# The Relationship between Tropical Cyclone Motion and Environmental Geostrophic Flows

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## ABSTRACT

Based on 920 cases, the relationship between Atlantic tropical cyclone motion and environmental geostrophic flows at ten levels (from 1000 to 100 mb) has been calculated and analyzed. For the average situation, it is shown that the steering relationship is considerably different between higher and lower tropospheric levels, and between easterlies and westerlies. Also, there are some differences in an optimal statistical steering function between different storm developmental states. The results of a further correlation and regression analysis of these same data show that the height of the optimum single steering level for hurricanes is higher than that for tropical storms, and the depth of the optimum deep layer for steering hurricanes is larger than that for steering tropical storms.

## 1. Introduction

Since the 1950s, considerable research has been focused on the steering concept and its application to forecasting. Most of these studies showed that the basic flow at a middle tropospheric level or a deep layer mean flow weighted by pressure could serve as a steering current for tropical cyclone motion (Jordan, 1952; Dong, 1958; Miller and Moore, 1962; Sanders and Burpee, 1968; George and Gray, 1976; Gray, 1977; Neumann, 1979; Brand *et al.*, 1981). Many of these authors have discussed the deviations of vortex motion from the basic current; however, there are inconsistencies. For example, Miller (1958) pointed out that most tropical storms moved to the right of the middle-lower-level flows, whereas George and Gray (1976), using composited observed data (as opposed to analyses), found that a tropical cyclone's mean motion for the western North Pacific basin had a leftward deviation from the mean flow in the middle troposphere. For that same basin in the easterlies a nearly opposite deviation of typhoon motion from the basic current was found by Dong and Liu (1965). For westward moving Atlantic storms, the rightward deviation from the 500 mb flow was also shown by Gray (1977) but for a smaller sample of storms. Brand *et al.* (1981) found that most western North Pacific storms moved to the left of the 500 mb flow at middle-higher latitudes, but to the right at lower latitudes. Thus, insofar as the tropical cyclone steering mechanism is concerned, some apparent conflicts still remain. These are addressed in this paper.

## 2. Method and data

The purpose of this study is to reanalyze the relationship between tropical cyclone motion and the environmental geostrophic flow at various levels. The study utilized 920 cases of the 24 h motion of Atlantic tropical cyclones (including 47 cases of subtropical cyclones) over the 13-year period, 1965–77. In each case, the storm's environmental geostrophic flow was calculated at ten levels and combinations of levels (from 1000 to 100 mb). The geopotential height field data were obtained from archived U.S. National Meteorological Center's operational hemispheric objective analyses.

The choice of proper grids in the height field is important in calculating the environmental geostrophic wind. Neumann (1979) has investigated the optimum points in the height field for statistical tropical cyclone motion prediction in the zonal and meridional sense. Partially based on Neumann's result (unpublished) and considering symmetry about the storm center and the scale of the basic flow, the grid points a, b, c, d/e, f, g, h and i, j, k/l, m, n in Fig. 1 were chosen respectively for calculating the meridional component ($V_g$) and the zonal component ($U_g$) of the geostrophic wind (km day$^{-1}$). These are given by

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* This study was completed while the first author was assigned to the National Hurricane Center, Coral Gables, Florida, as a WMO Fellow.

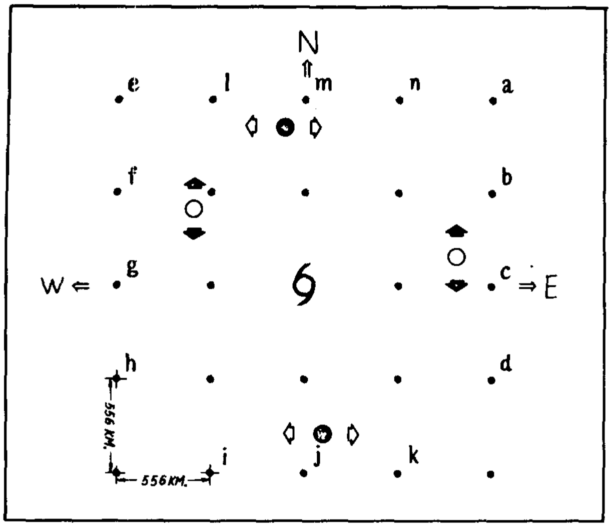

FIG. 1. Optimum location of 24 h height-predictors, (open circles) storm meridional motion and (dots) zonal motion, used for calculating the environmental geostrophic wind.

$$V_g = \frac{g}{f}(H_a + H_b + H_c + H_d - H_e - H_f - H_g - H_h)/16D$$

$$U_g = \frac{g}{f}(H_i + H_j + H_k - H_l - H_m - H_n)/12D$$

where $g$ is the gravitational acceleration, $f$ the Coriolis parameter, $H_i$ the geopotential heights at different grid points, and $D$ the distance between two grid points.

In the study, we considered only the future 24 h motion of the tropical cyclone. According to the direction of the tropical cyclone motion, the 873 cases of tropical cyclones (excluding the subtropical cyclones) were stratified into two main groups: storms in the easterlies (358 cases) and storms in the westerlies (515 cases). In our computer analysis program, storms were stratified into the easterlies category until their zonal 24 h displacements became negative (i.e., storms began to move eastward); the others categorized as westerlies. Additional substratifications were based on the current storm intensity and the future 24-h change of intensity.

## 3. The average situation

In this section, we present and discuss average results. It should be emphasized that directions of environmental geostrophic flows given in the following sections are relative to the storm motion; that is, the origin of the coordinate system is always positioned at the storm center and the positive direction of the $y$-axis coincides with the storm heading.

### *a. Averages for the entire sample*

Figure 2 shows the mean environmental flows at 10 levels for the total group of tropical cyclones. It is clear that there is considerable change between the lower and higher level basic flows. Storm motion is seen to be toward the left of the basic flow at 700 mb and above, but toward the right of the 1000 mb flow. The speed of basic flows increases with height to 200 mb. The mean speed of the storm is larger than the mean flow throughout all layers with the exception of the 300–200 mb layer. These results could confirm some common findings in earlier storm steering studies (see Section 1).

For the subtropical cyclone cases, the geostrophic flows at the ten levels are all biased to the right of subtropical cyclone motion and have smaller changes in direction in the vertical than those for the total tropical cyclone group (not shown).

### *b. Easterly and westerly stratification*

Figures 3 and 4 show the relationships between storm motion and environmental flows in the westerlies (for eastward moving storms) and in the easterlies (for westward moving storms), respectively. It is clear that the distribution pattern in the westerlies is very similar to that for the total unstratified group shown in Fig. 2. This is because storms in the westerlies outnumber those in the easterlies in our sample and also have stronger geostrophic flows. By making a comparison between the two stratifications, we found that the relationship in the easterlies (Fig. 4) is considerably different from that in the westerlies (Fig. 3). In the easterlies, the storm motion has a rightward deviation from the mean flows at middle-lower and high levels instead of the leftward deviation in the westerlies. Similarly to

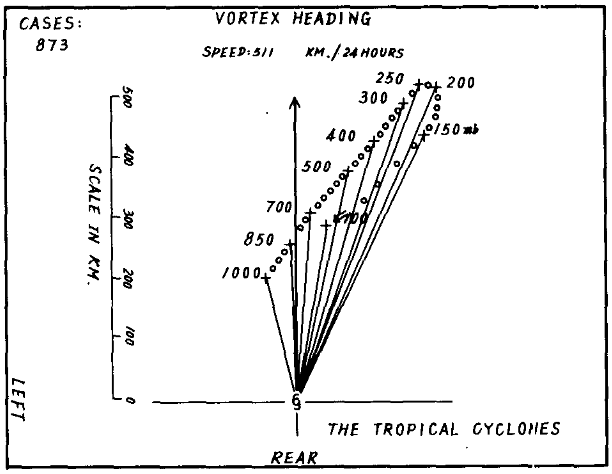

FIG. 2. Location of geostrophic wind centroid relative to 24 h storm motion centroid for each level and for all tropical cyclones.

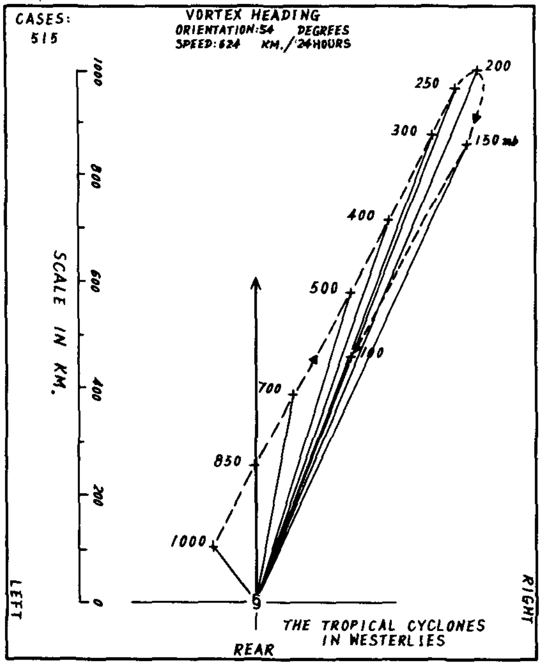

FIG. 3. As in Fig. 2 but for eastward moving tropical cyclones.

the distribution pattern for the total group, the basic flow in westerlies increases with the height to 200 mb, whereas the basic flow in the easterlies decreases with height from 1000 mb to 400 mb.

For the Atlantic storm motion, Miller (1958) showed a rightward deviation from the low and middle level surrounding flow based on composited wind data in the range of 2–6 degrees of latitude from the storm center. We do not know whether there were more westward moving storm cases in Miller's composited data. However, Dunn and Miller (1964) suggested that for hurricanes moving in westward and northwestward directions, the center should be forecast to move to the right of the indicated steering, but for northeastward-moving storms to the left of the steering current. A further extensive rawinsonde compositing study on the Atlantic storm steering was made by Gray (1977). His composites have been stratified into two groups by storm moving direction besides other classifications by storm intensity, latitude and speed. For the westward moving group, the storms moved to the right of the 500 mb flow averaged within 1 to 7 degrees of latitude radius of the storm. This was the only group to confirm Miller's (1958) result. For the northward moving group and others the storm moved to the left of the 500 mb mean wind. Therefore, there is no significant contradiction between ours and previous studies insofar as steering of Atlantic tropical cyclones is concerned.

In the northwest Pacific basin, Dong and Liu (1965), using geostrophic basic current analysis, found that most typhoons in the easterlies moved toward the right of the basic flow above 700 mb and toward the left below 700 mb; conversely, most typhoons in the westerlies moved to the left of the basic flows above 700 mb and to the right below 700 mb. Brand *et al.* (1981) compared the motion of northwest Pacific typhoons with the 500 mb geostrophic basic current. Their results indicated that most storms moved to the left of the basic flow at middle-higher latitudes, but to the right at lower latitudes. Those are in agreement with our foregoing results for Atlantic storms. However, George and Gray (1976) and Gray (1977) showed that northwest Pacific storms typically moved to the left of the 500 mb 1–7 (degrees of latitude) radius mean wind in their compositing studies, and that this was consistent for various stratifications. It is to be noted that there are some differences between their compositing techniques and our geostrophic analyses, including the data treatment and the time and space scale. These remain to be studied further.

As Anthes (1982) has noted, numerical modeling seems to indicate that storms move to the right of the basic flow. For example, Kuo (1969) and Jones (1977) showed that surface frictional drag will cause a vortex to move to the right of the basic flow. It is possible that the storm in the easterlies is simulated in most numerical models. For example, Jones' (1977) model did use an easterly basic flow.

For westward moving storms there are large changes of the environmental flow in the vertical. The storm's mean motion is closer to the lower-level mean flow than to the middle-level flow, and the higher-level mean flow is nearly opposite to the storm motion in direction. In their prediction model, Renard *et al.* (1973) found the 850 mb steering current superior to that at 700 mb in the 1971 Atlantic hurricane season. In that hurricane season, there were more cases of westward moving storms. This seems to be consistent with the depiction in Fig. 4. The fact that the lower-level steering is su-

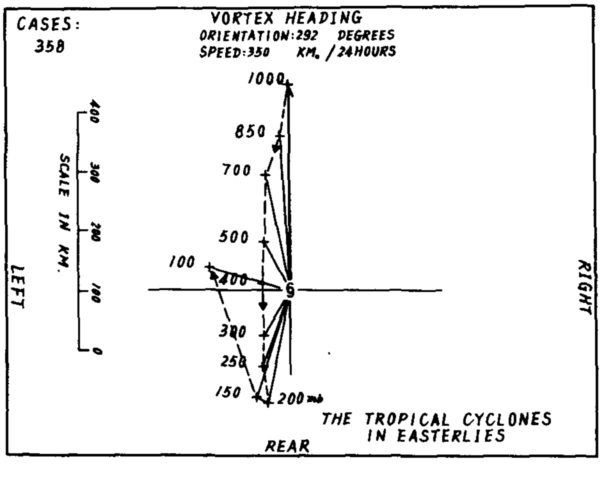

FIG. 4. As in Fig. 2 but for westward moving tropical cyclones.

perior to the middle-higher-level steering was also found in the western North Pacific typhoon basin in the late autumn of 1974 (Dong *et al.*, 1976).

### c. *Stratification based on vortex intensity*

Based on the present intensity and the future 24 h change in intensity of tropical cyclones, the easterly and the westerly group were divided respectively into hurricane and tropical storm substratifications, and into strengthening and weakening substratifications. Different relationships between vortex motion and environmental flows were found between different groups. For example, in the easterlies, the higher-level mean flow for the strengthening group is much weaker than that for the weakening group (Fig. 5). A similar difference is observed between the hurricane and the tropical storm stratification (Fig. 6). In addition, it is seen that an intensifying vortex tends to the right of the lower-level flow, while a weakening vortex tends to the left.

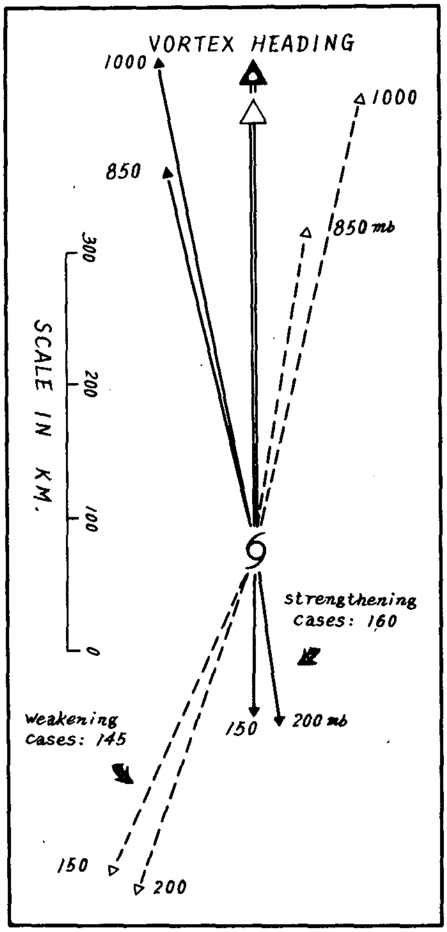

FIG. 5. The comparison of environmental flows between strengthening and weakening tropical cyclones in the easterlies. The solid lines and arrows denote strengthening cases, the dashed lines and blank arrows denote weakening cases.

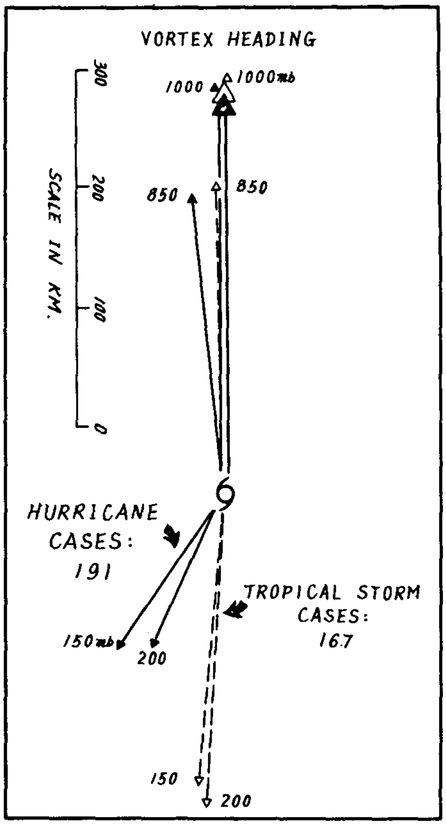

FIG. 6. The comparison of environmental flows between hurricanes and tropical storms in the easterlies. The solid lines and arrows denote hurricane cases, the dashed lines and blank arrows denote tropical storm cases.

## 4. Discussion

Holland (1983) has made an extensive theoretical study in explanation of the deviations of tropical storm motion from the basic current. According to his paper, the left deviation in the westerlies may be explained as an additional westward component resulting from the effect of the meridional gradient in earth vorticity. However, the right deviation in the easterlies may probably be related to the cyclonic wind shear of the basic current. This is because an environmental, cyclonic, basic flow pattern in the lower-middle troposphere is a necessary condition for the tropical storm formation. Of course, it is difficult to assess many different contributions to the deviation and further study is required.

Results presented in Section 3 demonstrate that tropical cyclones have environmental flows having marked changes in the vertical, and the change characteristics in the easterlies are quite different from those in the westerlies. These are denoted by the dashed lines and solid arrows in Figs. 3 and 4. In his experiment (the MFM model), Hovermale (1980) has pointed out that different vertical shears, somewhat like those de-

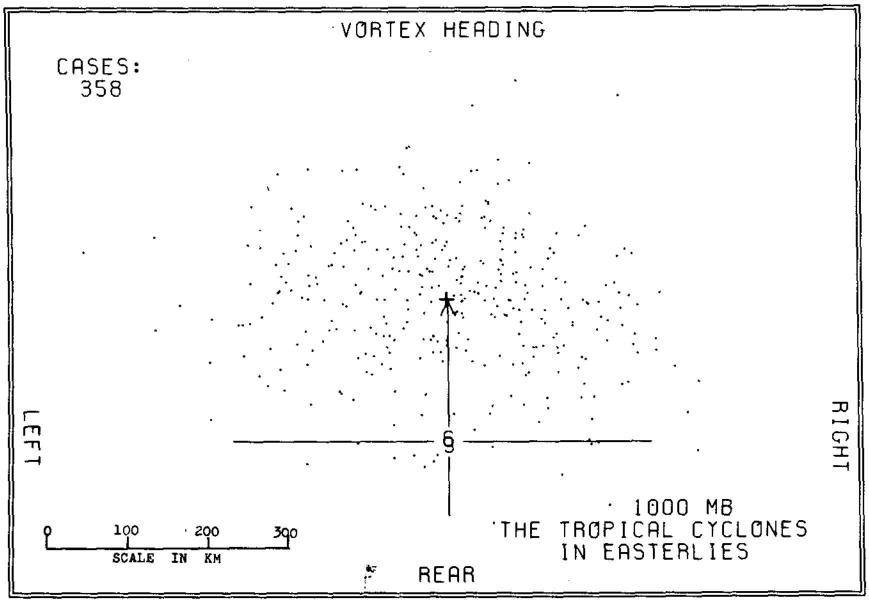

FIG. 7. The distribution of environmental geostrophic flows relative to the 24 h storm motion for specified stratification. Arrow represents centroid of storm motion; the cross shows centroid of geostrophic flow.

picted in Figs. 3 and 4, have different effects on the steering mechanism. His result showed that the height of the "steering level" in the easterlies is lower than that in the westerlies. This is basically consistent with our average result in Section 3. Neumann and Pelissier (1981) have pointed out that most of the hurricane prediction models had different performance characteristics between lower latitudes and higher latitudes. Xu and Gray (1982) have stressed that for their motion and environmental circulation, tropical cyclones south of the subtropical ridge must be handled quite differently from those located to the north of the ridge.

The foregoing average results may be helpful for further understanding the steering mechanism. However, we cannot merely use these mean results for prediction because there is a considerable deviation for each averaged flow. Figure 7 shows the scatter of all individual 1000 mb flows for the westward moving storm group. It is clear that the averaged flow is very close to the storm's mean motion, but there are large differences between the average and individual cases. Figure 8 gives the scatter of the individual 500 mb flows for the eastward moving storm group. The individual flows have considerable deviation from the average, too.

It should be pointed out that our results may be influenced by the method of objective analyses. In our data, the Cressman scan analysis was used through 1974 and the Flattery spectral analysis was used thereafter. In regard to tropical cyclone forecasting, deficiencies in the latter analysis have been noted by Leftwich *et al.* (1977).

## 5. The results of correlation and regression analysis

The same data and stratification schemes discussed here were used in a correlation and regression analysis. In addition, a number of deep layer-mean flows

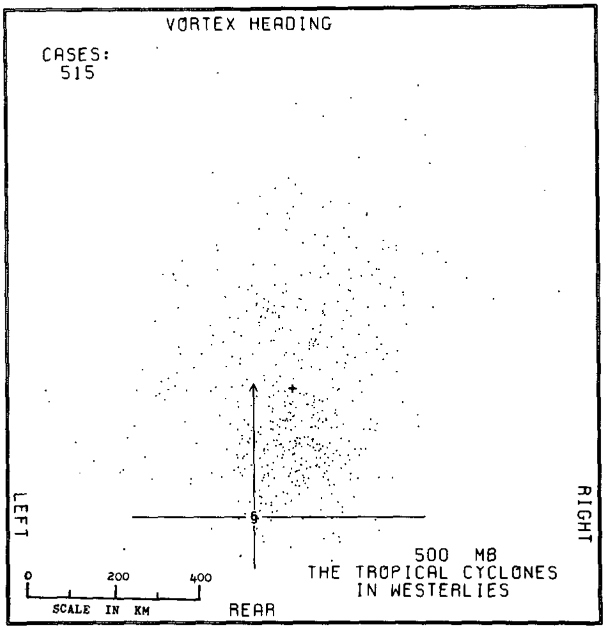

FIG. 8. As in Fig. 7 except at 500 mb in the westerlies.

TABLE 1. Correlation coefficients (meridional/zonal, in percentage) between 24 h tropical cyclone motion and environmental flow at each single level in the easterlies.

| Level (mb) | All tropical cyclones (358) | Hurricanes (191) | Tropical storms (167) | Strengthening cases (160) | Weakening cases (145) |
|---|---|---|---|---|---|
| 100 | 38/38 | 49/44 | 29/35 | 44/34 | 27/40 |
| 150 | 43/43 | 57/54 | 29/37 | 51/43 | 35/46 |
| 200 | 47/45 | 60/59 | 33/37 | 54/49 | 44/45 |
| 250 | 50/47 | 62/60 | 36/37 | 56/51 | 50/45 |
| 300 | 53/49 | 64/62* | 40/41 | 60/54 | 52/47* |
| 400 | *56/52 | *67/61 | 43/46 | *62/59 | 56/46 |
| 500 | 54/53* | 63/59 | 45/50 | 59/62* | 57/45 |
| 700 | 53/49 | 56/47 | *50/51* | 49/56 | *63/38 |
| 850 | 47/42 | 50/34 | 44/48 | 43/48 | 60/30 |
| 1000 | 44/24 | 46/13 | 41/34 | 41/28 | 53/13 |

* Maximum value.

weighted by the pressure were also tested in this manner.

For single level steering, the correlation coefficients between the 24 h storm motion and various level environmental flows in the easterlies and in the westerlies are shown in Tables 1 and 2 respectively. The flows in the middle troposphere show a larger correlation with storm motion. This is consistent with most previous studies. It can also be noted in these tabulations that, in both easterlies and westerlies, the optimum steering level for the hurricane group is higher than that for the tropical storm group. For each level, a pair of simple steering regression equations was found. For example, the equation group of the 400 mb flow for hurricanes in the easterlies is as follows,

$$\left.\begin{aligned} U_h &= 0.35U_g + 491.5 \\ V_h &= 0.56V_g + 318.0 \end{aligned}\right\}$$

where $U_h$ and $V_h$ denote the forecast hurricane motion. $U_g$ and $V_g$ represent the geostrophic flow calculated as in Fig. 1. Units for the numbers in the two equations are kilometers per 24 hours. Forecast errors produced by applying similar regression equations to a dependent sample show that for hurricanes, 400 mb is near an optimum steering level, and for tropical storms, 700 mb is optimal in both easterlies and westerlies (Fig. 9). By "optimum" or "optimal" is meant the minimum forecast error.

From his experience, Simpson (1971) has shown that for incipient tropical cyclones and storms, the circulation of the layer from 1000–400 mb should be the best index to instantaneous steering, but for extreme storms (central pressure less than 940 mb) the deeper layer 1000–100 or 1000–150 mb deep layer-mean steering should be optimal.

Our objective result (Fig. 10) appears to be in accordance with Simpson's subjective reasoning. Moreover, comparing Fig. 10 with Fig. 9, we may find that the optimum deep-layer steering is generally a little better than the equivalent optimum single-level steering for various stratifications except the hurricane group in the easterlies. However, the data relating to this comparision listed in Table 3 show that the differences in forecast error between the deep-layer and the equivalent single-level steering are not significant. There is

TABLE 2. As in Table 1, except in the westerlies.

| Level (mb) | All tropical cyclones (515) | Hurricanes (258) | Tropical storms (257) | Strengthening cases (194) | Weakening cases (227) |
|---|---|---|---|---|---|
| 100 | 44/48 | 53/58 | 34/35 | 27/47 | 49/41 |
| 150 | 53/59 | 65/66 | 39/48 | 37/57 | 58/53 |
| 200 | 60/65 | 72/71 | 44/57 | 44/64 | 65/60 |
| 250 | 63/69 | *75/74 | 47/61 | 48/68 | *68/65 |
| 300 | *64/71 | *75/76 | 48/63 | 49/70 | *68/68 |
| 400 | *64/75 | 73/78 | 51/68 | 52/73 | *68/72 |
| 500 | 63/76* | 71/80* | 53/71* | 55/74* | 67/74 |
| 700 | 61/76* | 71/80* | *58/71* | *57/71 | 64/75* |
| 850 | 49/71 | 45/73 | 55/65 | 50/62 | 52/72 |
| 1000 | 35/59 | 27/63 | 44/52 | 39/45 | 35/65 |

* Maximum value.

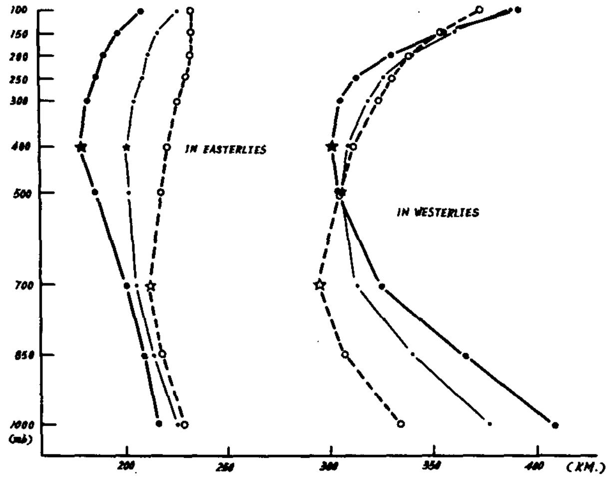

FIG. 9. Measures of single-level-steering effect. Explanation: Abscissa represents 24 h forecast error; — ● — for hurricanes; --O-- for tropical storms; —·— for all tropical cyclone and various stars denote relative optimum steering level for 3 categories respectively.

considerable evidence (Neumann, 1981) that midtropospheric analysis has deteriorated in recent years because of the lack of direct observational input at these levels, whereas analyses at the low and high levels has seen increased observational input. Thus, use of a optimum deep-layer concept would appear to be justified.

The results of this section further confirm and suggest that based on the optimum correlation relationship, the height of the steering level or the depth of the deep layer-steering increases in proportion to the tropical cyclone intensity, and it seems appropriate to divide all tropical cyclones into various intensity groups in track forecasting, especially in statistical models.

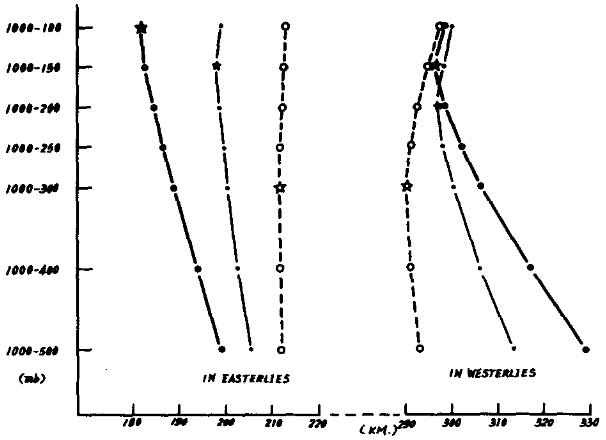

FIG. 10. Measures of deep-layer-steering effect. Symbols are the same as Fig. 9.

## 6. Conclusions

The steering relationship between 24 h projected motion of Atlantic tropical cyclones and geostrophic basic flows has been examined in this study.

Considerable differences in the steering relationships are found between storms in the easterlies and in the westerlies. Especially, storm motion has a rightward deviation from the midtropospheric flow in the easterlies, but a leftward deviation in the westerlies. In this connection, some of the contradictions or uncertainties in the steering relationship as reported by earlier authors may mainly be due to not specifying proper stratifications. It is also found that in the easterlies the upper tropospheric flows for the intensifying and the hurricane groups are much weaker than those for the weakening and the tropical storm groups.

TABLE 3. Optimum steering levels, correlation coefficients (between storm steering and actual motion) and resultant forecast error for the various stratifications.

| Classification (number of cases) | Optimum level (mb) | Correlation coefficients meridional/zonal | Dependent data 24 h forecast error (km) | Optimum deep-layer (mb) | Correlation coefficients meridional/zonal | Dependent data 24 h forecast error (km) |
|---|---|---|---|---|---|---|
| | | | In the easterlies | | | |
| Hurricanes (258) | 400 | 0.67/0.61 | 180 | 1000–100 | 0.66/0.60 | 182 |
| Total tropical cyclones (515) | 400 | 0.56/0.52 | 201 | 1000–150 | 0.58/0.54 | 199 |
| Tropical storms (257) | 700 | 0.50/0.51 | 213 | 1000–400 | 0.51/0.53 | 213 |
| | | | In the westerlies | | | |
| Hurricanes (191) | 400 | 0.73/0.78 | 300 | 1000–150 | 0.72/0.81 | 295 |
| Total tropical cyclones (358) | 500 | 0.63/0.76 | 302 | 1000–200 | 0.66/0.79 | 295 |
| Tropical storms (167) | 700 | 0.58/0.71 | 293 | 1000–300 | 0.60/0.73 | 288 |

The deviation between assumed geostrophic steering and observed storm motion is very high. Thus, a direct geostrophic steering has limited utility in forecasting. A simple regression analysis has been developed between 24-h storm motion and the steering function using flows at various pressure levels or their combinations. Our dependent data show that in general, minimum forecast error would be realized by utilizing the midtropospheric levels or a deep-layer average in statistical prediction schemes, while the height of the best steering level or the depth of the best deep-layer steering increases in proportion to tropical cyclone intensity in the correlation sense.

It is stressed that our results may be somewhat analysis dependent owing to the method of objective analyses.

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