Tropical Cyclone Motion: A Comparison of Theory and Observation

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ABSTRACT

The analytic predictions of tropical cyclone motion by Holland are shown to be in very good agreement with observations in the Australian/southwest Pacific region. These results indicate that a combined linear asymmetric advection and divergence of earth and cyclone vorticity provides the main mechanism for tropical cyclone motion. It is also shown that an accurate prediction requires a consideration of horizontal and vertical asymmetries in the wind field. Hence, care needs to be taken in defining a steering current.

1. Introduction

Tropical cyclone motion is a complex process, a complete description of which would require at least a detailed knowledge of the interactions between the cyclone circulation, the environmental wind field, the earth's vorticity field, the underlying surface and the fields of moist convection. However, though the detailed physics, and particularly the nonlinear interactions, are poorly understood at this stage, we have recently indicated (Holland, 1983a,b; hereafter Ha and Hb) that the short term motion is quasi-linear and dominated by a linear combination of two mechanisms, advection by the environmental wind field (including asymmetries) and propagation by interaction with the earth's vorticity field. Over a time span of days, slowly evolving nonlinear interactions or even rapid interactions at an abrupt change of environment, may substantially modify these linear motion mechanisms.

In this paper we shall summarize this theoretical work and discuss the results in terms of tropical cyclone observations in the Australian/southwest Pacific region.

2. Theory

In Ha we assumed that a tropical cyclone will move toward the region of maximum vorticity change in its vicinity with a speed given by the time rate of change of relative vorticity divided by the radial gradient of vorticity in the cyclone. We then appoximated the cyclone by a convergent, modified Rankine vortex and used the divergent, barotropic vorticity equation to analytically derive the resultant motion for a number of situations. In the most complex of these situations we used a symmetric, convergent cyclone on a beta-plane. We also superimposed a basic current with asymmetries defined by any combination of constant meridional and zonal components of divergence and vorticity. The linear cyclone motion tendency was then given by solutions to

$$\begin{aligned} r^3\beta_0[\zeta_1 \cos\theta_m + (2\delta_0 + \delta_1) \sin\theta_m] \\ + r^2\beta_0 v_s[\cos\theta_m - \gamma(2 - x) \sin\theta_m] \\ + r(1 - x^2)v_s[(\zeta_0 - \zeta_1) \cos 2\theta_m + (\delta_1 - \delta_0) \sin 2\theta_m] \\ - \bar{V}_B(1 - x^2)v_s \sin(\theta_m - \alpha) = 0, \quad (1) \end{aligned}$$

$$\begin{aligned} V_c = \bar{V}_B \cos(\theta_m - \alpha) \\ + \frac{\beta_0 r^2}{(1 - x^2)} [\gamma(2 - x) \cos\theta_m + \sin\theta_m] \\ + \frac{\beta_0 r^3}{v_s(1 - x^2)} [\zeta_1 \sin\theta_m - (2\delta_0 + \delta_1) \cos\theta_m], \quad (2) \end{aligned}$$

where r is radius; β_0 is the meridional gradient of Coriolis vorticity at the cyclone center; ζ_0, ζ_1 and δ_0, δ_1 are the constant meridional and zonal components of relative vorticity and divergence respectively; θ_m is the direction and V_c the speed of the cyclone; v_s is the symmetric component of azimuthal wind; γ the tangent of the constant inflow angle; x defines the shape of the Rankine vortex approximation; α and $\bar{V}_B$ are the direction and speed of the mean component of the basic current.

Complete details on the derivation of these equations and the solution procedures are given in Ha. In essence, for a given situation, the symmetric cyclone is subtracted to leave the basic current component; the basic current is then approximated by the domain mean $\bar{V}_B$, α and constant ζ_0, ζ_1, δ_0, δ_1. Eq. (1) is next solved iteratively for the direction of cyclone motion, θ_m; and

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finally, Eq. (2) is solved directly for the cyclone speed V_c.

Note that Eqs. (1) and (2) contain a cubic radial dependence. This dependence, which is largely due to the differential advection of earth vorticity by the vortex, implies rapid distortion of any symmetric cyclone. Such distortion cannot occur in nature for it would soon destroy the cyclone; rather, we believe that a nearly steady state generally prevails in which the distortion is compensated by additional vorticity advection and divergence effects. This belief is supported by numerical modeling experiments in which an initially unbalanced vortex quickly gains a steady state. A comprehensive discussion of these processes may be found in Ha and Hb.

When we take Eqs. (1) and (2) and solve for radius using observations and a known cyclone motion, we also find that a single radial band dominates for each cyclone. This band typically lies in the range of 200–300 km (Ha) and corresponds to a rapid change in inertial stability from the very stable core region to the weakly stable outer circulation. Thus, the motion may be conceptually viewed as a moving envelope at what we have described as the effective radius of interaction (Ha). At this effective radius, the cyclone/environmental interactions dominate in determining the subsequent motion. Inside, the high rotational stiffness prevents any significant distortion, and the center slavishly follows the outer envelope (though internal readjustments may result in an oscillation of the center about the mean track). Outside this effective radius envelope, the steady-state cyclone distortion induces a cyclonic gyre to the west and anticyclonic gyre to the east. As Anthes (1982, p. 107) has suggested and as we describe fully in Hb, these gyres introduce a meridional basic current component over the cyclone core.

The theory then predicts that a cyclone moves under two dominant linear mechanisms. These are

1) An asymmetric advection and divergence of the cyclone vorticity by the basic current and
2) A propagation by interactions between the earth's vorticity field and both the cyclone and basic current.

In the Southern Hemisphere, the second, beta-effect, mechanism will generally cause a west to southwestward deviation from the basic current advection.

This concept of motion by cyclone–environmental interaction at an envelope defined by the region of rapid increase in inertial stability predicts that

1) Intensity variations (i.e., maximum wind but no outer circulation changes) will not affect the motions and
2) Size and strength (i.e., outer circulation) changes will affect the motion by changing the effective radius.

These predictions are consistent with general observations that no track changes accompany oscillations in central pressure or maximum winds in hurricanes. Confirmation has also been provided in recent modeling experiments by M. DeMaria of Colorado State University (personal communication, 1982). DeMaria made a control, nondivergent barotropic integration of an initially axisymmetric vortex on a beta-plane. He then repeated the experiment with two new vortices. In the first experiment, the intensity was changed by doubling the maximum winds and keeping the outer circulation unchanged. In the second experiment, the size was changed by a 20% increase of winds outside the maximum wind belt with almost no intensity change.

The resulting trajectories are shown in Fig. 1, together with insets showing the three initial azimuthal wind profiles and the position differences from the control experiment. We can see that the substantial intensity change made almost no trajectory difference. But the modest size/strength change caused the larger vortex to move westward and poleward faster than the reference vortex. The increase in westward motion arose from the stronger beta effect on a larger effective radius. The extra poleward motion arose from a stronger (in absolute terms) outer region distortion and thus, generation of a meridional steering current.

Throughout our discussion of this theory we have neglected evolving nonlinear interactions together with the transient geostrophic adjustment aspects. Indeed, in using the vorticity equation approach we implicitly assume an instantaneous 100% adjustment of the mass to the wind fields. However, Schubert and Hack (1982) and Schubert (personal communications, 1981, 1982) have shown that the decreasing Rossby radius of deformation (a ratio of the speed of gravity waves to the system vorticity which indicates the degree of partitioning of perturbations to inertial and gravity wave modes) in mature hurricanes considerably reduces the efficiency of mass adjustment to wind field changes. For a barotropic vortex on a uniform basic current, with no beta effect, the mass and wind field move together with no adjustment requirements. But nonlinear effects, such as the westward beta drift or induced current asymmetries, involve wind field accelerations and subsequent mass adjustments (or vice versa).

Intuitively, the imperfect adjustments, with some energy being lost to gravity waves, should reduce the nonlinear effects. Tropical cyclones also typically move along steady trajectories with no evidence of large evolving nonlinear effects (note the trajectories in Fig. 1). But on occasions, such as during a change in environment, further couplings or feedbacks could conceivably cause larger changes. Any complete understanding of cyclone motion must include an assessment of these adjustment effects. However, such work is beyond the scope of our present theory and we simply presume a perfect adjustment and linear response throughout.

Surface friction also provides a small, but consistent asymmetric effect on tropical cyclone motion. This is because the frictional dissipation is proportional to the

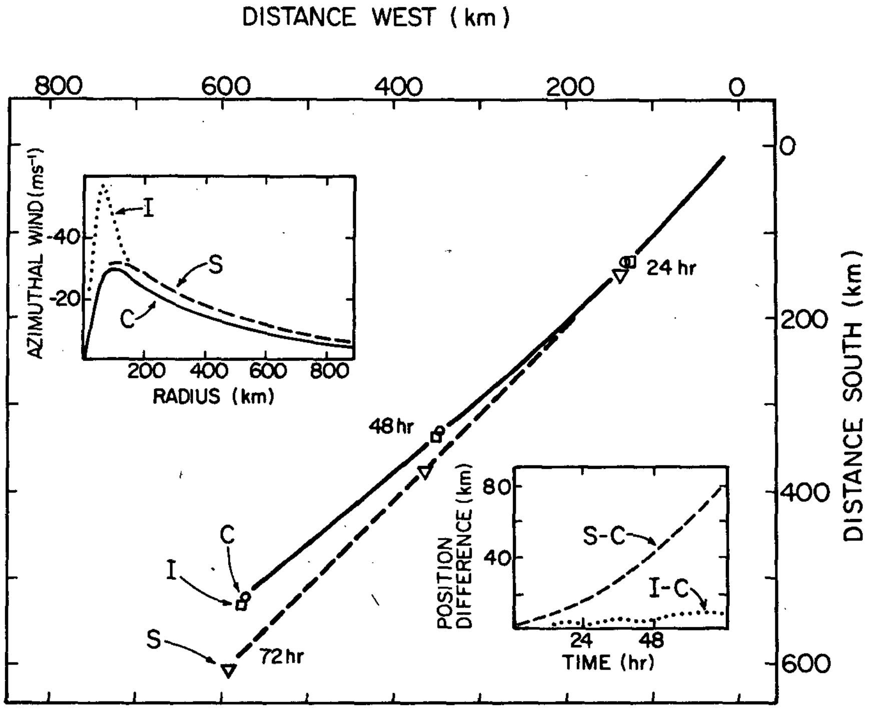

FIG. 1. Beta-plane trajectories for a control experiment (C), an intensity change experiment (I) and a size/strength change experiment (S). Insets show the initial azimuthal wind profiles and the position separation with time (M. DeMaria, personal communication, 1982).

wind speed squared. Thus, the addition of a symmetric cyclone and a uniform basic current in the Southern Hemisphere will produce a disproportionate increase in dissipation on the left-hand side (looking downstream). Numerical, f-plane model experiments (Jones, 1977) indicate that this will cause the Southern Hemisphere cyclone to move a few degrees (~5°) to the left of the basic current.

We do not explicitly incorporate this surface frictional effect in our analytic theory. However, it is likely that the induced motion deviation actually results from a modification of the basic current. Then, Eqs. (1) and (2) would implicitly contain the effects of surface friction. In any case, the deviation is quite small and is within the noise level of our data and our inability to precisely determine an effective radius. Thus, its neglect should have little impact on our discussion or conclusions.

3. Data and data reduction

The major problem with observations of tropical cyclone motion lies in determining the actual flow field from the normally very sparse observations. To overcome this problem, we have stratified a number of cyclones into specific motion classes and composited them to obtain a well-defined analysis of the mean flow fields for each type.

A complete description of the database and the compositing technique is contained in Chapters 2 and 3 of Hb. In essence, the data consist of all tropical cyclones and obtainable rawindsonde observations from the Australian–southwest Pacific region from 1959–79. After a stratification has been made, the compositing routines determine the position of each observation within a 15° latitude radius domain relative to the cyclone center. A cylindrical grid-point array is then derived with eight radials, 18 pressure levels and a nested radial grid of 1° latitude resolution inside 6° latitude and 2° outside. Specific statistical and climatological techniques are employed to denote biased or unrepresentative observations so that very narrow stratifications may be achieved.

The latitude and motion of each composite cyclone is simply the mean of all cyclones which comprise it; the basic current is derived by extracting a symmetric azimuthal and radial wind component from each grid point and the cyclone–motion deviations from this basic current are normally estimated by separately compositing the wind components parallel and normal to the cyclone direction of motion.

We shall use five steadily moving tropical cyclone composites AUS12 to AUS16, together with three recurving hurricane composites AUS01 to AUS03, to compare the observed cyclone motions under different basic currents with those predicted by the theory. The AUS12 to AUS16 steady moving stratifications were derived from Australian–southwest Pacific region cyclones with central pressure less than 1000 mb and which moved with speeds less than 7.5 m s^{-1}. Further, AUS15 and AUS16 contain all tropical cyclones which moved continuously towards the west, of which those moving between northwest and southwest comprise AUS16 and those moving between west and south comprise AUS15; AUS12 contains all cyclones moving continuously between southwest and southeast; AUS13 and AUS14 contain all cyclones which moved continuously eastward, of which those moving between south and east comprise AUS13 and those moving between southeast and northeast comprise AUS14. The speed and direction distributions of the cyclones in each of these composite categories are shown in Fig. 2.

Since our theory and the numerical modeling work discussed in Section 2 indicated that intensity or intensity change (defined by maximum wind speed) have no significant effect on motion, no account was taken of intensity in AUS12 to AUS16 (aside from removing the early tropical depression stages). One concern is that we have also not taken account of size (or outer circulation) changes in these composites. We have previously shown that size changes may alter the beta effect component of cyclone motion; however, the present lack of information on tropical cyclone size in the Australian–southwest Pacific region does not allow us to quantify these effects at this stage.

Our recurving hurricane composites consist of a homogeneous stratification of three successive stages of all recurving major hurricanes in the Australian region. These major hurricanes attained a minimum central pressure of less than 960 mb at, or just before, recurvature. The three stages then include: AUS01, all observations from the intensifying, southwestward moving tropical storm stage; AUS02, the intensifying hurricane stage (central pressure less than 980 mb) at, or before recurvature; and AUS03, the decaying hurricane stage after recurvature.

Since these three composites all contain the same cyclones at different stages, they should provide a good approximation of the mean characteristics of a single recurving cyclone. From our discussion in Section 2, the intensity variations should have no motion effect.

4. A comparison of theory and observations

a. *On determining a basic current*

Before a comparison of theory and observations can be made, we must address the question of what horizontal and vertical domain should be used in determining the basic current.

In the horizontal, a basic current defined by the wind field over a radial band centered on the effective radius, say 200–300 km, would be ideal, since we have shown that this is the region in which the cyclone interacts with the environment to produce an overall motion. But there are normally very few observations in this region, even in composite systems. Fortunately, however, the variations in basic current are generally linear to a first approximation out to 5 or 6° latitude radius (Hb; Shapiro and Neumann, 1984). Hence, we shall use the wind field averaged over a 5–7° latitude radius band. This is consistent with the work of Chan and Gray (1982). It also ensures sufficient observations for an accurate determination of the wind asymmetries, which should be relatively independent of the choice of mean vortex. When applying the model in Eqs. (1) and (2), we then linearly interpolate to the effective radius.

In the vertical, two parameters need to be considered: the vertical structure of the mean vortex and the vertical shear of the basic current. As we have shown in Hb, the low, middle or upper level gradients of azimuthal mean vorticity are very similar over the entire cyclone domain. Thus, the vorticity advection by a vertically uniform basic current will cause little, if any, tilting of the cyclone. A moderate vertical shear in the basic current may therefore be compensated by cumulus transports (cf, Lee, 1982). Since the radial gradient of vorticity is nearly uniform with height, the cyclone should then move with the mass-weighted vertical average of the basic current. However, if the vertical wind shear becomes too large, the convection can no longer "integrate" to remove the motion differential and the cyclone will be destroyed. Huntley and Diercks (1981) show some interesting examples of this tilting effect. They observed that weak tropical cyclones, with little convection near the center, generally tilt in the direction of the vertical wind shear and toward the major convective region. Such a tilt can exceed 100 km between the surface and 700 mb. As the cyclones intensify and convection becomes well established around the center, the tilt tends to disappear.

Unfortunately, we cannot directly incorporate the data-rich boundary and outflow layers into this vertically integrated estimate of the basic current. This is because the asymmetric inflow–outflow jets can significantly distort the basic current evaluations (cf. Hb; George and Gray, 1976). The effect of these jets on the cyclone motion has not been quantitatively determined, but it is our opinion that they contribute very little to the motion and their inclusion would merely introduce unwanted noise. The orientation and strength of the inflow or outflow jets are determined by boundary layer interactions with the moving cyclone (Shapiro, 1983), the distribution of convection and, as we have discussed in Hb, the surrounding environmental flow patterns which orientate and enhance the outflow channels. It is therefore possible that techniques could be derived to remove these asymmetries and allow better use of the boundary and outflow layers. However, at this stage we shall simply neglect these layers and use a mass-weighted 800–300 mb average to define the basic current.

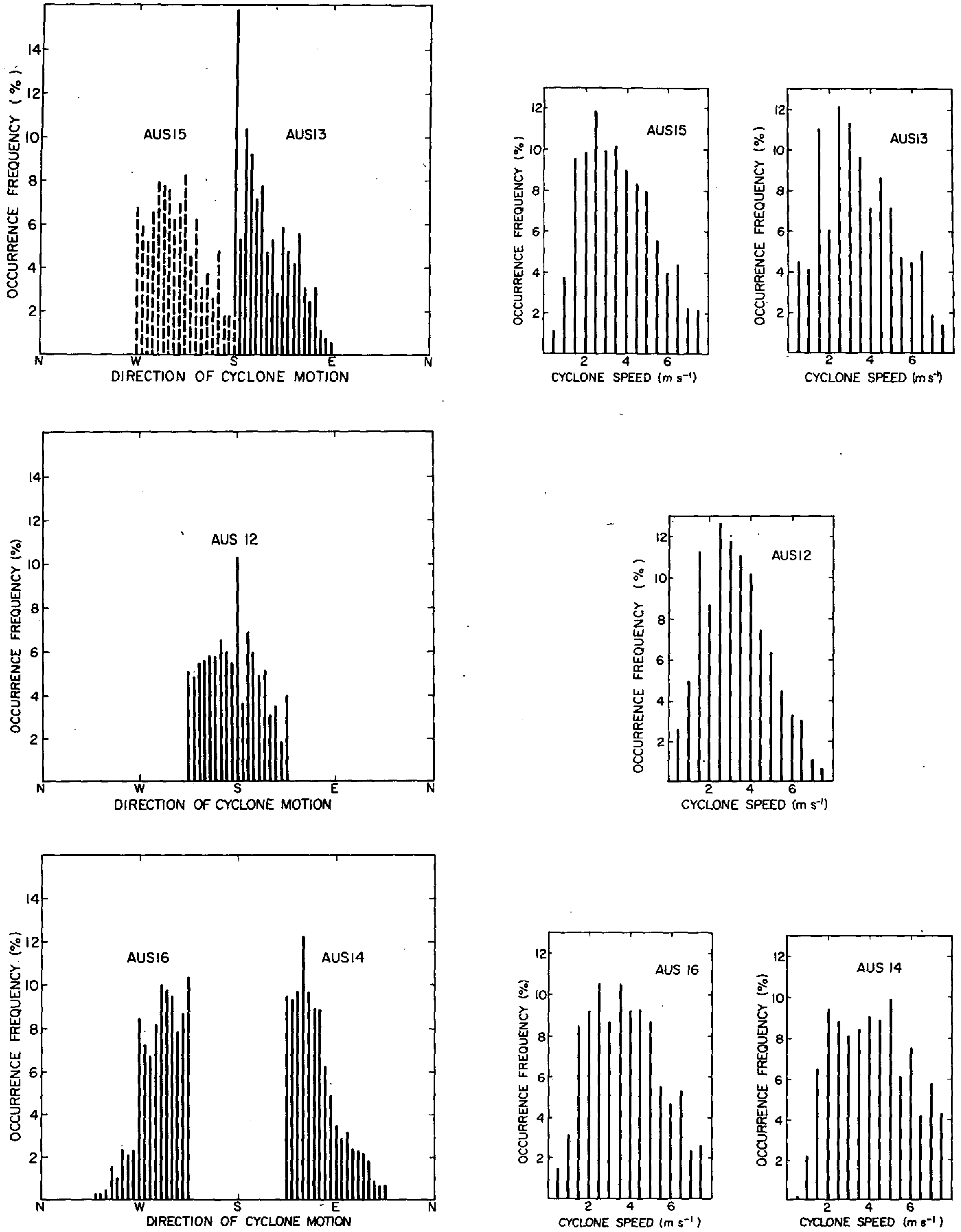

FIG. 2. Direction and speed distributions of the cyclones that comprise the AUS12 to AUS16 steadily moving cyclone composites.

b. *Steadily moving cyclone observations*

Table 1a contains the mean basic current and cyclone parameters for these motion composites, together with observed and predicted composite cyclone deviations from the basic current. Note that the observed deviations are calculated from the separately composited V_P and V_N components, hence they may differ slightly from an algebraic subtraction of the cyclone and basic current velocities. For the predicted deviations in Table 1a we used the mean latitude of each cyclone and constant cyclone parameters of $\gamma = -0.03$, $x = 0.05$, effective radius of 250 km and cyclone size and strength defined by a 6 m s^{-1} cyclonic azimuthal wind at 6° latitude radius. We also provide a comparison between the motion predicted by the azimuthally averaged basic current and beta effect alone (column A) and that predicted by the complete current including asymmetries (column B). These asymmetries may be seen in Fig. 3.

We can, of course, produce an exact agreement between observations and theory by modifying the above parameters and/or selecting the appropriate effective radius for each case. [An examination of the sensitivity of Eqs. (1) and (2) to parameter variations may be found in Ha and Hb.] However, as may be seen in Table 1a, simply using a standard cyclone introduces very few errors. In fact, the excellent agreement indicates that the major mechanisms responsible for moving these steady cyclones are contained in Eqs. (1) and (2). The dominant mechanisms are the advection of cyclone vorticity by the basic current and the beta effect which causes a west-southwestward deviation from the basic current advection. Notice how the beta effect causes the westward moving cyclones to move slightly to the right and faster than the basic current; by comparison, eastward moving cyclones have a larger angular deviation and move more slowly. For these steady moving cyclones including the basic current, asymmetries (Fig. 3 and column B of Table 1) produced only a slight improvement, if any, in accuracy.

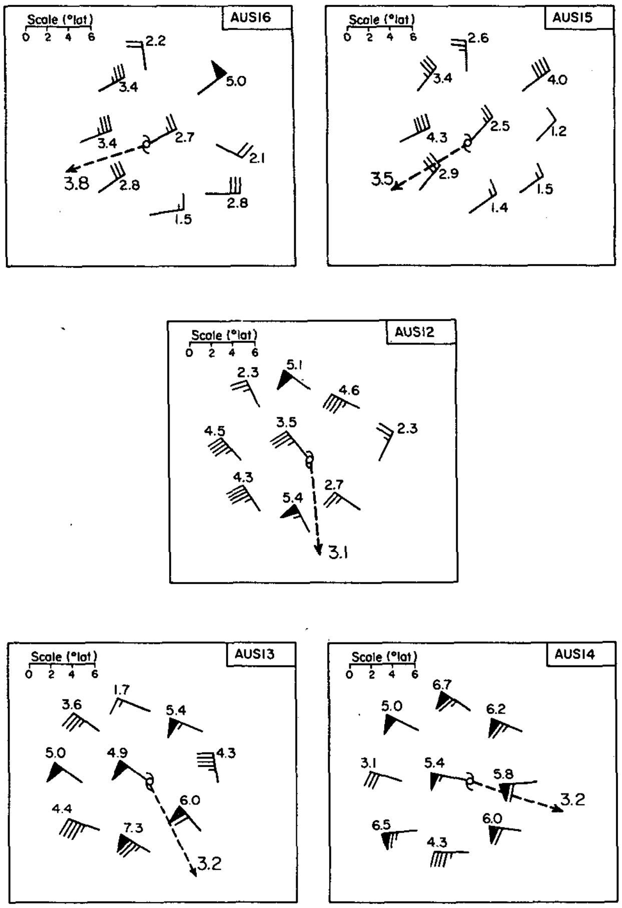

FIG. 3. Basic currents and cyclone motion for the AUS12 to AUS16 composite cyclones. Each inset contains the 800–300 mb mass-weighted mean current at eight octants and a nominal radius of 6° latitude; the azimuthally averaged basic current is shown at the cyclone center; and the direction of cyclone motion is indicated by the dashed arrow. Speed convention is one barb = 1 m s^{-1} and actual speeds are also shown.

c. Recurving hurricane observations

Table 1b contains the observations and model predictions for these composite tropical cyclones. The details are the same as for Table 1(a) (except that no V_P and V_N components were available) and the standard cyclone was used in deriving the predicted motions. Fig. 4 also shows the basic current asymmetries associated with each cyclone.

The model predictions were again in good agreement with observations, though the accuracy was degraded at and after recurvature. This reduced accuracy may be partially due to the increased scatter in cyclone directions at recurvature. However, we believe it is largely due to the inability of our simple model to adequately incorporate the complex horizontal and vertical basic current asymmetries, the effects of asymmetric fields of convection and possible nonlinear interactions during the changing environment. For example, the basic current over AUS03 has a strong vertical wind shear. Such decaying recurved hurricanes also typically develop a highly asymmetric field of moist convection; convective activity is suppressed to the west and enhanced to the east and southeast (cf. Hb or Lajoie, 1976). Since such convective activity is necessary to "vertically integrate" (Section 2) the basic current shear, these convective asymmetries may give additional weight to the current in the eastern semicircle. Alternatively, the mid-to-upper cyclone may be sheared off and leave a shallow, convection free disturbance moving under the influence of the low level environmental flow.

Nevertheless, these recurving hurricane composites show the importance that the beta effect and basic current asymmetries can have. The southwestward moving tropical storm (AUS01) moves essentially under a uniform current and beta effect. It thus deviates slightly to the right of, and moves faster than, this basic current. At the AUS02 hurricane stage, the basic current has backed to a northwesterly, increased in speed and developed some horizontal asymmetries. But the beta effect holds the cyclone on a south-southwestward course with virtually no increase in speed. We can see from Table 1(b) that a 68° and 0.8 m s^{-1} change in

TABLE 1. Vital statistics on (a) the AUS12 to 16; and (b) AUS01 to 03 motion composites. The table gives: the 800–300 mb mean direction (α) and speed (V_B) of the basic current and its components parallel (V_P) and normal (V_N) to the direction of cyclone motion; the 800–300 mb mean radial wind (u), azimuthal wind (v) and convergence (γ) into the cyclone at 6° latitude radius; the mean direction (θ_m) and speed (V_c) of the cyclone; and the observed and predicted deviations of the cyclone from the basic current. Column A lists the predicted deviations using the mean basic current only, column B incorporates the basic current asymmetries shown in Figs. 3 and 4.

Composite	Latitude (°S)	Basic current				Cyclone					Direction deviation			Speed deviation		
		α	V_B	V_P	V_N	u	v	γ	θ_m	V_c	Observed	A	B	Observed	A	B
(a)																
AUS16 Westward	16.2	117	2.7	2.7	−0.2	−0.2	−6.1	−0.03	108	3.8	−4	−9	−9	1.3	1.5	1.5
AUS15 Southwestward	16.7	137	2.5	2.7	−0.9	−0.2	−6.3	−0.03	121	3.5	−18	−18	−19	1.1	1.0	1.4
AUS12 Southward	19.1	220	3.5	3.0	−1.9	−0.4	−5.4	−0.07	175	3.1	−32	−29	−33	−0.5	−0.9	−0.8
AUS13 Southeastward	19.7	233	4.9	4.7	−2.0	−0.2	−5.0	−0.04	208	3.2	−23	−16	−20	−1.1	−1.3	−1.4
AUS14 Eastward	17.5	257	5.4	5.3	−0.3	−0.2	−4.3	−0.05	252	3.9	−3	−6	−3	−1.2	−1.7	−1.7
(b)																
AUS01 TS before recurvature	15.2	135	2.4	*	*	−0.2	−6.0	−0.03	123	3.5	−13	−7	−15	1.1	1.0	1.3
AUS02 Hurricane near recurvature	17.3	193	3.2	*	*	−0.2	−5.7	−0.04	167	3.7	−26	−32	−12	0.5	0.0	0.2
AUS03 Hurricane after recurvature	22.5	200	5.5	*	*	−0.1	−5.1	−0.02	202	5.0	−2	−26	−14	−0.5	−0.5	−0.6

the mean basic current produced only a 44° and 0.2 m s^{-1} change in cyclone velocity. As the AUS03 composite shows, recurvature is then accomplished by an increase in basic current speed and development of asymmetries, but with almost no direction change. A 7° and 2.3 m s^{-1} change in the mean basic current, combined with the development of downstream divergence and confluence (and possible convective asymmetries), produced a 35° and 1.3 m s^{-1} change in cyclone velocity.

These results indicate that an adequate understanding and accurate prediction of recurvature requires an explicit inclusion of the beta effect together with basic current asymmetries.

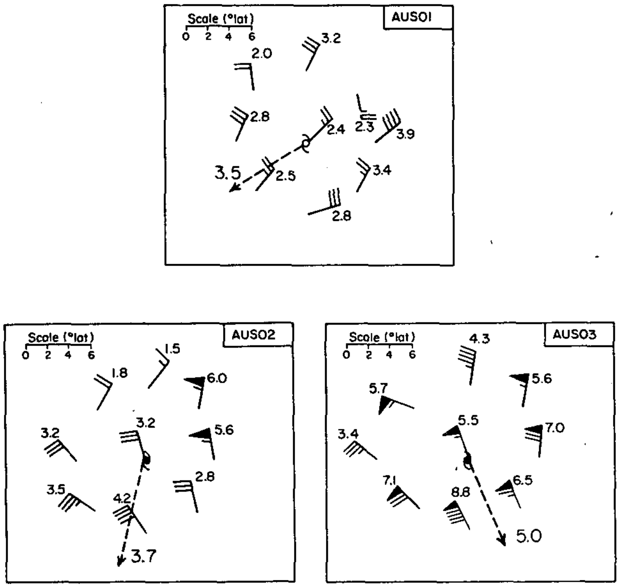

FIG. 4. Basic currents and cyclone motion for the AUS01 to AUS03 recurving hurricane composites. Each inset contains the 800–300 mb mass-weighted mean current at eight octants and a nominal radius of 6° latitude; the azimuthally averaged basic current is shown at the cyclone center and the direction of cyclone motion is indicated by the dashed arrow. Speed convention is one barb = 1 m s^{-1} and actual speeds are also shown.

5. Conclusions

We have demonstrated that there is a very close agreement between the vortex motion predicted by the linear analytic equations derived by Holland (1983a) and observations from composite steadily moving and recurving tropical cyclones. This close agreement supports our previous conclusions that cyclone motion is largely a linear response to environmental interactions in an envelope approximately 200–300 km from the center. The dominant mechanisms are an advection of the symmetric cyclone by the basic current (including asymmetries) and a beta effect which causes a westward deviation from the basic current direction. We have also shown that basic current asymmetries may, on occasion, be very important; in the recurving hurricane composite, recurvature seems to have been accomplished by the development of such asymmetries with no change in basic current direction.

We must emphasize that these are only "snapshot" results. Over long time periods, slowly evolving nonlinear interactions may substantially alter both the basic current and the tropical cyclone's reaction to it. Indeed, some erratically moving cyclones may be responding to large transient nonlinear processes, though we have demonstrated in Ha that at least some erratic behavior can be explained by the above linear processes.

Substantial questions thus remain on the types of situations in which basic current asymmetries and/or uncompensated nonlinear interactions become important and on the mechanisms whereby the central region follows the effective radius envelope. These are the topics of ongoing research.

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REFERENCES

Anthes, R. A., 1982: *Tropical cyclones: Their Evolution, Structure, and Effects. Meteor. Monogr.*, No. 41, Amer. Meteor. Soc., 208 pp.

Chan, J. C. L., and W. M. Gray, 1982: Tropical cyclone movement and surrounding flow relationships. *Mon. Wea. Rev.*, **110**, 1354–1374.

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

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, 260 pp.

Huntley, J. E., and J. W. Diercks, 1981: The occurrence of vertical tilt in tropical cyclones. *Mon. Wea. Rev.*, **109**, 1689–1700.

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

Lajoie, F. A., 1976: On the direction of movement of tropical cyclones. *Aust. Meteor. Mag.*, **24**, 95–104.

Lee, C. S., 1982: Cumulus momentum transports in tropical cyclones. Atmos. Sci. Paper No. 341, Colorado State University, 78 pp.

Schubert, W. H., and J. J. Hack, 1982: Inertial stability and tropical cyclone development. *J. Atmos. Sci.*, **39**, 1687–1697.

Shapiro, L. J., 1983: The asymmetric boundary layer flow under a translating hurricane. *J. Atmos. Sci.*, **40**, 1984–1998.

——, and C. J. Neumann, 1984: On the structure and orientation of grid systems for the statistical prediction of tropical cyclopne motion. *Mon. Wea. Rev.*, **112**, 188–199.