Further Applications of Empirical Orthogonal Functions of Wind Fields for Tropical Cyclone Motion Studies

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ABSTRACT

A physical basis is provided for representing the large-scale operationally analyzed wind fields around western North Pacific tropical cyclones by use of empirical orthogonal functions (EOFs). The synoptic differences in the environmental flow are demonstrated for cyclones having different initial directions and translation speeds. It is also shown that the wind-based EOF coefficients may be used to differentiate between future tracks of cyclones that have a similar initial direction of motion. Thus, the small sets of EOF coefficients that are used in statistical regression techniques for track prediction by Peak et al. have physical meaning and are not statistical artifacts.

A new application of the EOF coefficients is to post-process the track predictions from the One-way influence Tropical Cyclone Model (OTCM), which is presently the best objective aid at the Joint Typhoon Warning Center (Guam). A 30% reduction in the forecast error at 72 h is achieved in the dependent sample. Thus, the synoptic influences represented by the EOF coefficients can differentiate situations in which the dynamical model (OTCM) is likely to provide poor guidance.

1. Introduction

It has long been recognized that the movement of a tropical cyclone is largely governed by the synoptic-scale flow (the "steering flow") around the cyclone. Therefore, numerous statistical schemes have been developed to correlate this large-scale flow with the movement of the cyclone (e.g., World Meteorological Organization, 1979). The synoptic predictors in these schemes generally consist of gridpoint values of pressures or heights within a specified domain around a cyclone. One drawback in such an approach is the use of height gradients to estimate the steering flow, as geostrophy is a poor assumption in the tropics. More importantly, the few gridpoint values that are selected as predictors only represent the large-scale flow around these gridpoints. Any other features in the flow are thus neglected, even though all of the gridpoint values are potential predictors in the development of the forecast scheme. Consequently, large amounts of storage are required to represent the height fields, but a large fraction of the information contained in the gridpoint values is lost.

The use of empirical orthogonal functions (EOFs) has recently been proposed as a method to improve the efficiency of the statistical schemes. Shaffer and Elsberry (1982) demonstrated that with only ten eigenvectors associated with an EOF representation of the 500 mb height fields, physically realistic descriptions of the synoptic-scale environment around tropical cyclones can be made. Using these EOFs, Shaffer and Elsberry (1982) and Peak and Elsberry (1986) developed tropical cyclone track forecast schemes that are competitive with the current operational models. Shapiro and Neumann (1984) also found that certain EOFs derived from the deep-layer height fields correlate very well with tropical cyclone motion.

The potential problem of assuming geostrophy in the tropical height fields is eliminated by Wilson (1984), who derived sets of EOFs based on wind fields. Although a good dynamical basis exists for use of wind fields rather than height fields in the tropics, practical questions remain as to the veracity of operationally analyzed wind fields. Recently, Peak et al. (1986) used wind-based EOF coefficients in statistical regression equations that, in the dependent sample, appeared to have track prediction skill similar to the official Joint Typhoon Warning Center (JTWC) forecasts. Are these results with wind-based EOFs simply fortuitous? Or do the operationally analyzed wind fields also contain useful information on the synoptic-scale features that influence tropical cyclone tracks?

This paper will demonstrate the utility of the wind-based EOFs utility by calculating the differences in the large-scale flow associated with various cyclone groups stratified by *both* the present and the future motion. Peak et al. (1986) infer synoptic features such as troughs and ridges associated with individual zonal or merid-

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ional EOF patterns, but this approach is unsatisfactory when combinations of several eigenvalues are considered. In this paper, the reconstructed fields based on only a small set of EOF eigenvectors will be intercompared to demonstrate significant differences in the synoptic features. A new application of these wind-based EOF coefficients to adjust and improve the track predictions made by a dynamical model will also be described. The success of this post-processing technique further demonstrates that the wind-based EOFs contain important synoptic information that can distinguish between situations in which the dynamical model is likely to provide good track guidance.

2. Data and methodology

a. Wind data and selection of cases

The wind data used in this study are from the Global Band Analyses (GBA) that are operationally generated every 12 h at the U.S. Navy Fleet Numerical Oceanography Center (FNOC). The grid resolution of the GBA is 2.5° longitude by approximately 2.5° latitude on a Mercator projection true at 22.5° latitude. The GBA provide complete longitudinal coverage between 41°S and 59.8°N. Upper-air observations include rawinsondes, pibals, aircraft and cloud motion vectors. Winds are analyzed at the surface, 700, 400, 250 and 200 mb. When a tropical cyclone is present, eight bogus winds based on the reported intensity are inserted only at the surface at 80 km from the cyclone center. This symmetric vortex is inserted primarily for cosmetic purposes and has little effect at upper levels. Some vertical coupling is achieved via the thermal wind relation using temperature analyses at intermediate levels. In regions with no observations, the analysis is a blend of the 12-h old analysis and 5% climatology. For a detailed description of the GBA, the reader is referred to Grayson (1971) and Lewis and Langland (1972). The GBA zonal and meridional wind components are available at 00 and 12 UTC (two digit hours) since 1975. For this study, only data between 1979–83 at 700, 400 and 250 mb are used.

For each case, the wind data (zonal and meridional components) are projected using a bilinear interpolation method onto the relocatable grid developed by Wilson (1984). The grid consists of 527 points (31 zonal and 17 meridional) with fixed separation of 277.8 km (150 n mi) in both directions. For each case, the grid is positioned so that the warning position of the cyclone is always at the same gridpoint (16,9).

Several criteria are imposed in selecting a storm for inclusion in the sample. A tropical cyclone must have matured to at least tropical storm intensity (maximum sustained winds of 18 m s^{-1} or greater). The GBA must have been available for the zonal and meridional wind components at 700, 400 and 250 mb. Finally, the warning position issued by the Joint Typhoon Warning Center (JTWC) must have been south of 34.6°N and west of the dateline. This latitudinal restriction is necessary to ensure that GBA winds are available for a sufficient latitudinal extent north of the cyclone center. A total of 1357 cases meet these criteria.

b. The EOF method

The application of the EOF method in atmospheric sciences dates back to the work of Lorenz (1956). The methodology and procedures in obtaining the eigenvectors and the EOF coefficients have previously been described by Kutzbach (1967), Wilson (1984) and others.

Following Wilson (1984), scalar EOFs representing the zonal or meridional winds are used. Although vector EOFs have certain advantages (Legler, 1983), it is felt that scalar EOFs are more applicable in the study of tropical cyclone motion as they can be directly related to the zonal and meridional displacements of the cyclone. Wilson (1984) used the Monte Carlo technique described by Preisendorfer and Barnett (1977) to determine the number of EOF modes that should be retained. He was able to explain over 80% of the total variance in either the zonal or meridional wind field with only the first 35 EOF modes (out of a possible 527). Since Wilson's dataset is used here, only these 35 modes are retained in this study. It should be noted that only 682 cases of the 1357 are included in the derivation of the eigenvectors because of computer storage limitations. The EOF coefficients for the remaining cases are then derived from these eigenvectors using the standard procedure (Wilson, 1984; Schott, 1985).

3. Flow patterns associated with cyclones stratified by past motion

a. Categorization

As has been demonstrated by George and Gray (1977) and Chan (1985), cyclones with different initial directions and speeds should be associated with different synoptic flow patterns. If the EOF method is to provide a useful and efficient representation of the large-scale flow, the fields reconstructed from only a small number of EOF coefficients should show significant differences between cyclones moving in different directions or speeds.

The five past-motion categories proposed by Elsberry and Peak (1986) are used to subdivide the sample of 1357 cases. These five categories are depicted schematically in Fig. 1 and the sample sizes are given in Table 1. The largest sample is in Category 4, which includes storms moving toward the northwest between 2.5 and 8.0 m s^{-1}. The remaining categories have considerably fewer cases. Notice that 155 cases have been omitted because the past 12-h warning positions are not available.

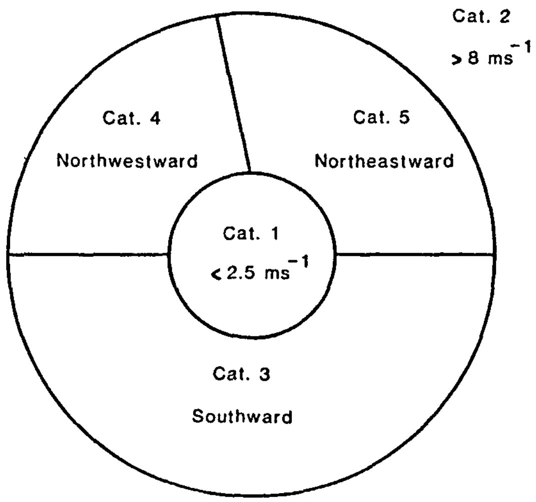


FIG. 1. Schematic of the five past-motion categories based on the past 12-h speed (categories 1 and 2) and direction (categories 3–5) of the tropical cyclone. The storms in categories 3–5 have translation speeds between 2.5 and 8 m s^{-1}.

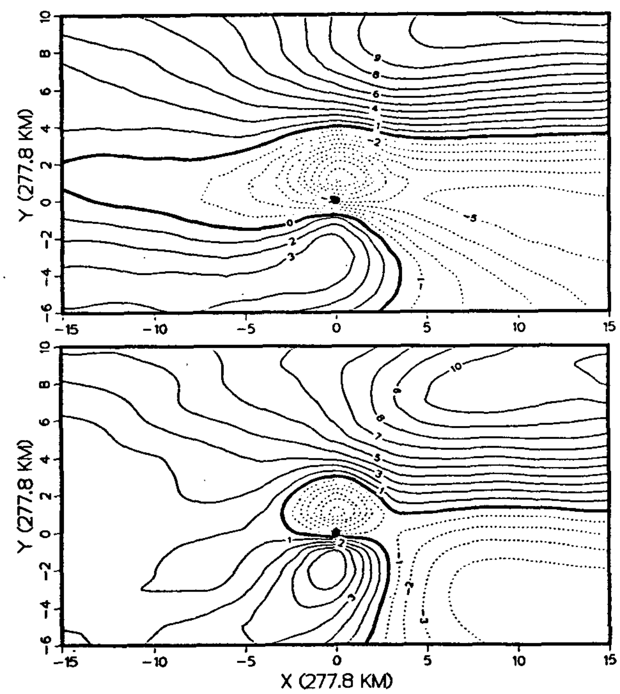


FIG. 2. The 700 mb zonal wind (u) component composites using 35 EOF modes for northwestward moving storms in Category 4 (top) and northeastward moving storms in Category 5 (bottom). Westerly components (m s^{-1}) are positive (solid lines), while easterlies are negative (dotted lines). Solid thick line is the zero contour. The large dot indicates the location of the cyclone.

The mean characteristics of the storms within these past-motion categories (not shown) indicate that the initial latitude, longitude, intensity and speed of the storms in categories 3, 4 and 5 are approximately the same. Similarly, storms in the slow and fast categories differ only in the speed (1.6 versus 10.9 m s^{-1}). For a detailed comparison of the track characteristics between these categories, the reader is referred to Schott (1985).

b. Comparisons of flow patterns

For each case, the flow field at a given level is reconstructed using 5, 10, 20 and 35 EOF modes. A composite of the flow field is then made from all cases in a given category. Only the flow fields reconstructed using 35 EOF modes will be presented as they contain the optimal amount of information (Wilson, 1984). Since categories 4 (Northwest) and 5 (Northeast) contain the largest number of cases, the reconstructed flow patterns for storms in these two categories will first be compared.

TABLE 1. Sample sizes in five categories defined by the past 12-h motion of the cyclone. Notice that the storms in Categories 3, 4 and 5 all have translation speeds between 2.5 and 8 m s^{-1}.

Category	Descriptor	Sample size
1 (<2.5 m s^{-1})	Slow	169
2 (>8.0 m s^{-1})	Fast	174
3 (90°–270°)	Southerly	125
4 (270°–340°)	Northwest	497
5 (340°–90°)	Northeast	237
Total		1202

For the northwestward (Category 4) storms, the composite 700 mb zonal (u) winds reconstructed using 35 EOF modes (Fig. 2) have a strong easterly component throughout the center of the grid, whereas the northeastward movers (Category 5) have weaker easterly components. The most significant feature in the 700 mb meridional field (Fig. 3) is the stronger southerly component east of Category 5 storms even though the mean intensities of the storms in these categories are approximately the same (not shown). Such a stronger southerly component and a weaker easterly component in the large-scale flow around Category 5 storms (compared to Category 4 storms) are consistent with the mean direction (20°) of these northeastward-moving storms. Thus, the 35 wind-based EOFs derived from operationally-analyzed fields appear to provide an adequate representation of the synoptic environments of the tropical cyclone.

Subtraction of the composite wind fields for the two categories demonstrates the usefulness of the EOFs in differentiating the environments of these two groups of storms (Fig. 4). Notice the strong easterly components in the difference field to the north of the storm, which is consistent with the results in Figs. 2 and 3. The largest differences (5 to 5.5 m s^{-1}) are found to the northeast of the vortex. If the differences in the wind components between the two categories are as-

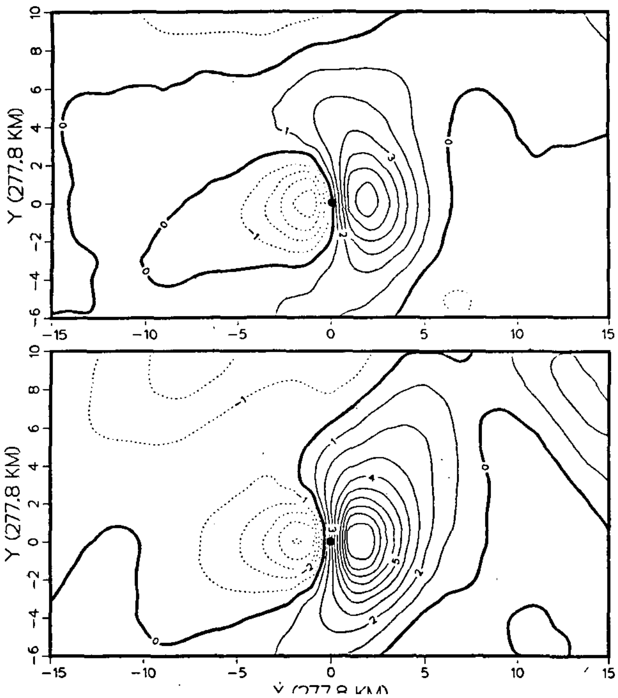


FIG. 3. As in Fig. 2, except for meridional wind (v) component with southerly components being positive (solid lines) and northerlies being negative (dotted lines).

sumed to be normally distributed at each gridpoint, the Student's t-test may be used to determine if the means of the u or v components at a gridpoint are significantly different. The null hypothesis is that no significant difference in the mean wind components exists between the two categories. At least one of the two mean wind components is found to be significantly different (with 95% confidence) between Categories 4 and 5 at 433 of the 527 gridpoints in Fig. 4.

The composite wind fields for these two categories at 400 and 250 mb have also been examined. As similar differences between the flow fields are found, these fields will not be shown. Interested readers can refer to Schott (1985).

The statistical test discussed above is also applied to the other past-motion categories using Category 4 (Northwest) as the standard for comparison because it contains the largest number of cases. The overall mean movement of tropical cyclones in the western North Pacific is also very similar to the mean movement in Category 4 (Chan, 1985). This Student's t-test is performed on the difference fields created using 5, 10, 20 and 35 EOF modes for the three levels (700, 400 and 250 mb). The number of gridpoints for which the mean u or v component is significantly different between each of the four categories (1, 2, 3 and 5) and Category 4 is shown in Table 2. The number of significant gridpoints varies from 96 to 491 of a possible 527 points. The smallest number of significant points is generally found in the Category 4 (Northwest) − Category 1 (slow movers) comparison, while the largest number of significant points is generally found in the Category 4 − Category 5 (Northeast) difference field. For example, using 35 EOF coefficients for compositing, the differences in the 700 mb u component field between Categories 4 and 5 are significant at 355 of the 527 gridpoints. Similar results can be found in the other category differences, although the number of gridpoints with significant differences is not as large. Based on Table 2, a statistical basis exists for stating that the operationally analyzed wind fields as reconstructed from the EOF coefficients for categories 1, 2, 3 and 5 are different from those in Category 4.

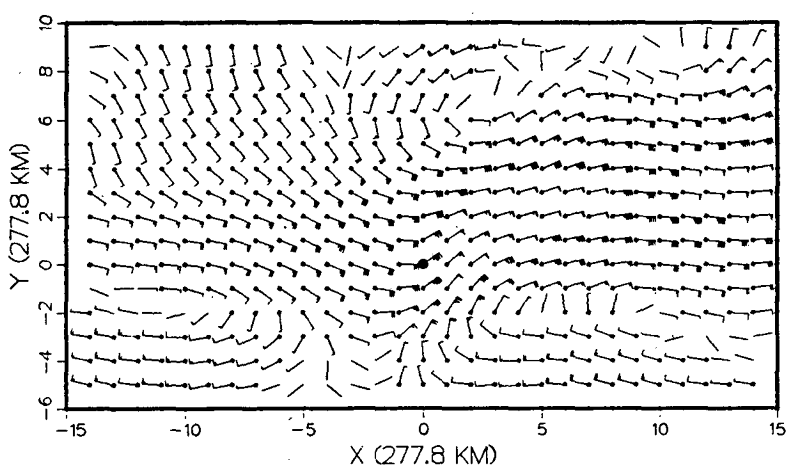


FIG. 4. The 700 mb wind difference field for Category 4 (Northwest) minus 5 (Northeast) based on 35 EOF modes. A pennant is 5 m s^{-1}, a barb is 1 m s^{-1} and a half-barb is 0.5 m s^{-1}. If either the u or the v component difference is significantly different from zero based on the Student's t-test with 95% confidence, a dot is plotted at the origin of the difference vector. The large dot indicates the location of the tropical cyclone.

TABLE 2. Number of the possible 527 gridpoints for which the mean u or v fields reconstructed from various sets of EOF models for Categories 1 (Slow), 2 (Fast), 3 (Southerly), or 5 (Northeast) are significantly different from that of Category 4 (Northwest).

			Number of EOF modes			
Level	Field	Category	5	10	20	35
700	u	4-1	285	279	236	229
		4-2	378	366	334	302
		4-3	249	244	265	258
		4-5	427	391	364	355
	v	4-1	297	257	248	231
		4-2	358	299	239	226
		4-3	324	305	275	242
		4-5	342	290	280	281
400	u	4-1	220	191	169	168
		4-2	377	312	297	297
		4-3	299	260	291	267
		4-5	455	418	420	405
	v	4-1	327	278	265	247
		4-2	345	312	249	224
		4-3	341	283	234	213
		4-5	335	280	262	240
250	u	4-1	126	136	101	96
		4-2	428	381	351	350
		4-3	305	285	284	285
		4-5	491	466	455	458
	v	4-1	241	202	212	190
		4-2	356	315	288	269
		4-3	357	351	322	293
		4-5	347	276	284	252

Notice that the number of significant points generally decreases as the number of EOF modes used in reconstructing the composites increases. For example, the Category 4 − 5 difference u composite fields at 700 mb decreases from 285 significant points for 5 modes to 229 significant points for 35 modes. This results from the increase in the amount of variance in the wind field as more modes are included (Wilson, 1984).

These results demonstrate statistically that a small number of the EOF coefficients may be used to differentiate the large-scale flow around cyclones that have different initial directions and speeds. Therefore, it is justified to use these coefficients to represent the synoptic factors affecting tropical cyclone motion. In particular, these results provide a physical basis for the use of the wind-based EOFs in the statistical track prediction schemes of Peak et al. (1986). The forecaster can have confidence that these EOF coefficients are not statistical artifacts. Rather, they represent significantly different synoptic patterns that can account for variability in future tracks among storms.

4. Flow patterns associated with different future tracks

a. Definition of cross-track and along-track components

The future tracks of cyclones having similar initial movements (direction and speed) can be differentiated by defining cross-track (CT) and along-track (AT) components (Fig. 5) of the future best-track positions relative to the climatology-persistence forecast scheme developed by Xu and Neumann (1985). Cross-track and along-track displacements in a storm motion oriented coordinate system was first proposed by Neumann and Pelissier (1981) in evaluating the accuracy of various operational forecast techniques for Atlantic hurricanes. Elsberry and Peak (1986) evaluated the forecast aids in the western North Pacific in a CT/AT framework, except a persistence forecast was used as the reference. The average CT component in the CLIPER reference system is near zero and the corresponding standard deviations of CT and AT are almost equal. Thus, the CLIPER track provides a very reasonable normalization of the tropical cyclone motion.

Using the CLIPER forecast as a reference also provides some physical insights into the cyclone track. For example, a positive CT component can be interpreted as a turning motion relative to the reference track. A directionality aspect of the track can thus be gained. Similarly, the AT components can be associated with speed changes, although a change in direction will also produce a negative AT component even when the translation speed remains constant (Neumann and Pelissier, 1981). If the CLIPER track is regarded as a "no-skill" forecast, then the focus should be on forecasting the departures from the CLIPER track.

b. Subdivision of northwestward cyclones

The large sample of northwestward moving storms in Category 4 discussed in the previous section is subdivided based on the magnitudes of the 72-h CT/AT components defined with respect to CLIPER. Components at 72 h are used to examine the discriminating power of the EOF coefficients in the longer forecast intervals that are of interest for diverting ships and other disaster preparedness measures.

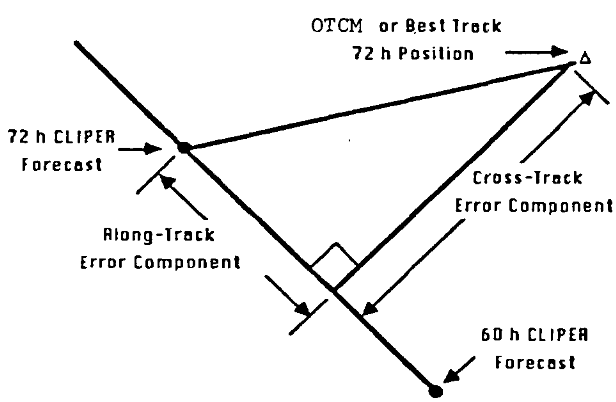


FIG. 5. Definition of cross-track and along-track components at 72 h relative to the forecast track based on the CLIPER positions at 60 and 72 h. In this example, CT is positive (right) and AT is negative (slow) with respect to the CLIPER track.

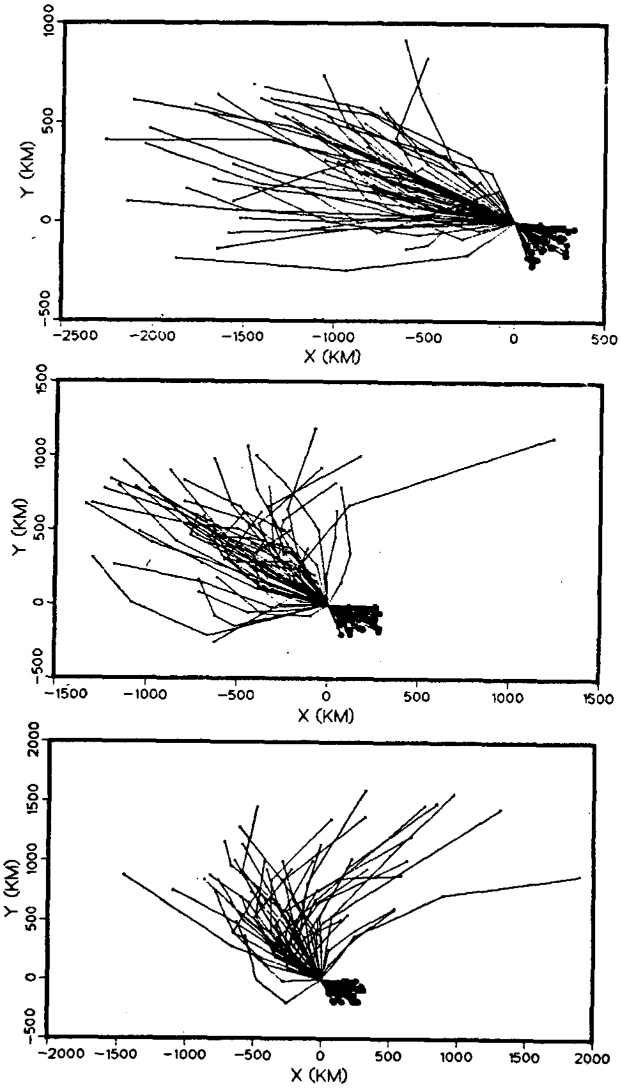


FIG. 6. Examples of 72-h tracks from Category 4 (Northwest) storms in tercile subcategories Left (top), Center (middle), and Right (bottom). Dots indicate the −12 h position and the 00 UTC position is located at (0, 0). Notice that the scales along the axes are different in these figures.

The CT and AT distributions at 72 h for the Category 4 storms are ranked and divided into three equal groups (terciles). For the CT distribution, the subcategories are referred to as left, center and right of the CLIPER forecast and those for the AT distribution as slow, center and fast. The center CT (AT) category contains all storms with 72-h cross-track (along-track) components relative to the CLIPER in the range −287 to 200 km (−341 to −13 km). Examples of the tracks in the CT terciles are shown in Fig. 6. Notice that the future tracks in the left tercile are mostly westward while those in the right tercile consist mainly of recurvature tracks. However, the average latitudes or longitudes of storms within the CT terciles at the initial time are very similar (not shown). Storms in the "slow" tercile of the AT components relative to the CLIPER forecast have a tendency to move westward (Fig. 7), while cyclones in the "fast" tercile either have a large westward displacement or recurve. Again, the storms in the different AT terciles can not be differentiated based only on the mean characteristics that are known at the initial time.

Since the storm-specific parameters cannot be used to distinguish storms with similar initial but very different future tracks, the large-scale flow must be the main controlling factor. If this flow associated with storms in different terciles can be reconstructed with the EOF coefficients, it can be concluded that these coefficients can be used in discriminating the future motion of cyclones that have similar initial directions.

c. Flow patterns for the CT terciles

As in the previous section, the u and v fields for storms within each tercile are first composited. Pairs

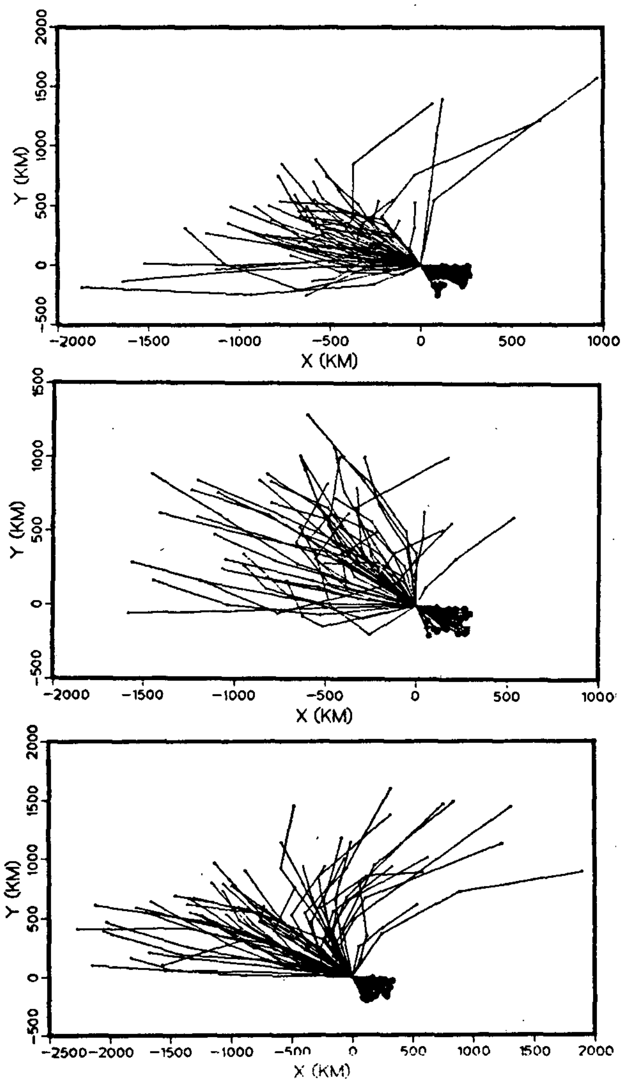


FIG. 7. As in Fig. 6, except for the Slow (top), Center (middle) and Fast (bottom) subcategories.

TABLE 3. As in Table 2 except the number of gridpoints at which the wind components are significantly different is computed between two 72-h CT terciles of northwestward moving (Category 4) storms.

Level	Field	Left-center	Left-right	Center-right
		Difference fields between		
700	u	178	282	123
	v	126	150	44
400	u	94	259	107
	v	33	120	48
250	u	72	256	149
	v	36	121	56

of tercile subcategory fields are then subtracted and a Student's t-test is applied (Table 3) to determine if the wind differences at each gridpoint are statistically significant (at the 95% confidence level). The smallest number of significant points is generally found in the left minus center category where the number of significant points decreases with elevation. By contrast, more gridpoints in the center minus right category, have wind components that are significantly different at higher levels. Thus, differences in the environmental flow for storms moving along versus those moving to the right of a CLIPER track are generally more significant at the upper than at the lower levels. The largest differences appear in the left-minus-right comparison with over half of the gridpoints (282 points) having significantly different 700 mb u components. The composite fields in the left minus right category will be further examined to identify the differences in the synoptic patterns.

The 700 mb mean u fields for the left and right subcategories (Fig. 8) appear to be very similar to those for the overall Category 4 (Northwest) sample (Fig. 2). However, the extent and magnitude of the easterlies north and east of storms in the left subcategory are larger than those in the right subcategory. This feature is consistent with the left subcategory storm having a stronger westward component of motion. As more storms in the right subcategory recurve (Fig. 6), the mean 700 mb v component fields for these storms have a stronger southerly component to the east of the vortex (Fig. 9). As might be expected from Figs. 8 and 9, the largest vector wind differences (Fig. 10) between the two subcategories are found to the east of the cyclone, which indicates that the anticyclone that is present to the northeast of the storm (not shown) plays an important role in the motion of the cyclones within these two subcategories. The composite wind fields at 400 and 250 mb (not shown) also indicate a more intense anticyclone to the northeast of the vortex in the right subcategory. Therefore, these results suggest that the small set of EOF coefficients does represent physically reasonable flow conditions that separate northwestward moving storms into subsets that subsequently turn to

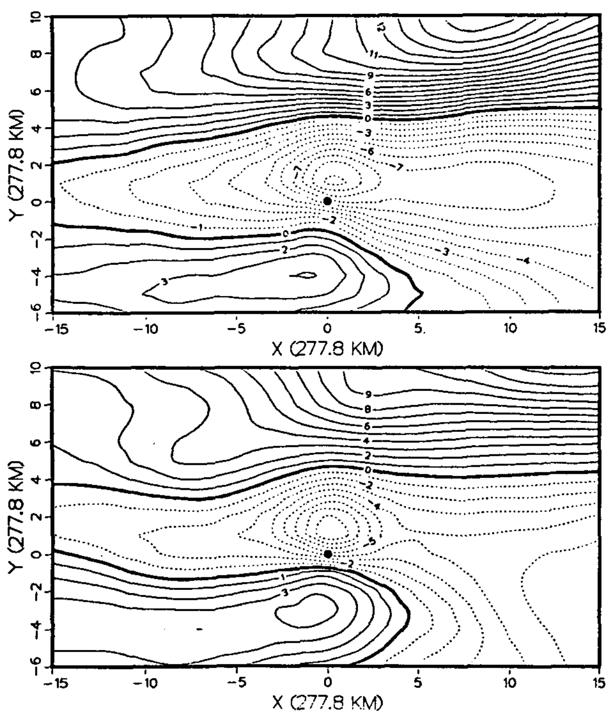


FIG. 8. As in Fig. 2, except for the 700 mb zonal wind composites in the Left (top) and Right (bottom) subcategories of the Category 4 (Northwest) storms. The composites are based on 35 EOF modes.

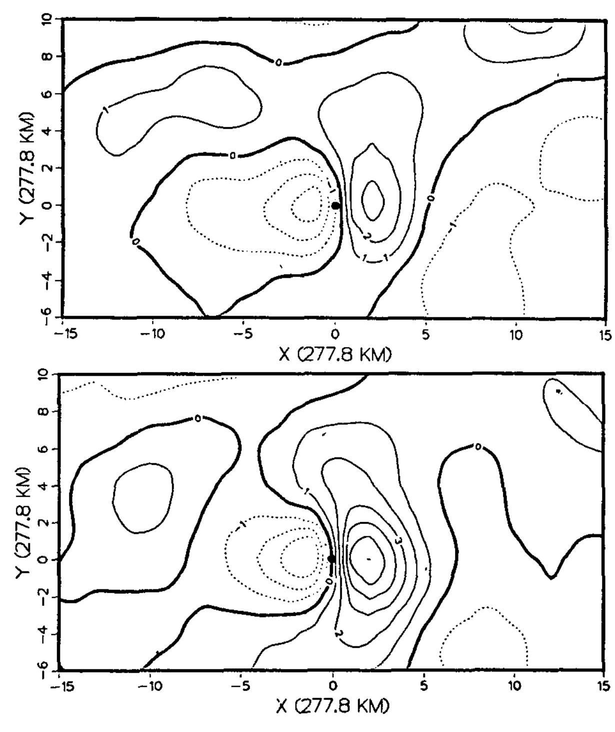


FIG. 9. As in Fig. 3, except for the 700 mb meridional wind composites in the Left (top) and Right (bottom) subcategories of Category 4 (Northwest) storms.

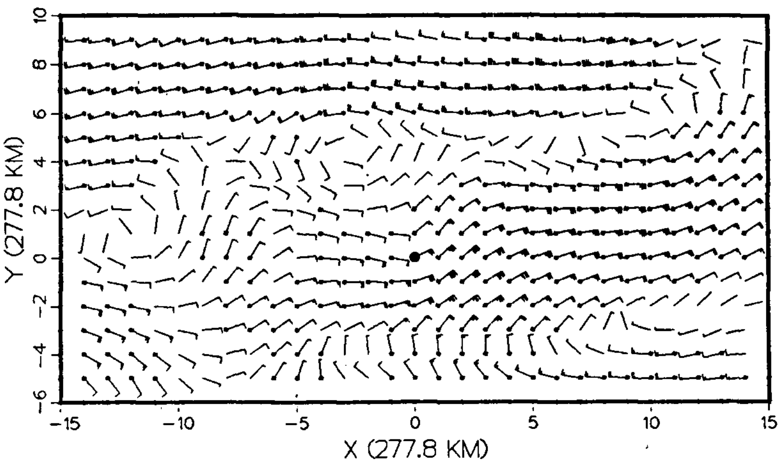


FIG. 10. As in Fig. 4 except using Category 4 Left minus Right terciles.

the left of a CLIPER track in 72 h from those that turn to the right.

d. *Flow patterns for the AT terciles*

As before, the composite u and v fields are subtracted between two AT terciles and at each gridpoint the Student's t-test is applied to determine if the difference is statistically significant (Table 4). In general, fewer points have significantly different wind fields between two terciles stratified by the AT component than in the CT stratifications. This suggests that less information content exists in the EOF wind components that relate to the 72-h AT components than the corresponding CT components. Notice the small number of points that have significantly different wind components between the center and the fast subcategories. In the other two combinations (slow minus center and slow minus fast), the smallest number of gridpoints with significant differences exists in the 400 mb u component. However, the v components at 400 mb appear to be very different between these subcategories. At 250 mb, both the zonal and meridional differences are important in differentiating between fast and slow storms within the northwestward mover category. As shown in Fig. 11, the meridional component differences tend to be more significant in the northern portion of the grid, whereas the zonal component differences are large to the southwest and east of the vortex.

TABLE 4. As in Table 2, except the number of gridpoints at which the wind components are significantly different for terciles in the 72-h AT distribution of Category 4 (Northwest) storms.

		Difference fields between		
Level	Field	Slow-center	Slow-fast	Center-fast
700	u	140	137	55
	v	94	112	6
400	u	77	87	14
	v	115	122	49
250	u	169	169	35
	v	107	123	65

e. *Summary*

As stated earlier, an advantage of the EOF approach is that the coefficients represent the flow characteristics not only in the vicinity of the cyclone but also in the large-scale environment. Thus, these coefficients can be used to distinguish future tracks of cyclones that have similar initial directions. Such a capability is well illustrated in this section. The results from this and the last section therefore demonstrate the effectiveness of the EOF coefficients in representing the synoptic factors that govern the motion of tropical cyclones. This conclusion suggests the possibility of using these EOF coefficients derived from operationally-analyzed fields to improve tropical cyclone track forecasting. A new application will be presented in the next section.

5. Post-processing dynamical model forecast tracks

Previous studies of the performance characteristics of the JTWC objective forecast aids show the One-way Tropical Cyclone Model (OTCM) is one of the best objective aids (Tsui, 1984; Elsberry and Peak, 1986). Because of this demonstrated consistent skill, the OTCM forecasts are used by the JTWC as the primary guidance for determining the future track of a tropical cyclone (Sandgathe, 1985). In this section, it will be shown that a post-processing technique (Elsberry and Frill, 1980; Peak and Elsberry, 1983) using the EOF coefficients will make the OTCM forecasts even better.

a. *Model description*

The current version of the OTCM is basically the model described by Hodur and Burk (1978). It is a three-layer, primitive equation model with a relatively coarse resolution of 205 km. The lateral boundaries

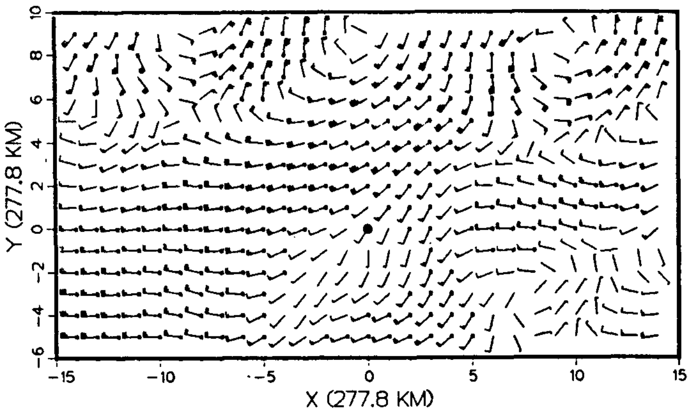


FIG. 11. 250 mb wind difference field for Slow minus Fast terciles of the northwestward moving (Category 4) storms. Symbols as in Fig. 4.

have a one-way influence from the FNOC global model. The tropical cyclone is initially defined in the model as a vorticity bogus. Since no moisture is included in the model, the vortex circulation is maintained by a specified analytical heating function. The only modifications to the 1978 version of the model have been a new method for locating the model grid relative to the initial storm position and a stronger storm bogus. A preprocessing technique developed by Shewchuk and Elsberry (1978) has been incorporated to include a persistence component of motion in the model forecast track. The 24, 48 and 72-h OTCM forecast positions are available at 00, 06, 12 and 18 UTC. To match the EOF dataset, only forecasts during 1979–83 are used.

b. Regression analysis

The variables used to adjust the OTCM forecasts towards the actual track are the post-processed cross-track (CTP) and along-track (ATP) components (Fig. 12) defined as

$$CTP = OCT - BCT$$

and

$$ATP = OAT - BAT,$$

where OCT and BCT are the cross-track components of the OTCM forecasts and the best tracks respectively and OAT and BAT are the corresponding AT components. The CT and AT components of the OTCM forecasts are computed as described in section 4a (Fig. 5).

The objective is to establish correlations between the CTP/ATP components and the wind-based EOF coefficients through a regression analysis. The regression equations developed can then be used to predict these components and hence adjust the OTCM forecasts towards the observed track. Regression equations with the CTP/ATP components as predictands are developed for the 24-, 48- and 72-h forecasts. Potential predictors related to the tropical cyclone at the current time are the Julian date, the JTWC warning latitude and longitude, and the maximum sustained wind speed. Although a persistence component is already introduced in the OTCM via the preprocessing technique of Shewchuk and Elsberry (1978), nine potential predictors representing past motion are still incorporated in the regression analysis. These past-motion predictors are based on JTWC warning positions to simulate operational conditions. Another set of predictors is derived from backward extrapolation of the OTCM forecast positions as suggested by Peak and Elsberry (1983).

The EOF coefficients described in the last three sections are used to represent quantitatively the environmental wind field. Peak et al. (1986) developed a

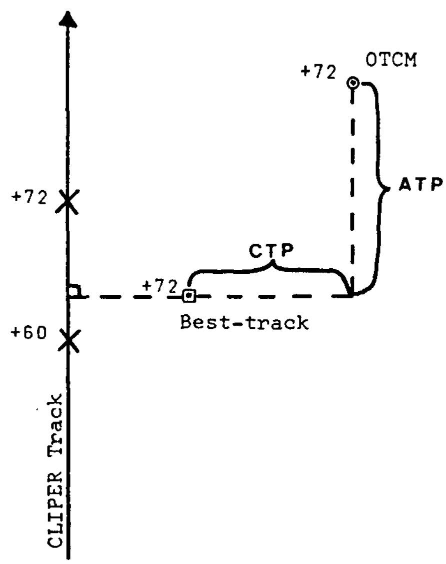


FIG. 12. Schematic of the OTCM modification scheme for a 72-h forecast. Post-processed cross-track (CTP) and along-track (ATP) components adjust the OTCM forecast position to the best-track position.

TABLE 5. Explained variance (R^2) for the CTP and ATP predictands for regression scheme in which only EOF coefficients are included as predictors (COE) and in which all potential predictors are permitted (ALL). Separate entries are given for sets limited to a maximum of 5 or 10 predictors (+ indicates only nine predictors selected).

Time	N	Number of predictors	Regression scheme	R^2 CTP	R^2 ATP
24	267	5	COE	0.24	0.19
		10	COE	0.34	0.29
		5	ALL	0.33	0.33
		10	ALL	0.44	0.44
48	212	5	COE	0.27	0.27
		10	COE	0.36	0.40
		5	ALL	0.37	0.35
		10	ALL	$^+$0.44	0.47
72	161	5	COE	0.35	0.29
		10	COE	0.48	0.44
		5	ALL	0.42	0.33
		10	ALL	0.55	0.53

TABLE 7. Mean ($\bar{X}$) and standard deviation (σ) of the forecast errors (km) for regression scheme which uses only the EOF coefficients with either five or ten predictors (OTCMP). Forecast errors for a homogeneous set of unmodified OTCM forecasts and a nearly homogeneous set of JTWC forecasts are also included.

Time	N	Number of predictors	Method	Forecast errors $\bar{X}$	Forecast errors σ
24	245	—	JTWC	206	127
	245	—	OTCM	203	121
	245	5	OTCMP	162	102
	245	10	OTCMP	158	95
48	190	—	JTWC	443	285
	200	—	OTCM	386	202
	200	5	OTCMP	329	192
	200	10	OTCMP	311	163
72	151	—	JTWC	631	400
	161	—	OTCM	593	357
	161	5	OTCMP	484	313
	161	10	OTCMP	427	279

promising track forecast scheme using these coefficients. In the present OTCM post-processing application, the predictor set includes only the first 25 zonal and meridional modes at each level. Thus, the total number of possible predictors is 187. No prescreening of the predictors is used, although the physical relationships among the predictors and the total tropical cyclone displacements has been demonstrated above. Consequently, there is some difficulty in determining statistical significance levels when the number of potential predictors is of the same magnitude as the sample size.

It is very important that the regression scheme simulates operational conditions. An OTCM forecast to provide guidance at 00 and 12 UTC is initiated from the 12-h old prediction fields while that for the 06 and 18 UTC predictions is initiated with the 00 and 12 UTC analysis fields. Since the GBA wind fields are only available at 00 and 12 UTC, the 06 and 18 UTC OTCM forecasts are used in the development of the regression equations. Unfortunately, very few OTCM forecasts at 06 and 18 UTC are available from 1979–81. Therefore, the dataset consists almost entirely of OTCM forecasts during 1982–83, with the sample size varying from 267 at 24 h to 161 at 72 h. Such a small number does not permit a separation into dependent and independent cases. All available cases are therefore used in developing the regression equations.

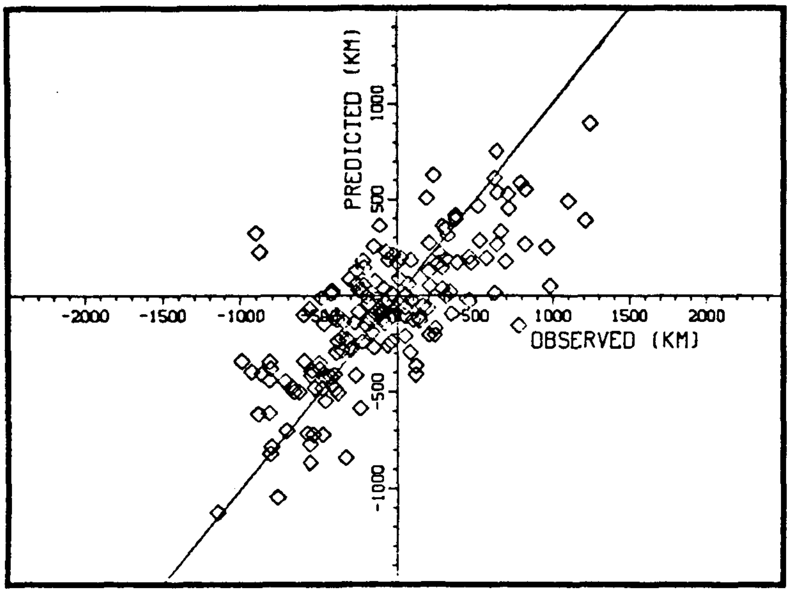
A set of regression equations is developed using only the EOF coefficients as predictors and another set includes all potential predictors described above. The amount of variance in the CTP and ATP explained by these two sets of equations ranges from 19% to 55% (Table 5). As expected, the regression set that selects from all potential predictors explains the largest

TABLE 6. The number of EOF coefficients selected in the regression scheme ALL for the 24-, 48- and 72-h equations for CTP and ATP.

Level	Field	CTP 24	CTP 48	CTP 72	ATP 24	ATP 48	ATP 72	Total
700	*u*	4	2	3	1	3	2	15
	v	1	2	1	0	0	1	5
400	*u*	1	1	1	3	3	2	11
	v	2	2	1	1	0	1	7
250	*u*	0	0	0	0	0	1	1
	v	0	0	2	1	1	0	4
	Total	8	7	8	6	7	7	43

TABLE 8. As in Table 7 except for regression scheme which includes either five or ten predictors selected from the set of all potential predictors (OTCMP).

Time	N	Number of predictors	Method	Forecast errors $\bar{X}$	Forecast errors σ
24	245	—	JTWC	206	127
	245	—	OTCM	203	121
	245	5	OTCMP	157	95
	245	10	OTCMP	143	88
48	190	—	JTWC	443	285
	200	—	OTCM	386	202
	200	5	OTCMP	302	177
	200	10	OTCMP	286	148
72	151	—	JTWC	631	400
	161	—	OTCM	593	357
	161	5	OTCMP	452	286
	161	10	OTCMP	383	256



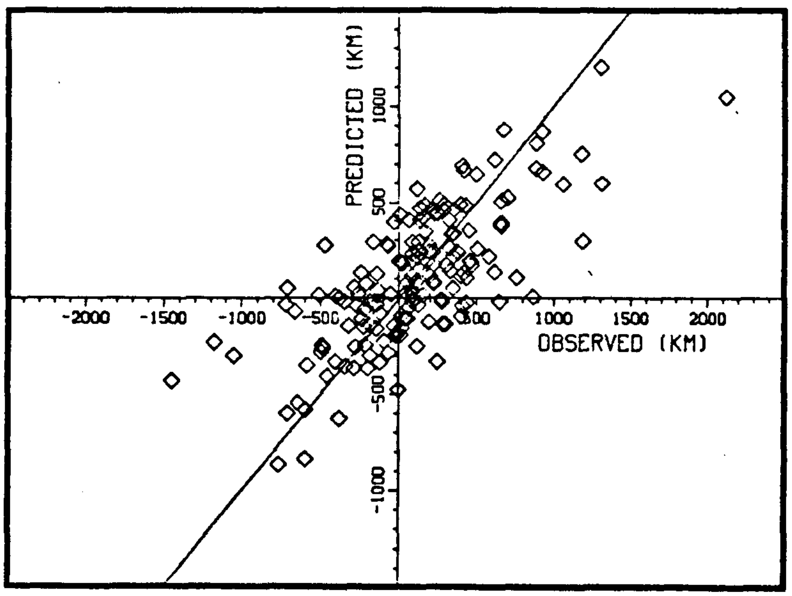


FIG. 13. Scatter plots of predicted versus observed CTP (top) and ATP (bottom) components. The predictions are from the 10-predictor regression scheme using all potential predictors.

amount of variance. When the number of predictors is increased from five to ten, the correlation also increases significantly. It is encouraging that the largest amount of explained variance occurs at the 72-h forecast interval.

In the ALL scheme, the EOF coefficients comprise between six and eight of the ten predictors chosen by the regression analysis (Table 6). The *u* coefficients at 700 mb are most often picked (15 times) and those at 250 mb the least (one time). Notice that the 400 mb *u* coefficients are selected to correct the relative speed (ATP) of the OTCM, whereas the 700 mb *u* coefficients are chosen most frequently to adjust the directional (CTP) aspect of the track.

A persistence-type predictor is also selected at all three forecast intervals. This variable is a measure of how closely the initial forecast track of the OTCM agrees with a meridional component of motion based on persistence. That is, future errors in the OTCM forecast track are highly correlated with the departure of the OTCM from a persistence component of motion early in the forecast period.

The regression-predicted CTP and ATP components are then used to modify the OTCM forecast position and the resulting forecast error is computed. Compared with the original OTCM forecasts and those of JTWC, these post-processed OTCM forecasts (OTCMP) have much smaller errors even if only the EOF coefficients are included in the prediction scheme (Table 7). The 72-h error decreases by ~170 km relative to the original OTCM when ten predictors are used. An even larger improvement occurs when all available predictors are included (Table 8). The mean forecast error at 72 h is reduced by over 210 km relative to the original OTCM. However, these results are obtained using the dependent sample. Testing with independent data is required to confirm these favorable results.

A desirable feature in any forecast scheme is consistency, which is indicated by small standard deviations in the forecast errors. Thus, it is encouraging that the standard deviations for the ALL regression scheme are about 100 km smaller than those of the unmodified OTCM (Table 8). The regression equations are therefore extremely successful in modifying the OTCM, at least for the dependent sample.

An example of the performance of the regression scheme using all potential predictors is illustrated in Fig. 13. The correlation coefficient between the observed and predicted CTP values is 0.74, while that for the ATP distribution is 0.73. The regression scheme appears to be rather successful in adjusting the OTCM to correct for large errors in CTP and ATP. However, the modification actually degrades some relatively good OTCM forecasts in a few instances.

6. Summary and conclusions

The key issue addressed in this research is whether a small number of EOF coefficients derived from operationally analyzed wind fields provide a useful physical representation of the synoptic-scale influences on tropical cyclone motion. Only 35 modes are used to represent zonal or meridional wind components from a 527 point grid. The large-scale flows as reconstructed from the 35 EOF coefficients show significant differences between groups of cyclones with different initial directions and speeds. Furthermore, the coefficients are capable of differentiating future tracks of cyclones that have similar initial directions. Thus, the EOF approach is an efficient and useful method of representing the synoptic environment in relation to tropical cyclone motion.

As a predictive tool, the EOF coefficients have been used as predictors in a statistical regression track forecast scheme by Peak et al. (1986). In this study, the EOF coefficients and other persistence-type predictors have been used to develop a post-processing scheme for statistically adjusting a dynamical model track forecast. Even though the One-way influence Tropical Cyclone Model (OTCM) uses the same wind fields as in the EOF coefficients, the synoptic conditions represented by the EOF coefficients are useful in adjusting for large errors in the OTCM tracks. Thus, the performance of the OTCM, which is already the best objective aid at the JTWC, can be further improved. Based on this preliminary result, these EOF coefficients might be used to diagnose the performance of other forecast schemes. Since the motion of a tropical cyclone is governed by storm-related factors and those related to the environmental flow, it may be possible to evaluate a model performance by grouping the forecasts based on the values of certain EOF coefficients. Choice of these coefficients might be made using a regression method, a discriminant analysis or a decision-tree approach.

Thus, it is clear that numerous applications of the wind EOFs can be made in both the analysis and prediction of tropical cyclone motion. Focus should now be directed to operational uses of such a powerful tool.

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