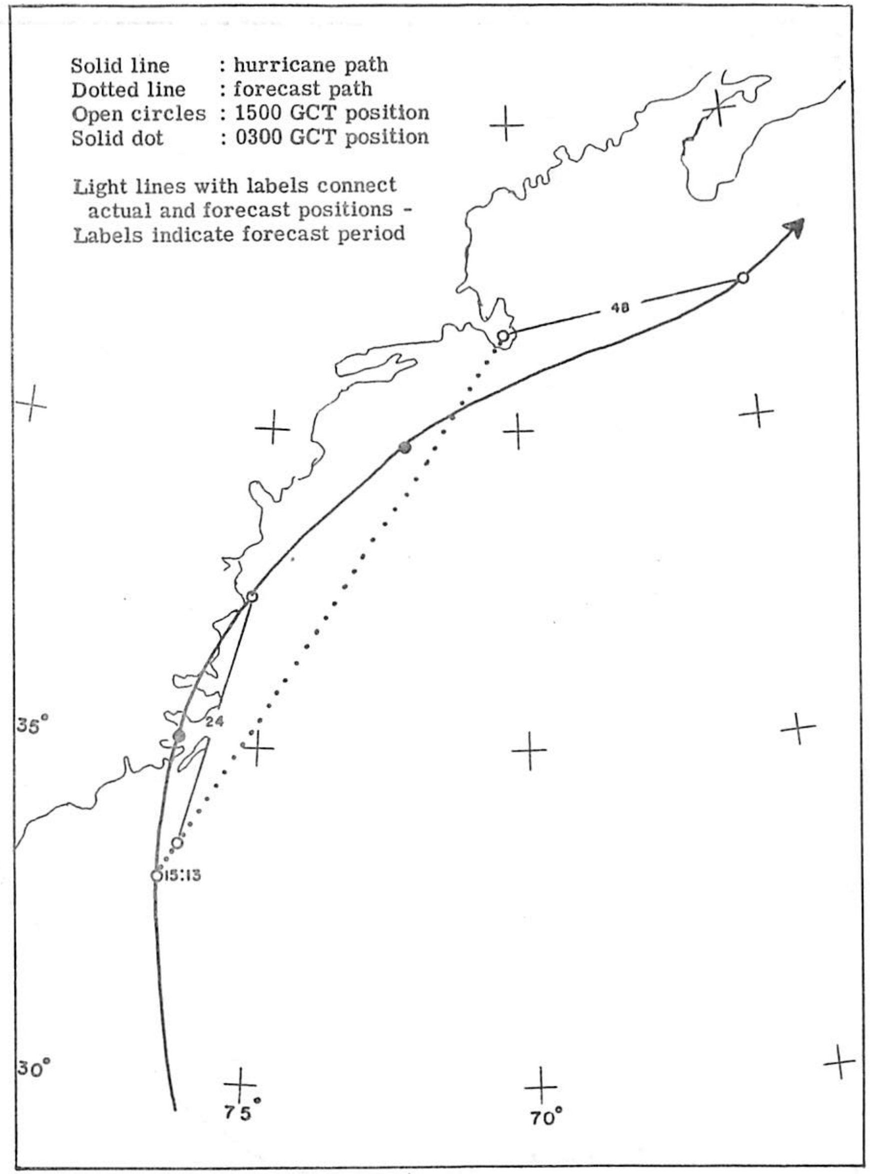


FIG. 5-B. BARBARA 1953 Barotropic forecast of vorticity maximum (corrected) from 1500 GCT 13 August.

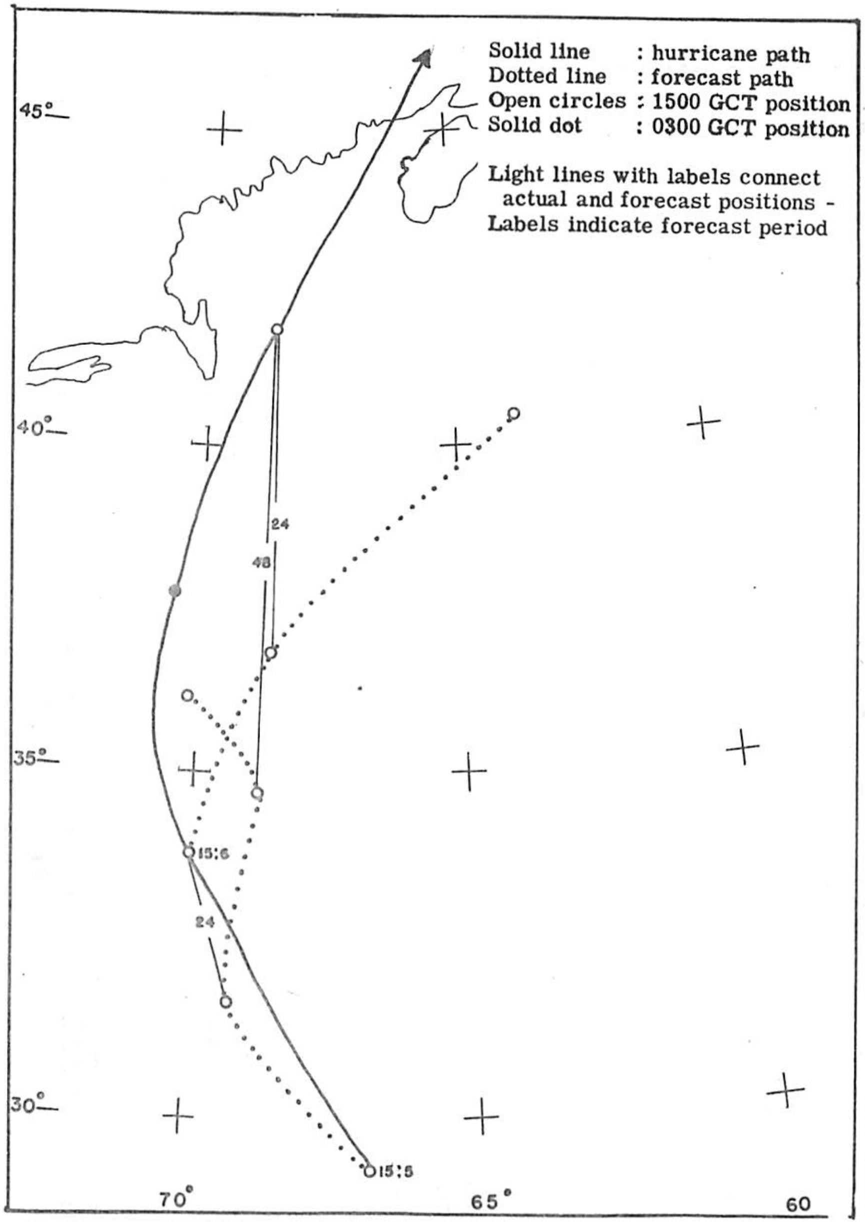


FIG. 6. CAROL 1953 Barotropic forecast of vorticity maximum (corrected) from 1500 GCT 5 September and 6 September.

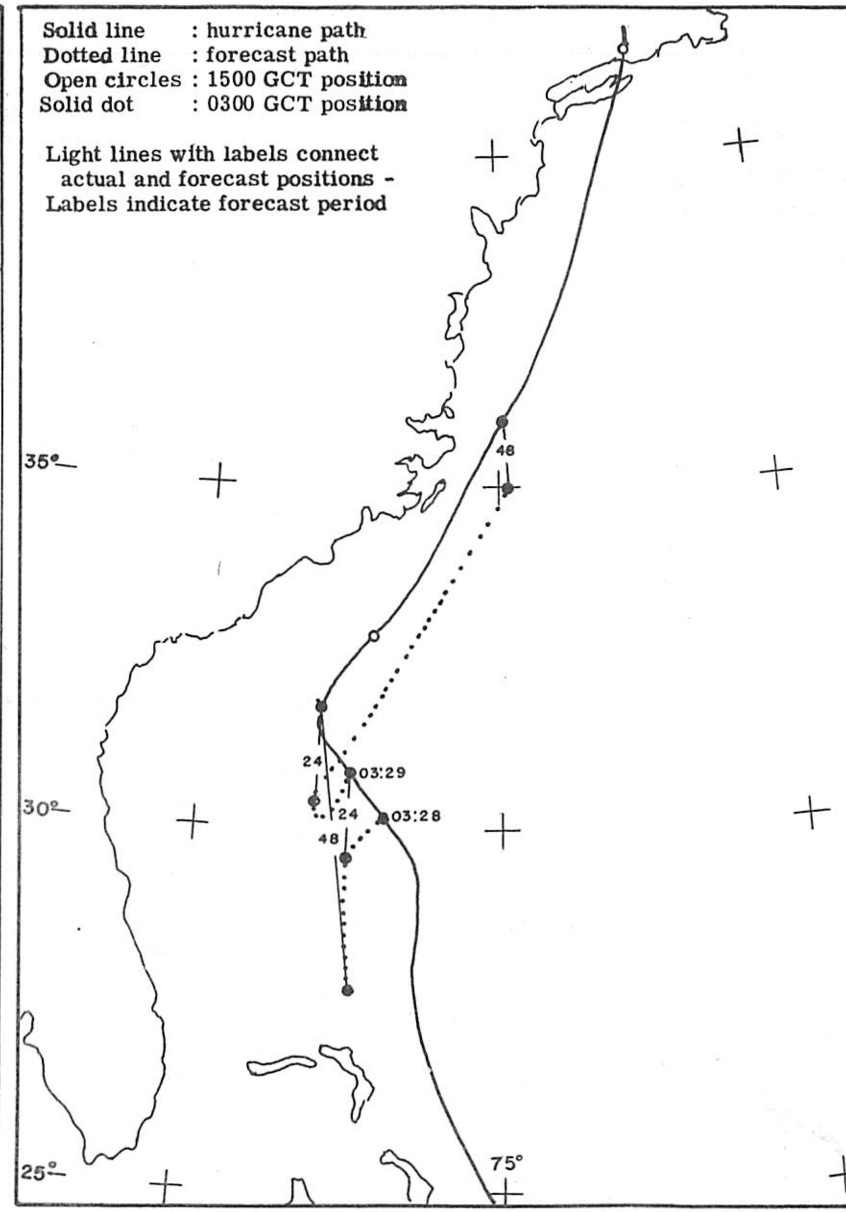


FIG. 7. CAROL 1954 Barotropic forecast of vorticity maximum (corrected) from 0300 GCT 28 August and 29 August.

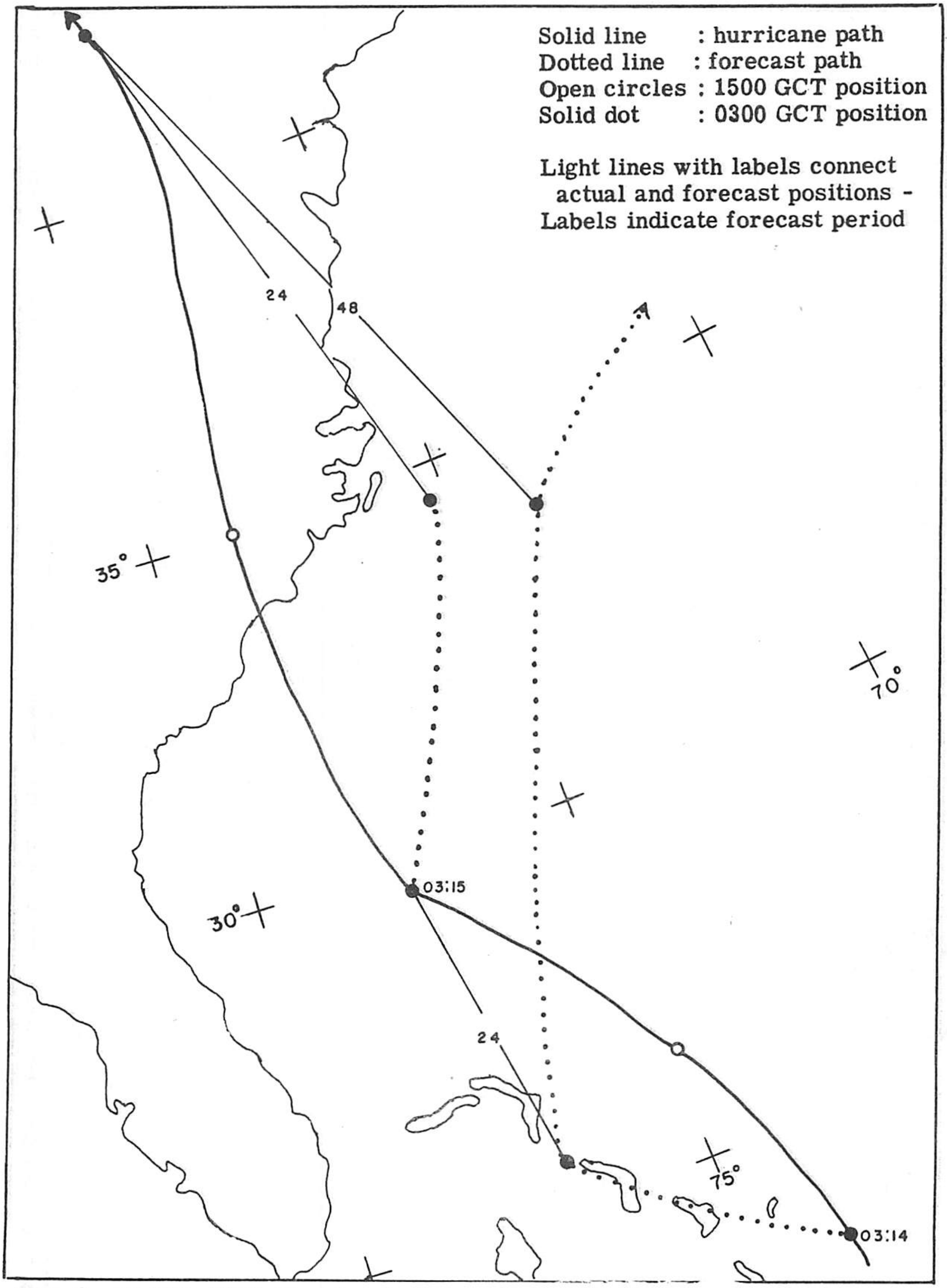


FIG. 8. HAZEL 1954 Barotropic forecast of vorticity maximum (corrected) from 0300 GCT 14 October and 15 October.

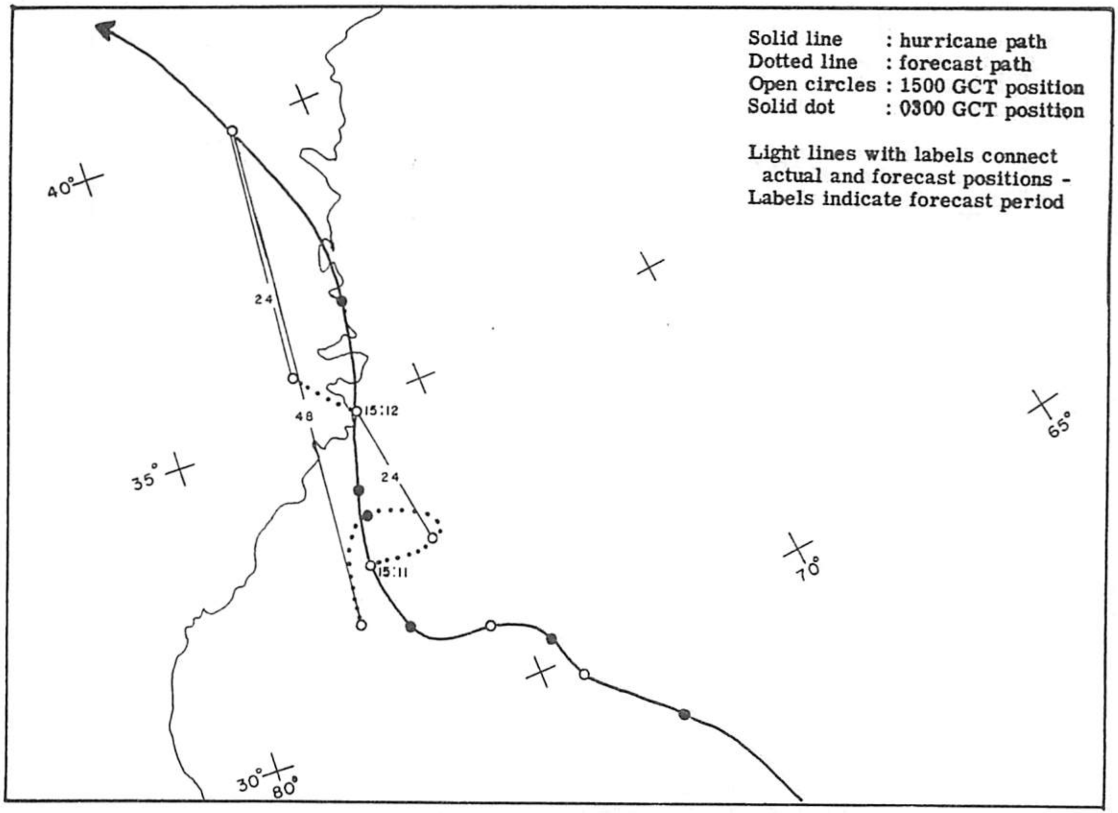


FIG. 9. CONNIE 1955 Barotropic forecast of 500-mb. low (corrected) from 1500 GCT 11 August and 12 August.

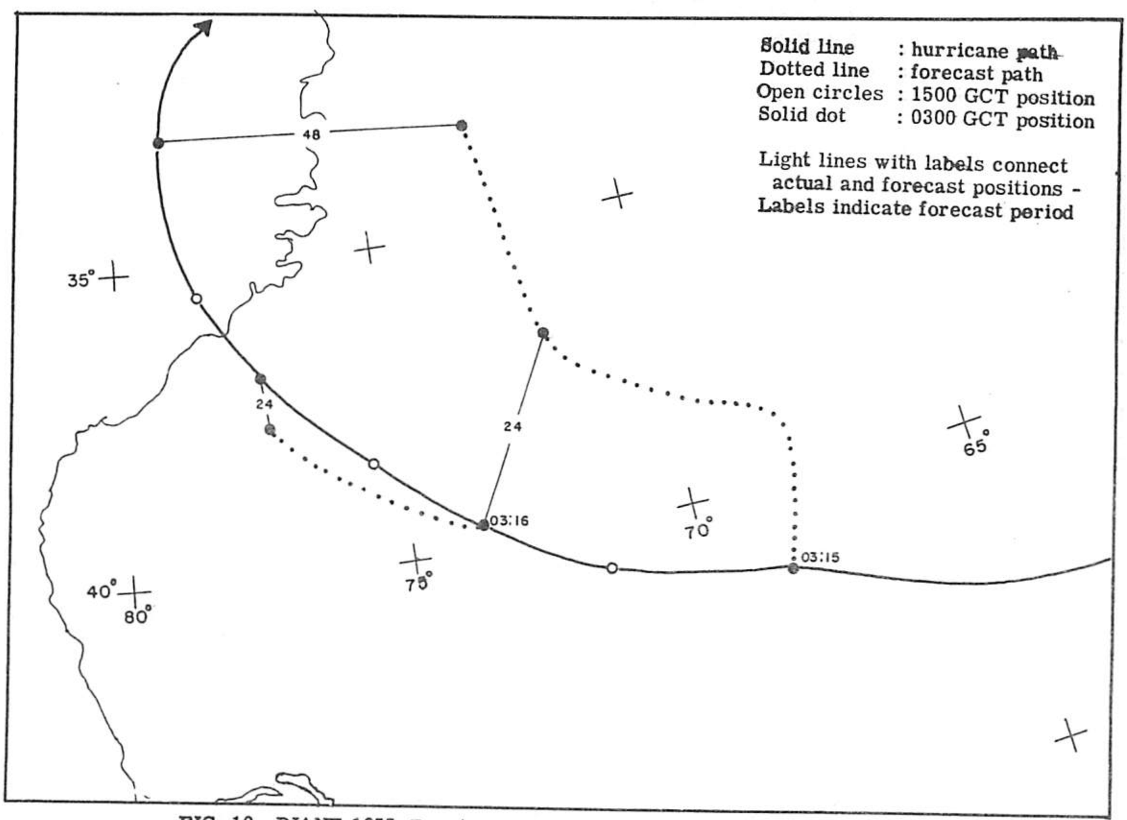


FIG. 10. DIANE 1955 Barotropic forecast of 500-mb. low (corrected) from 0300 GCT 15 August and 16 August.

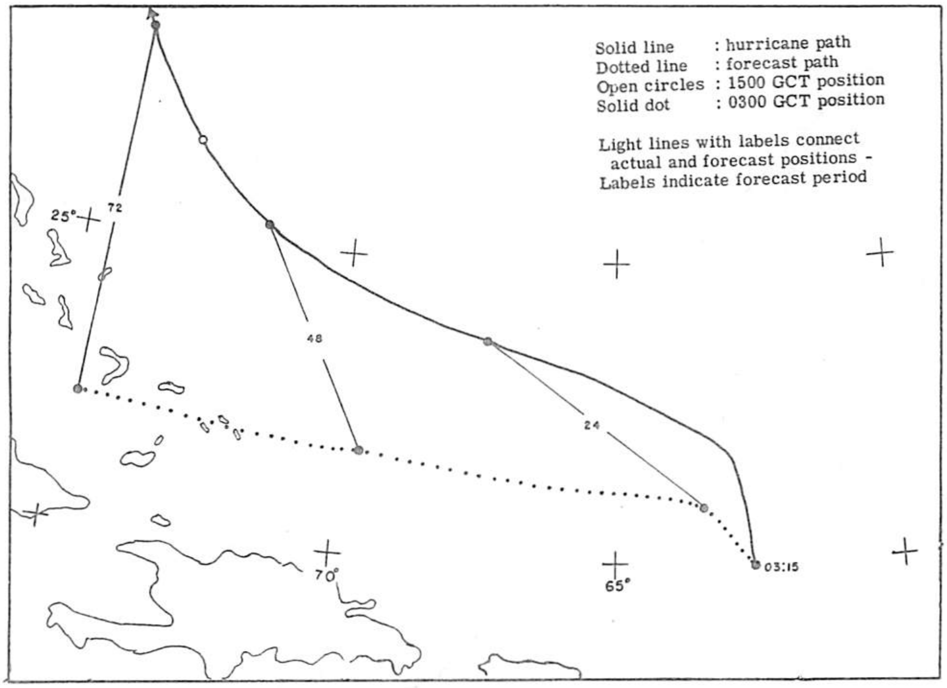


FIG. 11-A. IONE 1955 Barotropic forecast of 500-mb. low (corrected) from 0300 GCT 15 September.

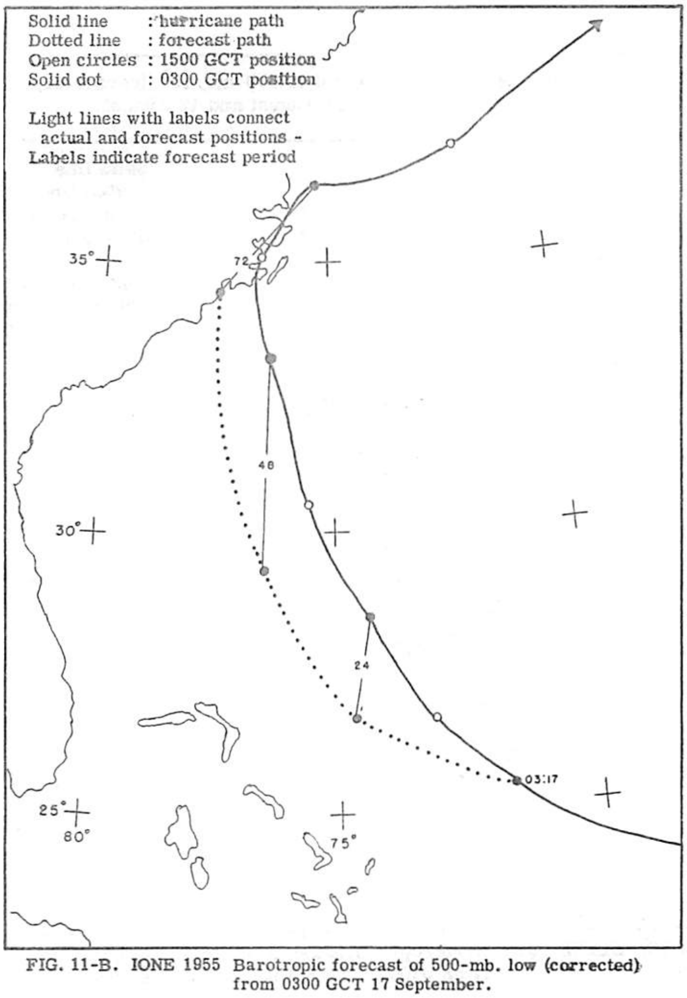


FIG. 11-B. IONE 1955 Barotropic forecast of 500-mb. low (corrected) from 0300 GCT 17 September.

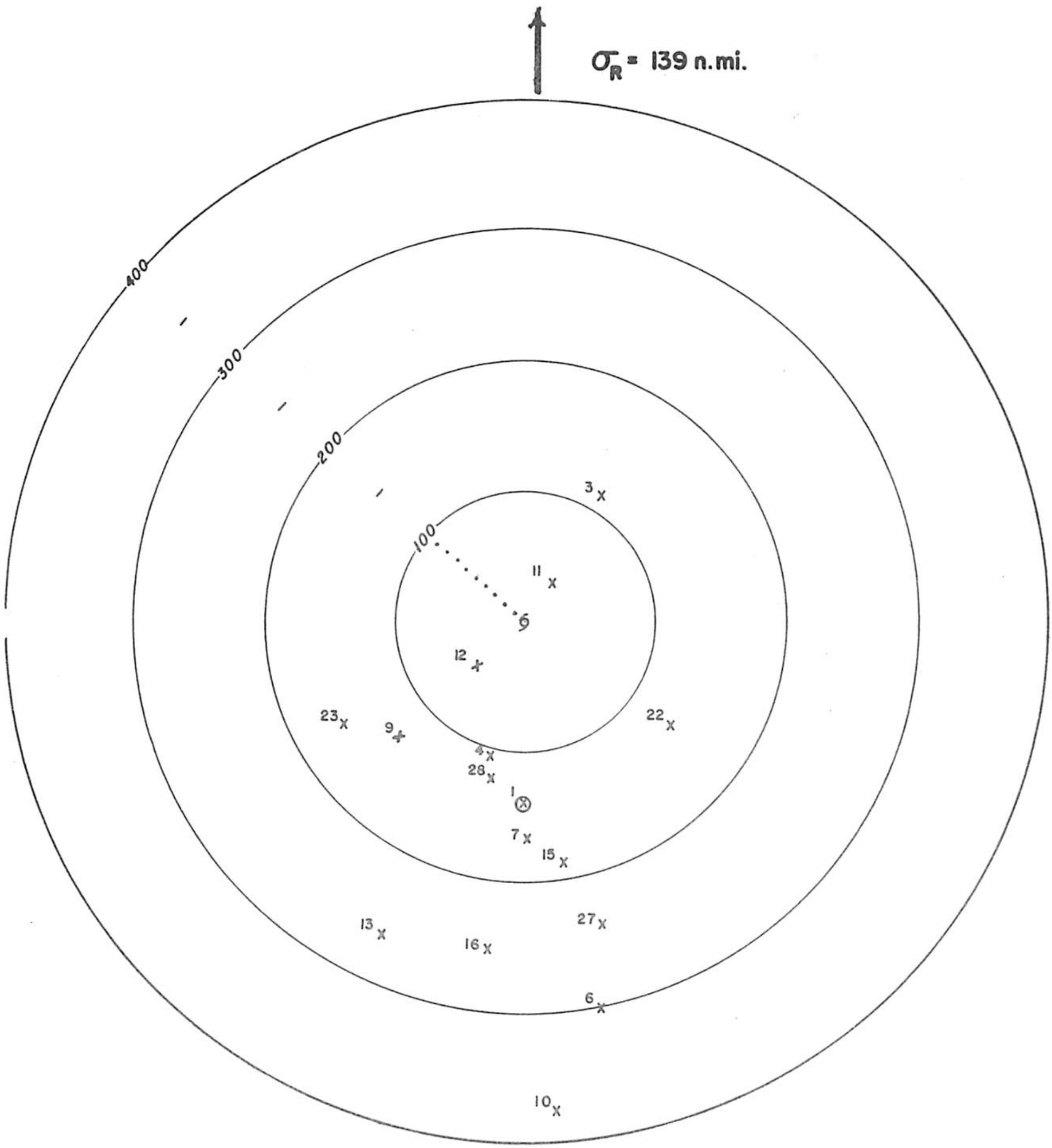


Fig. 12. BAROTROPIC 24-HR FORECASTS OF 500-MB LOW. Center of diagram is actual storm position. Numbers identify forecasts (See Table I). Open circle: mean of forecast positions.

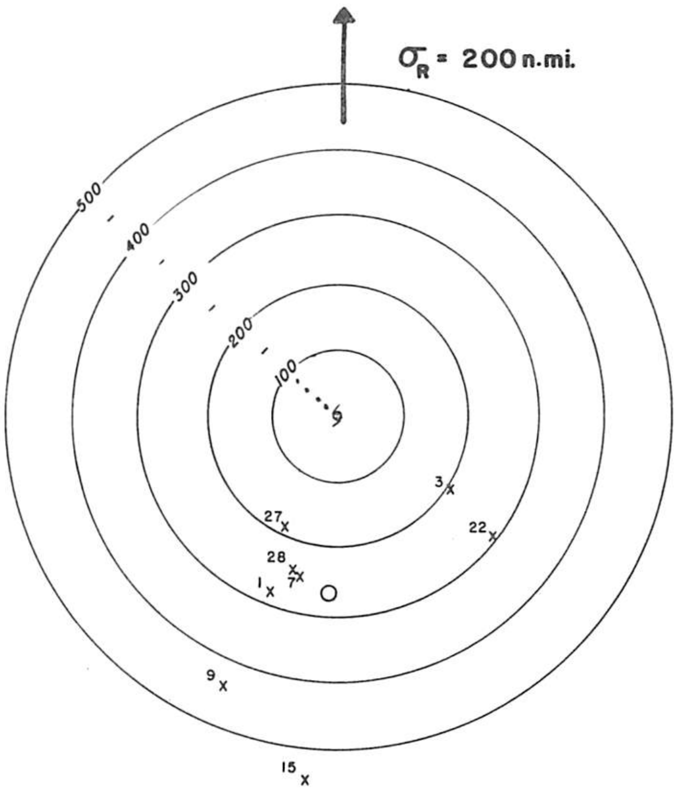


Fig. 13. BAROTROPIC 48-HR FORECASTS OF 500-MB LOW. Center of diagram is actual storm position. Numbers identify forecasts (See Table I). Open circle: mean of forecast positions.

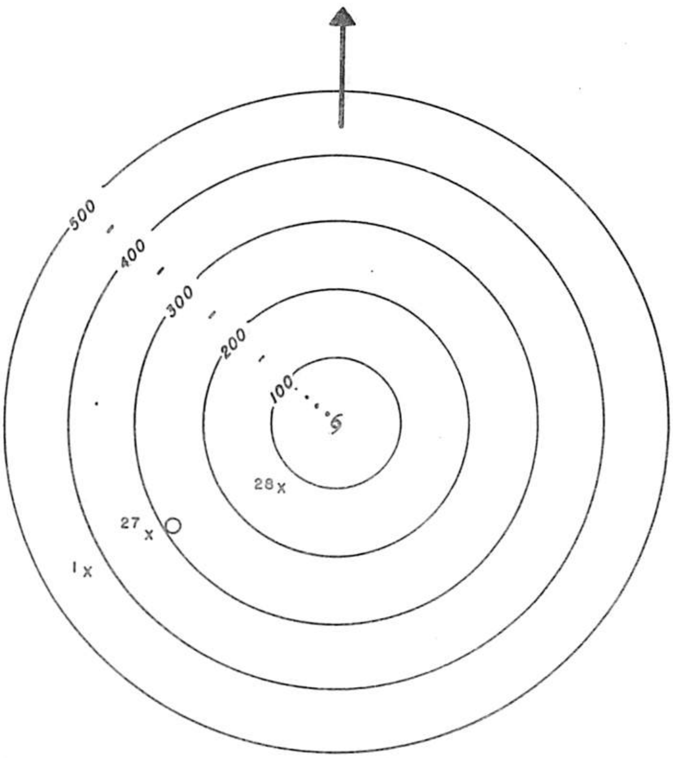


Fig. 14. BAROTROPIC 72-HR FORECASTS OF 500-MB LOW. Center of diagram is actual storm position. Numbers identify forecasts (See Table I). Open circle: mean of forecast positions.

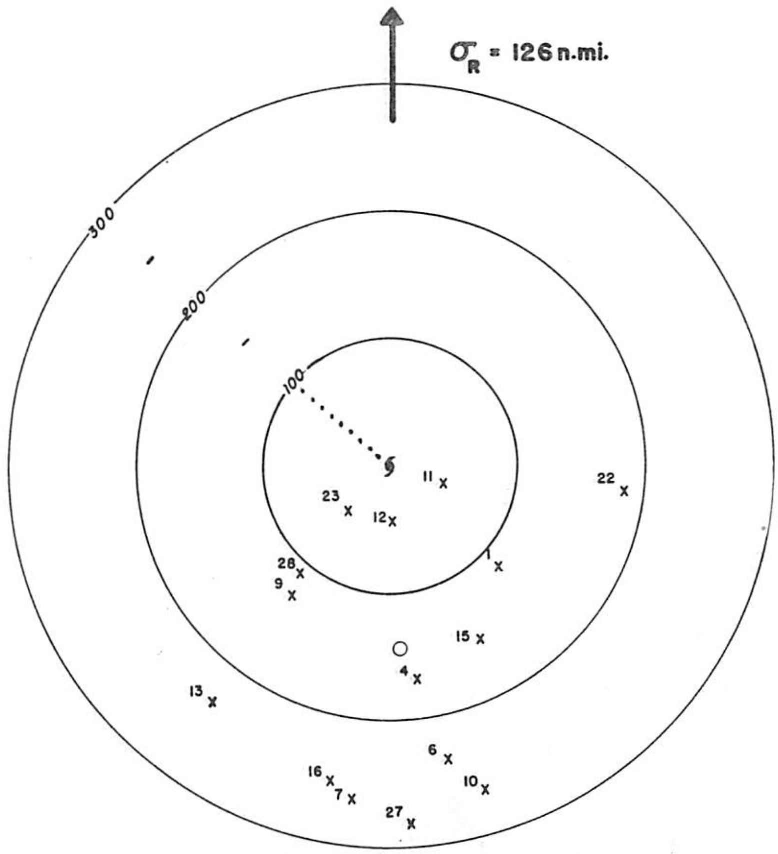


Fig. 15. BAROTROPIC 24-HR FORECASTS OF 500-MB LOW (CORRECTED). Center of diagram is actual storm position. Numbers identify forecasts (See Table I). Open circle: mean of forecast positions.

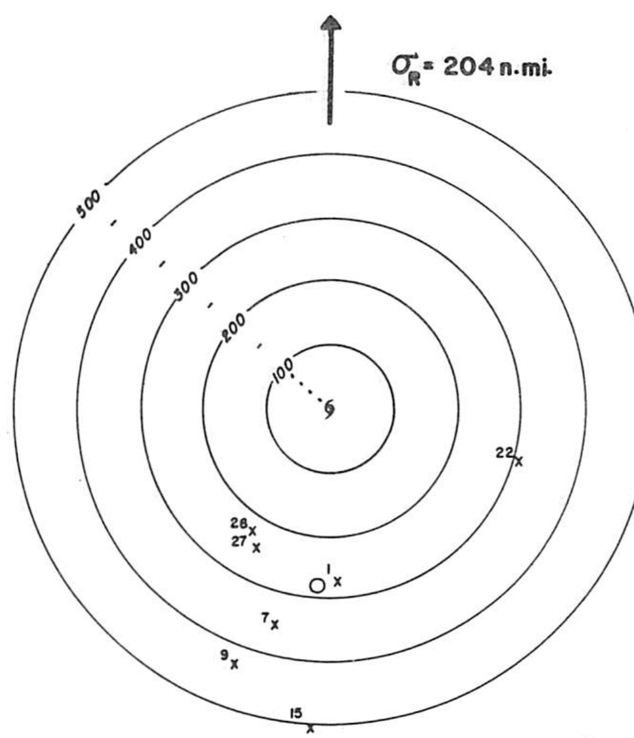


Fig. 16. BAROTROPIC 48-HR FORECASTS OF 500-MB LOW (CORRECTED). Center of diagram is actual storm position. Numbers identify forecasts (See Table I). Open circle: mean of forecast positions.

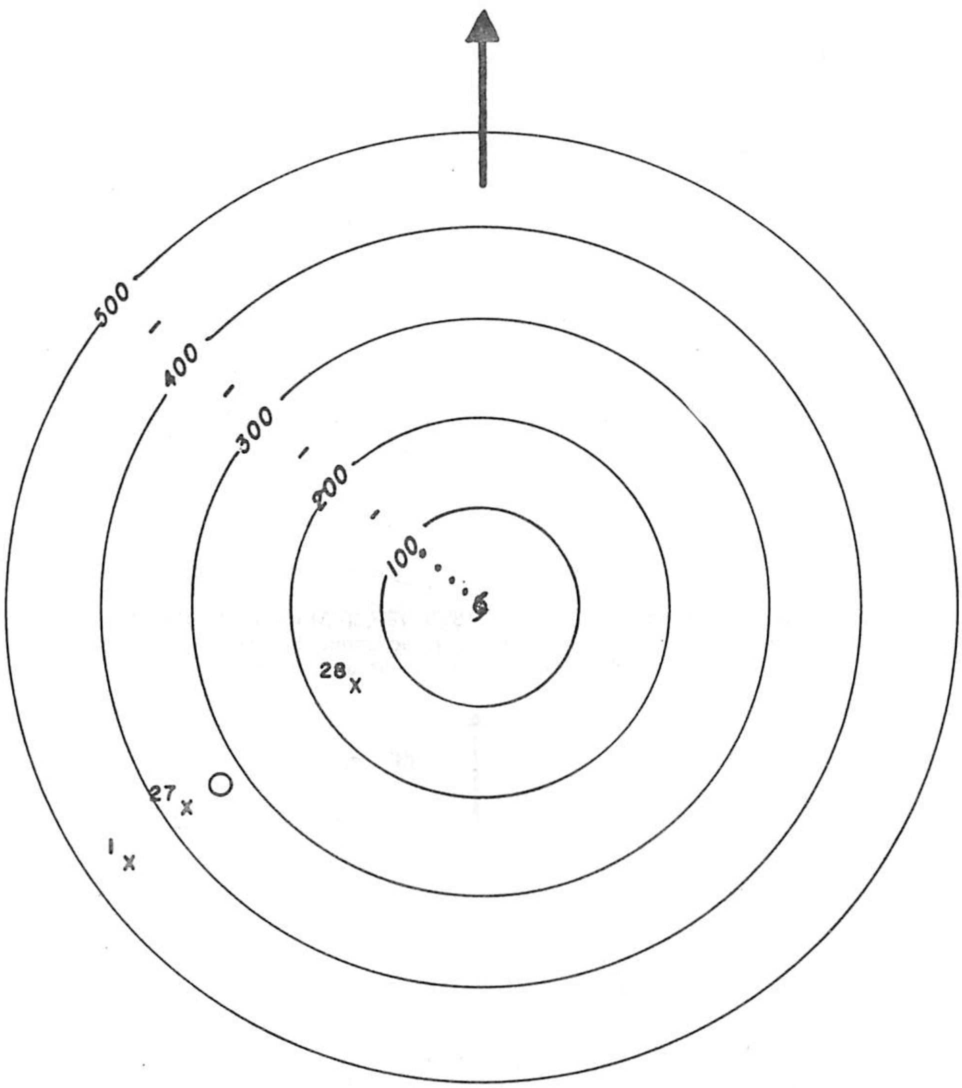


Fig. 17. BAROTROPIC 72-HR FORECASTS OF 500-MB LOW (CORRECTED). Center of diagram is actual storm position. Numbers identify forecasts (See Table I). Open circle: mean of forecast positions.

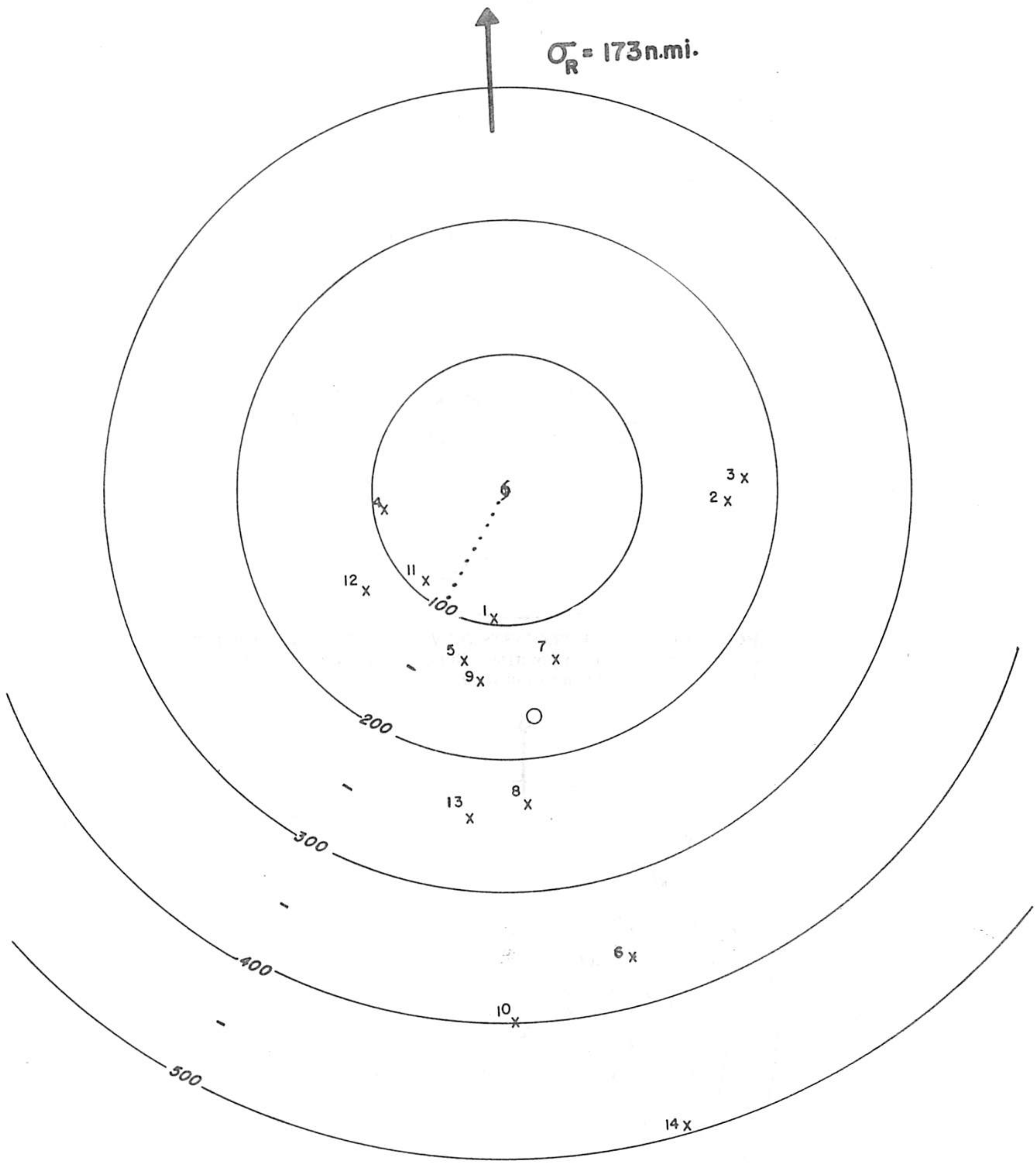


Fig. 18. BAROTROPIC 24-HR FORECASTS OF VORTICITY MAX. Center of diagram is actual storm position. Numbers identify forecasts (See Table I). Open circle: mean of forecast positions.

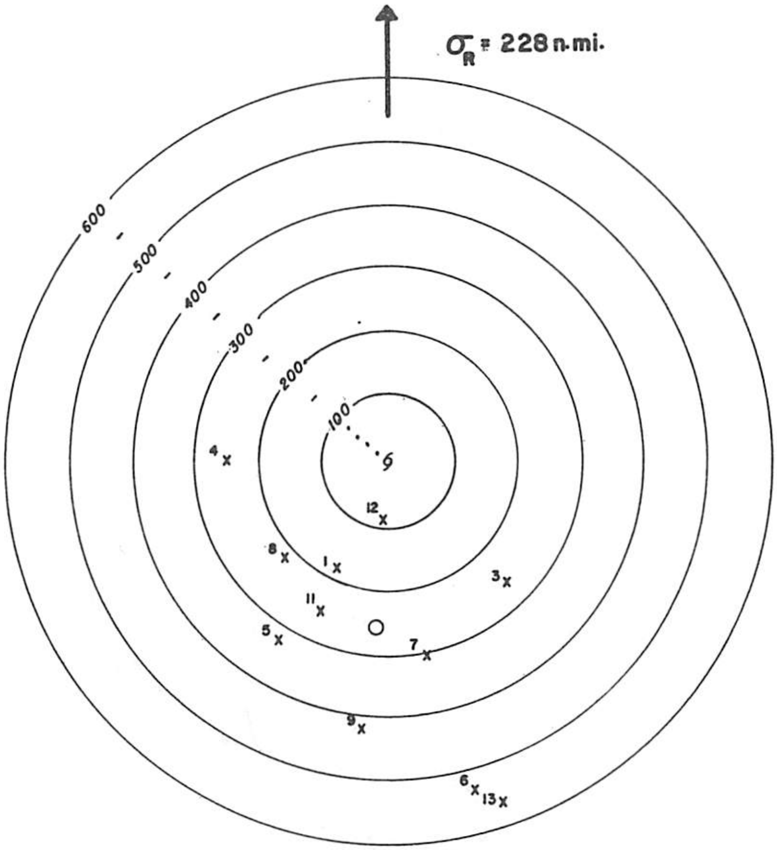


Fig. 19. BAROTROPIC 48-HR FORECASTS OF VORTICITY MAX. Center of diagram is actual storm position. Numbers identify forecasts (See Table I). Open circle: mean of forecast positions.

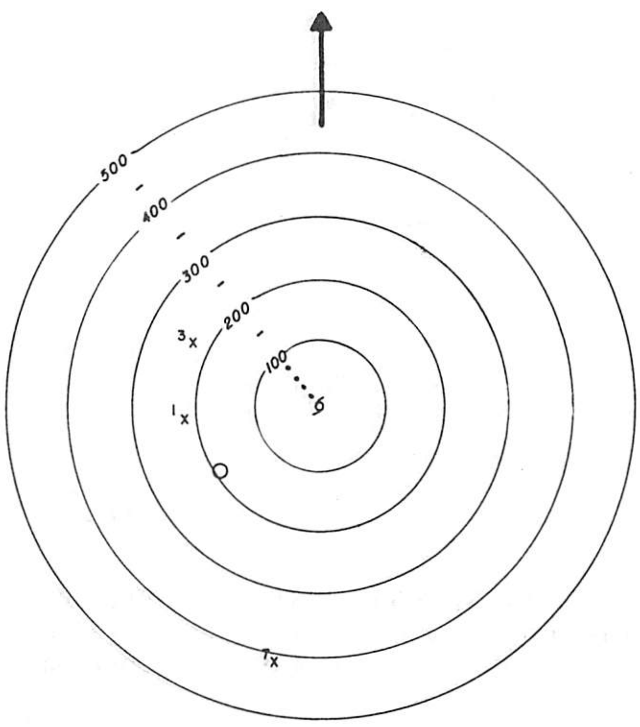


Fig. 20. BAROTROPIC 72-HR FORECASTS OF VORTICITY MAX: Center of diagram is actual storm position. Numbers identify forecasts (See Table I). Open circle: mean of forecast positions.

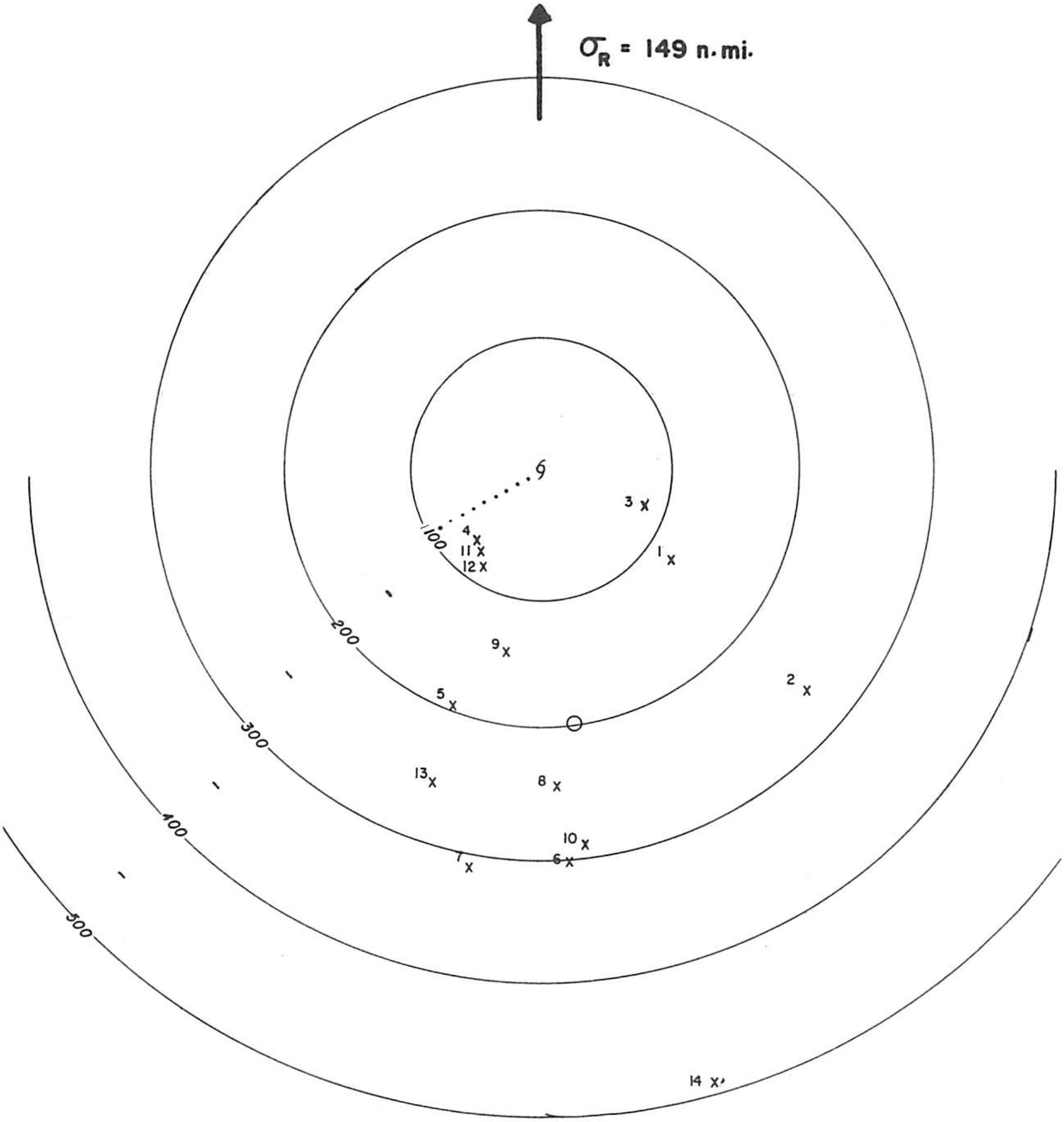


Fig. 21. BAROTROPIC 24-HR FORECASTS OF VORTICITY MAX (CORRECTED). Center of diagram is actual storm position. Numbers identify forecasts (See Table I). Open circle: mean of forecast positions.

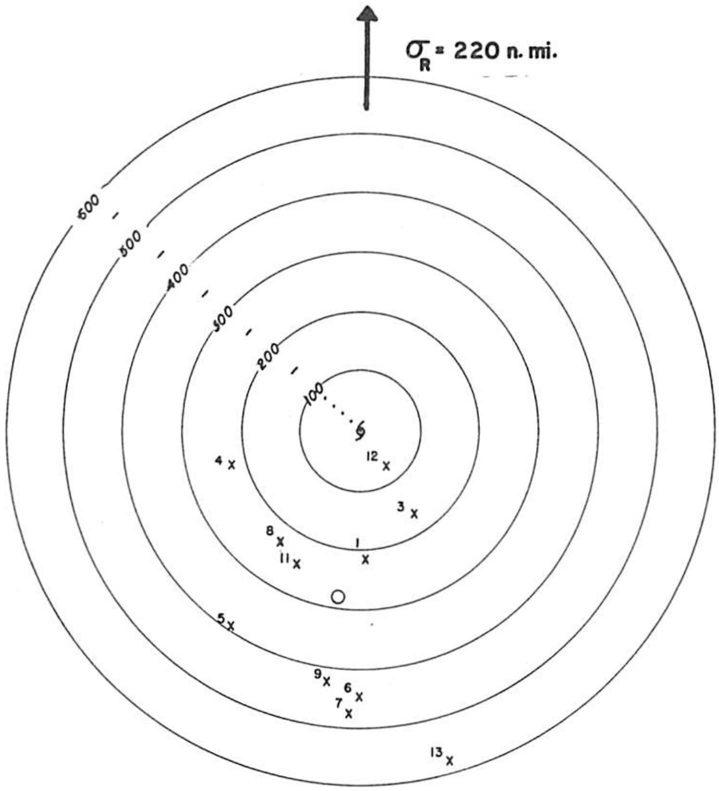


Fig. 22. BAROTROPIC 48-HR FORECASTS OF VORTICITY MAX (CORRECTED). Center of diagram is actual storm position. Numbers identify forecasts (See Table I). Open circle: mean of forecast positions.

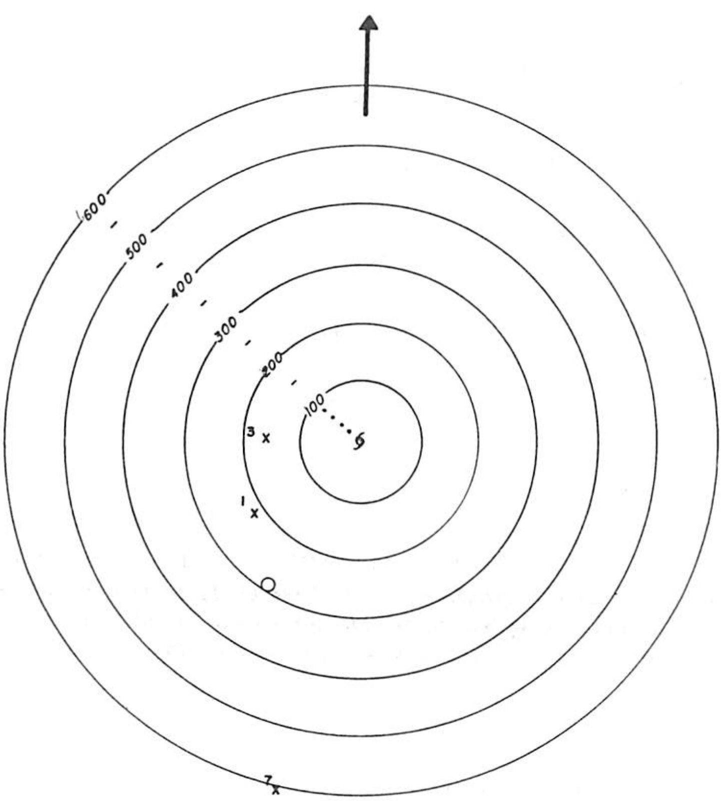


Fig. 23. BAROTROPIC 72-HR FORECASTS OF VORTICITY MAX (CORRECTED). Center of diagram is actual storm position. Numbers identify forecasts (See Table I). Open circle: mean of forecast positions.

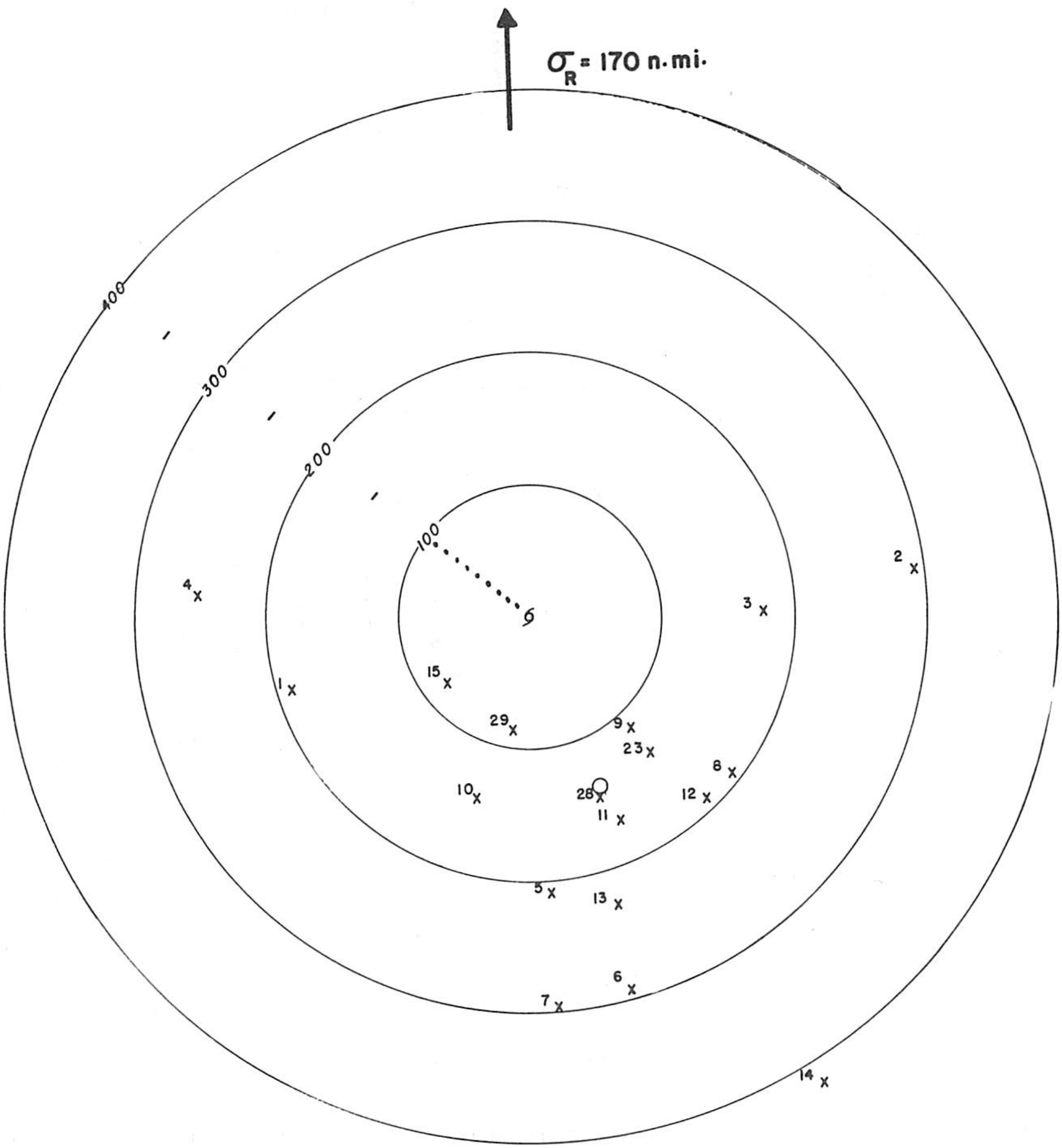


Fig. 24. BAROTROPIC 24-HR FORECASTS BY MOVABLE GRID. Center of diagram is actual storm position. Numbers identify forecasts. (See Table I). Open circle: mean of forecast positions.

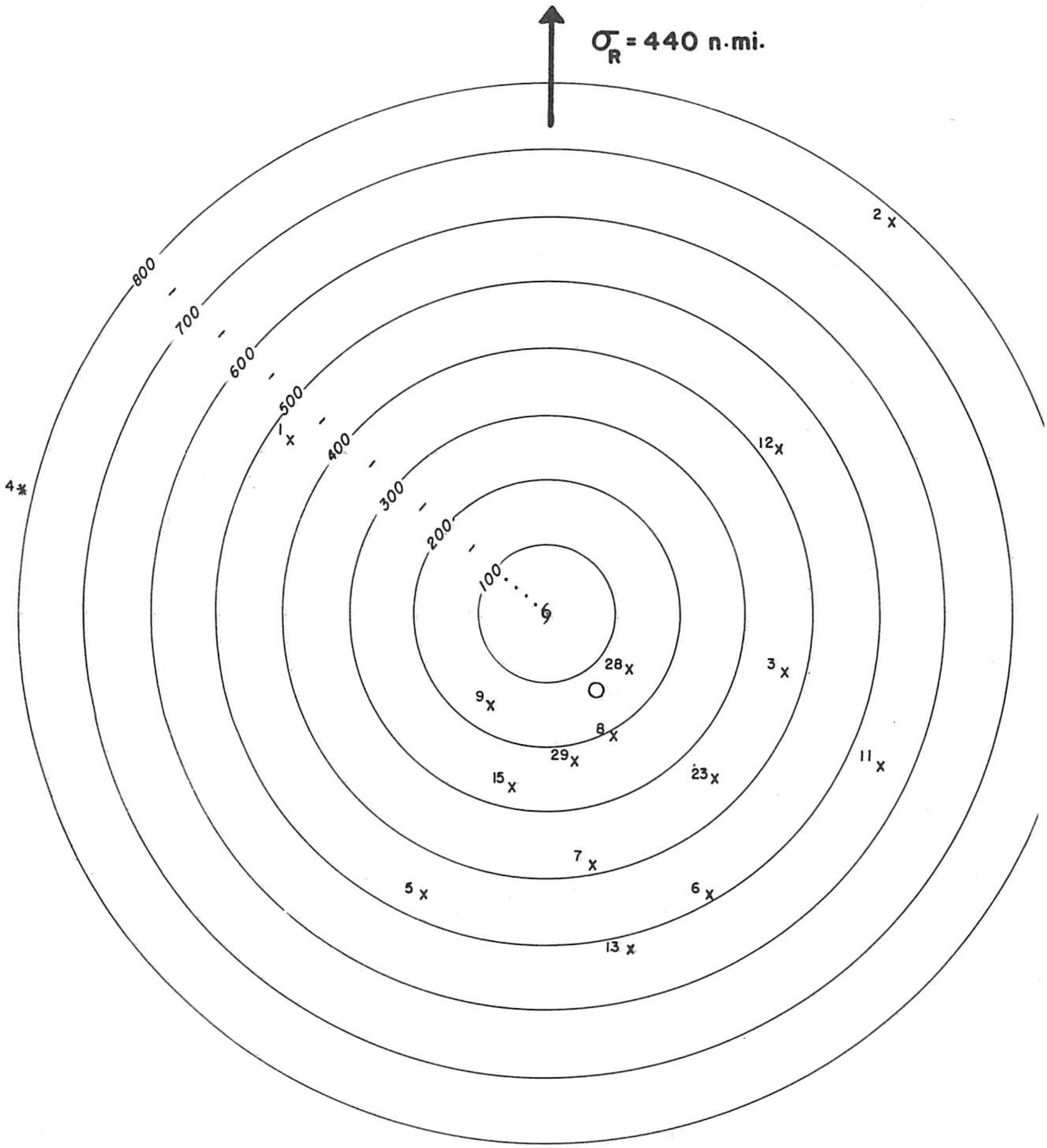


Fig. 25. BAROTROPIC 48-HR FORECASTS BY MOVABLE GRID. Center of diagram is actual storm position. Numbers identify forecasts (See Table I). Open circle: mean of forecast positions.

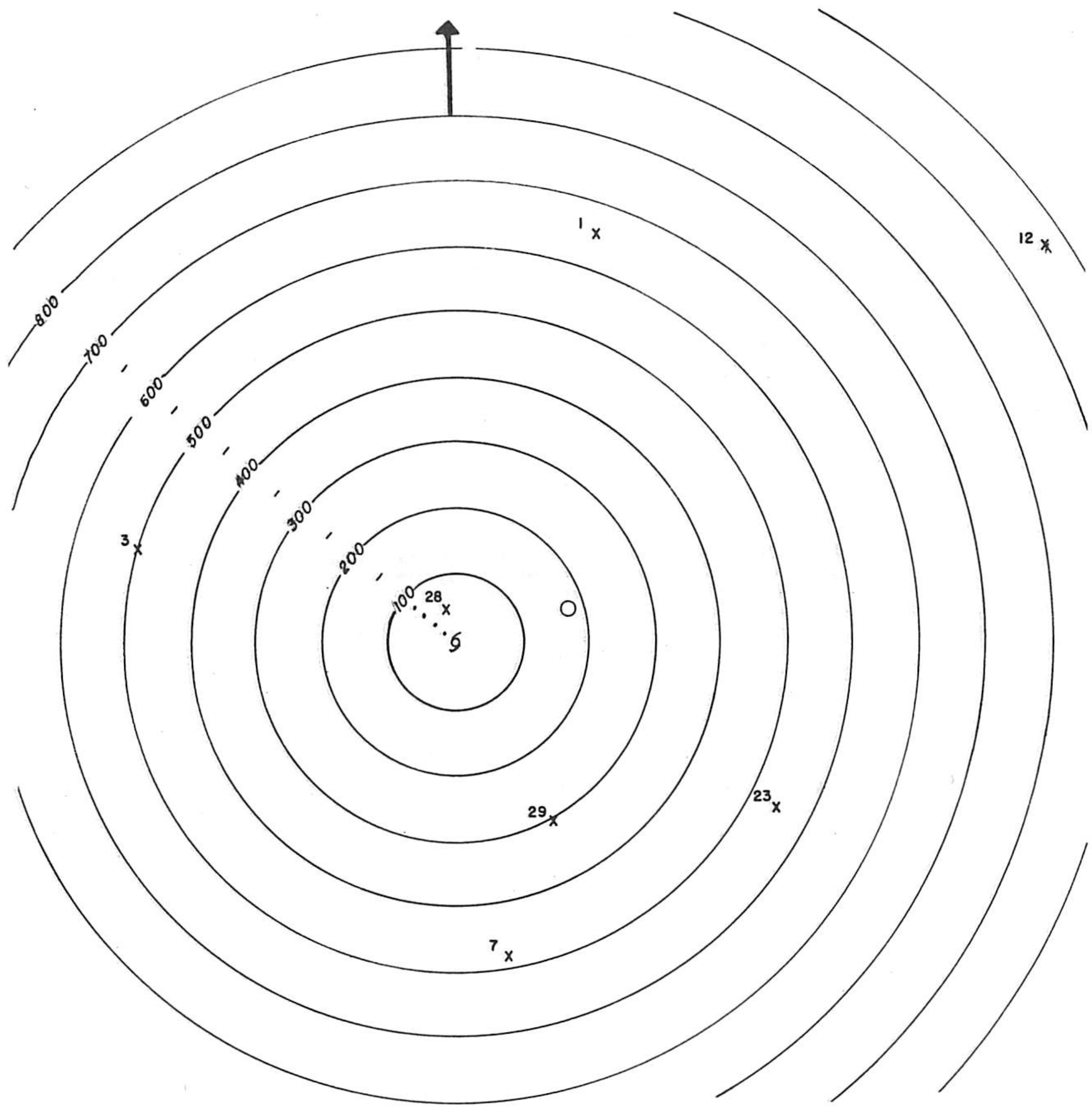


Fig. 26. BAROTROPIC 72-HR FORECASTS BY MOVABLE GRID. Center of diagram is actual storm position. Numbers identify forecasts (See Table I). Open circle: mean of forecast positions.

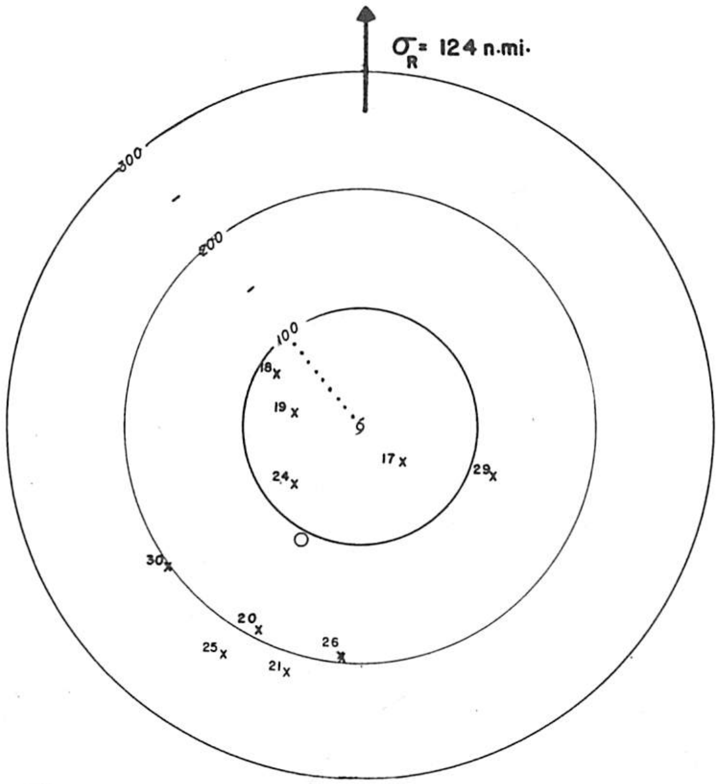


Fig. 27. BAROCLINIC 24-HR FORECASTS OF 500-MB LOW. Center of diagram is actual storm position. Numbers identify forecasts (See Table I). Open circle: mean of forecast positions.

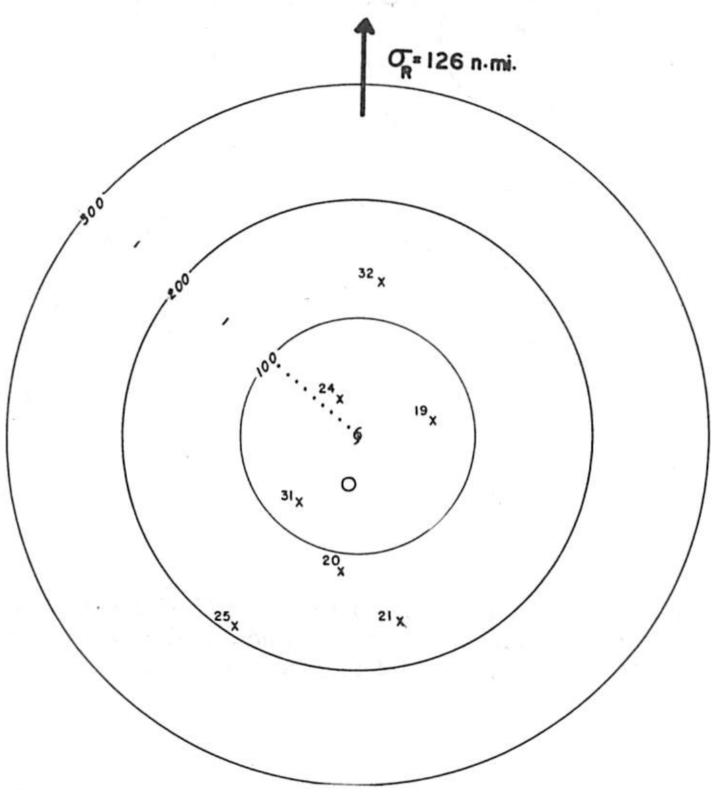


Fig. 28. BAROCLINIC 24-HR FORECASTS BY MOVABLE GRID. Center of diagram is actual storm position. Numbers identify forecasts (See Table I). Open circle: mean of forecast positions.

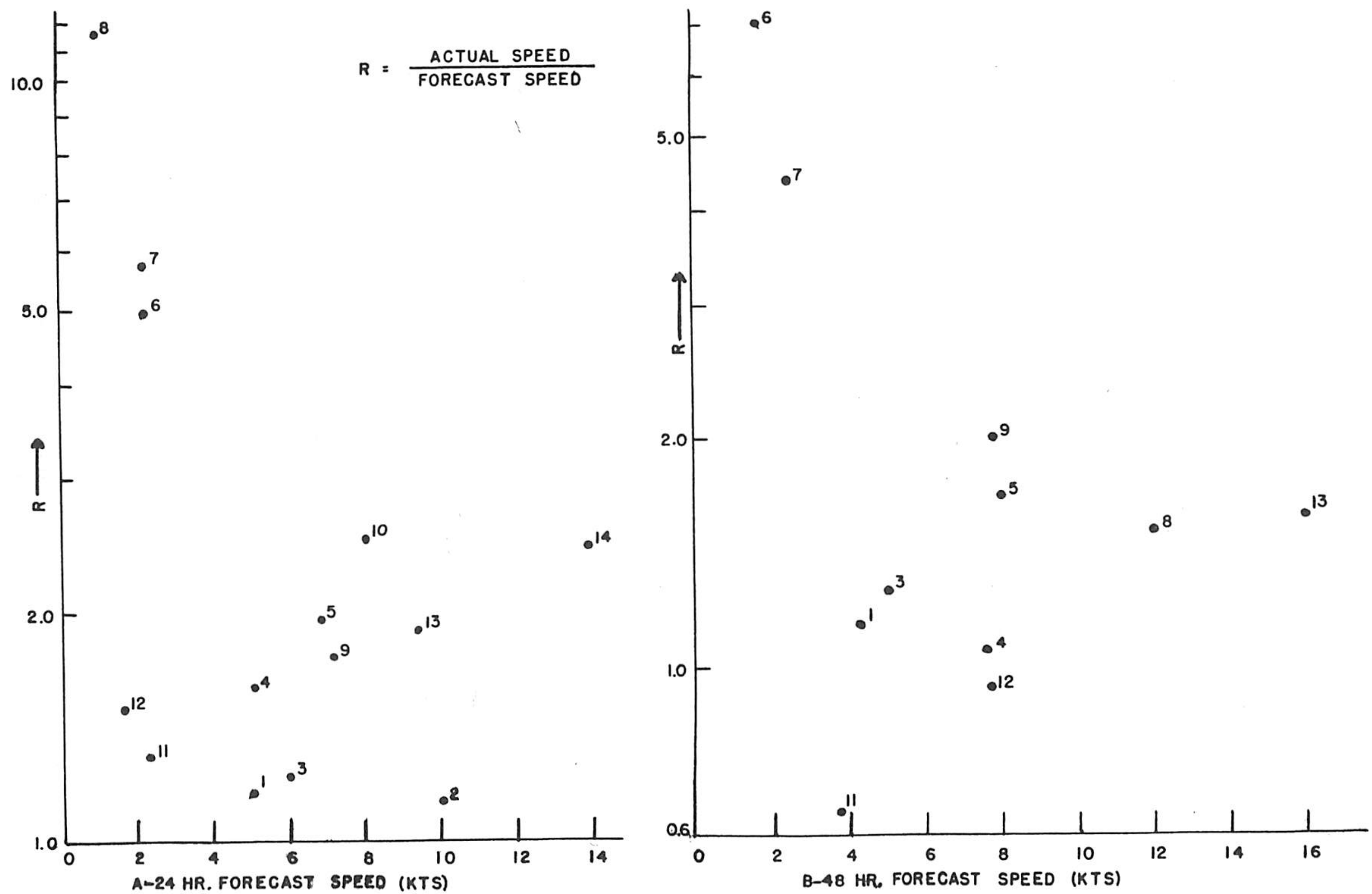


Fig. 29. Ratio of actual to forecast speed as function of forecast speed of vorticity maxima (corrected).