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APPLICATION OF THE NAVY'S NUMERICAL HURRICANE AND TYPHOON FORECAST SCHEME TO 1967 ATLANTIC TROPICAL-STORM DATA

by

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ABSTRACT:

Renard recently reported (Monthly Weather Review, July 1968) on a numerical scheme for predicting the motion of tropical storms for intervals up to 72 hours. The forecast technique is applied in two steps. First, numerical geostrophic steering of the cyclone center is accomplished using Fleet Numerical Weather Central's analyses and prognoses of smoothed isobaric height fields, called SR fields. Next, a statistical correction for vector bias in the numerical steering computation is used selectively in an attempt to improve the accuracy of the forecast track. The bias modification is dependent solely on the peculiarities of recent-history 12- and 24-hour forecasts in relation to the actual storm trajectory. Forecasts for intervals up to 72 hours, generated from the 1967 Atlantic operational storm positions, are compared to the results from previous experimental forecasts for 1965 using best-track positions of Atlantic storms.

Results indicate the numerical scheme shows skill in relation to both 1965 and 1967 official-forecast accuracy as documented by Fleet Weather Facility, Jacksonville, Florida. In 1967, the relative improvement over official forecasts, using 700 mb prognostic SR fields for steering, ranges from 52% at forecast intervals of 7-18 hours to 9% at forecast intervals of 43-54 hours.

Discussions of various forecast modes and selective modification schemes as well as stratification of error statistics by area, track, and storm stage are included.

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1. Introduction

Renard (1968) recently reported on the development and application of a numerical scheme to forecast the motion of tropical-storm centers[1] in the North Atlantic and Pacific Ocean areas. Geraldson (1968) presented a preliminary evaluation of the technique for the 1967 storm season in the west Pacific area. The forecast scheme, as discussed in both of these references, has two constituent parts. First, the storm center is moved with a geostrophic wind derived from a smoothed isobaric height field, as produced operationally by the Fleet Numerical Weather Central, Monterey, California (FNWC)[2]. Next, the geostrophic steering vector is selectively modified in direction and magnitude as a function of the recent-history behavior of this vector in relation to the storm's actual trajectory.

Regarding the first step, Figs. 1 and 2 illustrate operational FNWC analyses pertinent to storm forecasts generated at and after 1200 GMT, 16 September 1967. Fig. 1 depicts the surface pressure analysis which is closely related in pattern to the 1000 mb height field. Three hurricanes, Beulah (B), Chloe (C) and Doria (D), existed in the Atlantic area at this time. Upon application of FNWC's unique pattern separation program (Hughes, 1966) to the 1200 GMT 16 September 1967 1000 mb contour analysis, a smoothed height field, called SR 1000, is produced (Fig. 2). The chart

[1]In this and in following sections, the term tropical storm or storm includes all stages of named tropical cyclones, unless specified otherwise.

[2]Although Fleet Numerical Weather Central was designated Fleet Numerical Weather Facility prior to June, 1968, the former will be used throughout to designate this unit of the Naval Weather Service.

resembles a space-mean height field depicting long-wave features. That the hurricane circulations (i.e. perturbations) are removed by the smoothing program may be noted from a comparison of Figs. 1 and 2. The relation of the SR field to the storm trajectory is evident from the best-track positions of B, C, and D at twelve hour intervals (Fig. 2). The 1000 mb SR, rather than another level, is shown here since that particular level yielded accurate geostrophic steering components in the period following 1200 GMT, 16 September 1967.

The selective modification of the numerical geostrophic steering forecast (hereafter called the SR forecast or SR steer) may be described with reference to a schematic application shown in Fig. 3. Suppose that the current position of a tropical-storm center is T_o. Twenty-four hours before time "0", the position was T_{-24}. At that time a 24-hour forecast of storm motion, using only the geostrophic steering vector, located the center at F_o. Thus, at time "0" the vector error of forecast position F_o is known; $\underset{\sim}{E_{24}}$ represents this vector. A 36-hour SR forecast generated at time "0", locates the storm at F_{36}. Considering $\underset{\sim}{E_{24}}$ as a bias in the recent-history SR forecast, it is vectorially added to the 36-hour forecast position, F_{36}, in the appropriate multiple, which in this case is 1.5, (i.e. 1.5 x $\underset{\sim}{E_{24}}$). The result is the modified forecast position F_{36}^{24}, where the superscript denotes the error field from which the correction for bias is obtained. T_{36} represents the true position of the storm at time "0" plus 36 hours. In general, the error $\underset{\sim}{E_{xx}}$ is applied as a correction in the multiple YY/XX, where XX is the interval of the forecast from which the bias correction is derived and YY is the interval of the forecast being made. This procedure is based on a linear relation between error of the SR steer and forecast interval.

The numerical scheme, both steps of which have been outlined above, was applied first to Atlantic tropical-storm data for 1965 and subsequently to 1967. The former is summarized by Renard (1968); the latter is reported on here along with a relative comparison of the two years of application.

2. Comparison of the 1965 and 1967 SR-forecast models

Before presenting and interpreting forecast results from 1965 and 1967, it is necessary to specify the nature of the numerical geostrophic steering vector as it was used in each of the two years.

a. SR forecasts: 1965 data: (1) 1965 data were processed by a research-oriented SR-steering program written by personnel of the Department of Meteorology, Naval Postgraduate School, Monterey, California (PGS) and symbolized hereafter as the PGS program. (2) PGS geostrophic steering computations were made in one-hour time steps up to a 72-hour forecast interval. (3) The steering wind in the PGS program represents an average geostrophic SR wind derived from computations at four points surrounding the storm center. Each of the four points is one mesh length from the center, which, at 20 deg lat, is about 275 km. (4) Forecasts were made from best track positions at 0600 and 1800 GMT, as documented by Fleet Weather Facility, Jacksonville, Florida (FWFJAX) (1965). (5) The FNWC SR analysis fields at 1200 and 0000 GMT were used to compute forecast positions verifying 12, 24, 36, 48, and 72 hours after 0600 and 1800 GMT, respectively. SR forecasts generated from analyses only will be referred to as ANAL-mode forecasts. (6) SR fields from various isobaric levels and layers, between 1000 and 100 mb, were tested for relative accuracy in forecasting the storm centers.

b. SR forecasts: 1967 data: (1) 1967 data were processed by an operationally-oriented program written by personnel at FNWC, and symbolized hereafter as the HATRACK (Hurricane and Typhoon Tracking) program. (2) HATRACK geostrophic steering computations were made in three-hour time steps up to a 72-hour forecast interval. (3) The steering wind in the HATRACK program represents the geostrophic SR wind at the storm center. (4) Forecasts were made from operational positions in real time by FNWC or Fleet Weather Central, Norfolk, Virginia upon request from FWFJAX. Such positions are generally warning-time positions (i.e. position estimates at standard forecast times) at 0400, 1000, 1600 and 2200 GMT, or fix-time positions (i.e. positions fixed by radar, weather reconnaisance, etc.) at or near 0000, 0600, 1200, and 1800 GMT. (5) Both FNWC SR analyses and prognoses were employed for the purpose of obtaining geostrophic steering computations. In the former case, the most recently-dated SR analysis is used for computation of the geostrophic steering component (ANAL-mode). In the latter case, SR prognoses and analyses are used in the forecast of the storm trajectory; this approach will be symbolized as the PROG-mode forecast. (6) HATRACK forecasts were made regularly from SR fields at 1000, 700, and 500 mb.

Fig. 4 is an aid in understanding the differences in the ANAL- and PROG-mode forecasts. The figure also serves to introduce other terminology pertinent to the exposition of results from the 1967 tests. As an example, assume that the SR field is dated 0000 GMT, and that six-hour SR prognostic fields out to 72 hours are available. Further, assume a warning-time storm position at 0000 GMT. For the ANAL-mode storm forecast, the 0000 GMT SR field only is used to generate forecasts out to 72 hours. The same information is used for all subsequent warning-time positions until the 1200 GMT SR analysis becomes available. The PROG-mode forecast version utilizes the 0000 GMT analysis for the initial three-hour numerical steering step, the six-hour (12-hour) SR prognosis for the two subsequent three-hour steering steps, 0300-0600 and 0600-0900 (0900-1200 and 1200-1500) GMT, and so on, in similar fashion, to 72 hours.

As a further example, a storm position of 0400 (1000) GMT would employ the six- (12-) hour SR prognosis in a two-hour time step to 0600 (1200) GMT and a three-hour time step to 0900 (1500) GMT and so on. Thus, forecasts generated from the typical warning-time positions at 0400, 1000, 1600 and 2200 GMT yield estimates for intervals of 2, 8, 14, 20---44---68 hours. 8, 20, 44 and 68 hours are the standard intervals for official (OFFJAX) forecasts as issued in real time by FWFJAX[1]. Documentation of these forecasts, at the end of each calendar year, may be found in FWFJAX publications (1966, 1968).

The term, map age, represents the time difference between the SR analysis and the operational storm position from which the forecasts were started. In the schematic example of Fig. 4, warning times of 0000, 0400 and 1000 GMT indicate map ages of 0, 4 and 10 hours, respectively. It is to be noted that even if the SR analysis is not used in generating a forecast storm position (true for PROG-mode forecasts with map ages three and greater) the map age is still defined with reference to the time of this analysis. Map ages typically range from zero to as high as 18 since, as an example, the 1200 GMT SR analysis and its attendant prognoses may not be available for making storm forecasts until 1800 GMT. The earliest that HATRACK forecasts may be generated is approximately five hours after the synoptic times 0000 and 1200 GMT since analysis and prognosis fields are not available until that time.

[1]These intervals are labeled as 12, 24, 48 and 72 hours by FWFJAX (Fleet Weather Facility, 1968) since the warning-time positions, themselves, are regarded as forecast positions, usually generated by extrapolation from synoptic-time fix positions.

3. 1967 HATRACK forecasts in comparison with 1965 results

Due to several similar features of the 1965 PGS and 1967 HATRACK forecast programs as well as the nature of the tropical storm data to which they were applied (e.g. best track positions in 1965, operational positions in 1967), a comparative evaluation of the two years of data was undertaken. Detailed results of the 1965 tests are contained in a previous article (Renard, 1968). Here, the focus is on the 1967 data. All available operational HATRACK forecasts from the North Atlantic for the 1967 hurricane season were obtained from FNWC and FWFJAX for use in this study. All named storms, except Ginger, are represented in this sample. Arlene, Beulah, Chloe, Doria, Fern and Heide attained hurricane stage, while Edith and Ginger (short life in the eastern North Atlantic) did not develop beyond the storm stage.

The following serves as a common legend for Tables 1 - 3. The tables present HATRACK forecast errors for the isobaric SR level of best performance. With little exception, each forecast was made from the three SR fields, 1000, 700, and 500 mb. The level yielding the least forecast error is shown with its average error, separately by latitude and longitude component of error as well as by total error, in nautical miles per hour of forecast interval. The statistics are presented separately for the non-homogeneous and homogeneous samples. Non-homogeneous (homogeneous) means that the initiation time of the forecast and the forecast interval are not (are) necessarily the same for OFFJAX and HATRACK forecasts. In the non-homogeneous set, forecast statistics are arranged into five <u>grouped</u> forecast intervals. Such grouping became necessary since the HATRACK forecasts were not necessarily initiated at the same clock hours each day nor were they generally begun at hours divisible by six. Although the HATRACK program computes forecast positions every six hours out to 72 hours, the first forecast computes the storm position for the nearest whole hour divisible by six. As an example, more than half of the forecasts in the 7-18 (19-30) hour group are 8 and 14 (20 and 28) hour forecasts, since forecasts were frequently generated from standard warning-time positions at 0400, 1000, 1600 and 2200 GMT. The remainder of the 7-18 (19-30) hour sample are predominantly made up of 12 and 18 (24 and 30) hour forecasts extending from fix-time positions at 0000, 0600, 1200 and 1800 GMT.

The following is an interpretation of the 19-30 hour grouped forecast interval in Table 1, which will aid in understanding the remaining entries in this and subsequent tables. There are 219 numerical HATRACK forecasts at intervals of 19, 20, 21--28, 29, 30 hours while 209 20-hour OFFJAX forecasts were documented. For the latitude and longitude component as well as the total forecast vector, 700 mb SR fields gave the best result in comparison with the 1000 and 500 mb levels. The average latitude and longitude errors are each 3.9 kts, while the average total vector error is 6.2 kt. In the case of the latitude component, OFFJAX errors are less than HATRACK (OFFJAX error = .92 x 3.9 kt) but HATRACK excels OFFJAX in the longitudinal component as noted from an error ratio of 1.21. The total error is least for the HATRACK system with an error ratio of 1.05.

PROG- and ANAL-modes: all map ages: The following conclusions may be drawn from the non-homogeneous 1967 sample in Table 1. The SR 700 mb geostrophic steering winds are associated with the least error for longitude and total vector motion of the tropical storms. In the case of the latitude component, SR 500 (1000) is slightly better than SR 700 at the shorter (longer) forecast intervals. Error per hour generally decreases with increasing interval for component as well as total forecast motion. Relative to OFFJAX forecasts, the HATRACK estimates are best for the longitude component. The total error ratios reflect the influence of the longitudinal results since error ratios at all intervals exceed one. The average error ratio should be noted for comparison to similar data in the subsequent tables.

For the 1965 non-homogeneous data, only the total-error statistics were computed. Also, forecast intervals were limited to 12, 24, 48, and 72 hours only. As in 1967, 700 mb was the best level and the HATRACK forecast errors generally decreased with time. However, the error ratios are more favorable to the numerical scheme in 1967 than in 1965. This is due to the fact that, although the magnitude of forecast errors decreased for both the OFFJAX and HATRACK forecasts in 1967 as compared to 1965, the reduction was 10% in OFFJAX but 17% in the numerical forecasts.

Proceeding to the homogeneous section of Table 1, error statistics are shown for a sample of OFFJAX and HATRACK forecasts. Forecast interval is determined by that used in the OFFJAX forecasts. Conclusions on level of performance and time trend of forecast errors are the same as for the non-homogeneous sample. However, HATRACK (OFFJAX) forecast errors are higher (lower) and error ratios are lower for the homogeneous sample with exceptions for OFFJAX at 8 hours and HATRACK at 68 hours. The inconsistent behavior of this much smaller sample compared to the non-homogeneous set is largely due to differences in the ratio of the number of each storm's forecasts to the total forecasts for the year. For example, consider the 7-18 and 8-hour intervals in Table 1. Arlene, a storm with a relatively large error of 8.8 kt, considering all forecasts, constitutes 12% of the non-homogeneous sample but 17% of the homogeneous one. Heide, a storm with a relatively small error of 3.5 kt, considering all forecasts, constitutes 12% of the non-homogeneous sample but only 7% of the homogeneous one. All other storms appear with approximately the same ratios (to within 3%) in the two tables. In view of this fact, the homogeneous sample cannot be construed as contradicting the conclusions drawn from the consideration of all HATRACK forecasts.

PROG and ANAL modes: map ages 0-6 hours: The format of Table 1 is common to Table 2, however, the statistics in the latter refer to map ages 0-6 hours only. Thus, the storm-forecast sample is reduced by 18% at intervals 7-18 hours to 8% at intervals 55-72 hours from Table 1. From Tables 1 and 2, it is clear that forecast error is less and error ratio is more for the sample with small map age. All other conclusions from Table 1 generally apply to Table 2. It should be pointed out that stratification by map age is somewhat academic; in real-time operational application, the HATRACK program utilizes the most recent SR information regardless of map age. For forecasts initiated at times between 0600 and 1600 (1800 and 0400) GMT only 0000 (1200) GMT SR information is available, hence map ages, of necessity, exceed 6 hours. However, it is practical to rerun forecasts for storm positions at 1200 to 1600 (0000 and 0400) GMT when the 1200 (0000) GMT SR analyses and attendant prognoses become available, which is generally by 1700 (0500) GMT, thereby reducing map ages by 12 hours.

PROG-mode only: all map ages: Table 3 focuses on the PROG-mode forecasts only, for all map ages. Compared to the total possible sample (Table 1) the number of forecast cases is reduced from 33% at the 7-18 hour interval to 20% at the 55-72 hour interval. The results from this table contribute toward the important operational decision as to which forecast mode to apply: PROG or ANAL. On the whole, forecast error is reduced and error ratio increased relative to figures in Table 1. Thus, the PROG-mode excels the ANAL version. In the case of the PROG-mode forecasts, error ratios for every grouped interval in the non-homogeneous set exceeds one while this is true for most intervals in the homogeneous sample. In the latter, the average error ratios now equal or exceed one for latitude and longitude components as well as the total error.

4. 1967 modified HATRACK forecasts

From results shown in Tables 1 - 3, the SR 700 PROG-mode HATRACK forecasts appear to yield results most competitive with the OFFJAX forecast. Table 4 shows intercomparisons of these HATRACK forecasts with selectively modified HATRACK forecasts for homogeneous samples of storm data. Forecast statistics are given separately for 12, 24, and 12 and 24-hour modifications. A 12- or 24-hour modification indicates the <u>approximate</u> forecast interval from which a correction for bias was selected. The following explains the significance of the word <u>approximate</u> here. In order to simulate real-time operational conditions, the 12- and 24-hour corrections for bias were chosen in a particular way. In the case of the 12- (24-) hour modifications, it was arbitrarily decided to use only those 12- (24-) hour HATRACK verifications available within a period 12 hours before time of making forecast. Forecasts from intervals 10-15 (22-27) hours qualified for furnishing the corrections for bias; these are identified as 12- (24-) hour modifications. Further, the most recent forecast verification is chosen for the purpose of selectively modifying a geostrophic SR steer.

Table 4 indicates that, in the case of the latitude component, application of either the 12- or 24-hour bias correction improved upon or equaled the HATRACK forecast for every interval. In summary, the 24-hour modified

HATRACK forecasts result in the least error for the latitudinal component of storm motion. In the case of the longitude component, the modified forecasts equal or excel the HATRACK version only for forecast intervals up to 30 hours. After that, HATRACK, unmodified, is best. The total error reflects both the influence of the latitude and longitude components. The 24-hour modified HATRACK is best at intervals up to 42 hours while the HATRACK system excels for forecasts in intervals 43-72 hours.

It is desirable to present a homogeneous sample of modified and unmodified HATRACK forecasts to include the OFFJAX forecasts. However, since the number of such cases in 1967 (maximum of 15 in the 8-hour interval) is too small to give significance to the result, tables of such statistics are not shown here.

5. Optimal numerical forecast scheme, 1967 versus 1965

Table 5 compares the optimal results from 1965 and 1967 data samples, considering the total forecast storm motion only. SR 700 is the isobaric level which yields the least forecast error in both years. In 1965, only ANAL-mode forecasts were computed; in 1967 the PROG-mode gave better results than the ANAL-mode. In 1965, forecast statistics were stratified by individual forecast intervals whereas in 1967 interval grouping was necessary. The number of forecasts sampled increased from 3% at small to 120% at large forecast intervals from 1965 to 1967. The optimal (i.e. best performing) Navy numerical scheme utilizes a correction for bias for forecast intervals through 36 hours in both years with the 24- (12-) hour bias correction best in 1967 (1965). In 1967, the SR geostrophic steering scheme, unmodified, excels in the late forecast intervals, starting with 43 hours, while the same is not true for 1965 except for 72-hour forecasts. The numerical forecast errors are more stable with time in 1967 and represent an improvement over 1965 after the 24-hour interval.

The error ratios in Table 5 show a stability trend similar to the error itself in the two years sampled. However, the 1967 error ratios are more unfavorable to the optimal numerical scheme through 42 hours compared to 1965. The reverse is true after that time. There are several differences in the two years of storm data sampled, which contribute to this relative behavior of error ratios. In 1965, best track data were used for initial forecast positions whereas in 1967 only real-time operational positions were utilized for this purpose. In 1967, considering only those initial positions used to generate HATRACK forecasts, the average distance from the operational to best track position is 32 n. mi. The effect of this position error on the HATRACK forecast error per hour is greatest for the smallest forecast intervals but decreases with increasing interval. However, with increasing interval another influence prevails. A PROG-mode forecast utilizes a steering field dated within three hours of the storm position at any point in the forecast trajectory (see Fig. 4). For the ANAL-mode, the time of the steering field is earlier than the time of the storm position in its forecast trajectory by a number of hours equal to or greater than the forecast interval. In combination, these two factors may account for the lowering of the error ratio at small intervals but its increase at later intervals in 1967 compared to 1965. Another feature is evident in the 1967 data, namely the inability of the correction for bias to improve upon the unmodified HATRACK forecasts for intervals exceeding 42 hours and the relatively small improvement in forecast error due to this correction at intervals less than 43 hours. In 1965 the correction for bias gave an improvement over the unmodified forecast which amounted to 50% for 12-hour forecasts; in 1967 the improvement was only 18% in a similar forecast interval.

In explanation, one part of the bias inherent in the unmodified 1965 forecasts was removed by using SR prognostic fields vice a single SR analysis for deriving the steering winds in 1967.

6. Concluding remarks

An analysis of the behavior of the Navy's numerical hurricane forecast scheme, as applied to both 1967 and 1965 Atlantic data, indicates skill relative to the official forecast. The ready availability of such forecasts to the hurricane forecaster, in combination with its relative accuracy, suggests that the HATRACK forecast, selectively modified in accordance with Table 5, provides a suitable objective base from which further improvement may be achieved by the experienced official forecaster.

One further table is indicative of the direction in which the Navy's tropical storm research is being directed. Table 6, for all 1967 HATRACK forecasts, indicates errors by area, track, and stage. Minimal forecast errors are committed in Atlantic area B (see Fig. 5) for a depression or hurricane moving on a westward path at latitudes equatorward of the 700 mb subtropical ridge line. Thus, the next step is to stratify the forecast scheme by area, track, stage and other geographical and meteorological criteria in order to enhance and tailor its performance. Another year or more of data are needed for this purpose.

Although it is realized that a dynamic prognostic model ultimately holds the key for an all inclusive movement-development approach to the problem (Sanders 1968), results quoted here serve to suggest use of the selectively modified HATRACK scheme in the interim period of development of such a model.

7. Acknowledgments

The author wishes to thank the Navy Weather Research Facility, Norfolk, Virginia, for continuing financial support of the tropical-storm forecast project and Fleet Numerical Weather Central, Monterey, California, and Fleet Weather Facility, Jacksonville, Florida, for furnishing HATRACK forecast data and valuable advice.

Lieutenant William H. Levings, III, a graduate student in the Department of Meteorology, Naval Postgraduate School until June, 1968, contributed in a major way to the success of the project work described herein. He wrote most of the numerical programs used to process the data and assisted in compiling the voluminous amount of statistics. A coauthored paper with Lieutenant Levings (presently an instructor in the Naval Science Department, Naval Academy, Annapolis, Maryland) entitled "The Navy's Numerical Hurricane and Typhoon Forecast Scheme: Application to 1967 Atlantic Storm Data" will appear in the Journal of Applied Meteorology later this year.

Appreciation is also extended to Steve Rinard and James Cerullo, Department of Meteorology, Naval Postgraduate School, Monterey, California, for their contributions in data handling and computations.

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9. Figure Legends

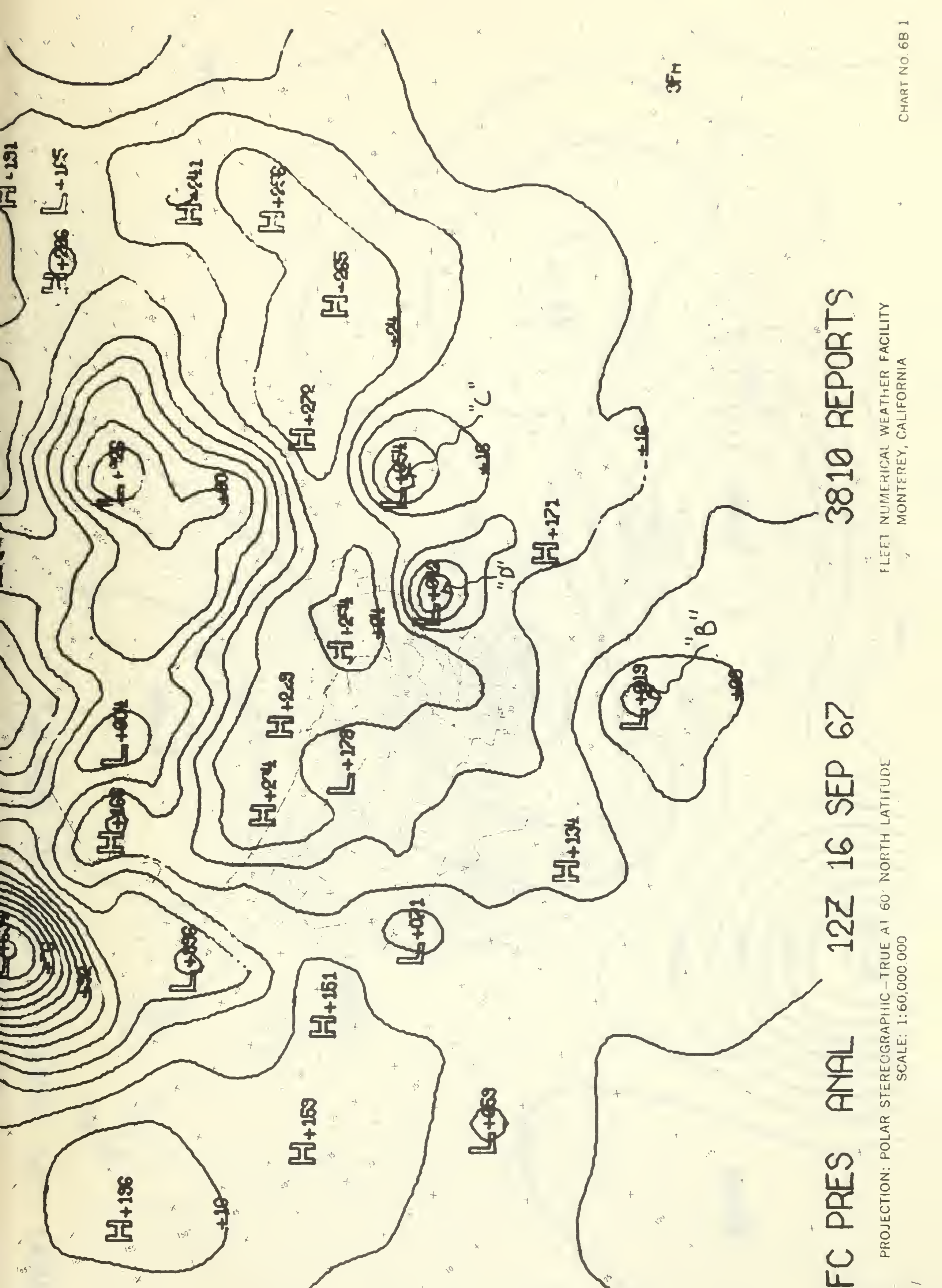
Fig. 1. Portion of the FNWC Northern Hemisphere surface pressure analysis 1200 GMT 16 September 1967. A, B, and C refer to hurricanes Arlene, Beulah, and Chloe. Isobars at 4 mb interval. Isoline (center) labels in tens and units (tens, units and tenths) with thousands and hundreds figures omitted.

Fig. 2. Portions of FNWC's Northern Hemisphere 1000 mb SR analysis, 0000 GMT 16 September 1967. Contours at a 30 m interval: isoline (center) labels in tens (units) of meters.

Fig. 3. Schematic example of a modified 36-hour SR forecast initiated from operational position, T_o. T(F) is best-track (forecast) position, E is error; subscript on T(F) refers to time (forecast interval); superscript on F refers to forecast interval from which correction for bias in F_{xx} is obtained.

Fig. 4. Schematic outline of FNWC's HATRACK steering program, both prognostic and analysis modes. See text for explanation.

Fig. 5. Typical geographical division of the North Atlantic area (A, B, C) for the purpose of stratifying tropical-storm forecast statistics (Tracy, 1966).


SFC PRES ANAL 12Z 16 SEP 67 3810 REPORTS
PROJECTION: POLAR STEREOGRAPHIC—TRUE AT 60° NORTH LATITUDE
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FLEET NUMERICAL WEATHER FACILITY
MONTEREY, CALIFORNIA
CHART NO. 6B 1
"B"
"C"
"D"

Fig. 1

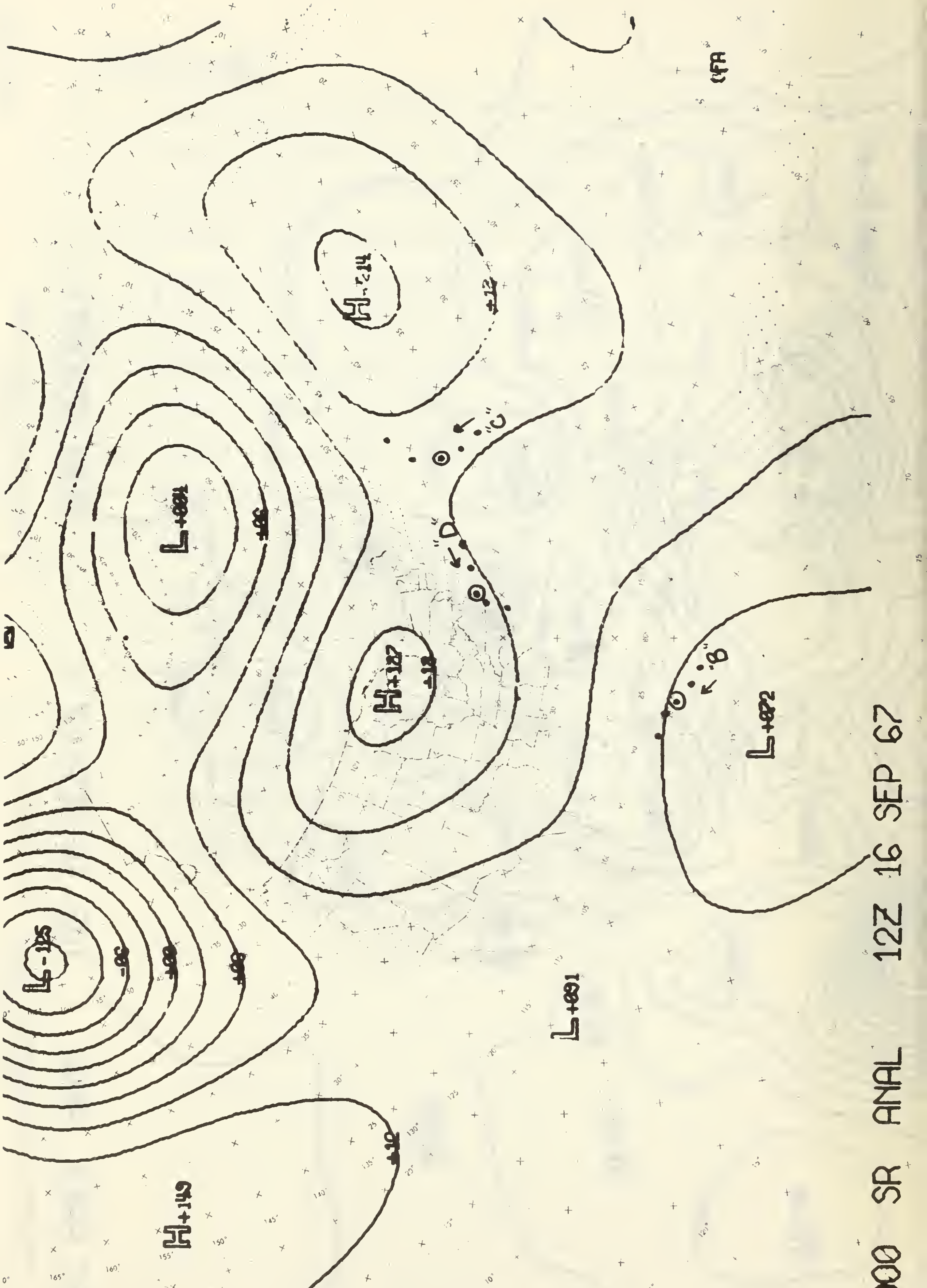


Fig. 2

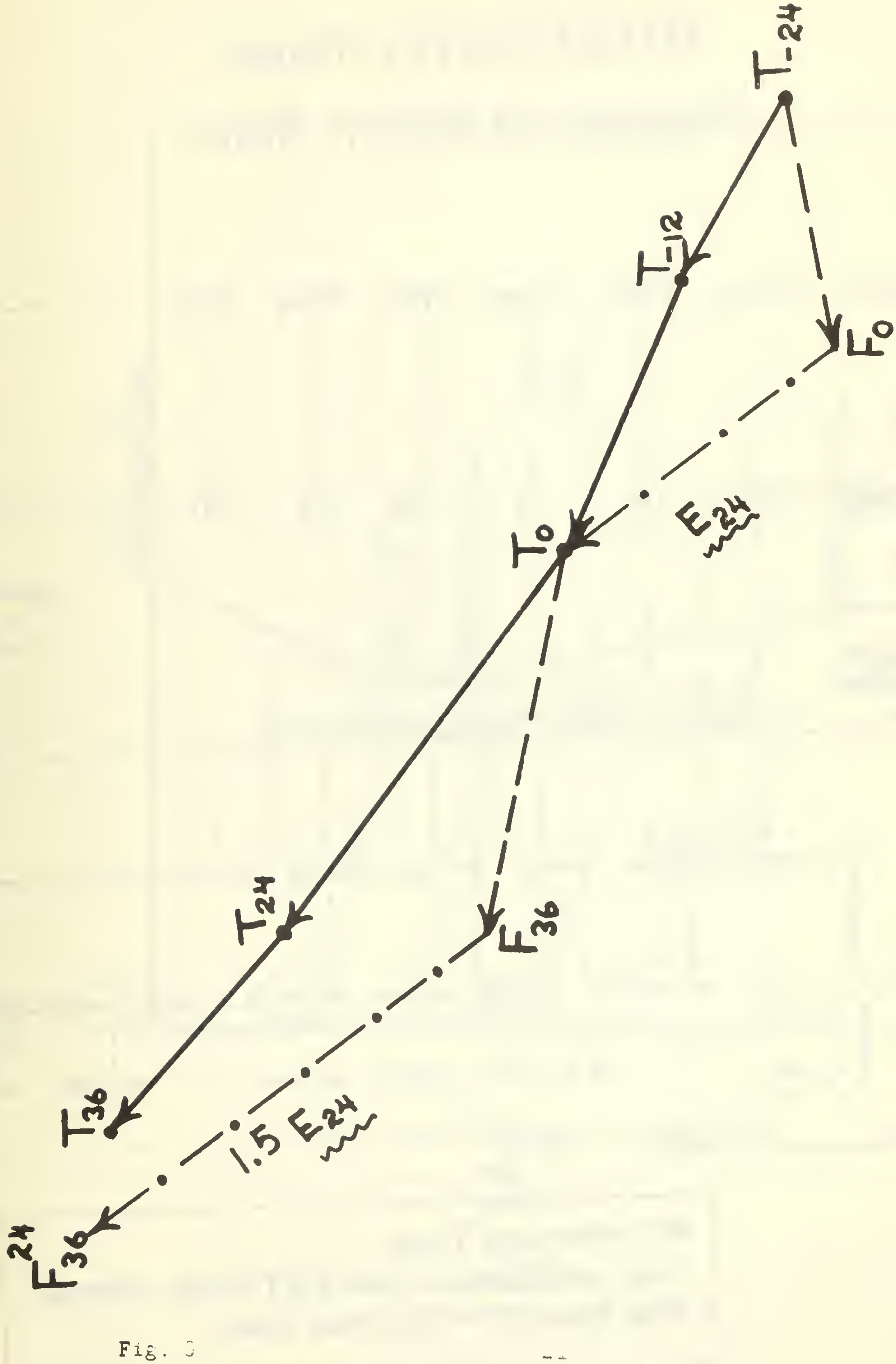
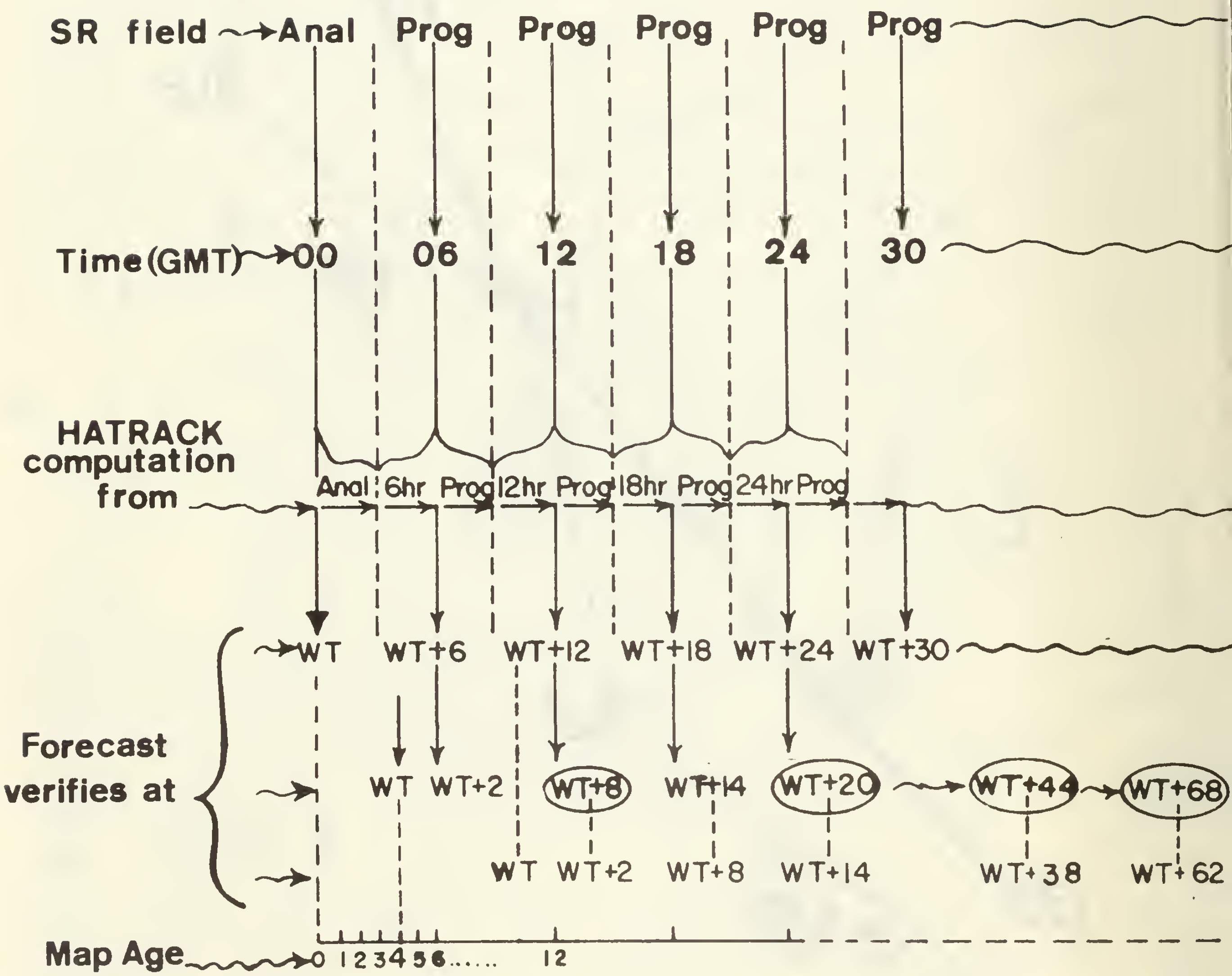


Fig. 3

HATRACK Steering Program
Prognostic and Analysis Modes



WT= Warning Time
Fcst verification time = WT+Fcst Interval
Map Age = WT−SR Anal time

Fig. 4

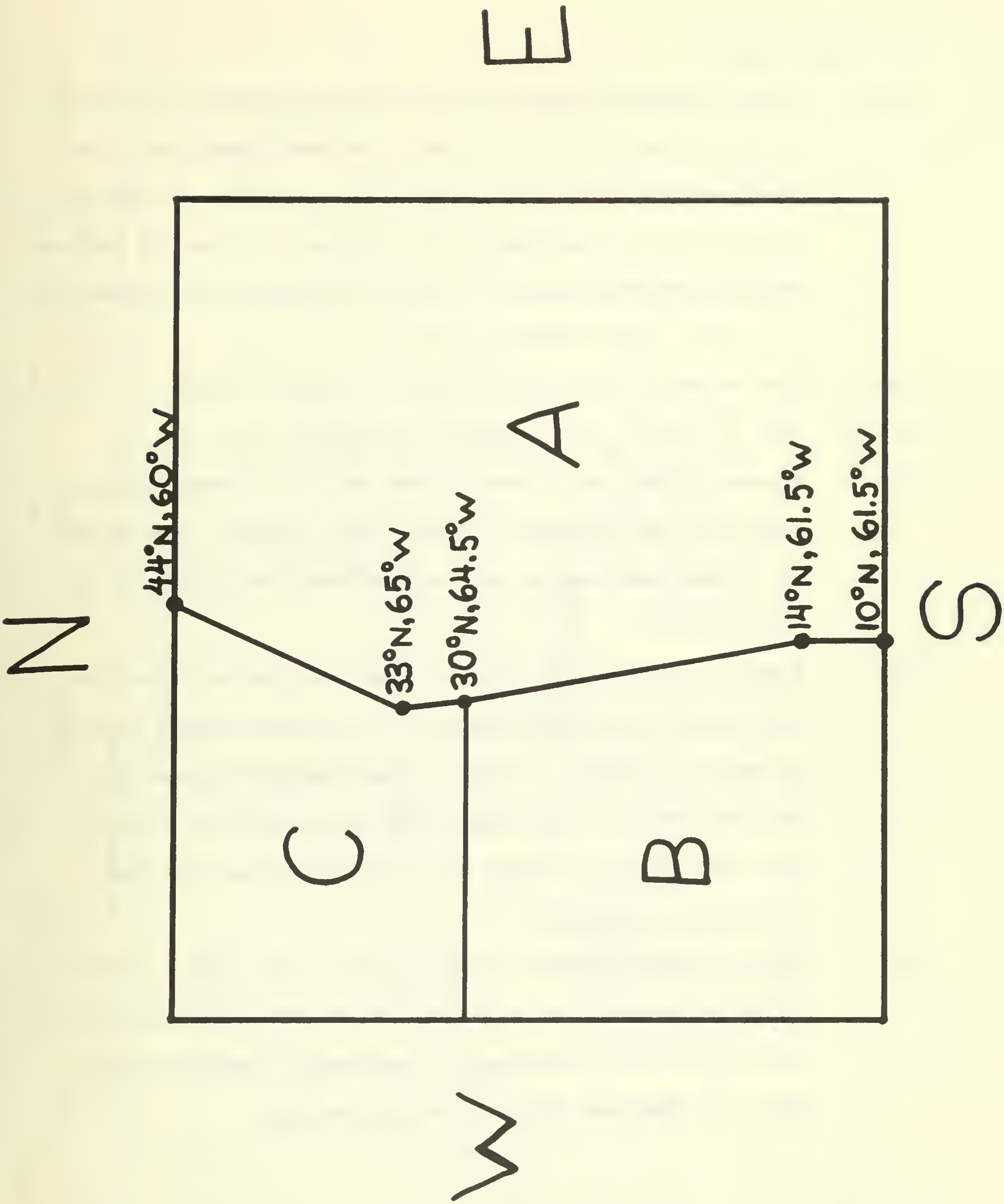


Fig. 5

10. Table Legends

Table 1. Average HATRACK forecast errors (kts) and isobaric SR level of best performance for 1967 Atlantic tropical storms, with comparative results for 1965. Sample includes PROG- and ANAL-mode forecasts for all mpa ages. N (O) represents number of numerical HATRACK (OFFJAX) forecasts. E is interpolated error estimate for intervals in which OFFJAX forecasts do not exist.

Table 2. Same as Table 1, except map ages 0-6 hours only, 1967.

Table 3. Same as Table 1, except PROG-mode forecasts only, 1967.

Table 4. Average HATRACK and 12- and 24-hour modified HATRACK forecast errors for 1967 Atlantic tropical storms, computed from SR 700 mb. Homogeneous samples are for PROG-mode forecasts only, for all map ages.

Table 5. Summary of performance of Navy's numerical tropical-storm forecast scheme from non-homogeneous 1965 and 1967 samples of SR 700 mb total forecast errors. Optimal indicates scheme with best performance, symbolized as F_{XX}^{YY}, where XX refers to forecast interval and YY refers to the interval from which bias correction is obtained.

Table 6. Average HATRACK forecast errors (kt) for 1967 Atlantic tropical storms as computed from SR 700 mb and stratified by geographical area, storm track, and stage of development. Sample includes PROG- and ANAL-mode forecasts for all map ages.

1967								1965			
Forecast Intervals (hrs)	Number of Forecasts	Latitude HATRACK	Latitude OFF/HATR	Longitude HATRACK	Longitude OFF/HATR	Total HATRACK	Total OFF/HATR	Forecast Interval (hrs)	Number of Forecasts	Total PGS	Total OFF/PGS
NON-HOMOGENEOUS SAMPLE											
7-18	N: 231 O: 213	500(700) 4.5(4.6)	1.07	700 4.4	1.43	700 7.1	1.01	12	N: 93 O: 137	700 7.8	.92
19-30	N: 219 O: 209	700 3.9	.92	700 3.9	1.21	700 6.2	1.05	24	N: 89 O: 134	700 7.4	.96
31-42	N: 207 O: ---	700 3.8	.92E	700 3.8	1.16E	700 6.1	1.02E	36	N: 84 O: ---	700 7.2	.99E
43-54	N: 170 O: 186	1000(700) 3.5(3.6)	.97	700 3.7	1.14	700 5.8	1.03	48	N: 80 O: 112	700 7.2	1.00
55-72	N: 190 O: 156	1000,700 3.1	1.13	700 3.7	1.27	700 5.3	1.21	72	N: 70 O: 98	700 7.1	1.06
Average			1.00		1.24		1.06				
HOMOGENEOUS SAMPLE											
8	59	500(700) 5.2(5.3)	.92	700 5.3	1.00	700 8.3	.93				
20	55	700 4.4	.84	700 4.0	1.08	700 6.7	.93				
44	42	1000,700 4.0	.85	700 3.7	1.08	700 6.2	.95				
68	20	1000(700) 3.0(3.3)	1.00	700 3.5	1.31	700 5.2	1.15				
Average			.90		1.12		.99				

TABLE 1

Forecast Intervals (hrs)	Number of Forecasts	Latitude HATRACK	Latitude OFF/HATR	Longitude HATRACK	Longitude OFF/HATR	Total HATRACK	Total OFF/HATR
NON-HOMOGENEOUS SAMPLE							
7-18	N: 189 O: 213	500(700) 4.3(4.4)	1.12	700 4.0	1.58	700 6.5	1.34
19-30	N: 179 O: 209	700 3.8	.95	700 3.6	1.30	700 5.8	1.12
31-42	N: 170 O: ---	700 3.6	.97E	700 3.5	1.26E	700 5.7	1.09E
43-54	N: 146 O: 186	1000(700) 3.4(3.5)	1.00	700 3.5	1.20	700 5.6	1.07
55-72	N: 175 O: 156	700 3.0	1.17	700 3.6	1.30	700 5.2	1.22
Average			1.04		1.33		1.17
HOMOGENEOUS SAMPLE							
8	48	500(700) 5.1(5.2)	.85	700 4.5	1.09	700 7.5	.96
20	45	700 4.3	.81	700 3.5	1.14	700 6.2	.94
44	38	1000,700 4.1	.85	700 3.5	1.03	700 6.1	.92
68	20	1000(700) 3.0(3.3)	1.00	700 3.5	1.31	700 5.2	1.15
Average			.88		1.14		.99

TABLE 2

Forecast Intervals (hrs)	Number of Forecasts	Latitude		Longitude		Total	
		HATRACK	OFF/HATR	HATRACK	OFF/HATR	HATRACK	OFF/HATR
NON-HOMOGENEOUS SAMPLE							
7-18	N: 154 O: 192	500(700) 3.6(3.7)	1.28	700 3.6	1.64	700 6.3	1.30
19-30	N: 146 O: 190	700 3.0	1.13	700 3.7	1.22	700 5.2	1.17
31-42	N: 138 O: ---	1000,700 3.1	1.03E	700 3.6	1.19E	700 5.5	1.13E
43-54	N: 129 O: 171	1000(700) 3.1(3.5)	1.06	700 3.6	1.22	700 5.5	1.09
55-72	N: 152 O: 145	1000(700) 3.1(3.2)	1.06	700 3.5	1.37	700 5.2	1.21
Average			1.11		1.33		1.18
HOMOGENEOUS SAMPLE							
8	35	700 3.6	1.06	700 5.2	1.00	700 7.1	.97
20	32	1000,700 2.9	1.15	700 3.8	1.08	700 5.3	1.04
44	26	1000(700) 2.8(3.1)	1.11	700 3.7	1.14	700 5.2	1.10
68	15	1000(700) 2.8(3.3)	.82	1000(700) 3.3(3.5)	1.09	1000,700 5.2	.88
Average			1.04		1.08		1.00

TABLE 3

Forecast Intervals (hrs)	Number of Forecasts	Latitude HATRACK	Latitude 12-Hour Modified HATRACK	Latitude 24-Hour Modified HATRACK	Longitude HATRACK	Longitude 12-Hour Modified HATRACK	Longitude 24-Hour Modified HATRACK	Total HATRACK	Total 12-Hour Modified HATRACK	Total 24-Hour Modified HATRACK
HATRACK VS 12-HOUR MODIFIED HATRACK										
7-18	106	3.6	3.1		3.8	3.4		5.8	5.2	
19-30	103	3.2	3.0		3.4	3.5		5.3	5.1	
31-42	102	3.2	3.1		3.4	3.7		5.2	5.3	
43-54	95	3.8	3.6		3.3	4.0		5.5	6.1	
55-72	118	3.4	3.4		3.3	4.2		5.2	6.3	
HATRACK VS 24-HOUR MODIFIED HATRACK										
7-18	90	3.8		3.2	3.9		3.9	5.8		5.4
19-30	85	2.9		2.8	3.4		3.5	5.1		4.9
31-42	83	3.0		2.8	3.5		3.9	5.1		5.2
43-54	75	3.6		3.6	3.6		3.6	5.8		6.3
55-72	90	3.3		3.3	3.8		5.0	5.6		6.9
HATRACK VS 12-HOUR AND 24-HOUR MODIFIED HATRACK										
7-18	75	3.5	3.5	2.9	3.9	3.2	3.3	5.9	5.3	4.9
19-30	73	3.1	3.4	2.7	3.6	3.6	3.4	5.4	5.4	4.7
31-42	74	3.1	3.3	2.7	3.6	3.7	3.7	5.3	5.6	5.1
43-54	67	3.8	4.1	3.5	3.7	4.0	4.4	6.0	6.6	6.3
55-72	79	3.4	3.7	3.4	3.8	4.3	4.9	5.6	6.5	6.7

TABLE 4

1965: ANAL-MODE FORECASTS

Forecast Intervals (hrs)	Optimal PGS Scheme	Number of Forecasts	Average Error (n.mi/hr of Forecast Interval)	OFF / Optimal PGS
12	F_{12}^{12}	N: 87 O: 137	3.9	1.83
24	F_{24}^{12}	N: 83 O: 134	4.9	1.46
36	F_{36}^{12}	N: 78 O: ---	5.9	1.23E
48	F_{48}^{12}	N: 75 O: 112	6.8	1.06
72	F_{72}	N: 70 O: 98	7.1	1.06

1967: PROG-MODE FORECASTS

Forecast Intervals (hrs)	Optimal NUM Scheme	Number of Forecasts	Average Error (n.mi/hr of Forecast Interval)	OFF / Optimal NUM
7-18	F_{xx}^{24}	N: 90 O: 192	5.4	1.52
19-30	F_{xx}^{24}	N: 85 O: 190	4.9	1.24
31-42	F_{xx}^{24}	N: 83 O: ---	5.2	1.13E
43-54	F_{xx}	N: 129 O: 171	5.5	1.09
55-72	F_{xx}	N: 152 O: 145	5.2	1.21

TABLE 5

	FORECAST INTERVALS																			
	7-18 Hours				19-30 Hours				31-42 Hours				43-54 Hours				55-72 Hours			
	No of Fcsts	Lat.	Long.	Total	No of Fcsts	Lat.	Long.	Total	No of Fcsts	Lat.	Long.	Total	No of Fcsts	Lat.	Long.	Total	No of Fcsts	Lat.	Long.	Total
AREA																				
A	119	5.4	4.8	8.2	117	4.6	4.4	7.2	112	4.6	4.1	7.1	89	4.0	4.3	6.5	95	3.5	4.7	6.4
B	74	2.7	3.1	4.5	65	2.0	2.3	3.5	60	1.9	2.3	3.2	51	2.1	2.0	3.3	62	2.2	1.8	3.1
C	38	5.7	5.8	8.8	37	5.0	5.2	7.8	35	4.5	5.4	7.8	30	5.0	4.9	8.0	33	3.6	4.4	6.3
TRACK																				
Before Re-curvature	159	3.8	4.2	6.2	144	3.1	3.3	5.1	131	3.0	3.0	4.8	111	3.3	2.9	4.9	123	2.9	2.7	4.3
After Re-curvature	72	6.4	4.9	9.1	75	5.5	5.1	8.3	76	5.2	5.2	8.3	59	4.2	5.2	7.5	67	3.5	5.5	7.2
STAGE																				
Depression	28	4.4	4.4	6.3	22	3.7	2.4	5.0	17	4.3	2.3	5.4	13	4.5	2.2	5.3	18	3.8	2.5	4.9
Storm	56	5.3	5.0	8.0	51	4.5	4.1	7.0	48	4.5	3.9	6.9	42	3.2	4.0	6.1	46	2.1	4.3	5.3
Hurricane	144	4.3	4.2	6.9	142	3.6	4.1	6.0	133	3.2	3.9	5.7	110	3.6	3.7	5.7	124	3.4	3.7	5.4
Extra-tropical	3	6.3	2.0	6.9	4	8.7	3.6	9.6	9	7.6	4.4	9.3	5	4.5	4.8	7.1	2	1.0	2.3	2.6

TABLE 6

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13. ABSTRACT

Renard recently reported (Monthly Weather Review, July 1968) on a numerical scheme for predicting the motion of tropical storms for intervals up to 72 hours. The forecast technique is applied in two steps. First, numerical geostrophic steering of the cyclone center is accomplished using Fleet Numerical Weather Central's analyses and prognoses of smoothed isobaric height fields, called SR fields. Next, a statistical correction for vector bias in the numerical steering computation is used selectively in an attempt to improve the accuracy of the forecast track. The bias modification is dependent solely on the peculiarities of recent-history 12- and 24-hour forecasts in relation to the actual storm trajectory. Forecasts for intervals up to 72 hours, generated from the 1967 Atlantic operational storm positions, are compared to the results from previous experimental forecasts for 1965 using best-track positions of Atlantic storms. Results indicate the numerical scheme shows skill in relation to both 1965 and 1967 official-forecast accuracy as documented by Fleet Weather Facility, Jacksonville, Florida. In 1967, the relative improvement over official forecasts, using 700 mb prognostic SR fields for steering, ranges from 52% at forecast intervals of 7-18 hours to 9% at forecast intervals of 43-54 hours. Discussions of various forecast modes and selective modification schemes as well as stratification of error statistics by area, track, and storm stage are included.

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