12C3 Numerical Simulation of Hurricane Erin (2001): Model Verification and Storm Evolution

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1. Introduction

Compared to improvements in hurricane track forecasts, the skill level in prediction of tropical cyclone structure and intensity remains relatively low. One reason is that the physical mechanisms related to intensity change are not well understood (Neuman 1997). Tropical cyclones are very complex atmospheric systems in terms of their interacting physical processes on multiple scales. A major part of the intensity change problem is the interaction of a tropical cyclone with external influence including large-scale environmental flows and the underlying ocean characteristics. Increasing attention has been given to sophisticated numerical models that can explicitly resolve multi-scale atmospheric processes associated with tropical cyclones. The Pennsylvania State University-National Center for Atmospheric Research fifth-generation, nonhydrostatic mesoscale model (MM5) has been become one of the most popular numerical models. Simulations have been successfully conducted without an initial bogus vortex (e.g., Braun and Tao 2000; Davis and Bosart 2001).

Our motivation for the present studies is to explore further the nature of hurricane development and intensity change by simulating Hurricane Erin (2001), which occurred during the field phase of the National Aeronautics and Space Administration Fourth Convection and Moisture Experiment (CAMEX-4). As the first part of this study, an in-depth validation of the simulated evolution of the Hurricane Erin including three stages of intensity change is presented against available observations.

2. Simulation description

As with many other Atlantic tropical cyclones, Hurricane Erin can be traced back to a tropical wave that emerged from western Africa on 30 August. The system strengthened into Tropical Storm Erin by 0600 UTC 2 September as the central pressure fell to 1002 mb. On 5 September, its development was disrupted due to southwesterly vertical wind shear associated with an upper-level trough. About a day later, the vertical shear weakened and a surface circulation redeveloped in the northern part of the area of disturbed weather that was associated with Erin. It regained tropical storm intensity at 1800 UTC 7 September with a central pressure of 1007 mb. Erin continued to strengthen and became a hurricane by 0000 UTC 9 September, reaching its peak intensity near 0000 UTC 10 September. Erin's intensification ended after it moved over cooler waters and the vertical wind shear peaked. By 0000 UTC 15 September, Erin had weakened into a tropical storm and eventually transitioned into an extratropical system.

The model integration begins at 0000 UTC 7 September when Erin was an area of disturbed weather. Erin was identifiable in the analysis as a weak tropical depression with a central pressure of 1013 mb and a maximum wind of about 15 m s^{-1}. The simulation is terminated at 0000 UTC 11 September, shortly after Erin began to weaken. The 96-h integration covers several important periods in the life cycle of Hurricane Erin including its formation, intensification, and maintenance stages.

Three two-way interactive domains on Mercator map projections are used with grid spacings of 36, 12, and 4 km, respectively. There are 28 uneven sigma levels with higher resolution in the planetary boundary layer (PBL). The model top is set to 50 mb. Primary model physics options include Betts-miller cumulus parameterization for the 36-km domain, the Goddard Cumulus Ensemble model cloud microphysics for 12-km and 4-km domains, a modified version of the Blackdarr PBL parameterization, in which the surface roughness calculations for momentum, temperature, and moisture follow Garratt (1992) and Pagowski and Moore (2001), and the cloud radiative scheme of Dudhia (1989).

3. Summary

The model successfully reproduces the evolution of Erin by capturing its three phases of development: formation, intensification and maintenance (Fig. 1). Erin develops in a weakly sheared environment on 7 September. When it crosses a warm pool of 302 K waters at 1200 UTC 8 September (36 h), it deepens rapidly. It reaches its peak intensity by the end of 9 September and then maintains a steady intensity through 10 September. Two factors appear to contribute to the cessation of intensification: movement over cooler SST's and increasing vertical wind shear associated with an approaching upper-level pressure system (Fig. 2b).

Comparisons of observed and simulated tracks, intensities, and wind and precipitation patterns are remarkably good. Of particular interest in this study is the

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model's ability to capture a transition in storm's intensity and structure between 9 and 10 September during which time the hurricane's intensification suddenly ends and its outer precipitation bands shift approximately from the northeastern to the western side of the storm. The simulation also shows indications of the initial development of a secondary eyewall. Deficiencies in the simulation are apparent in the vertical distribution of precipitation as the model tends to produce rainbands that are shallower than observed. However, despite this discrepancy, the simulated vertical structure of the temperature anomaly filed is in very good agreement with observations in terms of the magnitude and height of warm core.

The simulation is used to examine the evolution of Erin from a weak depression to an intense hurricane and to describe the structure changes that occur. Erin's formation stage is characterized by highly asymmetric convection that gradually intensifies the mean vortex and reduces the radius of maximum wind. Inflow during this stage is deep while outflow is confined to upper levels. During the intensification stage, characterized by a more rapid rate of deepening, the eyewall convection becomes stronger and deeper and inflow is confined to low levels while stronger outflow occurs at middle and upper levels. Strengthening wind shear during this period leads to an asymmetric distribution of precipitation with the heaviest eyewall precipitation and a wide area of the outer precipitation concentrated on the downshear-left side and more cellular outer band convection located on the downshear-right side. The shear reaches its peak intensity near 0000 UTC 10 September, at which time intensification stops. It then maintains a nearly steady intensity as the shear gradually weakens and the precipitation pattern shifts to the western side of the storm.

The change in precipitation structure can be understood in terms of the storm-relative flow (Bender 1997) and the vortex Rossby wave framework described by Reasor et al. (2003). In the Erin simulation, low-level convergence (divergence) occurs where there is relative inflow (outflow) in the eyewall, qualitatively consistent with the mechanism proposed by Bender. In the vortex Rossby wave framework, upward motion is assumed to occur in the downtilt direction and the tilt behavior is governed by two types of vortex Rossby waves: a discrete, or quasi-mode and sheared vortex Rossby waves. The quasi-mode produces precession of the upper vortex relative to the lower vortex, and in the presence of weak damping, leads to a steady tilt to the left of the shear vector. In this simulation, the tilt direction rotates cyclonically approximately 45° from 9 to 10 September. This suggests that the shift in the precipitation pattern is a change in the tilt direction caused partially by a smaller change in the shear direction as well as by a weakening of the shear that may allow the tilt direction to change relative to the shear direction.

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Figure 1 The maximum wind (above) at the lowest model level and minimum central pressure of Hurricane Erin (lower) from best track data and the simulation.