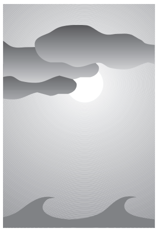
Improvements in Tropical Cyclone Track Forecasting in the Atlantic Basin, 1970–98



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ABSTRACT

Tropical cyclone track forecasts issued by the Tropical Prediction Center/National Hurricane Center for the Atlantic basin have improved over the period 1970–98. Improvement is shown at 24, 48, and 72 h. Although this improvement can be shown without any preconditioning of the data, the question of accounting for forecast difficulty is addressed, building upon the work of Neumann. A decrease in the initial position errors over the same period is also shown.

Track forecast errors generated by the Atlantic climatology and persistence (CLIPER) model (run in "best-track" mode) are used as a measure of forecast difficulty. Using the annual average CLIPER errors in a regression against the official forecast errors yields an equation giving an expected error for each year under consideration. The expected error (representing forecast difficulty) is then subtracted from the observed official errors. The resulting set of differences can then be examined for long-term trends, difficulty having been accounted for.

Fitting a straight line to these differences (1970–98) yields the result that official forecast errors have decreased by an average of 1.0% per year at 24 h, by 1.7% per year at 48 h, and by 1.9% per year at 72 h. A second-order fit, however, suggests that the rate of improvement has increased during the latter half of the period.

1. Introduction

The Tropical Prediction Center/National Hurricane Center (NHC)[1] issues tropical cyclone track and intensity forecasts and warnings for both the Atlantic and eastern North Pacific basins.[2] As responsibility for the eastern North Pacific was transferred to NHC in 1988 from what was then the Eastern Pacific Hurricane Center in Redwood City, California, this analysis of long-term trends in track forecast error will be confined to the Atlantic basin.

The costs of warning U.S. coastal residents for hurricane landfall are significant. Jarrell and DeMaria (1998) give a rough estimate of $600,000 per mile of warned coastline and find an average length of warned coastline over the last decade of about 400 n mi (741 km). Given the long-term average of 1.7 hurricane landfalls, or near-landfall events, per year along the U.S. Gulf of Mexico and Atlantic coastlines (Neumann et al. 1999), the average annual *warning* costs for hurricanes are then about $400 million. Pielke and Landsea (1998) find average annual hurricane *losses* (normalized to 1995 economic conditions and population) of $4.8 billion.

The issue of long-term trends in tropical cyclone track forecast error was addressed comprehensively by Neumann (1981). Neumann demonstrated the importance of first removing forecast difficulty from track errors before determining trends in forecast skill. That technique is described and used in this paper.

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[1] In 1995, the National Hurricane Center was renamed the Tropical Prediction Center (TPC), one of nine centers within the National Centers for Environmental Prediction, as part of the National Weather Service restructuring and modernization. At the time of this writing, only the hurricane forecast unit within TPC retained the title "National Hurricane Center."

[2] By convention, areas of the globe prone to tropical cyclone occurrence are referred to as "basins." The Atlantic basin includes the North Atlantic Ocean, the Caribbean Sea, and the Gulf of Mexico. In the eastern North Pacific basin, NHC's area of forecast responsibility extends from the Pacific coasts of North and South America westward to 140°W.

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The objectives of the present study are to provide an updated version of Neumann's earlier work, and to extend the method to include the 48- and 72-h forecasts. This study also includes weighting of trend lines by number of cases. We do not attempt to remove the effect of initial position errors on the forecast, as was done by Neumann. Any improvements in initial positioning are included here as a contribution to the forecast process. Simplifications to the procedure used to account for forecast difficulty are also discussed.

A 29-yr period (1970–98) is examined. While long enough to show any statistically significant trends, this period is reasonably uniform in the basic technology available to the forecaster. It does not, for example, extend back into the presatellite or precomputer era. Geostationary satellite data and computer-generated track forecast model guidance were available through the period, although in increasingly refined form in the latter part. Global model forecasts became available in 1974.

2. Data

The set of average[3] annual initial position errors and official forecast errors for forecasts issued by NHC during the period 1970–98 are given in Table 1. The origin of the data is as follows. The forecaster first determines the current (0 h) center position of a tropical cyclone, specified to tenths of degrees latitude and longitude. This position, two past positions (−12 h and −24 h), the initial motion (i.e., forward speed and direction), and the −12 h motion are supplied as input to the numerical guidance. The suite of track models (DeMaria et al. 1990; Gross 1999) that compose the guidance is run on demand, usually as soon as the input parameters have been determined. After the guidance has been run, the set of track forecasts thus generated are evaluated by the forecaster, along with the forecast fields generated by the global and regional models. The forecaster synthesizes this information and determines the "official" track forecast (specified as a set of latitude–longitude points representing the forecast center positions) for 12, 24, 36, 48, and 72 h. The process is repeated four times a day at 0000, 0600, 1200, and 1800 UTC.

Verification of these forecasts is provided by the Atlantic "best-track" file, also known as HURDAT (Jarvinen et al. 1984), updated annually. This file contains the final, official estimates of tropical cyclone position (given in tenths of degrees latitude and longitude) and maximum 1-min sustained winds 10 m above the surface (given in knots), as determined in poststorm analysis at NHC. Data that may not have been available in real time are used to modify and refine the operational track. The revised tracks are then entered into the best-track file.

In this study, initial position error is defined as the great-circle distance between each operationally determined initial position and its best-track (verifying) position. Likewise, forecast error is defined as the great-circle distance between each official forecast position at 24, 48, and 72 h and its corresponding best-track position.

Only forecasts for tropical cyclones having maximum 1-min sustained winds of 34 kt (17.5 m s^{-1}; tropical storm strength) or greater have been included. This requirement applies to both the time of the forecast and the verification time. Subtropical cases have been included, but extratropical cases have been excluded.[4]

3. Determination of trends in initial position error

As noted above, the first step in the forecast process is to determine the initial (0 h) position. Average annual initial position errors are given in Table 1 and plotted in Fig. 1. A downward trend is readily apparent. An unweighted linear least squares trend line (not shown) significant at the 95% level, using the F-test criterion (Draper and Smith 1966), gives an average annual improvement of about 2.1% (Table 2). This estimate does not, however, take into account the fact that interannual variation in tropical cyclone activity can cause a substantial change in the number of cases (Table 1). One method of accounting for this sample variability is to weight the linear least squares fit by the number of cases. This weighted line (shown in Fig. 1) yields an average annual improvement for ini-

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[3] "Average" is here defined as the arithmetic mean and is used in this sense throughout.

[4] The term "subtropical" refers to a low pressure system that develops over subtropical waters, initially having a nontropical circulation, but with some tropical cyclone cloud structure. Many evolve into tropical cyclones. The term "extratropical" refers to a tropical cyclone that has undergone modification by moving into a nontropical (baroclinic) environment; characteristic changes include expansion of wind field, decrease in maximum winds, and increasing asymmetry of the wind field (Neumann et al. 1999).

Table 1. NHC average initial positioning (0 h) errors, and average track forecast errors at 24, 48, and 72 h, 1970–98. Units are nautical miles (n mi). Average best-track (BT) CLIPER errors are calculated for a homogeneous sample.

	0 h		24 h			48 h			72 h		
Year	**Official**	**Cases**	**Official**	**BT clip**	**Cases**	**Official**	**BT clip**	**Cases**	**Official**	**BT clip**	**Cases**
1970	22.0	46	84.3	63.2	34	185.9	234.2	13	254.0	525.9	3
1971	22.6	203	110.7	66.7	183	242.1	183.3	137	381.9	330.4	118
1972	24.0	66	142.4	112.4	57	390.5	370.0	38	687.9	699.7	25
1973	24.3	98	116.8	93.0	84	246.3	245.6	54	363.2	374.8	29
1974	18.2	103	97.2	64.0	89	206.6	151.6	64	348.3	223.8	42
1975	15.5	143	117.0	84.6	121	256.9	210.3	92	401.9	316.4	68
1976	20.3	159	128.2	95.3	142	287.8	265.4	112	433.0	416.2	85
1977	11.4	40	133.0	108.5	30	331.1	324.2	14	484.7	574.0	5
1978	18.5	123	144.3	99.4	101	323.6	260.1	59	422.8	357.1	33
1979	17.8	156	89.5	63.1	138	160.2	149.7	98	238.6	244.0	83
1980	15.6	209	128.7	95.0	188	273.3	226.4	140	404.8	360.1	109
1981	19.7	211	126.0	83.3	190	248.4	222.0	146	422.9	394.4	106
1982	16.9	55	131.2	90.8	44	244.7	218.3	28	269.3	267.3	20
1983	10.2	45	85.3	71.0	33	197.1	219.1	17	439.6	443.5	9
1984	22.2	178	132.1	90.9	156	266.7	262.7	121	390.1	416.4	88
1985	16.5	175	109.9	95.3	149	221.7	246.0	104	330.1	350.2	67
1986	20.0	76	107.5	73.7	66	237.6	191.9	42	383.6	322.6	27
1987	19.0	131	108.6	82.5	119	229.7	242.7	95	349.1	418.9	67
1988	12.2	152	69.7	63.8	133	143.1	160.6	109	230.9	267.9	90
1989	17.5	239	95.7	68.4	215	192.9	182.9	166	283.5	287.4	129
1990	15.0	235	101.3	69.5	205	194.8	188.5	156	303.7	313.5	113
1991	15.0	69	113.6	100.1	55	192.0	243.8	31	296.8	391.2	17
1992	10.3	138	83.0	71.0	122	166.8	221.3	98	278.4	423.2	75
1993	14.0	103	102.4	88.4	80	177.9	235.0	58	240.7	348.6	41
1994	12.9	97	102.8	115.2	83	209.8	286.1	62	341.8	382.6	50
1995	12.2	444	87.1	72.3	402	159.4	191.7	335	233.3	292.4	272
1996	10.2	290	72.0	64.7	260	128.2	180.4	217	189.9	317.8	183
1997	11.8	91	85.5	72.9	74	150.2	182.0	51	229.3	325.1	38
1998	12.5	317	84.1	73.6	284	144.9	191.1	231	201.8	285.7	191

tial position errors of 2.2%. Although the percentage improvement is about the same as that taken from the unweighted line, the percentage of variance explained has increased from 50% to 62% (Table 2).

Increased skill in determining the initial position is clearly a contributing factor in lowering forecast error, primarily because successive positions determine the estimate of initial motion (speed and direction). This was shown by Neumann (1981), who sought to remove the effect of initial position errors from the forecasts, and in doing so found an average error reduction in those forecasts of 6%, 2%, and 1% at 24, 48, and 72 h, respectively. In other words, a perfect initial position would result, on average, in an improvement of 6% in the 24-h forecast, but the benefit damps out quickly beyond 24 h.

Several possible explanations for the improvement in initial positioning have been investigated. First, however, the possibility must be considered that factors independent of skill are responsible for the decrease in errors or at least bias the true trend. For example, well-defined, intense hurricanes with small eyes are easier to locate than ill-defined tropical storms (Mayfield et al. 1988). If a climatological increase in average intensity were present, the initial position errors shown in Fig. 1 might be attributable to that alone and not to any increase in skill. An examination of the best-track file, however, shows no such trend in average intensity. Another factor to be considered is the availability of aircraft reconnaissance, which is a key factor in center location (Gray et al. 1991). Data provided by the Air Force Reserve 53d Weather Reconnaissance Squadron were examined to determine if the number of center fixes (normalized by storm duration) had changed with time. No evidence of such a trend was found.

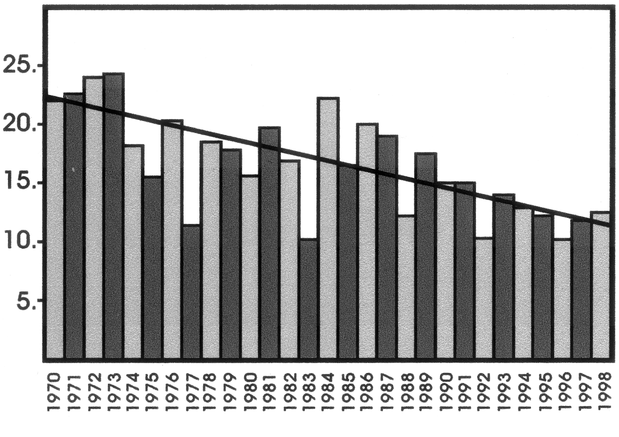

FIG. 1. Average annual NHC initial positioning errors, 1970–98. Data appear in Table 1. Trend line is weighted by number of cases. Units are nautical miles.

TABLE 2. Percentage improvement per year, taken from trend lines. Variance explained given in parentheses.

Forecast	Unweighted	Weighted by no. of cases	Adjusted and weighted
0 h	2.1% (0.50)	2.2% (0.62)	N/A
24 h	1.2% (0.27)	1.5% (0.45)	1.0% (0.80)
48 h	2.1% (0.43)	2.3% (0.60)	1.7% (0.88)
72 h	2.2% (0.38)	2.5% (0.62)	1.9% (0.87)

Geographic location is another possible influence. More tropical cyclone occurrences in the western (data dense) portion of the basin over a span of years might result in lower initial position errors. Nevertheless, the annual average initial longitude shows no identifiable trend.

Having ruled out these possible spurious effects in trend, the strongest contributing factor to lower initial position errors appears to be the forecaster's enhanced ability to acquire, view, and manipulate satellite data. Notable in this regard is the acquisition of the University of Wisconsin Man-computer Interactive Data Access System (McIDAS) in the early 1980s, and the installation of the visible and infrared spin scan radiometer atmospheric sounder Data Utilization Center at NHC in 1989 (Sheets 1990).

We conclude then, based upon these data, that there has been an improvement of about 2% per year in the initial position errors over the 29-yr period.

4. Determination of trends in track forecast error

a. Unadjusted trend lines

As in the case of initial position errors above, the most straightforward approach to finding a trend in track forecast errors is to employ a linear least squares fit of the average errors against time. The unadjusted average annual track forecast errors (Table 1) with trend lines (weighted by number of cases) are shown in Figs. 2a (24 h), 2c (48 h), and 2e (72 h). The trend lines have negative slopes, indicating improvement, for all three forecast periods.

Improvement found is 1.5% per year at 24 h, 2.3% per year at 48 h, and 2.5% per year at 72 h (Table 2). (For comparison, corresponding rates of improvement taken from unweighted trend lines are 1.2%, 2.1%, and 2.2% at 24, 48, and 72 h, respectively.) Although the weighted trend lines are significant at the 95% level, using the F-test criterion, note that considerable variability remains about these lines (Figs. 2a, 2c, and 2e). A reduction of variance of 45%, 60%, and 62% at 24, 48, and 72 h, respectively (Table 2), indicates that time has accounted for some of the year-to-year variation in average error but leaves a portion unexplained. Weighting by number of cases, as was true with initial position error, does not change the rate of improvement very much but does obtain a greater reduction of variance.

b. *Use of CLIPER to account for forecast difficulty*

In the computation of the trends in Figs. 2a, 2c, and 2e forecast difficulty has not been taken into account. The chance occurrence of a group of relatively "easy" forecasts toward the end of the period might create the erroneous impression of an increase in skill or exaggerate the slope of the trend line. Following Neumann (1981), the track forecast errors generated by the Atlantic climatology and persistence (CLIPER) model (Neumann 1972; Neumann and Pelissier 1981) are taken as a measure of forecast difficulty. CLIPER is a simple track prediction model derived by regression against a set of previous tracks with future position as the dependent variable. In the version of the Atlantic CLIPER model used in this study, 240 tropical cyclone tracks occurring between 1930 and 1970 provide 3156 dependent cases (Neumann 1972).

The use of the CLIPER model errors as a measure of forecast difficulty has a quantitative basis. Neumann (1981) considered a number of possibilities, including initial positioning error, latitude, longitude, translational speed, *u* and *v* component of motion, CLIPER errors, and others. Screening for correlation with official forecast error, the three most highly correlated were CLIPER error, latitude, and *u* component of motion. Because of the nature of its derivation, however, CLIPER contains information about the other two. Inserting all three quantities into a stepwise multiple regression against official errors demonstrated that neither latitude nor the *u* component of motion provided any significant additional reduction of variance beyond that provided by CLIPER error alone. Thus it emerged as the best single "predictor" of official forecast error or, stated in another way, as a predictor of forecast difficulty.

In the Atlantic, tropical cyclones traveling westward, generally south of 20°N, are propelled by a persistent deep easterly flow and tend to have small CLIPER track errors. As systems become caught up in the westerlies (recurve), forward speed increases and tracks become more difficult to predict; CLIPER errors are large. CLIPER errors may thus be used to characterize areas of typical tropical cyclone motion within a basin or, indeed, to characterize an entire basin (Pike and Neumann 1987). When the CLIPER model is run retroactively on archived tracks, its errors become a measure of forecast difficulty. This is the central contribution of Neumann's technique. The

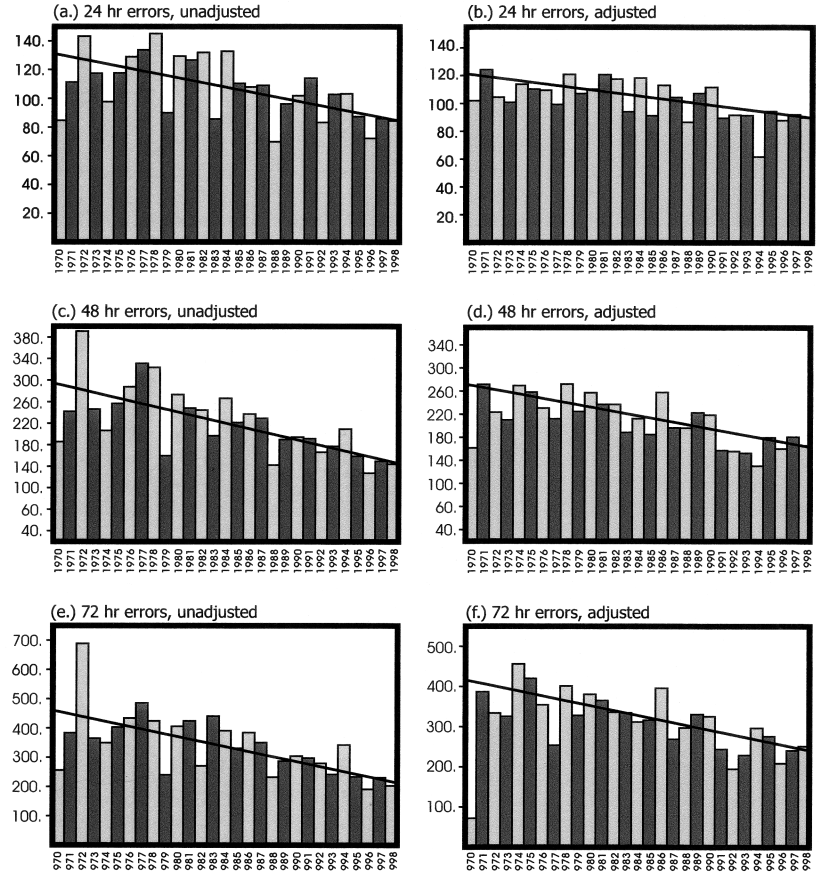

FIG. 2. Average NHC official track forecast errors over the period 1970–98 for the Atlantic basin. Average errors are shown unadjusted for difficulty at (a) 24, (c) 48, and (e) 72 h, and adjusted for difficulty using the best-track CLIPER errors at (b) 24, (d) 48, and (f) 72 h. Vertical axis units are nautical miles.

advantage is that years during which a preponderance of forecasts occur south of 20°N can be fairly weighed against those years containing more erratic tracks; further, increased skill in predicting those erratic tracks, if present, will become evident by comparison with the CLIPER bench mark.

In this work, CLIPER-model errors have been generated using best-track data rather than operational input. Although either will serve the purpose outlined above, the use of the best-track CLIPER has an advantage in that it is completely objective and reproducible, whereas the operational CLIPER is subject to the skill of a particular forecaster in determining initial motion.

For each official forecast (1970–98), a best-track CLIPER error was generated, forming a homogeneous sample. Yearly averages of these best-track CLIPER errors are given in Table 1. In spite of the simplicity of the CLIPER model, note in Table 1 that the average best-track CLIPER errors are lower than the average official errors at 24 h, in all years except 1994.

c. *Longitude as an additional measure of forecast difficulty*

Although CLIPER error is the single best predictor of forecast difficulty, chosen objectively in favor of latitude and *u* component of motion, Neumann (1981) found that longitude provided some additional reduction of variance (5.6% at 24 h)[5] when used in conjunction with CLIPER. Longitude acted to decrease expected forecast difficulty as one traveled westward in the basin. Presumably, this reflected the increased data density in the western part of the basin, resulting in a better analysis of the steering flow and better model initialization.

In the present work the reduction of variance due to longitude is much smaller (about 0.9% at 24 h). At 48 h the reduction of variance is about 0.1%, and at 72 h is negligible. For comparison with Neumann's work, these numbers were computed without accounting for number of cases. When the number of cases is accounted for, the reduction of variance due to longitude essentially vanishes at 24 and 48 h, and is about 1.7% at 72 h. We have thus chosen to exclude longitude in this work and use CLIPER as the sole predictor of forecast difficulty. It is possible that advances in global modeling, a technology not available during the first part of Neumann's original dataset, have damped this longitudinal signal.

d. *Adjustment procedure*

The sole measure of forecast difficulty (CLIPER) is now applied to the average official errors, prior to fitting them against time. This step is accomplished through regression, exploiting the correlation between the average official track forecast errors and the average CLIPER errors. The regression, using average official errors as the dependent variable, is weighted by the number of cases composing the respective annual averages. As mentioned above, weighting was considered necessary because the number of cases per year varies widely. With only one predictor of difficulty (CLIPER), the result of the regression simply assumes the form

$$\hat{y} = a + bx,$$

where $\hat{y}$ is the expected (or predicted) official error for any particular year under consideration, and x is the annual average best-track CLIPER error for that year. In this procedure, an expected official error is calculated and then subtracted from the annual average observed error. The difference $(y - \hat{y})$ represents forecast skill, difficulty having been accounted for. The set of adjusted official errors is finally obtained by adding the mean error for the entire period (1970–98) to each of these annual differences. Since the objective is to identify any trends in forecast skill, the final step is to fit these adjusted official errors against time (Figs. 2b, 2d, and 2f). Fitting a straight line to these data, adjusted official track forecast errors over the period 1970–98 are shown to have decreased by an average of 1.0% per year at 24 h, by 1.7% per year at 48 h, and by 1.9% per year at 72 h (rounded to the nearest 0.1%). These lines are significant at the 95% level, using F-test criteria.

e. *Use of a second-order fit*

Inspection of the adjusted errors in Figs. 2b, 2d, and 2f suggests that the rate of improvement is greater during the latter part of the period. The first half shows a relatively flat trend and perhaps even some deterioration in skill at 24 h. This change in rate of improvement can be shown with a second-order fit against time, plotted in Figs. 3a–c. The curves are found by using time (year number) and the square of time as the independent variables. The curves are significant at the

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[5] Neumann used the period 1954–80. Since 48- and 72-h forecasts did not begin until 1961 and 1964, respectively, they were not available for comparison over the same interval at that time.

95% level, again using F-test criteria. Using values from the curves, the rates of improvement for the final 5-yr period (1994–98), for example, are about 2.1% per year at 24 h, 3.1% per year at 48 h, and 3.5% per year at 72 h.

Choice of fit focuses attention on different timescales. The linear fit is perhaps the more conservative of the two, giving a longer-term perspective. If forecast errors should remain constant or rise slightly over the next several years, the linear fit will give about the same result; the second-order fit will react more quickly.

It is interesting to compare this to Neumann's result for the period 1954–80, in which he found most of the improvement in the 24-h forecast during the earlier part, with essentially no improvement during the 1970s. There was concern at the time that a plateau in skill had been reached, attributed in part to a degradation in the initial analysis over the mid-Atlantic. It is now evident that this plateau was overcome with a substantial increase in skill during the ensuing 18-yr period.

5. Discussion

Tropical cyclone track forecasting, in its present state, is heavily dependent upon numerical guidance. This guidance is provided both by the global models directly and by the suite of track forecast models using the global model forecast fields as input. There has been a steady increase in the skill of the global models over the last several decades (Shuman 1989; Kalnay et al. 1990; Caplan et al. 1997). In addition, increasingly skillful tropical cyclone prediction models have been introduced. Near the midpoint of the period under consideration, the statistical/dynamical NHC83 model was introduced (Neumann 1988) and later revised as NHC90 (Neumann and McAdie 1991). The Beta and Advection Model (Marks 1990) became routinely available in 1990. More recently, a tropical cyclone prediction model developed at the NOAA/ERL/Geophysical Fluid Dynamics Laboratory (Kurihara et al. 1995) became operational in 1995. This model has performed exceptionally well, with average 72-h track errors during the 1998 hurricane season of 223 n mi (Gross 1999). It is our opinion that improvement such as this in the numerical guidance has been largely responsible for the decrease shown in the official tropical cyclone track forecast errors. This linkage was also suggested by Sheets (1990).

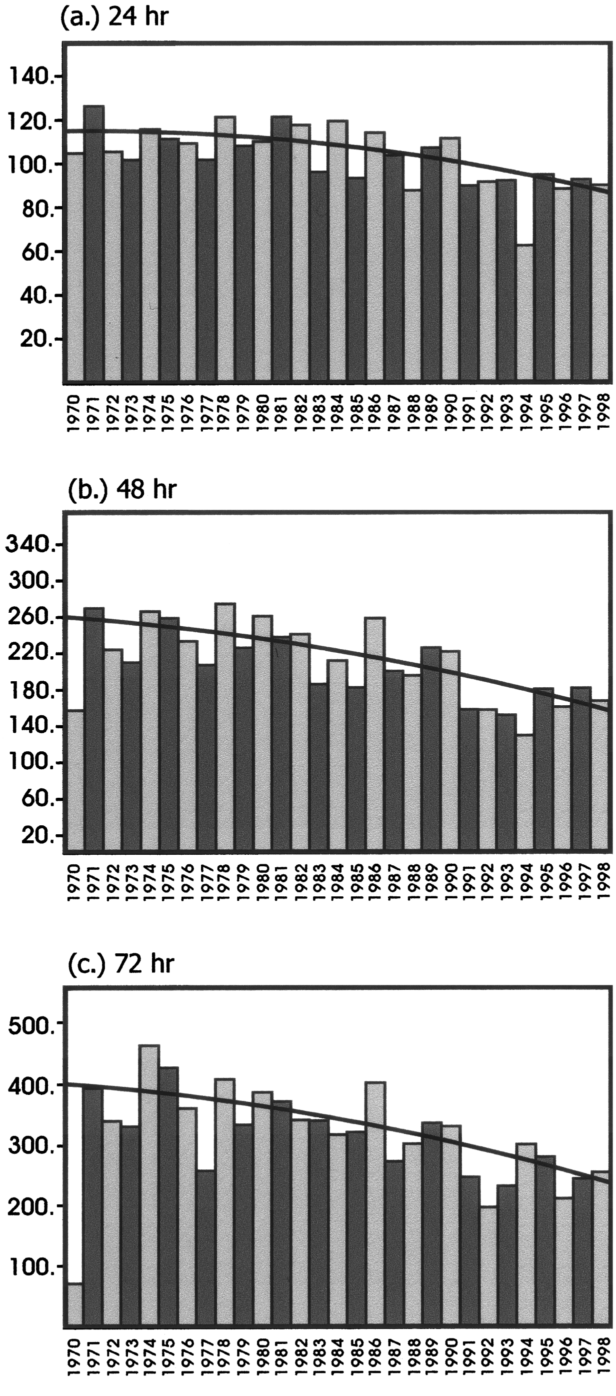

FIG. 3. As in Fig. 2, except that adjusted errors are shown with second-order fit. Vertical axis units are nautical miles.

Given this improvement in the numerical guidance, and the steady decrease in official track forecast errors, the question arises as to how long this trend might continue. An estimate of the amount of improvement still possible in the numerical guidance is provided in a discussion by Neumann (OFCM 1997) using a statistical/dynamical model in the North Atlantic basin.

He finds that average errors of 53, 107, and 145 n mi at 24, 48, and 72 h, respectively, should be attainable. Leslie et al. (1998) used a baroclinic model to obtain inherent lower bound average errors of 52, 83, and 121 n mi at 24, 48, and 72 h, respectively, in the Atlantic.

Given either of the above estimates, and taking the final 5-yr average (weighted by number of cases) of the official NHC track forecast errors given in Table 1 as a measure of current skill in the Atlantic basin (84, 151, and 221 n mi, at 24, 48, and 72, h, respectively) it would appear that there is room for further improvement. Looking ahead, it is entirely possible that other plateaus in skill such as that experienced during the decade of the 1970s will be reached, and it should therefore not be assumed that the *rate* of improvement shown over the last decades will apply to the future.

6. Conclusions

A small, but statistically significant, long-term downward trend is evident both in the initial position errors and in the official tropical cyclone track forecast errors, in the Atlantic basin, over the period 1970–98. Forecast errors are found to decrease at all forecast intervals examined, specifically at 24, 48, and 72 h. (Official NHC tropical cyclone forecasts do not currently extend beyond 72 h.)

During this period, tropical cyclone initial positioning errors have decreased by an average of 2.2% per year, and official track forecast errors have decreased by an average of 1.0% per year at 24 h, by 1.7% per year at 48 h, and by 1.9% per year at 72 h, when determined by linear trend lines, using the best-track CLIPER as a measure of forecast difficulty, and weighting by number of cases. These trend lines are significant at the 95% level.

While accounting for difficulty does (sometimes markedly) change year-to-year comparisons, it does not change the sense of the trend, nor does it significantly change the magnitude of the trend. Removal of difficulty does, however, result in greater reduction of variance.

A second-order fit gives a shorter-term improvement over the last five years (1994–98) of 2.1% per year at 24 h, 3.1% per year at 48 h, and 3.5% per year at 72 h.

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