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NOTES AND CORRESPONDENCE

Observational Evidence for Predictions of Tropical Cyclone Propagation Relative to Environmental Steering

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ABSTRACT

Theories of vortex motion due to the variations of the Coriolis parameter and environmental vorticity are compared to observations of tropical cyclone motion relative to computed "steering flows" using previously published composite data. The composite results are manipulated to obtain a vector quantity for the difference between tropical cyclone motion and steering, and this vector difference is termed "propagation." The properties of these propagation vectors within various composite data stratifications provide tentative support for nonlinear numerical results such as: (i) the general magnitude and direction of the β-induced propagation; (ii) the dependence of such propagation on the outer-wind strength of the tropical cyclone; and (iii) the dependence of such propagation on the direction of the environmental vorticity gradient. Ambiguities in the composite data are discussed with respect to linear and nonlinear theories of tropical cyclone propagation, and several new composite data stratifications are suggested to facilitate detecting individual propagation-inducing processes.

1. Introduction

Tropical cyclone (TC) motion is closely related to advection by the surrounding environmental windfield. Unfortunately, data deficiencies have hindered precise verification of this "steering flow" concept for individual TCs. As a result, compositing techniques have been used to confirm the dominant influence of environmental steering, which is typically defined as the pressured-weighted average wind within an annulus (e.g., 5°–7° latitude radius) centered on the TC (George and Gray 1976; Chan and Gray 1982; Holland 1984). These studies also noted that TC motion persistently differs from steering by a small amount that remains significant even when the steering flow definition is chosen to minimize the difference (George and Gray 1976). This motion difference is systematic in that westward (eastward) moving TCs tend to move faster (slower) than steering and tend to move to the left (right) of steering in the Northern (Southern) Hemisphere. This observed deviation resembles theoretical predictions (Adem 1956; Kasahara and Platzman 1963; Holland 1983), as well as numerical demonstrations (Anthes and Hoke 1975; DeMaria 1985; Chan and Williams 1987; Fiorino and Elsberry 1989) of TC motion relative to the environment due to variations of the Coriolis parameter and environmental vorticity across the TC. Such motion relative to a defined steering, whether predicted or observed, will hereafter be referred to as "propagation."

The results of the composite studies cannot be regarded as confirmation of any of the theoretical or numerical results because of two problems. First, a consensus as to all the mechanisms responsible for TC propagation does not exist, in part because theoretical studies to date have been limited to relatively simple models that ignore the baroclinic natures of the TC and the surrounding environment (see Willoughby 1988 for a review of the current theories). Some modeling evidence suggests that other processes such as asymmetric convection due to variations in sea surface temperature (Chang and Madala 1980) or surface friction (Jones 1977) could also cause TC propagation. Most research to date, however, has focused on the barotropic vorticity advection processes described above, and the scope of this note is limited to those processes.

Second, the above composite studies have characterized TC propagation in relative terms (e.g., speed and direction differences) using a rotated coordinate system aligned with storm motion. This compositing methodology tends to make theoretical interpretations of the data difficult because the analytical and numerical studies predict that TC propagation will possess a particular orientation with respect to the direction of the large-scale vorticity gradient. In particular, a rotated storm-relative coordinate system would tend to obscure TC propagation associated with the gradient of the Coriolis parameter, since that gradient has a storm and environment-independent northward orientation.

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Thus, part of the difficulty in comparing theory with the composite observations may be readily overcome by representing TC propagation as a vector quantity in a north-oriented earth-relative coordinate system.

The purpose of this note is to compare the theoretical predictions of TC propagation with previously published composite data by converting the composite results as indicated above. Section 2 describes the data and conversion technique. Section 3 compares the converted data with some theoretical and numerical results. In section 4, the usefulness of the data conversion and presentation scheme for comparison with theoretical studies is emphasized, and recommendations for several new theoretically-based composite data stratifications are suggested.

2. Data conversion

The TC motion and steering flow composite data are taken from the latitude, direction, speed and intensity stratifications of Chan and Gray (1982) and George and Gray (1976) for the western North Pacific region, and the direction and recurvature stratifications of Holland (1984) for the Australian–Southwest Pacific region. Holland used a single steering flow definition based on a 800 to 300 mb pressure-weighted mean wind averaged over an annulus extending 5° to 7° latitude from the TC center. Although Chan and Gray used the same horizontal domain, several vertical averaging schemes were tested. Only the Chan and Gray steering flow based on a surface to 300 mb vertical average is used here, since it most closely approximates the steering flow definition used by Holland. Vertically averaged steering flows have been chosen for this analysis rather than individual steering levels (e.g., George and Gray 1976) to more appropriately compare the observations with the theoretical modeling results that are predominantly based on barotropic dynamics.

Table 1 summarizes the conversion process for the western North Pacific composite data. The columns labeled V_{PM}, DD, V_C and D_C contain previously published data, and the last two columns have been computed using the relationships

$$D_B = D_C + DD \tag{1}$$

$$V_B = \frac{V_C + V_{PM}}{\cos DD}. \tag{2}$$

All column labels are defined in the table caption. Table 2 is analogous to Table 1 for the Australian–Southwest Pacific composite data. The columns labeled SD, DD, V_B and D_B contain previously published data, and the columns labeled V_C and D_C have been computed using (1) and

$$V_C = V_B - SD. \tag{3}$$

TABLE 1. Original and converted composite *TC* motion data for the western North Pacific region. Column heading meanings: V_{PM} is the speed of the steering flow component parallel to the direction of the composite *TC* minus the speed of the *TC*; *DD* is the difference between the direction of *TC* motion and the steering flow; V_C and D_C are the speed and direction of motion of the *TC*, respectively; and V_B and D_B are the speed and direction of the steering flow, respectively. The data in columns V_{PM} and *DD* are taken directly from Chan and Gray (1982), and the data in columns V_C and D_C are taken directly from George and Gray (1976). The data in columns V_B and D_B have been computed as described in the text. Directions are measured clockwise from North and the data in the last four columns are relative to a reference frame fixed to the surface of the earth.

Composite stratification	V_{PM} (m s^{-1})	DD (deg)	V_C (m s^{-1})	D_C (deg)	V_B (m s^{-1})	D_B (deg)
Latitude:						
>20°N (GT)	−1.0	19	5.6	352	4.9	011
<20°N (LT)	−1.6	6	5.1	300	3.5	306
Direction:						
Westward (W)	−2.3	17	6.2	285	4.0	302
Northward (N)	−1.0	17	5.3	324	4.5	341
Eastward (E)	−0.5	16	7.1	027	6.8	043
Speed:						
Slow (SL)	−0.9	27	2.4	338	1.7	005
Moderate (M)	−1.1	20	5.2	326	4.4	346
Fast (F)	−1.3	14	10.1	006	9.1	020
Intensity:						
Weak (WK)	−1.1	14	4.9	319	3.9	333
Intense (I)	−1.1	20	5.0	326	4.2	346
Very Intense (VI)	−1.7	26	5.2	319	3.9	345

The vector difference of TC motion minus steering (Fig. 1) is computed for each composite stratification using the last four entries in each row of Tables 1 and 2.

3. Discussion

The propagation vectors in Fig. 1 exhibit a number of interesting properties that strongly resemble a combination of β and environmentally induced TC propagation. Except for the anomalous "after recurvature" vector (Fig. 1f), the vectors have magnitudes ranging from 1.0 to 2.5 m s^{-1} and directions that tend to be westward and poleward in both hemispheres, which is consistent with the numerical and analytical results previously cited. In addition, the rotation of the propagation vector direction from west-southwestward for westward moving TCs to northwestward for eastward moving TCs in the direction stratification (Fig. 1b) is consistent with DeMaria's (1985) numerical results. DeMaria showed that the change in the direction of the environmental vorticity gradient from poleward on the poleward side of the subtropical ridge to equatorward on the equatorward side caused a decrease in the meridional component of TC propagation similar to that in Fig. 1b. Finally, the propagation vectors in the intensity stratification (Fig. 1d) have a direct dependence on TC intensity. The modeling studies of DeMaria (1985) and Fiorino and Elsberry (1989)

TABLE 2. Analogous to Table 1 for the Australian–Southwest Pacific region. The column headings DD, V_C, D_C, V_B and D_B have the same meanings as in Table 1 and SD is the speed difference between the composite TC and steering. The data in columns SD, DD, V_B and D_B are taken directly from Holland (1984), except that the steering flow directions are measured clockwise from North. The data in columns V_C and D_C have been computed as described in the text.

Composite stratification	SD (m s^{-1})	DD (deg)	V_C (m s^{-1})	D_C (deg)	V_B (m s^{-1})	D_B (deg)
Direction:						
Westward (W)	1.3	−4	4.0	247	2.7	243
Southwestward (SW)	1.1	−18	3.6	241	2.5	223
Southward (S)	−0.5	−32	3.0	172	3.5	140
Southeastward (SE)	−1.1	−23	3.8	150	4.9	127
Eastward (E)	−1.2	−3	4.2	106	5.4	103
Recurvature:						
Before (B)	1.1	−13	3.5	238	2.4	225
Near (N)	0.5	−26	3.7	193	3.2	167
After (A)	−0.5	−2	5.0	162	5.5	160

demonstrate that a nondivergent barotropic prediction of TC propagation due to β is independent of TC intensity, but is well correlated with outer wind strength (see Merrill 1984 for typical definitions of strength and intensity). Since a weak correlation exists between the intensity and strength of TCs (Weatherford and Gray 1988), the increase in propagation vector magnitude in Fig. 1d may be a manifestation of the numerically predicted dependence of β-induced propagation on TC strength.

The results in Fig. 1 also contain some apparent inconsistencies. Examples are: (i) the significantly larger meridional component of the Northern Hemisphere vectors compared to that of the Southern Hemisphere vectors; and (ii) the presence of equatorward components in some of the propagation vectors. Such properties may be associated with boundary layer or baroclinic processes not considered in the barotropic theories. A possible barotropic explanation, however, might be the presence of east–west vorticity gradients in the TC environment that were excluded by DeMaria (1985). For example, a large-scale westward relative vorticity gradient is present during the summer in the troposphere between the anticyclone over the western North Pacific and the heat-low over southeastern Asia. Based on DeMaria's results, a TC vortex embedded in such a vorticity gradient should have a westward, and more importantly, a southward component of propagation. Since the meridional gradient of environmental relative vorticity and β are in opposite directions south of the Northern Hemisphere subtropical ridge, the zonal gradient of environmental vorticity might tend to dominate, and thus explain, the southward component of vector W in Fig. 1b. In contrast, north of the Northern Hemisphere subtropical ridge the meridional environmental vorticity gradient and β are in the same direction, and thus might dominate over the influence of a zonal vorticity gradient in the cases of vectors N and E in Fig. 1b. Differences in the environmental vorticity gradients in the Northern and South-

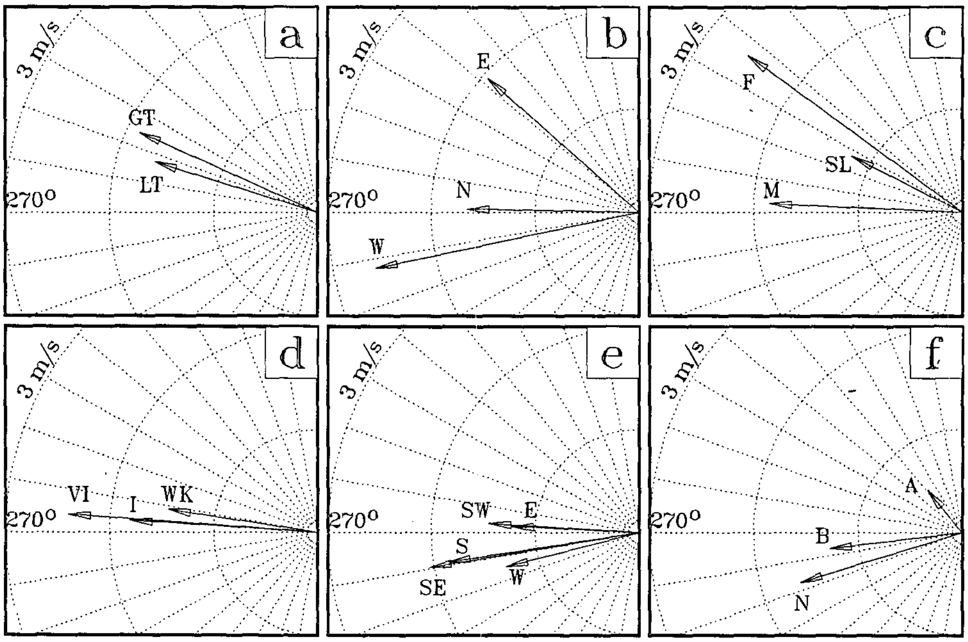

FIG. 1. Vector differences of composite TC motion minus steering for the (a) latitude, (b) direction, (c) speed and (d) intensity stratifications of Chan and Gray (1982), and the (e) direction and (f) recurvature stratifications of Holland (1984). The vector identification labels correspond to those in column 1 of Tables 1 and 2.

ern hemispheres thus may contribute to the hemispheric variability of the data shown here.

Statistical influences also must be considered, such as: (i) ambiguities introduced by composite stratifications that may incorporate multiple propagation-inducing influences; and (ii) possible random or systematic errors in the composite data that may be significant relative to the small size of the propagation vectors being analyzed (e.g., accuracy of rawinsonde wind measurements and errors in locating the TC center). Random and systematic errors should be reduced as sample sizes are increased and observational measurements are improved respectively.

The stratification methodology can in principle be modified to test new theories or assess the cause of ambiguous results. For example, both data sets used here include a stratification based on direction of TC motion. The results are ambiguous in that the western North Pacific data (Fig. 1b) seem to confirm DeMaria's (1985) modeling results concerning the influence of the subtropical ridge, whereas the Australian–Southwest Pacific data (Fig. 1e) fail to confirm the theory. A possible explanation is that the direction stratification is so general that the effect of latitudinal variations of environmental vorticity is obscured by competing influences. For example, variations of TC strength or longitudinal and seasonal variations of subtropical ridge position and the associated equatorward and poleward environmental vorticity patterns are not accounted for in a stratification by direction of motion. Recommendations for stratification schemes that minimize the conflicting influence of multiple propagation-inducing processes are given in section 4.

It might be noted that the ambiguous aspects of the composite data discussed above may have contributed to two different viewpoints for explaining β-induced TC motion. Holland's (1983) linear model is consistent with the near-zonal orientation of the Australian–Southwest Pacific difference vectors (Figs. 1e, f). Holland assumes that inertial stability constrains the inner core of the TC to move with the outer envelope, which is assumed to propagate westward as a Rossby wave with a phase speed appropriate to an "effective radius." In practice, the "effective radius" parameter for a particular storm and time is chosen to give a barotropic Rossby wave propagation speed that equals the observed westward component of TC propagation over a preceding time interval. Holland must include low-level convergence to account for small deviations from pure westward motion, and assumes that any nonlinear, TC-induced contribution to environmental steering is already contained in the computed steering flow.

In contrast, a number of factors suggest that observed TC propagation is a manifestation of the nonlinear β-induced motion consistently seen in numerical models. For example, Chan and Williams (1987) have shown that linear processes alone generate negligible motion of the vortex center in the absence of environmental winds. In addition, several of the difference vectors from the western North Pacific data (Figs. 1a–d) have significant meridional components, and Chan's (1986) study of Supertyphoon Abby (which occurred in 1983) identified significant meridional motion of the typhoon center in the presence of weak near-zonal steering. Extreme inflow angles would be required in Holland's model to generate such significant meridional motion. Finally, Fiorino and Elsberry (1989) showed that the motion of a TC center in a quiescent environment corresponded very closely to advection of symmetric TC vorticity by the central uniform flow portion ($r < 300$ km) of a β-induced wind asymmetry.

Such an asymmetry in an initially symmetric barotropic TC vortex has appeared repeatedly in numerical simulations (e.g., Anthes and Hoke 1975; Chan and Williams 1987), and a quasi-steady state is typically achieved in 24–48 h (DeMaria 1985; Fiorino and Elsberry 1989). By extracting the asymmetric component from the total TC windfield, Fiorino and Elsberry found an essentially azimuthal wavenumber 1 structure with very weak flow outside the uniform flow region identified above. This suggests that "self-advection" of the TC by the induced asymmetric flow would be largely unaccounted for in a steering flow calculation based on an annulus that excludes a large central region (within 5° latitude radius). Thus, "self-advection" will be manifested primarily as propagation, rather than as a contribution to conventionally calculated steering flows as hypothesized by Holland (1983). Consequently, it would seem that Holland's linear model may actually include nonlinear motion-inducing processes since the selection of an effective radius is based on the observed difference between TC motion and steering over a preceding time interval.

Since accurate measurement of steering near the TC center is difficult, it may be advisable as a practical matter to continue to compute steering at a large scale (≈ 1000 km) as is now done, and to regard the self-advection flow as a separate TC-related propagation phenomenon as recommended by Elsberry (1986). Since the self-advective flow is influential in a subsynoptic scale region, such a flow partitioning may also be a good approximation to the desired scheme to uniquely separate the TC from its environment.

4. Conclusion and recommendations

The technique of representing composite TC motion relative to steering as a propagation vector in a north-oriented and earth-relative coordinate system clearly identifies the vector properties as illustrated in Fig. 1, and facilitates comparison with theoretical results. The analysis of previously published composite data provides some evidence for the existence of β and environment-induced propagation due to nonlinear self-advection seen in recent numerical studies. Ambiguities in the results, however, prevent the present analysis from being considered definitive. Although baroclinic processes may also be involved, it is believed that ambiguities in Fig. 1 are largely due to data stratifications that did not specifically focus on those vortex and environment properties that barotropic theoretical studies indicate are important.

It is recommended that new stratifications be developed based on these theoretical expectations and be applied as in section 2. Since multiple physical mechanisms are probably operating simultaneously, the data stratification groupings should be sufficiently narrow in scope (consistent with statistical stability of the data) to permit only one vortex or environment property to vary significantly. For example, the numerically predicted dependence of the magnitude of β-induced propagation on TC outer wind strength could be tested by using a grouping that varies TC strength while limiting the variation of season and restricting the position of the TC to be either poleward or equatorward of the subtropical ridge. Restricting TC position relative to the subtropical ridge would ensure that the environmental vorticity gradient has a consistent poleward or equatorward component. Limiting the time period to 1 or 2 months would limit the seasonal variability of subtropical ridge strength and associated environmental vorticity gradients to the climatological average for the particular month(s) chosen. Conversely, restricting the variability of TC strength and season while stratifying by TC position relative to the subtropical ridge may provide clear evidence for the influence of the environmental vorticity gradient. These examples are only guidelines and may be modified as future theoretical insights and data availability may dictate.

The likelihood of ambiguous results arising from future studies of composite or individual TC propagation will also be lessened if all researchers use the same steering flow definition to the maximum extent possible. Thus, it is recommended that a standardized steering flow definition should be a 850–300 mb pressure-weighted wind over a 5°–7° latitude radius annulus as discussed in Elsberry (1988).

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REFERENCES

Adem, J., 1956: A series solution for the barotropic vorticity equation and its application in the study of atmospheric vortices. *Tellus*, **8**, 364–372.

Anthes, R. A., and J. E. Hoke, 1975: The effect of horizontal divergence and the latitudinal variation of the Coriolis parameter of the drift of a model hurricane. *Mon. Wea. Rev.*, **9**, 757–763.

Chan, J. C.-L., 1986: Supertyphoon Abby—An example of present track forecast inadequacies. *Wea. Forecasting*, **1**, 113–126.

——, and W. M. Gray, 1982: Tropical cyclone movement and surrounding flow relationship. *Mon. Wea. Rev.*, **110**, 1354–1374.

——, and R. T. Williams, 1987: Analytical and numerical studies of the beta-effect in tropical cyclone motion. Part I: Zero mean flow. *J. Atmos. Sci.*, **44**, 1257–1265.

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.

DeMaria, M., 1985: Tropical cyclone motion in a nondivergent barotropic model. *Mon. Wea. Rev.*, **113**, 1199–1210.

Elsberry, R. L., 1986: Some issues related to the theory of tropical cyclone motion. Tech. Rep. NPS 63-86-005, Naval Postgraduate School, Monterey, CA 93943, 25 pp.

——, 1988: ONR Tropical Cyclone Motion Research Initiative: Mid-year review, discussion and working group reports. Tech. Rep. NPS 63-88-005, Naval Postgraduate School, Monterey, CA 93943, 86 pp.

Fiorino, M., and R. L. Elsberry, 1989: Some aspects of vortex structure related to tropical cyclone motion. *J. Atmos. Sci.*, **46**, 975–990.

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

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

——, 1984: Tropical cyclone motion: A comparison of theory and observation. *J. Atmos. Sci.*, **41**, 68–75.

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

Kasahara, A., and G. W. Platzman, 1963: Interaction of a hurricane with the steering flow and its effect on the hurricane trajectory. *Tellus*, **15**, 321–335.

Merrill, R. T., 1984: A comparison of large and small tropical cyclones. *Mon. Wea. Rev.*, **112**, 1408–1418.

Rossby, C.-G., 1948: On the displacements and intensity changes of atmospheric vortices. *J. Mar. Res.*, **7**, 175–196.

Weatherford, C. L., and W. M. Gray, 1988: Typhoon structure as revealed by aircraft reconnaissance. Part II: Structural variability. *Mon. Wea. Rev.*, **116**, 1044–1056.

Willoughby, H. E., 1988: Linear motion of a shallow-water, barotropic vortex. *J. Atmos. Sci.*, **45**, 1906–1928.