8B.5

Effects of Cumulus Parameterizations on Tropical Cyclone Potential Vorticity Structure and Steering Flow

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1. BACKGROUND and MOTIVATION

Tropical cyclone (TC) motion is determined by the advection of the cyclonic portion of TC potential vorticity (PV); the flow that advects the TC PV, the *steering flow*, is typically calculated by azimuthally and vertically averaging the wind field centered above the TC through some depth of the troposphere. Many strategies exist for defining an accurate steering flow column, but while relationships have been observed between TC intensity and depth of TC steering flow and between TC intensity and TC PV structure, no relationship between TC PV structure and TC steering flow has been quantified.

Chan and Gray (1982) have shown that the wind, averaged between 500 and 700 hPa and between 550 and 770 km radius, most closely correlates with TC motion. Other studies have shown a more complex relationship between a TC and the winds that drive its movement. For example, Simpson (1971), Dong and Neumann (1986), Pike (1987), and Velden and Leslie (1991 -- hereafter VL) have noted that relatively weak TCs move with a shallow lower-tropospheric flow, while more intense TCs move with a deeper-layer flow. VL suggest a hypothesis for this relationship: increases in the intensity of a TC are "associated with greater vertical development of the cyclonic vortex, which in turn is advected by an environmental flow of greater depth." Using a barotropic track-forecasting model, VL demonstrated that mean forecast errors in TC tracks may be reduced if the depth of the vertically-averaged initial wind analysis is based on the TC intensity.

The numerical simulations of the morphology and evolution of the PV associated with Hurricane Bob by Wu and Kurihara (1996) support the existence of a relationship between vortex intensity and vortex depth (VI-VD). In particular, their results (based on the GFDL hurricane model) showed that the height of the PV column associated with Bob decreased with time as the storm weakened. The lack of attention that the literature has given to the VI-VD relationship in TCs of various intensities (including relatively weak TCs) suggests that the structure-steering relationship needs further investigation. In the present study, we wish to quantify the relationship between the PV structure of a TC and its corresponding best-fit steering flow depth.

Our initial efforts to explore this relationship will focus on the diagnosis of the TC PV structure. Unlike the mid-latitude cyclone, wherein the three-dimensional PV distribution is linked to complex near-surface and upper tropospheric frontal structures, the PV structure of a TC is comparatively simple: observational and modeling studies have shown that it may be viewed as a cyclonic PV column that is located above a surface equivalent potential-temperature maximum and beneath an elevated dynamic tropopause (Shapiro and Franklin 1995; Wu and Emanuel 1995a,b; Shapiro 1996; Wu and Kurihara 1996). The PV structure of an observed TC is dependent most on the distribution of heating associated with phase changes of water substance, and friction in the boundary layer. The diabatic heating associated with phase changes in water substance results in a redistribution of PV wherein PV is depleted aloft and increased the column near the TC's center. As the PV structure of the TC is changed, the portion of the environmental flow which most effectively advects the TC center is also changed. Therefore, a relationship between the changes in TC PV structure induced by diabatic heating and changes in TC steering can be inferred, and it is the goal of this study to quantify this relationship.

In model simulations, the PV structure of a TC is determined, in part, by the distribution of diabatic heating within the storm, which is governed largely by the explicit and parameterized representation of cumulus and the ice physics used in the simulation. In this presentation, an ensemble of hurricane simulations, differing only in the choice of cumulus parameterization schemes chosen, are run to test the hypothesis that the choice of cumulus parameterization effects hurricane steering through changes in the PV attributed to the heating. Since the only change between model runs is the choice of cumulus parameterization, the changes in the PV structure for each model run must be diabatically generated. We expect that changes in storm track for each model run can be diagnosed from changes in the PV structure.

Because we are attempting to understand how modeled thermodynamic processes affect the track of a modeled storm, we do not require our hurricane simulations to be accurate representations of an observed hurricane.

2. METHODOLOGY

a) Model setup

The NCAR/Penn State MM5 model is used to perform 30 km, 23 sigma level, 96-h simulations of Hurricane Andrew (1992) starting from the time that the storm was declared a tropical depression (0000 UTC 8 August 1992). The model was initialized using 2.5° x 2.5° NCEP final analyses available from the National

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Center for Atmospheric Research (NCAR) as data set DS83.0. A 'bogus' vortex was inserted at the initial time to represent the nascent TC in the initial conditions. The five model simulations differed only in choice of cumulus parameterization: Kain-Fritsch (KF), Kain-Fritsch 2 (KF2), Grell, Kuo, and Betts-Miller (BM). Figure 1 shows the time evolution of mean sea level pressure for each of the runs as well as the actual evolution of the TC as defined by 12 hour observations. Excluding the Kuo run, all other model simulations weaken the hurricane for the first 30 hours of integration. The Kuo run, on the other hand, never re-intensifies.

Figure 1 is a plot of minimum sea level pressures for the entire 96 hour run of each model simulation. In addition, the actual sea level pressure minimum of Hurricane Andrew (1992) as defined by 12 hour observations is also presented. The figure illustrates the strong deviation of all of the model simulations with the real world case. Note the adjustment of the minimum sea level pressure that occurs during the first 18 hours of spin up.

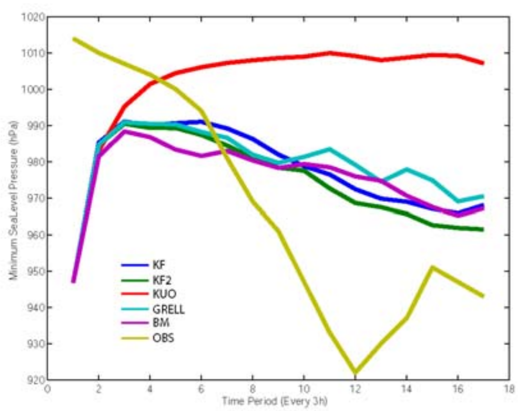

Figure 1. Minimum sea level pressure from model initialization to 96 hours. The actual minimum sea level pressure of Hurricane Andrew (1992) at the same time is also shown.

b) Computation of PV "center of mass"

For each simulation, Ertel PV was calculated on a 35 x 35 grid point volume centered on the hurricane's minimum sea level pressure. A PV 'center of mass' (hereafter, COM) was calculated for the volume. The nearest integer-value for the vertical position of the PV COM is then used as the vertical coordinate of the COM. We expect that since TC motion can be diagnosed by advection of the PV tower, the best-fit steering flow column should be (nearly) centered on the vertical position of the PV COM.

c) Computation of Steering Flow

We perform layer-averages of the wind field centered on the PV COM. Since the level of the PV COM corresponds to a half-sigma level, the layer-average wind field consists of layer averages for a given number of full sigma levels above and below the PV COM, which are then averaged together and weighted by the depth of the sigma layer between two consecutive full sigma levels.

PV-centered steering flow columns are computed for as many thicknesses as possible, which usually ranged from two to 16 sigma levels deep (only even numbers of full sigma levels were used in this computation to ensure the steering column was centered on the PV COM). For each PV-centered steering flow column of a given depth, a steering flow column was also computed for every possible column of the same depth. For example, for the two-level deep steering flow columns, columns encompassing every range from sigma levels 1 and 2 to sigma levels 22 and 23 were calculated.

d) Comparison of Steering Flow Columns

The steering flow column centered over the PV COM is compared to all other columns of the same vertical depth. We calculate the modeled hurricane motion vector (MHMV; u_m, v_m) at time, *t*, by evaluating the motion of the hurricane minimum sea level pressure from time *t* = *t* - 3h to time *t* = *t* + 3h. For a given column, we define the *steering flow vector* (u_s, v_s) as the average wind vector in that column weighted by the sigma-depth of each of the layers comprising the column. For the purpose of identifying that steering flow vector which best matches the MHMV, we define a cost function, *J,* which measures the deviation of the MHMV from the steering flow vector:

$$J = (u_s - u_m)^2 + (v_s - v_m)^2 .$$

The cost function is calculated for both the PV-centered steering flow columns and the non-PV-centered steering flow columns. To eliminate the effects of the adjustment of the model flow to the imposed initial vortex, the values of *J* for each steering flow column are analyzed beginning 18h into the simulation. Those instances for which the lowest *J* value corresponds to either the PV-centered steering flow column or a column centered within an adjacent σ-layer are counted as a "success" for the PV-centered steering flow column.

3. PRELIMINARY RESULTS

Figure 2 is a 5-panel plot of west-east cross-sections of PV at 48 hours into each model simulation. Every model simulation except the Kuo scheme run has a robust PV tower. The intensity of the PV in the Kuo scheme is much weaker (roughly half the strength of the other model simulations) and the structure of the PV in the Kuo scheme has a down-shear tilt.

a) Effectiveness of a PV-Centered Steering Flow Column

For each model simulation except the Kuo scheme run, steering flow columns of depths 2, 4, 6, 8, 10, 12, 14, and 16 full sigma levels deep were calculated. The Kuo scheme run does not have a 16 level deep column because the PV COM was too high to center a 16 level deep column over it. A value for *J* is calculated for each time analyzed. Finally, the final two time periods of the

Kuo scheme run take the center of the TC too close to the western boundary of the MM5 model run to extract a 35 by 35 point grid. After all of these considerations, there were 25 time periods available for analysis for all parameterizations except for the Kuo scheme run, and 23 time periods for the Kuo scheme run.

The table below shows the number of times the PV-COM was considered the 'best fit' steering flow column for various parameterizations and depths of steering flow columns:

	KF	KF2	Kuo	Grell	BM
2 Levels	12	21	4	18	10
4 Levels	15	22	4	21	13
6 Levels	16	12	4	21	13
8 Levels	13	14	6	17	14
10 Levels	16	9	8	15	15
12 Levels	18	15	5	16	19
14 Levels	21	16	5	11	14
16 Levels	22	18	N/A	17	13
Average	16.625	15.875	5.143	17.000	13.875

Table 1. Number of time periods the PV-centered column is considered the 'best fit' column. For each of the model simulations using the KF, KF2, Grell, and BM schemes, 25 time periods were analyzed. For the Kuo scheme run, 23 time periods were analyzed.

These initial results indicate that, with the exception of the Kuo scheme, the PV-centered steering flow column out-performs any other arbitrarily chosen steering flow column of the same depth more than half the time. The large deviation of the Kuo scheme from both the typical PV profile and the success of a PV-centered steering flow column suggests that the PV structure of the Kuo scheme TC has a profound impact on the optimal steering flow level.

4. FUTURE WORK

While these results are supportive of the hypothesis that TC motion is governed by advection of the PV tower's PV 'COM', the question of what the effect of changing the cumulus parameterization of the model has on the PV structure remains unanswered. The analysis of PV-centered steering flow columns is predicated on the hypothesis that the change in cumulus parameterization results in changes in the diabatic redistribution of PV. These changes in the Lagrangian PV tendency result in changes in the PV COM. An analysis of the choice of cumulus parameterizations will focus on the drastic changes in PV structure brought on by the Kuo scheme, and the effect it has on the accuracy of a PV-centered steering flow column.

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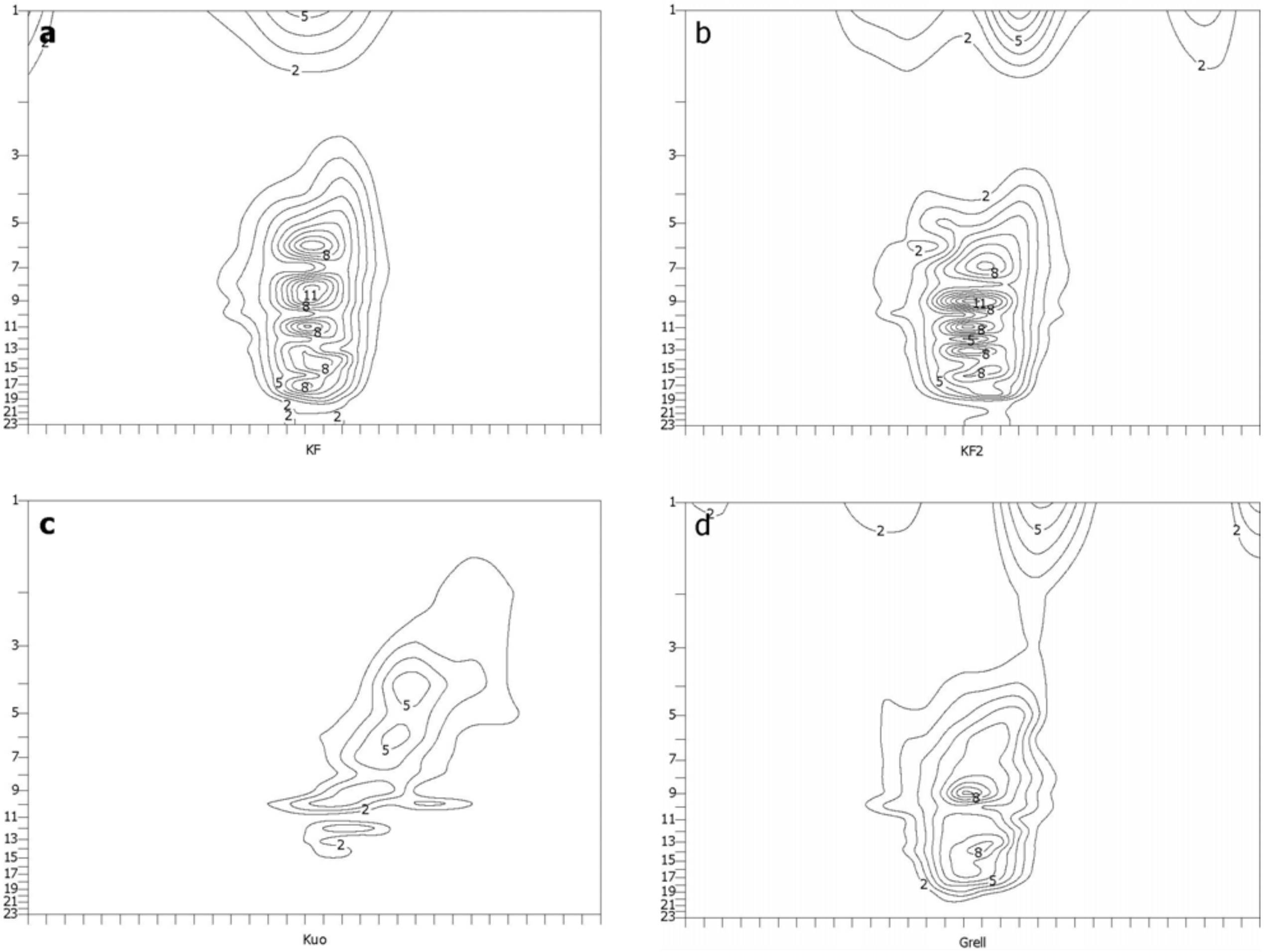

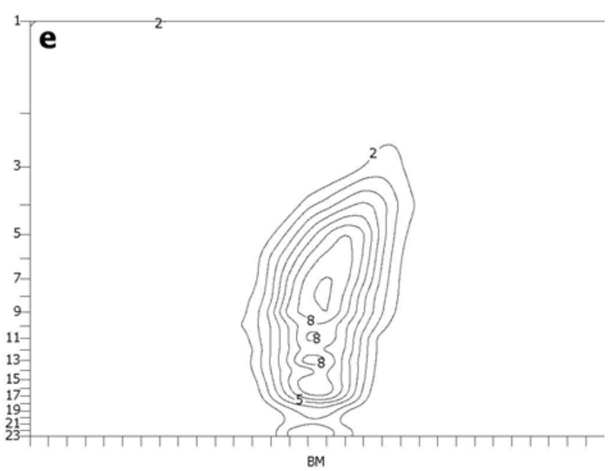

Figure 2. West-east cross sections of PV through the TC center for each model simulation. Contours are in PVU with a 2 PVU minimum. Cross sections were taken at 48 hours into each model run.

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