Vorticity thresholds in developing storms

Mike McGauley

Abstract

The evolution of vorticity in a developing storm is studied to reveal the relationship between the advection of absolute vorticity into a storm compared to the frictional losses at the surface. The findings suggest that an increase in planetary vorticity does not aid in the development of a storm, primarily due to the fact that inward radial winds are weakened through an adjustment caused by a negative angular momentum gradient. It is also shown that surface drag does not play a significant role in a developing storm.

MOTIVATION

The development of a tropical storm from a nascent disturbance has puzzled forecasters for many years. Although research has progressed significantly with regard to what properties are important for cyclogenesis, research has yet failed to determine the subtle, yet important, transition (or threshold) characteristics that separate a developing storm from a non-developing storm. In particular, absolute vorticity is considered an important feature for cyclogenesis. Yet, it is not clear as to what amount of vorticity is actually needed and how this vorticity interacts with the developing storm to allow for cyclogenesis.

BACKGROUND

A fully developed tropical storm gains energy by utilizing the water vapor taken from the ocean and converting it into heat at upper levels by the exothermic vapor to liquid phase transition. This heat, in turn, creates an inward pressure gradient near the surface that can advect angular momentum from the outer sections. This increase in angular momentum near the center is then offset by frictional drag at the surface. A storm that has balanced the inward advection of angular momentum with the frictional drag should (in principle) be at steady state with constant wind speed. However, this theory is known to be incomplete. For example, absolute angular momentum encompasses both planetary vorticity and relative vorticity. Any inward advection of either (or both) of these components should aid in development. Tippett et al. (2011) performed a Poisson regression (Figure 1) on cyclogenesis events related to absolute vorticity and found a relationship between the two only up to a value of $3.8 \times 10^{-5}$ s$^{-1}$ beyond which no additional absolute vorticity benefited cyclogenesis. Although an argument could be made that the weak relationship between additional absolute vorticity could be attributed to cooler ocean temperatures since additional absolute vorticity is generally associated with higher latitude, the research showed this was not an influence. The conclusion in their study was absolute vorticity beyond a certain ‘threshold limit’ did not aid in development of a storm.

ANALYSIS

In order to investigate the threshold phenomenon, numerical simulations using the Weather Research and Forecasting model (WRF), version 3.1.1 was used (Skamarock et al, 2008). The WRF model is a fully compressible, doubly-periodic model with a nested grid of 2km and 41 vertical levels. For each simulation the cumulus parameterizations and radiative schemes were disabled. To initialize each simulation, the horizontal parameters for temperature, water vapor and winds were represented by a single vertical profile taken...
from the Atlantic Main Development Region (MDR) thereby representing a highly conducive environment for cyclogenesis. Only a vertical
dependence in these parameters existed. In addition, simulations were performed on an f-
plane simulating a fixed latitude. Embedded on this initialized state was a weak modified
Rankine vortex that closely represents a weak
disturbance in the Atlantic Ocean (Pytharoulis and Thornicroft, 1999). The winds peak at 15m/s
at 3750m at a radius of maximum winds of 80km
decaying to 7.5 m/s at the surface. For each
simulation, only latitude was adjusted.

To investigate the angular momentum budget, Figure 2 shows the various components
analyzed. Two sections are created to investigate
the relationship between the momentum fluxes
between the lower and upper sections of the
developing storm. The top of the upper cylinder
is the top of the domain at approximately 20 km
while the bottom represents the ocean surface.
The inner cylinder is arbitrarily chosen at 5 km
to analyze momentum fluxes in the center of an
organizing storm. The outer radius of the
cylinder is chosen to be 100km to contain the
initial Rankine vortex with a RMW of 80 km.
The height of the lower cylinder was also
arbitrarily chosen at an eta level of 20
(approximately 9 km) to compare the lower
momentum fluxes to the outward propagating
fluxes at the top.

To quantify the fluxes into and/or out of the
lower and upper cylinders, Equation 1 is used.
Although the inner radius of the cylinder could
contribute to the momentum budget, analysis
showed it had negligible contribution and is
therefore excluded from the momentum budget.

\[
\text{momentum flux} = \int_0^{\text{Ztop}} \int_0^{100\text{km}} \rho(r, z) M(r, z) U_{\text{max}}(r, z) r dz (1)
\]

Equation 2 quantifies the momentum flux from
the lower cylinder into the upper cylinder while
Equation 3 quantifies the momentum lost to the
ocean from surface drag.

\[
\text{upward momentum flux} = \int_0^{\text{Ztop}} \int_0^{100\text{km}} \rho(r, z = \text{Ztop}) M(r, z = \text{Ztop}) W(r, z = \text{Ztop}) r dr (2)
\]

\[
\text{surface drag} = \int_0^{\text{Ztop}} \int_0^{100\text{km}} \rho(r, z = 0) U^2(r) r dr (3)
\]

**RESULTS**

Figure 3 shows the evolution of the modified Rankine vortex at a latitude of 7 degrees. The top
panel shows the angular momentum budgets of the
lower region (blue), the upper region (green),
the drag (red) and the combined results (black).
As shown by the sea level pressure (bottom
panel), the storm never develops. Although there
is a large initial advection of angular momentum
at the lower boundary until Day 3½, a precipitous
drop follows preventing any deepening of the
storm. Beyond Day 3½, any advection
of momentum at the bottom is significantly offset
by the outward momentum flux at the upper
region (although not completely). The combined
momentum beyond Day 3½ fluctuates from a net
positive to net negative with a mean fluctuation
of zero preventing the storm from ever
accumulating enough momentum to strengthen.
In addition, since surface winds never increase
beyond that of the initial vortex, surface drag
never plays a role in the momentum budget.

By increasing latitude to 9 degrees, Figure 4
shows the evolution of the modified Rankine vortex to a
developing storm (albeit late, at Day 4). Again, as with Latitude 7 degrees, there
is a large initial increase in combined angular
momentum followed by a large drop. Other
common features to the Latitude 7 degree
simulation is the inward angular momentum flux
is instantly offset by outward flux aloft and the
drag term has no affect throughout the
simulation. The differences in the Latitude 9
simulation come near the end of the simulation
period (Day 3½) when a quick drop in combined
angular momentum is quickly restored. Fluctuations beyond this time are mostly positive and the integrated angular momentum begins to allow development at Day 4. Again, drag has no contribution to the momentum budget.

Figure 3: Top: Momentum budget for a non-developing storm at 7 degrees latitude. Bottom: Minimum sea level pressure.

The third simulation (Figure 5) at a latitude of 13 degrees is the first rapid development simulation. Although the drop in angular momentum at Day ¾ occurs, beyond this time, the inward angular momentum at the surface remains above zero until Day 2¼. Although the outward angular momentum flux aloft is offsetting the inward angular momentum, the offset is not strong enough and the integrated combined angular momentum is large enough to allow development at Day 2. At this point, drag now contributes to the momentum budget and its combination with the outgoing momentum aloft is enough to reduce the combined angular momentum. At this stage of development, the continued deepening of the storm seems to be due to the slight positive mean value of the combined angular momentum. At Day 3½, however, the mean value of the fluctuations approaches zero and the storm begins to weaken.

For the final simulation at Latitude 25 degrees, Figure 6 shows approximately the same evolution as Figure 5: the initial increase followed by a sudden drop, the integrated angular momentum causing a quick development, the subsequent deepening of the storm, the onset of drag, and the subsequent weakening of the storm.

Figure 4: Top: Momentum budget for a late-developing storm at 9 degrees latitude. Bottom: Minimum sea level pressure.

Figure 5: Top: Momentum budget for a developing storm at 13 degrees latitude. Bottom: Minimum sea level pressure.
The significant difference between the two simulations that could affect cyclogenesis comes at the beginning of the simulation. In Figure 5 (latitude 13 degrees), at Day ¼, the value of the combined angular momentum is approximately $4.0 \times 10^{15}$ kgm²s⁻² while that of Figure 6 (latitude 25 degrees) at the same time is only half of that value at $2.0 \times 10^{15}$ kgm²s⁻². This is a contradiction considering there is a lot more planetary vorticity available at the higher latitude. However, by analysis of Equation 1, another component to the inward momentum flux are the radial winds.

To investigate if converging winds are indeed weaker at higher latitudes, Figures 7 and 8 show radial winds at Latitude 13 and Latitude 25 degrees, respectively. The center of the storm is positioned at the center of the grid box. Although both figures show converging winds around the center of the storm (with the exception of a small zonal outward jet) the strength of the converging radial winds at Latitude 13 degrees is clearly stronger than Latitude 25 degrees.

**CONCLUSIONS**

An interesting conclusion from the work by Tippet et al (2011) is that additional absolute vorticity does not coincide with additional cyclogenesis events. Although a developing storm requires the inward advection of angular momentum near the surface, and an increase in latitude ‘should’ allow for more advection of planetary vorticity, present studies suggest the advantage of increased latitude is largely offset by reduced radial winds.

These reduced radial winds are likely due to an increase in inertial stability. Since the Rankine vortex is fixed in magnitude, thereby fixing the radial pressure gradient, an adjustment of this vortex to higher latitudes will cause the winds to adjust outwards to a larger radius. This adjustment process prevents large radial inflow and reduces the advected angular momentum. The storm, therefore, cannot initially benefit from the additional planetary vorticity. Although additional planetary vorticity beyond a certain latitude is shown not to further aid cyclogenesis, the storm must have enough planetary vorticity at lower latitudes to advect ‘enough’ angular momentum inwards. Although this research could not quantify what ‘enough’ is, this research suggests at least a day of nearly uninterrupted inflow of angular momentum will allow for development.
REFERENCES

