TROPICAL CYCLONE MOTION

Introduction

Forecasting tropical cyclone motion is still difficult, but considerable progress has been made both in understanding processes controlling motion and in predicting tropical cyclone tracks. Here is an overview on this subject:

General Processes

Some of the main controlling processes include: 1) The mean steering level; 2) The Beta effect; and 3) the Fujiwhara effect.

Mean steering level

The most important predictor is the environmental steering of tropical cyclones. However, this is a tricky process because: 1) how does one adequately remove the vortex to find the steering current; and 2) what is the most representative level of the steering current, and does it vary with storm intensity? Issue 1 is still being researched, but there has been progress on issue 2.

In general, it is found that the depth of the environmental steering flow increases with storm intensity, which reflects the deeper layer of cyclonic rotation. Figure 1 shows that optimum steering layers for weaker storms are in the lower troposphere, whereas the most intense tropical cyclones seem to be steered by deep tropospheric flow. It may be summarized as:

[ ] The 850-500 mb layer average works best for Atlantic storms with $p_{sfc} \geq 990$ mb.

[ ] The 850-400 mb layer average works best for Atlantic storms with $989 \geq p_{sfc} \geq 970$ mb.

[ ] The 850-300 mb layer average works best for Atlantic storms with $969 \geq p_{sfc} \geq 950$ mb.

[ ] The 850-200 mb layer average works best for Atlantic storms with $p_{sfc} \leq 949$ mb.

However, such simplifications mask the difficulties in finding the steering current. Often the steering current is not obvious even after layer averaging, especially when the environmental winds vary greatly with height. Sometimes the environmental winds are weak, resulting in a meandering or stationary storm. Another problem is recurvature, which results in the greatest forecast track errors. Recurvature refers to a generally northwestward moving storm encountering the mid-latitude westerlies or an upper-level trough, and turning to the north and eventually northeast. The general rule is that *if upper and mid-level westerlies are within 6 deg of the northwest sector of a storm, recurvature is likely.* However, sometimes a recurving storm due to a trough "breaks off" from the trough, and resumes its original northwest track. Such difficult situations are what makes tropical cyclones famous for their "loop" tracks, and are predicted best (though still sometimes poorly) by numerical models. Some examples are Hurricanes Betsy and Elena.

The Beta effect

Regardless of these steering definitions, studies show that significant deviations occur from the apparent steering flow. This is because the tropical cyclone interacts with the environment, which is a highly nonlinear process. This can result in surprising, unanticipated tracks. Numerical models can only handle such interactions, and while they are becoming better at such situations, it is often poorly modeled.

We have begun to understand environmental interactions better using simple analytical and numerical models. These studies show one type of interaction, called the *Beta effect*, plays a minor role. Consider a vortex with relative vorticity ζ and no environmental steering. Further assume that conservation of absolute vorticity applies:

$$\frac{\partial \zeta}{\partial t} + u\frac{\partial \zeta}{\partial x} + v\frac{\partial \zeta}{\partial y} + \beta v = 0$$

where $f = 2\Omega \sin\phi$ is the Coriolis parameter and $\beta = \partial f/\partial y$ (pronounced "Bay-tuh") is the meridional variation of f. f is also sometimes called *earth vorticity* (see handout). First, let's examine what happens for the *linear* solution

First, let's ignore the nonlinear interaction of the wind advecting ζ, and just consider how $\partial\zeta/\partial t$ is affected by the advection of earth vorticity (βv), which is a linear process when β is set to some constant (called the *β-plane approximation*). Numerical models solving the linearized version of this equation show that an isolated, symmetric vortex with no steering flow will develop an east-west asymmetry as shown in Fig. 2. (The contours represent *streamfunctions*, to which winds blow parallel.) The vortex elongates westward with time as a result of the dispersive effects of *Rossby waves* (see handout on phase speeds, wave dispersion, and Rossby waves). The atmosphere contains a multitude of Rossby waves of different wavelengths which are initially superimposed together, but the longer waves have larger westward phase speeds than the shorter Rossby waves. This results in stretching the vortex westward.

An alternative explanation may also be seen in the resulting east-west wind asymmetry in the linear solution is shown in the v component (Fig. 3). Advection of the earth vorticity produces an increase (decrease) in ζ to the west (east) of the vortex. These changes in ζ will induce a southerly flow near the storm center, thus strengthening (weakening) winds to the east (west). A feedback process begins in which this induced southerly flow further decreases ζ east of the vortex, and therefore the asymmetry increases with time. It is important to note that in the linear case, the vortex does not move much (it's displaced slightly to the west), but it's wind field becomes more distorted with time.

When *nonlinear* advection processes are then included, the flow associated with the vortex will advect ζ, with cyclonic (anticyclonic) ζ being transported to the poleward (equatorward) side (Fig. 4). The advection will tend to restore symmetry to the vortex, but displace the vortex to the northwest. However, the outer part of the vortex maintains a westward stretching as a result of the linear β-effect. Therefore, the vortex is in a continuous state of being distorted by Rossby wave distortion, and being brought back near a symmetric state by nonlinear advection of ζ, which results in a westward and poleward motion even in the absence of a basic flow. This process is called *self-advection*, resulting in a northwestward motion of 1–3 ms^{-1} even without steering currents!

In fact, if a uniform westerly environmental flow were superimposed on the vortex, the storm motion would be faster than (and to the right of), the mean westerly steering current. Furthermore, in the real world where the steering current varies horizontally and vertically, and where β is not constant, this interaction could be even more significant. This shows the importance of the vortex interaction with the environmental flow in determining storm motion. Furthermore, research has shown that this northwestward displacement (and the storm's translational speed) increases with storm size, outer-core wind strength, and $\Delta\zeta$ associated with the environmental flow. However, storm intensity (dictated by inner-core wind strength) *does not* increase or decrease this northwest displacement.

This interaction may be significant enough that a "forecast signal" has recently been sought showing this northwest drift. It has been proposed that the total flow associated with tropical cyclone motion be divided into three components: 1) the symmetric circulation associated with the vortex; 2) the asymmetric circulation that arises from an interaction between the symmetric circulation and the "environment" (the earth's vorticity field and large-scale flows); and 3) a horizontally steering flow. The forecast signal would be associated with item 2. Figure 5 displays such a signal by computing "asymmetric streamfunctions," resulting in two counterrotating gyres. These are called *β gyres*, and show the northwestward displacement associated with item 2. Currently scientists are investigating research flight data to see how strong this signal is in reality. However, separating items 1, 2, and 3 is a difficult process since it depends on one's definition of the storm environment and the storm vortex, and currently no universal definition exists.

Finally, another fact emerges from the storm interaction with the environment. It is known that the fastest winds in a northwest moving storm occur in the right front quadrant partially because the storm translation speed is superimposed on the cyclonic rotation. However, as shown in Fig. 6 in which there is no steering current and the storm motion is less than 3 ms^{-1}, an asymmetry still occurs in this quadrant. A combination of the linear β-effect and the nonlinear advection of ζ also produces a wind maximum to the northeast of the storm!

It is also observed that storms tend to "wobble" as they move. Research has shown this wobble occurs due to the asymmetry of the wind field. This wobble is analogous to a moving spinning top which is slightly tilted, and therefore it has asymmetric velocities.

See Fig. 7 on Beta effect's dependence on storm size

The Fujiwhara effect

Another factor affecting tropical cyclone motion is when two storms become relatively close to each other. When they approach a critical distance from each other, the *Fujiwhara effect* can become important (also called binary cyclone interaction). This results in unusual tracks that rotate cyclonically about an intermediate point (Fig. 8). In these binary cyclone interactions, the circulation of one cyclone becomes the steering flow for the other cyclone, and vice versa. A rule of thumb is that the Fujiwhara effect is dominant if the separation distance is less than 6 deg, and as the separation distance increases from 7 to 15 deg, the environmental steering becomes progressively more important. The Fujiwhara affect begins when one (or both) of the cyclones approaches a "capture point," and ends when the approach a release point." An example of the Fujiwhara effect is shown for typhoons Polly and Rose in the western North Pacific. Determining these points are a challenging forecast problem.

The Fujiwhara effect occurs in all basins, but it's most frequent in the western Pacific, followed by the eastern Pacific, Australia, Atlantic, and North India. Forecasting this phenomenon is even trickier when one cyclone is large and the other small. Usually the weaker vortex will become distorted by vertical wind shear and by the horizontal tangential shear of the larger storm, resulting in the weak storm eventually dissipating. However, one time the two storms have been observed to merge (see handout of journal article by Landers and Holland)!

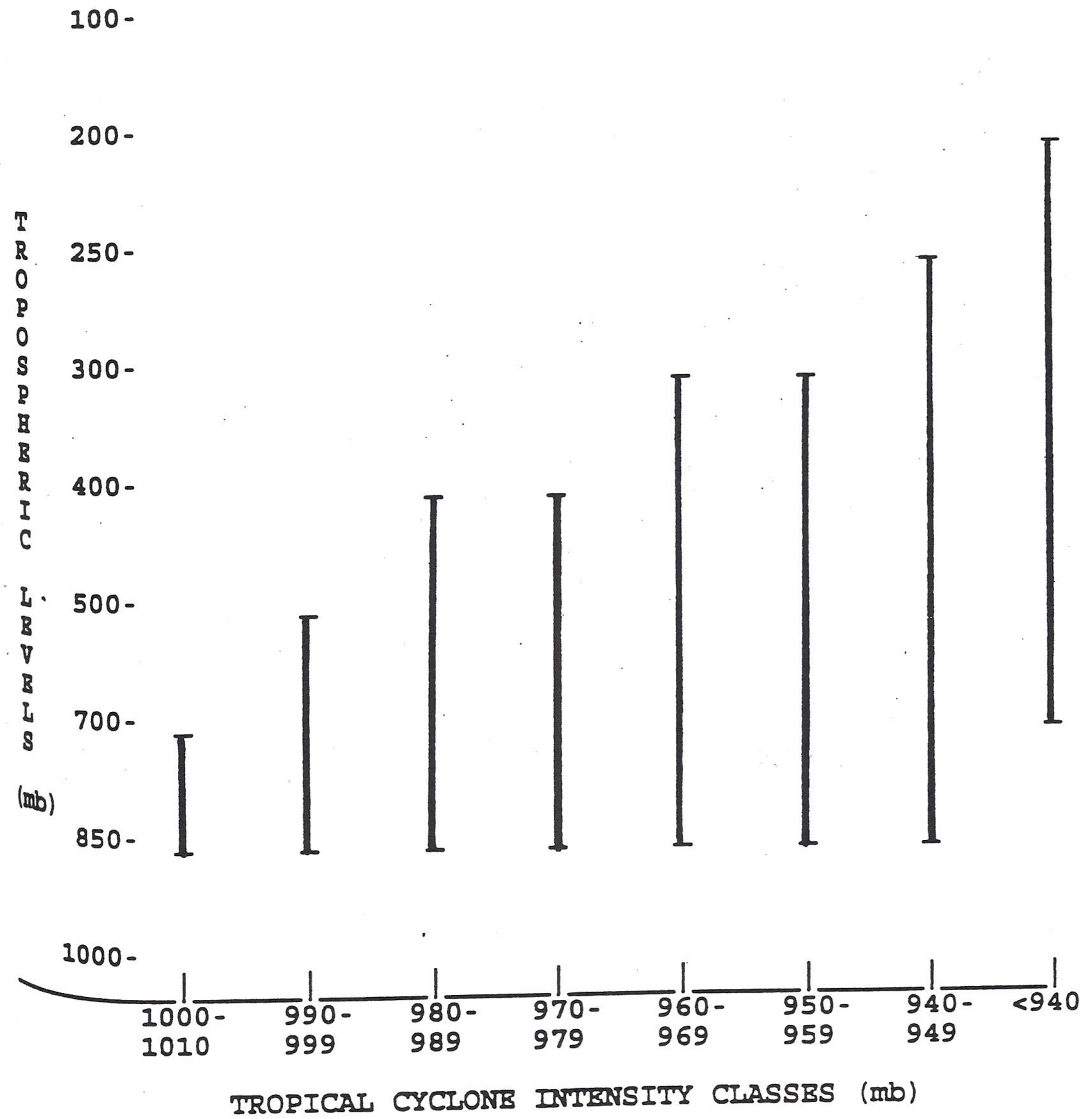


Figure 1 [redacted]: Optimal depth of the deep-layer mean flow (based at 850 hPa) used in barotropic model forecasts of tropical cyclone motion in the North Atlantic and Australian regions (after Velden, 1990).

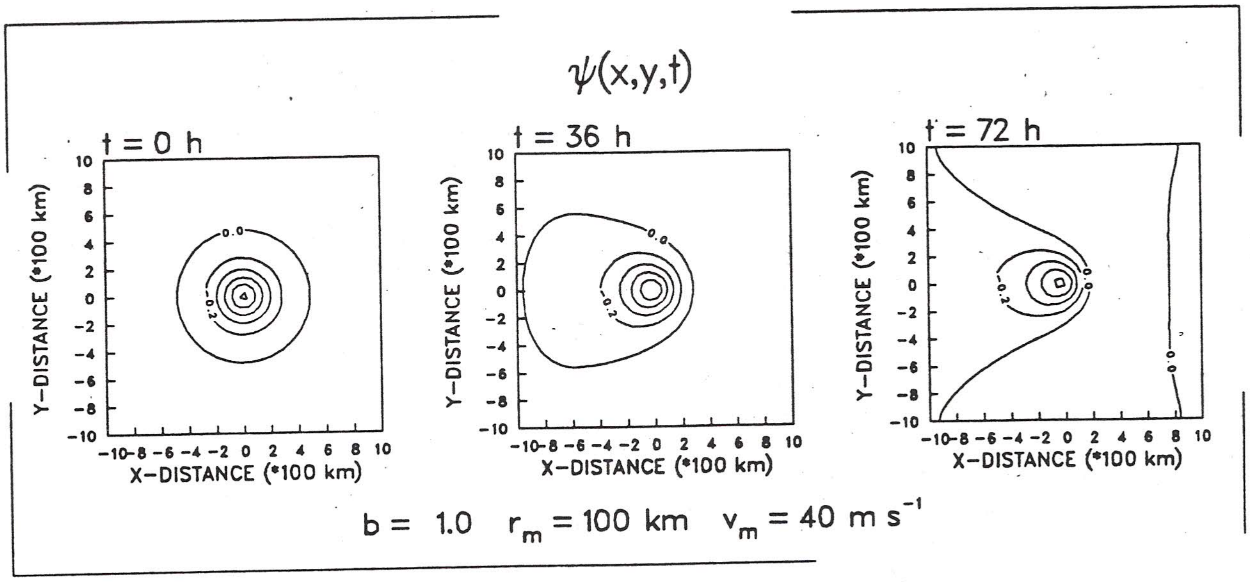


FIG. 2. Streamfunction fields (ψ) at 0, 36 and 72 h for the analytical model using the vortex profile in (2.10) with $V_m = 40$ m s^{-1}, $r_m = 100$ km and $b = 1.0$. The contour interval is 0.2×10^6 m^2 s^{-1}.

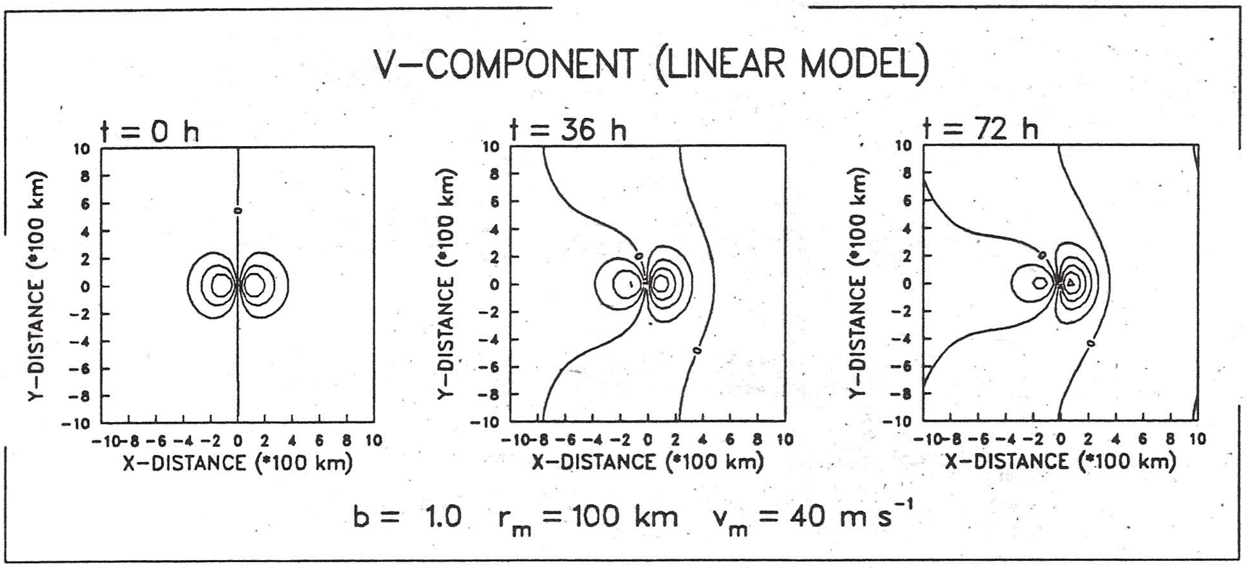


FIG. ~~4~~3. Meridional (v) wind component at 0, 36 and 72 h derived from the solutions in Fig. 2. The contour interval is 10 m s^{-1}.

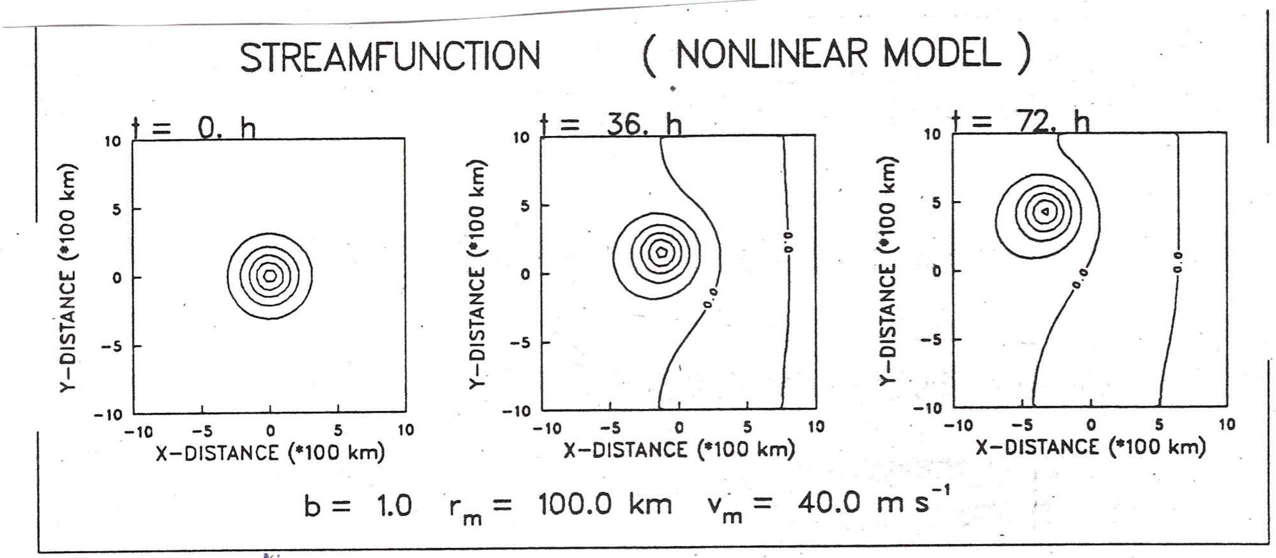


FIG. ~~5~~ 4. As in Fig. 2 except for the nonlinear numerical simulations. The contour interval is 0.1×10^6 m^2 s^{-1}.

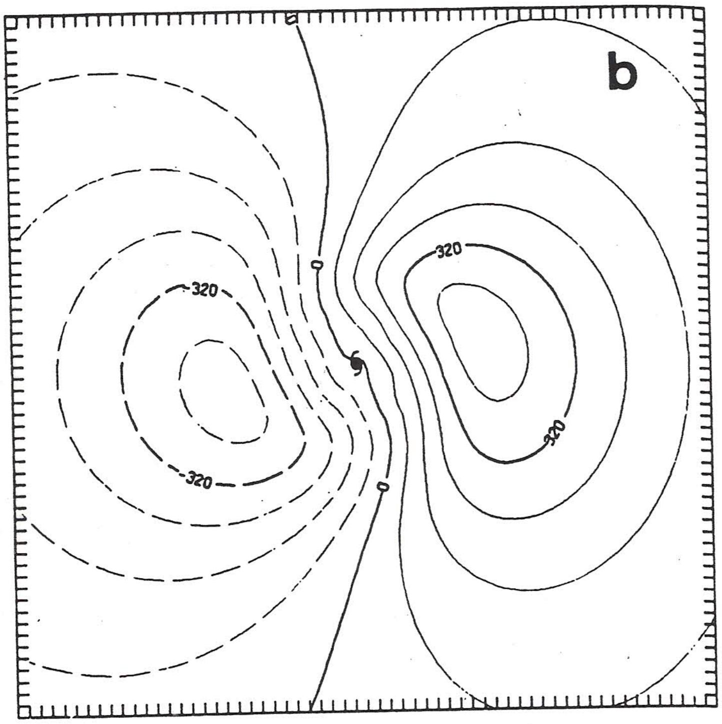


Fig. 5 Asymmetric streamfunction ($m^2 s^{-1}$) showing "Beta gyres"

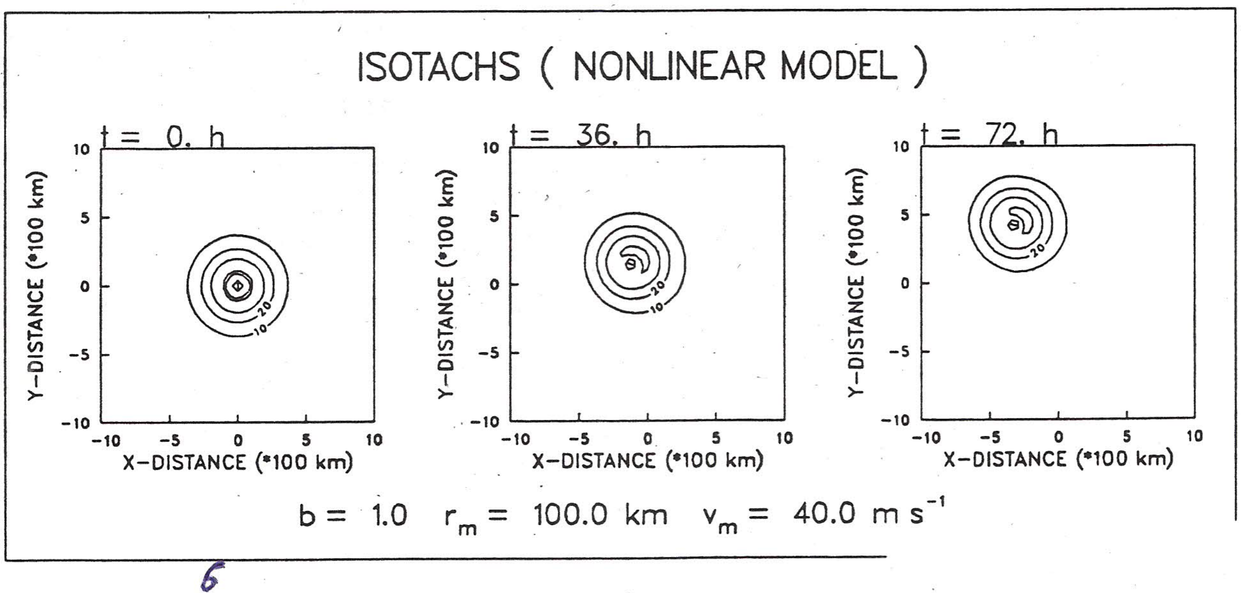


FIG. ~~7~~ 6. Isotachs derived from the nonlinear numerical simulation given in Fig. ~~5~~ 4. The contour interval is 10 m s^{-1}.

Beta Effect on Different Size Storms

In dimensional form, the resulting "β-drift law" becomes

$$V_d = 0.12\beta^{0.55} f_o^{0.45} (R_o^{500})^{1.55}, \qquad (12)$$

which may be expressed in terms of the more readily ascertainable R_o^{850} (via one of the methods proposed in section 2c) by substituting Eq. (8) for R_o^{500} to give

$$V_d = 0.074\beta^{0.55} f_o^{0.45} (R_o^{850})^{1.55}. \qquad (13)$$

As expected, the BEP speed given by (13) depends directly on both f_o (latitude) and R_o^{850}, which together completely specify the outer tangential wind structure of the angular momentum TC wind profile model given by (5) and (7). An outer wind structure or "strength" parameter may be defined as

$$S^{850} = f_o^{0.45} (R_o^{850})^{1.55} \qquad (14)$$

to emphasize that combinations of f_o and R_o^{850} giving a constant value of S^{850} also result in a constant propagation speed V_d for a specific β value.

In summary, the expression for BEP speed in (13) and a direction ranging from 320° to 360° provide a BEP vector given the TC latitude and R_o^{850} value. Based on the fit of (12) to the line in Fig. 14, and the fact that only barotropic propagation processes are represented, the use of (13) should be limited to the Tropics (i.e., equatorward of 30° latitude), with the additional caveat that the propagation speed of the smallest TCs may be underestimated to some degree.

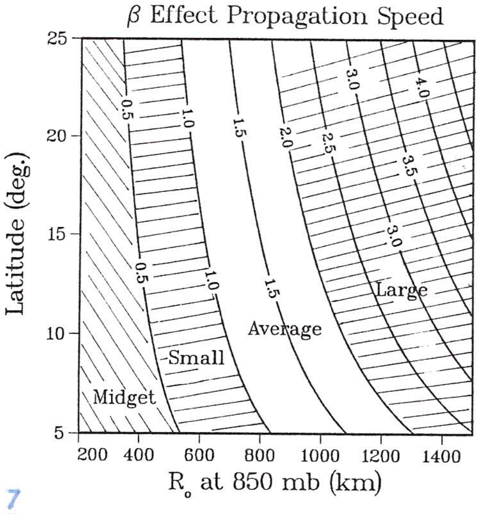
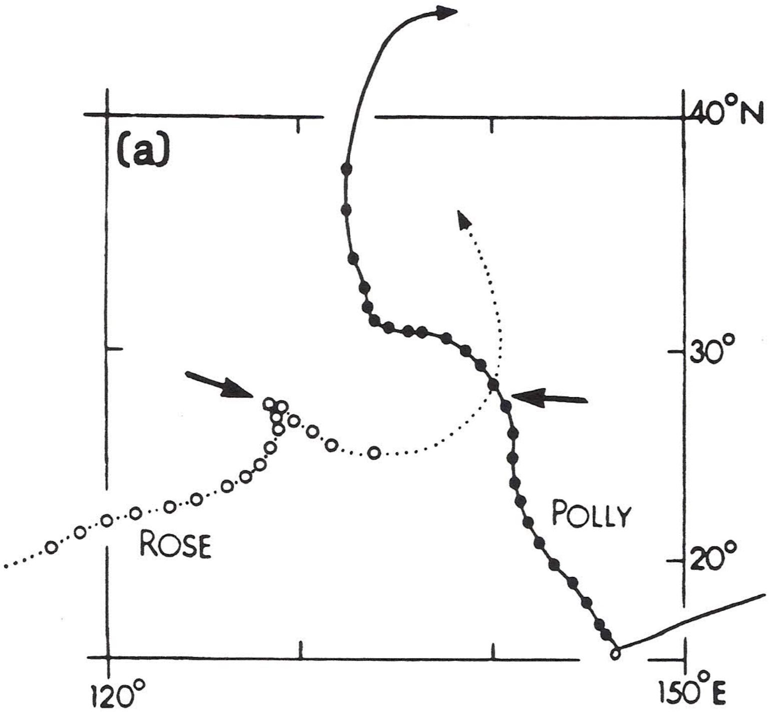


Fig. ~~15~~ 7. Beta-effect propagation speed (m s^{-1}) from the nondivergent, barotropic model as a function of latitude (ordinate) and 850-mb radial extent (abscissa) of the initial vortices defined by the angular momentum model.

c. BEP model application

Application of (13) is simplified by holding the value of β constant.[3] The functional dependence of (13) on latitude and R_o^{850} with β at 10°N is shown in Fig. ~~16~~ 7. For practical application, areas bounded by BEP speed contours of 0.5, 1.0, and 2.0 m s^{-1} are defined to represent four categories of TC outer wind structure: midget, small, average, and large.



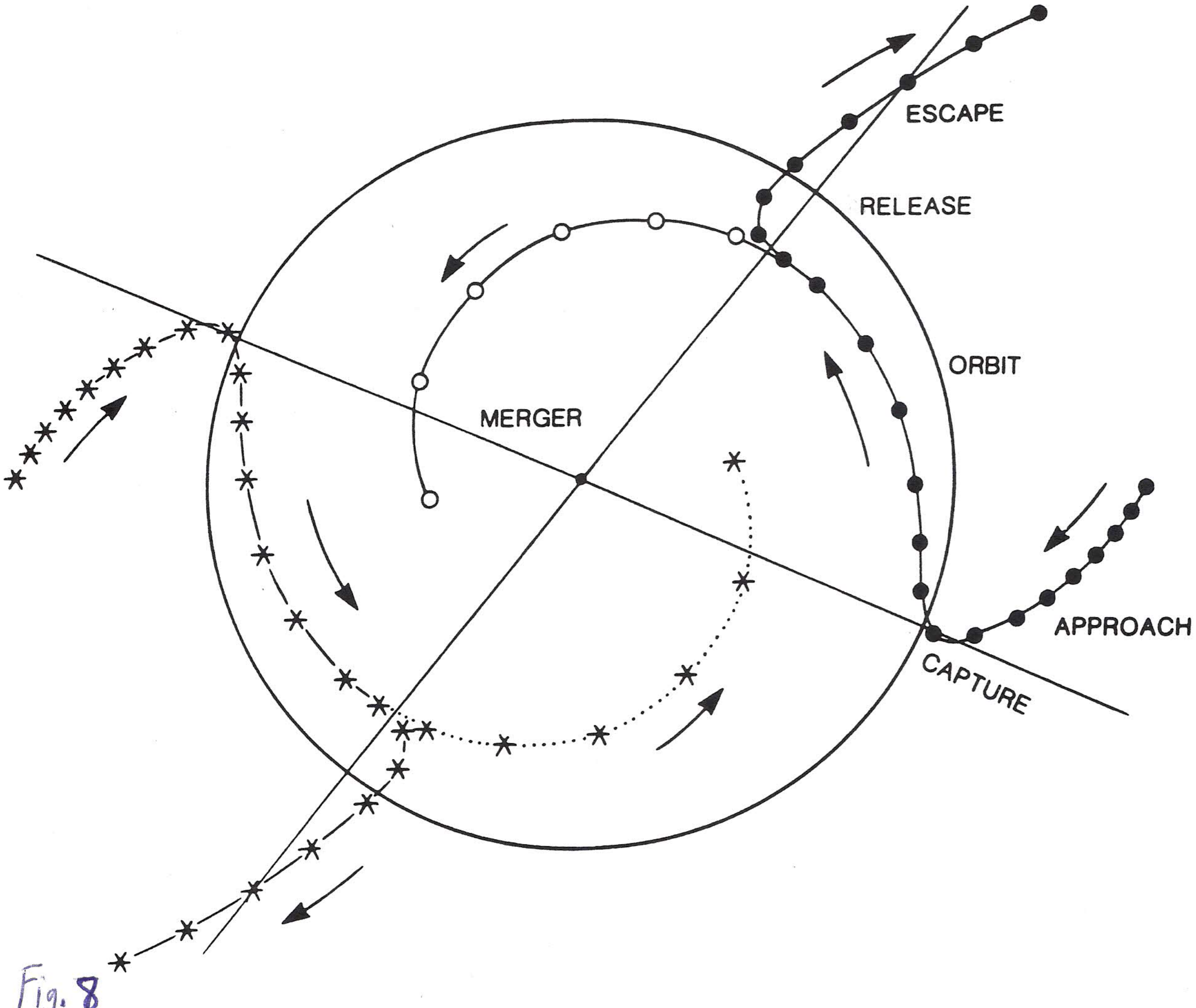


Fig. 8

Model of binary interaction of two cyclonic mesoscale vortices that contain the major elements of approach and capture, followed by mutual orbit, then release and escape, or merger.