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Dynamics in Tropical Cyclone Motion: A Review

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The complexity of tropical cyclone (TC) motion results from a wide variety of external and internal dynamical forcings and their interaction. A particularly intricate interaction is among the large–scale environmental flow, the axially symmetric circulation of the TC, and the planetary vorticity (or ambient potential vorticity) gradient, which generates a secondary asymmetric flow (beta gyre circulation) that alters TC movement. Over the last decade, it has become clear that a primary source of the discrepancy between large–scale steering and the TC movement is associated with this complex interaction and the resulting track deflection relative to the environmental flow, which is referred to as propagation. This paper summarizes some of the physical processes that determine the asymmetric gyre dynamics and propagation. Impacts of the vortex structure and environmental horizontal and vertical shears on propagation are a major theme. In addition, the processes involved in the binary cyclone interaction, trochoidal motion, and the lower boundary forcing are reviewed. Applications of these new theoretical concepts to TC track forecasting and a prospectus for future research are also discussed.

Key words: tropical cyclone motion; β–gyres; β–drift.

1. INTRODUCTION

Over the global tropics, about 80 tropical cyclones (TCs) reach tropical storm intensity each year. The climatological TC tracks exhibit prominent geographic, latitudinal, seasonal, and interannual variations[1]. The variability in TC tracks on various time scales is sufficiently large to have tremendous social impacts. Therefore, improvement of TC track prediction has been the highest priority since the birth of the tropical weather forecast.

The dynamics determining various forms of TC motion (straight and curved translation, meandering, trochoidal, looping, and other irregular tracks) is complex. The causes of TC motion may be classified into three categories: external, internal, and interactive. The external forcing includes the most consequential "steering" effect of large–scale environmental flows, the influence from adjacently tropical cyclones or other circulation systems, and lower boundary conditions: surface friction, topography, and the buoyancy fluxes from the upper ocean. Examples of the internal dynamic factors include convective asymmetry, mesoscale systems, the vertical coupling of upper– and lower–level vortex circulations, and the outflow layer instability. Among the interactive dynamics, the most fundamental process is the interaction between the TC primary (axially symmetric) circulation and the planetary vorticity gradient (the beta effect). This interaction creates an axially asymmetric circulation that has a secondary steering effect on the primary vortex. The asymmetric circulation is thus an essential element of the interactive dynamics. The beta effect–symmetric vortex interaction can be further complicated by other types of environmental forcing, such as the presence of horizontal and vertical shears in the environmental flow, the vertical coupling due to diabatic heating and convective momentum transports, and air–sea interaction, etc.

In the last decade, tremendous progress has been made in the understanding of the dynamics of tropical cyclone motion. A comprehensive review on TC motion is presented by Elsberry[1] who summarized, in great length, the progress in observational, theoretical, and numerical studies of TC motion and track prediction. This review focuses primarily on the advances achieved during the last decade in theoretical understanding of the physical mechanisms governing TC motion. Critical issues that call for further investigation will also be discussed.

The two fundamental concepts of translation: environmental steering and beta drift are discussed first (Section 2). Although the steering is a primary driving force, the theoretical understanding of it is trivial. The beta drift is a smaller but critical deviation from the steering and involves challenging problems of nonlinear dynamics. For this reason, a large portion of the review is devoted to the dynamics of the propagation. Section 3 discusses fundamental causes of the beta drift in a quiescent environment. Sections 4 and 5 address impacts on propagation of horizontal and vertical variations of the environmental flows. Next, the causes of the irregular tracks are explored, especially the binary TC interaction (Section 6), trochoidal motion (Section 7), and the effects of lower boundary forcing on TC motion (Section 8). The last section presents a brief summary and stresses issues that need to be resolved.

2. ENVIRONMENTAL STEERING AND BETA DRIFT

2.1 *Environmental Steering*

From the viewpoint of vorticity dynamics, the movement of TCs is primarily controlled by relative vorticity advection. The high value of positive relative vorticity in a TC is concentrated within a few hundred kilometer radius from the center. The vorticity associated with TCs is advected by the large–scale background circulation, as if a relatively small vortex is steered by the large–scale ambient flow.

In theory, the large–scale steering flow may be defined without ambiguity in idealized models. A barotropic symmetric vortex embedded in a uniform flow on an f–plane moves precisely with the uniform flow[2]. The steering flow in this ideal case is the uniformly ambient flow. In reality, TCs do not maintain perfect symmetry; the ambient flows also vary considerably with height and radial distance from the TC center, and the asymmetry varies with TC characteristics such as size, intensity, translation speed and direction[3,4]. It is not possible to unambigiously separate environmental steering flows from the TC circulation in observational studies. Therefore; the empirical relations between TC movement and surrounding large–scale environmental flows are necessarily dependent on the definition of the environmental flow. Even though no unique definition can be given, the following discussion may provide relevant background information for an " optimum" definition of the environmental steering flow.

Observational analyses indicate that a deep–layer mean (e.g., 1000 hPa to 150 hPa or 100 hPa) steering is better correlated with storm motion than any single level steering[5,6]. The reason is probably because the TC is a vertically coupled system moving as an entity. Since the boundary layer and the upper–most tropospheric layer have large divergence / convergence that induces a non–negligible contamination of the assessment of the vorticity advection[7], a vertical mean steering between 850 and 300 hPa may be an optimum choice[8]. The above statistical results did not distinguish strong and weak TCs. As demonstrated by numerical models, the optimum steering level increases with intensity[9,10], because a more intense cyclone normally has a deeper cyclonic circulation that must be steered by a deeper layer of environmental flow.

Using vertically averaged rawinsonde composite winds between 850–300 hPa, Gray[11] found that the steering flow averaged over inner radial bands produces a better agreement with the storm motion. Based on airborne Doppler radar data, Marks et al.[12], and Franklin et al.[13] concluded that the TC motion is best correlated with the depth–mean flow averaged over the inner–core region within 3° lat. from the center. Notice that the steering flows defined over the inner core include not only environmentally steering flow but also the secondary steering flow that is generated by internal dynamics and the interaction between the TC and external forcing. Since the latter is confined in the inner core region, it appears to be more appropriate to define the flow averaged over the 5–7°lat. radial band as the environmental steering flow.

2.2 *Beta Drift*

Based on the composite rawinsonde studies of Chan and Gray [3] and Holland[8], Carr and Elsberry[14] displayed the difference vector of cyclone motion minus the depth–mean (850–300 hPa) steering flow averaged over the 5–7° lat. bands as functions of latitude, translation direction and speed, and intensity of TCs (Fig. 1). They found two interesting charac-

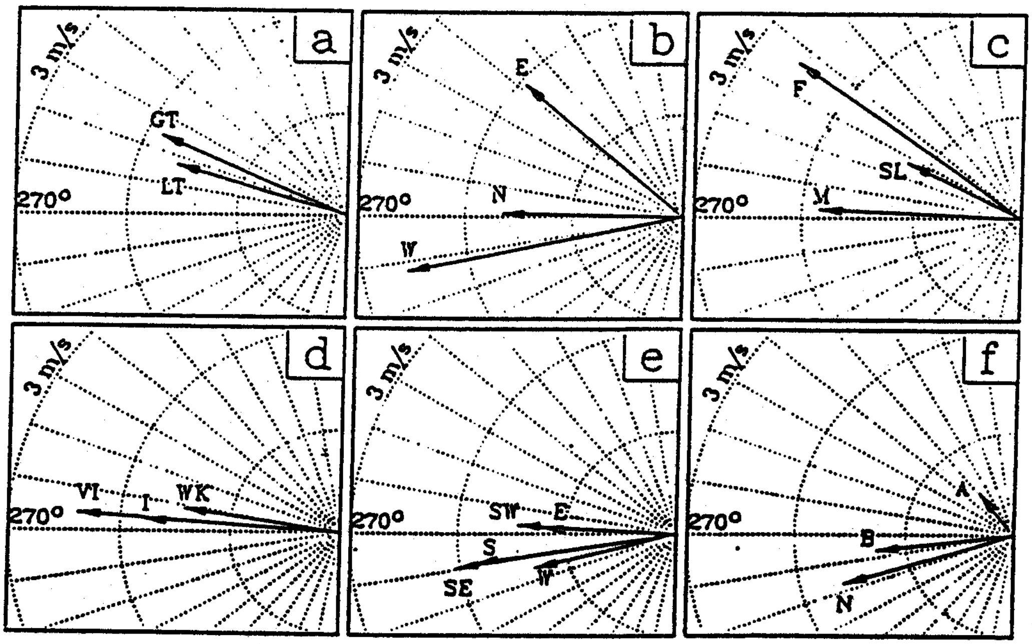

FIGURE 1. Vector differences of tropical cyclone motion minus composite steering for the (a) latitude relative to 20°N, (b) direction, (c) translation speed, and (d) intensity stratification of Chan and Gray (1982), and (e) direction and (f) recurvature stratification of Holland (1984) after conversion to a geographical coordinate system by Carr and Elsberry (1990).

teristics of the non–steering component of TC motion: (i) It is generally westward and poleward in each hemisphere with magnitudes ranging from 1–3 m / s; and (ii) Its speed tends to increase with latitude and the TC intensity.

The significantly non–steering component of the TC translation was termed propagation by Holland[15]. Since the propagation accounts for a large portion of the observed deviation of TC motion from environmental steering, especially when the ambient steering current is weak, study of the propagation has been of great interest in the last decade. These studies have also provided fundamental understanding of the interaction between the nonlinear vortex dynamics and the environmental forcing.

An example of TC propagation was first conceptualized by Rossby[16], who examined the motion of an isolated rigid–body–rotation vortex in a resting environment on a beta–plane. Such a movement is now commonly referred to as beta drift. Adem[17] first obtained a correct approximate solution for the beta drift by solving the nondivergent, barotropic vorticity equation. Due to the variation of the Coriolis parameter, the cyclone embedded in a resting atmosphere moves westward and poleward.

What factors determine the beta drift speed? In a resting environment, the beta drift of a barotropic vortex depends on the vortex structure and the Earth rotation (or latitude) and its meridional variation (the beta effect). DeMaria[18] found that the vortex track is much more sensitive to changes in the outer region (size change) than to changes in the inner region (intensity). This was confirmed by Fiorino and Elsberry's[19,20] numerical experiments. For quasi–steady beta drift, Wang and Li[21] showed that for a family of isolated vortices with positive angular momentum, both the beta–drift speed and its meridional component are approximately proportional to the square root of the magnitude of TRAM (total relative angular momentum) of the initial (or quasi–steady state) symmetric circulation. Since the TRAM is largely determined by the outer circulation of the vortex, this assertion agrees with the DeMaria[18] and Fiorino and Elsberry[19] findings. It should be pointed out that the beta drift is not necessarily quasi–steady. Depending on the vortex structure, the beta drift may have a variety of tracks ranging from a quasi–steady displacement to a wobbling or a cycloidal track[22]. During a non–steady drift, the TRAM within a large circle centered on the vortex would decrease with time owing to Rossby wave dispersion, and thus the subsequent motion of the vortex could not be related to the initial TRAM in any simple way[23].

When the Coriolis parameter is constant, the beta drift speed was suggested to be proportional to beta[24]. However, applying the principle of dimensional analysis to the numerical results of Chan and Williams, Smith[25] showed dependence of beta drift speed on beta3 / 2. In a three–dimensional model, the meridional beta drift displacement decreases by about 45% when the latitude of the vortex increases from 10°N to 30°N, which implies that a cyclone in low latitudes has a tendency to drift poleward more rapidly[21]. This cannot be explained by change of beta with latitude, because from 10°N to 30°N the beta parameter reduces only by about 11%. For a baroclinic vortex; the beta drift is also related to vertical potential vorticity penetration depth, which is a function of the Coriolis parameter and environmental stratification[26].

3. CAUSES OF THE BETA DRIFT: BETA–GYRE DYNAMICS

What processes cause a TC to drift westward and poleward without environmental steering? A numerical study by Fiorino and Elsberry[19] documented a close association between the beta drift and the asymmetric circulation, which is dominated by an azimuthal wavenumber–one component that is associated with a pair of counter–rotating gyres (termed beta gyres) with the cyclonic to the southwest and anticyclonic to the northeast in the Northern Hemisphere (Fig. 2). The near–uniform asymmetric flow between the two gyres across the vortex center was designated the "ventilation flow", which determines TC drift. This important finding has been confirmed by numerous experiments and theoretical studies with a variety of models[21,27–30]. The beta drift results from advection of symmetric vortex by the beta–induced secondary steering flow — ventilation flow — over the core region of the cyclone.

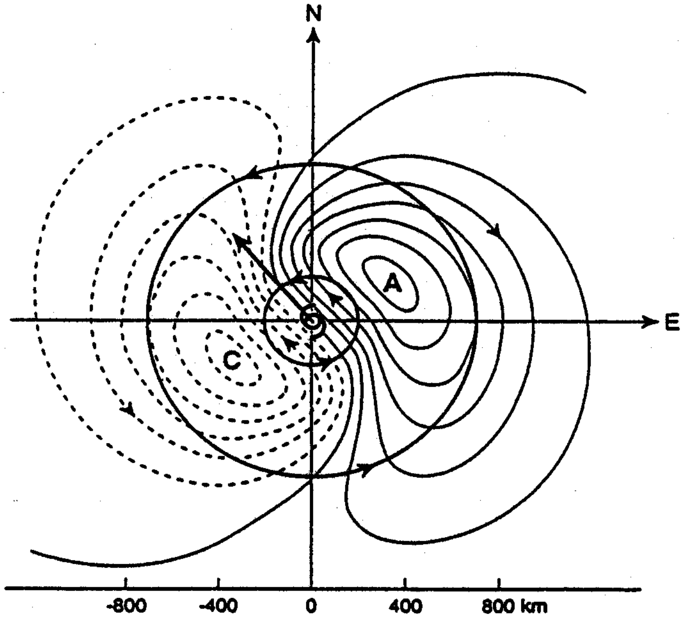

FIGURE 2. Asymmetric streamfunction depicting the beta gyres of a barotropic cyclone vortex averaged over a 48–hour period from 24 h to 72 h in a beta–plane shallow water model (contour interval 10^5 m^2/s). The corresponding beta–drift velocity is shown by the arrow between two gyres designated by "A" and "C".

A key to understanding the beta drift is to comprehend the dynamics of the beta gyres. A basic question that must be addressed is how are the beta gyres formed and maintained in a quasi–steady drift? As argued by Holland[15], the initial formation of the asymmetric gyres is owing to differential meridional advection of planetary vorticity by symmetric azimuthal winds that produces negative and positive vorticity tendencies east and west of the cyclonic vortex. These initially zonally oriented gyres can also be considered as a result of vortex deformation due to Rossby wave dispersion[24]. Without nonlinearity, the linear distortion cannot make the vortex move.

From the standpoint of vorticity balance, the vorticity associated with the beta gyres is maintained by a balance of three major advective processes[19]: (i) differential meridional advection of planetary vorticity that constantly generates zonally–oriented anticyclonic and cyclonic gyres east and west of the vortex center; (ii) advection of asymmetric vorticity by the primary vortex circulation that rotates the gyres cyclonically, and creates poleward and westward asymmetric ventilation flow over the vortex center; and (iii) advection of the symmetric vortex by ventilation flow (poleward and westward drift of the primary vortex) that balances the generation and rotation of asymmetric vorticity anomalies.

The development and maintenance of the beta gyres can also be understood from energetics considerations. Li and Wang[22] demonstrated that the beta gyres can be intensified by extracting kinetic energy from the primary symmetric vortex circulation. This energy conversion involves two processes. The first process depends on beta effect, and the transfer of energy to beta gyres requires the anticyclonic gyre be located to the east of the TC center; and the rate of conversion depends on the covariance between the beta gyres and the relative angular momentum (RAM) of the isolated primary vortex. As the total RAM of the vortex increases, the generation of gyre kinetic energy strengthens, which results in stronger beta gyres and a faster beta drift. This explains the relationship between the outer vortex structure (or total RAM) and the beta drift speed found in numerical experiments. The second process is related to nonlinear advection, which creates or destroys beta gyre kinetic energy depending on the radial variation of the phase of asymmetric circulation, while the rate of energy exchange is proportional to the inward eddy momentum flux and the angular wind shear of the primary vortex[31].

In a quasi–steady beta drift, the near–uniformity of the secondary steering (ventilation) flow implies that the core region of the primary vortex is advected at the same speed, so that the vortex maintains integrity. This is a result of dynamical stabilization of the vortex core and homogenization of the asymmetric absolute vorticity within the vortex core. The inertial stability parameter within 200–300 km of an axially symmetric vortex is typically one or two orders of magnitude greater than f^2[15]. The radial variation of the symmetric circulation may stretch the asymmetric perturbation by differential advection, and thus weaken the asymmetric circulation and homogenize the asymmetric absolute vorticity[23,31].

4. EFFECTS OF HORIZONTAL ENVIRONMENTAL SHEARS ON BETA DRIFT

When the environmental flow varies with time and space, the ambient flow not only provides a steering effect, but also interacts with the vortex circulation by modifying the beta gyres, which thus affects propagation. The discussion here will be confined to the impacts of horizontal variations of a steady environmental flow on the beta drift.

4.1 *Ambient Relative Vorticity Gradient*

Since the ambient relative vorticity gradient may induce vortex drift similar to that induced by the beta effect, the beta drift was thought to be related to environmental absolute vorticity gradient[18,32]. However, Smith and Ulrich[33] demonstrate that the poleward displacement of the cyclonic vortex on an f–plane caused by ambient relative vorticity gradient is much smaller than that induced by an equivalent planetary vorticity gradient on a beta plane without an environmental flow. Wang and Li[34] showed that an ambient relative vorticity gradient affects the strength of beta gyres by both directly changing the energy conversion rate from the primary vortex to the gyres and by indirectly changing the energy conversion from environmental flow to the primary vortex. The two processes have opposing effects. On the one hand, a poleward relative vorticity gradient makes the beta gyres stronger and the drift faster by enhancing the planetary vorticity gradient (increasing effective beta). On the other hand, it can distort the primary vortex. A poleward relative vorticity gradient can make the vortex more anticyclonic in the outer regions[35], which would in turn tend to decrease the amplitude of the beta gyres and reduce the drift speed.

4.2 *Linear Shear Environment*

Horizontally varying ambient flows can affect beta drift even without a relative vorticity gradient. In fact, linear shears of the environmental flow appear to have more influence on the beta drift. In a linear zonal flow with cyclonic shear, the beta drift is slightly slower, whereas it is considerably faster in an anticyclonic shear than the drift in a resting environment[35–37]. Li and Wang[38] found that in a linear meridional flow with a cyclonic (anticyclonic) shear, the beta drift is faster (slower) than in a resting environment. This suggests that the beta–drift speed does not depend only on the relative vorticity sign of the shear. Rather, they found that the beta drift depends on environmental shear strain rate, $\partial V / \partial x + \partial U / \partial y$: It is faster (slower) for a positive (negative) shear strain rate. This is because the rate of kinetic energy conversion from the ambient flow to the beta gyres is proportional to the shear strain rate. Thus, the strength of the gyres, which control the magnitude of the secondary steering flow and the drift speed, is also determined by the ambient shear strain rate.

The environmental shears not only influence the beta–drift speed but also the drift angle. Whereas in a moderately sheared zonal flow (weak $\partial U / \partial y$) beta–drift direction does not change appreciably[35], but a larger $\partial U / \partial y$ can affect drift angle. More importantly, the longitudinal shear ($\partial V / \partial x$) is much more effective than meridional shear $\partial U / \partial y$ in deflecting the beta drift[39]. A cyclonic shear (either zonal or meridional or a combination of the two) turns the beta drift to the left in the Northern Hemisphere when facing the direction of the drift (further westward). An anticyclonic shear turns the beta drift further poleward. To interpret the above results, one may examine how the ambient shear affects the beta gyre orientation, which can be conveniently measured by the azimuthal phase angle of the beta gyre axis. The change in the gyre phase angle is expressed in terms of the tendency of beta–gyre vorticity. With a number of simplifications, Wang et al.[39] derived an approximate model describing the phase angle of quasi– steady state beta gyres. The theory predicts that the longitudinal environmental shear is considerably more effective than the meridional shear in changing the beta drift direction.

5. BAROCLINIC PROCESSES AFFECTING BETA DRIFT

5.1 *Baroclinic Forcing*

In nature, both the TCs and their environments are baroclinic. Considering the baroclinity in both the TC structure and environment introduces an array of problems. A number of prototype models have been proposed along this line to isolate specific mechanism(s) or process(es) to better understand the basic dynamics involved in baroclinic TC motion. These studies have identified the following major baroclinic forcings to TC motion: (i) vertically differential beta drift; (ii) ambient vertical shear; and (iii) convective heating. The vertically differential beta drift forcing arises from the beta effect or, in general, the ambient potential vorticity (PV) gradient and the vertical variation of TC circulation. Since the cyclonic circulation decreases with height, so do the beta gyres that gives rise to a vertical differential beta drift forcing[21]. The vertically differential PV gradient forcing and vertical shear are two major adiabatic baroclinic forcing effects on TC motion by deforming (tilt or shearing) a baroclinic vortex and inducing vertical interaction.

5.2 *Vertical Interaction*

Baroclinic forcing tends to vertically tilt or shear baroclinic cyclones. Once the vortex is tilted, the upper and lower circulations of the vortex may interact with each other. Wu and Emanuel[40] proposed that the upper–level negative PV anomalies (anticyclonic circulation) can have a significant impact on the motion of cyclonic vortex below. Using an idealized two–level quasi–geostrophic model and a contour dynamics approach, they showed that the ambient vertical shear first induces a vertical deformation of the vortex with a downshear displacement of the upper–level anticyclone (Fig. 3). In their two–layer model, the anticyclonic flow projects downward to the lower layer, which advects cyclonic vortex to the left of the vertical shear (a propagation component). Even without vertical shear, the vertical differential beta drift forcing can induce a tilt of the vortex with a southward and eastward displacement of upper-level anticyclonic anomalies in the Northern Hemisphere. In such a case, the downward penetration of the flow associated with upper-level negative PV anomaly would reduce the westward component of the beta drift of the cyclonic vortex below.

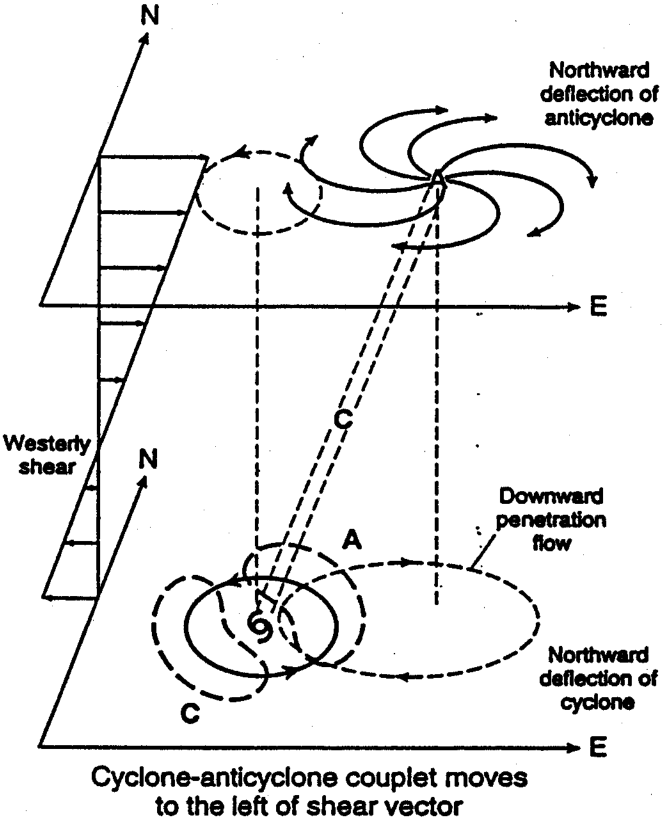

FIGURE 3. Schematic of potential interaction between an upper-level anticyclone and a low-level cyclone that are initially vertically oriented, but are then exposed to a westerly shear[1].

The vertical interaction may be conveniently visualized in terms of PV thinking. Given a specified background flow, an appropriate balance condition, and boundary conditions, a PV anomaly (deviation from the background flow) can be inverted to yield the corresponding 3-D wind distribution[41,42]. The winds associated with the PV anomalies at a particular level can extend horizontally and vertically. The latter extension is referred to as the vertical penetration flow. The circulations at different levels interact via penetration flows associated with the PV anomalies at different levels. The depth of the penetration flow depends on the strength and horizontal scale of the anomaly, the Coriolis parameter, and the ambient static stability[41,43]. It can be more than 10 km in a typical TC[44].

5.3 *Effect of Diabatic Heating*

The vertical differential beta drift or vertical shear will tend to destroy the vortex by vertical shearing. Diabatic heating and convective momentum transport maintain the vertically stacked baroclinic vortex structure through enhanced vertical coupling. The convective heating redistributes PV, and creates a PV sink in the upper part and a PV source in the lower part of the vortex. This tendency is largely compensated by the upward transport of high–PV air from lower to upper levels[45]. In this sense, the diabatic heating plays a critical role in establishing the vertical baroclinic structure so that the vertical interaction induced by baroclinic forcing becomes possible. On the other hand, it acts against the vertical tilt or shearing effects, and thus reduces the effects of the baroclinic forcing. The net result depends on the competition between the heating strength and the baroclinic forcing. When heating is strong and baroclinic forcing is weak (e.g., no vertical shear), the vortex tilt will be small. In that case, the penetration flow associated with upper–level anticyclonic PV anomalies primarily causes a rotation of the beta gyres associated with the cyclonic vortex, which results in a more poleward secondary steering flow over the low–level vortex core and increases the northward component of beta drift as demonstrated by Wang and Holland[46]. In the presence of both the earth vorticity gradient and the vertical shear, the processes are highly nonlinear[47,48].

The upper–level PV anomalies generated by diabatic heating are often strongly asymmetric. This asymmetry may occur due to the advection of the PV anomalies by the TC outflow and ambient flow[45] or by Rossby wave dispersion[46]. The latter forms a band of negative PV anomalies stretching from the vortex core to several hundred kilometers equatorward and westward. If downward penetration occurs, these PV anomalies might substantially affect the cyclonic vortex motion below. Wang and Holland[48] suggested that the presence of ambient vertical shear leads to a sloping absolute vorticity vector and thus to an asymmetric diabatic PV modification that could influence the motion.

The interaction between the heating and the symmetric circulation can also result in convective asymmetries that induce asymmetric divergent flow over the vortex core, which may affect vortex motion by deflecting the vortex toward the region of maximum convection[46]. Wang and Holland[48] suggested three possible mechanisms: the vortex–tube stretching arising from the relative flow crossing the high relative vorticity core in the lower troposphere and the boundary layer; the divergent circulation associated with the vertical tilt of the vortex; and the asymmetric heat fluxes from the ocean arising from the asymmetric boundary layer flow.

Since the development and structure of the upper–level anticyclone depend on the diabatic heating and the momentum transports associated with convection, different parameterizations of cumulus heating and momentum transports can result in variable strengths and extents of the upper–level anticyclones, which in turn result in different impacts on TC motion[49]. The change in motion in this case is related to changes in the intensity and structure of the TC.

5.4 *Diagnostic Studies*

Studies by Wu and Emanuel[50,51] and Wu and Kurihara[45] used a piecewise inversion technique to evaluate the influence of upper– and lower–level PV anomalies on the motion of several hurricanes[52,53]. An improved piecewise inversion technique was recently developed by Shapiro[54] and applied to Hurricane Gloria of 1985. Motivated by the weak asymmetries in the core of Gloria[43], his inversion technique is based on decomposition of the horizontal wind into symmetric (vortex) and asymmetric (environmental) components from which PV anomalies can be better defined. Because the nonlinear terms in the PV and balance equation were found to be small, a linear decomposition was made. Thus, the *ad hoc* nature of the previous piecewise decomposition is avoided. Moreover, removal of hurricane vortex and use of a climatological basic state were also avoided. In a set of benchmark analyses, Shapiro[54] found that the wind that steered Gloria was primarily attributable to the PV anomalies confined within a cylinder of radius 1000 km and levels 500 hPa and above. The results imply that in order to improve prediction of short–term changes in the environmental flow, measurements of upper–level winds and heights are required up to at least 1000 km. A set of nine synoptic–flow cases have been recently used to evaluate how representative the result for Gloria is[55]. Note that the PV diagnostics cannot address the relative roles of the ambient PV anomalies and the PV anomalies associated with the vortex. Neither can it address the cause of the PV anomalies. A new technique — PV tendency diagnostics, developed by Wu and Wang (personal communication) attempts to overcome these deficiencies by examining the evolution of PV anomalies and the processes that contribute to generation of the PV anomalies.

6. BINARY CYCLONE INTERACTION

A variety of irregular tracks can be caused by interactions between two tropical cyclones. The small separation distance normally results in a mutual cyclonic rotation of the two cyclones about an intermediate point, which is called the Fujiwara effect[56]. A tropical cyclone can also interact with a mid–latitude upper–level cold vortex or a mid–tropospheric convective vortex in an adjacent mesoscale convective system, provided both have approximately the same horizontal scale and are at a sufficiently small separation distance[57,58]. In a conceptual model by Lander and Holland[59], the relative motion of the two cyclones with regard to a centroid position consists of three stages: approach (which tends to be more often anticyclonic than cyclonic) and capture; mutual orbit; and the cessation of the rotation either by a rapid escape from the orbit or by destruction of one of the systems by a merger into the other. As the beginning (capture) and the end (release) of the mutual cyclonic rotation are relatively rapid, anticipation of these events is critical to the track forecast.

The essential dynamics can be understood in a barotropic dynamic framework. The cause of cyclonic rotation results primarily from mutual steering of the vortices. What determines the tendency for attraction, repulsion, and merger is a more important question to be addressed from both theoretical and forecast points of view. A number of factors have been recognized as critical: the environmental shear; the outer wind structures of the cyclones; the separation distance between vortex centers; and the relative intensities of the two vortices. Chan and Law[60] suggested that whether the vortices in a binary system attract or repel each other depends on the asymmetric vorticity distribution associated with the two vortices. On the other hand, Holland and Dietachmayer[61] argued that the distortion of weak outer vorticity fields changes the advecting flow over each vortex core, which leads to mutual approach or retreat depending on the shape of the vorticity fields. The beta effect inhibits mutual approach. The core merger of two cyclones depends critically on the separation distance and the intensities of the two vortices, and much less on the environmental factors. Using a contour dynamics model, Ritchie and Holland[62] demonstrated that two vortices having equal intensity begin to merge when the separation distance becomes smaller than 3.3 times the radius of the vortex. Two opposing processes exist in the merger. One is the mutual straining effect of the horizontal shear of one vortex on the other, and the other is the vortex self–stabilization effect. The former tends to distort the vortex patch, while the latter tends to restore circular flow. Once the separation distance is smaller than the critical separation distance for merger, the former dominates and the merger proceeds rapidly. An escape from the mutual orbit may occur when one of the cyclones comes close enough to, and is captured by, an adjacent circulation system, or when the beta–induced asymmetric gyres of the two vortices are enhanced[61,63]. In the latter case, an anticyclonic gyre to the east of the combined circulation of the two vortices may become sufficiently intense to deflect the eastern vortex around the anticyclone to the east.

In addition to the direct binary cyclone interaction, Carr et al.[64] defined a semi–direct interaction in which (by definition) the two TCs are sufficiently separated that no overlap of the two circulations occurs. Because they are close to the subtropical ridge, the pressure gradient between the low associated with the western (eastern) TC and the high pressure in the anticyclonic cell to the east (west) establishes a poleward (equatorward) steering flow across the eastern (western) TC. During 1989–1995, 18 (14) cases affecting the tracks of the eastern (western) TC were detected. In their third TC interaction (TCI) conceptual model, which Carr et al.[64] call indirect TCI, an anticyclone (usually as a result of Rossby wave dispersion from the western TC) is present between the two TCs. The strength of this anticyclone determines the relative contributions to the motion of both TCs, with a tendency for poleward (equatorward) steering of the western (eastern) TC. The approach of the eastern TC toward this anticyclone may diminish its strength or cause the anticyclone to split from the subtropical anticyclone farther polward. In this weakening anticyclone scenario, the western (eastern) TC has a diminished (increased) poleward (equatorward) steering flow and thus may turn further westward (poleward). This indirect TCI occurs quite frequently in the western North Pacific, and has also been detected by Boothe[65] in the eastern / central North Pacific and by Bannister et al.[66] in Southern Hemisphere binary TC situations.

7. CAUSES OF OSCILLATORY AND TROCHOIDAL (INCLUDING LOOPING) MOTIONS

Oscillatory or trochoidal motion with a scale greater than 50 km and period greater than one day may mask the translation motion and therefore cause difficulties in the track forecast. The primary causes of oscillatory and trochoidal motion are associated with the cyclone internal dynamics, while external forcing plays a secondary role. A number of mechanisms have been proposed to explain the existence of oscillatory TC tracks.

7.1 *Rotating Convective Asymmetry*

An asymmetric heat release and associated asymmetric divergent flow may induce an asymmetric rotational circulations that may cause a meander track[67]. This has been confirmed by a numerical model of Willoughby[68]. In a similar manner, mesoscale vortices embedded in a cyclone may also induce a track meander[69].

7.2 *Vertical Coupling of a Vertically Titled Vortex*

This was demonstrated by Khandekar[70]. For a baroclinic vortex, both ambient vertical shear or vertical differential beta drift can tilt the vortex. Once the vortex tilt develops, the upper– and lower–level centers begin to rotate cyclonically about the mid–level center due to the vertical penetration of the circulation associated with the PV anomalies of the tilted vortex. This has been shown by numerical experiments[26,44]. Jones argued that such a rotation of the tilted vortex may act to oppose the destructive action of the vertical shear on the vortex.

7.3 *Inertial Instability and Waves in the Outflow Layer of Tropical Cyclones*

Anthes[71] first noticed the looping motion of a cyclone in a baroclinic model that was associated with asymmetries in divergence induced by dynamically unstable eddies (the inertial instability). Flatau and Stevens[72] found that intense model vortices may display a looping motion with a period (of a few days) that corresponds to the period of a barotropically unstable mode in the outflow layer. The development of the instability depends on the structure and frequency of the environmental forcing. The strongest response occurs when the frequency of the forcing matches that of the intrinsic unstable mode. On the other hand, Abe[73] found that the looping motion in his model was caused by stable inertial waves propagating on the eyewall, which induced a rotation of the mean asymmetric wind around the cyclone center. When the pressure field is flat, and thus the basic flow is very weak, snake–shaped motion is possible due to an inertial oscillation.

8. EFFECTS OF LOWER BOUNDARY FORCING

8.1 *Topography*

Island topographic effects on TC motion have been studied by means of three–dimensional TC models. In their numerical experiments, Bender et al.[74] found that the island topography affected storm motion via changing both the basic flow and the storm circulation. An island topography similar to Taiwan first induces a northward (southward) deflection for a TC moving westward toward the northern (southern) end of the topography due to the blocking effect[75]. When the TC is close enough to the topography that frictional dissipation and disruption of the outer flow occurs, a wavenumber one asymmetry develops that deflects the TC toward the topography[76,77]. This interaction with the topography is more effective for weaker and slower–moving TCs. Formation of a secondary vortex center on the lee side has been simulated as the low–level cyclonic center was blocked upstream of the terrain. Development of a secondary low on the lee side of Taiwan depends on the speed of the basic easterly flow. When a barotropic vortex passes over a large–scale topography, the vortex motion is affected through modification of the asymmetric circulation by vortex stretching as the flow across topography[78]. In this case, a vortex approaching topography from the east is accelerated and deflected southward.

8.2 *Sea–Surface Temperature and TC–Ocean Interaction*

A complete review of the ocean response to TCs is given by Ginis[79]. Hurricanes may induce an SST decrease of a few degrees, with maximum cooling to the right of the path[80]. For stationary or slowly moving TCs, these changes in SST might be expected to feedback to TC intensity and tracks.

In coupled TC–ocean models, the sensitivity of the TC tracks to the air–sea interaction depends on the direction of the steering flows. The largest impact of the SST decrease on the storm track occurs when there is no basic flow[81]. A TC in an easterly (westerly) mean flow tends to be deflected less (more) toward the north than in uncoupled models[82]. Ginis and Khain[82] attributed this difference to the TC intensity and the asymmetries of heat and moisture fluxes from the ocean with respect to the storm center. Falkovich et al.[83] speculated that two processes might be responsible for the differences. One is via change of vertically averaged cyclone structure (barotropic process), and the other is associated with asymmetric heat and moisture fluxes at the surface, which causes an asymmetry in condensational heating (baroclinic process).

9. SUMMARY

Tropical cyclones move primarily due to nonlinear vorticity advection that is caused by

(i) large–scale ambient flows and flows associated with adjacent synoptic–scale systems; and (ii) secondary asymmetric flows induced by interaction of the primary vortex with the ambient PV gradients. Figure 4 is a summary of the causes and factors determining these two components. The environmental steering effect plays a central role in TC translation. The interaction between a TC and an adjacent TC or other synoptic systems often causes irregular tracks. The beta drift represents a major deviation of the TC motion from the environmental steering. Since the secondary steering flow is associated with the beta gyres (the wavenumber one asymmetric circulation), the dynamics of beta gyres plays a central role in the beta drift. Whereas the beta gyres result primarily from the interaction of the primary vortex circulation and the earth vorticity gradient, the presence of horizontal and vertical environmental wind shears have significant impacts on the strength and orientation of the beta gyres, and thus the beta drift. In these model simulations, the horizontal shear strain rate can considerably affect the beta–drift speed, the longitudinal shear of the meridional environmental wind component can significantly change beta–drift direction, and the vertical shear can generate a propagation component and effectively deflect the beta drift in the presence of an upper–level anticyclonic circulation. The diabatic heating, by maintaining the baroclinic structure of the TC and generating asymmetries, may also affect TC motion. The internal dynamical processes (e.g., asymmetric convective heating, mesoscale systems embedded in the TCs, outflow instability, and the vertical tilt of TCs) are primarily responsible for the oscillatory motion of TCs. In addition, external forcing (e.g., surface friction, topography, SST variation, and TC–ocean interaction) may also influence TC motion.

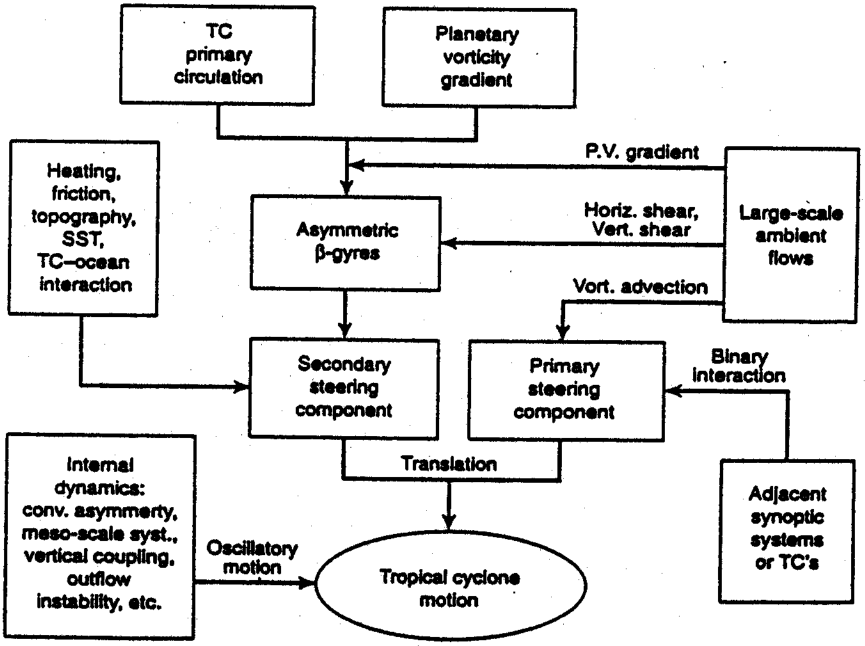

FIGURE 4. Schematic of causes and processes that determine primary environmental steering, secondary steering, and oscillatory components of tropical cyclone motion.

The physical mechanisms derived from conceptual or simple numerical models have been shown to explain many aspects of the beta gyre dynamics and beta drift in a wide variety of environments. In realistic situations, none of them alone can explain the observations. Forecast applications require knowledge of the key processes and factors that are most influential to TC motion. This calls for future studies with better quantitative analyses or diagnostics using well-designed experiments with realistic TC models, especially the baroclinic processes in the presence of diabatic heating and convective momentum transports.

The ultimate goal of understanding the dynamics of tropical cyclone motion is to provide a physical basis and guidance for improving dynamical models and the track predictions. In the past, dynamical models performed better than a persistence forecast only after 24 hours. The poor performance during the first 24 hours was primarily caused by an inadequate representation of both the large-scale flow and the structure of the TC in the initial conditions of the hurricane models. Krishnamurti et al.[84] demonstrated the potential contribution of physical initialization in the improvement of the nowcasting and 24-h tropical environmental flow forecast.

Kurihara et al.[85,86] devoted special efforts to the specification of initial conditions in their TC prediction model. They first determined carefully the domain defining the extent of the TC, and then interpolated the environmental fields across this domain using an optimum interpolation technique. After removal of the poorly analyzed TC vortex, they represented the symmetric vortex circulation with a "spin-up vortex" to ensure the compatibility and consistency with the model numerics, resolution, and physics. During this process, the tangential wind is forced toward a target profile specified from available observations. In addition, the symmetric vortex is used to generate an asymmetric circulation by time integration of a barotropic model, which is then included as part of the initial vortex structure. While these procedures are not perfect, they do produce much improved initial conditions and alleviate the long-standing problems of initial adjustment and false spin-up in dynamical track forecast models.

A recent study by Abbey et al.[87] analyzed the inherent and practical predictability of TC track errors. Their results suggested that a large gap exists between the current mean forecast errors and the "lower bound" errors that might be expected given a perfect model and perfect ensemble approach. Predictability of TC tracks on various time scales has been given little attention in the past. Its practical importance deserves enhanced research in the future.

Further advances in understanding of TC motion dynamics and improving track predictions remains a long-term challenge. A key strategy is to have two-way feedbacks between forecast communities and the researchers. Precise diagnosis of the weaknesses and problems with the performance of dynamical models is critical to stimulate basic research on TC motion. Comprehensive and systematic analyses of the primary causes for forecast errors in various oceanic regions are needed to provide a guidance for the future TC motion research.

Large forecast errors often arise during irregular TC movement. These irregular tracks include looping, mutual rotation of binary storms, scillatory or trochoidal motion (wobbling, snake-shape), and sharp turns or sudden accelerations in translation. In a region with a larger fraction of these unusual tracks, or during a season with higher than normal percentage of these situations, the average track forecast errors may increase[1]. Whereas individual types of irregular tracks may be rare; as a group, they are not small-probability events. The irregular motion involves dynamical processes that are substantially different from the concepts of quasi-steady, large-scale steering, and propagation associated with the beta gyres. In particular, the sharp turns and sudden accelerations in TC translation are often found when background steering flows experience abrupt changes or when tropical cyclones strongly interact with large-scale systems, such as the monsoon gyre in the western North Pacific as documented by Carr and Elsberry[88]. Large TC track errors are also often associated with incorrect assessments of the recurvature situation.

The large–scale steering flow varies on various time scales ranging from synoptic to intraseasonal. The persistence and adjustment of the planetary scale circulation system on intraseasonal time scales has a fundamental influence on the prevailing trends for TC movement. Examples are given by Harr and Elsberry[89–91]. The subseasonal variations in the tropical storm track are significant in the western North Pacific[92]. The seasonal TC activity and track patterns are also remarkably affected by changes in SST and large–scale circulation associated with El Niño–Southern Oscillation[93–95]. The intense hurricane activity in North Atlantic has experienced remarkable interdecadal changes[96], which appear to be strongly correlated with rainfall in the Sahel region[97]. The forecasts of major Atlantic hurricane activity appear to have a firm physical basis[98]. Study of non–steady environmental steering effects on various time scales should become a pressing task, because it is critical not only to the recurvature dynamics and erratic tracks, but also to medium–range and short–term climate variations of the tropical storm tracks in which society has increasing interests.

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