Understanding Hurricanes

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Introduction

Hurricanes are one of the most fascinating of all atmospheric phenomena. Much of their intricate dynamics and thermodynamics can be explained within the realm of classical physics. However, some of their secrets remain to be unlocked. Many aspects of these weather systems are discussed by Emanuel (2005) in his erudite book entitled "Divine wind: The history and science of hurricanes". In the decade since this book appeared, further progress has been made in understanding these storms.

New insights have been obtained from idealized thought experiments using numerical model simulations, supported by aircraft reconnaissance data and dropsonde soundings. These insights have led to a new paradigm for understanding hurricane intensification and structure change. Some of the key elements of recent findings will be reviewed in this article.

Most previous theories of hurricanes are based on the assumption that, to a first approximation, the storms are axisymmetric. However, this assumption is really only valid for mature storms and then only in the inner core region of these storms. Nevertheless, the assumption proves to be a useful starting point for understanding some of the basic features of storms in an environment with weak vertical shear.

In vertical flows such as a hurricane, it is convenient to think in terms of a primary circulation, i.e. the tangential wind component, v, and the secondary (or overturning, or in-up-out) circulation comprising the radial and vertical components of flow, u and w, respectively. An important concept for understanding the spin up mechanism is the conservation of angular momentum. Other useful concepts are those of approximate balance in the radial and vertical directions. These concepts are discussed next.

Conservation of angular momentum

With the assumption of axial symmetry and in the absence of frictional processes, the tangential momentum equation reduces to a statement that the absolute angular momentum per unit mass, M, is approximately conserved as air parcels (or more strictly rings of air) move around in the meridional plane, i.e. a vertical plane through the vortex axis (assumed here to be upright). The quantity $M = rv + \frac{1}{2}fr^2$, where r is the radius and f the Coriolis parameter, assumed for simplicity to be constant. In terms of M, $v = M/r - \frac{1}{2}fr$. Thus, if a ring of air parcels moves to smaller radius while conserving M, v will increase and if the ring moves to a larger radius, v will decrease (see Figure 1).

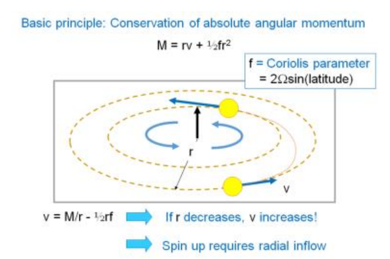

Figure 1. Schematic diagram illustrating the spin up associated with the inward-movement of the M-surfaces. Here, Ω is the Earth's angular rotation rate.

Hydrostatic and gradient wind balance

A scale analysis of the axisymmetric radial and vertical momentum equations shows that to a first approximation, the tangential flow is in gradient wind balance (at least above the surface-based frictional boundary layer) and that, on the vortex scale, there is hydrostatic balance in the vertical. That is:

$$\frac{\partial p}{\partial r} = \rho\left(\frac{v^2}{r} + fv\right)$$

and

$$\frac{\partial p}{\partial z} = -\rho g$$

where p is the pressure, ρ is the density, z is the height and g is the acceleration due to gravity. These equations lead to a constraint on the secondary circulation forced by latent heat release in deep convective clouds and friction (see below).

Boundary layer convergence

A scale analysis of the momentum equations in the frictional boundary layer (typically 1 km deep) shows amongst other things that gradient wind balance is no longer valid and that to a first approximation, the radial pressure gradient in the boundary layer is equal to that just above the boundary layer. Since the tangential wind is less in the boundary layer than its value above the boundary layer (at least beyond some inner-core radius), it follows that there must be a net inward force acting on air parcels in the boundary layer. This force drives a relatively strong inflow in the boundary layer (see Figure 2). Such a layer is found in observations as well as in numerical model simulations. In the absence of deep convection in the inner core region of the storm, the frictional convergence would drive a secondary circulation in the vortex with outflow above the boundary layer (which is typically 1 km deep). On account of the conservation of M discussed above, the vortex would thereby spin down. We consider further aspects of boundary layer dynamics in due course.

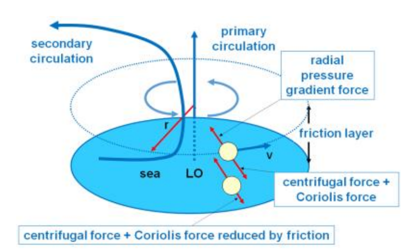

Figure 2. Schematic diagram illustrating the force imbalance in the friction layer of a tropical cyclone and the secondary circulation that it generates. LO refers to the low central pressure.

The classical theory for hurricane intensification

The classical theory of hurricane intensification goes back to a seminal paper by Ooyama (1969) and is shown schematically in Figure 3. The collective effects of deep convection in some inner region of the storm is to carry the air into the upper tropospheric outflow layer and at the same time draw air inwards in the lower troposphere, both in and above the boundary layer.

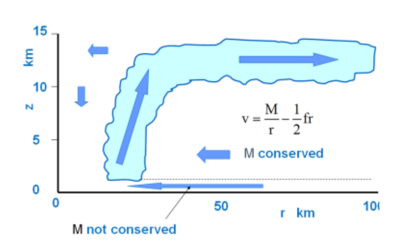

Figure 3. Schematic of the classical theory for hurricane intensification.

Above the boundary layer, rings of air moving inwards conserve their M and spin faster, while air parcels flowing outwards in the upper troposphere spin more slowly and eventually spin anticyclonically when $v < 0$, or equivalently, $\frac{1}{2}rf > M/r$.

The classical theory assumes that at all radii, the tangential wind in the boundary layer is less than that just above the layer, while the strong spiralling inflow in the boundary layer picks up moisture from the sea surface and supplies it to the inner core deep convection to sustain the intensification process. Of course, the convectively-induced inflow above the boundary layer has to be strong enough to negate the tendency of frictionally-induced outflow there. From an alternative perspective, for intensification to occur, the convective mass flux in the deep convective clouds has to be more than sufficient to ventilate the air converging in the boundary layer.

The latent heat release in the clouds tends to warm the inner core of the vortex, making the vortex less unstable to deep convection. To compensate for this stabilization effect, the latent heat fluxes at the ocean surface help restore the instability. Although the wind-speed dependence of the latent heat fluxes does augment the spin up rate to some degree, this dependence is not critical for supporting the intensification process (Montgomery *et al*. 2015).

The boundary layer spin up mechanism

To a first approximation, the flow in the boundary layer is effectively steady and hence slaved to the flow above the boundary layer. Idealized studies treating the steady boundary layer as a single layer with uniform properties in the vertical indicate the ubiquitous tendency of the tangential wind to become larger in the boundary layer than that just above at the same radius. This happens in some inner core region, typically inside the radius of maximum tangential wind near the top of the boundary layer (Smith and Vogl, 2008). A similar process has been suggested to occur outside the radius of maximum wind in conjunction with secondary eyewall formation (Huang *et al*. 2012). At such radii, the net force in the boundary layer changes sign and is directed outwards. In this region, the inflow rapidly decelerates and turns upwards, carrying its angular momentum (and moisture) with it.

The ability of the tangential wind speed to become larger in the boundary layer than directly above it may be understood heuristically in terms of the formula $v = M/r - \frac{1}{2}fr$ (see previous page). Of course, M is not materially conserved in the boundary layer because of the surface torque acting against the tangential wind. Nevertheless, if for an air parcel spiralling inwards in the boundary layer, the relative rate at which M is reduced by friction is less than the relative rate at which the parcel's radius decreases, then v will increase. One has to do a nonlinear boundary layer calculation to see if this will happen, but it is more likely to happen if the inflow is strong, since in that case, an air parcel undergoes fewer spiral revolutions on its way in to small radius and friction has a smaller path length along which to act.

We refer to the foregoing mechanism as the boundary-layer spin up mechanism. However, it is not independent of the classical mechanism because, as a consequence of the slaving property, a spin up of the tangential wind above the boundary layer is required for the maximum tangential wind in the boundary layer to increase. Observations and numerical modelling show the maximum tangential wind speed to be found in the boundary layer, supporting the foregoing interpretation.

The relatively high tangential momentum developed in the boundary layer is lofted into the convective clouds in the inner region of the vortex and spins up this region of the vortex above the boundary layer.

Boundary layer control of intensification

In the early stages of hurricane formation, while the primary circulation is still relatively weak, the inflow induced by deep convection dominates that which occurs in the boundary layer and the classical mechanism acts to spin up the nascent vortex. However, as the vortex strengthens, the boundary layer plays an increasingly important dynamical and thermodynamical role in the vortex intensification. As shown in some recent numerical simulations by Kilroy *et al.* (2016), the boundary layer inflow begins to dominate that induced by deep convection and boundary layer dynamics exert a progressively increasing control on the radii at which air ascends to feed the convection and on the maximum tangential wind speed that can be attained.

As the hurricane matures, deep convection tends to form into an annular ring at some finite radius from the rotation axis, the so-called eyewall cloud. In turn the cloud in this ring leads to subsidence inside the ring, which is free of deep cloud. This is the eye of the storm.

Since the deep convection feeds on moisture supplied by the boundary layer inflow and since the source of moisture lies at the ocean surface, boundary-layer thermodynamics exert a further important control on the intensification process. In particular, the thermodynamics influences the ability of the deep convection to ventilate the air that is converging in the boundary layer as discussed earlier.

Three dimensional aspects

As noted in the Introduction, it is only mature storms that are approximately axisymmetric and then only in their inner core region. In the genesis and intensification stages, deep convection is not organized into ring-like structures and the flow is quite asymmetric as depicted in Figure 4. Thus the flow generated by the convection is asymmetric. It is still possible to understand the intensification from an axisymmetric viewpoint, but then the flow asymmetries appear as "eddy terms" in the equations for the axisymmetric mean and if the flow is highly asymmetric, they must make an important contribution to the mean dynamical and thermodynamical equations, requiring a modification to the axisymmetric paradigm for intensification (e.g. Persing *et al*. 2013).

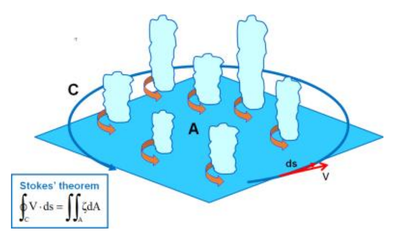

Figure 4. Schematic of a region of deep rotating updrafts with two hypothetical circuits indicated by circles. By Stokes' theorem, the relative circulation about either circle is equal to the areal integral of the relative vorticity enclosed by that circuit. See text for further discussion.

Since *M* is not generally conserved following air parcels when the flow is asymmetric (in that case azimuthal pressure gradients lead to changes in *M*), the spin up may be understood in terms of vorticity dynamics as indicated in Figure 4. At any instant of time, a simplified version of Stokes` theorem equates the integral of the vertical component of relative vorticity, ζ, over an area A enclosed by a closed loop C to the relative circulation about this loop, Γ. Here, Γ is the line integral of the horizontal velocity vector along the loop. Mathematically

$$\Gamma = \oint_C \mathbf{V}.d\mathbf{s} = \iint_A \zeta dA.$$

Imagine now a fixed loop surrounding a region of deep convection. If the convection is growing in an environment of cyclonic vertical vorticity, it will locally amplify this vorticity by the process of vortex tube stretching. However, because of continuity, vortex-tube stretching reduces the cross-sectional area of the enhanced vorticity and there is no net contribution from the stretching, by itself, to the circulation around the loop. What does contribute to this circulation is the horizontal flux of absolute vorticity into the loop by the convectively-induced inflow. A more comprehensive discussion of the vorticity dynamics must include the effects of the tilting of horizontal vorticity into the vertical. These and other aspects of vorticity dynamics are discussed by Haynes and McIntyre (1987).

In the axisymmetric case, the convectively-induced influx of absolute vorticity is analogous to the inward advection of M. Then, the absolute vertical vorticity, $\zeta + f$ = $(1/r)dM/dr$ and the circulation about a circular loop in Stokes` theorem is just $2\pi M$.

In the non-axisymmetric case shown in the schematic of Figure 4, a further consideration is the aggregation of convectively-amplified vorticity to form a cyclonic vortex core.

A new paradigm for hurricane intensification

Figure 5 shows a revised schematic for hurricane intensification. The essential differences between the classical paradigm and the new paradigm are:

- The classical mechanism involving the radial import of *M* above the boundary layer acts to spin up the outer circulation of the vortex and accounts for the growth in size of the vortex as measured, for example, by the radial extent of gale-force winds.
- The spin up of the maximum tangential wind occurs in the frictional boundary layer and the associated angular momentum is lofted into the vortex where the boundary layer terminates, thereby spinning up the tangential winds in the inner core in the free troposphere and what ultimately becomes an approximately axi-symmetric cloud comprising the eyewall.
- The intensification process is intrinsically three-dimensional on account of the asymmetric nature of rotating deep convection that develops in the cumulus zone of the vortex. The eddy terms in the azimuthally-averaged equations of motion are generally important and can lead to counter-gradient momentum fluxes, which act to accelerate the swirling and overturning circulations in the convective region of the vortex.

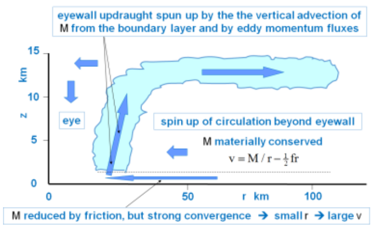

Figure 5. Schematic diagram illustrating the revised, axisymmetric view of hurricane intensification.

A unified view of tropical cyclogenesis and intensification

Insights into the asymmetric aspects of hurricane intensification emerged from early numerical studies of tropical cyclogenesis by Hendricks *et al*. (2004) and Montgomery *et al*. (2006). These papers drew attention to and explored the role of vorticity aggregation in the formation of a system-scale core of cyclonic vorticity. Dunkerton *et al*. (2009) found that a favourable environment for this aggregation to occur is a horizontally recirculating region in the low to mid troposphere within a tropical easterly wave. Recent calculations by Kilroy (personal communication) indicate that in such a recirculation region, the processes described above to explain hurricane intensification are essentially the same as those that operate during the genesis stage, although in the early stage, the frictional boundary layer plays a less prominent role. Moreover, in the early stage, the evolution is particularly asymmetric so that eddy terms make an important contribution in the azimuthally-averaged equations.

Kilroy's results offer a seamless view of genesis and intensification without the need to invoke separate mechanisms for these stages as traditionally taught in the classroom (e.g. Holton 2004).

Intensification of tropical lows over land

The unified view of hurricane formation and intensification has been shown to apply also to tropical lows that form and intensify over land (e.g. Smith *et al*. 2015, Kilroy *et al*. 2016, Tang *et al*. 2016). Over land, surface frictional stresses are higher than over the sea and the surface moisture fluxes are typically smaller. However, in the monsoon regime, surface moisture fluxes are adequate to maintain convective instability over land to a sufficient level for deep convection to be sustained near the centre of circulation of the low.

Effects of vertical wind shear

In the real world, tropical cyclone intensification usually takes place in environments where the background flow as well as the magnitude of the vertical shear are not negligible. While the presence of a uniform background flow contributes significantly to vortex translation, it leads also to the development of flow asymmetries because of surface friction (Thomsen *et al*. 2015). However, moderate to strong vertical shear leads to a significant change in vortex structure.

One effect of shear will be to tilt the vortex axis from the vertical (Jones 1995) and another will be to excite various types of wave motions (Reasor and Montgomery 2015, and references). In turn, these waves couple with the boundary layer and convection (Riemer *et al*. 2013, and references). Both the waves and the asymmetric motions they generate will collectively project on to the azimuthally averaged view of the new intensification paradigm in the form of eddy terms in the equations of motion. A recent review of some of the complexities of vertical shear in the context of tropical cyclogenesis is presented by Nolan and McCauley (2012).

Besides the tilting effect, the emerging picture is that moderate or weak vertical shear introduces new pathways by which relatively dry air from the low-to-mid troposphere may enter the moist envelope region of the vortex. The dry air strengthens or promotes mesoscale downdrafts that floods portions of the boundary layer with cool dry air, thereby reducing the level of convective instability (Riemer et al. 2013). The instability reduction lowers the ability of deep convection to ventilate the mass that is converging in the boundary layer.

Discussion

Over the last decade, considerable progress has been made in understanding the dynamics of hurricanes, and their interaction with their environment. Some of this work has highlighted the intrinsic three-dimensional nature of the intensification process. Some of this work has highlighted also the important role of the boundary layer in influencing the spin up rate and structure of storms. These latter advances have stimulated efforts to better quantify the relevant sub-grid scale parameters required for boundary layer formulations in forecast models used to predict these damaging storms.

A more in-depth discussion of the new intensification paradigm and its relation to previous ones is given by Montgomery and Smith (2014). Fluid dynamical aspects of the hurricane problem including an elaboration of the processes described in this article are discussed in a forthcoming paper by Montgomery and Smith (2017).

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