

VORTEX ROSSBY WAVES AND HURRICANE EVOLUTION IN THE PRESENCE OF CONVECTION AND POTENTIAL VORTICITY AND HURRICANE MOTION

Michael T. Montgomery
Department of Atmospheric Science
Colorado State University
Fort Collins, CO 80523
(970)491-8355, mtm@charney.atmos.colostate.edu

Lloyd J. Shapiro
Department of Atmospheric Science
Colorado State University
Fort Collins, CO 80523
(970)491-0604, shapiro@chandra.atmos.colostate.edu

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LONG-TERM GOALS/OBJECTIVES:

a) The first purpose of this study is to elucidate the physical mechanisms underlying changes in hurricane structure and intensity, including rapid deepening and eyewall replacement cycles. Specifically, the role of cumulus convection and the atmospheric boundary layer in the evolution of outward-propagating Rossby wave disturbances and their interactions with a developing hurricane is being investigated.

b) The second purpose of this study is to describe and understand how three-dimensional asymmetric interactions between a hurricane and its environment determine the hurricane's motion. Specific questions to be addressed include: What atmospheric levels steer the storm? What spatial scales?

APPROACH:

a) Second possibly only to track, prediction of hurricane intensity is the most important problem facing forecasters. Rapid intensification, and the development of secondary eyewalls that lead to a cycle of intensification and weakening, are significant events in the evolution of a hurricane, whose origins are not well understood. Propagating and stationary spiral bands are ubiquitous asymmetric features of a hurricane, whose dynamics is central to understanding the storm's development. Recently, Montgomery and Kallenbach (1997; hereafter MK) investigated the characteristics of spiral bands by studying the properties of outward-propagating Rossby waves whose restoring mechanism is associated with the radial gradient of the storm vorticity. These waves provide a mechanism for transferring energy from the hurricane's inner core to larger radius. Thus, they are fundamental to the process by which a hurricane responds to a changing environment, and may play an important role in hurricane intensification as well as the creation of secondary eyewalls.

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A hurricane is essentially a thermodynamic engine, and its eyewall and spiral band features are convective in nature. Therefore, any complete understanding of the role of asymmetric wave disturbances in a storm's evolution must include the influence of cumulus convection on both the symmetric vortex and the asymmetries. The approach of the present study is to use a three-layer primitive equation model to couple the waves investigated by MK to the boundary layer and convection.

b) In recent research supported by ONR (Shapiro 1996) a piecewise inversion technique was developed and implemented to deduce the three-dimensional distribution of potential vorticity (PV) that contributed to the deep-layer mean (DLM) flow that steered Hurricane Gloria of 1985 toward the northwest. In the piecewise inversion, advantage was taken of the near-linearity of the weak asymmetries near the hurricane's core, and of PV in the environment. Wind anomalies attributable to pieces of anomalous PV restricted to cylinders of different radii centered on the hurricane were evaluated. The DLM wind that steered Gloria was found to be primarily attributable to PV anomalies confined within a cylinder of radius 1000 km and levels 500 mb and above, including positive anomalies associated with a cold low over Cuba. The results imply that in order to improve prediction of short-term changes in the environmental flow field that steered Gloria, measurements of upper-level winds and heights are required at least out to 1000 km. A larger sample of cases is required, however, to confirm the results. The present project continues the analysis by performing a piecewise inversion for other hurricanes in addition to Gloria.

RESULTS:

a) Completed experiments with a dry version of the three-layer model essentially replicate those of MK (in a quasi-linear context) and Moeller and Montgomery (1997) (in a weakly nonlinear context). A weak azimuthal-wavenumber two PV asymmetry confined to the middle (entrainment) layer of the model is added to a symmetric hurricane-like vortex near its radius of maximum wind (RMW), with corresponding wind and height fields deduced from the nonlinear balance equation. The symmetrizing disturbance accelerates the tangential wind near the radius at which the initial asymmetry is maximum, and decelerates it to a lesser degree at larger radii.

When moist physics is used (including boundary layer friction, convection and horizontal diffusion) the results are more complex. In a benchmark experiment, a symmetric vortex is first spun up on an f-plane for 24 h. As in the dry case an azimuthal-wavenumber two PV asymmetry confined to the middle layer of the model is then added to the vortex near its RMW. The initial PV asymmetry is confined to radii between 20 and 80 km, with maximum amplitude equal to 20% of the symmetric PV at 50-km radius. After an additional 6 h (for a total 30-h simulation) the change in the azimuthally-averaged tangential wind in the middle layer [Fig. 1a] due to the asymmetry is qualitatively the same as in the dry case, with a maximum acceleration inside the RMW, and a maximum deceleration outside. In the boundary layer the maximum acceleration is inside that in the middle layer. The acceleration in the upper (detrainment) layer is about one-third as strong. Due to the presence of boundary-layer friction the asymmetry has induced a change in the azimuthally-averaged vertical velocity at the top of the boundary layer [Fig. 1b], with a maximum increase inside and a maximum decrease near the RMW. The change in distribution of vertical velocity due to the asymmetry induces an increase in convective heating inside about 40 km, and a decrease outside that radius. These preliminary results indicate that the dry results remain qualitatively valid in the presence of moist physics at least for short times. The continued evolution of the vortex after 30h (not shown) evidences substantial deviations from the dry results, however, indicating a substantial impact of the moist physics at later times.

b) A set of nine synoptic-flow cases, incorporating Omega dropwindsonde observations for six tropical storms and hurricanes, has been used to generalize the results for Hurricane Gloria. This work is being performed with Mr. James Franklin of the Hurricane Research Division, AOML/NOAA.

It is found that the results can be loosely placed into two categories describing the spatial scale of the PV anomalies that influenced the cyclone's motion. Four of the cases, including Hurricane Gloria, had "local" control, with a good match (to within about 40%) between the observed DLM wind near the cyclone center and the DLM wind attributable to a cylinder of PV with a given radius less than or equal to 1500 km. Further decomposition of the PV anomaly into upper (400 mb and above) and lower levels (500 mb and below) indicates the dominance of upper-level features in steering two of the cyclones (Hurricanes Gloria of 1985 and Andrew of 1992 [Figure 2]), while Hurricane Debby of 1982 evidenced a more barotropic steering. These results supplement those found in other studies.

Five of the cases, by contrast, had "large-scale" control, with no cylinder of radius less than or equal to 2000 km having a good match between the induced and observed DLM wind. Hurricanes Emily of 1987 and 1993 fell into this category, as did Hurricane Josephine of 1984. Due to the temporal persistence of the spatial scale of the control, the methodology presented has potential as an aid in guiding the deployment of operational and research aircraft that make in situ wind measurements of the hurricane's environment.

TRANSITIONS:

a) During FY-98 the preliminary results from the benchmark experiment will be evaluated diagnostically, with particular attention given to the physical mechanisms responsible for the long-term evolution. It is anticipated that the results of this experiment, as well as some that vary the amplitude and structure of the imposed asymmetry, will be written up for formal publication.

b) The results of the PV inversions for the nine synoptic-flow cases, including the implications for guiding in situ measurements to improve hurricane track forecasts, are being written up and will be submitted for publication during FY-98.

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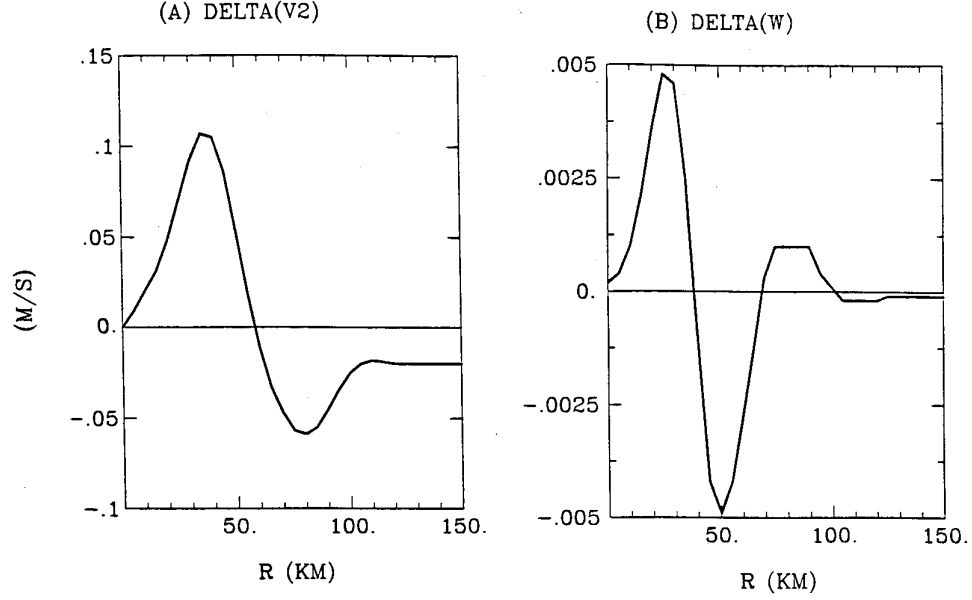


Figure 1. Change in (a) tangential wind in middle layer ($\Delta \bar{v}_2$) and (b) vertical velocity at the top of boundary layer ($\Delta \bar{w}$) after 30 h due to asymmetry in benchmark experiment with moist physics. The acceleration in tangential wind (a) in the inner region and deceleration outside are similar to the dry case; the induced boundary layer response, with the increase in vertical velocity (b) near the center and decrease further out, is a result of the moist physics.

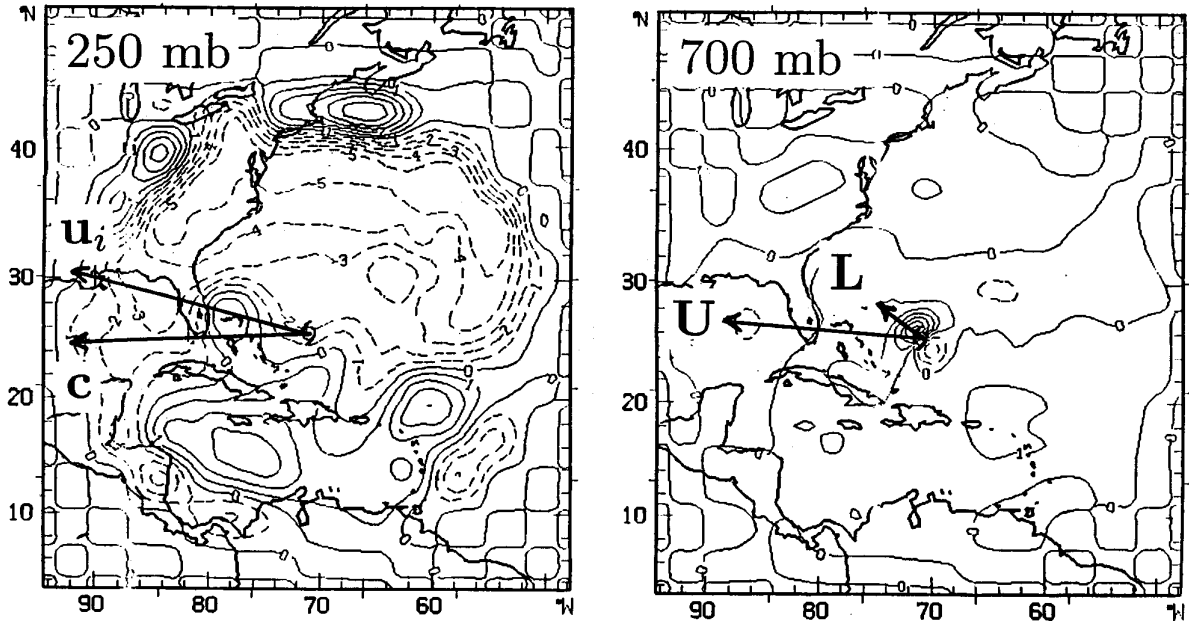


Figure 2. Potential vorticity anomalies within 2000 km of the center of Hurricane Andrew of 1992 at 250 (left panel) and 700 mb (right panel). Values outside 2000-km radius are set to 0. Contours are 0, ± 1 , ± 2 , ± 3 , ± 4 , $\pm 5 \times 10^{-8} \text{ m}^2 \text{ s}^{-1} \text{ K/kg}$. Vectors in top panel indicate the hurricane's mean motion (c) of 6.5 ms⁻¹ and the deep-layer mean wind (u_i) at the center of the hurricane attributable to potential vorticity (PV) anomalies confined to a cylinder of radius 1500 km; the vector difference between the two is 2.0 ms⁻¹, indicating that the PV anomalies control ~70% of the motion. Vectors in bottom panel indicate contributions to this wind from upper-level (400 mb and above) PV anomalies (U) and lower-level (500 mb and above) PV anomalies (L); in this case the upper-level PV, primarily, controls the motion.