On the Predictability of Tropical Cyclone Tracks in the Northwest Pacific Basin

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ABSTRACT

A new Northwest Pacific climatology and persistence (CLIPER) model is derived with historical tropical cyclone tracks during the satellite and aircraft reconnaissance era (1970–95). The new CLIPER extends the forecasts from 3 to 5 days and exhibits smaller forecast biases than the previous CLIPER, although forecast errors are comparable. The new model is based on more accurate historical tropical cyclone track data, and a simpler derivation of the regression equations, than is the old model. Nonlinear systems analysis shows that the predictability timescale in which the average errors increase by a factor *e* is just over 15 h, which is about the same as that calculated by similar methods near Australia and in the North Atlantic. This suggests that 5-day tropical cyclone track forecasts may be beneficial, assuming small initial errors; therefore, a CLIPER model extended to 5 days is needed as a baseline to measure the forecast skill.

1. Introduction

The Tropical Prediction Center in the North Atlantic and Northeast Pacific basins, the Central Pacific Hurricane Center in the north-central Pacific basin, and the Joint Typhoon Warning Center (JTWC) in the West Pacific and Indian Ocean basins have historically produced tropical cyclone track predictions out to 3 days from the initial time. Forecasts have improved steadily during recent decades (e.g., Aberson 2001; McAdie and Lawrence 1993) and skill, as measured by comparison of forecasts to similar forecasts from a simple statistical technique based on climatology and persistence (CLIPER), has steadily increased. For example, in the North Atlantic basin, the average 48-h model absolute track forecast errors in 1976 were larger than current 72-h errors, and average 24-h model errors in 1976 are comparable to current 48-h errors (Aberson 2001). Due to these improvements in short-range track forecasts, operational centers may soon begin to provide track forecasts to 5 days. A new CLIPER model must be derived in each basin to assess the skill of these new forecasts.

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Fraedrich and Leslie (1989) have shown that the timescale for tropical cyclone track errors to increase by a factor of *e* in the Australia region is approximately 15 h. Pike and Neumann (1987), by ranking CLIPER forecast track errors by tropical cyclone basin, have shown that the Australia region is the most difficult basin in which to forecast tropical cyclone tracks. Aberson (1998) found that the predictability timescale for tropical cyclone tracks in the North Atlantic basin is also near 15 h. Therefore, track forecasts beyond 3 days are likely to be as accurate in the North Atlantic basin as those near Australia. Pike and Neumann's results suggest an even longer predictability timescale in the northwest Pacific basin than those derived for the other two basins.

The current work involves an effort to quantify the tropical cyclone track predictability timescale in the northwest Pacific basin and to extend the baseline for track prediction skill past that previously used. In section 2, a brief climatology of the recent record of tropical cyclone tracks is presented, with comparisons made to data used in previous studies. In section 3, the predictability timescale 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, similar to the model presented in Aberson (1998) in the north Atlantic basin, is

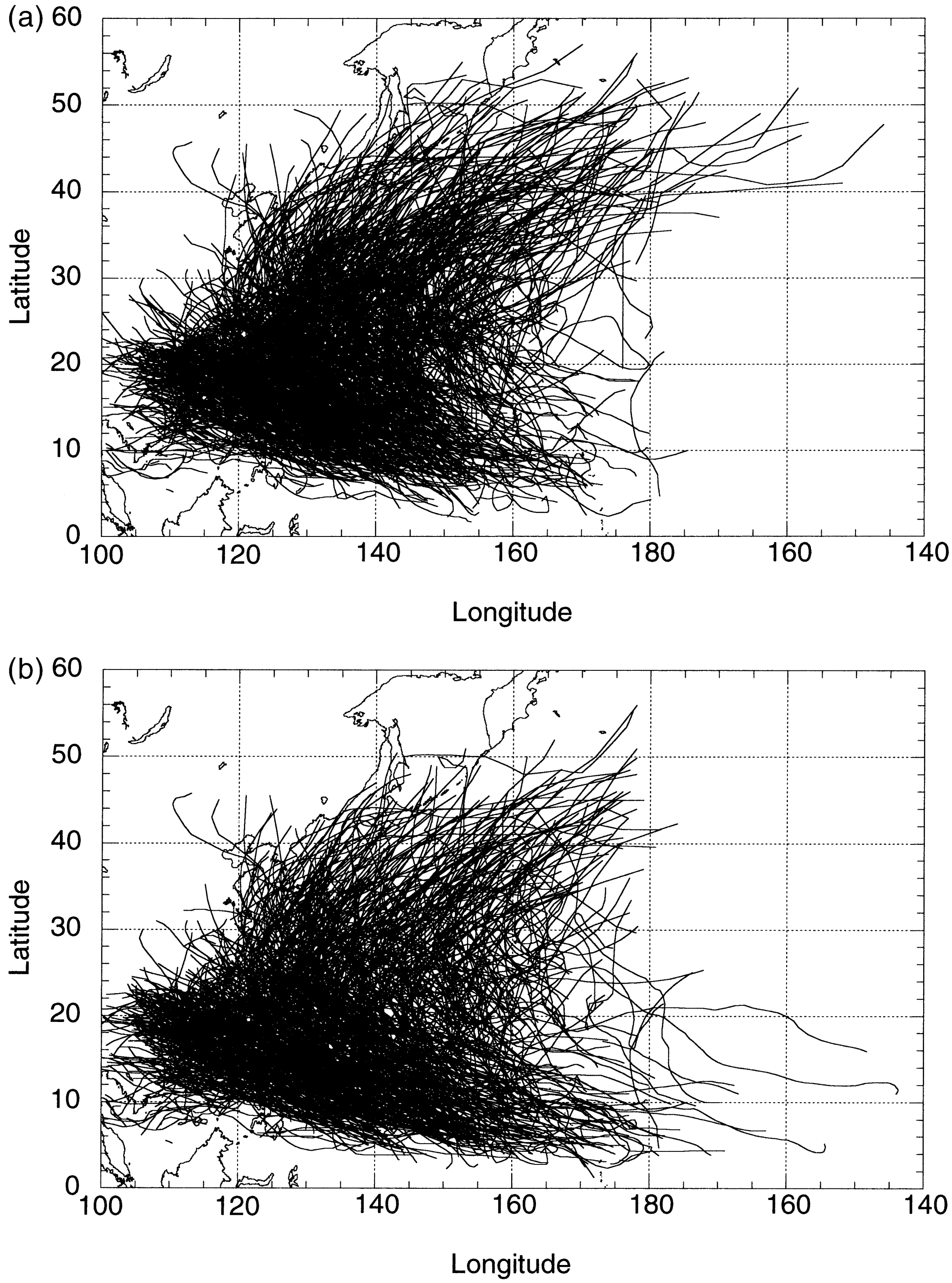

FIG. 1. Tracks of northwest Pacific tropical cyclones during the periods (a) 1946–80 and (b) 1970–95.

derived in section 4, and results for both dependent and independent data are shown in section 5.

2. The data

The northwest Pacific CLIPER was developed using best track data from 1946 to 1980 (Xu and Neumann 1985). Xu and Neumann limited the dependent data to those storms between 5° and 35°N, west of 150°E, and between 15 May and 15 December. No CLIPER forecasts have been available for tropical cyclones outside these bounds.

Though all the best track data were compiled in the tropical cyclone aircraft reconnaissance era, more than

TABLE 1. Mean values of linear predictors and predictands for old (1946–80) and new (1970–95) data for the northwest Pacific basin.

	1946–80	1970–95
LAT = initial lat (°N)	19.8	18.1
LON = initial lon (°E)	134.8	136.6
INT = initial intensity (m s^{-1})	32.1	26.3
DAY = initial day number	237.0	238.2
U = initial zonal motion (m s^{-1})	−1.8	−2.4
V = initial meridional motion (m s^{-1})	2.7	2.2

two-thirds of the data were compiled before satellite monitoring commenced. The best track data are as accurate as possible, though accuracy has likely increased since the time when chance ship reports, landfalls, and aircraft missions provided the only available observations. Some tropical cyclones during the early period may have been missed entirely by the observational network, and the tracks and intensities were conjecture through much of the early tropical cyclone climatology. Different methods of estimating maximum sustained winds in time (such as different sensors on reconnaissance aircraft and evolving interpretation of these data, reliance on interpretations of satellite imagery or other remotely sensed wind speeds) may also contribute to errors in the best track data. As a result, a new, more accurate dataset comprising tracks from the satellite era (since 1970) has been studied. Due to the usual high level of tropical cyclone activity in the northwest Pacific basin, the data should be sufficient for derivation of an updated CLIPER. Further CLIPER updates can be made annually if desired.

Figure 1 compares all tracks in the northwest Pacific for the original CLIPER data (1946–80) with those from the recent period during which satellite observations were available (1970–95). Fewer tropical cyclones were tracked through the area near the date line in the early data due to a lack of satellite observations. A few tropical cyclones moved into the Bay of Bengal from east of Vietnam in the recent dataset. The most noticeable change is that the tracks did not extend as far to the northeast in midlatitudes in the new versus the old data, which is the opposite of the behavior in the North Atlantic basin (Aberson 1998).

Means of the basic predictors and predictands in the old and new data are compared in Table 1. The mean initial location in the old dataset is just southwest of Parece Vela, a small island about midway between Saipan and Okinawa, whereas the initial location in the new dataset is 270 km to the southeast of this point. This suggests the importance of satellite observations in tracking tropical cyclones away from the traditional areas near land where aircraft reconnaissance was concentrated in the early data, though some of this difference may be due to climatic changes. The average initial intensity of the recent tropical cyclones is lower than that of the old data, possibly because the satellites are able to identify some weak tropical cyclones that were

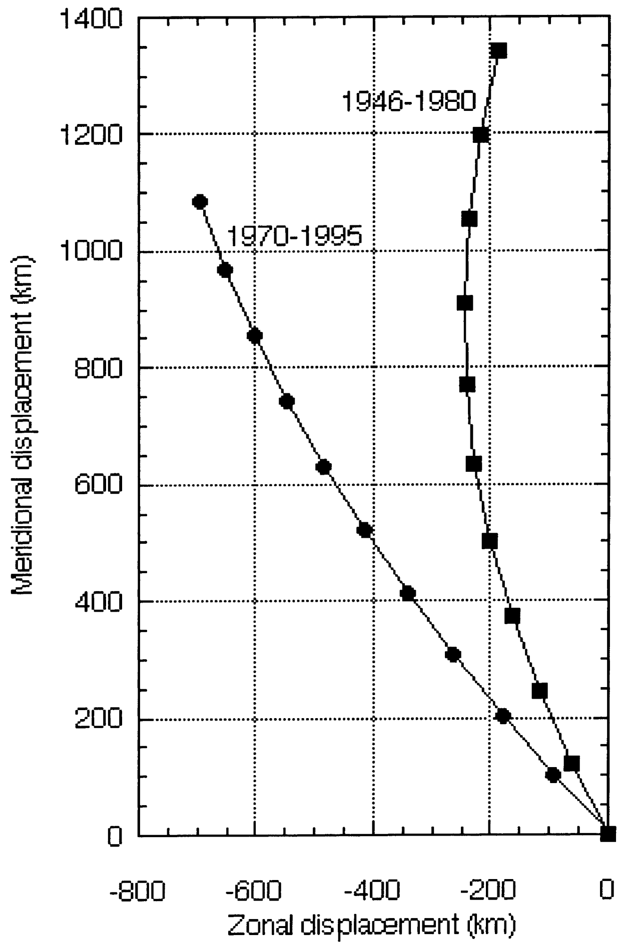

FIG. 2. Average displacements of tropical cyclones in the northwest Pacific for the 1946–80 data, and the 1970–95 data. Marks are every 12 h from the origin.

missed with previously available observing systems. The average storm motion is also different in the two datasets.

Figure 2 shows the mean tropical cyclone trajectories for the different datasets through 120 h. The average motion in the new dataset is somewhat more westward and more slowly toward the north than in the old data. This is likely due to the ability of satellites to track tropical cyclones in the southern part of the basin where regular aircraft reconnaissance data were not available and where tropical cyclones tend to move to the west or west-northwest. The average tropical cyclone in the old dataset tended to recurve, whereas the more recent tropical cyclones tended to continue northwestward. The distance between the average old and new tropical cyclones at 120 h is approximately 575 km. These differences are similar to those seen in the Gulf of Mexico area (Aberson 1998). Because the new data include longer westward-moving tropical cyclone tracks in the Tropics than the old data, the number of available forecasts falls off more sharply in the old than in the new

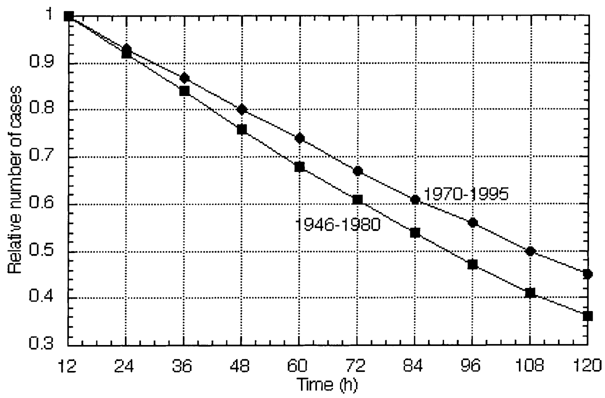

FIG. 3. The change in the ratio of available cases at each forecast time vs the number of cases available at 12 h.

data (Fig. 3). This is similar to the behavior in both the North Atlantic and Gulf of Mexico data (Aberson 1998).

3. Predictability of Northwest Pacific tropical cyclone tracks

An important question in this endeavor is the potential predictability of tropical cyclone tracks in the northwest Pacific basin given a perfect model or, more clearly, whether accurate 5-day track forecasts are possible. Small differences in initial conditions are known to become large in time in nonlinear 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 tropical cyclone trajectories (tracks) 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 upper bound of predictability by calculating the separation rate between independent tropical cyclone trajectory pairs in the Australia region, and the same technique was used in the North Atlantic basin (Aberson 1998). They calculated the second-order entropy, a lower bound of the Kolmogorov–Sinai entropy (Kolmogorov 1958; Sinai 1959), for the tropical cyclone tracks. The inverse of the entropy defines a predictability timescale. They showed that the predictability timescale approaches 15 h in the Australia region and is near 15 h in the North Atlantic. This method is used here to quantify the predictability timescale in the northwest Pacific basin. A short review of the method follows.

All tropical cyclone tracks are 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

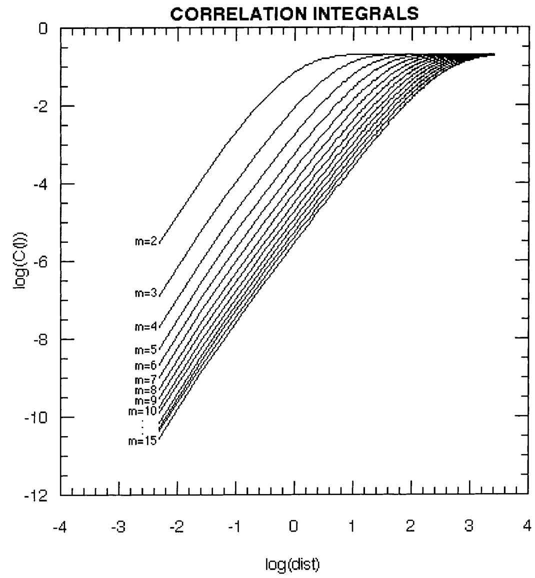

FIG. 4. Correlation integrals for pairs of independent trajectories in the northwest Pacific (m = 2–15). The distance l is given in degrees latitude for simplicity. Note that the slopes of the lines do not change as m increases for distances between 50 and 500 km.

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

where t_i and t_j are the initial times of the two trajectories i and j; x and y are the longitude and latitude, respectively; t is the time step (6 h); and k is the number of

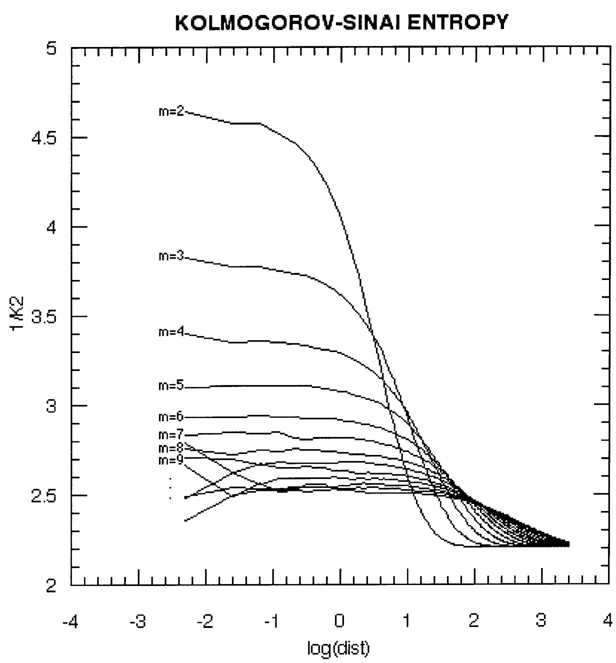

FIG. 5. The predictability timescale for tropical cyclone tracks in the northwest Pacific (m = 2–15). Here, $1/K_2$ does not change as m increases, so the value of the timescale is about 15 h.

TABLE 2. Predictors chosen and percentage of variance explained for each predictand in each basin for the dependent data (1970–95) for the (a) meridional and (b) zonal displacements from the initial location in the northwest Pacific basin. Abbreviations are defined in Table 1.

a)	12 h	24 h	36 h	48 h	60 h	72 h	84 h	96 h	108 h	120 h
V	74.2	41.7	1.5	0.2						
U	0.5		0.8	0.3		0.3	0.3			
INT × V	0.3	1.7	23.1	14.2	9.3	6.7	4.9	3.7	3.0	2.4
U × V	0.1			0.3	0.6	0.3				
DAY × DAY	0.1	0.2	0.3	0.7	0.8	0.9	0.9	0.9	0.9	1.0
LON × DAY	0.1	0.3	0.8	0.2		0.3	0.3	0.4	0.3	0.5
INT × U		0.9								0.3
LAT × INT		0.3	0.4	0.3	0.3					0.3
LON × LON		0.1	0.2			0.2	0.3	0.3	0.4	0.3
LON		0.2	0.3			0.7	0.6	0.6	0.5	0.6
INT × INT			0.1	0.4	0.2					
LAT × LAT			0.4	0.2	0.3					
LAT × LON					1.0					
DAY				0.8	1.0					
U × U				0.2						
LAT × U					0.3			0.3	0.3	
LON × INT						0.6	0.7	0.7	0.5	0.4
b)	**12 h**	**24 h**	**36 h**	**48 h**	**60 h**	**72 h**	**84 h**	**96 h**	**108 h**	**120 h**
U	86.0	62.7	42.0	0.6	0.7	0.4	0.2	0.6		
LAT	0.2	1.2				17.6	15.2	12.8	10.6	8.7
INT × V	0.1	3.3	7.1	10.0	6.9	6.7	6.0	5.4	4.8	4.0
INT × U	0.1	0.5	0.6	0.5						
U × U	0.1	0.3	0.2						0.3	0.3
LAT × LON	0.1	0.3				1.1	1.4	2.0	2.0	
LON × V	0.1	0.1								
LON × U	0.1	0.1	0.1	27.0	6.3	3.5				
LAT × LAT			0.0	0.1	0.1					
LON × LON			0.1	0.2	0.1					2.2

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

$$C_m(l) = N_m(l)/(N_m - 1)^2, \tag{3}$$

where N_m is the total number of independent track pairs under consideration (Grassberger and Proccacia 1984). The number of independent tropical cyclone track pairs 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

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

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 the e-folding divergence rate of initially close trajectories.

Figure 4 shows the correlation integral for various values of m versus distance l. The values of l are given in degrees of latitude for simplicity. The slopes of the lines stop changing as m increases, so the correlation integral is said to saturate. The constant slope region at saturation corresponds to length scales between 50 and 500 km, a larger scale than in the Australia region, and encompassing that in the North Atlantic. The predictability timescale is found in Fig. 5 in the region of constant slope in Fig. 4 where the lines converge as m increases. The K_2 for large m corresponds to a predictability timescale of about two and a half 6-h periods or 15 h, which is about the same as the values calculated in the Australia and North Atlantic regions. This value disagrees with Pike and Neumann (1987) who, by comparing track errors from each basin's CLIPER model, concluded that the Australia region was the most difficult area in which to forecast tropical cyclone tracks, followed by the North Atlantic and then the northwest

TABLE 3. Homogeneous comparison of the absolute errors (in km) between the old and new CLIPER models through 120 h, for 1996–98.

	12 h	24 h	36 h	48 h	72 h	84 h	96 h	108 h	120 h
Old	74.9	177.7	292.9	416.3	658.9				
New	80.2	188.9	308.3	427.0	651.9	758.3	860.9	957.3	1046.3
No. of cases	3113	2946	2776	2602	2257	2100	1948	1797	1651

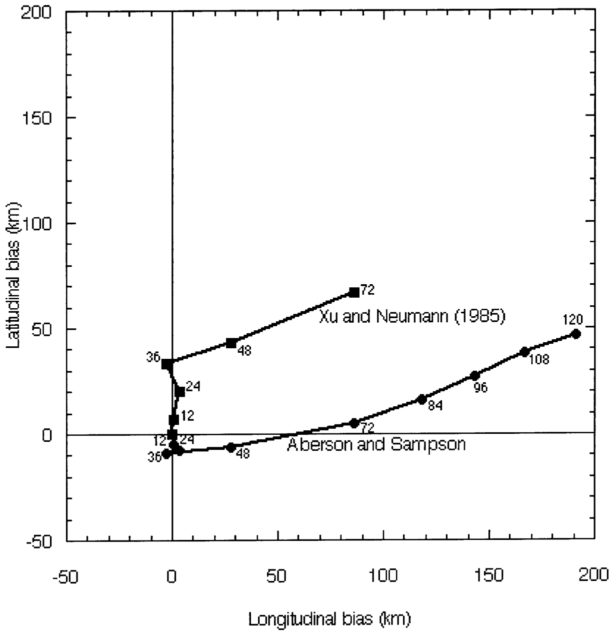

FIG. 6. Average meridional and zonal biases of the two CLIPER models for all cases 1996–98.

Pacific basins. Because tropical cyclone tracks are serially correlated (Aberson and DeMaria 1994), the above calculations were redone using only those tracks that are 24 h apart from each other, with no change in the results. This provides further evidence of the stability of these calculations given the relatively small sample size. 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 calculated in this manner is an upper bound to the expected ability of deterministic forecast models to predict tropical cyclone tracks. However, this procedure presupposes exponential error growth, which may not be the correct assumption.

4. Regression analysis and choice of predictors

The previous section showed that accurate 5-day tropical cyclone track forecasts theoretically may be possible. In order to accurately assess these medium-range forecasts, a new version of the CLIPER statistical track model, the baseline by which track forecast skill is measured, must be derived. The previous CLIPER model for the northwest Pacific basin provided forecasts to 3 days (Xu and Neumann 1985). In this CLIPER, the predictands were the displacements at each forecast time from the initial position. The model was derived by choosing from linear predictors and their cross and third-order terms. Thirty-two of the possible predictors were chosen at least once for the six (12–72 h, every 12 h) regression equations in both the meridional and zonal directions (12 equations total). The 32 predictors for the meridional motion were used for all forecast times in the meridional direction, and likewise for the zonal motion, to alleviate problems with discontinuous tracks due to changes in predictors chosen. The current CLIPER minimizes the least squares fit between the predictors, chosen from the linear and all possible cross terms, and the predictands, and retains only those predictors that are statistically significant at the 95% level. The predictands are either the zonal or meridional displacement each 12-h period to alleviate the discontinuous track problem.

Table 2 shows the predictors chosen, and the variance explained by each. Persistence (the current storm motion) is initially the most important predictor. For the zonal motion, persistence is replaced by the latitude as forecast time increases, 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. The most important predictor after 24 h is the intensity–persistence cross product, since strong storms may be able to resist shear and recurve when westerly winds aloft are encountered.

5. Results

Both the old and new CLIPER models were run for all cases during the 1996–98 typhoon seasons. These 3 yr encompass a very strong cold and a strong warm sea surface temperature anomaly in the eastern Pacific Ocean, and because of the large number of storms in the basin annually, are representative of climatology in the basin. For both CLIPER models, these three seasons are not included in the developmental (dependent) data and, so, are considered to be independent data. The biases and errors are shown in Fig. 6 and Table 3, respectively. The average errors of the two models are within 7% of each other, and the differences are not statistically significant. The old CLIPER performs better than the new one during the first 48 h of the forecasts. However, the biases of the new CLIPER are much smaller than those of the old CLIPER (Fig. 6). The old CLIPER has a northward bias through 36 h, and then a northeastward bias. The new CLIPER has an eastward bias through 72 h, and an east-northeastward bias thereafter. Error growth is approximately linear through 120 h for the new CLIPER.

6. Summary

Forecasters evaluate tropical cyclone track prediction skill by comparing model errors to those from a simple statistical model based upon climatology and persistence. A new northwest Pacific tropical cyclone CLIPER track forecast model has been described. Since tropical cyclone tracks based upon satellite observations are more accurate than those from any other source except aircraft reconnaissance, the updated data with tracks from the satellite and aircraft reconnaissance era provide a more accurate dependent dataset than was available for the old CLIPER derivation. Track forecast errors from the current CLIPER are comparable in size to those from the old CLIPER. However, relatively large northward biases in track forecasts from the old CLIPER are nearly eliminated in the new one.

Track forecasting in the northwest Pacific basin has been shown to be somewhat easier on average than in the Australia region and North Atlantic basin, using nonlinear system science techniques. An *e*-folding timescale of about 15 h was calculated for the northwest Pacific basin, compared to just under 15 h in the Australia basin, and near 15 h in the North Atlantic. 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 in the northwest Pacific basin, and the current (now operational at the Joint Typhoon Warning Center) CLIPER model provides a baseline by which the track prediction skill can be measured.

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