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TROPICAL CYCLONES IN COMPLEX VERTICAL SHEARS

William M. Frank*
Penn State University, University Park, PA

Elizabeth A. Ritchie
University of New Mexico, Albuquerque, NM

1. INTRODUCTION

Recent observational and modeling studies of tropical cyclones have shown that the storms tend to have strong and persistent wavenumber one asymmetries, particularly in the rainfall and vertical velocity fields. Both observations and idealized numerical modeling studies of hurricane-like vortices suggest that the primary environmental mechanism forcing these asymmetries is probably vertical wind shear. (Bender, 1997; Frank and Ritchie, 2001).

Our earlier modeling studies (Frank and Ritchie, 2001) used a full-physics numerical model to study the responses of idealized hurricanes to vertical shear on an f-plane. This was done to simplify the interpretation of the physical interactions between imposed shear and the vortex. However, as noted by Bender (1997), the use of a variable Coriolis parameter (f) results in quite a different vertical shear over the core of the storm than is imposed in the large-scale environment. In a balanced, quasi-steady environment the so-called beta gyres cause a low-level jet-like structure with a maximum near the top of the boundary layer. In the Northern Hemisphere, this jet tends to create a shear component opposite to the jet direction through most of the lower and middle troposphere. The combination of the beta-gyre shear and the large-scale shear create the net shear experienced by the core of the storm.

In this study we examine the interactions between imposed unidirectional environmental shear and hurricanes with a variable Coriolis parameter, as well as interactions caused by shear patterns in which the wind direction changes with height. Only the first topic is addressed in this paper. The numerical simulations use the Penn State/NCAR Mesoscale Model, Version 5 (MM5). The idealized environment includes a uniform sea surface temperature of 28.5 C and variable f. The initialization procedure is described in Frank and Ritchie (2001). Briefly, a tropical-depression-like vortex in a zero-flow environment is allowed to intensify into a hurricane for 48 hours. At that point we add unidirectional vertical wind shear and adjust the pressure and temperature fields to balance the winds and pressure gradients. The vertical shear pattern is as used by Frank and Ritchie (2001), and the shears used in this study have a total wind velocity change of 10 m/s. The two runs illustrated below are for easterly and westerly shear (east-10b and west-10b, respectively).

2. RESULTS

The conceptual model that evolved from our earlier studies is that the response of a hurricane to shear results primarily from the tendency for the shear to advect potential vorticity (PV) downshear at higher levels. The dynamic response of the vortex causes convergence directly downshear of the center, and this leads to upward motion and rainfall in the downwind hemisphere of the storm. For example, a storm with easterly shear over the center would tend to have a wavenumber-one asymmetry with maximum upward motion and rainfall on the south side.

Figures 1 and 2 show schematically the net shear and shear-induced vertical velocity patterns in the lower troposphere for the East 10b and West 10b cases. For easterly environmental shear the net shear vector points towards the southwest and should induce maximum convection and rainfall on the south side of the storm. In general, the location of the rainfall maximum tends to occur about 45 degrees counterclockwise (downwind) of the location of the maximum updraft and cloud water areas. However, the locations of the rainfall maxima tend to vary with time within a broader area covering about half of the eyewall cloud. The single most stationary feature of the asymmetry of the secondary circulation in the eyewall is the weak-echo region, which often appears as a break in the eyewall cloud. For the westerly shear case the shear vector is stronger and points towards the southeast. This would be expected to produce convection and rainfall maxima that occur within the storm hemisphere located centered generally northeast of the center, with the convective

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Corresponding Author: William M. Frank, Department of Meteorology, 503 Walker Building, Penn State University, University Park, PA 16827. email: frank@ems.psu.edu

minimum occurring in the southwestern portion of the eyewall.

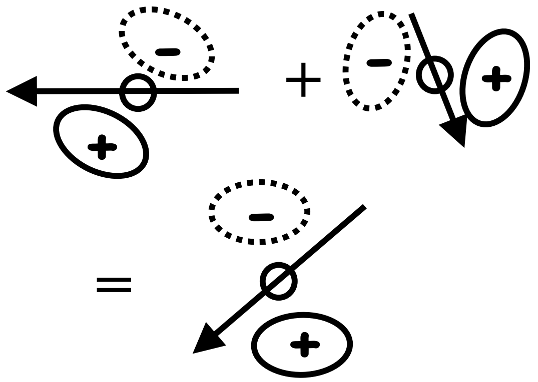

Figure 1: Imposed easterly shear and induced vertical velocity anomalies (upper left), typical beta-gyre shear vector and its induced vertical velocity anomalies (upper right), and the net shear and vertical velocities (bottom).

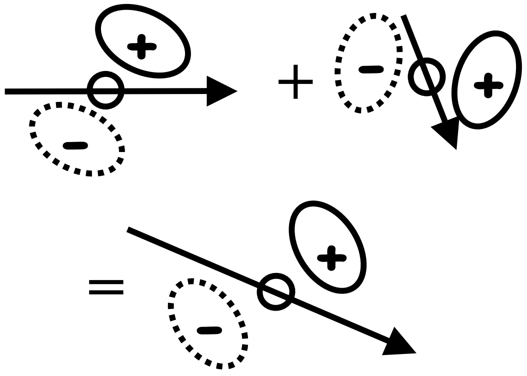

Figure 2: As in Figure 1, but for westerly imposed shear (upper left), assumed beta-gyre shear (upper right) and net shear and its effects (bottom).

Figure 3 shows the schematic net shear and induced vertical motion from the bottom of Figure 1 superimposed upon the three-hour accumulated rainfall from the easterly shear run for the period between t=81 and t=84 hours. (The shear was imposed at t=48 hours.) Figure 4 is similar, but shows the lower portion of the schematic of Figure 2 imposed on the three-hour rainfall from t=69 through t=72 hours of the westerly shear run. The rainfall patterns (including the weak echo region) reflect the patterns expected for the combination of imposed and beta-gyre shear based on the results of early work. While the patterns vary with time, they are consistently within the regions predicted by these arguments throughout both simulations.

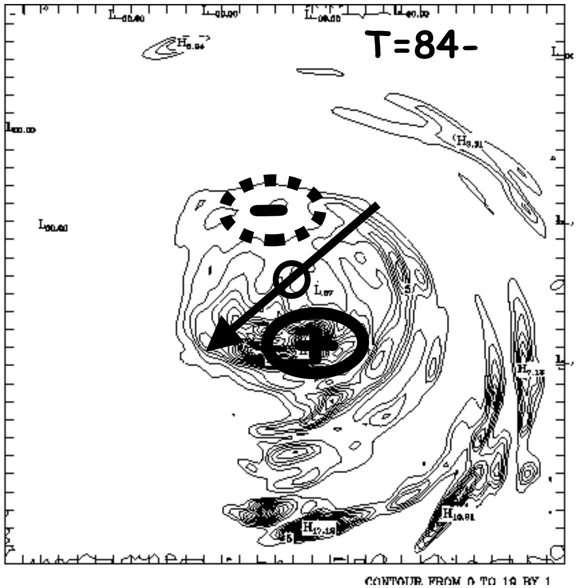

Figure 3: Scematic of the net shear and the expected secondary circulation induced by the shear for the easterly shear case (heavy black arrow and lines) and contours of accumulated rainfall from t=81 through t=84 hours of the easterly shear case.

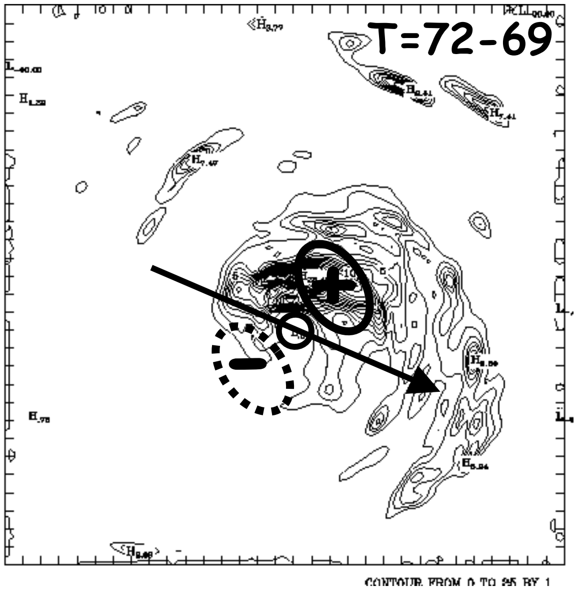

Figure 4: As in Figure 3, but for the westerly shear case for t=69 through t=72 hours.

3. References:

Bender, M. A., 1997: The effect of relative flow on the asymmetric structure of the interior of hurricanes. *J. Atmos. Sci.,* **54,** 703-734.

Frank, W. M., and E. A. Ritchie, 2001: Effects of vertical wind shear on the intensity and structure of numerically simulated hurricanes. *Mon. Wea. Rev.,* **128**, 2249-2269.