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ENERGETICS OF HURRICANE BONNIE (1998)

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1. INTRODUCTION

Despite advances in the understanding of tropical cyclones (TCs), forecasting intensity change remains problematic. Vertical shear is well known to dramatically and detrimentally affect the structure and intensity of TCs. Vertical shear enhances upward motion on the downshear side of the vortex, and cyclonic advection of precipitation enhances radar reflectivity on the downshear-left side of the storm. Such structure has been observed (Reasor et al. 2000) and confirmed in idealized (Frank and Ritchie 1999) and real-data (Rogers et al. 2003, and Zhu et al. 2004) simulations. While asymmetric convection is generally detrimental to storm intensity, in certain cases, e.g., the present case, TCs are able to maintain high intensity under the influence of vertical shear. Since vertical shear alone is insufficient to explain the intensity changes, higher order processes must play an important role. However, due to data limitations few studies have been able to investigate these details of intensity change in a sheared environment.

If one considers the azimuthal mean and the shear-forced circulations (Zhang and Kieu 2005) of a TC as the wavenumber-0 and wavenumber-1 modes, respectively, then the processes at higher wavenumbers must play a role in rapid intensity changes that are less well understood. Vortex Rossby waves (VRWs) have been shown (Montgomery and Kallenbach 1997, Wang 2002) to be active during mature TCs and related to intensity changes. More recently, Corbosiero et al. (2006) conducted a comprehensive observational study of a sheared TC and showed the existence of wavenumber-2 features that propagated around the eyewall and resembled VRWs. As of yet, however, a distinct connection between intensity changes and VRW phenomena has yet to be established.

Hurricane Bonnie (1998) evolved in a sheared environment and has been well-simulated using the MM5 (Zhu et al. 2004). This simulation provides data sufficient to investigate intensity changes at high spatial and temporal resolutions. Zhu et al. (2004) has shown clearly the general structure and evolution of Bonnie, including the structural changes caused by vertical shear.

In the present study, we build on the work of Zhu et al. by analyzing their data at very high temporal resolution. We investigate the evolution of Hurricane Bonnie from an energetics point of view to identify intensity changes while under the influence of vertical shear, and utilize Fourier decomposition to isolate VRW-like low wavenumber processes and demonstrate that they are active during intensity changes.

2. DATA AND METHODOLOGY

The present study will utilize data from the finest 4-km moving nest of an MM5 simulation conducted by Zhu et al. (2004). The nest dimensions are 164 x 164 horizontal grid points with 24 vertical levels, and data has been saved every 15 min.

To address the intensity changes within Bonnie, a system of energy equations is derived from the fundamental MM5 equations. Equations for total potential energy (TPE), latent energy (LE), and kinetic energy (KE) comprise the system. The single connection among the energies is the diabatic heating in the eyewall, during which LE is converted to TPE, which is subsequently converted to KE. The KE equation (1) is used herein to diagnose the source of the intensity fluctuations via an integrated budget calculation.

The KE equation is,

$$\frac{d}{dt}(KE) = -\vec{V}_H \bullet \nabla p' - \vec{V} \bullet \vec{F}\,, \qquad (1)$$

where KE = $\rho(V_H{*}V_H)/2$ and the two terms on the right hand side of (1) represent the production of KE via cross isobaric flow and the loss of KE due to friction. When the KE equation is volume-integrated, another term arises on the right hand side which represents the import of KE into the domain.

Fourier decomposition of various quantities is conducted to separate the storm into discrete processes. The wavenumbers-0 and -1 represent the azimuthal mean vortex and shear-forced circulation, respectively. Since the impact of low-order TC evolution has been discussed in depth in Zhu et al. (2004), the present study focuses on wavenumber-2 evolution in the context of VRWs and intensity change.

3. RESULTS

Figure 1 shows the evolution of storm intensity throughout the MM5 simulation of Bonnie. Even when the magnitude of vertical shear is above 15 m s^{-1}

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(during model hours 42 – 66), Bonnie maintains its high intensity. Superimposed on the maintenance, however, the maximum wind speed and minimum pressure exhibit fluctuations that are near-regular and significantly large. In fact, during a single three-hour period (52 – 55 h) the wind speed increases by 20% during the first 90 min and subsequently decreases by 20% during the next 90 min. The minimum sea-level pressure is expectedly inversely correlated to the maximum wind speed and also exhibits semi-regular fluctuations every three hours when the magnitude of vertical shear is large. Since the intensity fluctuations are largest when the shear is large, vertical shear undoubtedly plays some role in the intensity change. However, considering that the vertical shear imposed on Bonnie is of synoptic origin and slowly varying in time (not shown), some other mechanism must also play a role in the high frequency intensity changes.

Once the shear subsides (after 60 h), high frequency intensity fluctuations are no longer noticeable in the minimum sea-level pressure time series and of much smaller magnitude in the maximum wind speed field. The present study will focus on the 42 – 48 h period, as indicated in Fig. 1.

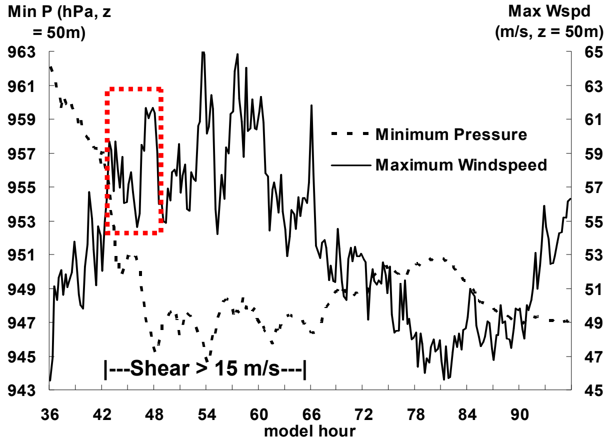

Figure 1: Time series (15 m) of the minimum central pressure (dashed, hPa) and the maximum near-surface winds (solid, m/s) from the MM5 simulation. The time period enclosed by the dashed box is the focus of sections 3.2 and 3.3.

3.1 Kinetic Energy Budget

The integrated KE budget (Fig. 2) is calculated using (1) within a 200 km radius from the storm center to isolate the processes responsible for the intensity fluctuations. The primary balance in Eq. (1) is between the two terms on the right hand side, which represent the production and dissipation of KE. A small amount of KE is imported through the boundaries of the integration domain and serves to balance the budget. The production of KE can be described as the adjustment of the wind field, which becomes imbalanced due to latent heat release, to gradient balance. Thus in the vicinity of large latent heat release, KE production will be large.

While friction and KE production are both large (Fig. 2) in magnitude, the KE production contains almost all of the *variability* in the KE budget while the vertical shear is large (42 – 66 h). The KE production is also positively correlated to the variability in the maximum wind speed. Since the KE production term is a direct response to latent heating, most of which occurs in the core of the TC, it can be concluded that the intensity fluctuations in Fig. 1 are directly related to fluctuations in latent heat release within the inner core of Bonnie.

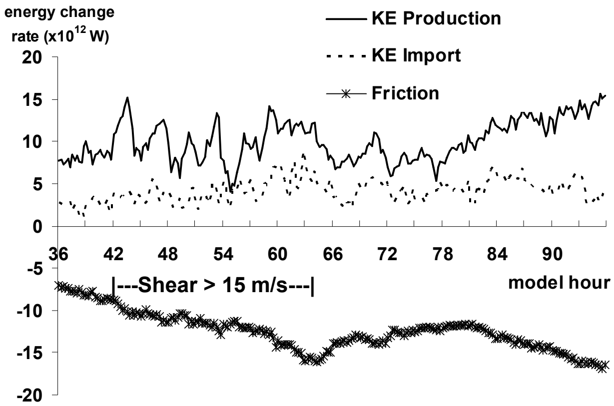

Figure 2: Time series (every 15 min) of the integrated KE budget for a cylindrical volume with R = 200 km and Z = 15 km. The volume of integration is moved with the storm every 15 min.

3.2 Inner Core Evolution

The horizontal structure of vertical motion within Bonnie during one intensity fluctuation cycle (43 – 48 h) is shown in Fig. 3. Mesovortices (not shown) in pressure can be seen to propagate around the eye, resulting in various eye shapes and providing evidence of asymmetric processes. Of particular interest is the evolution of the vertical motion, since it is directly related to the intensity changes via latent heat release.

During this period of significant vertical shear, the downshear direction is east-southeast (Zhu et al. 2004). Accordingly, the mid-level ascending motion is confined to the downshear-left half of the storm. So, throughout the 43 – 48 h period, the preferred region for latent heat release is the northeast quadrant of the storm. In fact, Fig. 3 shows convective elements confined primarily to the downshear-left half of the storm, though they are not stationary. The convective elements undergo a cycle of intensification and weakening that is closely correlated to the intensity changes shown in Fig. 1. Convection develops in the downshear half of the storm, strengthens as it propagates cyclonically, and weakens as it exits the shear-preferred half of the storm. Several full cycles of intensity fluctuation can be seen in Fig. 1 between 42 – 60 h, and the structure of vertical motion during a particular intensification between 46 – 48 h is shown in detail in Fig. 3.

The convective element of interest forms at 45 h 30 min (Fig. 3) exactly in the preferred downshear region of the eyewall (east-southeast). At the time of formation, the maximum surface wind speed of Bonnie is at a relative minimum (see Fig. 1). As the convection strengthens, it propagates cyclonically around the eyewall and eventually decays as it moves into a region unfavorable for convection. The element moves more slowly than the tangential winds and changes shape from an initially cellular shape at 45 h to a more linear shape by 48 h.

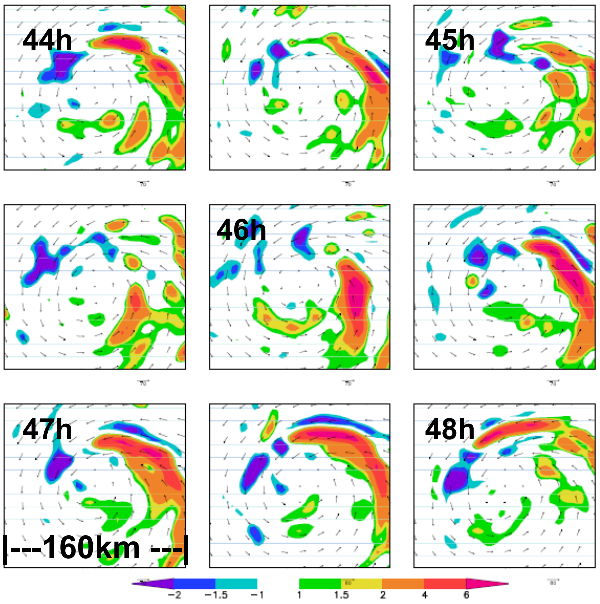

Figure 3: Evolution (30 min, top left to bottom right) of the inner-core vertical motion (z = 8 km) during the 44 – 48 h period. The dimensions of each plot are 160 km x 160 km, and the near-surface wind vectors are superimposed.

In several ways this evolution appears qualitatively characteristic of VRWs as shown in previous studies:

- Initially cellular convection becomes elongated with time.
- Convection propagates cyclonically and outward with time.
- Bands propagate at a speed slower than that of the maximum tangential wind speed and spiral slowly radially outward.

3.3 Wavenumber Decomposition

To address the mechanisms for the intensity changes observed in Fig. 1 and the convective processes observed in Fig. 3, it is desirable to decompose the storm into its wavenumber (WN) components. The WN-0 (not shown) component represents the azimuthal mean circulation, the WN-1 component is dominated by vertical shear, and the WN-2 component captures most of the higher order features. Since the WN-1 asymmetries are forced by shear, however, they are nearly quasi-stationary and time-invariant (not shown) and cannot fully explain the cyclonic propagation or the growth-decay cycle of the convective elements shown in Fig. 3. Thus to address the intensity fluctuations, we are particularly interested in the evolution of the WN-2 component.

An example of the WN-1 and WN-2 horizontal structure during an episode of rapid intensification is shown in Fig. 4. WN-1 structure exhibits the classic shear-forced patterns of enhanced (suppressed) vertical motion downshear (upshear) and enhanced (suppressed) inflow downshear (upshear). The WN-1 pressure patterns are less stationary than the vertical motion, but are also very sensitive to errors in identifying the center of the storm and will not be discussed further.

The WN-2 evolution is shown in Fig. 4. Initially cellular vertical motion anomalies form in the eastern half of the storm and propagate cyclonically outward. As they evolve, the WN-2 vertical motion features also change shape from cellular to curvilinear, evidently becoming sheared by the tangential flow. The WN-2 pressure perturbations propagate cyclonically at about 35 ms-1, which is about half of the maximum tangential wind speed. The WN-2 vertical motion features propagate tangentially more slowly than the pressure perturbations and outward at approximately 5 ms-1, consistent with previous studies that have identified VRWs. This evolution is similar to that shown theoretically by Montgomery and Kallenbach (1997) as VRWs, and in this case convection associated with the waves is directly related to significant intensity changes within Bonnie.

In this way, the vertical shear provides a WN-1 asymmetry favorable for vertical motion on the downshear left side of the storm. Upon initiation of a convective element, the evolution thereafter is shown to be closely related with the WN-2 processes, which appear to be VRWs. Thus WN-2 features bearing close resemblance to VRWs are shown to be active in the eyewall and are directly related to fluctuations in the maximum surface wind (Fig. 1).

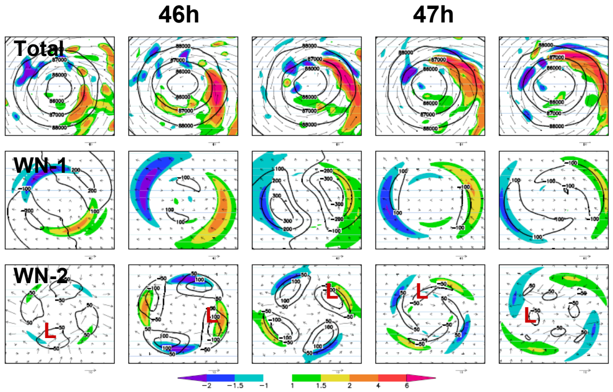

Figure 4: Evolution (30 min) of vertical motion (z = 8 km, shaded) and pressure (z = 3 km) for the total field (top), the WN-1 component (middle row), and the WN-2 component (bottom row). Near surface wind fields for each component are superimposed. The letter “L” on the bottom row follows a WN-2 pressure feature as it propagates around the eyewall. The dimensions of each plot are 160 km x 160 km.

4. SUMMARY AND CONCLUSIONS

Hurricane Bonnie (1998), as simulated with the MM5, exhibits significant intensity fluctuations on a timescale of a few hours while under the influence of significant vertical shear. The fluctuations in maximum wind speed are shown to be closely related to energy conversions, which have maximum magnitude in the vicinity of the eyewall. Analysis of the structure of convection in the eyewall shows that the cycle of growth and decay of convective elements correlates well with the intensity fluctuations, and the evolution of the convective elements is shown through Fourier analysis to be characteristic of low wavenumber vortex Rossby waves. In this way, vortex Rossby waves are active during and closely related to the intensity fluctuations of Hurricane Bonnie.

5. REFERENCES

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