The combined effects of beta-shear and environmental shear on a dry tropical cyclone in a numerical model

William A. Komaromi

Rosenstiel School of Marine and Atmospheric Science
University of Miami, Miami, FL

1. INTRODUCTION

High values of vertical wind shear have been shown to inhibit tropical cyclone (TC) genesis and intensification, while low shear values favor genesis and intensification (Gray 1975). Studies have demonstrated that shear generates a tilt in TC core, resulting in persistent wavenumber-1 asymmetry in vertical motion (e.g. Jones 1995; DeMaria 1996; Bender 1997; Frank and Ritchie 1999, 2001). This asymmetry weakens convection in the downshear-right sector of the storm. The TC weakens due to the advection of the upper-level structure of the TC downstream, less optimal eye warming forced by asymmetric convection, and outward mixing of moist static energy by transient eddies in upper-levels (Frank and Ritchie 2001).

Jones (1995, 2004) has shown moist processes are not necessary for TC to maintain structure in presence of vertical shear. As vortex begins to tilt due to shear, structure of thermal fields adjust such that vortex reaches new balanced state, with only gradual weakening over course of several days. Dry simulations of TCs in vertical shear are possible. Similar to moist simulations, wavenumber-1 asymmetry is produced and descent (–w) develops on the downshear hemisphere of the TC. Ritchie and Frank 2007 (RF07) simulate a TC on a β-plane using MM5 version 5.3, with a 5 km resolution inner nest, 23 vertical levels, Burk-Thompson boundary layer, and full moist physics. This configuration is unprecedented amongst studies of the β-effect on an idealized vortex. In a β-plane, β-shear may exist over the TC center due to a change in strength of β-gyres with height corresponding to a vertical change in strength of the vortex. β-gyres are produced by the advection of planetary vorticity by the storm circulation and the restraint of conserving absolute vorticity. A +ζ (-ζ) anomaly develops to in the southwest (northeast) quadrant of the cyclone, resulting in a self-induced β-advection. RF07 suggest that previous simulations that do incorporate β-plane (e.g., Chan and Williams 1987; Fiori and Elsberry 1989; Carr and Williams 1989) are too low resolution to resolve low-level jet that develops through core of TC due to β-shear. RF07 compare effects of β-shear versus no β-shear (in an f-plane) without background environmental shear. They find persistent NNW shear develops over storm center as a result of interaction between primary circulation of TC and gradient in absolute vorticity. An asymmetry resembling that produced by environmental shear is observed.

This research seeks simulate the impacts of varying between an f-plane and a β-plane, and between easterly shear and westerly shear, on a TC-like vortex. An identification of β-shear in the model is also sought.

2. METHODOLOGY

The storm motion and vertical profile of a modified Rankine vortex in hydrostatic and gradient wind balance is analyzed in this study (Mallen et al. 2005). The vortex is generated from a number of prescribed parameters, namely, a radius of maximum winds (RMW) of 90 km, a maximum tangential velocity (V_{max}) of 60 ms⁻¹, and a decay rate of 0.4. A mean zonal background flow in geostrophic and hydrostatic balance is added, and allowed to vary between easterly and westerly, and from 5 ms⁻¹ to 10 ms⁻¹. In the case of 5 ms⁻¹ easterly (westerly) shear, the zonal wind is set to zero (5 ms⁻¹ easterly) at and below 850 hPa and transitions to 5 ms⁻¹ (zero) easterly flow at and above 200 hPa, with a smooth, sinusoidal transition between the two levels (Fig. 1). In the case of 10 ms⁻¹ easterly (westerly) shear, the zonal wind is set to 2.5 ms⁻¹ westerly (7.5 ms⁻¹...
easterly) flow at and below 850 hPa and transitions to 7.5 m/s easterly (2.5 m/s westerly) flow at and above 200 hPa. Note that for all four shear profiles, the 850-200 hPa layer mean flow is 2.5 m/s easterly.

The vertical tilt of the center of the TC with height will be assessed using rose diagrams. The center of the diagram will correspond to the center of the vortex at 850 hPa, with the difference \( (r, \theta) \) in the position of the vortex from the 850 hPa location at 700, 500 and 300 hPa represented by successive vortex center tick marks on the rose diagrams.

3. Results

3.1 Track of Vortex

The vortex propagates with a net westward motion in all simulations (Fig. 2). This result is expected, considering that all simulations are initialized with an 850-200 hPa deep layer 2.5 m/s easterly wind. However, the magnitude of westward propagation and the magnitude and direction of meridional propagation varies considerably amongst the various simulations. In the case of easterly (westerly) shear and an f-plane, vortex motion during the first 24 h is slightly to the left (right) of the mean environmental flow and consistent with the literature. However, after this initial timeframe a discrepancy emerges. Regardless of the magnitude of the shear or whether or not Coriolis varies with latitude, the vortex propagates to the left of the mean flow when initialized in a westerly shear environment and to the right of the mean flow in an easterly sheared environment beyond day 1. For westward-propagating vortices, this equates to a more southerly motion of the vortex in westerly shear. These results appear to be contradictory of the results typically seen in the literature.

An understanding of the observed discrepancy between the literature and the presented results begins with acknowledging the fact that the initial vortex has a higher \( V_{max} \) than any other initial vortices in the literature, and is also relatively broad. Since the shear is balanced by the temperature gradient, and the temperature gradient is allowed to vary with time in the model, it is possible that the cyclone is significantly modifying the environmental temperature gradient through advection. This appears to exactly be the case, resulting in a shear vector that changes substantially throughout the simulation. For the simulation with 10 ms^-1 easterly shear, the initially zero meridional shear grows to -7.5
ms\(^{-1}\) within 30 h of initialization (Fig. 3), due to a cyclone-induced zonal temperature gradient. Zonal shear increases to -12.5 ms\(^{-1}\) during the initial 24 h, but then decreases to only -3.0 ms\(^{-1}\) beyond day 3. As the dry cyclone weakens with time, its ability to modify the temperature gradient also diminishes. So for large \(t\), as the cyclone moves away from the vortex-modified environment into an unperturbed environment, shear actually begins to approach its initial values again. However, this is not until after the majority of the simulation has completed, and the TC has already propagated several thousand kilometers in an environment with a shear profile vastly different than what was initially specified.

Fig. 2: Tracks of all simulated tropical cyclones in 12 h increments through 120 h. The vortex is initially located at \((x,y) = (2750 \text{ km, } 2200 \text{ km})\).

It is also apparent that the \(\beta\)-effect is a significant contributor to storm motion. Since \(\beta\)-gyres induce a southeasterly motion vector across the TC, for a westward propagating vortex, the \(\beta\)-effect will act to displace the TC north and further west. The 5-day displacement due to the \(\beta\)-effect is as much as 1475 km in the case of 10 ms\(^{-1}\) westerly shear, with a mean difference of 1163 km across all simulations.

Fig. 3: Mean winds and wind shear averaged over nested domain for 10 ms\(^{-1}\) easterly shear on an f-plane.

An interesting occurrence is that the vortex in westerly shear decelerates slightly with time, while the vortex in easterly shear initially propagates eastward, reverses direction, and then accelerates westward. Both observations can be attributed to the fact that the region of strongest tangential wind “lifts” with time, and therefore the level of maximum environmentally-induced steering is of higher elevation with time (Fig. 4). The lifting of the low-level vortex center can be primarily attributed to vertical advection induced by the tilt of the vortex. In the absence of moist convective processes, a replacement low-level vortex is not generated and the surface cyclone decays. In the case of westerly shear, this means that the strongest part of the cyclone is subject to a weaker steering flow aloft with time (Fig. 1b,d), and therefore decelerates. In the case of easterly shear, the vortex is initially subject to surface westerlies, and therefore propagates eastward. Once the vortex core lifts to lower pressure levels, the cyclone is exposed to a reversal of the flow (Fig. 1a,c) and correspondingly accelerates westward at later times.
3.2 Vertical Profile

Vertical wind shear is one attribute of the vertical structure of a background environment, and therefore naturally necessitates examination of the vertical structure of the TC within such an environment. One immediate effect of shear visible within the first hour of simulation is that shear induces a vertical tilt of the vortex. Logically, in the presence of westerly shear, the TC will be advected further east at the upper levels than at the lower levels. This process is evident in these simulations. However, at longer time periods, it becomes obvious that the actual tilt of the vortex is much smaller than that which would be observed if the tilt were due to a relative advection of the upper levels of the vortex alone. For example, in the presence of 5 ms$^{-1}$ westerly shear, the 200 hPa vortex should be 1296 km further east than the 850 hPa vortex after 72 h. However, the actual vertical displacement is only 30 km. This phenomenon can be explained through the development of a secondary circulation in the TC. While the vortex is initialized in the absence of vertical motion, within minutes of initialization, a net inward momentum flux develops at the surface, as does a net outward momentum flux aloft. This is expected of a TC-like vortex in gradient wind balance. In order to close the circulation, rising motion develops in the eyewall of the TC, along with sinking far from the center. The shear acts not only to induce wavenumber 1 asymmetry in the u and v structure of the TC, but also in the w structure (Fig. 5). Higher potential temperature air is advected towards the surface in the region of $-w$, while lower potential temperature air is advected aloft in the region of $+w$. The end result is a balanced vortex in which the mass fields ultimately adjust to prevent the vortex from shearing apart (Jones 1995).

The vertical profiles of the TC are depicted in a rose diagram format. Vortex tilt was calculated both hourly and daily in order to discern short- and long-term temporal variations at 700, 500 and 300 hPa relative to the 850 hPa level in each simulation. There is initially zero vortex tilt. At successive time periods, there is significant variation in the vortex tilt with time, due to both the temporal variation of the shear vector within a varying thermal gradient (section 3.1) and vortex centroid oscillations (section 3.3). However, an examination of the mean vortex tilt in each environment can nonetheless provide some enlightenment. In both easterly and westerly shear environments, as shear increases, the vortex tilt increases. Secondly, the effect of $\beta$-shear is evident in the time-mean vortex tilt. Given equal background shear direction and magnitude, the vortex tilt is consistently lesser for a northwesterly tilting vortex in a $\beta$-plane and consistently greater for a southeasterly tilting vortex. This implies that, on a $\beta$-plane, an additional northwesterly shear vector exists in addition to the background flow. In the case of 10 ms$^{-1}$ easterly shear, the mean 850-300 hPa vortex tilt is 31 km at 310° (northwesterly) on an f-plane and 27 km at 290° on the $\beta$-plane. While not a massive shift in vortex tilt, this is certainly evident of
a β-shear modifying the total shear imposed on the TC.

Fig. x: Simulation of vortex in 5 ms⁻¹ easterly shear on (a) an f-plane; (b) a β-plane. The center of the diagram corresponds to the vorticity centroid at 850 hPa, and each successive tick mark represents the relative locations (km,deg) of the centroids at 700, 500 and 300 hPa at 24 (blue), 48 (cyan), 72 (green) and 96 h (yellow) into the simulation.

Tuleya and Kurihara (1981) proposed the idea that westerly shear is more detrimental to TCs than easterly shear, due to the β-effect. A northwesterly β-shear should be additive to a westerly environmental shear and counteractive to easterly environmental shear. However, in this study the strength of the vortex after 5 days is nearly identical with and without the β-effect. This is likely another effect of the time-varying environmental shear producing inconsistent results.

3.3 VORTEX CENTROID OSCILLATIONS

While the various shear regimes induce a variety of distinct mean vertical tilts as described in section 3.2, there is a large spread in the tilt with time in any particular simulation. Setting aside the aforementioned processes that may contribute to a time-varying change in vortex tilt, an observable oscillatory nature to the vorticity centroid is evident. Relative to the 850 hPa centroid, the centroids of levels above tend to increase then decrease in r and θ in a cyclonic, oscillatory nature.

Fig. x: 300 hPa vorticity centroid oscillations relative to 850 hPa centroid. Successive 300 hPa relative centers are located at x marks in 4 h increments. The red line tracks the variation of the location of the centroid with time, with time increasing cyclonically.

Vortex centroid oscillation begins with the vortex nearly vertically stacked, reach a maximum in r at 1π oscillation, and return to a nearly vertically stacked position again at one complete rotation, or 2π oscillations. The period of the first oscillation in these experiments ranged between 22 and 26 h, which are about half of the 44 h found in Jones (2004). Also, the mean radius of oscillation in this study was found to be 12 km, which is smaller than the roughly 18 km radius found in Jones (2004). The balanced flow associated with the tilted PV anomaly penetrates upwards and downwards and leads to the upper and lower portions of the anomaly rotating cyclonically about the mid-level vortex centre. This rotation rate has been shown to depend upon the parameters which determine the Rossby penetration depth (Khandekar and Rao 1974; Jones 1995; Smith et al. 2000). For an intense atmospheric vortex, the Rossby penetration depth can be defined as:

\[ R_{pd} = \frac{L}{N} \sqrt{f_{1oc}(f + \zeta)} \]

where \( f_{1oc} = f + 2V_T/r \), f is the Coriolis parameter, \( V_T \) the tangential wind, r the radius, \( \zeta \) is the vertical component of relative vorticity, L the horizontal scale of the PV anomaly and N the Brunt-Vaisala frequency (Hoskins et al. 1985; Shapiro and Montgomery 1993).
For large penetration depths, the upper and lower portions of the cyclonic vortex can execute many rotations. In this case, the vortex track contains small-scale oscillations about the direction of the deep-layer-mean flow (Jones 2000a). For the vortex in this study, with \( V_T = 60 \text{ m/s} \), compared to \( 40 \text{ m/s} \) in Jones (1995), the oscillations should be of smaller radius and more rapid. Similar results have been concluded in terms of the Rossby deformation radius (Reasor et al. 2004).

4. SUMMARY

High resolution WRF-ARW simulations have been utilized in this study to depict the TC motion, vertical structure, and oscillations of the vortex centroid associated with environmental and \( \beta \)-shear. Vertical shear induces a wavenumber 1 asymmetry that advects cyclonically about the TC. Shear causes the vortex to tilt in the vertical, but due to a secondary circulation and the balance of mass fields, the top of the vortex is not simply advected apart from the low-level vortex. This tilt has been demonstrated to be proportional to the magnitude of the shear. It has also been shown that accounting for the \( \beta \)-effect can mean the difference of 1000+ km in a 5 day forecast.

Some inconsistencies in the vortex motion as compared to the literature have been associated with the both the strength of the initial vortex used in this study, as well as the freedom in the model for the vortex to modify the zonal thermal gradient and thereby meridional shear. Once this is accounted for, the results are consistent. Oddities associated with the vortex changing direction have been associated with the vertical advection of the strongest level of the vortex with time amid a vertical wind profile that switches from positive to negative with height.

Finally, the effect of \( \beta \)-shear is evident in centroid difference diagrams in polar coordinates, and must be accounted for in determining the total shear. It was also shown that the rate of oscillation of the vortex on its vertical axis is proportional to the strength of the storm, while the time it takes to complete such an oscillation is inversely proportional.

REFERENCES


