A NUMERICAL SCHEME FOR THE PREDICTION OF HURRICANE AND TYPHOON MOVEMENT[1,2]

By Robert J. Renard

Department of Meteorology and Oceanography
Naval Postgraduate School
Monterey, California

Progress Report #1, 1967: Project Order 7-002, Jun 67
Navy Weather Research Facility
Norfolk, Virginia 23511

December 1967

---

[1] Modified version presented at the IUGG-AMS Fifth Technical Conference on Hurricanes and Tropical Meteorology, November 20-28, 1967, Caracas, Venezuela.

[2] Submitted to Monthly Weather Review for publication.

58

A NUMERICAL SCHEME FOR THE PREDICTION OF HURRICANE AND TYPHOON MOVEMENT

by

Robert J. Renard
Department of Meteorology and Oceanography
Naval Postgraduate School
Monterey, California

ABSTRACT

The vector motion of severe tropical cyclones (including storm, hurricane/typhoon stages) is forecasted by a numerical scheme which involves two steps:

a. Numerical geostrophic steering of the center of the cyclone using the U.S. Navy Fleet Numerical Weather Facility's (FNWF) operationally-produced smoothed isobaric height fields, called SR. The tropical perturbations are steered in one-hour time steps up to 72 hours, using winds derived from the SR analysis dated closest to warning time. SR 500 mb. in the Pacific and SR 700 mb. in the Atlantic gave the most accurate forecasts on tests of ten northwest Pacific typhoons and all five north Atlantic tropical storms and hurricanes in the period 15 August-1 November 1965. Forecasts were made twice daily, 0600 and 1800 GMT, during this period using best-track information.

b. Next, the numerical-steering prediction is objectively modified to adjust for bias (i.e., deficiency in both zonal and meridonal motion) by utilizing errors made in the most recent 12- and 24-hour numerical-steering forecasts. Several modes of adjustment are employed; the most recent 12-(12- and 24-) hour numerical-steering bias yields the most accurate correction of subsequent Atlantic (Pacific) forecasts out to periods of 72 hours. The optimal Naval Postgraduate School (NPGS) technique produces forecast errors ranging from an average of 4.2 knots for 12-hour forecasts to 6.2 knots for 72-hour forecasts. The U.S. Navy's official forecast accuracy is excelled by the NPGS scheme for all time periods.

Stratification of error statistics by area, trajectory and stage of storm, intercomparison with ESSA's NHC-64 technique, discussion of merits and deficiencies of the research program relative to operational forecasts and current experiments at FNWF, are discussed.

TABLE OF CONTENTS

BLANK PAGE

A NUMERICAL SCHEME FOR THE PREDICTION OF HURRICANE AND TYPHOON MOVEMENT[1,2]

by

Robert J. Renard
Department of Meteorology and Oceanography
Naval Postgraduate School
Monterey, California

1. INTRODUCTION

The Statement on Hurricanes issued by the American Meteorological Society [1] indicates that the desired degree of accuracy in forecasting the position of severe tropical cyclones is 50 miles or less in a 24- to 36-hour period. Such verification figures are far from being realized at the present time as noted in recently published error statistics from the United States Fleet Weather Facility, Jacksonville, Florida [10], the United States Fleet Weather Central/Joint Typhoon Warning Center, Guam [8], the National Meteorological Center, Environmental Science Services Administration (ESSA) [11], and ESSA's National Hurricane Research Laboratory, Miami, Florida [4,5,6].

The official hurricane/typhoon forecast, based on a careful consideration of all the available and pertinent subjective and objective techniques, is becoming increasingly dependent on the competitive contributions from the numerical approach. Both the United States Navy's and ESSA's numerical techniques already exceed the accuracy of many of the forecast schemes used faithfully by operational forecasters for many years [8,10] and yet have potential for still greater improvement. Some of this potential has been realized recently by the development of a forecast scheme using certain numerically-analyzed operational products generated by the United States Navy's Fleet Numerical Weather Facility (FNWF), Monterey, California. When coupled with an objective adjustment, dependent only on the characteristics of the storm's recent trajectory, the numerical scheme appears to offer a substantial increase in the accuracy of predicting movement of tropical cyclones, as compared to official forecasts, for forecast intervals up to 72 hours. The subject research reported on here represents a

---

1. Modified version presented at the IUGG-AMS Fifth Technical Conference on Hurricanes and Tropical Meteorology, November 20-28, 1967, Caracas, Venezuela.
2. Submitted to Monthly Weather Review for publication.

coordinated effort of the Naval Postgraduate School (NPGS) and FNWF, Monterey, California.

2. THE NUMERICAL-STEERING PROGRAM

In addition to the analyses of heights of mandatory isobaric levels, FNWF operationally produces analyses of certain additive components of these height fields on a twice-daily basis, 0000GMT and 1200GMT [3]. This unique numerical program, as developed for FNWF by Holl [2], performs a mathematical smoothing of the isobaric height fields with the degree of smoothing dependent on the amplitude and wave length inherent in the isohyptic field. The arithmetic difference between the height field (Z) and the smoothed height field (Z_{SR}) is called the disturbance field (Z_{SD}). Thus, at any point on the isobaric surface $Z = Z_{SR} + Z_{SD}$. The Z_{SR} pattern may be viewed as a space-mean height field, portraying long wave features, while the Z_{SD} contours depict the short or minor wave components of the original isohypses. Accordingly, the Z_{SR} field, void of the disturbance flow to a certain degree, may be used to generate a current appropriate to the steering of tropical cyclones, which are regarded as the disturbance elements.

The foregoing interrelations between Z, Z_{SR} and Z_{SD} may be seen in figures 1a, b, and c, each of which portrays a portion of these isobaric height fields for 0000GMT, 20 August 1965. Z and Z_{SR} contours are at 60-meter intervals while Z_{SD} isolines are at a 30-meter interval. Plotted central values include the units figure. Isolines are labeled in tens of meters; the thousands figure is omitted on both the Z and Z_{SR} fields.

The nature of the decomposition analyses in the case of severe tropical cyclones may be noted from the situation just equatorward of Japan. Typhoon Lucy is located at 28.5°N, 140.2°E at map time according to the best track position [7]. Figure 1a shows that FNWF's 500-mb operational position of Lucy is very close to the best-track location with a central 500-mb height of 5806 meters. The SD field emphasizes the perturbation character of Lucy with a minimum value of -75 meters at the typhoon center. Thus, $Z - Z_{SD} = Z_{SR}$ or $5806 - (-75) = 5881$ meters, which may be verified from figure 1b.

Having selected a steering field, namely the SR, geostrophic winds are computed to yield the steering or basic current used to forecast the motion of the tropical cyclone centers. Figure 2 is a schematic diagram illustrating a section of the Z_{SR} field appropriate to the tropics with superimposed grid points representative of the FNWF linear I, J mesh. The numerical computation of the geostrophic steering wind is accomplished by first locating the tropical cyclone center to the nearest .1° latitude and longitude. This point is identified as I, J in figure 2. Next, geostrophic winds (V_{gSR}) are computed by I, J components and converted to latitude and longitude at each of the four points, I, J+1; I-1, J; I, J-1; and I+1, J. An average of the four geostrophic winds is used to steer the cyclone center for one hour. For each subsequent hour, up to 72 hours, the process is repeated.

The finite difference form of the geostrophic wind equation necessitated obtaining height information from a distance of two mesh lengths from the cyclone center in the cardinal I, J directions (i.e. at I, J+2; I-2, J; I, J-2; I+2, J). One mesh length, D, (as I, J to I+1, J) is 381 kms at 60° latitude, which reduces to about 305 km at 30° lat., 275 km at 20° lat., and 240 km at 10° lat.

A potential problem with the Coriolis parameter, used in geostrophic wind computations at low latitudes, was avoided by using a modified form of the sin function for latitudes less than 30° lat.:

$$\text{Mod } \sin \theta = 2[(.25 \sin \theta + .25)^2 + .25 \sin \theta)] \ .$$

The function is graphed in figure 3. The magnitude of mod sin θ ranges from .125 at 0° lat. to .53 at 30° lat. The lower limit, .125, is the value of the sin θ at 7.2°. Along with using an average geostrophic wind, as described above, the adjustment of the Coriolis parameter may be viewed as a further reduction of the steering wind relative to the true value at the position of the tropical cyclone center.

The steering section of the forecast program was written for operation on the Control Data Corporation's 1604 digital computer. Both NPGS and FNWF computers were utilized for these computations.

3. COMPOSITION OF THE TEST

Due to limited manpower and computer time, only those named North Pacific and North Atlantic tropical cyclones in existence during the period 15 August to 1 November 1965 were incorporated into the test. The sample included all 1965 Atlantic hurricanes and tropical storms (Anna, Betsy, Carol, Debbie, Elena) and ten Pacific typhoons (Lucy, Mary, Olive, Rose, Shirley, Trix, Virginia, Bess, Carmen and Della). Only 0600 and 1800 GMT best track positions, as given in [7] and [9] were used, except for hurricane Carol, in which case 0000 and 1200 GMT positions were employed. Cyclone-position forecasts, made in one-hour time steps, were printed out for each 12-hour forecast interval up to 48 hours and at 72 hours. Depression, tropical storm, hurricane/typhoon and extratropical stages were included if the position was listed in the annual summaries. For the Atlantic area, 79% of the forecasts were made during storm and hurricane stages, 13% from depression and 8% from extratropical stages. In the Pacific the vast majority, 98%, were from the storm/typhoon stages; the remainder, 2%, were depressions.

It is important to note that best-track cyclone positions were used in generating the forecasts up to 72 hours using geostrophic steering winds computed from a single SR analysis dated at best-track time plus six hours. Thus, in order to forecast the movement of a cyclone positioned at I, J (figure 2) at 0600 GMT (1800 GMT) the analyzed SR field for 1200 GMT (0000 GMT) was used. However, in the case of Carol, initial hurricane position and SR steering flow were for the same synoptic time.

Although a different combination of best-track time and time of numerical analysis may have been more operationally realistic the major effort to this point was directed toward establishing the feasibility of using the SR field to derive a steering current. In addition, initial efforts were concentrated on the 12-hour forecasts for which time-mean SR steering winds are appropriate. From an operational point of view the SR analyses used in the test may be regarded as "perfect" 12-hour SR prognostic fields initiated six hours before warning time. Using SR analyses rather than prognoses to derive the steering current has the advantage that the forecast errors do not include contributions from the deficiencies of a numerical prognostic model.

4. PRELIMINARY FINDINGS

Some of the preliminary findings which established the format for uniformly processing the forecast data to 72 hours is important and will be outlined here. The initial experiments were designed to provide answers to the following questions:

a) Which SR field(s) will generate the most accurate forecasts considering both Atlantic and Pacific areas, and

b) does the forecast accuracy deteriorate as the forecast interval is increased to 72 hours?

Table 1 indicates the average 12-hour forecast errors (in nautical miles) for each cyclone which resulted from applying the numerical steering program (section 2) to SR fields from several selected isobaric levels (1000, 700, 500, 200 mb) and layers (1000/500, 1000/200, 500/200 mb). The official forecast errors from [7] and [9] are also shown. In the case of the Pacific cyclones the overall-average official forecast error (70n.mi.) was derived from a linear extrapolation of published error data at 24, 48 and 72 hours. The number of forecasts made are shown in parentheses. Although a forecast for every 0600 and 1800 GMT best-track position given in [7] and [9] was attempted, missing or unretrievable SR data disallowed some cases, especially those involving 200-mb data. Superscripts "1" and "2" indicate the relative merits of the two SR fields yielding the most accurate 12-hour forecasts, for each named storm and for the overall average.

Following are pertinent conclusions to be drawn from table 1.

a. Considering both oceans collectively, SR 500 performed best (i.e. least forecast error), SR 700 second best and SR 1000/500 a close third.

b. In the Atlantic, on the average, SR 700 is best, followed by SR 1000 and SR 1000/500. The majority of individual cyclones (three out of five) behaved like the overall average.

c. In the Pacific, on the average, SR 500 is best, followed by SR 700 and SR 1000/500, each with similar results. The vast majority of storms (seven out of ten) behaved like the overall average.

d. SRs at the higher levels and layers (SR 200, SR 1000/200 and SR 500/200) generally yielded the poorest results.

e. Even considering the best numerical steering result for the Atlantic (SR 700) and Pacific (SR 500), the official forecast accuracy is superior by more than 10%.

In view of the good performance of SR 500 in both oceans this field was selected to test the feasibility of SR steering computations for forecast intervals out to 72 hours. Table 2 shows the result. Format of error data for this and most of the following tables is similar to table 1. Official 36-hour errors (from [7] and [9]) are linear extrapolations from published error data at 24, 48 and 72 hours in the Pacific and 12, 24, 48 and 72 hours in the Atlantic. Table 3 is offered as an aid in summarizing the results shown in table 2.

a. For each of the forecast-time intervals tested, official results excel the NPGS steering system, except for 72 hours in the Atlantic.

b. The forecast error, in nautical miles/hour of forecast interval, generally decreased or held steady with time for the NPGS system, while the official error figure increased or held steady with time.

c. In a relative sense, the NPGS scheme shows improvement compared to the official out to 72 hours, especially in the Atlantic. This may be seen from the calculations of NPGS-OFFICIAL errors at each forecast interval.

A consideration of the results shown in tables 1-3 suggested continued and more extensive experimentation with the steering technique. However, before embarking on further testing and possible modification of the numerical scheme for periods out to 72 hours, some further, but limited, checks on the apparent merits of SR 700 in the Atlantic and SR 500 in the Pacific were attempted.

Due to the favorable performance of both SR 500 and SR 700, considering both oceans, and similarly good behavior of these levels from other but related forecast techniques [6], the two levels were intercompared at other than the 12-hour forecast intervals.

Table 4 shows the relative merits of SR 700 and SR 500 for Atlantic forecasts up to a period of 72 hours. Error statistics are shown for all forecast data as well as for a homogeneous sample of forecast times. For example, 93 SR 700 and 89 SR 500 forecasts were possible for the 12-hour interval while a maximum of 87 forecast times were common to the SR 500 and SR 700 computations. Results indicate the excellence of the SR 700 forecasts out to 48 hours and SR 500 thereafter. The official forecast is superior to the optimal NPGS system in the Atlantic (i.e. SR 700) at 12 and 24 hours, while the official is worse than the optimal NPGS scheme at 72 hours. At 36 and 48 hours official and NPGS accuracy are nearly equivalent.

Testing of the relative worth of SR 700 and SR 500 in the Pacific was limited to 12 and 24 hours only (table 5). SR 500 maintained a lead in accuracy over SR 700 through 24 hours but, as in the Atlantic, official forecast accuracy surpassed the NPGS SR 500 geostrophic steering forecasts.

The preliminary findings displayed in tables 1-5 led to the decision to use SR 500 in the Pacific and SR 700 in the Atlantic, exclusively, for all subsequent testing of the numerical tropical cyclone steering scheme.

5. THE MODIFIED NPGS FORECAST SCHEME USING A CORRECTION FOR BIAS IN THE NUMERICAL STEERING COMPUTATION

A typical example of using the SR 700 geostrophic steering computation is shown in figure 4. The best track positions (from [9]) and the 24-hour forecast positions, using numerical steering only, denoted by F_{24}, are plotted for hurricane Elena. Numbered positions on the best track are at 12-hour intervals, starting with 1800 GMT 12 October 1965, which is labeled position "O". Corresponding numbers along the F_{24} forecast track refer to the same times as those on the best track. For example, "5" on the best track is the cyclone-center position for 0600 GMT 15 October 1965 while position "5" along F_{24} is the forecast cyclone-center position for the same time. 24-hour forecast position "5" was generated from best track position "3" at 0600 GMT 14 October 1965, using the SR 700 analysis at 1200 GMT 14 October 1965.

Figure 4 indicates that the forecast and best tracks are similar in shape but positions at given times are not identical. This feature, common to most hurricanes and typhoons considered in this research, may be described as a consistent deficiency in both zonal and meridional components of the numerical-steering forecast. Thus, the vector error between forecast and best-track positions represents a bias which may be used, with advantage, as a correction or modification to the subsequent numerical-steering forecasts.

Figure 5 schematically indicates the mechanics of applying one type of correction for the bias in the numerical steering forecast (F_{xx}). For this figure and in the discussion which follows the subscripts associated with T and F (as, -12, 0, 12, 24, etc.) refer to time before or after "0", where "0" is the time at which the forecast in question is made (i.e. warning time). The solid lines connect best-track positions for -24, -12, 0 and 24 hours, while F_o and F_{24} indicate the 24-hour numerical forecast positions. $\vec{E}_{24}$ is the vector error of the 24-hour forecast made from the T_{-24} position. This forecast error, known at time "0", is then employed as a correction to the 24-hour forecast made at time "0". Such a procedure generates modified numerical forecast positions, as F_{24}^{24} in figure 5. The superscripts on F, as used in figure 5, and in the text, figures and tables which follow refer to the forecast interval from which the correction for numerical-forecast bias was selected. Hence, superscript "24" refers to use of the most recent 24-hour numerical forecast error as a correction to the numerical steering forecast made at time "0". Applied to a 48-hour forecast, the scheme symbolized in figure 5 yields a modified forecast position designated F_{48}^{48}. It is to be noted that as the forecast interval increases so does the necessary time lag for application increase. Thus, in order to make a modified 72-hour forecast one 72-hour forecast period must pass before $\vec{E}_{72}$ is known. This limits quite severely the totality of application in the forecasting of tropical cyclones.

In view of the difficulty just mentioned a scheme similar to that shown in figure 5 was developed, but in this case only the most recent 12-hour numerical forecast errors were used, regardless of forecast interval. Figure 6 shows a modified 24-hour forecast made at time "0" employing numerical steering, F_{24}, plus a correction for bias, $2\vec{E}_{12}$. The modified-forecast position is designated F_{24}^{12}. When applied to a 48-hour (72-hour) forecast the modified-forecast position is F_{48}^{12} (F_{72}^{12}) and $4\vec{E}_{12}$ ($6\vec{E}_{12}$) is the appropriate vector correction for bias.

The two modes of modifications just outlined are applied to 24-hour forecasts of Elena and are shown in figure 7. It is obvious that the modified forecasts result in cyclone-position forecasts superior to F_{24} with the F_{24}^{12} scheme best.

For forecast intervals beyond 12 and 24 hours two other modification schemes, involving the bias correction, were used. Figures 8 and 9 indicate these modes as applied to 36-hour forecasts made at time "0". The scheme in figure 8 is exactly like that in figure 6 only 24- rather than 12-hour values of $\vec{E}$ are employed. Figure 9 shows a scheme for which the most recent 12- and 24-hour numerical forecast errors are used, the former weighted twice that of the latter.

Examples of the type of modifications portrayed in figures 8 and 9 are shown in figure 10 for 48-hour forecasts of typhoon Carmen. Though not entirely obvious at this point the F_{48}^{24} system gives the optimal forecast track for Carmen.

Each one of the adjustment schemes described in figures 5, 6, 8 and 9 was applied to each Pacific typhoon for every possible 0600 and 1800 GMT forecast time while application to Atlantic tropical storms and hurricanes was somewhat more limited. Tables 6 to 16 give the basic results using SR 500 in the Pacific and SR 700 in the Atlantic. Wherever possible, averages for homogeneous sets of forecast data are shown. In the case of official forecasts, such comparisons are limited due to different forecast times in the Atlantic (04, 10, 16, 22 GMT) and the availability of individual official forecasts for 24 and 48 hours only in the Pacific. Various aspects of these error statistics are summarized below:

12 hours: Atlantic (table 6): The modified forecasts (F_{12}^{12}) represent a 48% improvement over the F_{12} forecasts as well as significantly excelling the accuracy of the official forecasts. This is true for the overall average and for each individual storm.

Pacific (table 7): The situation in the Pacific is similar to the Atlantic with F_{12}^{12} representing a 34% improvement relative to F_{12} and a 23% increase in accuracy over the estimated official-forecast score.

24 hours: Atlantic (table 8): The 12-hour numerical-steering forecast bias is most significant for the 24-hour forecast, a not unexpected result in view of the relation of F_{12}^{12} to F_{12}. Again the official-forecast error is considerably greater than that of the NPGS optimal scheme, namely F_{24}^{12}.

Pacific (table 9): Unlike the Atlantic, application of the 24-hour bias correction yields the optimal scheme, F_{24}^{24}, with the official forecast error, 150 n.mi., again in considerable excess of the 108 n.mi. error for a homogeneous sample of 61 F_{24}^{24} forecasts. Every cyclone, except Rose, shows the F_{24}^{24} error less than the official figure.

36 hours: Atlantic (table 10): Although all three schemes equal or surpass the extrapolated official forecast accuracy, F_{36}^{12} is optimum, again emphasizing the importance of the most recent history. Anna provides a minor exception to this trend.

Pacific (table 11): The importance of the 24-hour forecast to the modified 36-hour forecasts is seen from the performance of F_{36}^{24} with an average error of 170 n.mi. (63 cases) compared to 225 n.mi. for the official forecasts.

48 hours: Atlantic (table 12): At this point in the range of forecast intervals considered, a correction for bias taken from the same interval as the forecast (i.e. 48 hours) is detrimental. That is, the errors using F_{48}^{48} are greater than for F_{48}. The F_{xx}^{12} scheme continues to be best while the official and optimal NPGS schemes are producing results quantitatively more similar than for shorter forecast periods.

Pacific (table 13): The Pacific sample continues to behave differently than the Atlantic with the most complex modification, $F_{48}^{12,24}$, yielding the best forecast accuracy, although all four types of bias corrections improve upon F_{48}. The official forecast continues to be excelled by the optimal NPGS scheme.

72 hours: Atlantic (table 14): Comments for the Atlantic at 48-hours are true for the 72-hour forecast interval as well except that bias corrections of any type considered did not improve upon F_{72}. However, official-forecast accuracy is still surpassed, namely by F_{72}.

Pacific (table 15): This is the most difficult table to interpret since the averages for non-homogeneous sets of forecast data suggest $F_{72}^{12,24}$ is best while the homogeneous sets of data indicates F_{72}^{24} is optimum. But, since the number of cases is relatively small for the homogeneous sets, the latter figures cannot be regarded as significant.

Summarizing information for tables 6-15 is shown in table 16. The forecast error per unit of time, using the optimal NPGS scheme, increases with time, particularly so in the Atlantic. However, the NPGS system always surpasses the official forecast accuracy although the ratio generally decreases with increasing time. In addition, table 16 gives information on the distribution of NPGS forecast errors, using the optimal scheme. In the Atlantic, on the average, about 2/3 (1/2) of the forecast errors lie within 3 kts. of the average forecast error through 36 (for 48 and 72) hours. The dispersion of errors is considerably less in the Pacific where 3/4 (2/3) represents the corresponding number of cases for 12, 24 and 36 (48 and 72) hours. Considering both oceans, the remaining 1/3 of the cases are about evenly distributed between the very large (greater than average plus 3 knots) and very small (less than average minus 3 knots) forecast errors. It is also evident from the listing of optimal schemes that the short-term peculiarities (i.e. 12, 24 hours) in cyclone trajectories have long-term application (up to 72 hours) in the modified forecast procedure.

Figures 11 and 12 show Atlantic and Pacific examples of forecasts to 72 hours, each made from a given synoptic time. The best track, the NPGS numerical-steering forecast track (F_{xx}) and the optimal NPGS forecast track (F^{opt}_{xxx}) are shown for the two cases portrayed. Additionally, the available official-forecast positions are indicated. The inadequacy of the numerical-steering forecast relative to the modified forecast is clearly indicated in both the Debbie and Rose figures. The reasonable continuity of successive forecast positions, 12 to 72 hours, using the optimal scheme is evident. The extreme disparity which may occur between the official and the modified numerical schemes is also shown in the case of Debbie.

6. NHC-64 vs NPGS OPTIMAL FORECAST SCHEME

A further evaluation of the NPGS forecast errors was made through an intercomparison with the NHC-64 statistical technique [4,5,6] as developed by the National Hurricane Research Laboratory, Miami, Florida. Table 17 shows results for 12-, 24-, 36- and 48-hour forecasts. Since the NHC-64 forecasts were made at 0000 and 1200 GMT, an average of the errors from 0600 and 1800 GMT optimal NPGS forecasts were compared to each NHC-64 forecast considered. This is the closest approach to homogeneity that could be made here. Carol is an exception, since 0000 and 1200 GMT NPGS forecasts were computed making this storm's sample truly homogeneous with the NHC-64 cases. Average errors indicate the NPGS optimal scheme excelled NHC-64 for 12 and 24 hours while the latter surpassed the former at 48 hours, although even here two out of three storms representing 50% of the forecasts favor the NPGS scheme. 36-hour statistics yield inconclusive results. 72-hour forecasts were not available from Miami. For Carol, whose forecast times exactly matched those of NHC-64, the results show the NPGS scheme to be an improvement over NHC-64 at all forecast intervals.

7. STRATIFICATION OF ERROR STATISTICS BY AREA, TRACK AND STORM STAGE

Atlantic: The Atlantic area was divided into three zones, A, B, and C, in accordance with a similar division used by the NHC group at Miami [6]. See figure 13. Area A represents the Atlantic area generally east of 60°W.; while B covers the Caribbean, Gulf of Mexico and Atlantic areas south of

30°N, and north and west of 60°W. C encompasses the eastern United States and ocean areas immediately to the east which are north of 30°N.

Table 18 shows the predominance of cyclone positions in areas A and B and the superiority of optimal NPGS forecast accuracy in the latter compared to A and C for all forecast time intervals. In the case of 72-hour forecasts, errors in areas A and C, collectively, average about 100% greater than those in area B. Such statistics compare well with findings by Tracy [6] using the NHC-64 technique.

The distribution of forecast errors relative to path is also quite interesting. Without exception, forecast errors are less for all forecast intervals for cyclone stages before the time of recurvature. After-recurvature areas for the storm/hurricane stages are most frequently in C and northern sections of A as shown in [9].

The interrelationship of area and path are also manifest in the error statistics relative to cyclone stage. Table 18 indicates that, collectively, the intensifying tropical depression (TD dev) and tropical storm (TS) are associated with the most reliable results when using the optimal NPGS scheme. These stages are generally before recurvature and in area B or southwestern A. Hurricane (H) statistics are next best, partly due to inclusion of some after-recurvature cases in areas A and C. The extratropical (EXT) and dissipating tropical depression TD(dis) stages should be combined as case histories in [9] lead to the conclusion that the differences between the two stages are quite tenuous. All in all EXT and TD(dis) categories perform poorest and represent after-recurvature cases in area A for the most part.

Pacific: Table 19 for Pacific typhoons shows the breakdown by path only. Area analysis has not received the same focus as in the Atlantic and analysis by stage from published 1965 storm data [7] does not discriminate sufficiently between cyclone categories to warrant analysis like that presented for the Atlantic. Before recurvature, error values are much less than the overall average official errors while after recurvature the optimal NPGS errors jump by as much as 100%. These results closely parallel the Atlantic.

8. CONCLUSIONS

The NPGS scheme for forecasting tracks of tropical storms, hurricanes and typhoons is objective, numerical, easy to apply and readily adaptable to field use. The errors for forecast intervals up to 72 hours are consistently below those from most other well known subjective and objective techniques.

Part of the success of the NPGS scheme in relation to the official and NHC-64 forecasts may be ascribed to the following.

a. Best-track vice operational-track positions were used as initial cyclone locations from which NPGS forecasts were generated, while the operational positions are germane to the official and NHC-64 statistics. However, all three techniques used best-track data for verifications. Thirteen miles is the average difference between aircraft reconnaissance and best-track locations in the Pacific in 1965 [7]. Such a difference represents a range from about 25% to 4% of the magnitudes of the forecast errors for periods from 12 to 72 hours, respectively. This factor does not appear to change the conclusions cited to this point.

b. Perhaps more serious than (a) above is the following. In the case of JTWC/FWC Guam the operational positions at forecast times (0600 and 1800 GMT) are determined by three- to twelve-hour forecasts from fixes determined by recent land radar and/or aircraft reconnaissance observations or by surface upper air analyses. Such a procedure puts the official forecast at a disadvantage compared to the research program used here. The magnitude of the disadvantage is difficult to assess.

c. As noted in Section 3, SR analyses, six hours after initial time, were used to forecast cyclone tracks out to 72 hours. This is not operationally realistic and may have contributed somewhat to the success of the NPGS scheme, particularly in the short-period forecasts as 12 and 24 hours.

Balancing the scale in favor of the relative merits of the NPGS scheme is the recent operational experience of JTWC/FWC Guam. In the summer of 1967 FNWF began an experimental numerical tropical cyclone steering program which utilizes the SR fields in essentially the same way as the research program outlined here. The movement forecasts are produced separately from SR analyses and prognostic fields. Guam has used these numerical steering forecasts along with corrections for bias in the manner just described. Preliminary indications suggest that the accuracy of 24-hour forecasts, accomplished under operational real-time conditions is commensurate with that shown in this paper, as performed under a post-season research environment.[3] Definite statements on this matter await extensive post-season analysis.

9. FINAL REMARKS AND AVENUES FOR FURTHER RESEARCH

The merits of the bias correction are derived from the information content inherent in the recent behavior of the storm relative to the numerical scheme used to predict it. This is a simple, however unique, application of continuity. As such, the correction for bias using SR analyses only may be viewed as serving one or more of the following purposes. It compensates for (a) the use of an improper steering field and/or derived current, and/or (b) the use of an inappropriate level or layer in the SR steering field and/or (c) erroneous information in the particular SR field selected as the steering medium, and/or (d) changes with time in the SR steering field. The last point is tantamount to stating that the correction for bias, especially at increasing forecast intervals, substitutes for movement and development in the SR steering current, but, of course, with lag. Since prognostic fields are imperfect, especially in the tropics, the procedure of using a bias correction to approximate changes in the SR field may be preferable. Experiments are being conducted at both the FNWF and the NPGS to determine the merits and deficiencies of using SR analyses only or SR analyses and prognoses in combination, to generate forecasts of tropical-cyclone movement. Perhaps the temporal deterioration of the information content in the initial SR analyses suggests using a relatively reliable short period SR prognostic field, as the 36-hour, for cyclone forecasts from 36 to 72 hours.

---

[3] Private communication with personnel at JTWC/FWC Guam

More directly, a consistent bias in the numerical steering program strongly suggests tuning the steering field or its derived current to the movement of tropical cyclones. In other words, changes may be made to the mathematical smoothing program to allow increased meridional steering components as well as magnification of the basic zonal current.

Further, utilizing the geostrophic SR wind at the point of the storm center instead of a mean geostrophic wind from the area surrounding the storm is likely to give some increase in the steering values. Such a modification is already a part of the present FNWF experimental tropical-cyclone steering program.

The possible modifications of the numerical forecast procedure according to storm stage, path, area, latitude, season, etc., are almost limitless. Given what appears to be a suitable numerical steering environment, namely SR, various statistical adjustments may now be derived to reduce the errors, especially after recurvature, during the dissipating stage and in east-ocean areas.

ACKNOWLEDGEMENTS

As with any research endeavor many individuals have contributed much. In the early stages of the program LCDR R. E. Hughes, then of FNWF, provided considerable incentive for the project. Navy LTS J. E. Kerr and J. S. Hardie, then students at the NPGS, wrote the numerical programs and carried out many phases of the evaluation. More recently, Navy LCDRS S. R. Graham and D. B. Fickenscher and Miss Joan Felder furthered the testing through application of various bias corrections. CAPT P. M. Wolff, FNWF, and members of his staff, especially LTJG G. A. Brearton and Mr. T. S. Hesse, provided the numerical fields, consulted on programming and application and generally aided in advancing the research to this reporting point. Dr. R. C. Gentry, NHC, Miami, kindly supplied NHC-64 data for comparison. Last but not least, the Naval Weather Research Facility, Norfolk, Va., financially and morally supported the project throughout its entirety.

REFERENCES

1. American Meteorological Society, "Statement on Hurricanes," Bulletin of the American Meteorological Society, vol. 44, No. 7, July 1963, pp. 443-444.
2. M.M. Holl, "Scale-and-Pattern Spectra and Decompositions," Technical Memorandum No. 3, Meteorology International, Monterey, California, November 1963, 28 pp.
3. R.E. Hughes, "Computer Products Manual," Technical Note No. 21, Fleet Numerical Weather Facility, Monterey, California, July 1966, 310 pp.
4. B.I. Miller and P.P. Chase, "Prediction of Hurricane Motion by Statistical Methods," Monthly Weather Review, Vol. 94, No. 6, June 1966, pp. 399-406.
5. B.I. Miller and R.C. Gentry, "Prediction of Hurricane Movement," AWS Technical Report 196, Proceedings of the Technical Exchange Conference, 4-7 April 1967, AWS(MAC), U.S. Air Force, July 1967, pp. 215-223.
6. J.D. Tracy, "Accuracy of Atlantic Tropical Cyclone Forecasts," Monthly Weather Review, Vol. 94, No. 6, June 1966, pp. 407-418.
7. United States Fleet Weather Central/Joint Typhoon Warning Center, Annual Typhoon Report, 1965, Guam, Marianas Islands, 1965, 258 pp.
8. United States Fleet Weather Central/Joint Typhoon Warning Center, Annual Typhoon Report, 1966, Guam, Marianas Islands, 1966, 268 pp.
9. United States Fleet Weather Facility, Annual Tropical Storm Report, 1965, Jacksonville, Florida, 1965, 73 pp.
10. United States Fleet Weather Facility, Annual Tropical Storm Report, 1966, Jacksonville, Florida, 1966, 128 pp.
11. L.W. Vanderman, "Summary of Verification of Numerical Operational Tropical Cyclone Forecast Tracks for 1965," Technical Note 37-NMC-36, National Meteorological Center, Weather Bureau, ESSA, U.S. Dept. of Commerce, Washington, D.C., March 1966, 6 pp.

TABLE 1.-1965 - 12-HOUR FORECAST ERRORS in Nautical Miles. Number of Forecasts in Parentheses.

	Official	SR 1000	SR 700	SR 500	SR 200	SR 1000/500	SR 1000/200	SR 500/200
Hurricanes:								
Anna	119 (6)	60^1(8)	70^2(8)	82 (6)	---	98 (6)	---	---
Betsy	67 (57)	78^2(29)	74^1(32)	83 (29)	168 (32)	96 (28)	142 (29)	172 (29)
Carol	105 (38)	93^1(31)	94^2(30)	127 (31)	290 (31)	101 (31)	143 (31)	171 (31)
Debbie	65 (16)	58^2(10)	54^1(9)	89 (10)	209 (10)	90 (10)	167 (10)	196 (10)
Elena	114 (20)	215 (13)	170^1(14)	194^2(13)	306 (13)	197 (13)	217 (13)	254 (13)
Average	86(137)	99^2(91)	93^1(93)	115 (89)	238 (86)	112 (88)	157 (83)	187 (83)
Typhoons:								
Lucy		53^1(16)	98 (16)	84^2(12)	---	134 (11)	---	---
Mary		44^2 (8)	55 (8)	28^1(7)	---	65 (7)	---	---
Olive		72^2 (6)	77 (8)	61^1(6)	115 (9)	81 (6)	122 (6)	139 (6)
Rose		140 (10)	117 (9)	34^1(9)	356 (9)	78^2(9)	168 (9)	234 (9)
Shirley		140 (13)	131 (13)	122^1(13)	146 (13)	130^2(13)	132 (13)	134 (13)
Trix		134 (14)	108 (15)	97 (14)	92^2(14)	101 (14)	81^1(14)	111 (14)
Virginia		146 (6)	108^2(7)	104^1(6)	181 (6)	133 (6)	192 (6)	261 (6)
Bess		123 (14)	81^2(12)	84 (14)	138 (14)	75^1(14)	130 (14)	132 (14)
Carmen		131 (17)	103 (16)	67^1(17)	95 (14)	86^2(17)	89 (14)	93 (14)
Della		130 (12)	100^2(13)	85^1(12)	136 (12)	118 (12)	134 (12)	129 (12)
Average	70	113 (116)	100^2(117)	80^1(110)	147 (91)	100^2(109)	124 (88)	142 (88)

TABLE 2. - 1965 - SR 500 FORECAST ERRORS in Nautical Miles. Number of forecasts in parentheses.

	12 HOUR		24 HOUR		36 HOUR		48 HOUR		72 HOUR	
Hurricanes	SR	OFFICIAL	SR	OFFICIAL	SR	OFFICIAL	SR	OFFICIAL	SR	OFFICIAL
Anna	82 (6)	119 (6)	149 (5)	217 (4)	234 (4)		322 (3)	-	-	-
Betsy	83 (29)	67 (57)	157 (28)	130 (56)	231 (27)		308 (26)	273 (52)	463 (24)	469 (48)
Carol	127 (31)	105 (38)	181 (30)	192 (40)	266 (29)		352 (28)	355 (36)	514 (26)	448 (32)
Debbie	89 (10)	65 (16)	149 (9)	135 (14)	220 (8)		287 (7)	310 (8)	390 (5)	512 (6)
Elena	194 (13)	114 (20)	353 (12)	260 (20)	493 (11)		510 (10)	581 (16)	705 (8)	1104 (12)
Average	115 (89)	86(137)	192 (84)	171(134)	279 (79)	260	351 (74)	346(112)	509 (63,	543 (98)
Typhoons:										
Lucy	84 (12)		216 (11)	169 (29)	318 (10)		370 (11)	329 (25)	526 (9)	481 (19)
Mary	28 (7)		111 (6)	107 (14)	187 (5)		293 (4)	154 (10)	437 (3)	170 (5)
Olive	61 (6)		130 (5)	138 (17)	-		313 (3)	284 (13)	548 (2)	449 (9)
Rose	34 (9)		139 (8)	55 (15)	199 (7)		254 (6)	127 (11)	453 (4)	245 (3)
Shirley	122 (13)		231 (12)	231 (16)	335 (11)		425 (10)	589 (12)	591 (8)	871 (3)
Trix	97 (14)		187 (13)	138 (27)	275 (12)		348 (11)	302 (23)	401 (9)	426 (18)
Virginia	104 (6)		201 (5)	289 (11)	318 (4)		418 (3)	615 (7)	786 (2)	1055 (3)
Bess	84 (14)		120 (13)	106 (26)	173 (12)		229 (11)	256 (22)	360 (9)	401 (16)
Carmen	67 (17)		157 (16)	148 (21)	223 (15)		307 (14)	238 (15)	441 (12)	289 (11)
Della	85 (12)		197 (11)	152 (23)	286 (9)		366 (9)	277 (17)	550 (6)	484 (11)
	80(110)	70	173(100)	148(199)	256 (85)	225	331 (82)	304(155)	480 (64)	440 (98)

TABLE 3. - 1965 - SR 500 FORECAST ERRORS in nautical miles per hour of forecast interval

Forecast Interval (hrs):		12	24	36	48	72
Hurricanes	NPGS	9.6	8.0	7.8	7.3	7.1
	OFF	7.2	7.1	7.2	7.2	7.5
	NPGS-OFF	2.4	0.9	0.6	0.1	-0.4
Typhoons:	NPGS	6.7	7.2	7.1	6.9	6.7
	OFF	5.8	6.2	6.2	6.3	6.1
	NPGS-OFF	0.9	1.0	0.9	0.6	0.6

TABLE 4. - 1965 SR 700 FORECAST ERRORS in nautical miles.
Number of forecasts in parentheses

Hurricanes	12 Hour	24 Hour	36 Hour	48 Hour	72 Hour
Anna	70(8)	127(7)	189(6)	284(5)	524(3)
Betsy	74(32)	141(31)	205(30)	273(29)	399(27)
Carol	94(30)	183(29)	276(28)	363(28)	561(26)
Debbie	54(9)	112(9)	173(8)	220(7)	261(5)
Elena	170(14)	328(13)	471(12)	595(11)	857(9)
SR 700 Average	93(93)	178(89)	262(84)	345(80)	514(70)
	95(87)	183(83)	270(78)	348(74)	516(63)
SR 500 Average	115(89)	192(84)	279(79)	351(74)	509(63)
	114(87)	191(83)	279(78)		
Official Average	86(137	171(134)	260	346(112)	543(98)

TABLE 5. - 1965 SR 500 FORECAST ERRORS in nautical miles.
Number of forecasts in parentheses

Typhoons	12 Hour	24 Hour
Lucy	84(12)	216(11)
Mary	28(7)	111(6)
Olive	61(6)	130(5)
Rose	34(9)	139(8)
Shirley	122(13)	231(12)
Trix	97(14)	187(13)
Virginia	104(6)	201(5)
Bess	84(14)	120(13)
Carmen	67(17)	157(16)
Della	85(12)	197(11)
SR 500 Average	80(110) 80(106)	173(100) 168(85)
SR 700 Average	100(117) 102(106)	180(92) 182(85)
Official Average	70	148(199)

TABLE 6. - 1965 - 12-HOUR FORECAST ERRORS in nautical miles.
Number of forecasts in parentheses

		SR 700 mb	
Hurricanes	Official	F_{12}	F^{12}_{12}
Anna	119(6)	70(8)	47(7)
Betsy	67(57)	74(32)	45(31)
Carol	105(38)	94(30)	42(28)
Debbie	65(16)	54(9)	28(8)
Elena	114(20)	170(14)	71(13)
Average	86(137)	93(93)	47(87)
		91(87)	47(87)

TABLE 7. - 1965 - 12-HOUR FORECAST ERRORS in nautical miles.
Number of forecasts in parentheses

Typhoons	Official	SR 500 mb	
		F_{12}	F_{12}^{12}
Lucy		84(12)	60(8)
Mary		28(7)	41(5)
Olive		61(6)	46(4)
Rose		34(9)	43(8)
Shirley		122(13)	53(12)
Trix		97(14)	52(12)
Virginia		104(6)	51(4)
Bess		84(14)	54(13)
Carmen		67(17)	62(16)
Della		85(12)	63(10)
Average	70	80(110)	54(92)
		82(92)	54(92)

TABLE 8. - 1965 - 24-HOUR FORECAST ERRORS in nautical miles.
Number of forecasts in parentheses

Hurricanes	Official	SR 700 mb		
		F_{24}	F_{24}^{12}	F_{24}^{24}
Anna	217(4)	127(7)	127(6)	126(5)
Betsy	130(56)	141(31)	110(30)	114(29)
Carol	192(40)	183(29)	108(27)	117(26)
Debbie	135(14)	112(9)	72(8)	99(7)
Elena	260(20)	328(13)	182(12)	226(11)
Average	171(134)	178(89)	117(83)	130(78)
		174(83)	117(83)	
		173(77)	119(77)	128(77)

TABLE 9. - 1965 - 24-HOUR FORECAST ERRORS in Nautical Miles.

Number of Forecasts in Parentheses.

Typhoons	Official	F_{24}	SR 500mb F^{12}_{24}	F^{24}_{24}
Lucy	169(29)	216(11)	133(8)	107(7)
Mary	107(14)	111(6)	136(4)	95(3)
Olive	138(17)	130(5)	56(3)	124(1)
Rose	55(15)	139(8)	147(7)	58(6)
Shirley	231(16)	231(12)	139(11)	163(10)
Trix	138(27)	187(13)	106(11)	118(10)
Virginia	289(11)	201(5)	173(3)	94(2)
Bess	106(26)	120(13)	124(12)	85(11)
Carmen	148(21)	157(16)	134(15)	89(14)
Della	152(23)	197(11)	153(9)	145(8)
Average	148(199)	173(100)	131(83)	109(72)
	155(90)	177(90)		
	154(76)	177(76)	131(76)	
	150(61)	181(61)	134(61)	108(61)

TABLE 10. - 1965 - 36-HOUR FORECAST ERRORS in nautical miles.
Number of Forecasts in Parentheses

Hurricanes	Official	SR 700 mb		
		F_{36}	F_{36}^{12}	F_{36}^{36}
Anna		189(6)	215(5)	246(3)
Betsy		205(30)	198(29)	220(27)
Carol		276(28)	195(26)	217(25)
Debbie		173(8)	122(7)	202(5)
Elena		471(12)	338(11)	431(9)
Average	260	262(84)	211(78)	246(69)
		259(78)	211(78)	
		260(68)	215(68)	244(68)

TABLE 11. - 1965 - 36-HOUR FORECAST ERRORS in Nautical Miles
Number of Forecasts in Parentheses

Typhoons	Official	SR 500 mb				
		F_{36}	F_{36}^{12}	F_{36}^{24}	$F_{36}^{12,24}$	F_{36}^{36}
Lucy		318(10)	181(7)	162(6)	152(4)	130(5)
Mary		187(5)	266(3)	174(3)	226(2)	152(2)
Olive		---	---	---	---	---
Rose		199(7)	213(6)	92(5)	141(5)	100(4)
Shirley		335(11)	256(10)	278(9)	270(9)	308(8)
Trix		275(12)	197(10)	215(9)	180(8)	236(8)
Virginia		318(4)	341(2)	270(2)	252(1)	329(1)
Bess		173(12)	194(11)	139(10)	146(10)	137(9)
Carmen		223(15)	385(14)	126(13)	149(13)	145(12)
Della		286(9)	174(7)	128(6)	104(5)	142(5)
Average	225	256(85)	247(70)	170(63)	172(57)	180(54)
		255(70)	247(70)			
		259(57)	251(57)	162(57)		
		259(57)	251(57)	162(57)	172(57)	
		257(44)	255(44)	152(44)	163(44)	169(44)

TABLE 12. - 1965 - 48-HOUR FORECAST ERRORS in nautical miles.
Number of Forecasts in Parentheses

Hurricanes	Official	SR 700 mb		
		F_{48}	F^{12}_{48}	F^{48}_{48}
Anna	---	284(5)	304(4)	432(1)
Betsy	273(52)	273(29)	313(28)	353(25)
Carol	355(36)	363(28)	319(27)	349(24)
Debbie	310(8)	220(7)	198(6)	315(3)
Elena	581(16)	595(11)	478(10)	695(7)
Average	346(112)	345(80)	327(75)	391(60)
		341(75)	327(75)	
		349(60)	346(60)	391(60)

TABLE 13. - 1965 - 48-HOUR FORECAST ERRORS in Nautical Miles
Number of Forecasts in Parentheses

Typhoons	Official	SR 500 mb				
		F_{48}	F^{12}_{48}	F^{24}_{48}	$F^{12,24}_{48}$	F^{48}_{48}
Lucy	329(25)	370(11)	276(8)	243(7)	223(5)	267(6)
Mary	154(10)	293(4)	364(3)	190(2)	284(2)	---
Olive	284(13)	313(3)	73(1)	---	---	115(1)
Rose	127(11)	254(6)	242(5)	117(4)	173(4)	128(2)
Shirley	589(12)	425(10)	383(9)	379(8)	364(8)	419(6)
Trix	302(23)	348(11)	299(9)	319(8)	261(7)	438(7)
Virginia	615(7)	418(3)	488(2)	298(1)	374(1)	---
Bess	256(22)	229(11)	278(10)	240(9)	219(9)	211(7)
Carmen	238(15)	307(14)	267(13)	187(12)	212(12)	263(10)
Della	277(17)	366(9)	273(7)	214(6)	200(5)	170(4)
Average	304(155)	331(82)	296(67)	248(57)	245(53)	287(43)
	311(70)	343(70)				
	310(59)	342(59)	300(59)			
	314(45)	346(45)	293(45)	253(45)		
	314(45)	346(45)	293(45)	253(45)	250(45)	
	338(32)	341(32)	285(32)	264(32)	253(32)	282(32)

TABLE 14. - 1965 - 72-HOUR FORECAST ERRORS in Nautical Miles.

Number of Forecasts in Parentheses.

		SR 700 mb				
Hurricanes	Official	F_{72}	F_{72}^{12}	F_{72}^{24}	$F_{72}^{12,24}$	F_{72}^{72}
Anna	---	524(3)	574(2)	798(1)		---
Betsy	469(48)	399(27)	564(26)	563(25)		553(21)
Carol	448(32)	561(26)	571(25)	564(24)		658(20)
Debbie	512(6)	261(5)	239(4)	222(3)		---
Elena	1104(12)	857(9)	888(8)	1004(7)		1395(3)
Average	543(98)	514(70)	587(65)	602(60)		658(44)
		512(65)	587(65)			
		517(60)	602(60)	602(60)		

TABLE 15. - 1965 - 72-HOUR FORECAST ERRORS in Nautical Miles.

Number of Forecasts in Parentheses.

		SR 500 mb				
Typhoons	Official	F_{72}	F^{12}_{72}	F^{24}_{72}	F^{1}_{72}	F^{72}_{72}
Lucy	481(19)	526(9)	332(6)	444(5)	308(3)	705(3)
Mary	170(5)	437(3)	518(2)	187(1)	365(1)	---
Olive	449(9)	548(2)	132(1)	---	---	---
Rose	245(3)	453(4)	431(3)	148(2)	268(2)	---
Shirley	871(3)	591(8)	562(7)	532(6)	535(6)	474(2)
Trix	426(18)	401(9)	376(7)	508(7)	367(6)	706(3)
Virginia	1055(3)	786(2)	690(1)	---	---	---
Bess	401(16)	360(9)	501(8)	323(7)	360(7)	265(3)
Carmen	289(11)	441(12)	466(11)	329(10)	397(10)	516(6)
Della	484(11)	550(6)	294(4)	237(4)	203(3)	42(1)
Average	440(98)	480(64)	440(50)	380(42)	377(38)	506(18)
		458(50)	440(50)			
		463(38)	446(38)	354(38)	377(38)	
		463(38)	446(38)	354(38)	377(38)	
		483(14)	552(14)	481(14)	504(14)	473(14)

TABLE 16. - Highlights of the evaluation of the optimal NPGS forecast scheme

ATLANTIC:

Forecast Interval (hrs)	Optimal NPGS Scheme	Avg. NPGS Error (n.mi/hr of fcst interval)	% NPGS Errors Within:			Official / Optimal NPGS Error
			1kt of Ave.	2kt of Ave.	3kt of Ave.	
12	F_{12}^{12}	3.9	30	56	76	1.8
24	F_{24}^{12}	4.9	23	46	64	1.4
36	F_{36}^{12}	5.9	22	42	60	1.2
48	F_{48}^{12}	6.8	18	40	55	1.1
72	F_{72}	7.1	17	34	50	1.1
PACIFIC:						
12	F_{12}^{12}	4.5	28	60	82	1.3
24	F_{24}^{24}	4.5	34	51	74	1.5
36	F_{36}^{24}	4.7	30	54	69	1.2
48	$F_{48}^{12,24}$	5.1	21	46	64	1.2
72	$F_{72}^{12,24}$	5.2	21	41	62	1.2

TABLE 17. - FORECAST ERRORS: NHC-64 VS. NPGS-67 in Nautical Miles.

Number of Forecasts in Parentheses

Hurricanes	12 Hour NHC-64	 NPGS(F^{12}_{12})	24 Hour NHC-64	 NPGS(F^{12}_{24})	36 Hour NHC-64	 NPGS(F^{12}_{36})	48 Hour NHC-64	 NPGS(F^{12}_{48})
Anna	---	---	---	---	---	---	---	---
Betsy	49(24)	40(24)	80(19)	109(19)	143(21)	187(21)	186(20)	306(20)
Carol	117(15)	39(15)	143(14)	102(14)	215(15)	200(15)	302(15)	269(15)
Debbie	66(2)	41(2)	201(1)	98(1)	---	---	---	---
Elena	130(8)	55(8)	204(9)	128(9)	388(7)	274(7)	532(5)	300(5)
Average	84(49)	42(49)	129(43)	110(43)	208(43)	206(43)	273(40)	291(40)

TABLE 18. - 1965 ATLANTIC HURRICANES: ERROR DISTRIBUTION FOR OPTIMAL NPGS SR 700 SCHEME BY AREA, PATH AND STORM STAGE
Errors in Nautical Miles. Number of Forecasts in Parentheses

	AREA			RECURVATURE		STORM STAGE				
	A	B	C	Before	After	TD(dev)	TS	H	EXT	TD(dis)
F^{12}_{12}	50(48)	42(34)	[illegible](5)	39(63)	67(24)	47(15)	36(14)	44(50)	74(6)	101(2)
F^{12}_{24}	131(45)	97(33)	130(5)	95(58)	169(25)	72(11)	108(13)	116(51)	197(6)	220(2)
F^{12}_{36}	235(42)	171(31)	256(5)	174(54)	294(24)	112(8)	209(11)	216(52)	328(6)	55(1)
F^{12}_{48}	356(41)	269(29)	429(5)	276(50)	430(25)	219(6)	278(9)	327(51)	493(6)	351(3)
F_{72}	628(38)	323(27)	675(5)	427(46)	680(24)	473(4)	404(7)	480(50)	869(6)	679(3)

TABLE 19. - 1965 PACIFIC TYPHOONS: ERROR DISTRIBUTION FOR OPTIMAL NPGS SR 500 SCHEME BY PATH
Errors in Nautical Miles. Number of Forecasts in Parentheses

	RECURVATURE	
	Before	After
F^{12}_{12}	46(70)	79(22)
F^{24}_{24}	84(51)	170(21)
F^{24}_{36}	138(45)	251(18)
F^{24}_{48}	189(37)	356(20)
F^{24}_{72}	291(24)	499(18)

CAPTIONS FOR FIGURES

FIGURE 1a - Portion of FNWF's operational 500-mb height (Z) and temperature analysis for 0000 GMT 20 August 1965. Contours at 60-meter interval (dark solid lines); isoline (center) labels in tens (units) of meters with thousands figure omitted. Isotherms (light solid lines) not labeled.

FIGURE 1b - Portion of FNWF's operational 500-mb analysis of the disturbance component, Z_{SD}, derived from the 500-mb height field, Z, at 0000 GMT 20 August 1965. Contours at 30-meter interval; isoline (center) labels in tens (units) of meters.

FIGURE 1c - Portion of FNWF's operational 500-mb analysis of the residual or smoothed component, Z_{SR}, derived from the 500-mb height field, Z, at 0000 GMT 20 August 1965. Contours at 60-meter interval; labels as in figure 1a.

FIGURE 2 - Schematic representation of Z_{SR} contours with superimposed FNWF linear grid. I, J is tropical cyclone location. Geostrophic winds (V_g), are computed, by component (V_{gi}, V_{gj}), at the four identified grid points, each at a distance D from I, J.

FIGURE 3 - Graph of sin θ and mod sin $\theta = 2[(.25 \sin\theta + .25)^2 + .25 \sin\theta]$.

FIGURE 4 - Hurricane Elena positions at 12-hour intervals, starting at 1800 GMT 12 October 1965 (position "0"): best track (x——x) and numerical-steering forecast track, F_{24} (—∇—).

FIGURE 5 - Schematic example of a modified 24-hour numerical steering forecast (using $\vec{E}_{24}$) made from best track position T_o. In general, the vector correction for the bias in numerical steering, $\vec{E}_{yy}$, is for the same time period as the forecast interval implied by F_{xx} and results in the modified position designated as F_{xx}^{yy}, where yy = xx.

FIGURE 6 - Schematic example of a modified 24-hour numerical steering forecast (using $\vec{E}_{12}$) made from best track position T_o. In general, the vector correction for bias in numerical steering is $\vec{E}_{12} \times \frac{\text{forecast interval}}{12}$ and results in the modified position designated as F_{xx}^{12}.

FIGURE 7 - Same as figure 4 with the addition of forecast tracks F_{24}^{24} (—•—Δ—•—) and F_{24}^{12} (•• 0 ••) .

FIGURE 8 - Schematic example of a modified 36-hour numerical steering forecast (using E_{24}) made from best track position T_o . In general, the vector correction for bias in numerical steering is $\vec{E}_{24} \times \frac{\text{forecast interval}}{24}$ and results in the modified position designated as F_{xx}^{24} .

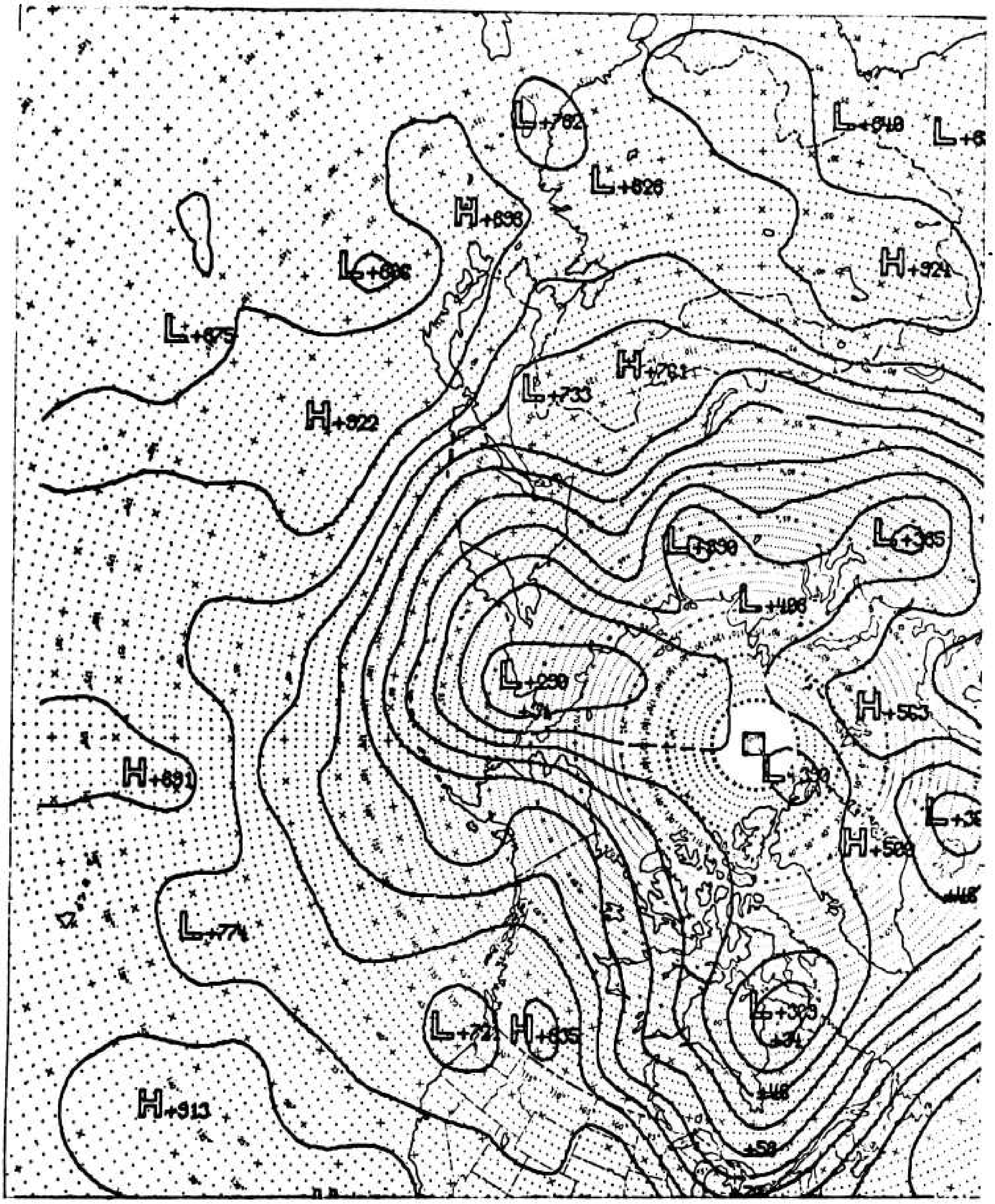
FIGURE 9 - Schematic example of a modified 36-hour numerical steering forecast (using $\vec{E}_{12}$ and $\vec{E}_{24}$) made from best track position T_o. In general, the vector correction for bias in numerical steering is $A\vec{E}_{12} + B\vec{E}_{24}$ where $A = \frac{\text{forecast interval}}{24}$ and B = .5A, and results in the modified position designated as $F_{xx}^{12,24}$.

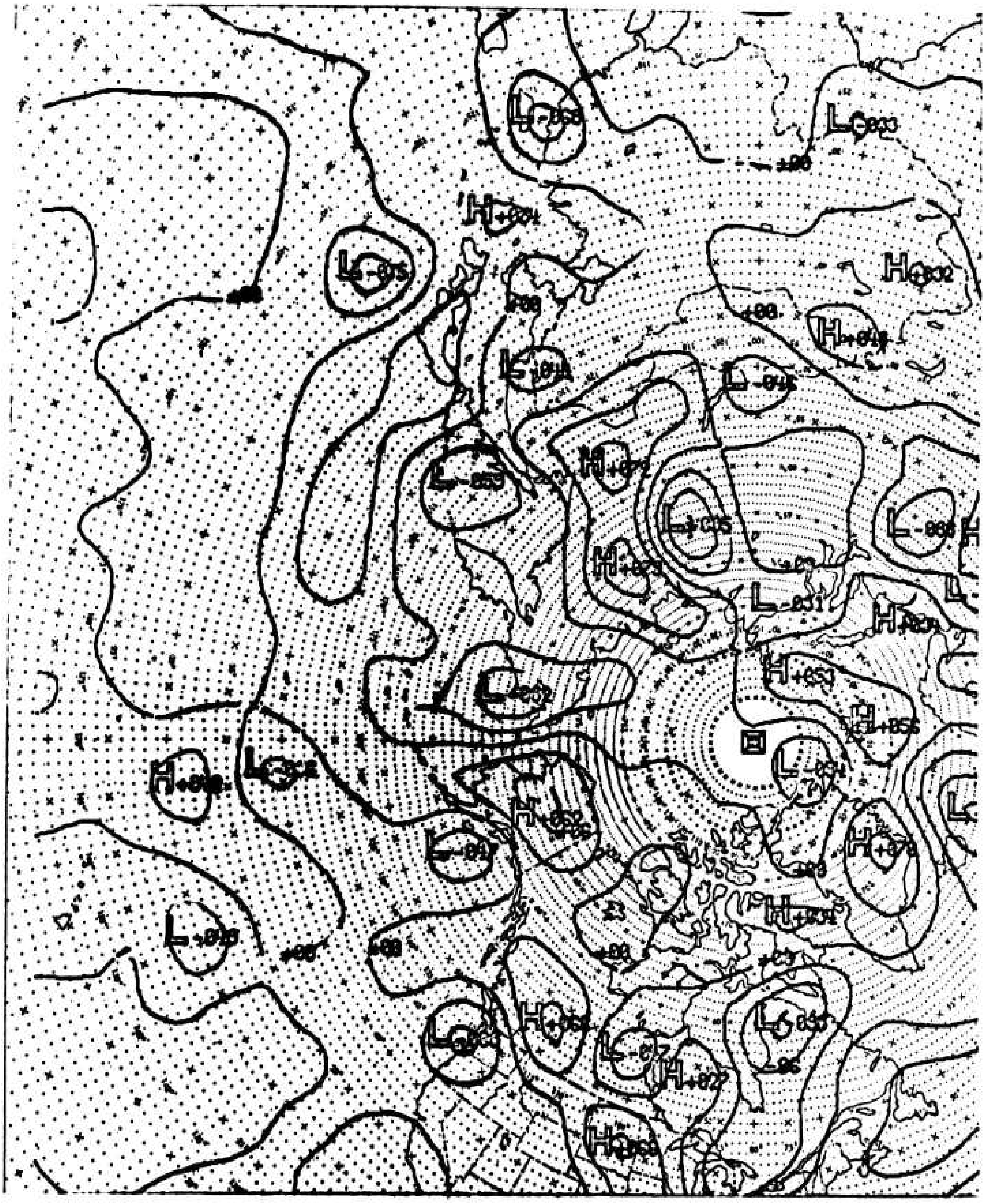
FIGURE 10 - Typhoon Carmen positions at 12-hour intervals, starting with 0600 GMT 1 October 1965 (position "0"): best track (—×——×—) and modified numerical-steering forecast tracks, F_{48}^{48} (• —Δ—•), F_{48}^{24} (— ∇ —), and $F_{48}^{12,24}$ (•• 0 ••) .

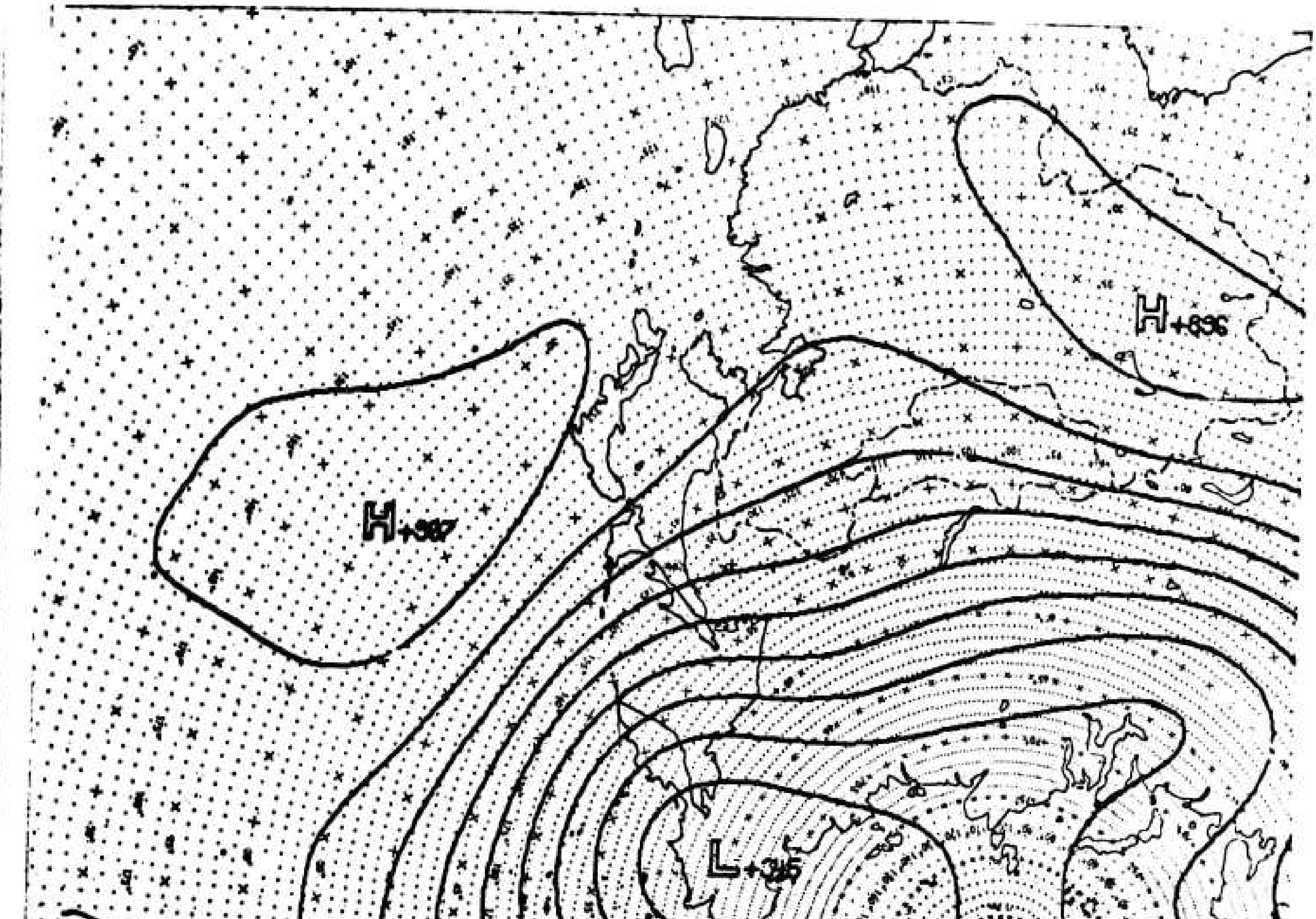
FIGURE 11 - Tropical storm Debbie. 12, 24, 36, 48 and 72 hour forecasts made at 1800 GMT 25 September 1965, using the numerical-steering computation F_{xx} (— ∇ —), and optimal scheme $F_{xx}^{opt.}$ (•• 0 ••) . Best track (—×——×—) and available official-forecast positions (Δ) are shown.

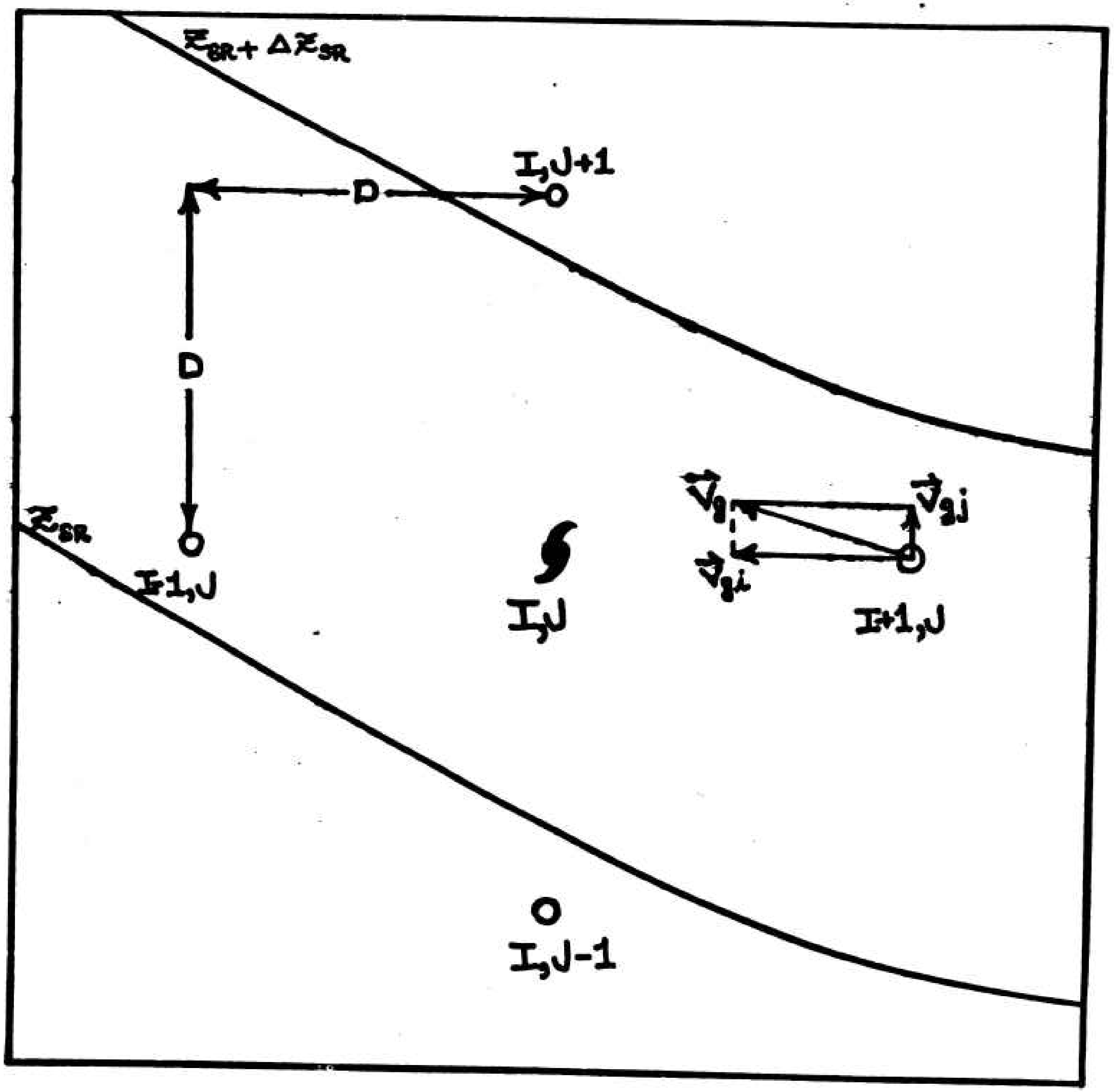
FIGURE 12 - Typhoon Rose, forecasts made at 1800 GMT 2 September 1965. Remainder of legend as in figure 11.

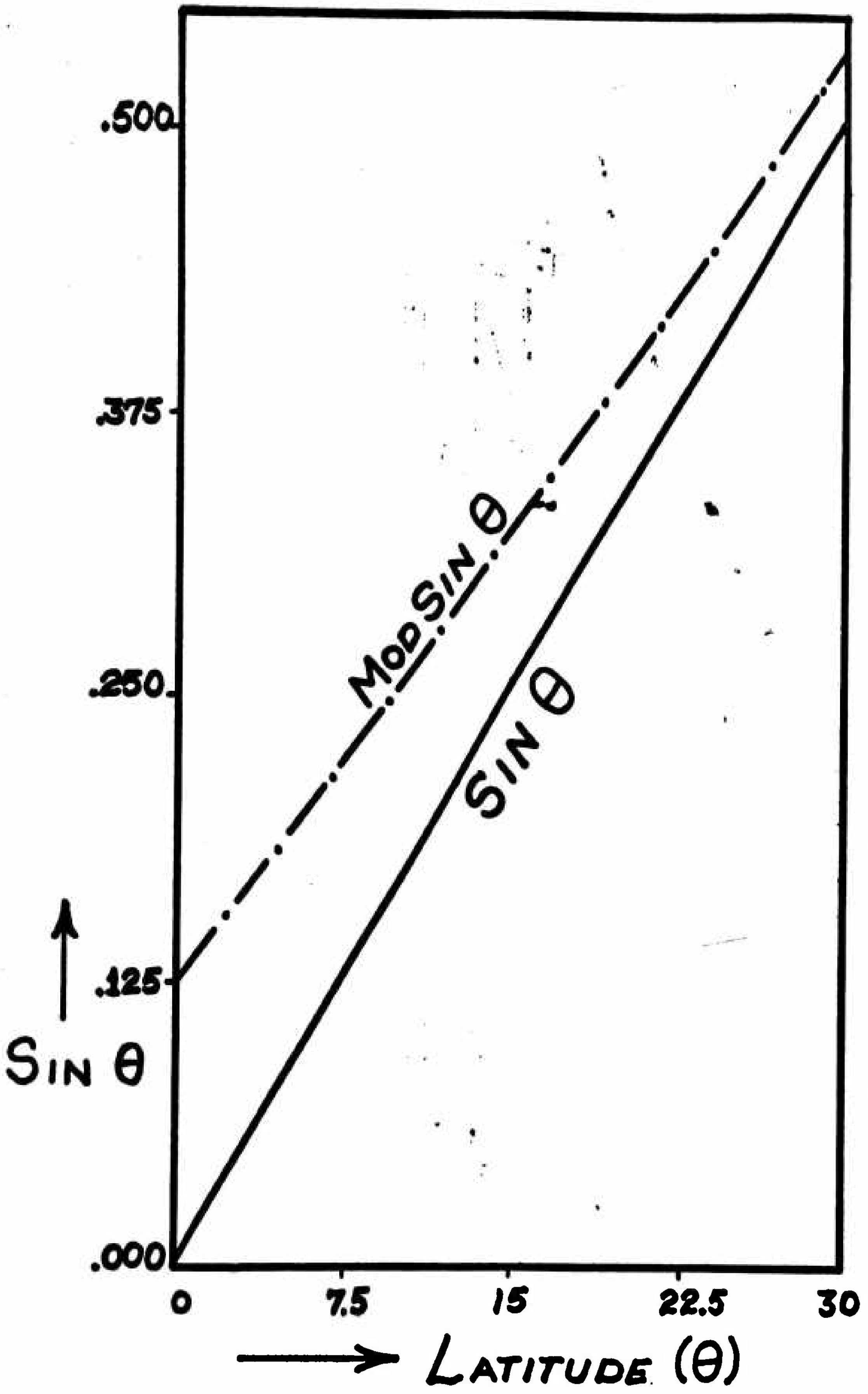
FIGURE 13 - Division of North Atlantic area (A, B, C) used in stratifying forecast statistics in table 18.

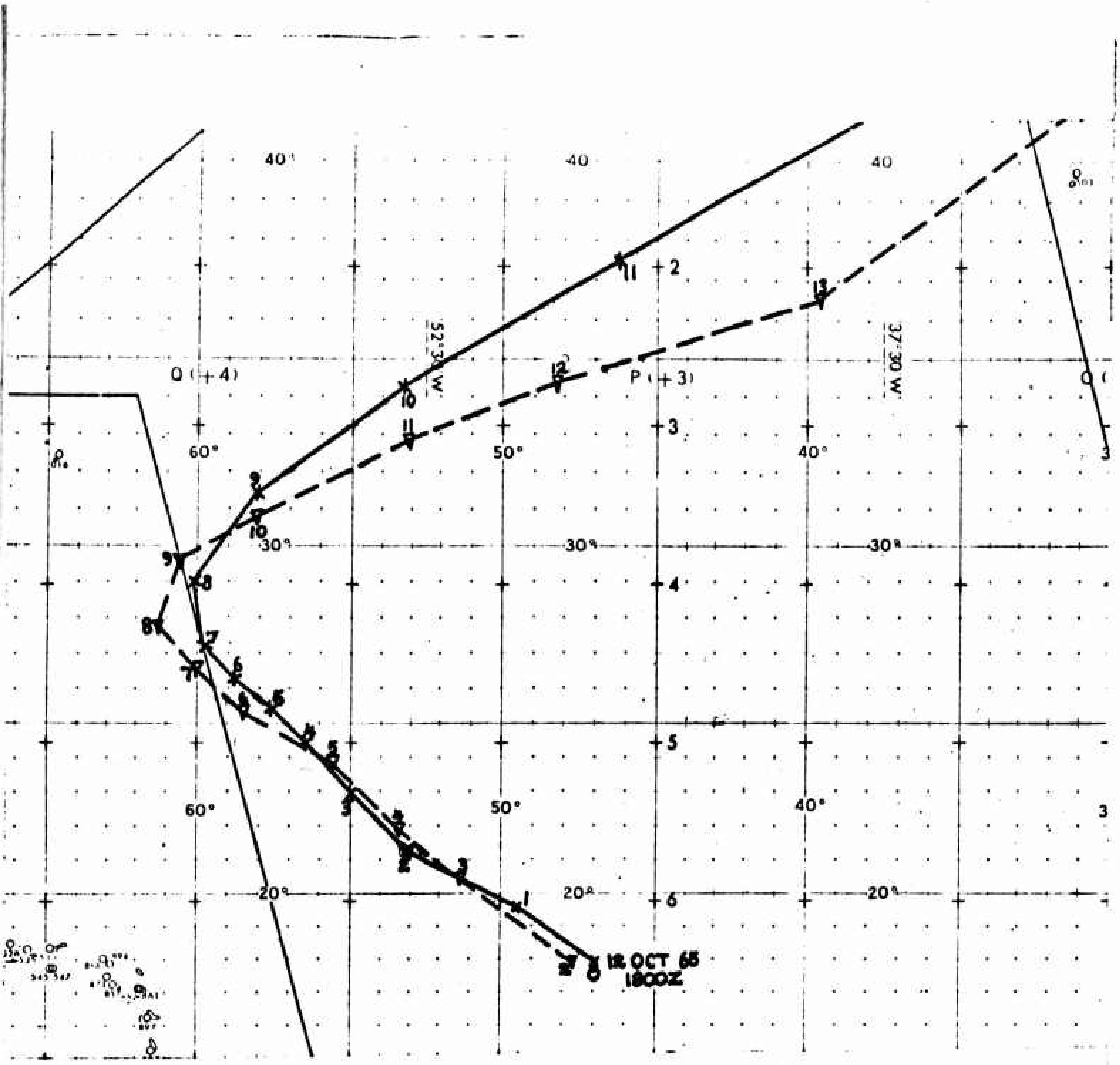

L+782
L+826
L+848
L+8
H+838
L+886
H+924
L+875
H+761
L+733
H+922
L+390
L+365
L+406
L+250
H+563
L+330
H+891
H+588
L+3
L+74
L+72
H+835
L+303
H+913

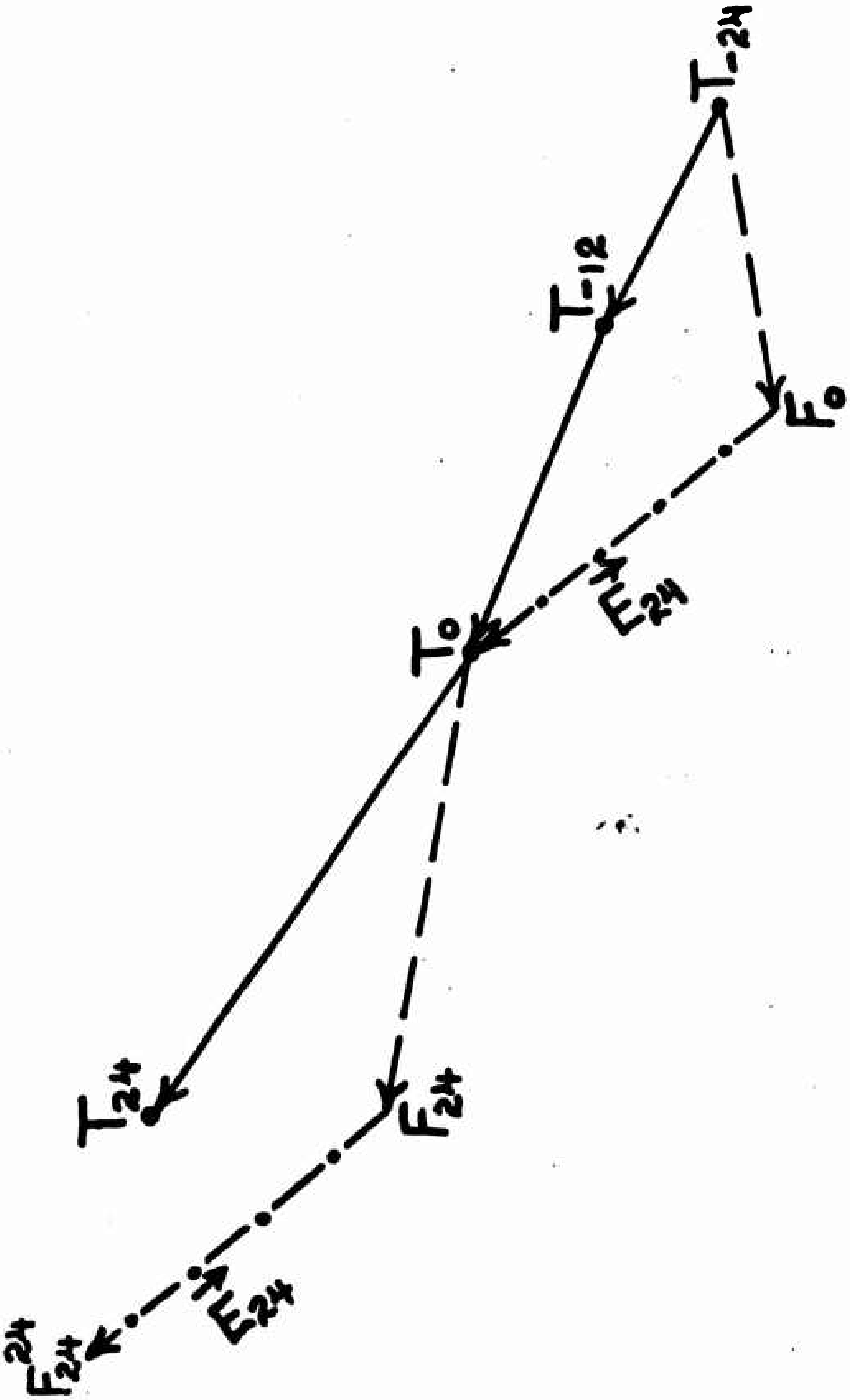

H +804
+88
L -888
H +823
L -831
H +853
H +856
H +827

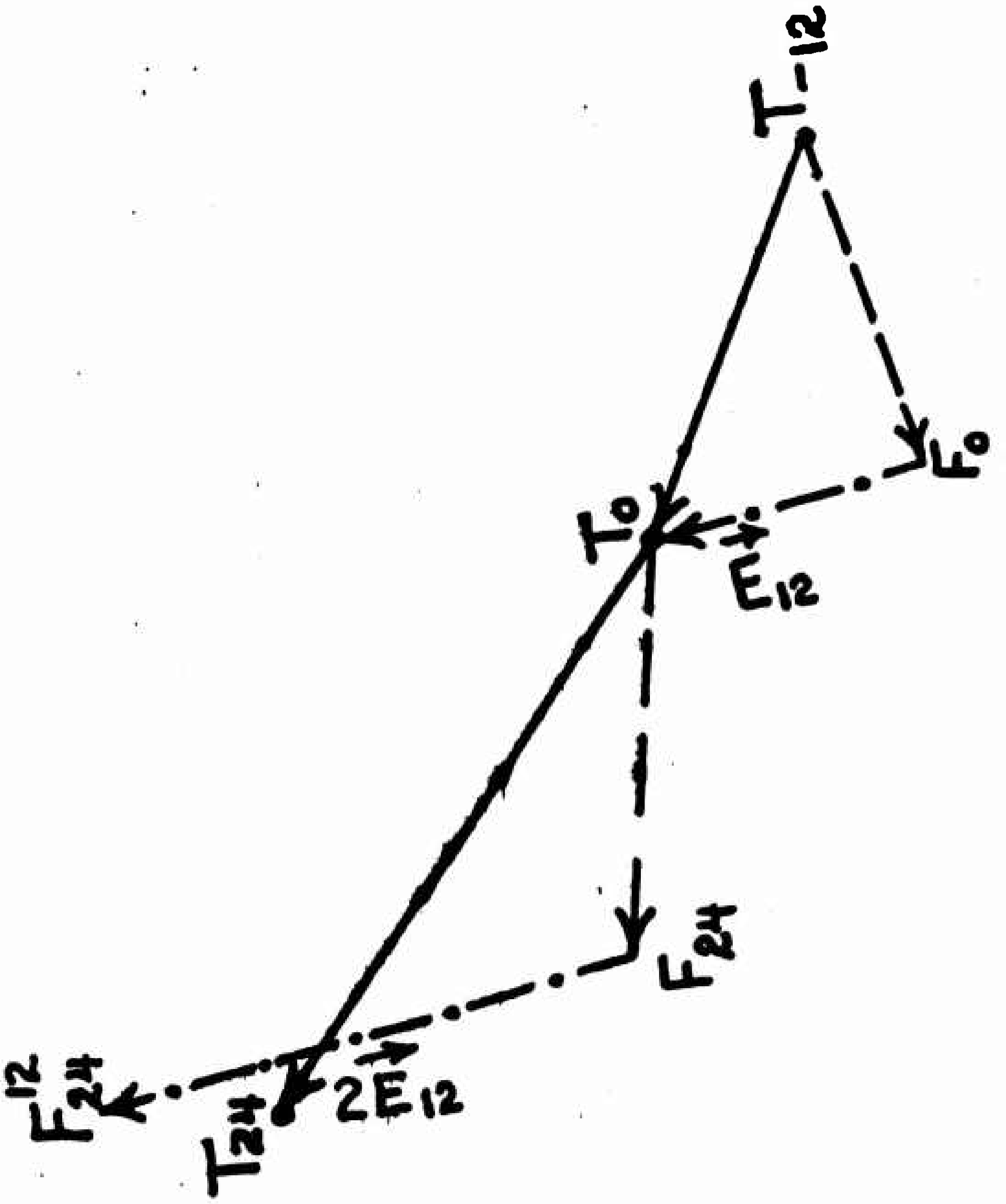

H +587
H +636
L +315
L +092
+40
+58
+20
H +696
H +657

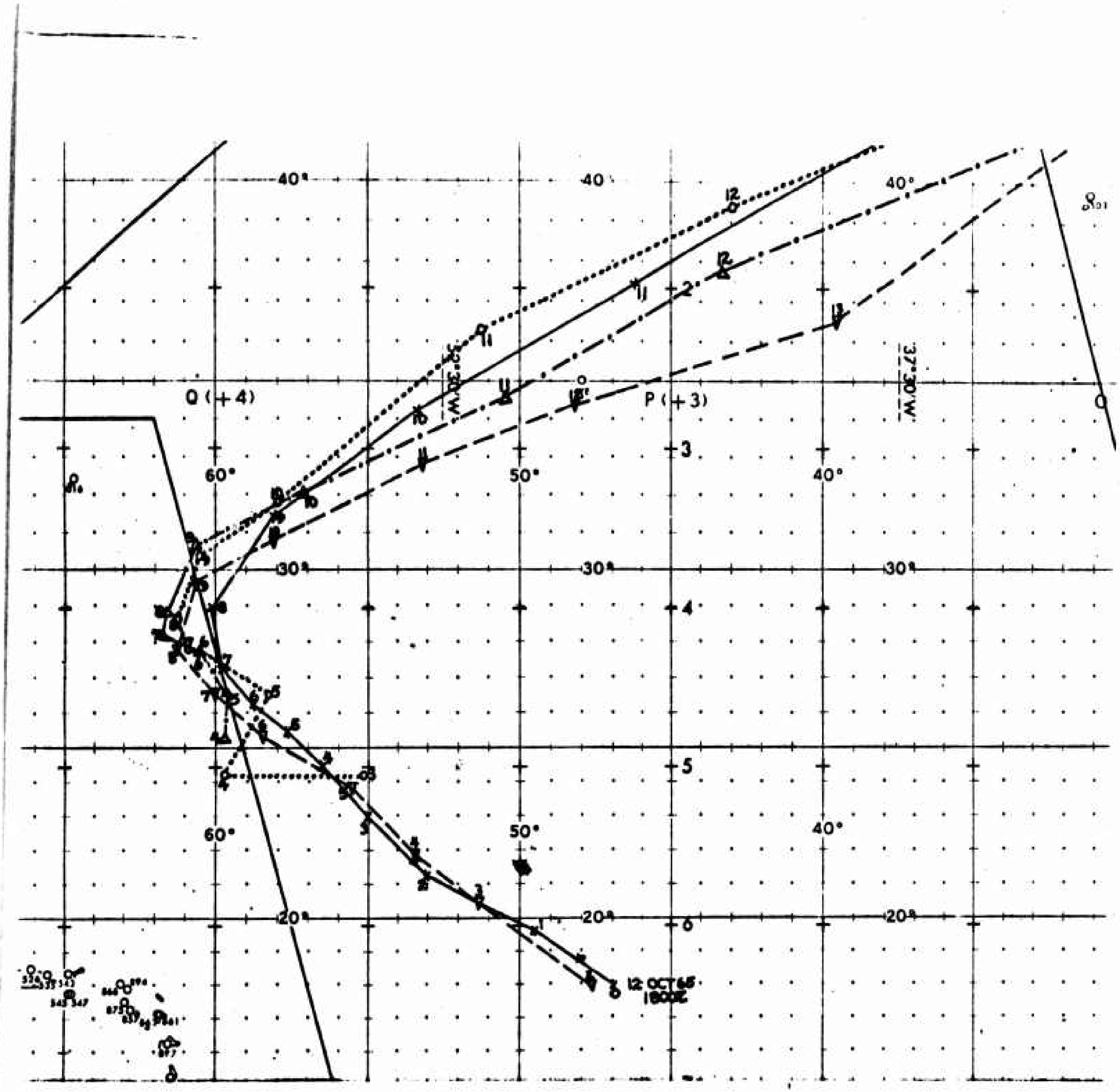

$Z_{SR}+\Delta Z_{SR}$
I,J+1
D
D
Z_{SR}
I-1,J
I,J
$\vec{V}_g$
$\vec{V}_{gj}$
$\vec{V}_{gi}$
I+1,J
I,J-1

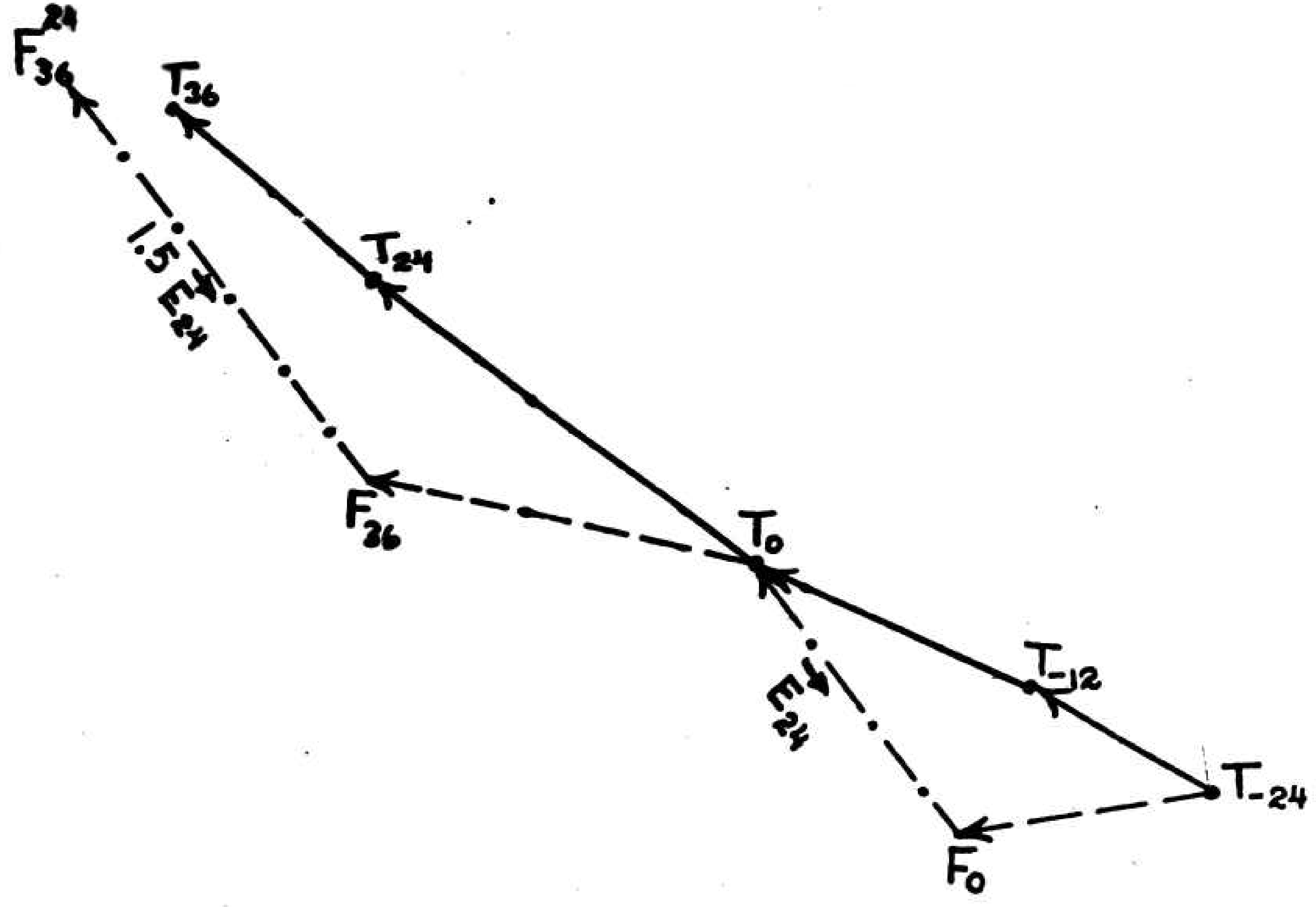

.500
.375
.250
.125
.000
Sin θ
Mod Sin θ
Sin θ
0
7.5
15
22.5
30
Latitude (θ)


40°
40
40
2
11
13
52°30'W
37°30'W
Q (+4)
P (+3)
12
10
11
3
60°
50°
40°
9
10
30°
30°
30°
9
8
4
8
7
6
7
6
5
5
4
5
60°
50°
40°
3
4
3
2
1
20°
20°
20°
6
1
1R OCT 65
1800Z

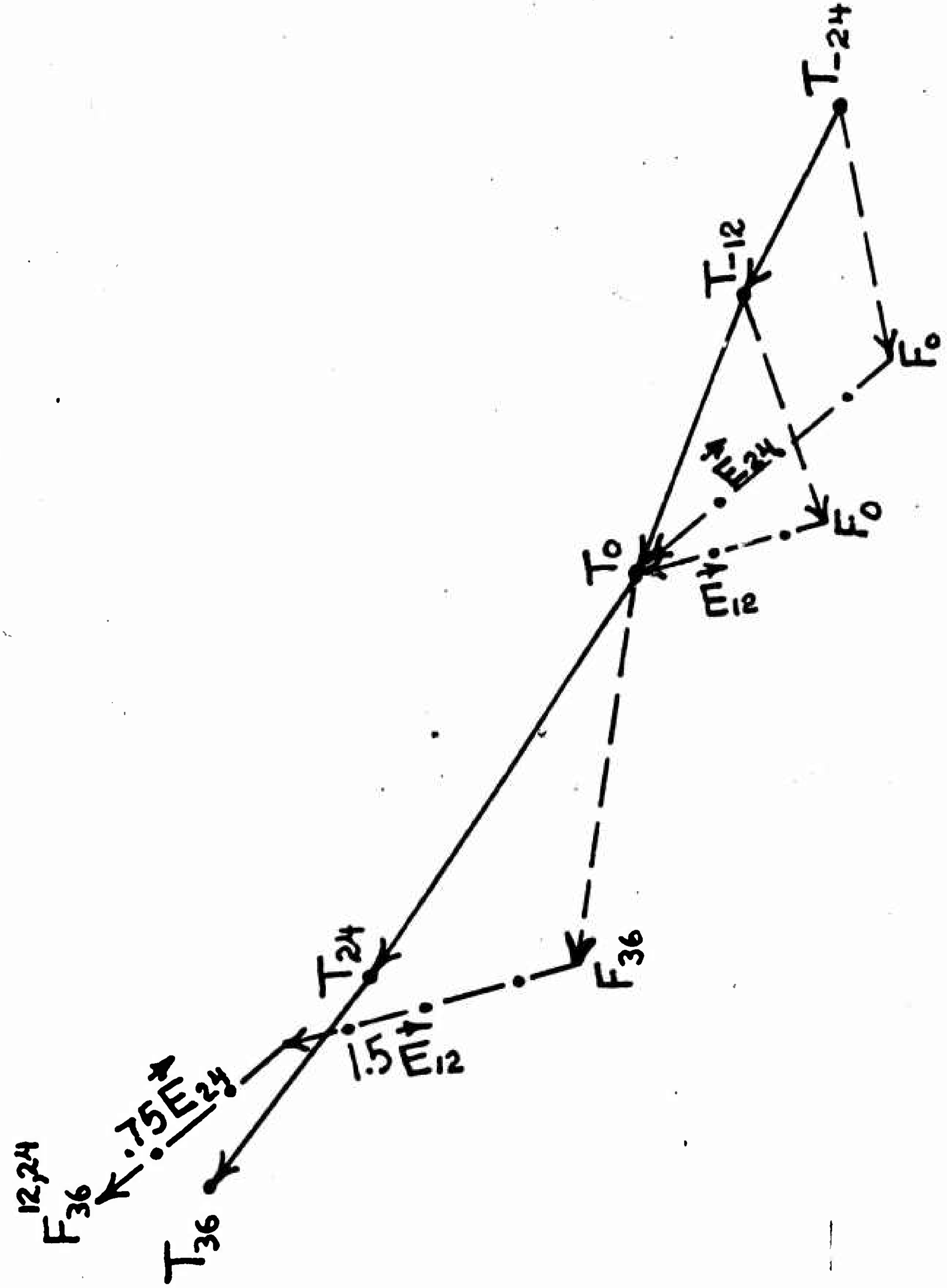

T_{-24}
T_{-12}
F_0
E_{24}
T_0
T_{24}
F_{24}
E_{24}
F_{24}^{24}


T_{-12}
F_0
T_0
$\vec{E}_{12}$
F_{24}
$2\vec{E}_{12}$
F^{12}_{24}
T_{24}

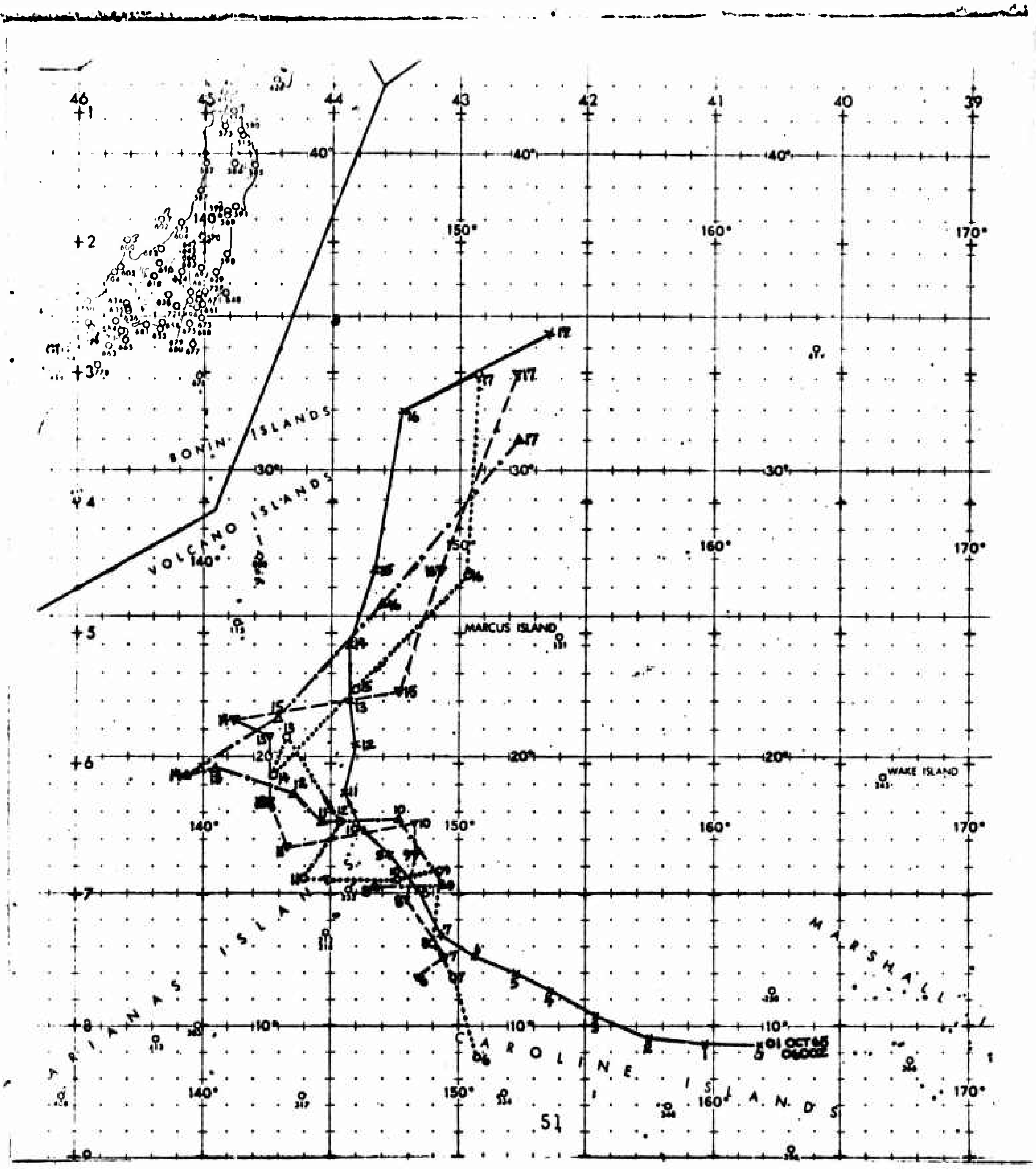

40°
40
40°
12
12
11
2
13
37°30'W
37°30'W
11
11
12
Q (+4)
P (+3)
10
11
3
60°
50°
40°
30°
30°
30°
4
5
60°
50°
40°
20°
20°
20°
6
12 OCT 65
1800Z

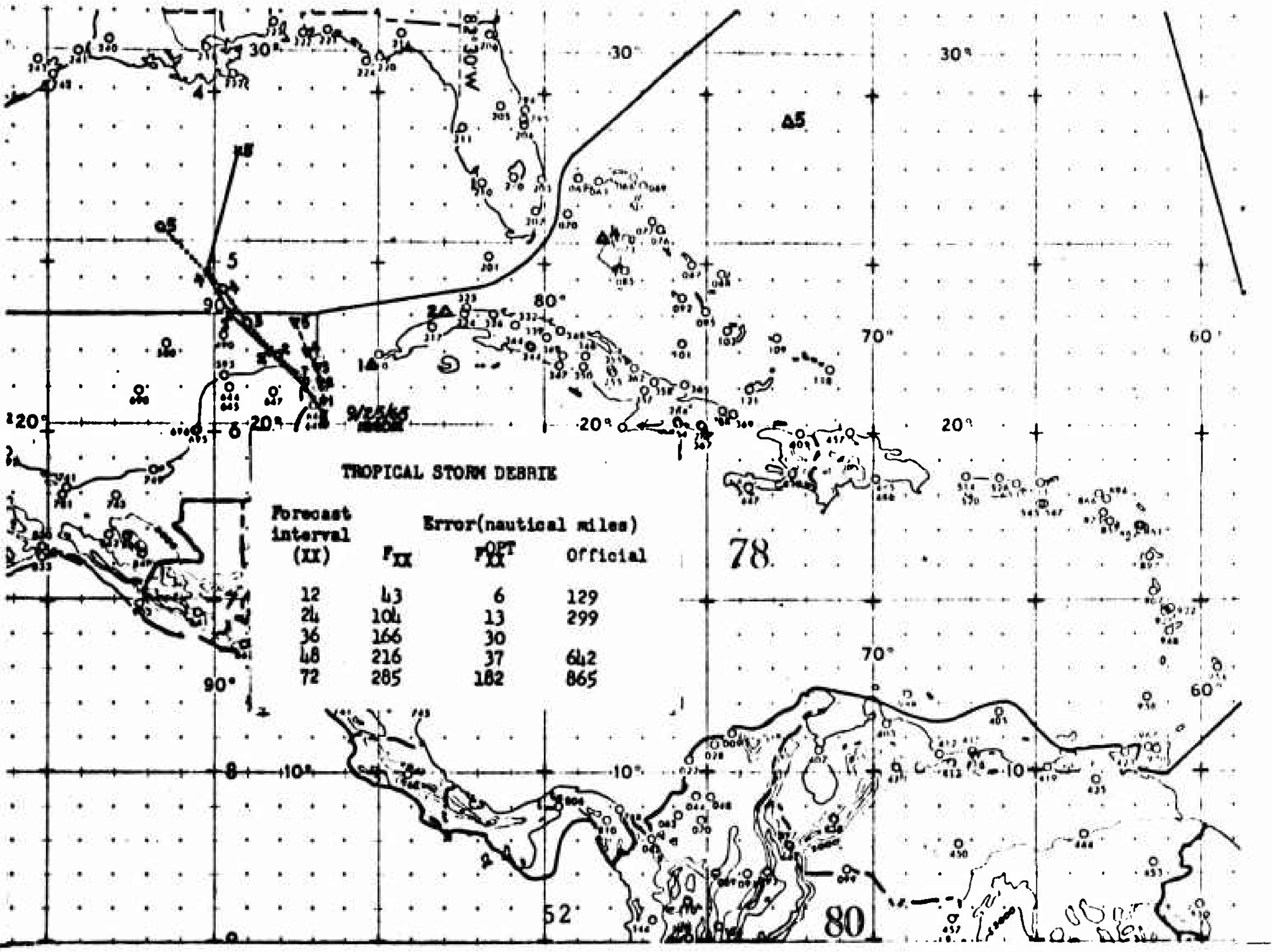


F_{36}^{24}
T_{36}
$1.5\,E_{24}$
T_{24}
F_{36}
T_0
T_{-12}
E_{24}
T_{-24}
F_0



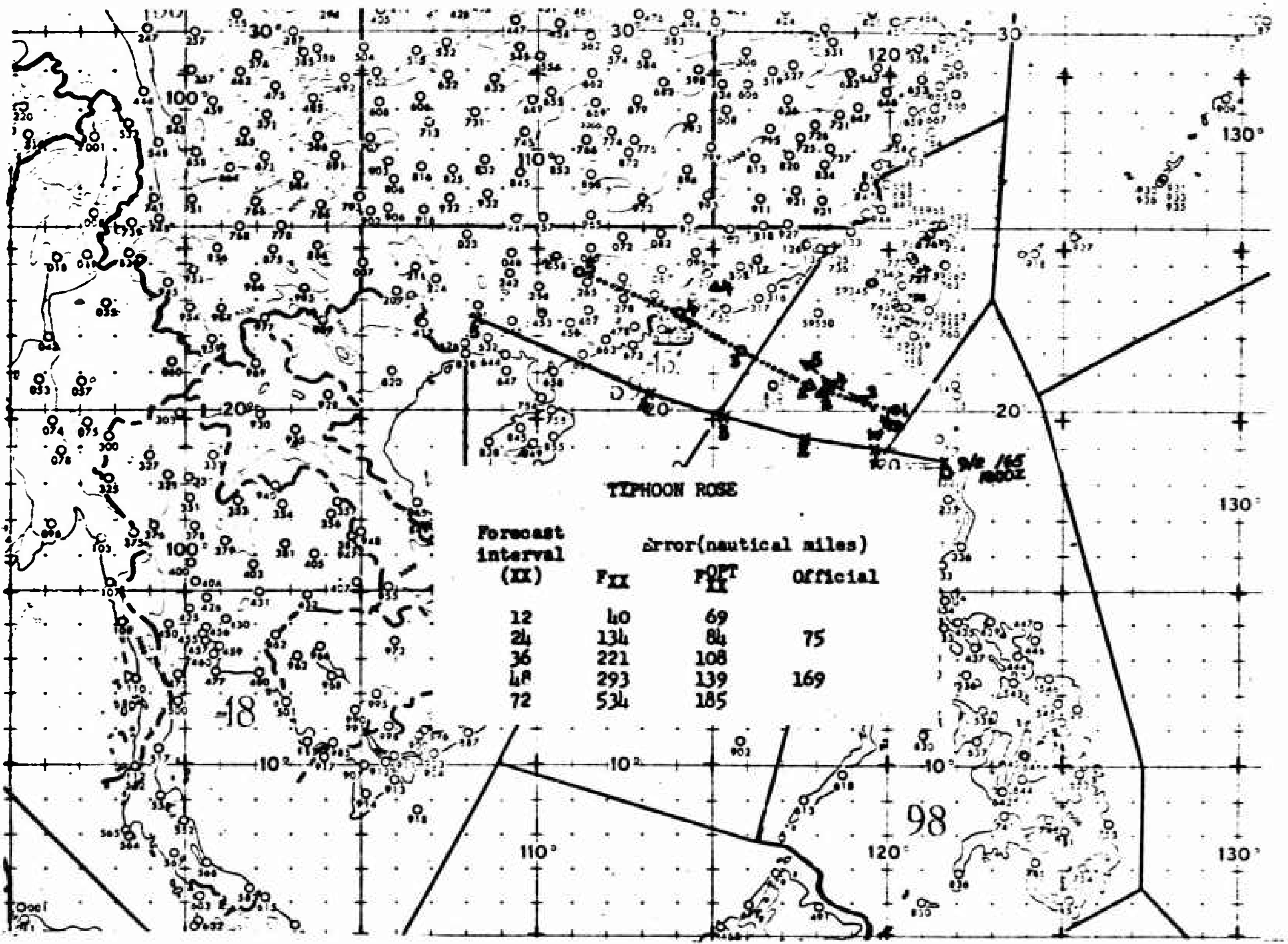
T_{-24}
T_{-12}
F_0
$\vec{E}_{24}$
F_0
T_0
$\vec{E}_{12}$
F_{36}
T_{24}
$1.5\vec{E}_{12}$
$.75\vec{E}_{24}$
$F_{36}^{12,24}$
T_{36}


46
45
44
43
42
41
40
39
+1
+2
+3
Y4
+5
+6
+7
+8
+9
40°
30°
20°
10°
140°
150°
160°
170°
BONIN ISLANDS
VOLCANO ISLANDS
MARCUS ISLAND
WAKE ISLAND
MARIANAS ISLANDS
MARSHALL
CAROLINE ISLANDS
01 OCT 65 0600Z



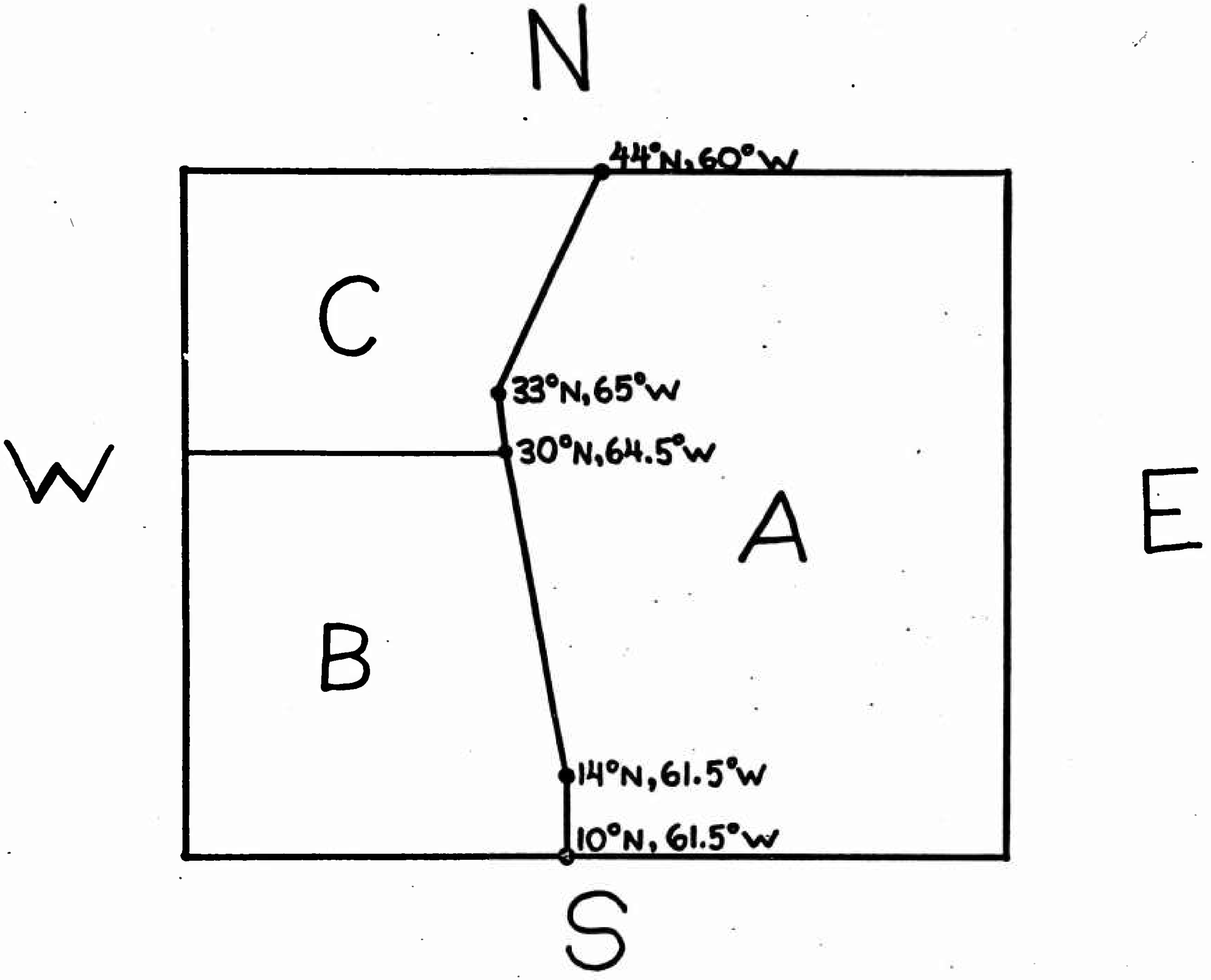
TROPICAL STORM DEBBIE

Forecast interval (XX)	Error(nautical miles) F_{XX}	F_{XX}^{OPT}	Official
12	43	6	129
24	104	13	299
36	166	30	
48	216	37	642
72	285	182	865



TYPHOON ROSE

Forecast interval (XX)	Error(nautical miles) F_{XX}	F^{OPT}_{XX}	Official
12	40	69	
24	134	84	75
36	221	108	
48	293	139	169
72	534	185	


N
44°N,60°W
C
33°N,65°W
30°N,64.5°W
W
A
E
B
14°N,61.5°W
10°N,61.5°W
S