Five-Day Tropical Cyclone Track Forecasts in the North Atlantic Basin

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ABSTRACT

Statistical analyses of the most recent 40 yr of hurricane tracks (1956–95) are presented, leading to a version of the North Atlantic climatology and persistence (CLIPER) model that exhibits much smaller forecast biases but similar forecast errors compared to the previously used version. Changes to the model involve the inclusion of more accurate historical tropical cyclone track data and a simpler derivation of the regression equations. Nonlinear systems analysis shows that the predictability timescale in which the average errors increase by a factor *e* is approximately 2.5 days in the Atlantic basin, which is larger than that found by similar methods near Australia. This suggests that 5-day tropical cyclone track forecasts may have some benefit, and therefore a version of CLIPER extended to 5 days to be used as a baseline to measure this skill is needed.

1. Introduction

Current tropical cyclone track prediction models for the Atlantic basin produce forecasts to 3 days. These forecasts have shown steady improvements (Sheets 1990), and forecast skill, measured by comparing forecast tracks to those produced by climatology and persistence (Neumann 1972; Merrill 1980), now approaches 40% at 72 h (Aberson and DeMaria 1994), where it is a maximum for three-dimensional primitive equation models. Because of this skill level, interest in longer-range track forecasts has increased. As a result, a new climatology and persistence (CLIPER) model must be derived, and an assessment made of the possibilities of longer-range forecasts.

Fraedrich and Leslie (1989) have shown that the predictability timescale for tropical cyclone tracks in the Australian region is approximately 24 h. Pike and Neumann (1987), by ranking errors of the CLIPER track forecast model by tropical cyclone basin, have shown that the Australian region is the most difficult basin in which to forecast tropical cyclone tracks. Therefore, track forecasts extending past 3 days may be easier in the Atlantic basin than near Australia. The current work involves an effort to quantify the predictability timescale in the Atlantic basin using the most recent 40 yr of tropical cyclone tracks and to extend the baseline for track prediction skill past that currently used. In section 2, a brief climatology of the most recent 40 yr of tropical cyclone tracks is presented, with comparisons made to data used in previous studies. In section 3, the predictability timescale for the Atlantic region is calculated to show the feasibility of extending tropical cyclone track forecasts to 5 days. A statistical model combining predictors based upon both climatology and persistence is derived in section 4, and results for both dependent and independent data are shown in section 5.

2. The data

CLIPER was developed in the early 1970s using best track data from all tropical cyclones in the Atlantic basin during the most recent 40-yr period, through 1970 (Neumann 1972). Merrill (1980) found that CLIPER performed poorly in the extreme western portion of the Atlantic basin and attributed this to different climatological behavior of tropical cyclone tracks in that area. The Gulf of Mexico CLIPER was developed with tropical cyclone tracks in the western Gulf of Mexico and Caribbean Sea between 1886 and 1979. Because Merrill (1980) studied tropical cyclones in this small region bounded by landmass, the number of cases reaching the 3-day limit was small, and the data falsely accentuated slow-moving and recurving cases. To correct this, Merrill linearly extrapolated the available cases for 36 h. Since the average 12-h error of CLIPER is about 100 km, this introduced nonclimatological behaviors and large errors into the Gulf of Mexico CLIPER.

Approximately one-third of both sets of original data was compiled before aircraft reconnaissance of tropical cyclones, and almost all the data are before satellite monitoring commenced (Sheets 1990). While these data are as accurate as possible, accuracy has likely increased since the time when chance ship reports and landfalls were the only available observations. A number of trop-

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ical cyclones during the early period may have been missed entirely by the then-current observational network, and the tracks and intensities were conjecture through much of the history of each tropical cyclone. Systematic errors in intensity were found to exist in the early years of the original CLIPER data, such that the more intense hurricanes had wind speeds that averaged 2.5 m s^{-1} too high (Landsea 1993).

As a result, a newer and more accurate set of data comprising the most recent 40 yr, 1956–95, has been studied. While the first quarter of the new data was compiled before the advent of satellite monitoring, the entire set is within the era of regular aircraft reconnaissance. Some tropical cyclones could have been completely missed in the early portion of this data, and the accuracy of these data are not optimal. However, the need for a large set of data calls for using these less accurate data. CLIPER should be updated again early in the next century to account for the most accurate data possible.

Figure 1 shows all tracks in the North Atlantic for the original CLIPER data (1931–70), and for the most recent 40 yr (1956–95). Fewer tropical cyclones were tracked through the subtropical North Atlantic after recurvature in the earlier data due to lack of satellite observations. Tropical cyclones have been observed closer to the African coast in later years than the earlier ones, due to the availability of satellite observations. The newer data do show a relative dearth of tropical cyclones in the southwestern Caribbean Sea. This change is likely due to climatic differences such as the relative lack of rainfall in the Sahel region during this time period, since the likelihood of not observing tropical cyclones close to landmasses is very small (Landsea and Gray 1992).

Means of the basic predictors and predictands in the old and new data are compared in Table 1. The initial location in the Gulf of Mexico is near Merida in the older data and more than 300 km to the west in the newer data. The initial location in the Atlantic is about midway between Bermuda and Puerto Rico in the older data, and almost 600 km to the east in the newer data, suggesting the importance of satellite observations in tracking eastern Atlantic tropical cyclones. The intensity of the more recent tropical cyclones is lower than that of the older data, likely due to biases already mentioned (Landsea 1993). Initial motion vectors are also quite different in the different sets of data, especially in the Atlantic Ocean.

Figure 2 shows the mean tropical cyclone trajectories for the different data through 120 h. The important differences between the older and newer Atlantic data are in the zonal direction, with the newer tropical cyclones on average moving somewhat more eastward than the older ones. This is likely due to the increased number of recurved tropical cyclones in the newer data. Large differences in the Gulf of Mexico data are not as easy to explain, although of the seven tropical cyclones known to have passed from the Caribbean Sea or Gulf of Mexico into the eastern Pacific Ocean, only one was in the older data. The average tropical cyclone in the older data tended to recurve, whereas more recent tropical cyclones tended to continue northwestward. The average distance between the old and new tropical cyclone cases in the Gulf of Mexico at 120 h is approximately 600 km.

Because the newer data include longer tropical cyclone tracks after recurvature than the older data, the number of available forecasts falls off more sharply in the older than in the newer Atlantic data (Fig. 3). The number of available forecasts falls off more quickly in the older Gulf of Mexico data due to the lack of tropical cyclones passing through Central America intact relative to the new data. The number of cases falls off more quickly in the Gulf of Mexico data than in the Atlantic Ocean data due to the proximity to land in the former.

3. Predictability of Atlantic tropical cyclone tracks

An important question in this endeavor is the potential predictability of tropical cyclone tracks in the Atlantic basin given a perfect model or, more clearly, whether 5-day track forecasting can be feasible. Small differences in initial conditions are known to become large in time in dynamical systems such as the atmosphere. Given a perfect model, the predictability of the system can be measured by finding the rate at which small initial differences grow, and so the divergence of initially close trajectories (tracks) of independent tropical cyclones can be used as a predictability measure. Once a threshold distance between two initially close trajectories is reached, the process is said to be unpredictable. Fraedrich and Leslie (1989) estimate the average bounds of predictability by calculating the rate of separation between pairs of independent tropical cyclone trajectories in the Australian region. They calculate the second-order entropy, a lower bound for the Kolmogorov–Sinai entropy (Kolmogorov 1958; Sinai 1959) for the tropical cyclones, the inverse of which defines a preditability timescale. They showed that the predictability timescale approaches 24 h in the distance range between 150 and 400 km. Their method is used here to quantify the predictability timescale in the Atlantic region. A review of their method follows.

All tropical cyclone tracks are here assumed to start at a common location for simplicity. The distance between two independent tropical cyclone tracks with m successive positions,

$$X_m(t_i) = \{X(t_i), \ldots, X[t_i + (m - 1)t]\}, \qquad (1)$$

where $X(t) = [x(t), y(t)]$ is a position vector at time t, is represented by

$$d_{ij}(k) = \{[x(t_i + kt) - x(t_j + kt)]^2 + [y(t_i + kt) - y(t_j + kt)]^2\}^{1/2}, \qquad (2)$$

where t_i and t_j are the initial times of the two trajec-

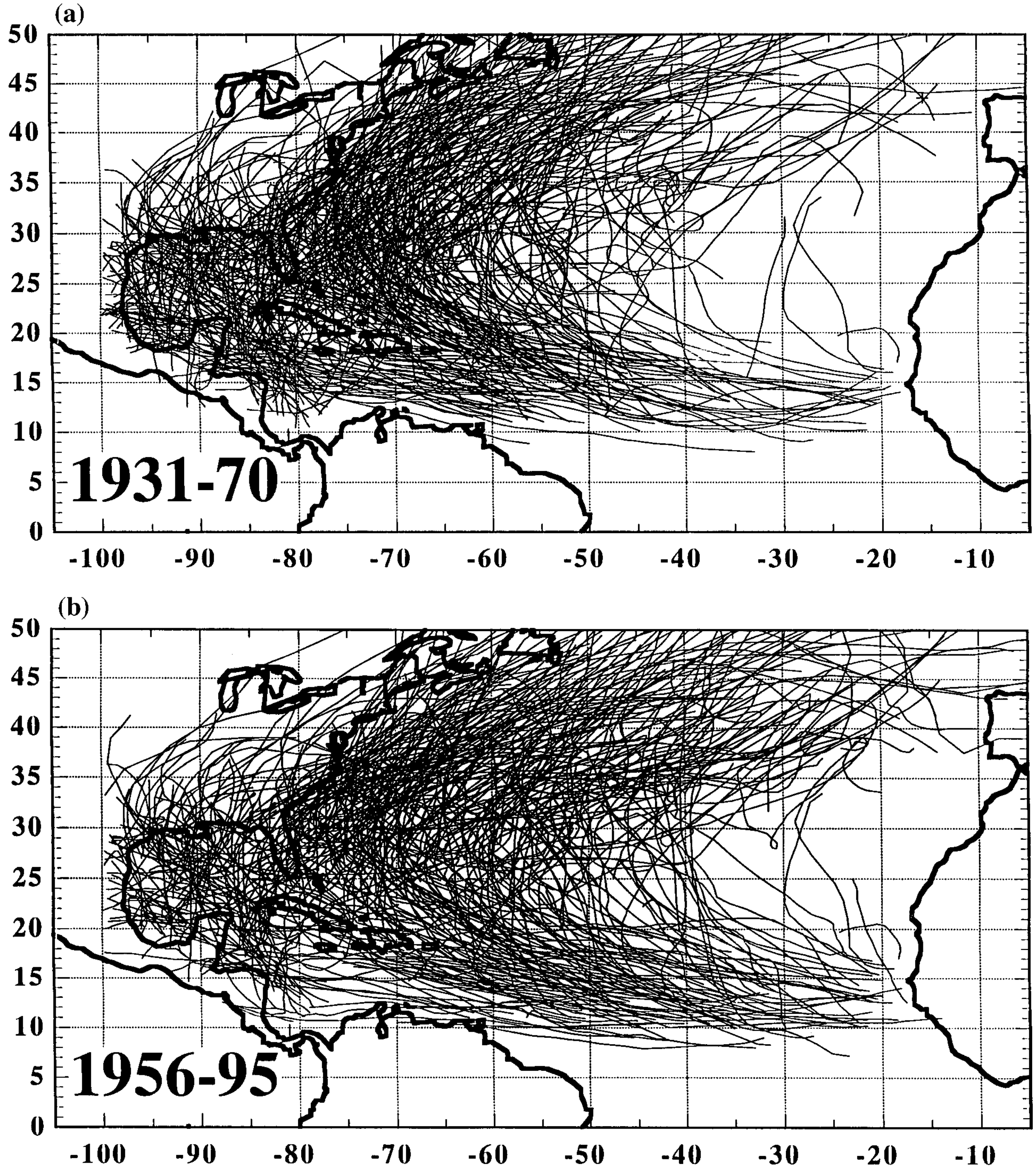

FIG. 1. Tracks of North Atlantic tropical cyclones during the periods (a) 1931–70 and (b) 1956–95.

tories i and j, x is the longitude, y is the latitude, t is time (in this case 6 h), and k is the number of 6-h time steps used. The number of pairs whose distance $d_{ij}(k)$ remains below a threshold value, l, is counted $[N_m(l)]$, leading to a probability estimate that the two trajectories remain within a certain distance from each other. This value, known as the correlation integral, is given by

$$C_m(l) = N_m(l)/(N_m - 1)^2, \qquad (3)$$

where N_m is the total number of pairs of independent tracks under consideration (Grassberger and Proccacia

TABLE 1. Mean values of linear predictors and predictands for old and new data for the Atlantic Ocean and Gulf of Mexico basins.

	Gulf of Mexico		Atlantic Ocean	
	1886–1979	1956–95	1931–70	1956–95
LAT—Initial latitude (°N)	20.9	20.9	25.5	26.0
LON—Initial longitude (°W)	89.6	92.5	66.1	60.9
INT—Initial intensity (m s^{-1})	28.8	26.8	31.3	28.6
DAY—Initial day number	249.6	253.6	251.2	251.3
U—Initial zonal motion (m s^{-1})	-2.5	-1.6	-1.5	-2.8
V—Initial meridional motion (m s^{-1})	2.0	2.5	2.9	1.0

1984). The number of pairs of independent tropical cyclones remaining within a fixed distance of each other decreases with increasing time. The ratio of C_m to C_{m+1} measures the rate at which close trajectory pairs diverge. The order-two entropy given by

$$K_2 = (1/t) \exp[C_m(l)/C_{m+1}(l)] \quad \text{for } l \rightarrow 0 \quad \text{and} \quad m \rightarrow \infty \tag{4}$$

provides a lower bound for the Kolmogorov–Sinai entropy, which is itself a bound for predictability. The inverse of K_2 in the region of the constant slope of correlation integral with distance defines a mean timescale over the dynamical system up to which deterministic predictability may be possible, considering an *e*-folding rate of the divergence of initially close trajectories.

Figure 4 shows the correlation integral for various values of *m* versus the distance. The slopes of the lines do not change as *m* increases, so the correlation integral is said to saturate. The region of constant slope at saturation corresponds to length scales between 50 and 500 km, a slightly larger scale than found in the Australian region. The value of K_2 found in the Atlantic for sufficiently large values of *m* corresponds to a predictability timescale of just below 2.5 days (Fig. 5), which also is larger than that found in the Australian region. This higher value agrees with the conclusion of Pike and Neumann (1987), who found that the Australian region was the most difficult area in which to forecast tropical cyclone tracks. Because hurricane tracks are serially correlated (Aberson and DeMaria 1994), the above calculations were again done using only those tracks that are 24 h apart from each other, with no change in the results. This gives further evidence of the stability of these calculations given the relatively small sample size.

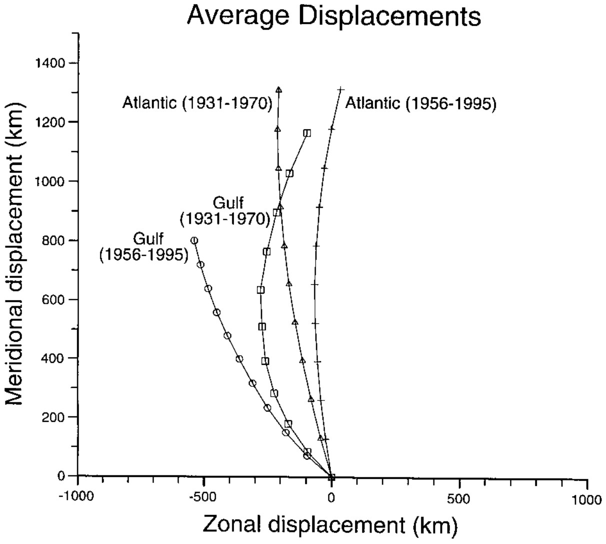

FIG. 2. Average displacements of tropical cyclones in the North Atlantic. Triangles represent displacements in the Atlantic region (1931–70), plus marks those in the Atlantic region (1956–95), squares those in the Gulf of Mexico region (1886–1979), and octagons those in the Gulf of Mexico region (1956–95). Marks are every 12 h from the origin.

As in any study of this type, the relatively small amount of data prevents the tropical cyclone tracks from completely covering the attractor (i.e., all possible tracks) and, thus, makes the values calculated only estimates of the true predictability timescales. Fraedrich and Leslie (1989) suggest that the predictability timescale is an upper bound to the expected ability of deterministic forecast models to predict tropical cyclone tracks, and that the limited skill of forecast models in the Australian region confirms this. However, forecast models in the Atlantic basin routinely show maximum skill at 72 h (Aberson and DeMaria 1994), slightly past the predictability timescale found in this study. The discrepancy may be due in part to the difference in the definitions of skill and error, since forecasts with very large errors may be skillful if the CLIPER forecast errors are even larger.

4. Regression analysis and choice of predictors

Two different statistical track models for the Atlantic basin have been derived for 3-day forecasts, one for the Atlantic (Neumann 1972) and one for the Gulf of Mexico (Merrill 1980). After the Merrill (1980) update to the model, the Gulf of Mexico data had not been removed from the dependent data for the Atlantic CLIPER; the two basins have been completely separated in this study. The two previous versions of CLIPER were derived by choosing from a number of predictors and their possible cross products (Merrill 1980) and third-order polynomials (Neumann 1972) in a stepwise regression. Neumann chose the nine predictors that most impacted the explained variance of the trajectories, whereas Merrill included all of the possible predictors in the final model. Both versions chose to min-

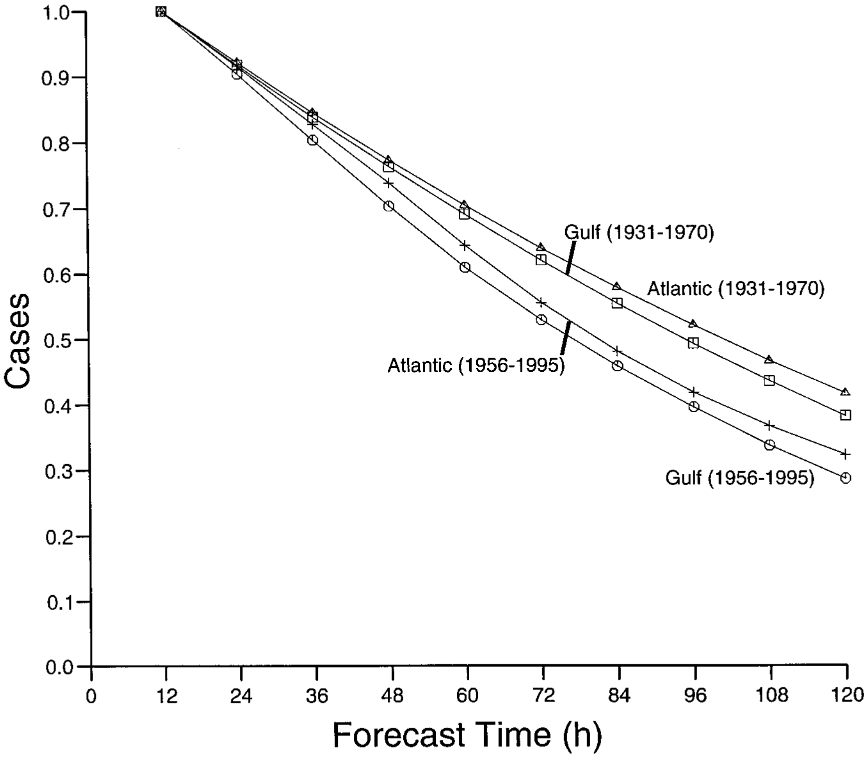

FIG. 3. The change in the ratio of available cases at each forecast time vs the number of cases available at 12 h. Symbols are as in Fig. 2.

imize the least squares fit in the regression. The current version serves to minimize the least squares fit and to retain only those predictors, chosen from the linear and all possible cross terms, that explain at least 0.5% of the variance of the predictand, a procedure that closely mirrors that of Neumann. In this study, each predictand is either the zonal or meridional displacement over the particular 12-h period, so that two sets of regression equations are needed to predict the track. In the original studies, the

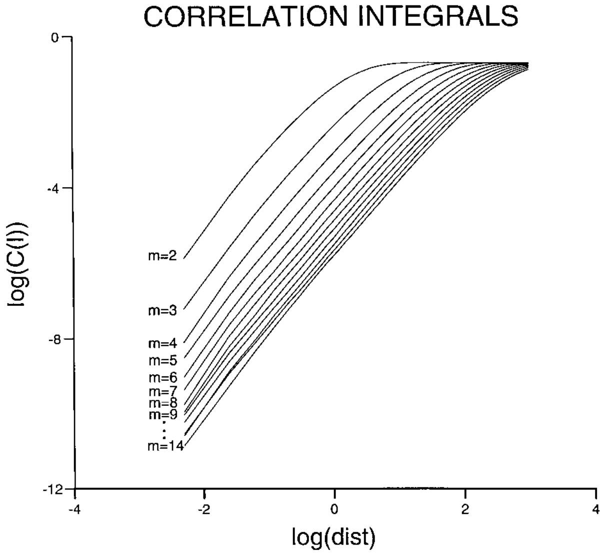

FIG. 4. Correlation integrals for pairs of independent trajectories in the North Atlantic ($m = 2$ to 14). Note that the slopes of the lines do not change as m increases for distances between 50 and 500 km.

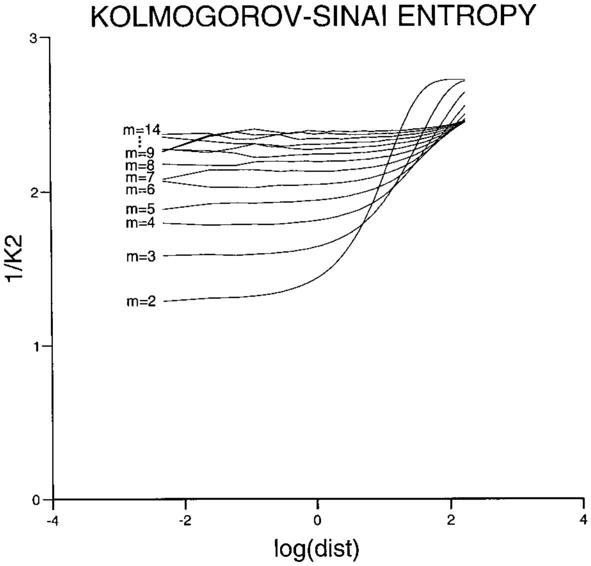

FIG. 5. The predictability timescale for tropical cyclone tracks in the North Atlantic ($m = 2$ to 14). The values of $1/K$ do not change as m increases, giving the value of the timescale of about 2.5 days.

TABLE 2. Predictors chosen and percentage of variance explained for each predictand in each basin for the dependent data (1956–95). Parts a and b are for the meridional and zonal displacements from the initial location in the Atlantic basin, respectively. Parts c and d are for the meridional and zonal displacements from the initial location in the Gulf of Mexico basin, respectively. Abbreviations are explained in Table 1.

	12 h	24 h	36 h	48 h	60 h	72 h	84 h	96 h	108 h	120 h
a										
V	74.8	40.5	18.0							
INT × U		0.5					0.7			
LAT × INT			0.6							0.5
INT × V				6.8	2.4	1.1	0.8	0.9	0.7	
U × V						0.6				
LON × DAY							0.6	0.9	1.1	1.1
INT × INT										0.6
LON × V										0.5
b										
U	89.5	70.9	53.0	4.2	1.7	0.8				
LON × V	0.6	2.8	4.4	5.7	4.9	3.9	3.3			1.0
LAT		1.6	5.9	43.2	38.5	34.2	30.2	26.7	23.2	20.0
LAT × U					0.7					
LAT × LAT						1.2	1.8	3.4	3.8	3.9
DAY × U						0.6				
INT × V								1.8	1.4	
c										
V	68.7			3.4						
U × V	1.6			2.1						
LAT × V		37.3	18.8							
LAT × DAY		1.9								
INT × U		1.7	1.7							
DAY			3.4	78.8	6.7	6.8	7.5			
LON × U					2.1					
LON × DAY								8.2	6.9	6.5
d										
U	74.8	45.4	26.7	18.6	3.7					
V × V	1.3	3.7	5.4	5.7	2.4				2.2	
LAT × LAT		1.2	2.5							3.3
LAT × INT		1.2	2.2	3.1	7.8	7.1				
DAY × U		0.6	1.2	1.0						
LAT				4.0	11.3	11.4	14.1	18.6	21.2	23.0
INT × U					1.4	1.6				
LON × U						2.3				
LON × INT							7.1	4.0		
DAY × DAY									5.9	3.1
LAT × LON									4.8	
LAT × DAY									2.0	3.4
LON × DAY										7.0

predictands were the displacements at each forecast time from the initial position. This change was made because, at longer forecast times, the most important predictor chosen varies, causing discontinuous forecast tracks, and the new method alleviates this problem.

Table 2 shows the predictors chosen for each basin, and the amount of variance explained by them. In both basins, persistence (the current storm motion) is initially the most important predictor. For the zonal component of motion, persistence is replaced by the latitude at later forecast times, since storms in the deep Tropics tend to move westward and recurve toward the east with increasing latitude. The meridional component is more complicated and the variance explained is smaller than for the zonal motion component. Predictors at early forecast times involve combinations of persistence, which gives way to combinations involving the day number. This is likely due to tropical cyclones later in the season moving northward more rapidly than those in the early season.

Because of the limited amount of dependent data, the regression was tried again removing the last year, so that the dependent data represented 39 yr of tropical cyclone tracks. The average values of the predictors showed only minimal changes. Table 3 shows the predictors chosen and the amount of variance explained in this slightly smaller set of data. In the Atlantic basin, the predictors chosen in each set were very close for the east–west component. The three additional predictors were chosen at only one forecast time each and explained only relatively small amounts of the variance compared to the most important predictors. For the meridional displacement, each set allowed the choice of two predictors that were not chosen in the other,

Table 3. Predictors chosen and percentage of variance explained for each predictand in each basin for the dependent data (1956–94). Parts a and b are for the meridional and zonal displacements in the Atlantic basin, respectively. Parts c and d are for the meridional and zonal displacements in the Gulf of Mexico basin, respectively. Abbreviations are explained in Table 1.

	12 h	24 h	36 h	48 h	60 h	72 h	84 h	96 h	108 h	120 h
a										
V	74.8	40.7	18.4	7.0						
INT × U		0.5								
LAT × INT			0.5							
INT × V				0.5	2.4	1.1	0.6	0.9	0.6	0.5
U × V					0.6	0.7	0.9			
DAY × U					0.5					
LON × DAY							0.5	1.0	1.3	1.3
LAT × V						0.6				
U							0.5			
b										
U	89.7	71.0	53.2	4.2	1.5	0.6				
LON × V	0.5	2.8	4.4	5.9	5.1	4.1	3.5			1.1
LAT		1.6	5.0	43.2	38.6	34.2	30.2	26.7	23.2	20.0
LAT × V			5.7							
LON × DAY			0.5							
LAT × U					0.7					
LAT × LAT						1.3	1.8	4.3	3.8	3.8
DAY × U						0.5				
U × V						0.5				
INT × V								2.0	1.4	
c										
V	68.7									
U × V	1.7								3.1	3.7
LAT × V		38.3	19.3	3.9						
INT × DAY		2.0	1.8							
LAT × U		1.3								
INT × INT		1.1								
DAY			3.3	7.5		6.9	7.6			
LON × DAY					6.6			8.6	7.2	6.7
U					2.3					
d										
U	75.2	45.8	27.4	20.0	12.7					
V × V	1.4	3.9	5.8	5.8	2.6	1.6			2.2	
LAT × LAT		1.2	2.2							3.2
LAT × INT		1.2	2.5	3.5	5.0	7.9				
DAY × U		0.8	1.1							
LAT				3.6	6.4	11.0	13.8	18.3	21.2	23.4
INT × U					1.8	1.8				
LON × U						2.9				
LON × INT							6.6	4.2		
LAT × LON									4.7	
LON × DAY										6.8
LAT × DAY										3.5
DAY × DAY										2.9

and again, each of these was only chosen at one forecast time and explained only small amounts of the variance. However, at 48 h, the most important predictor changed from persistence in the smaller set of data to persistence multiplied by intensity in the larger. The total variance explained in both samples at 48 h was similar.

In the Gulf of Mexico basin, the differences were much larger, probably because of the smaller size of the dependent data. In the regression for the meridional component, seven different predictors were chosen, and of those, three were selected at more than one forecast time. For the 60-h forecast, none of the predictors chosen in either set of data matched those chosen in the other. In the zonal regression, the same 13 predictors were chosen in each set of dependent data. However, at 60 h, the two most important predictors chosen in each set of data did not agree with the other.

Because of the larger differences in the Gulf of Mexico basin, and due to the smaller amount of dependent data, a purely linear regression has been tested, and the results for both the shorter and longer datasets are shown in Table 4. The same predictors were chosen for both sets of displacement predictands with only slight differences at each forecast time. However, the most important predictor for the 60-h zonal displacement was again different in the two sets of data. Despite the smaller differences in the linear

TABLE 4. Linear predictors chosen and percentage of variance explained for each predictand in the Gulf of Mexico for the dependent data. Parts a and b are for the meridional and zonal displacements (1956–95), respectively. Parts c and d are for the meridional and zonal displacements (1956–94), respectively. Abbreviations are explained in Table 1.

	12 h	24 h	36 h	48 h	60 h	72 h	84 h	96 h	108 h	120 h
a										
V	74.8	40.5	18.0	6.6	1.8					
INT				0.5	0.5	0.6	0.6	0.6	0.6	0.5
DAY						0.6	0.6	0.6	0.7	0.7
LON								0.5	0.7	0.7
b										
U	89.5	70.9	53.0	4.3	1.7	0.7				
LAT		2.5	5.9	43.2	38.5	34.2	30.2	26.7	23.2	20.0
V		1.9	3.9	5.0	4.4	3.5	3.0	2.6	2.2	1.7
LON				0.6	0.9	1.4	1.4	1.3	1.4	1.4
c										
V	68.7	37.3	18.1	3.4						
DAY		1.8	3.9	7.8	6.7	6.8	7.5	7.6	5.5	4.0
U		1.2	1.4	1.8	2.0					
d										
U	74.8	45.4	26.7	18.6	4.0	2.3				
V	0.5	2.2	1.7							
LAT		1.3	3.7	5.2	11.3	11.4	14.1	18.6	21.2	23.0
INT		1.2	3.1	4.1	7.4	6.7	5.7	3.2		
LON								2.0	4.5	6.0
DAY										2.9

regressions, major differences are the same in the linear and nonlinear regressions (60-h forecast of zonal displacement), and the nonlinear regression explains much more of the variance especially at the very important early forecast times for the zonal displacement. As a result, the quadratic versions are used in both basins.

5. Results

a. Dependent data (1989–95)

Since the older data (1931–70) likely do not approach the accuracy currently available, the statistical model developed from that data may not provide the most accurate forecasts. For example, these purely statistical forecasts would not be expected to exhibit directional biases in large sets of independent forecasts. However, during the years 1989–96, CLIPER exhibited rather large westward to west southwestward biases (Fig. 6). This is likely a result of the differences in the older and newer sets of data described above.

The new version of CLIPER was run on the dependent data for comparison. Results using the independent data are not likely to be as successful. The new version of CLIPER has much smaller biases than the older version (Fig. 6). The 84-h bias of the current version of CLIPER is comparable to the 24-h bias of the older version. This reduction in bias is most likely the result of the updated data used in the study, and not the elimination of third-order terms in the regressions analysis, since these added only small amounts of explained variance to the old versions of CLIPER. The absolute errors obtained with the new version of CLIPER are less than 2% smaller than those from the older version through 72 h (Table 5a), and significance tests (Aberson and DeMaria, 1994) show that the differences are not statistically significant at even the 90% level. Average 120-h forecast error for the new version of CLIPER for a relatively large sample of cases (805) is 1110 km, and error growth is approximately linear throughout the forecast.

b. Independent data (1996)

The new version of CLIPER was also run for all cases during the 1996 hurricane season, the independent data. In this comparison, results from both the older and newer versions are comparable in that for both models, 1996 is independent data. The biases are shown in Fig. 7 and the errors in Table 5b. The errors of the two different versions of the model are again comparable, with average errors within 2% of each other, and the differences not statistically significant. However, again the biases of the newer version are much smaller, although in these data, the newer version of CLIPER shows a southerly bias. Average errors in the independent data are slightly smaller than those from the dependent data. Error growth is approximately linear through 120 h for the new CLIPER.

6. Summary

The average skill of tropical cyclone track predictions is calculated by comparing model errors to those from a simple regression based upon climatology and persistence. An update of the CLIPER track forecast model for the North Atlantic hurricane basin has been done. Since trop-

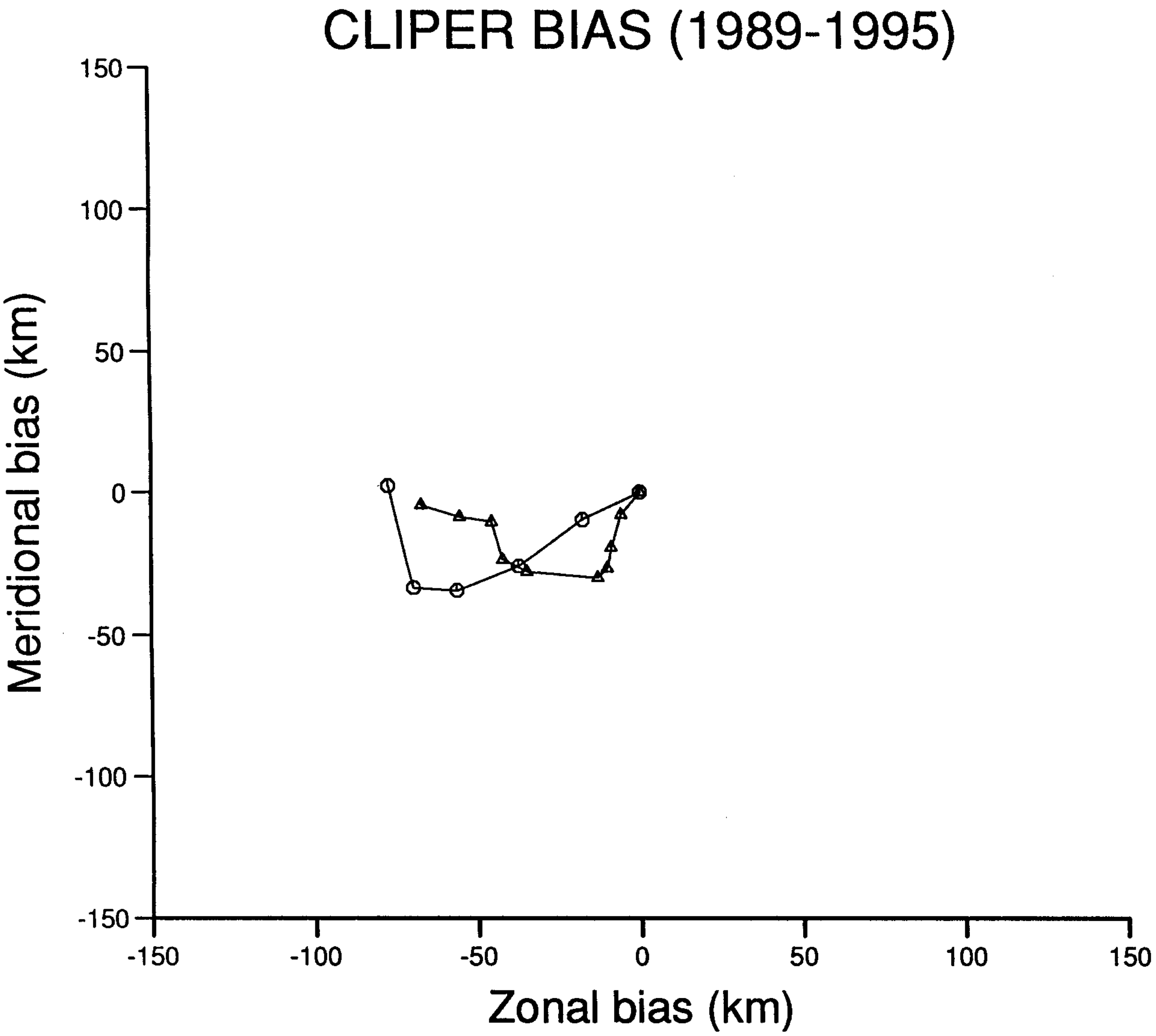

FIG. 6. Average meridional and zonal biases of the two versions of CLIPER for all cases 1989–95. The current version of CLIPER is represented by octagons; the new version by triangles. The values shown from the origin are for 12, 24, 36, 48, 72, 84, 96, 108, and 120 h. The current version extends only to 72 h.

TABLE 5. Comparison of the absolute errors between the old and new versions of CLIPER through 120 h in km, for (a) the dependent data (1956–95) and (b) the independent data (1996).

	12 h	24 h	36 h	48 h	72 h	84 h	96 h	108 h	120 h
a									
Old	111.0	224.2	346.5	471.6	718.9				
New	108.9	221.7	345.2	469.3	706.8	814.5	910.7	1012.8	1110.0
No. of cases	1809	1699	1583	1459	1218	1102	995	897	805
b									
Old	94.7	182.5	282.1	388.3	597.4				
New	93.6	184.1	287.6	397.7	603.0	701.7	813.5	918.8	1009.3
No. of cases	375	355	334	314	270	248	229	211	193

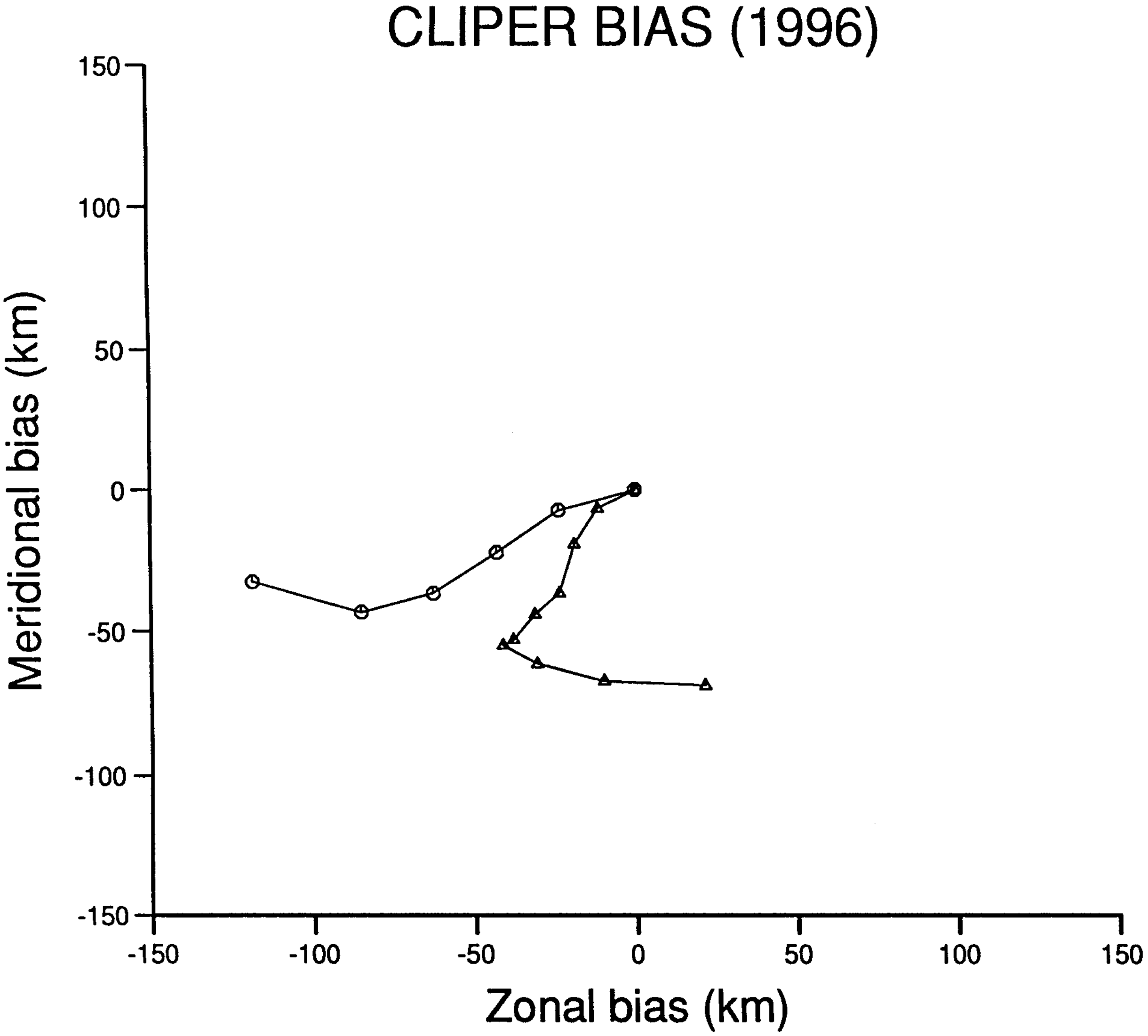

FIG. 7. Average meridional and zonal biases of the two versions of CLIPER for all cases in 1996. The current version of CLIPER is represented by octagons; the new version by triangles. The values shown from the origin are for 12, 24, 36, 48, 72, 84, 96, 108, and 120 h. The current version extends only to 72 h.

ical cyclone tracks based upon satellite observations are more accurate than by any other method except reconnaissance, the updated dependent data, with tracks from the era of regular satellite and aircraft reconnaissance, are more accurate than that from which the older version of CLIPER was derived. However, the early portion of the current dependent data is before the advent of satellite observations, so CLIPER must again be derived when a 40-yr sample of satellite observations is available. Nevertheless, track forecast errors from the current version of CLIPER are comparable in size to those from the older version. However, large biases in track forecasts from the older version are virtually eliminated in the new, current version.

Track forecasting in the Atlantic basin has been shown to be a bit easier on average than in the Australian basin, using techniques from nonlinear system science. An *e*-folding timescale of about 2.5 days was calculated for the Atlantic basin, compared to approximately 1 day in the Australian basin. With *e*-folding error growth on that scale, 5-day forecasts can be expected to show some skill. As a result, interest has increased in medium-range tropical cyclone track prediction, and the current CLIPER model provides a baseline by which the skill of such predictions can be measured.

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