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Forecasting the motion of North Atlantic tropical cyclones by the objective MOHATT scheme

Renard, R.J.

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Forecasting the Motion of North Atlantic Tropical Cyclones by the Objective MOHATT Scheme

R. J. RENARD, S. G. COLGAN,[1] M. J. DALEY,[2] and S. K. RINARD
Department of Meteorology, Naval Postgraduate School, Monterey, Calif.

ABSTRACT—An objective scheme for forecasting the motion of tropical cyclones (MOHATT), under development since 1967 by the U.S. Navy Fleet Numerical Weather Central and the U.S. Naval Postgraduate School, Monterey, Calif., is described and applied to the 1967–71 North Atlantic tropical cyclones for forecast intervals up to 72 hr. The MOHATT scheme involves steering of the center of the cyclone by geostrophic winds derived from heavily smoothed isobaric height fields (both analyzed and prognostic) and a statistical correction determined by the behavior of the first 12 hr of the steering forecast. The developmental sample (1967–70) used to establish the potential accuracy of MOHATT indicates 700 mb as the optimum steering level, but the fully operational test in 1971 suggests that the 850-mb level may be an improvement for forecast intervals beyond 36 hr.

An analysis of the 1971 forecast data shows errors (expressed as nautical miles per hour of forecast interval) ranging from 6.1 kt at 12 hr (252 cases) to 5.1 kt at 42 hr (199 cases) and 5.5 kt at 72 hr (158 cases). Relative to stage of development, hurricanes are forecast with the most success, errors ranging from 4.4 kt at 18 hr (98 forecasts) to 5.5 kt at 72 hr (85 forecasts); relative to area, the eastern Atlantic yields the more accurate forecasts.

Comparison of MOHATT with the National Hurricane Center's (NHC) NHC–67 technique using a homogeneous sample of 1971 forecasts indicates that MOHATT accuracy exceeds that of NHC at intervals beyond 24 hr, with the improvement exceeding 30 percent at 72 hr. Similar tests relative to the typhoon-tracking forecast scheme (TYRACK) developed at the U.S. Navy Fleet Weather Central, Honolulu, Hawaii, show that MOHATT errors averaged 38 percent less than TYRACK in 1971. Interpretation of the results of comparing operational Official and MOHATT forecasts is complicated by differences in the forecast intervals of the two systems. In any case, based on the 1971 operational test, the MOHATT forecasts are more accurate than the Official ones after 36 hr, while near equivalence prevails in the earlier intervals. Forecast examples and a discussion of various facets of the MOHATT scheme are included.

1. INTRODUCTION

An objective scheme for forecasting the motion of all stages of tropical cyclones has been under development since 1967 as a cooperative effort of the Department of Meteorology, U.S. Naval Postgraduate School (NPS) and the U.S. Navy Fleet Numerical Weather Central (FNWC), Monterey, Calif. Recent and extensive testing on both experimental and operational data from the North Atlantic Ocean area has empirically established both the potential and existent accuracy of the subject forecast scheme, hereby identified as MOHATT. MOHATT is an acronym for Modified HATRACK, where HATRACK refers to a particular technique for forecasting tropical cyclone tracks and Modified signifies an improved version of HATRACK. Although certain aspects of the MOHATT scheme have been reported in the literature (Renard 1968, Renard and Levings 1969, Renard et al. 1970), it is deemed advisable to specify the nature of the MOHATT forecast program before presenting details on the most recent evaluation.

2. MOHATT FORECAST PROGRAM

The MOHATT forecast scheme comprises numerical and statistical segments. The numerical component, known operationally as HATRACK, is derived by regarding the tropical cyclone as a perturbation with a trajectory that is well related to a much larger scale circulation feature on which the cyclone is superimposed. The circulation feature, hereafter called the steering field, is represented by a heavily smoothed isobaric height analysis and/or prognosis, as produced at FNWC. The numerical processing involved in obtaining the steering field, known operationally as SR, yields an isohypsic pattern resembling long waves, since SR is mostly composed of wave number components $\leq$ 6. Quasi-geostrophic SR winds [3] are computed at the location of the tropical cyclone center to steer the cyclone in 3-hr time steps, using the operationally available analysis and/or attendant prognoses that most closely match the time of the cyclone's forecast trajectory. Although details on the SR levels used and the forecast intervals computed will be described in the sections that follow, figure 1 exemplifies the typical relationship between the cyclone's actual track and the steering implied by the 1000- and 500-mb SR height fields. In this example, one depression, three tropical storms, and one hurricane existed at 1200 GMT on Sept 12, 1971, in the North Atlantic–

[1] Now at U.S. Fleet Weather Central/Joint Typhoon Warning Center, Guam, Marianas Islands

[2] Now at Fleet Weather Facility, Keflavik, Iceland

[3] "Quasi" refers to the use of a sine function, $\sin\theta'$, of the following form in the geostrophic wind equation at latitudes less than 30°: $\sin\theta' = 2[0.25 \sin\theta + 0.25)^2 + 0.25 \sin\theta]$. $\sin\theta'$ ranges from 0.125 at the Equator (the $\sin\theta$ value at 7.2° lat.) to 0.53 at 30° latitude.

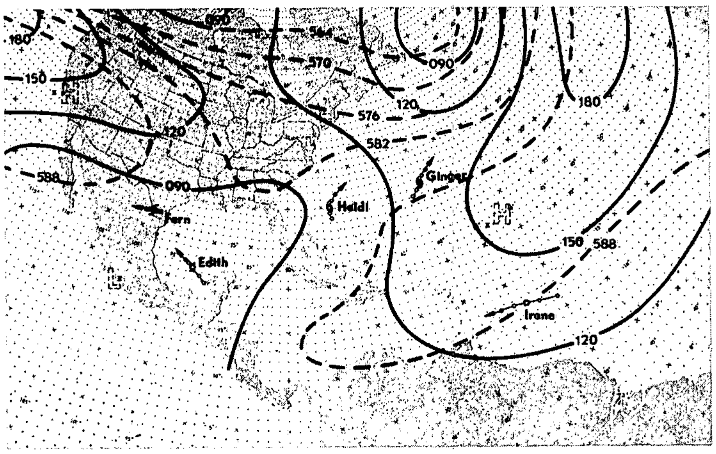

FIGURE 1.—The FNWC 1000-mb (solid lines, m) and 500-mb (dashed lines, dam) SR analyses for 1200 GMT, Sept. 12, 1971. Best-track positions are shown for each tropical cyclone at 6-hr intervals from 0000 GMT, Sept. 12, to 0000 GMT, Sept. 13, 1971.

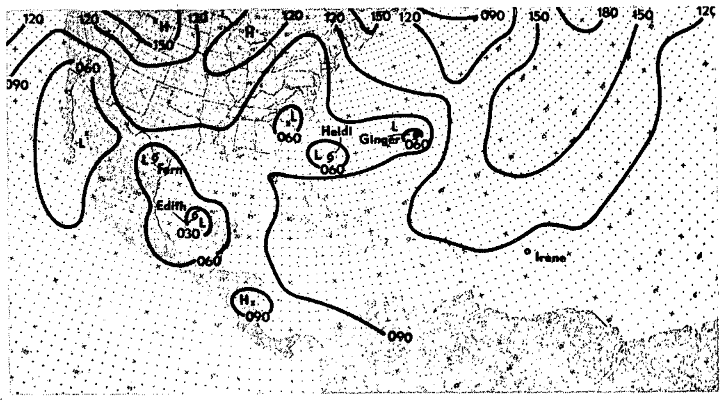

FIGURE 2.—FNWC 1000-mb analysis (m) for 1200 GMT, Sept. 12, 1971.

Gulf of Mexico area (fig. 2). Figure 1 clearly indicates that the cyclone track orientation is best related to a geostrophic SR-wind direction at a level between 1000 and 500 mb.

Historically, HATRACK was the first operationally used component of MOHATT. Such forecasts have been issued for field use by the appropriate Navy Weather Centrals [e.g., U.S. Fleet Weather Central (FWC) Norfolk, Va., for Fleet Weather Facility (FWF) Jacksonville, Fla., in the Atlantic Ocean area; FNWC Monterey, Calif., for use by FWF Alameda, Calif., in the eastern Pacific Ocean area; and FWC/Joint Typhoon Warning Center, Guam, in the western Pacific area].

Figure 3 shows a HATRACK forecast (hereafter called forecast set), typical of those issued in real time. The forecast information is for tropical cyclone Chloe whose center was located at 13.7°N, 57.3°W at 0000 GMT on Aug. 19, 1971. Subsequent entries are forecast positions at 6-hr intervals. The figures in the last column indicate the 6-hr forecast motion (degrees and knots) centered at the time given in the first column with the exception that the first-line entry (2911) indicates the predicted motion for the 3-hr period 0000 to 0300 GMT on Aug. 19, 1971.

A study of HATRACK forecasts for several years (especially in the North Atlantic area) indicated that, although the track orientations were reasonably forecast, the cyclone center speeds were generally slow. This inaccuracy of the geostrophic steering, hereafter referred to as a bias,[4] led to various statistical attempts to improve the HATRACK forecasts. There evolved from these experiments the present mode of coupling HATRACK with a statistical correction for its bias, considering the errors of a HATRACK forecast set to be linearly related to the forecast interval with certain empirical limitations. Specifically, the bias correction requires knowledge of the 6- and 12-hr errors, E_6 and E_{12}, in a given HATRACK forecast set. These errors, separately by latitude and longitude, are then extrapolated linearly in time, t, as estimated errors, E'_t, in the HATRACK forecasts for $t > 12$ hr. Thus,

$$E'_t = E_{12} + \frac{(E_{12} - E_6)(t-12)}{6}, \qquad (1)$$

and the MOHATT forecast, F', for any time, $t-12$, is given by

$$F'_{t-12} = F_t + E'_t \qquad (2)$$

where F_t represents the HATRACK forecast at time t and E'_t is applied as a correction to F_t.

Figure 4 shows a schematic illustration of the relation of the MOHATT forecast scheme to its component parts. It is to be noted that, for intervals $\geq$ 24 hr, each HATRACK forecast generates a MOHATT forecast for an interval 12 hr less than its associated HATRACK forecast. The empirical restrictions imposed on the statistical correction for bias in HATRACK are illustrated in figure 5. The ratio of observed HATRACK errors, E_6/E_{12}, is

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TROPICAL CYCLONE STEERING
PROG MODE
J01 TD05
ANAL TIME     00190871
LEVEL     700 MB
00190871      137N 0573W   2911
06190871      140N 0587W   2815
12190871      143N 0603W   2815
18190871      146N 0618W   2813
00200871      149N 0634W   2815
06200871      152N 0652W   2817
12200871      155N 0673W   2821
18200871      158N 0694W   2819
00210871      162N 0715W   2819
06210871      165N 0737W   2819
12210871      169N 0758W   2817
18210871      172N 0778W   2817
00220871      176N 0795W   2915
06220871      181N 0812W   2915
12220871      187N 0829W   2915
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FIGURE 3.—Sample HATRACK forecast set for tropical-cyclone Chloe initiated from 13.7°N, 57.3°W at 0000 GMT, Aug. 19, 1971.

[4] Bias, as used here, is not only a function of the ageostrophic wind at the steering level selected but of the collective errors arising from operational and best-track cyclone positioning, numerical analysis and prognosis, and specification of the appropriate steering parameter and level, among others.

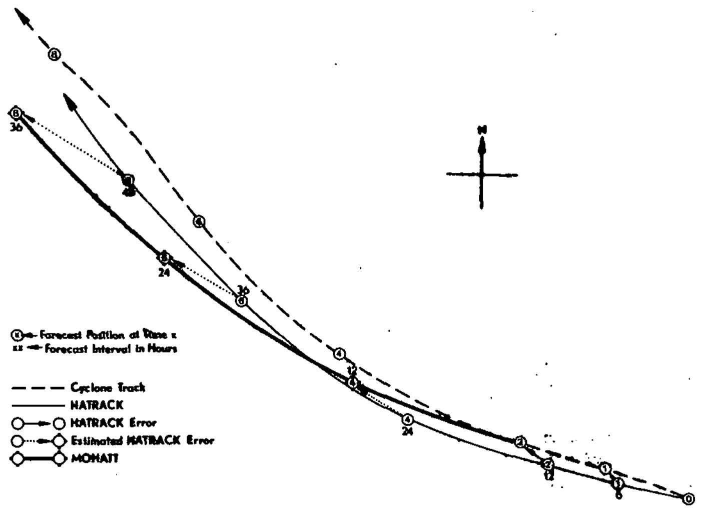


FIGURE 4.—Schematic HATRACK and MOHATT tropical cyclone forecast tracks and typical actual cyclone track (i.e., best track).

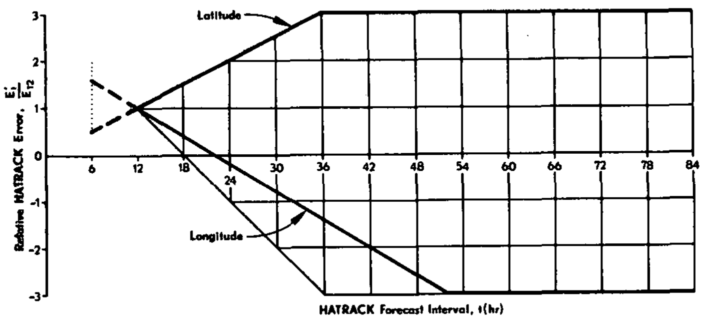


FIGURE 5.—Pictorial representation of the zone (gridded area) of allowable estimated HATRACK errors expressed as a function of HATRACK forecast interval and relative HATRACK error (ratio of known or estimated HATRACK error at time t to HATRACK error at 12 hr). The known relative errors (heavy dashed lines) and estimated relative errors (heavy solid lines) are plotted for the forecast set shown in figure 3.

constrained to be within the range 0.5 to 2.0. The ratio of the estimated error at time t to the known error at 12 hr, E'_t/E_{12}, is algebraically restricted to the zone $\leq|3|$ relative error units.

A worksheet facilitating the manual computation of MOHATT from its HATRACK and modified portions is shown in figure 6. As an illustration, the worksheet is entered with information from the HATRACK forecast set in figure 3, to generate MOHATT forecasts. The example shows application of a few of the empirical restrictions described above and listed at the bottom of the worksheet. A graphical representation of the actual (at 6 and 12 hr) and estimated (at $t > 12$ hr) relative HATRACK errors for this case is given in figure 5. Although the modification calculation manually takes only 5–10 min for a typical HATRACK set, the MOHATT program was automated for the 1972 tropical cyclone season.

One further restriction in the MOHATT program invalidates any cyclone position, initial or forecast, HATRACK or MOHATT, at latitudes $\leq$5°N or $\geq$ 50°N. Such locations automatically terminate the forecast procedure at that point.

3. DEVELOPMENT AND EVALUATION

Although some developmental testing of MOHATT was accomplished for the western North Pacific Ocean area (Renard et al. 1970), the emphasis has been on the North Atlantic Ocean. Only the latter area will be discussed.

a. The Nature of the Developmental Test, 1967–70

The experimental test comprised tropical cyclones in the years 1967 through 1970. This period is to be viewed as establishing the *potential* accuracy of MOHATT (vice the existent operational accuracy discussed in sec. 4). There follows a résumé of the important procedural aspects concerned with the testing.

HATRACK component

1. The steering component (i.e., HATRACK) of MOHATT was calculated operationally from SR fields at cyclone center positions. For most of the 4-yr period, HATRACK forecasts were made available (via computer processing at FNWC or FWF Norfolk) to FWF Jacksonville for guidance in real-time forecasting.

2. The HATRACK forecasts were generated *irregularly* at the request of FWF Jacksonville, using cyclone center positions at warning times [5] (0400, 1000, 1600, 2200 GMT) and/or synoptic times (0000, 0600, 1200, 1800 GMT). This forecast sample was not enhanced or changed by employing data or analyses determined in post-season.

3. HATRACK forecasts were based on 1000-, 700-, and 500-mb SR fields. The 700-mb level was selected as the optimum steering level from this developmental sample. Consequently, all results for 1967–70 are derived from 700-mb steering.

4. The steering program has two options. Either the SR analysis (anal mode) *only* is used for all 3-hr forecast increments, or the SR analysis and prognoses generated therefrom (prog mode) are used to compute the forecasts in 3-hr increments.

For the 1967–70 period, the SR prognoses, derived from FNWC's modified barotropic model, were available for 6-hr intervals to 48 hr. The prog mode version proved to be superior and was used in all forecasts evaluated here. The scheme is outlined in figure 7. For example, a 0000 GMT cyclone center position would be steered for 3 hr in the 0000 GMT SR analysis field, for two 3-hr time steps in the 6-hr SR prognostic field verifying at 0600 GMT, and so forth; a cyclone position initiated at 0600 GMT would be steered for one time step using the 6-hr SR prognosis, for two time steps using the 12-hr SR prognosis verifying at 1200 GMT, and so forth. Forecasts may be initiated from other than synoptic times. For example, for a position initiated at the 1000 GMT warning time, the 12-hr SR prognosis is employed for one 2-hr and one 3-hr time step, and so forth.

[5] Times at which the tropical cyclones are operationally documented and from which positions the Official forecasts are issued

Worksheet for Computing 12, 24, 36, 48, and 72 hour MOHATT Forecasts

Basic Formulae: $E'_t = E_{12} + [(E_{12} - E_6)(t-12)]/6$ $\quad F'_{t-12} = F_t + E'_t$

F_t = HATRACK forecast position at time t

F'_{t-12} = MOHATT forecast position at time t-12

E_t = Error in F_t, computed as true minus forecast position

E'_t = Estimated error of F_t for forecast interval > 12 hr.

Tropical cyclone 5 (#), CHLOE (name), 700 MB (steering level) HATRACK forecast initiated from 13.7N 57.3W (lat-long) at t_o = 00 (time) Z 1908 (date) 1972

	Latitude component	Longitude component
at t_o + 6 hr:	$a = E_6$ = ~~0.0~~° lat.* -0.15	$a = E_6$ = +0.8° long.*
at t_o + 12 hr:	$b = E_{12}$ = -0.3° lat.*	$b = E_{12}$ = +0.5° long.*
	$c = b-a$ = -0.15° lat.	$c = b-a$ = -0.3° long.

	Latitude ($F'= F + E'$)	Longitude ($F' = F + E'$)
F'_{12} at t_o + 24 hr = 00 Z 20 (time date):	F'_{12} = 14.9 (F_{24}) + -0.6 (E'_{24} = b+2c) = 14.3° lat.	F'_{12} = 63.4 (F_{24}) + -0.1 (E'_{24} = b+2c) = 63.3° long.
F'_{24} at t_o + 36 hr = 12 Z 20 (time date):	F'_{24} = 15.5 (F_{36}) + -0.9 (E'_{36} = b+4c) = 14.6° lat.	F'_{24} = 67.3 (F_{36}) + -0.7 (E'_{36} = b+4c) = 66.6° long.
F'_{36} at t_o + 48 hr = 00 Z 21 (time date):	F'_{36} = 16.2 (F_{48}) + ~~-1.2~~ -0.9 (E'_{48} = b+6c) = 15.3° lat.$	F'_{36} = 71.5 (F_{48}) + -1.3 (E'_{48} = b+6c) = 70.2° long.$
F'_{48} at t_o + 60 hr = 12 Z 21 (time date):	F'_{48} = 16.9 (F_{60}) + -0.9 (E'_{60} = b+8c) = 16.0° lat.$	F'_{48} = 75.8 (F_{60}) + ~~-1.9~~ -1.5 (E'_{60} = b+8c) = 74.3° long.$
F'_{72} at t_o + 84 hr = 12 Z 22 (time date):	F'_{72} = 18.7 (F_{84}) + -0.9 (E'_{84} = b+12c) = 17.8° lat.$	F'_{72} = 82.9 (F_{84}) + -1.5 (E'_{84} = b+12c) = 81.4° long.$

SPECIAL RULES:

*(1) For b=0 If $a \geq 0$, set $b = +0.1$; If $a < 0$, set $b = -0.1$; and if $|a| > 0.2$, set $|a| = 0.2$

*(2) For a and b with opposite algebraic signs, set $a = 0.5b$

*(3) For $a = 0$ and $b \neq 0$ or both a and b with same algebraic sign:
If $|a|/|b| > 2.0$, change $|a|$ so that $a/b = +2.0$
If $|a|/|b| < 0.5$, change $|a|$ so that $a/b = +0.5$

$(4) For $E'_t/b > +3.0$, change E'_t so that $E'_t/b = +3.0$
For $E'_t/b < -3.0$, change $|E'_t|$ so that $E'_t/b = -3.0$

FIGURE 6.—Worksheet for computing 12-, 24-, 36-, 48-, and 72-hr MOHATT forecast positions. The example plotted is derived from the HATRACK forecast set in figure 3 and known positions of Chloe at 0600 GMT, Aug. 19, 1971 (14.0°N, 59.5°W) and 1200 GMT, Aug. 19, 1971 (14.0°N, 60.8°W).

In actual practice, an analysis (and associated prognoses) dated more than 12 hr before the initial time of the cyclone may have been used. For example, only the 0000 GMT analysis and desired prognoses would be operationally available for steering a 1200 GMT position. Although tests have shown a deterioration of forecast accuracy as a function of age of the SR fields, this facet was not considered worthy of special treatment in the evaluation.

5. The maximum HATRACK interval for this period was 72 hr.

Modification of the HATRACK Component

1. It is important to note that modifications to HATRACK for the 1967–70 data were run in post-season and that *best-track* positions (i.e., documentary cyclone positions determined in post-season) published by FWF, Jacksonville (U.S. Fleet Weather Facility 1968, 1969, 1970, 1971), were used to establish the 6- and 12-hr HATRACK errors. Since this procedure for determining the bias corrections was followed, the MOHATT results were obviously not available for field use in real time.

2. Since the maximum interval for HATRACK was 72 hr, the maximum interval for MOHATT was 60 hr.

b. Evaluation of the Developmental Test, 1967–70

Figures 8 and 9 show statistics on the MOHATT forecasts as a function of all available 1967–70 HATRACK forecasts run in real time. In particular, the average

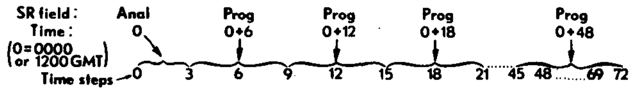
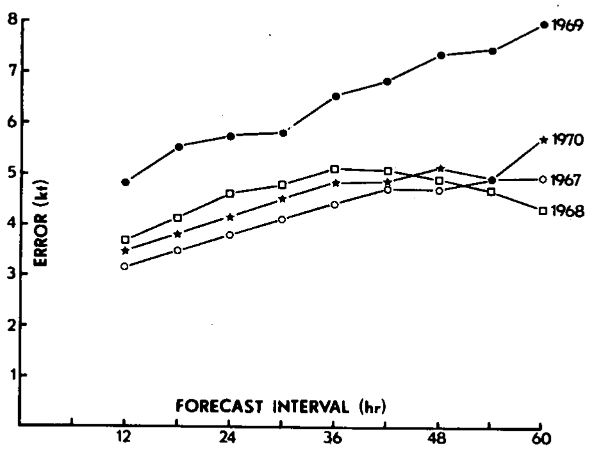


FIGURE 7.—Schematic prog-mode HATRACK computation using SR analysis and prognoses.

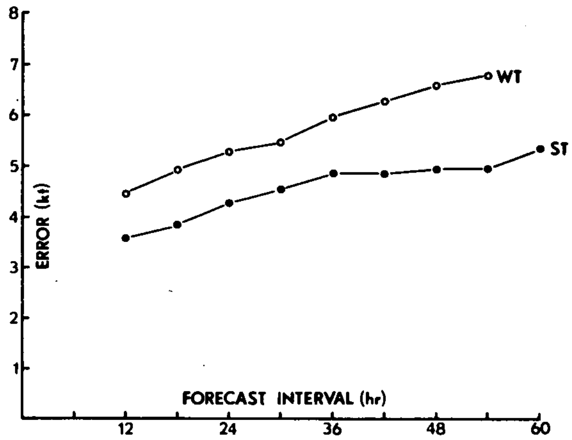
MOHATT errors are prescribed as a function of the forecast intervals for each 6 hr from 12 to 60 hr and for each of the 4 yr tested. Depression, storm, hurricane, and extratropical stages of all named tropical cyclones are included. The number of forecasts in the sample range from 252 at 12 hr to 43 at 60 hr. Six-hour forecasts were omitted since the timeliness of such forecasts in the field yields little interest in this interval. The magnitude of the vector forecast error is normalized to units of nautical miles per hour to allow comparison of errors from one time interval to another.

For example, in figure 8, the 12-hr errors range from 3.2 to 4.8 kt, deteriorating to between 4.3 and 7.9 kt at 60 hr. The error curves tend to reach a plateau in the intervals 36–42 hr with the exception of 1969, which shows higher range and greater errors than the other years. The behavior of the 1969 MOHATT forecasts has been associated with the initiation time of the forecasts. Nearly 90 percent of the 1969 HATRACK forecasts were generated from warning time positions, whereas in 1968 and 1970, an average of 95 percent of the cases were synoptic time starts. In 1967, there was a 50-percent split in warning time and synoptic time positions. This



1967:	72	70	68	67	64	61	60	47	25
1968:	58	55	51	48	44	42	40	37	2
1969:	78	74	70	68	65	61	55	51	2
1970:	44	41	38	36	33	29	25	23	14
Total:	252	240	227	219	206	193	180	158	43

FIGURE 8.—MOHATT (700-mb steering, best-track bias) forecast errors (kt) for 1967–70 North Atlantic tropical cyclones. Number of forecasts for each interval is indicated beneath x axis.



WT:	106	101	96	93	90	82	75	67	0
ST:	146	139	131	126	116	111	105	91	43
TOT:	252	240	227	219	206	193	180	158	43

FIGURE 9.—Same as figure 8, stratified by time from which steering is initiated. WT indicates steering initiated at warning times (0400, 1000, 1600, 2200 GMT) and ST indicates steering initiated from synoptic times (0000, 0600, 1200, 1800 GMT).

fact is important since warning time positions may be extrapolations for periods up to several hours. As a consequence, they may be a source of extra error because of their use in combination with synoptic time positions to establish the bias corrections in the MOHATT scheme. Evidence of the comparative reliability of warning time and synoptic time positions is given by the 4-yr average distance between the operational and best-track cyclone center positions;[6] namely, 26.4 n.mi. for the synoptic time and 38.6 n.mi. for the warning time locations.

Figure 9 indicates the MOHATT errors for each class of starting position, composited for the 4 yr. The forecast error for warning time starts is 25 percent greater than that for synoptic time starts at 12 hr, increasing to 35 percent at the 54-hr forecast interval.

The 1967–70 test must be interpreted as describing the *potential*, not the actual, operational accuracy of MOHATT. Specifically, given documentary (i.e., best-track) positions of the cyclone center for establishing 6- and 12-hr errors, the MOHATT accuracy would be as shown in figures 8 and 9. It is to be noted that, in common with the verification of all other tropical-cyclone forecast systems, the MOHATT forecasts are originated from operational positions but verified against best-track positions.[7] In view of the nature and goals of the developmental test, it is not appropriate at this point to compare MOHATT to other subjective or objective forecast schemes. Such comparisons will be discussed in connection with the 1971 field test which follows.

[6] Best-track positions at warning times linearly interpolated between published synoptic time positions

[7] A better measure of the potential accuracy of MOHATT would have resulted from initiating the steering at best-track, rather than operational, positions in addition to the other specifications cited in section 3. However, this was not done since best-track information generally was not available before the necessary FNWC prognostic fields were destroyed.

4. THE OPERATIONAL TEST

The experience of the 1967-70 period served to eliminate problem areas in the MOHATT scheme and ready the program for operational use. Thus, we decided to simulate the timeliness of operational MOHATT forecasts during the 1971 North Atlantic hurricane season and make such forecasts available to FWF Jacksonville for real-time use. The HATRACK program was run by FNWC Monterey; the MOHATT calculations were performed at the NPS, Monterey. Daily telephone contact was maintained with FWF Jacksonville during the life history of each tropical cyclone.

a. The Nature of the Operational Test, 1971

It is important to note the special features of the 1971 test inasmuch as they clearly identify the state-of-the-art in applying MOHATT operationally. In addition, the test allowed a further appraisal of the potential accuracy of MOHATT (as discussed in sec. 3) as well as making possible a comparison with other operationally used subjective and objective schemes. The numbering in the following sub-subsections, concerned with the HATRACK component and its modification, relate to numbers in similar sub-subsections in subsection 3a.

HATRACK component

1. As in the 4-yr test, the steering component (i.e., HATRACK) of MOHATT was calculated operationally from SR height fields using operational cyclone-center positions and was made available to FWF Jacksonville for guidance in real-time forecasting.

2. Unlike the 4-yr test, HATRACK forecasts were generated *regularly* for every available operational tropical cyclone-center position, but only at synoptic times (0000, 0600, 1200, 1800 GMT).

3. Based on previous experience, 700 mb was used as the optimum steering level. However, since 1000 mb was a close second in producing accurate steering components in 1967–70, the levels 1000, 850, 700, and 500 mb were tested as steering levels.

4. Two changes were made with regard to the SR field used to calculate the steering components for the prog-mode version of MOHATT. The FNWC operational prognostic model was changed to a primitive-equation model in late September 1970 from the modified barotropic model of previous years. Also, the SR prognoses were extended beyond the 48-hr period to include the 60- and 72-hr SR prognoses. Therefore, with reference to figure 7, the 48-hr SR prognosis in 1971 generated the forecast trajectory from 0+45 to 0+54 hr (vice 0+45 to 0+72 hr as in 1967–70), the 60-hr SR prognosis covered the 54- to 66-hr period, and the 72-hr prognosis extended the forecast trajectory beyond 66 hr.

5. The HATRACK steering forecasts were extended to 84 hr instead of 72 hr as in the previous years.

Modification of the HATRACK Component

1. The most important change from the developmental sample concerned the corrections for bias in the steering, which were computed using *operational* real-time cyclone-center positions. As in previous years, the bias corrections were computed post-season, using best-track data, for comparison with similar calculations based on operational data as well as the MOHATT forecasts of prior years.

2. With the extension of the HATRACK component to 84-hr, MOHATT forecasts could be computed for a forecast interval of 72 hr.

b. Evaluation of the Operational Test, 1971

To relate the 1971 results to the earlier tests, we repeat figure 8 and add to it two 1971 MOHATT curves, one a function of best-track data and the other dependent on operational data for the bias corrections (fig. 10). The best-track data curve gives a measure of the potential accuracy for 1971 data in relation to that for the previous years, and the latter is expressive of the existent operational accuracy.

As expected, the 1971 curve indicating potential accuracy is as good as or better than those of the previous years because of the controlled nature of the test and the innovations introduced in 1971. Use of operational-bias corrections, however, results in a sharp deterioration of short-interval forecast accuracy, in relation to the curve dependent on best-track data. For example, the accuracy is reduced by nearly 50 percent at 12 hr using operational information instead of best-track information for the bias correction. However, the advantage of the latter over the former is of little consequence after 42 hr. Associated with the situation at early forecast intervals is an average difference of 26.5 n.mi. between the operational and best-track cyclone-center positions used in the 1971 test. It should also be noted that the number of 1971 forecasts

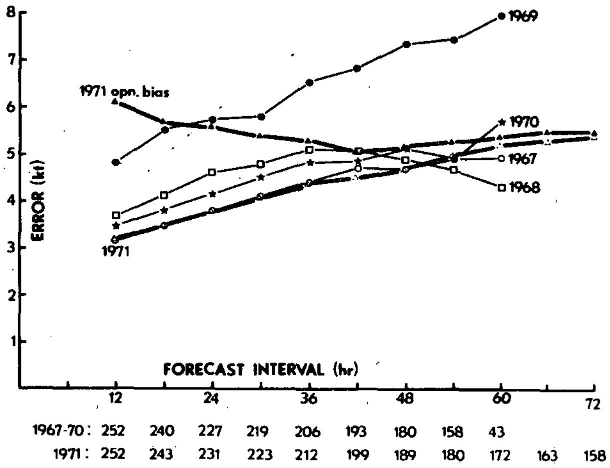


FIGURE 10.—Same as figure 8 with 1971 curves for best-track bias and operational bias added.

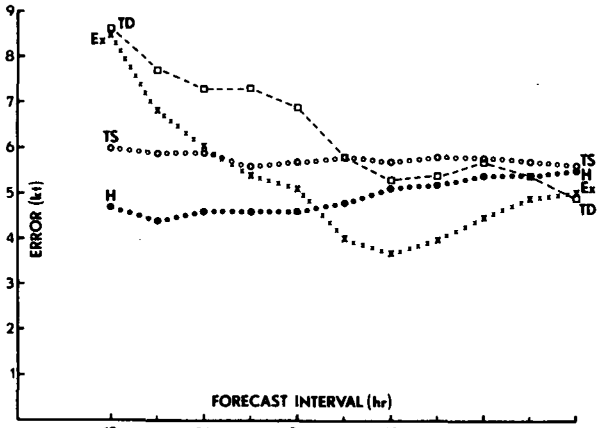
ranged from 252 at 12 hr (equivalent to the number in all four previous years) to 172 at 60 hr (or 400 percent more than 1967–70) and 158 cases at 72 hr (comparable to none in this category for 1967–70). Such a large number of forecasts from 11 named cyclones (Kristie omitted) spread over 6 mo of 1971 gives considerable credibility to the conclusions drawn from the 1971 test.

Since a relatively large number of tropical depressions and extratropical cases are included in the 1971 sample, the MOHATT errors were stratified by cyclone stage (fig. 11). Stage is assigned to a forecast appropriate to the time of verification. The most stable and overall best results, especially when considering the number of cases and slopes of the error curves, are obtained for the most severe cyclone stage; namely, the hurricane. Thus, the result for hurricanes in 1971, using operational data for the bias corrections, compares favorably with the 1967–70 1- to 3-day forecasts for all stages, using best-track data for the bias corrections (fig. 8). The depression and extratropical stages appear to give the poorest results in the short forecast intervals with relative improvement increasing with forecast interval. It may be argued that depression and extratropical stages occur more often than not in the sparse data regions where weather reconnaissance documentation is minimal; thus, a considerable difference in operational and best-track positions is to be expected, yielding the poor results in early intervals.

c. Comparison With Other Forecast Schemes

MOHATT versus OFFICIAL. The potential worth of any forecast system is best viewed in relation to its strongest competitor, in this case, the Official (OFF) forecasts as disseminated by FWF Jacksonville in real time. With minor exception, such forecasts are the same as those issued by the National Hurricane Center, Miami, Fla. (NHC).

Figure 12 relates the OFF and MOHATT forecast accuracy. The ordinate indicates the ratios of OFF to



	12		24		36		48		60		72
TD:	42	38	34	30	24	18	14	12	10	9	8
TS:	90	87	84	79	75	69	64	60	55	51	48
H:	100	98	93	94	93	92	91	88	87	86	85
Ex:	20	20	20	20	20	20	20	20	20	17	17
Total:	252	243	231	223	212	199	189	180	172	163	158

FIGURE 11.—MOHATT (700-mb steering, operational bias) forecast errors for 1971 North Atlantic tropical cyclones, stratified by stage (TD=depression, TS=tropical storm, H=hurricane, EX=extratropical). Number of forecasts for each interval and category is also indicated.

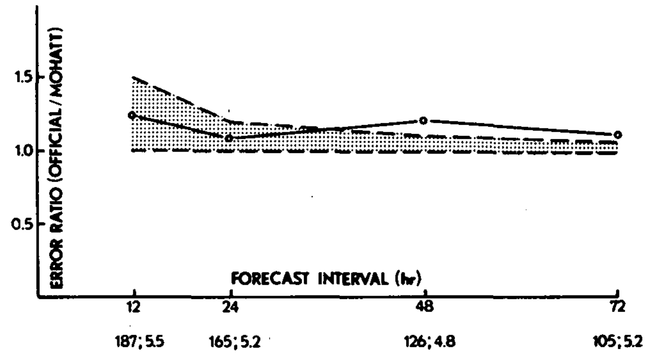


FIGURE 12.—Error ratios of Official to MOHATT (700-mb steering, operational bias) forecasts for 1971 North Atlantic tropical cyclones. Line of equivalent accuracy of MOHATT and OFF lies in the shaded area. Number of forecasts and MOHATT errors (kt) are also indicated.

MOHATT forecast errors based on errors expressed in nautical miles per hour. Since the comparison is a function of error in units of "per hour," the nature of the forecast intervals is important. In this regard, one should note that the OFF forecasts are issued at warning times for forecast intervals beginning at the immediately preceding synoptic time. For example, forecasts disseminated shortly after the 0400 GMT day 0 warning time from the operational cyclone position at 0400 GMT day 0 are labeled 12-, 24-, 48-, and 72-hr forecasts verifying at 1200 GMT day 0, 0000 GMT day 1, 0000 GMT day 2, and 0000 GMT day 3, respectively.

If, in fact, information on the cyclone is available up to warning time, then the true intervals are 8, 20, 44, and 68 hr instead of 12, 24, 48, and 72 hr. The former set of interval values was used to establish the errors of the OFF forecasts, while the latter intervals were used for MOHATT since MOHATT forecast information is truncated to the time from which the forecasts are initiated. Thus, in cases where information up to warning time is used in the OFF forecasts, error ratios >1 (<1) indicate MOHATT accuracy is greater (less) than OFF. However, if the information available to the Official forecaster was not enhanced after the synoptic time immediately preceding the warning time, then the error ratios dividing the relative accuracy of the two forecast types would be 1.5 at 12 hr, 1.2 at 24 hr, 1.1 at 48 hr, and 1.06 at 72 hr. In reality, the line of equivalent accuracy between OFF and MOHATT is unknown for a given forecast set and is variable from one forecast set to the other, being highly dependent on the location of the cyclone with respect to such observing platforms as radar, aircraft reconnaissance, and so forth. For this reason, the stipled area in figure 12 indicates the envelope of lines of equivalent accuracy of the two homogeneous forecast samples. In this case, homogeneous means that the verifying times of the MOHATT and OFF forecasts are the same, but the starting times of the stated intervals may differ by 0–4 hr, as discussed above.

Figure 12 indicates that the relative accuracy of MOHATT is greater than the smallest critical value of equivalent accuracy (i.e., 1) for all intervals but is greater than the upper critical limit only for forecast intervals >36 hr. Thus, regardless of the interpretation of the forecast intervals, MOHATT accuracy exceeds that of OFF for intervals >36 hr, while the two forecast systems are nearly equivalent at intervals ≤ 36 hr.

Since OFF forecasts from depression and extratropical positions were not available, most early- and late-stage cyclone forecasts are not included in the OFF/MOHATT comparisons. This amounts to a 26- to 34-percent reduction from 12 to 72 hr, respectively, between all MOHATT forecasts and those that could be compared with OFF.

Figure 13 relates MOHATT and OFF accuracy stratified by area, track, and stage of the tropical cyclone. Compared to OFF, the best MOHATT results are obtained for the hurricane stage, in area A and before recurvature. In the intervals beyond 36 hr, however, accuracy is equally as good for storm and hurricane stages. The significance of track in later intervals cannot be interpreted from the 1971 data since so few after-recurvature forecasts existed beyond 36 hr.

The previously untested level of 850 mb was evaluated in 1971. Figure 14 shows the relative skill of 700 and 850 mb in relation to the OFF forecasts. For all forecast intervals, MOHATT derived from 850-mb steering proved to be superior to that from 700 mb. The significance of the 850-mb forecast accuracy is especially notable at the extensive intervals. Until at least 1 more yr is evaluated, however, the case for 850 mb as the optimum steering level will not be pursued.

The authors doubt that the MOHATT forecasts had much, if any, effect on the 1971 OFF forecasts; thus, it is most encouraging that an objective scheme, fully meeting all operational criteria, can even match the OFF forecast in accuracy. Further, as weather reconnaissance, communication, and documentation improve, the operational positions will tend toward the best-track positions, and

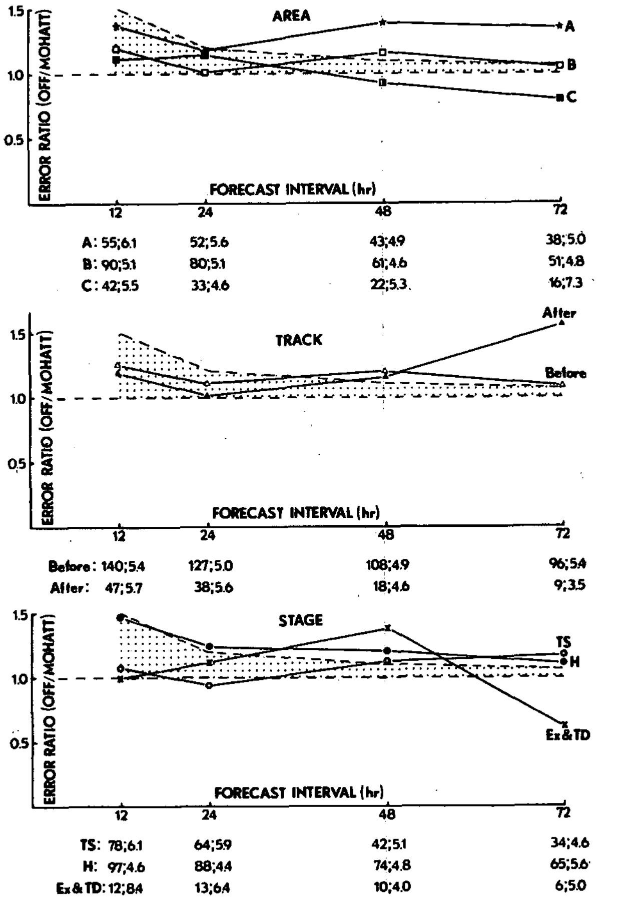


FIGURE 13.—Error ratios of Official to MOHATT (700-mb steering, operational bias) forecasts for 1971 North Atlantic tropical cyclones stratified by area (A=east of 62°W, B=south of 30°N and west of 62°W, C=north of 30°N and west of 62°W), track (before and after recurvature), and stage (TD=depression, TS=tropical storm, H=hurricane, EX=extratropical).

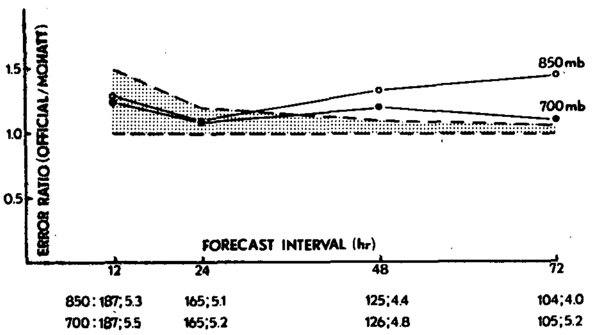


FIGURE 14.—Same as figure 12 for 700 and 850 mb.

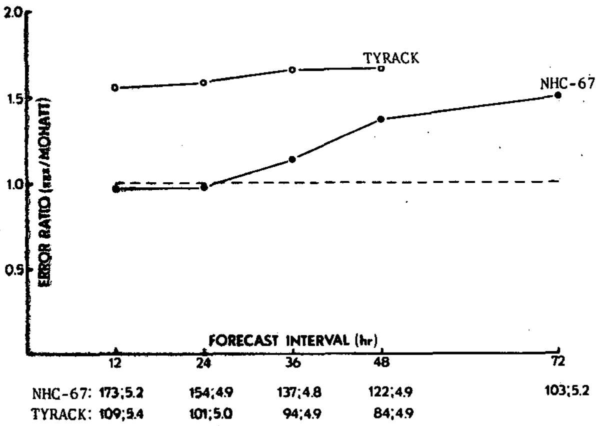


FIGURE 15.—Error ratios of NHC-67 and TYRACK to MOHATT (700-mb steering, operational bias) forecasts for 1971 North Atlantic tropical cyclones. Line of equivalent accuracy is 1.0 (dashed). Number of forecasts and MOHATT errors (kt) are also indicated.

the state-of-the-art accuracy of MOHATT will approach or exceed that referred to here as "potential." The effect of these improvements in positioning is likely to be greater on MOHATT than OFF forecasts since the accuracy of the former is closely tied to three positions of the cyclone (initial and those at the 6- and 12-hr verifications).

MOHATT versus NHC-67. Currently, there are two prominent operationally used objective forecast schemes for which data were available to compare with MOHATT. The first of these, NHC-67, has been used operationally for a number of years by NHC Miami as guidance for the hurricane forecaster (Tracy 1966, Miller et al. 1968). This very useful and successful statistical approach has been compared to MOHATT, using NHC-67 data for 1971 kindly supplied by NHC Miami (fig. 15). The relative accuracy is near unity through 24 hr with MOHATT showing a sharp increase in relative accuracy over NHC-67 from 36 to 72 hr. Only one case in each of the depression and extratropical categories were available from NHC-67. Therefore, the statistic is almost totally derived from hurricane and tropical storm cases.

A qualitative analysis of the two schemes, in light of these results, again points out the short-interval problems in MOHATT due to errors in cyclone-center positioning. In the latter intervals, the relative success of MOHATT may be due to the use of prognostic fields for steering, since NHC-67 is dependent exclusively on the initial state or recent-history tendencies of analyzed atmospheric parameters.

MOHATT versus TYRACK. The second operationally used objective forecast scheme, TYRACK (*ty*phoon *track*ing), was developed in the late 1960s at U.S. Fleet Weather Central, Honolulu, guided by earlier work on HATRACK (U.S. Fleet Weather Central/Joint Typhoon Warning Center 1968). TYRACK is basically a steering technique utilizing the wind analysis from a steering level (700, 500, 300, or 200 mb) or layer (700–500 mb, 700–300 mb, or 700–200 mb) as determined by the accuracy of each with reference to the past 12-hr movement, if available. If a past 12-hr movement is not available, the 700-mb level is used. This scheme has been used primarily in the western North Pacific area with generally best results at forecast intervals < 36 hr. In 1971, however, the TYRACK program was run in the Atlantic area by FWC Norfolk. The TYRACK forecasts used the optimum steering level (determined by the performance of each level in forecasting the past 12-hr cyclone movement) in preference to simple 700-mb steering if both were available. This procedure conforms to utilizing the best TYRACK forecast.

Figure 15 shows the results for a homogeneous comparison of TYRACK and MOHATT. There is little contest between the two schemes, especially in the hurricane stage (not shown) where the TYRACK errors are about twice that of MOHATT for all forecast intervals tested. The difference between the two schemes is believed to be caused by the absence of prognostic information in TYRACK and the use of over-detailed wind fields.

5. CONCLUSIONS AND RECOMMENDATIONS

The MOHATT forecast scheme for predicting the motion of tropical cyclones is fully objective and easily adapted to field use. The forecasts may be totally (HATRACK plus modification) or partially (HATRACK part only) processed by computer. In either case, the delay time in issuing the forecast, beyond the availability of input parameters, is less than ½ hr for any or all forecast intervals to 3 days. The numerical-statistical features of MOHATT allow automatic improvement of forecast accuracy corresponding to any increase in accuracy of positioning tropical cyclones or enhancement of prognostic models. Further, the universality of approach allows adaptation of MOHATT to any tropical-cyclone region in the world.

The extensive 5-yr test of the MOHATT scheme in the North Atlantic area indicates results competitive with other objective and subjective approaches. However, only the year 1971 can be considered completely operational. Based on the 1971 data and supported by a suitable interpretation of the complete 5-yr test, the MOHATT scheme, using either 700- or 850-mb winds, appears to be equivalent to the Official forecasts for the short-period intervals while exceeding Official in the 36- to 72-hr range. Comparison of MOHATT with the objective schemes, TYRACK and NHC–67, during the 1971 season, indicates superiority of MOHATT over the former (latter) for all intervals (for intervals >24 hr). In general, relative accuracy of MOHATT increases with increasing cyclone intensity, a most desirable feature. Although it is realized that it usually takes several years to obtain a statistically meaningful comparison of related forecast systems, each year is important as it represents a unique situation for this purpose, since each system and the data and/or meteorological fields supporting it are in a continuous state of change.

Some increase in accuracy of MOHATT may be expected with the following improvements now under development: (1) statistical selection of the optimum steering level for each forecast, and (2) stratification of the forecast scheme according to location and/or track and/or stage of the tropical cyclone. Increased forecast accuracy may also be expected with improvement in the data base and prognostic model at the Fleet Numerical Weather Central.

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