Tropical Cyclone Motion

Introduction

To first order, tropical cyclones are steered by the large-scale flow averaged over an appropriate layer that scales with the cyclone's intensity. However, several other features have small but non-negligible roles in steering a tropical cyclone. This lecture develops dynamical frameworks through which we can understand these influences.

Key Questions

- What are the two leading factors influencing a tropical cyclone's motion?
- How does the depth of the steering layer governing a tropical cyclone's motion vary as a function of the tropical cyclone's intensity?
- How does the meridional variation in the Coriolis parameter influence tropical cyclone motion, particularly in isolation from other influences?
- How does non-uniformity in the large-scale horizontal flow influence a tropical cyclone's motion, whether in isolation or in conjunction with the beta effect?
- How does vertical wind shear influence a tropical cyclone's motion?
- What is the Fujiwara effect, and how does it influence the motion of two tropical cyclones close to each other?
- How do convective asymmetries, however they may be formed, influence a tropical cyclone's motion?

Tropical Cyclone Motion Climatology

As we previously noted, tropical cyclones generally track around the periphery of subtropical anticyclones: predominantly westward in the tropics, poleward turning into the midlatitudes, and predominantly eastward at higher latitudes. The average recurvature latitude, defined as the latitude at which a tropical cyclone no longer has a westward component of motion, ranges from 20°S in the Southern Hemisphere and 25-30°N in the Northern Hemisphere. Average motions are relatively low (~10 kt/5 m s^{-1}) in the tropics but increase with poleward extent. Given that track forecast errors are proportional to translation speed, this implies that larger track forecast errors may be expected for tropical cyclones recurving into the midlatitudes.

Large-Scale Influences on Tropical Cyclone Motion

Let's conceptualize a tropical cyclone as a solid rotating body, like a cylinder, with approximate horizontal and vertical scales of 500-1000 km and 10-15 km, respectively. The large-scale flow within which a tropical cyclone is embedded has a much larger horizontal scale, however: on the order of thousands of kilometers. As a result, a tropical cyclone can be viewed as an object that is moved by the surrounding flow – referred to here as the *steering flow*. (Note that this steering flow does not include the tropical cyclone's circulation.)

We can dynamically conceptualize a tropical cyclone's steering by the large-scale flow using the absolute vorticity tendency equation. The local absolute vorticity tendency, representing the local change of absolute vorticity (η = relative vorticity ζ plus planetary vorticity f), is a function of five forcings:

- horizontal advection (movement of absolute vorticity by the horizontal components of the wind)
- vertical advection (movement of absolute vorticity by the vertical component of the wind)
- stretching (amplification of absolute vorticity through changes in vertical velocity with height)
- tilting (the transformation of rotation in a horizontal plane into rotation in a vertical plane)
- friction (dissipation, primarily that associated with the surface)

In a cylindrical framework, the local absolute vorticity tendency is expressed as:

$$\frac{\partial \eta}{\partial t} = -\vec{v} \bullet \nabla(\zeta + f) - (\zeta + f)(\nabla \bullet \vec{v}) - \omega \frac{\partial \zeta}{\partial p} + \left(\frac{\partial u}{\partial p}\frac{\partial \omega}{r\partial \lambda} - \frac{\partial v}{\partial p}\frac{\partial \omega}{\partial r}\right) + \vec{F} \quad (1)$$

where derivatives taken with respect to λ are in the azimuthal direction (i.e., around a circle) and those taken with respect to r are in the radial direction (i.e., at different radii). Velocity vectors are two-dimensional, as defined by u = radial wind (positive for outward flow) and v = tangential wind (positive for cyclonic flow). The terms on the right side of (1) are listed in the same order as in the bulleted list above.

Horizontal advection dominates the local absolute vorticity tendency (Chan 1984). This is conceptualized as a tropical cyclone moving toward the location(s) at which the absolute vorticity tendency is largest, akin to how extratropical cyclones move toward the location(s) where their development parameters are largest.

Because the large-scale flow varies with height, defining the large-scale flow responsible for steering any given tropical cyclone can be challenging. Consequently, we often use a vertically integrated or averaged wind to define the large-scale flow. The vertical depth of the steering flow increases with increasing tropical cyclone intensity, as more intense tropical cyclones are vertically deeper than their shallower counterparts.

About 50-80% of the variance in tropical cyclone motion can be explained by the large-scale steering flow. Several mechanisms result in deviant motion from this steering flow. These are discussed next, with each considered in isolation to clearly identify their individual contributions to tropical cyclone motion.

Other Influences on Tropical Cyclone Motion

Beta Effect

The beta, or β, effect stems from the meridional variation in the Coriolis parameter f. This effect, sometimes referred to as β drift, superposes a weak northwestward steering current on Northern Hemisphere tropical cyclones and a weak southwestward steering current on Southern Hemisphere tropical cyclones.

Consider the barotropic (here meaning that intensity does not vary with height) relative vorticity equation in a Cartesian framework:

$$\frac{\partial \zeta}{\partial t} = -\vec{v} \bullet \nabla(\zeta + f) \quad (2)$$

Or, equivalently, assuming that f only varies in the meridional direction,

(3) $$\frac{\partial \zeta}{\partial t} = -\vec{v} \bullet \nabla \zeta - \beta v$$

The first right-side term in (3) represents horizontal relative-vorticity advection. The second right-side term in (3) represents horizontal planetary-vorticity advection, manifest as $\beta = \frac{\partial f}{\partial y}$, by the meridional wind (note that $\partial f/\partial x = 0$ by definition). Note that β is a positive-definite quantity in both hemispheres.

Consider a symmetric tropical-cyclone vortex on a β plane (i.e., β = constant) with no mean environmental flow. A streamfunction can be defined to represent this vortex, such that:

$$u = -\frac{\partial \psi}{\partial y} \quad \text{and} \quad v = \frac{\partial \psi}{\partial x}, \quad \text{where} \quad \zeta = \nabla^2 \psi$$

At the initial time, the streamfunction and relative vorticity are concentric. As a result, there is no horizontal relative vorticity advection and, thus, the second right-hand side term of (3) is the only term impacting the local relative vorticity tendency.

Let's consider a Northern Hemisphere tropical cyclone. To the west, where the cyclone's flow is from north to south, $v < 0$ and thus $-\beta v > 0$. Conversely, where the cyclone's flow is from south to north to the east, $v > 0$ and thus $-\beta v < 0$. In other words, there is a positive relative vorticity tendency to the west and negative relative vorticity tendency to the east. This describes the westward motion contribution from the beta effect.

There is also a northward motion contribution from the beta effect, however. We can understand this using the anomalous flows associated with the relative vorticity tendencies described above. The positive relative vorticity tendency to the west is associated with anomalous cyclonic rotation that imparts a south-to-north steering current across the tropical cyclone. Likewise, the negative relative vorticity tendency to the east is associated with anomalous anticyclonic rotation that also imparts a south-to-north steering current across the tropical cyclone. These describe the northward motion contribution from the beta effect. Altogether, the beta effect induces a northwestward-directed steering current atop a Northern Hemisphere tropical cyclone.

The beta effect also influences Southern Hemisphere tropical cyclones in the same way as described above.

Although the beta effect's magnitude is sensitive to the tropical cyclone's outer-core structure, it generally imparts a 1-2 m s^{-1} northwestward steering current on a Northern Hemisphere tropical cyclone. It accounts for ~10% of the steering flow influencing a tropical cyclone's motion. The beta effect is strongest for larger, stronger, and higher-latitude tropical cyclones.

Non-Uniform Horizontal Flow (Horizontal Wind Shear)

Our discussion to this point has neglected horizontal variations in the large-scale flow. These variations can be important, however, whether on their own or in conjunction with the beta effect.

Non-uniform horizontal flow across a tropical cyclone differentially horizontally advects relative vorticity, with cyclonic relative vorticity advection downwind and anticyclonic relative vorticity advection upwind. The anomalous horizontal flow associated with these implied vorticity tendencies imparts a weak steering current across a tropical cyclone, the details of which depend on the non-uniform horizontal flow structure. To illustrate, consider two conceptual examples:

- *Easterly wind to the north, zero wind over the center, and westerly wind to the south of the vortex, with the wind speed varying linearly from south to north.* In this case, the vortex's northern half is distorted westward whereas the vortex's southern half is distorted eastward. This is associated with cyclonic relative vorticity tendency to the northeast/southwest and anticyclonic relative vorticity tendency to the northwest/southeast of a tropical cyclone. Although this flow deforms the vortex, it does not induce an anomalous steering current across the center.
- *Westerly flow to the north that decays to zero moving toward the south.* The vortex's northern half is distorted eastward, but there is little to no distortion of the vortex's southern half. This results in cyclonic relative vorticity tendency to the northwest and anticyclonic relative vorticity tendency to the northeast, together imparting an anomalous southward steering current over the center.

More complex horizontally sheared flows exist and can influence tropical cyclone motion, and their precise impacts will vary based on the horizontal flow's specific geometry.

For simplicity, we have considered non-uniform horizontal flow separate from the beta effect; however, the two act together to influence a tropical cyclone's motion. Whether the two are additive or counteract each other depends on the precise configuration of the non-uniform horizontal flow.

Non-Uniform Vertical Flow (Vertical Wind Shear)

The influence of non-uniform vertical flow is identical to that considered with the precession of the tropical cyclone vortex against vertical wind shear with one difference: the tropical cyclone weakens with increasing height, with the rotational flow becoming anticyclonic (rather than just weakly cyclonic) at the tropopause. Consider a westerly sheared tropical cyclone, with the upper-tropospheric anticyclone displaced to the west of the near-surface cyclonic circulation. The near-surface cyclonic circulation has a weak influence on the upper-tropospheric flow, imparting a northward motion on the upper-tropospheric anticyclone. Likewise, the upper-tropospheric anticyclone has a weak influence on the near-surface flow, imparting a northward motion on the near-surface cyclone. Similar arguments can be made for other shear directions and/or more complex shear configurations.

Fujiwara Interaction

Fujiwara interaction describes mutual rotation of two vortices about a common locus. This locus is typically the strength-weighted centroid of the two vortices; if they are of equal strength, this center is precisely the middle point between their centers.

Consider two vortices of equal strength, wherein the flow around each steers the other. Neglecting the large-scale steering flow and beta effect, the two vortices will rotate around each other relative to their centroid. In the presence of the beta effect, the two vortices still rotate around each other relative to their centroid as the centroid moves northwestward (for Northern Hemisphere tropical cyclones) due to the beta effect. This mutual rotation favors the stronger vortex if the two vortices are not of equal strength, such that the weaker of the two vortices gradually becomes enveloped by its stronger counterpart.

Convective Asymmetries

Asymmetries in deep, moist convection (thunderstorms) around a tropical cyclone's center can also result in the cyclone's motion deviating from that solely associated with the large-scale steering flow and the beta effect. To illustrate, consider the isentropic potential vorticity tendency equation, neglecting friction but not diabatic heating:

$$\frac{DP}{Dt} = P\frac{\partial \dot{\theta}}{\partial \theta} - g\frac{\partial \theta}{\partial p}\left(\frac{\partial u}{\partial \theta}\frac{\partial \dot{\theta}}{\partial y} - \frac{\partial v}{\partial \theta}\frac{\partial \dot{\theta}}{\partial x}\right)$$

where P is isentropic potential vorticity (positive for cyclonic rotation and static stability), θ is the isentropic vertical coordinate (positive upward because potential temperature generally increases with height), $\dot{\theta}$ is the diabatic heating rate (positive for warming), and u, v, and g have their typical meteorological meanings. The first right side term is known as the vertical diabatic term given its relationship to vertical gradients in diabatic heating whereas the second right side term is known as the shear diabatic term given its relationship to vertical wind shear (since θ is the vertical coordinate) and horizontal gradients in diabatic heating.

Let's consider these two forcing terms independently. In the context of the vertical diabatic term, convective heating vertically redistributes potential vorticity to increase it near the surface and reduce it aloft. Tropical cyclones can thus move toward convective asymmetries – i.e., toward where near-surface cyclonic rotation is increasing due to convective heating. The shear diabatic term results in potential vorticity dipoles aligned perpendicular to the vertical wind shear vector, with an anticyclonic anomaly left of the shear vector and a cyclonic anomaly right of the shear vector. The flow between these anomalies counteracts the vertical wind shear (and thus large-scale flow) whereas the flow on the outside of each anomaly adds to the vertical wind shear (and thus large-scale flow). Where these anomalies are found with respect to the tropical cyclone's center determines their specific impact on the cyclone's motion.

References

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