12A.2 THE EYEWALL REPLACEMENT AND INTENSITY CHANGES IN HURRICANE BONNIE (1998)

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1. INTRODUCTION

Because of their significance in hurricane intensity changes, the eyewall replacement processes have attracted significant attention since the publication of Willoughby et al. (1982). In this presentation, a series of 5-day explicit simulations of Hurricane Bonnie (1998) is performed, using the fifth-generation Pennsylvania State University-National Center of Atmospheric Research Mesoscale Model (MM5) with the finest grid length of 4 km, in order to examine (a) the predictability of hurricane intensity and intensity changes, and (b) the mechanisms whereby the intensity changes occur.

2. EXPERIMENTAL DESIGN

Zhu et al. (2004) showed a 5-day control simulation (CTL) of Hurricane Bonnie (1998) with the MM5 that covers the initial rapid deepening, steady variation and landfalling stages of the storm. It was shown that the 5-day control simulation reproduces reasonably well the track, intensity change and asymmetric inner-core structures of the storm, including a partial eyewall, an eyewall replacement cycle. In this study, four sensitivity experiments are designed to examine the effects of cloud microphysics parameterizations on the hurricane intensity and intensity changes, and the development of cloud and rainfall asymmetries as well as the eyewall replacement scenarios, by modifying different routines of the Tao-Simpson (1993) cloud microphysics scheme.

In the first experiment, the prognostic equations of cloud ice, snow and graupel are excluded from the control simulation (NICE), namely, only the warm-rain physics is allowed. To minimize the initial differences in phase-change rates, the initial 3D relative humidity field, calculated with ice saturation for the water vapor above the 0°C layer, is kept identical between the CTL and NICE experiments. In the second experiment, the prognostic equation for graupel is removed from the control model, and no conversion of snow to graupel is allowed (NGP). These two sensitivity simulations are designed to examine to what extent the simulated hurricane intensity and structures are directly affected by the incorporation of ice microphysics.

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In the third experiment, the melting of ice, snow and graupel to form rainwater as falling through the 0°C isothermal layer is neglected, so the associated cooling and phase change effects are absent (NMLT). In the fourth experiment, evaporation of cloud water and rainwater in sub-saturated regions are turned off from the control simulation (NEVP). These two experiments are designed to investigate the roles of melting and evaporative cooling in determining the intensity of tropical cyclones, and they are also closely related to ice microphysical processes.

3. INTENSITY CHANGE

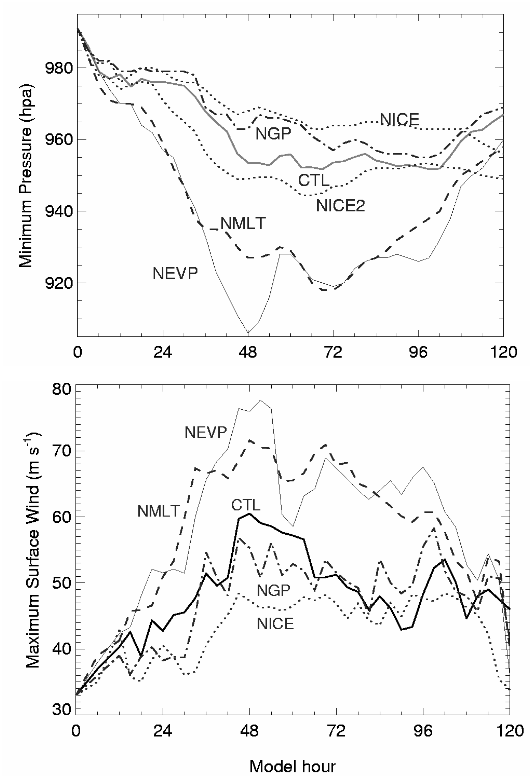

Fig. 1. Three hourly time series of (a) the minimum central pressure (P_{min}, hPa), (b) the maximum surface wind (V_{max}, m s^{-1}) for all the model simulations.

Pronounced differences (or sensitivity) in hurricane intensity from the control simulation are evident between

24- and 120-h into the integration, with the extreme amplitudes ranging from 50 hPa (or 20 m s^{-1}) overdeepening to 10 hPa (or 12 m s^{-1}) underdeepening in P_{min} (V_{max}) (Fig. 1). Note that all the storms deepen in coincidence with the rapid increase in vertical wind shear as they move toward a midlatitude upper-level disturbance (see Zhu et al. 2004). Despite the large differences in intensity, all the storms begin to weaken after 3 days as they move over a colder water surface and approach the east coast. Subsequently, they gradually converge to the control simulated, and all are eventually absorbed by the large-scale mean flows. Of interest is that the simulated storms weaken prior to and deepen after the eyewall replacement, which is consistent with the previous observational finding.

4. EYEWALL REPLACEMENT

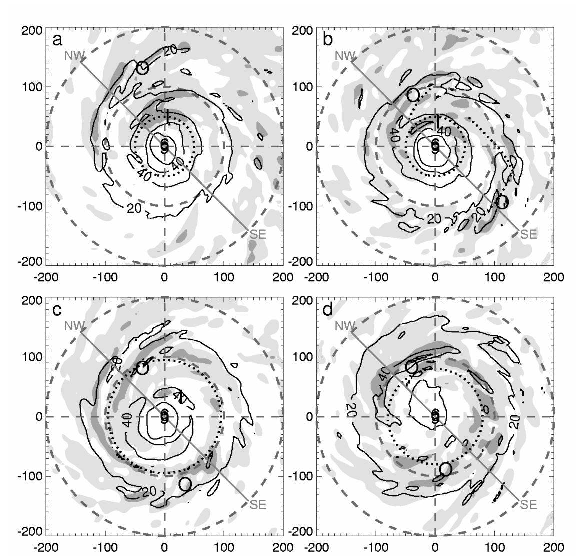

Fig. 2. Distribution of surface pressure gradients (i.e., |? p|, solid) at intervals of 20 Pa km^{-1} and the layer (i.e., from the surface to 700 hPa) averaged reflectivities (shaded at 30 and 40 dBZ) from control simulation at (a) 78-h, (b) 84-h, (c) 90-h and (d) 96-h simulations. Dotted lines denote the RMW or the axis of local wind maximum. Thick dashed lines are the radius of 100 and 200 km. Letters, 'O' and 'I', denote the outer and inner rainbands, respectively.

It is found that a control simulation and four sensitivity experiments with varying cloud microphysics processes all captured the eyewall replacement cycles, and their developments appear to be closely related to hurricane intensity changes. The control simulation (Fig. 2) shows that the eyewall evolves from a partial to double and a near-concentric eyewall during the eyewall replacement period. Specifically, one outer spiral rainband at R = 120 km begins to propagate into the northwest-to-western quadrant as the large-scale descending inflow weakens. Similarly, more rainbands develops in the outer regions and propagate cyclonically into the northwestern quadrant. Meanwhile, the inner eyewall weakens with time. Subsequently, the newly formed eyewall shrinks in width and radius, so do the outer rainbands. The outer rainbands also intensify in terms of upward motion, local tangential winds and surface pressure gradients as they move cyclonically inward. A secondary wind maximum starts to emerge at R = 150 km, and intensify with time as its radius of maximum wind shrinks. These developments are consistent with the moderate deepening of the storm during the period. By the end of replacement cycle, the inner eyewall becomes disintegrated with a few weak convective cells, and the inner RMW loses its characteristics starting from the surface. It takes less than 6 h to complete this eyewall replacement cycle. It is shown that the eyewall replacement scenarios are more or less determined by the large-scale sheared environment, but their associated inner-core structural changes, timing and location differ markedly, depending on the hurricane intensity.

5. CONCLUDING REMARKS

Based on the above sensitivity study, we may conclude that varying cloud microphysics processes could affect not only the intensity and intensity changes of tropical cyclones, but also their inner-core structural changes. It is found that the eyewall replacement scenarios, more or less determined by the large-scale sheared environment, could develop during the different stages of all the sensitivity simulations, albeit in different extents. However, their associated inner-core structural changes differ, depending on the storm intensity. For relatively weaker storms, the inner eyewall convection diminishes after an outer rainband and a secondary wind maximum develop and block the inward energy supply. The outer rainband then forms a new eyewall, completing an eyewall replacement cycle. By comparison, the outer rainband in stronger storms does not have detrimental impact on the eyewall convection, but they tend to be merged into one new eyewall with different RMW. Nevertheless, the eyewall replacement cycle is seen closely related to the simulated hurricane intensity changes.

ACKNOWLEDGMENTS

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