

Vortex Rossby Waves and Hurricane Evolution in the Presence of Convection and Potential Vorticity and Hurricane Motion

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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) and Möller and Montgomery (1998; hereafter MM) 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. In more recent research supported by ONR, a three-layer model has been used to couple the waves investigated by MK and MM in a dry context 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. 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 implied 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 was required, however, to confirm the results. The present project continued the analysis by performing a piecewise inversion for other hurricanes in addition to Gloria.

RESULTS

a) In a benchmark experiment, a symmetric vortex is first spun up on an f-plane for 24 h. A weak azimuthal-wavenumber two PV asymmetry confined to the middle layer of the model is then added to the vortex near its radius of maximum wind (RMW). After an additional 6 h (for a total 30-h simulation) the change in the azimuthally-averaged tangential wind in the middle layer due to the asymmetry is qualitatively the same as in a dry simulation, with a maximum acceleration inside the RMW, a maximum deceleration outside, and a net intensification of the vortex. The preliminary results indicate that the eddy "kick" provided by the imposed asymmetry lasts ~1h. The early symmetric response (to ~6h) is similar to the barotropic results of MK and MM. The changes in the tangential wind induce corresponding changes in the boundary layer convergence and convective mass flux, with a maximum increase inside and a maximum decrease near the RMW. Later evolution of the symmetric vortex in this experiment leads to a net weakening within ~24h. Some of these preliminary results are presented in Shapiro (1998).

A diagnosis of the contributions to changes in the symmetric wind tendency due to the asymmetry confirm the dominance of horizontal eddy momentum fluxes in the very early evolution of the vortex (24h30m; Fig. 1a). At later times the contribution from the eddy fluxes decreases, and that from changes in the symmetric momentum fluxes and horizontal diffusion dominate (30h; Fig. 1b).

Additional experiments with an imposed isolated double-PV anomaly instead of wavenumber-two have been completed. When the double-anomaly is placed near the RMW, the evolution of the symmetric vortex is similar to that with the wavenumber two asymmetry. Contrary to expectation, moving the anomaly closer to the center of the vortex or further out does not change the overall evolution of the symmetric vortex, which strengthens to ~6h and weakens within ~24h. The physical mechanism responsible for the robustness of this result is being investigated using a budget for the asymmetric vorticity.

b) A set of nine synoptic-flow cases, incorporating Omega dropwindsonde observations for six tropical storms and hurricanes, was used to generalize the results for Hurricane Gloria. It was 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. 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. 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. The results of the PV inversions were written up, submitted and accepted for publication (Shapiro and Franklin 1998).

TRANSITIONS

a) During FY-99 it is anticipated that the investigation of the physical mechanism responsible for the robustness of the vortex evolution in the double-PV anomaly experiments will be completed, and that the results of these as well as the benchmark experiments will be written up for formal publication. The investigation will then be extended to anomalies of varying radial and azimuthal scale, amplitude and vertical structure.

b) Results of research on potential vorticity and tropical cyclone motion, including its implication for guiding in situ wind measurements to improve hurricane track forecasts, were discussed and presented in May at the Naval Research Laboratory, Monterey.

IN-HOUSE/OUT-OF-HOUSE RATIOS

All work was performed "out-of-house" in an academic setting.

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Publications during FY-1998:

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