Identification of the Steering Flow for Tropical Cyclone Motion from Objectively Analyzed Wind Fields[1]

JOHNNY C. L. CHAN[2]

Department of Meteorology, Naval Postgraduate School, Monterey, CA 93943

(Manuscript received 17 April 1984, in final form 24 September 1984)

ABSTRACT

The flow patterns at various levels in the atmosphere around northwest Pacific tropical cyclones are studied using objectively-analyzed wind fields produced by the United States Navy. The results show large differences in the flow fields among groups of cyclones moving in different directions. Appreciable baroclinity is found in cyclones moving northward or northeastward. The results also demonstrate the importance of stratifying cyclones by their characteristics and synoptic environment in the study and prediction of tropical cyclone motion.

The relationships between tropical cyclone motion and the midtropospheric flow averaged around the 5–7° latitude radial band are also investigated using both the composite and individual cases. The composite results are generally consistent with those obtained from individual cases. In most cases, these relationships also agree with those derived in previous studies from rawinsonde composites and objectively-analyzed height fields. Since the objectively-analyzed wind fields used in this study are available for individual cases, the results suggest possible application of these fields to additional research studies of tropical cyclone motion as well as to development of short-term prediction techniques.

1. Introduction

The concept of steering flow has long been used to describe and predict the movement of tropical cyclones. Two general methods have been employed in identifying the steering current. One method defines the steering flow as the observed winds in a certain area around the cyclone at a particular vertical level or a combination of levels (e.g., Jordan, 1952; Miller, 1958; George and Gray, 1976; Gray, 1977; Chan and Gray, 1982). In the other method, the steering is estimated from height or pressure gradients (e.g., Miller and Moore, 1960; Tse, 1966; Neumann, 1979; Brand *et al.*, 1981) either by assuming the flow to be geostrophic or through regression analysis techniques. Most of these studies have emphasized the statistical correlation between the steering flow and components of the cyclone motion vector. Seldom has the two- or three-dimensional flow field been displayed to examine such a relationship. Such a depiction is essential for studying the horizontal and vertical variability of the relationship between the environmental flow and cyclone motion. Furthermore, previous studies of tropical cyclone motion were based either on composites of observed winds or on objectively-analyzed height fields. In the tropics, height gradients are generally weak so that the level of accuracy of height observations may not provide a good estimate of the wind field. Studies of the flow around tropical cyclones using actual wind observations have almost inevitably involved the method of compositing due to the sparseness of the data. While compositing can isolate characteristics common to the cyclones, verification and application of the composite results to individual cases is generally rather difficult.

The objectives of the present study are twofold: (1) to examine composite two- and three-dimensional wind fields around tropical cyclones with different directions of motion, and (2) to compare steering flow calculations from previous observational studies with those from objectively-analyzed wind fields provided by the U.S. Navy (see Section 2). The composite approach is used in the first part of this study in order to identify the characteristic features of each group of cyclones. The direction of cyclone motion was chosen as the criterion for stratifying the cyclones mainly to examine further the disagreement between modeling and observational results.

Numerical models often show a cyclonic vortex in the Northern Hemisphere moving to the *right* of the model "steering flow", which is often a uniform easterly current (Madala and Piacsek, 1975; Anthes and Hoke, 1975; Jones, 1977; Chang and Madala, 1980; Tuleya and Kurihara, 1982). Anthes and Hoke (1975) explained this "right-deflection" in terms of vorticity advection. An increase (decrease) in relative

---

[1] A preliminary and abbreviated version of this paper was presented at the 15th Technical Conference on Hurricanes and Tropical Meteorology, Miami, FL (Chan, 1984)

[2] National Research Council Research Associate

vorticity to the west (east) of the vortex as a result of advection produces a "secondary" circulation with a southerly current at the center of the vortex. This secondary current then advects the cyclone northward, and hence a movement to the right of the initial easterly flow. If this theory is valid, the steering flow will be constantly changing with time. The motion of the cyclone then should not be compared with the initial flow. Nevertheless, this comparison was made in all of these studies, with the conclusion that the motion of the model vortex veers to the right of the basic flow.

However, observational studies (George and Gray, 1976; Gray, 1977; Brand *et al.*, 1981; Chan and Gray, 1982) show that in most cases, tropical cyclones in the Northern Hemisphere move to the *left* of the steering current. An attempt to explain these observations was made by Chan (1982) and Holland (1983a) with a simple analytical model. They suggested that the advection of earth's vorticity by the vortex tangential wind and the coupling between the vortex convergence and the earth's vorticity will usually lead to a movement of the model vortex to the left of a uniform flow. However, cyclones with a strong westward component of motion could move to the right of the flow. Chan (1982) further showed that a nonuniform flow may change the relationship between the motion of the cyclone with its surrounding flow due to coupling between this flow and that of the vortex. It is therefore necessary to reexamine the flow around westward- and eastward-moving cyclones using a different data base.

In order to compare previous observational results with steering flow calculations using objectively-analyzed wind fields, azimuthally-averaged (centered on the cyclone) wind vectors will be correlated with cyclone motion vectors using the method of Chan and Gray (1982). The validity of the composite results will be examined through the study of individual cases in the data sample. Possible applications of the results from the present study will also be discussed.

2. Data and method of analysis

a. Wind data

Grid point wind analyses performed twice daily at the U.S. Navy Fleet Numerical Oceanography Center form the data base for this study. These analyses are global in longitude and banded between 41°S and 59.8°N and hence are referred to as Global Band Analyses (GBA). The grid spacing is 2.5° longitude by about 2.5° latitude on a Mercator projection true at 22.5°N. Wind analyses are performed at the surface, 700, 400, 250 and 200 mb. Vertical coupling is achieved using temperature analyses at intermediate levels. The surface data consist of ship reports and land-based observations. When a tropical cyclone is present, eight surface "pseudo-wind" vectors (with speeds derived from cyclone warnings) are inserted symmetrically at an 80 km radius around the cyclone center. Upper-air data include observations from rawinsondes, pibals, aircraft and cloud motion vectors derived from satellites. Surface wind and pressure climatologies are included in the analysis scheme. The first-guess field is the 12 h old analysis plus 5% climatology. In regions of no observations, the final analysis is therefore the previous analysis reverted towards climatology. Initially, the contribution from climatology is small, but it increases with the number of synoptic periods in which no observations are present in the area. For a more detailed description of the analysis procedure, the reader is referred to the U.S. Naval Weather Service (1975). The GBA are available only between 1975 and 1982.

b. Tropical cyclone data and selection of cases

Tropical cyclones in the northwest Pacific during the period when the GBA are available were chosen for the present study. Best-track positions at 6 h intervals were provided by the Joint Typhoon Warning Center. The direction and speed of a cyclone at each time period were computed from the ±6 h positions.

To determine how the cyclones in the sample should be grouped based on their direction of movement, the distribution of tropical cyclone directions during the 8-year period (1975–82) is examined (Fig. 1). As might be expected, the maximum percentage is between 285–295°. The distribution is largely bimodal, with peaks at 290 and 40°. A third, but less

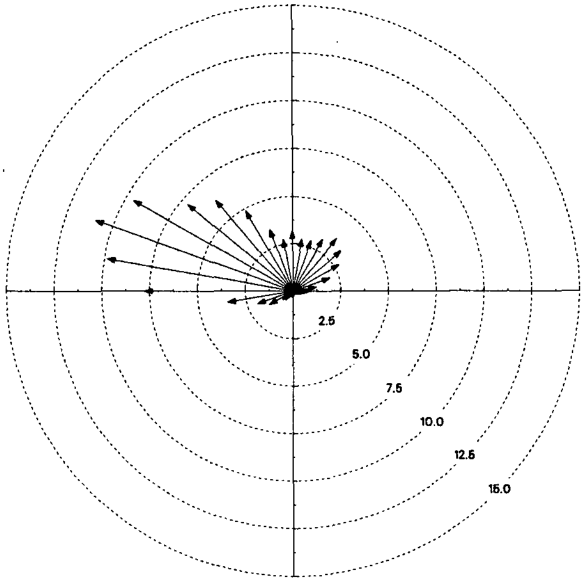


FIG. 1. Percentage direction distribution of northwest Pacific tropical cyclones between 1975–1982. Only 00 GMT and 12 GMT positions were included. Each arrow represents the percentage within a 10° (±5°) range. A total of 3334 positions is in the sample.

significant, maximum appears to be present at 0°. Based on this distribution, three groups of cyclones were selected: 265–285° (westward), 345–015° (northward) and 025–055° (northeastward). Chan (1982) and Holland (1983a) noted that cyclones with a strong westward component of motion tend to bear a relationship with their surrounding flow different from those with a strong northward or eastward component of motion. Therefore, rather than selecting cyclones moving with directions between 285–295° (the group with a maximum in the direction distribution), those in the interval 265–275° were also included in the westward group. Another reason for choosing the northward stratification is to compare the motion of these cyclones that have weak zonal components of motion with those in the other two groups of cyclones in which strong zonal movements were observed.

Intuitively, the relationship between the surrounding flow and cyclone motion should be best identified in the presence of a steady-state steering current. To approximate this ideal condition as closely as possible, only tropical cyclones that moved relatively straight and with little change in translation speed were considered. Two restrictions were therefore imposed in the selection of cases: 1) the +6, +12, +18 and +24 h direction change must be less than 20° from the current direction; and 2) the corresponding speed change during this 24 h period must not exceed 2 m s^{-1}. Even though these conditions are rather stringent, they were chosen to maximize the discrimination between samples. In addition, only cyclones with a maximum sustained wind of greater than 20 m s^{-1} were included. The results of this selection process are shown in Table 1.

Although relatively few cyclones could be found in the northward or northeastward stratification that satisfied the specified criteria, the fact that analyzed data are available at each grid point for all the cases should allow a meaningful composite to be made. It will be shown later that the composite results are in most cases representative of individual cases.

c. *Compositing method*

The grid point of the GBA that was closest to the best-track position of a cyclone at any given time was chosen to be the center grid point C. Analyzed zonal and meridional wind components at grid points that were within 10 grid lengths from C were then extracted. Compositing was performed on each wind component at each pressure level with the grid centered on the point C for all cases in a given stratification. Because the distance between grid points on a Mercator projection is not constant, such a procedure introduces some distortion. However, since most of the cyclone positions are in the tropics where the variations between grid distances are small, the compositing procedure should be fairly accurate. Data at the surface, 700, 400, 250 and 200 mb were composited. However, the results at 250 mb will not be presented because no significant difference was found between the flow fields at 250 and 200 mb.

TABLE 1. Number of cases in each classification of tropical cyclones studied. The mean direction, speed (m s^{-1}) and intensity (m s^{-1}) are also given.

Stratification		Number of cases	Direction	Mean speed	Intensity
Westward	(265–285°)	86	276	5.7	37
Northward	(345–015°)	16	358	4.7	43
Northeastward	(025–055°)	12	41	5.1	38

3. Composite flow fields

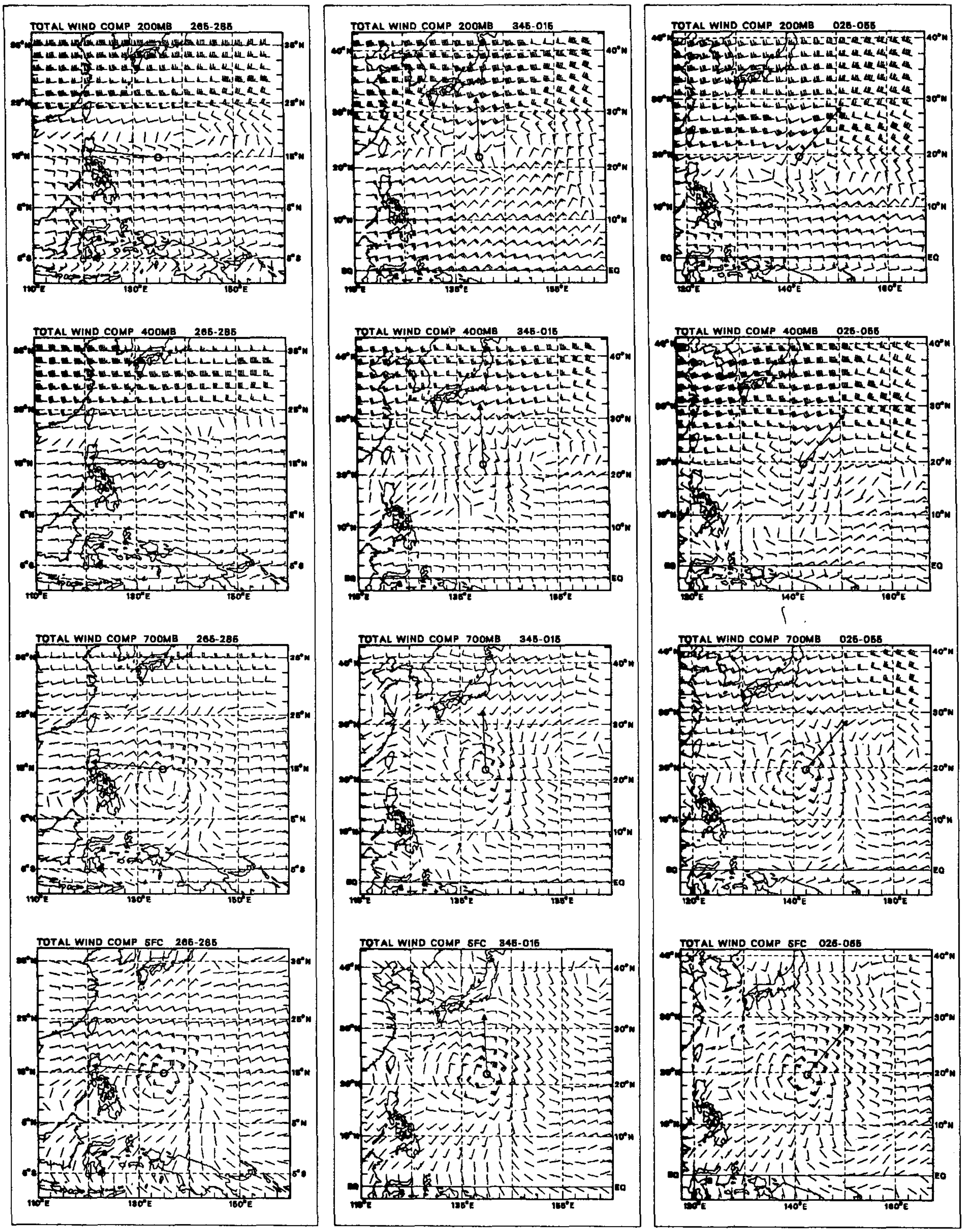
a. *Westward (265–285°) stratification*

As might be expected, the cyclones in this stratification are embedded in easterlies which extend throughout the troposphere (Fig. 2). A closed circulation exists at both the surface and 700 mb. However, the cyclone appears only as an open wave in the 400 mb flow field. Such a wave disappears almost completely at 200 mb, which could be partially a result of the lack of data.

At the two mid-tropospheric levels (700 and 400 mb), the cyclone appears to be moving to the *right* of the downstream flow. A possible reason for the inability of the analysis to define the vortex above 700 mb is the size of the vortex. If the vortex circulation has a small radial extent, its interaction with the environment may only extend over a relatively small area so that the grid resolution of the analysis may not be adequate to identify the presence of the vortex, especially when the vortex is in a data-sparse region.

b. *Northward (345–015°) stratification*

At the surface, a strong inflow exists to the southwest of the cyclones in this stratification (Fig. 2). A large area of cyclonic circulation can also be seen at both the surface and 700 mb. This second feature seems to suggest that northward-moving cyclones have, on the average, a larger radial extent in their low and midlevel circulation than the westward-moving cyclones. The average intensity of northward-moving cyclones is also higher (Table 1). These size and intensity characteristics may partially explain the ability of the analysis to define a closed circulation at 400 mb. The pattern at this level also shows that the cyclone is "sandwiched" between two anticyclonic cells. Such a pattern has been found by Merrill (1982) to be associated with large Atlantic hurricanes. The "steering current" for these cyclones cannot be easily discerned from the rather nonuniform 700 or the 400



(a) (b) (c)

FIG. 2. Composite wind fields at the surface, 700, 400 and 200 mb for the (a) westward, (b) northward and (c) northeastward data set. The circle represents the center grid point (one closest to the cyclone center). The grid is arranged so that this point is closest to the mean position of the composite data set. The arrow indicates the average direction of movement with the length proportional to the mean speed. The wind barbs were plotted with the usual meteorological convention, with one full barb equal to 5 m s^{-1} and one pennant equal to 25 m s^{-1}.

mb flow fields, because the cyclones appear to be masking the surrounding flow.

At 200 mb, an anticyclonic center exists just to the east of the composite cyclone. This appears to be part of the vortex circulation. Notice also the strong diffluent flow just south of the cyclone and the speed divergence associated with the flow towards the southwest. Observational (e.g., Sadler, 1976, 1978; McBride and Zehr, 1981; Chen and Gray, 1984) and theoretical (e.g., Holland, 1983b) studies have suggested that intense or intensifying tropical cyclones have outflow "jets" to the northeast and/or the southwest. Therefore, these analyzed flow fields might imply that the northward-moving cyclones were intensifying. Of the 16 cases in the sample, seven increased in intensity and four maintained the same intensity (of >45 m s^{-1}) in the next 24 h. Of the remaining five that decreased in intensity during the same time period, all but one had already reached typhoon intensity. The GBA therefore appear to have some potential in identifying large-scale flow patterns associated with intense or intensifying cyclones.

c. Northeastward (025–055°) stratification

As in the composite of the northward-moving cases, cyclones in this stratification have a strong inflow at the surface (Fig. 2). Whereas surface easterlies are present to the northwest of northward-moving cyclones, a surface trough can be seen in the same region relative to the northeastward-moving cyclones. The westerlies to the northwest of the cyclone center appear to be more pronounced at the other three levels. At 700 mb, westerlies are at about 5 grid points (1200 km) to the north and northwest of northward-moving cyclones. On the other hand, the westerlies are much closer to the center of the cyclones in the northeastward category. At 400 mb, the composite vortex appears as part of a deep westerly trough. Notice that at this level the cyclone center is to the west-northwest of the subtropical anticyclone. However, it is located to the west-southwest of this anticyclone at both the surface and 700 mb.

At 200 mb, the anticyclonic cell to the southeast of the cyclone center is probably associated with the vortex circulation. In contrast to northward-moving cyclones, however, no outflow channels can be found. The absence of outflow channels usually indicates a weakening in the intensity of a cyclone, as might be expected for recurved cyclones.

The direction of cyclone movement appears to be parallel to the downstream 400 mb flow. However, the cyclone seems to be moving almost perpendicular to the lower tropospheric flow (surface and 700 mb) and to the left of the upper level flow (200 mb).

d. Discussion

The composite results presented here illustrate differences in the flow fields between cyclones moving in different directions. Westward-moving cyclones, in general, are embedded in a near-barotropic environment so that either 700 or 400 mb may be used to approximate the steering flow. In addition, the easterlies associated with these cyclones appear to be rather spatially uniform so that visual inspection of the flow pattern may provide a first estimate of the steering flow. On the other hand, both northward- and northeastward-moving cyclones have baroclinic surrounding flows. In these cases, the determination of the steering level becomes rather difficult. The flow at each level in either stratification also appears to be rather nonuniform, which makes it almost impossible to estimate the steering flow qualitatively. A quantitative method of identifying the steering flow will be discussed in the next section.

One implication of these results is that the use of barotropic track prediction models is most applicable for cyclones with a strong westward component of motion. For cyclones moving northward or northeastward, it might be more appropriate to use a baroclinic model to predict their future track. Neumann and Pelissier (1981) have shown that in the Atlantic, the statistical–dynamical track prediction model (NHC-73) performs better than the barotropic model (SANBAR) when the cyclone is north of 24.5°N (where the cyclone is more likely to have a strong northward component of motion).

The flow fields shown in Fig. 2 also suggest that the cyclones in the sample are either south of, on, or north of the subtropical ridge. The fact that these flows are so different suggests that statistical models which correlate cyclone motion with surrounding wind/height fields may perform differently for different directions of cyclone motion. This further demonstrates the necessity to have different regression equations depending on the cyclone direction and other synoptic conditions, as has been suggested by a number of researchers in the past. Miller and Chase (1966) and Miller *et al.* (1968) stratified the cyclones based on their latitude while Tse (1966) divided his sample based on synoptic patterns. Neumann and Hope (1973) discussed the improvement of track forecasts by stratifying cyclones moving in different directions. Xu and Gray (1982) examined the flow patterns of cyclones at different locations relative to the subtropical ridge. Based on this idea, Matsumoto (1984) has developed a rather promising statistical track prediction model. Peak and Elsberry (1984) have also proposed stratifying cyclones based on synoptic conditions as defined by empirical orthogonal functions. It is therefore imperative that future development or analysis of track prediction schemes continue to take this into consideration.

4. Azimuthally-averaged flow

One common method of making a quantitative estimate of the steering flow around tropical cyclones is to average the wind vectors azimuthally around the cyclone center. If the vortex is symmetric and the data uniformly distributed, such a method will eliminate the cyclone circulation and give the mean flow around the cyclone.

George and Gray (1976) and Gray (1977) related the motion of tropical cyclones to composite rawinsonde winds averaged between 1 and 7° latitude radii from the cyclone center. A similar study by Chan and Gray (1982) used the winds within the 5–7° latitude radial band which excludes most of the inner cyclone circulation. This radial band will be adopted here so that a comparison can be made with the rawinsonde composite results. Since previous observational studies (e.g., WMO, 1979) have indicated that the midtropospheric flow has the best correlation with cyclone motion, the 700 and 400 mb fields were analyzed. The azimuthally-averaged winds within the 5–7° latitude radial band were determined by averaging the zonal and meridional components at all grid points that were within this band. Following Chan and Gray (1982), we then computed the direction and speed deviations (of the wind vector from the cyclone motion vector).

a. Composite results

The directional and speed deviations for the three composites are shown in Table 2. As might be expected from Fig. 2, these values for the westward-moving cyclones are very similar at 700 and 400 mb. At both levels, the westward-moving cyclones move to the *right* of and *faster* than the surrounding flow within the 5–7° latitude radial band. By contrast, George and Gray (1976) and Chan and Gray (1982) found that cyclones with directions 250–310° move to the *left* of the midtropospheric flow. A possible reason for such discrepancy may be the difference between the range of directions chosen in these studies and the present study. Both of these previous studies include a much larger range of cyclone directions (250–310°), of which a large proportion is in the group 290–310° (see Fig. 1). Since in these two studies, cyclones moving in the direction range 310–350° move to the left of the mean flow, it is quite possible that cyclones in the subgroup (290–310°) are also moving to the left of the mean flow. If this is true, then the average directional deviation in the composite will be positive. Therefore, the present results cannot be compared directly with those from these two studies. If a new rawinsonde composite study is made using the selection criteria defined in this paper, a more definitive comparison can then be made.

TABLE 2. Direction and speed deviations from the mean cyclone motion vector of the azimuthally-averaged winds within the 5–7° latitude radial band at 700 and 400 mb for the three composite data sets. A positive number for the direction (speed) deviation means the cyclone is moving to the left of (slower than) the azimuthally-averaged flow.

		700 mb deviation		400 mb deviation	
Stratification		Direction	Speed ($m\ s^{-1}$)	Direction	Speed ($m\ s^{-1}$)
Westward	(265–285°)	−7	−1.7	−7	−1.5
Northward	(305–015°)	13	−1.7	30	−2.3
Northeastward	(025–055°)	−25	−2.2	27	2.0

On the other hand, the present results appear to be consistent with those from composite studies in the Atlantic (Gray, 1977) and the southwest Pacific (Holland, 1983b) as well as analytical studies (Chan, 1982 and Holland, 1983a); that is, Northern (Southern) Hemisphere cyclones with a strong westward component of motion tend to move to the right (left) of and faster than their environmental flow. Brand *et al.* (1981) also found that northwest Pacific tropical cyclones south of ~15°N generally move to the right of the geostrophic flow at 500 mb. About 75% of the cyclones in the present sample of westward-moving cyclones were at latitudes south of 15°N (not shown). It might therefore be concluded that, in general, cyclones with a strong westward component of motion move to the *right* of the midtropospheric environmental flow. The sign and magnitudes of the speed deviations found in the present sample are consistent with those of Chan and Gray (1982).

The results in Table 2 for the northward-moving cyclones agree with all previous observational studies in that these cyclones move to the *left* of and *faster* than their surrounding azimuthally-averaged midtropospheric flow. Notice that the directional deviation at 400 mb is twice that at 700 mb, which indicates the presence of vertical wind shear. Thus, barotropic dynamics might not be very applicable here.

The vertical wind shear in the mean flow surroundings northeastward cyclones appears to be even stronger, as can be seen from the directional and speed deviations in Table 2. Whereas the cyclone motion is to the *right* of and *faster* than the 5–7° azimuthally-averaged flow at 700 mb, it is to the *left* of and *slower* than the flow at 400 mb. This situation is illustrated in Fig. 2. Since cyclones that had an acceleration of $>2\ m\ s^{-1}$ per 6 h were excluded, this stratification does not include most of the cyclones that recurved in the proximity of a deep trough. Rather, the cyclones in this class have moved through a weakness in the subtropical anticyclone and continued steadily northeastward. From the flow fields depicted in Fig. 2, it appears that this weakness occurred at a level above 700 mb. Therefore, the cyclone seems to move "into" the 700 mb anticyclone rather than around it.

The direction and speed deviations for northeastward-moving cyclones obtained here differ somewhat from those found in previous studies. According to the analytical studies of Chan (1982) and Holland

(1983a), advection of the earth's vorticity by the tangential wind of the cyclone and the coupling between the vortex convergence and the earth's vorticity should cause a northeastward-moving cyclone to move to the left of and slower than the surrounding flow. While this is observed at the 400 mb level, the reverse is true at 700 mb. The results at 400 mb are also consistent with those obtained by Chan and Gray (1982). However, they found that northeastward-moving cyclones move to the left and faster than the 700 mb flow.

A possible explanation of the apparent discrepancy between the analytical results and the present observations at 700 mb may be the assumption of a uniform flow used in the analytical studies cited here. While this assumption might be approximately valid downstream of the cyclone at 400 mb (Fig. 2), the same cannot be said for the 700 mb flow. In fact, an anticyclonic curvature in this flow ahead of the cyclone can be discerned. According to Chan (1982), this would cause the cyclone to move to the right of and faster than the mean flow, in agreement with the present results.

In their observational study, Chan and Gray (1982) included all cyclones with directions within the range 350–060°. Most of these cyclones were therefore the ones that were under the influence of a strong baroclinic trough. In this case, the directional shear between the 700 mb and 400 mb is not very large (see Figs. 7 and 8 in their paper). This might explain the discrepancy between their results and the present observations at 700 mb.

To summarize, the relationships between tropical cyclone motion and the surrounding flow derived from these composites appear to be consistent with those obtained from other studies. However, some discrepancies still exist, possibly due to differences in the samples or between observations and model assumptions. These results again demonstrate the difficulty in the definition of the steering flow. Nevertheless, the concept of the azimuthally-averaged flow still appears to be useful in describing the short-term (0–12 h) movement of a cyclone. If these composite results are valid in individual cases, it is possible to apply this concept in real-time because the azimuthally-averaged flow can be computed from the GBA which are available every 12 h.

b. Individual cases

For each individual case in each stratification in the sample, the mean winds within the 5–7° latitude radial band at 700 and 400 mb were computed. The directional and speed deviations were then determined in the same way as previously. It was found that a large variability exists in the directional deviations among the individual cases within each stratification. On the other hand, variations in the speed deviations appear to be much less.

A large percentage of the cases with a large directional deviation (absolute value > 40°) has translation speeds of <2.6 m s^{-1} (5 kt). A possible explanation is that misrepresentation of the flow is more likely in weak steering flow situations (corresponding to slow cyclone movement). These cases, however, will not affect the composite results because the weak flow does not contribute significantly to the mean value of the winds in the composites. These slow-moving cases will be ignored in the statistical analyses of individual cases.

To study the relationship between cyclone motion and the surrounding flow for individual cases, the 5–7° azimuthally-averaged wind vector in each case (for both 700 and 400 mb) is plotted relative to the direction of cyclone movement. These wind vector positions for the westward stratification at 700 mb is shown in Fig. 3. A total of 74 cases is included. The data points are clustered rather close to the direction of cyclone motion but with more cases to the left side of the cyclone motion vector, as indicated by the mean of all cases (solid dot and arrow). Most of the points are within the 1.0 circle which means that the cyclone speed is larger than the wind speed. These results therefore verify the composite results that the cyclones move to the *right* of and *faster* than the 700 mb flow. At 400 mb, the situation is rather similar (Fig. 4). A larger spread of the points can be seen, with a few cases having direction deviations of over

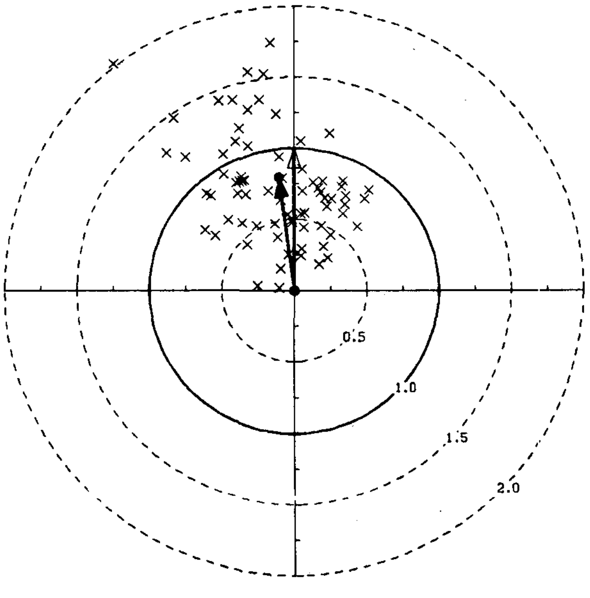


FIG. 3. Positions of 700 mb wind vectors for individual cases in the westward stratification. Each cross represents location of the wind vector averaged between the 5–7° latitude radial band relative to *the direction of cyclone motion* for one case. The distance from the location to the origin is the ratio of the wind speed to the cyclone speed, open arrow indicates the direction of cyclone motion, dot represents the mean location of all individual cases with the solid arrow depicting the mean wind vector.

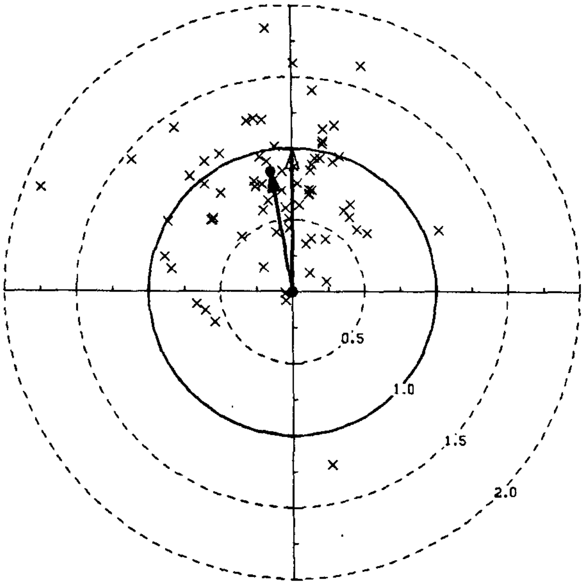


FIG. 4. As in Fig. 3, except for the 400 mb flow.

−90°. However, most wind vectors cluster around the cyclone motion vector.

Several factors may contribute to the scatter of individual cases about the mean. The noise in the observations and/or the analyzed fields can certainly lead to errors in computing the average flow. If a cyclone is asymmetric, the azimuthally-averaged flow will not give a good estimate of the steering flow, and thus may contribute to the scatter. In addition, characteristics of individual cyclones such as size and intensity may also result in the observed scatter.

The Student's t-test was performed to test the statistical significance of each data sample, with the results shown in Table 3. The null hypothesis is that the mean directional and speed deviations are both zero; that is, the cyclone moves parallel to the surrounding flow with the same speed as the flow. For the westward stratification, both the directional and speed deviations at both levels are significantly different from zero. The similarity in the directional and speed deviations between the two levels also implies the near-barotropic nature of the environment in which these cyclones are embedded.

TABLE 3. Statistics of directional (degrees) and speed (m s^{-1}) deviations at 700 and 400 mb (at the 5–7° radial band) for the three direction stratifications. The *t*-values* correspond to those obtained from the Student's t-test with a hypothetical mean equal to 0.

Level	Westward	Northward	Northeastward
	Directional Deviation		
700 mb			
Number of cases	74	12	11
Mean	−8	5	−48
Standard deviation	28	54	37
t-value	2.44*	0.30	4.07*
400 mb			
Number of cases	72	12	10
Mean	−11	30	23
Standard deviation	46	57	16
t-value	1.94*	1.89*	4.43*
	Speed Deviation		
700 mb			
Number of cases	74	12	11
Mean	−1.5	−1.6	−2.2
Standard deviation	2.3	2.1	2.2
t-value	5.54*	2.79*	3.13*
400 mb			
Number of cases	72	12	10
Mean	−1.1	−1.4	0.7
Standard deviation	2.2	2.3	2.5
t-value	4.12*	2.16*	0.87

* The *t*-value is significant at 95% or greater (for a one-sided test).

For the northward stratification, quite a large scatter exists in the 700 mb wind vectors, as can be seen from Fig. 5. The mean directional deviation is not significant at 95% (Table 3). An examination of flow patterns in individual cases seems to suggest that the circulation in these cyclones generally has a larger radial extent that those in the other two stratifications. This may indicate that the "optimum" radial band may be further outward. Indeed, 700 mb wind vectors for the 7–9° radial band average have a smaller scatter about the cyclone direction (Fig. 6), with a mean of 22° and a standard deviation of 35°. The *t*-value in this case is 2.32 which is significant at the 95% level. The corresponding speed deviations give a mean of −1.9 m s^{-1}, a standard deviation of 2.3 m

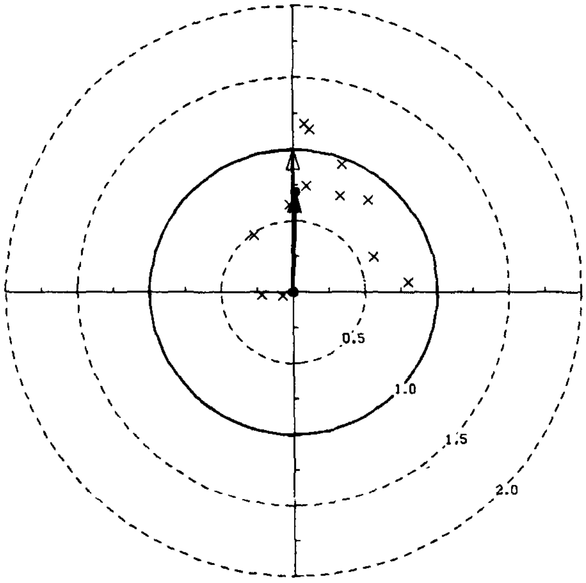


FIG. 5. As in Fig. 3, except for the 700 mb flow in the northward stratification.

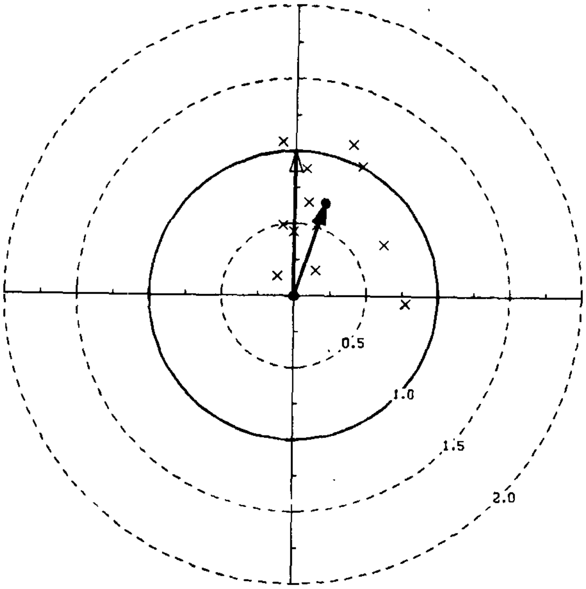


FIG. 6. As in Fig. 3 except for the 700 mb flow averaged between the 7–9° latitude radial band in the northward stratification.

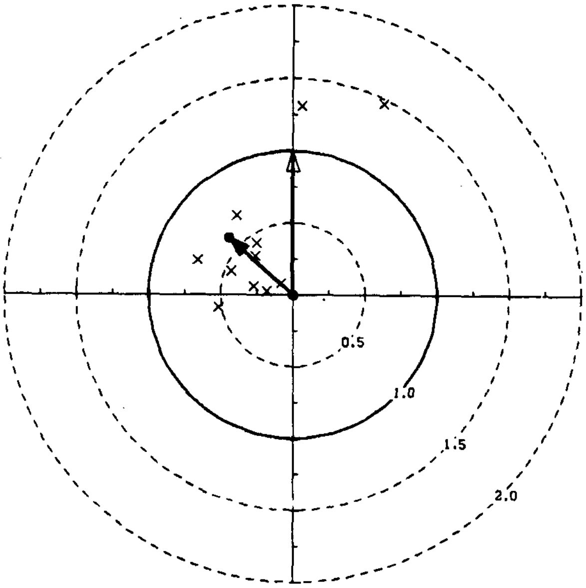


FIG. 8. As in Fig. 3 except for the 700 mb flow in the northeastward stratification.

s^{-1} and a t-value of 3.10. It seems, therefore, that the size of a cyclone may have an impact on the selection of the optimum radial band in the definition of the steering flow. However, because of the small number of cases involved here, further study is necessary before this speculation can be confirmed. The scatter of the 5–7° wind vectors at 400 mb for the northward stratification (Fig. 7) appears to be smaller and both the directional and speed deviations are significant at the 95% level (Table 3). Therefore, these individual cases are consistent with the composite results; that is, northward-moving cyclones tend to move to the *left* of and faster than their surrounding flow.

Most of the data points for the 700 mb flow cluster around one another for northeastward-moving cyclones, as shown in Fig. 8. The mean directional deviation is rather large (Table 3). Both the directional and speed deviations are statistically significant. For the 400 mb flow, although most of the data points are along the same general direction (Fig. 9), the ratio

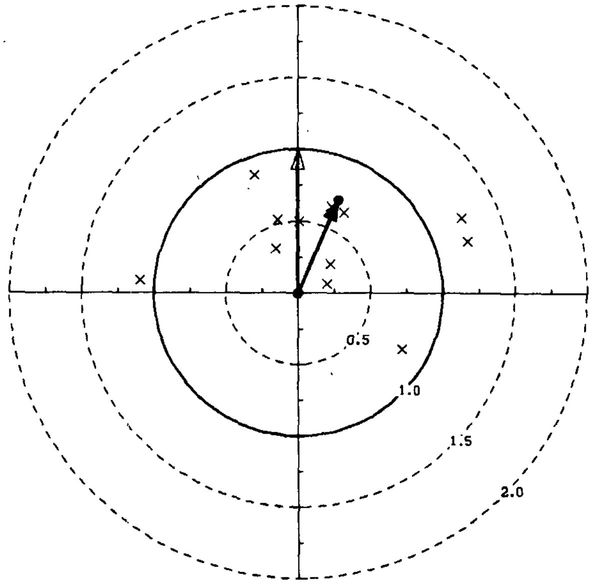


FIG. 7. As in Fig. 3 except for the 400 mb flow in the northward stratification.

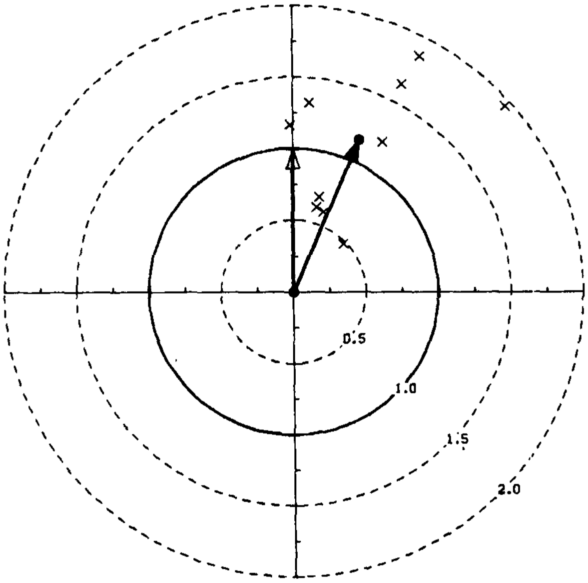


FIG. 9. As in Fig. 3 except for the 400 mb flow in the northeastward stratification.

of the wind speed to cyclone speed differs by a large amount, and thus contributes to the failure of the t-test (Table 3). Among the ten cases, six moved slower than the flow and four moved faster. According to Chan (1982) and Holland (1983a), if a cyclone has a large eastward component, it tends to move slower than the surrounding flow. The mean direction of the six slower (than the 5–7° mean flow) cyclones is 44° while that of the four faster ones is 36°. Therefore, the difference in cyclone direction may be used to explain the difference in the relative (to the surrounding flow) speed of the cyclone. However, the present sample is too small to allow a definitive conclusion to be drawn. Other than the speed deviations at 400 mb, the individual case results are statistically significant. The directional deviations suggest that northeastward cyclones are embedded in a baroclinic atmosphere. They tend to move to the *right* of the 700 mb flow but to the *left* of the 400 mb flow. They also move *faster* than the 700 mb flow.

In summary, it may be concluded that most of the individual case results are consistent with those from the composite. These results also point to the difficulty in defining the steering flow due to the variability of the flow around tropical cyclones. However, the 5–7° azimuthally-averaged flow appears to be useful in most cases. The variabilities present in the individual cases also suggest that although compositing can provide some ideas on the general characteristics of the environmental flow, quantitative application of the results must come from detailed analyses of individual cases. Such analyses appear to be possible through the use of the GBA.

5. Concluding remarks

The U.S. Navy Global Band Analyses have been used to study the environmental flow at different levels around northwest Pacific tropical cyclones. The composites at all levels show significantly different flow patterns associated with cyclones moving in different directions. Appreciable wind shear in the vertical is observed in the surrounding flow for northward- and northeastward-moving cyclones. In addition, the differences in flow patterns suggest the importance of stratifying cyclones in the development of track forecast schemes and the study of cyclone motion.

The relationships between tropical cyclone motion and the azimuthally-averaged flow computed from the composite objectively-analyzed wind fields are, in most cases, consistent with those estimated from rawinsonde composites and height gradients. Differences among the studies do arise due to differences in the samples. Analyses of individual cases confirm most of the established relationships. These results suggest that it is possible to use the Global Band Analyses on an individual case basis in describing the steering flow. However, other variables such as the size of the cyclone may have to be taken into account in determining the "optimum" radial band from which to extract the steering flow.

In studies which utilize objectively-analyzed data, the question of the dependence of the results on the analysis methodology often arises. Two specific problems need to be addressed here. One concerns the climatology component in the analyses and the other the presence of a bogus vortex in the surface analysis. Since the initial guess field consists of the 12 h old analysis plus 5% of climatology, any observation present in a previously data-void area should outweigh the contribution from climatology. Furthermore, because the maximum scan radius used in the Cressman interpolation scheme is 555 km (300 nmi), information from other areas can be projected into the data-void area to a certain extent. Thus, climatology should not be a major contributor to the results in most cases.

Since the symmetric vortex is only bogus at the surface, the vortex circulation will weaken significantly at higher levels if no temperature or wind observation is in the vicinity. Even under these conditions, observations present within the scan radius of the interpolation scheme should lead to a reasonable analysis around the vortex. Thus, apart from cyclones with a very small horizontal circulation (in which case the flow farther out will only be that of the environment), the final analysis near the cyclone should be rather representative of the vortex circulation. If observations do exist around the cyclone, the vortex circulation will be very well-defined. Furthermore, because the bogus vortex is symmetric, its influence will be eliminated by studying the azimuthally-averaged winds, as in the present study. Therefore, the effect of the bogus on the results should be minimal.

This qualitative evaluation of the question of analysis dependence is supported by the fact that most of the present results agree with those obtained from rawinsonde composites. Of course, a better way to investigate such an analysis-dependency is to compare calculations derived from different objective analyses. Rawinsonde composites may be used as the "ground truth" in these comparisons.

However, even if this dependency problem is resolved, other questions still need to be answered before a more definitive relationship between tropical cyclone motion and its surrounding flow may be established. For example, in what percentage of tropical cyclones can the 5–7° azimuthally-averaged flow be used as an estimate of the steering flow? Also, how much variation in directional deviations exist among cyclones of different sizes (and other cyclone characteristics such as intensity, intensity change, etc)? Chan and Gray (1982) showed in their composite study that such variations, if any, are probably in the noise level. With the GBA, cyclones with these characteristics can be studied *individually* to test the above assertion. The answers to these questions are important in the understanding of tropical cyclone motion. Formulations of theoretical and numerical studies of tropical cyclone motion may then have an observational basis in the definition of their steering flow. Forecasters in the field may also use this information in providing a short-term track prediction.

Acknowledgments. The author thanks Professor R. L. Elsberry for his helpful comments on the manuscript and Ms Marion Marks for her professional help in its preparation. This work was supported by the Foundation Research Program at the Naval Postgraduate School.

REFERENCES

Anthes, R. A., and J. A. Hoke, 1975: The effect of horizontal divergence and the latitudinal variation of the Coriolis parameter on the drift of a model hurricane. *Mon. Wea. Rev.*, **103**, 757–763.

Brand, S., C. A. Buenafe and H. D. Hamilton, 1981: Comparison of tropical cyclone motion and environmental steering. *Mon. Wea. Rev.*, **109**, 908–909.

Chan, J. C. L., 1982: On the physical processes responsible for tropical cyclone motion. Atmos. Sci. Paper No. 358, Colorado State University, Ft. Collins, CO, 80523, 200 pp.

——, 1984: Definition of the steering flow for tropical cyclone motion. *Proc. 15th Tech. Conf. on Hurricanes and Tropical Meteorology,* Miami, FL, Amer. Meteor. Soc., 559–566.

——, and W. M. Gray, 1982: Tropical cyclone movement and surrounding flow relationships. *Mon. Wea. Rev.,* **110,** 1354–1384.

Chang, S. W., and R. V. Madala, 1980: Numerical simulation of the influence of sea surface temperature on translating tropical cyclones. *J. Atmos. Sci.,* **37,** 2617–2630.

Chen, L.-S., and W. M. Gray, 1984: Global view of the upper level flow patterns associated with tropical cyclone intensity change during FGGE. *Proc. 15th Tech. Conf. on Hurricanes and Tropical Meteorology,* Miami, Amer. Meteor. Soc., 224–231.

George, J. E., and W. M. Gray, 1976: Tropical cyclone motion and surrounding parameter relationships. *J. Appl. Meteor.,* **15,** 1252–1264.

Gray, W. M., 1977: Tropical cyclone motion and steering flow relationships in the western Atlantic and in the western Pacific. *Proc. 11th Tech. Conf. on Hurricanes and Tropical Meteorology,* Miami Beach, Amer. Meteor. Soc., 472–477.

Holland, G. J., 1983a: Tropical cyclone motion: Environmental interaction plus a beta effect. *J. Atmos. Sci.,* **40,** 328–342.

——, 1983b: Tropical cyclones in the Australian/Southwest Pacific region. Atmos. Sci. Paper No. 363, Colorado State University, Fort Collins, CO, 80523, 264 pp.

Jones, R. W., 1977: Vortex motion in a tropical cyclone model. *J. Atmos. Sci.,* **34,** 1518–1527.

Jordan, E. S., 1952: An observational study of the upper wind circulation around tropical storms. *J. Meteor.,* **9,** 340–346.

Madala, R. V., and S. A. Piacsek, 1975: Numerical simulation of asymmetric hurricane on a beta-plane with vertical shear. *Tellus,* **27,** 453–467.

Matsumoto, C. R., 1984: On predicting 3-day tropical cyclone motion—an improved statistical scheme. *Proc. 15th Tech. Conf. on Hurricanes and Tropical Meteorology,* Miami, Amer. Meteor. Soc., 21–27.

McBride, J. L., and R. Zehr, 1981: Observational analysis of tropical cyclone formation. Part II: Comparison of nondevelopment versus developing systems. *J. Atmos. Sci.,* **38,** 1132–1151.

Merrill, R. T., 1982: A comparison of large and small tropical cyclones. Atmos. Sci. Paper No. 352, Colorado State University, Ft. Collins, CO, 80523, 75 pp.

Miller, B. I., 1958: The use of mean layer winds as a hurricane steering mechanism. Natl. Hurricane Res. Proj. Rep. No. 18, 24 pp. [Available from Hurricane Research Div., AOML, 4301 Rickenbacker Causeway, Miami, FL 33149.]

——, and P. L. Moore, 1960: A comparison of hurricane steering levels. *Bull. Amer. Meteor. Soc.,* **41,** 59–63.

——, ——, 1966: Prediction of hurricane motion by statistical methods. *Mon. Wea. Rev.,* **94,** 399–406.

——, E. C. Hill and P. P. Chase, 1968: A revised technique for forecasting hurricane movement by statistical methods. *Mon. Wea. Rev.,* **96,** 540–548.

Neumann, C. J. 1979: On the use of deep-layer mean geopotential height fields in statistical prediction of tropical cyclone motion. *Preprints, 6th Conf. on Probability and Statistics in Atmospheric Science,* Banff Alta, Canada, Amer. Meteor. Soc., 32–38.

——, and J. R. Hope, 1973: A diagnostic study on the statistical predictability of tropical cyclone motion. *J. Appl. Meteor.,* **12,** 62–73.

——, and J. M. Pelissier, 1981: Models for the prediction of tropical cyclone motion over the North Atlantic: An operational evaluation. *Mon. Wea. Rev.,* **109,** 522–538.

Peak, J. E., and R. L. Elsberry, 1984: Prediction of tropical cyclone turning and acceleration using empirical orthogonal function representations. *Proc. 15th Tech. Conf. on Hurricanes and Tropical Meteorology,* Miami, Amer. Meteor. Soc., 45–50.

Sadler, J. C., 1976: Tropical cyclone initiation by the tropical upper tropospheric trough. *Mon. Wea. Rev.,* **104,** 1266–1278.

——, 1978: Mid-season typhoon development and intensity changes and the tropical upper tropospheric trough. *Mon. Wea. Rev.,* **106,** 1137–1152.

Tse, S. Y. W., 1966: A new method for the prediction of typhoon movement using the 700 mb chart. *Quart. J. Roy. Meteor. Soc.,* **92,** 239–254.

Tuleya, R. E., and Y. Kurihara, 1982: A note on the sea surface temperature sensitivity of a numerical model of tropical storm genesis. *Mon. Wea. Rev.,* **110,** 2063–2069.

U.S. Naval Weather Service, 1975: *Numerical Environmental Products Manual.* NAVAIR 50-1G-522. 155 pp. [Available from Naval Environmental Prediction Research Facility, Monterey, CA 93943.]

World Meteorological Organization, 1979: Operational techniques for forecasting tropical cyclone intensity and movement. WMO No. 528, World Meteorological Organization, Geneva, 138 pp.

Xu, J., and W. M. Gray, 1982: Environmental circulations associated with tropical cyclones experiencing fast, slow and looping motion. Atmos. Sci. Paper No. 346, Colorado State University, Fort Collins, CO, 80523, 273 pp.