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High-resolution numerical simulations of Hurricane Isabel (2003) over North Carolina

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Abstract Two numerical simulations were performed to study the ability of a high-resolution mesoscale model to predict the track and structure of Hurricane Isabel over North Carolina. One simulation (Control) used standard NCEP climatologically-based sea surface temperature (SST) data for the lower boundary condition while another simulation (Experimental) prescribed real-time high-resolution SST data for the lower boundary. Results from this study show that both simulations predict the track of Isabel over North Carolina reasonably well, although the track predicted by the experimental simulation agrees more closely with observations. The experimental simulation more closely agrees with observations of the intensity of Isabel and the amount and spatial distribution of precipitation. These results reinforce the importance of accurate high-resolution SST data on numerical simulations of tropical cyclones.

Keywords Sea surface temperature · Flux · Climatological · Resolution · Data assimilation

1 Introduction

A rapid advance in computer processing speeds is allowing numerical weather simulations to be conducted at progressively smaller scales. Data assimilation systems with observations from a variety of platforms, including satellites, are helping weather forecasts become more accurate. However, not many numerical modeling systems take full advantage of the semi-daily, high-resolution sea surface temperature (SST) data provided by the satellites. With the increasing reliance on numerical weather prediction models by operational weather forecasters, it is becoming increasingly important that modelers use the most up-to-date set of available

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observations to initialize weather prediction models. This is of importance for any type of weather forecasting, particularly tropical cyclones. Tropical cyclones form exclusively over tropical waters and dissipate quickly after landfall, mostly as a result of the much-reduced surface heat fluxes present over land. Surface heat fluxes have long been recognized as the main source of energy for hurricanes. Warm core rings (Shay et al. 2000) or regions of enhanced SST's and heat potential play important roles in tropical cyclone structure and intensity.

Over the past several decades, the skill of operational track forecasts of Atlantic tropical cyclones has steadily increased (McAdie and Lawrence 1993), but still needs improvement (Sheets 1990). Several objective guidance models are available for the prediction of tropical cyclone track forecasts, particularly for the Atlantic Basin (DeMaria and Kaplan 1994). These include the SHIFOR (Jarvinen and Neumann 1979), SHIPS (DeMaria and Kaplan 1994) and GFDL (Kurihara et al 1998). Both the SHIFOR and SHIPS models are statistical models while the GFDL is a fully three-dimensional dynamical model. One of the key variables of the ''initial conditions'' in all these intensity prediction models is the SST. For example, in the SHIPS model, the SSTs are obtained from the weekly analyses prescribed by Reynolds and Smith (1994). However, none of these intensity models utilize real-time highly resolved SST data. It will be of interest to investigate the effect of highly resolved and accurate near-real time SST's on tropical cyclone intensity forecasting models. Research by Cione and Uhlhorn (2003) has shown that relatively small changes in inner-core (within 100 km of the vortex center) SST's can alter surface energy fluxes by 40% or more. Because surface flux is the primary energy source driving tropical cyclones, altering these fluxes can have a profound effect on cyclone intensity. Horizontal gradients in these fluxes also need to be properly represented.

While several studies on hurricane intensity prediction have focused on coupled ocean-atmosphere models (Schade and Emanuel 1999), few studies have attempted to incorporate real-time high-resolution (1.44 km) SST data in numerical simulations. Studies by Bister and Emanuel (1998) have addressed the importance of dissipative heating on hurricane intensity. They have shown that inclusion of dissipative heating in numerical models can increase maximum surface wind speeds by 10%, and decrease central pressure by 5–7 hPa. However, the significance of dissipative heating appears to be important only in intense (150 kt maximum winds) hurricanes. Warm core eddies and other mesoscale regions of enhanced SST are likely more influential on tropical cyclone intensity and structure than dissipative heating. Obviously, our success in forecasting tropical cyclone intensity is directly related to our ability to detect and resolve these mesoscale oceanic features. The main goal of this research is to study the ability of a high-resolution numerical model to simulate the track and structure of Hurricane Isabel (2003) over North Carolina. A second objective is to study the effects of highly resolved SST data on the simulations.

2 Synoptic conditions

Hurricane Isabel was a classic Cape Verde Hurricane that made landfall in eastern North Carolina on September 18, 2003. Isabel became the first tropical cyclone to attain hurricane intensity east of 40 W and hit the United States coastline since Hurricane Donna struck Florida in 1960. Isabel made landfall as a Category 2 hurricane with sustained winds of 90 kt (168 km/h) and a central pressure of 957 hPa. As is typical with landfalling hurricanes, reliable wind observations were hard to collect. Winds gusted to 169 km/h on Ocracoke Island with several reports of sustained winds between 120 and 137 km/h. Winds likely gusted to 175 km/h or greater over portions of the Outer Banks and extreme southeastern Virginia. Widespread damage was reported over the Outer Banks as a result of the strong winds and high storm surge exceeding 3.3 m (10 ft). Isabel was directly responsible for 16 deaths and indirectly responsible for 34 deaths. Damage estimates from the cyclone exceeded $3.35 billion (Data courtesy of the Tropical Prediction Center).

3 Numerical methods

The PSU/NCAR Mesoscale Model 5 (MM5) is used to study the track and structure of Hurricane Isabel over North Carolina. Two simulations of the MM5 were performed in this study. The first simulation (Control Simulation) and the second one (Experimental Simulation) are single nested domains centered over the southeastern United States. The outer domain has a grid spacing of 36 km with (76×112) grid points and 37 vertical sigma levels. The inner domain has a horizontal grid spacing of 12 km with (86×122) grid points in the horizontal and 37 vertical sigma levels. The Domain configuration used in this study is shown in Fig. 1. Using results from Zhang and Wang (2003), vertical resolution in the lower troposphere was increased to 15 sigma levels while the time step was adjusted to allow for maximum numerical diffusion and computational stability.

Reisner 2 moisture physics is used to simulate explicit cloud processes in both domains, while the Betts–Miller cumulus parameterization is used to account for the sub-grid scale water cycle. The Eta Mellor-Yamada 1.5 order TKE closure model is used for boundary layer processes, and the Noah Land Surface Model for land-atmosphere interactions. For a more detailed description of the MM5 modeling

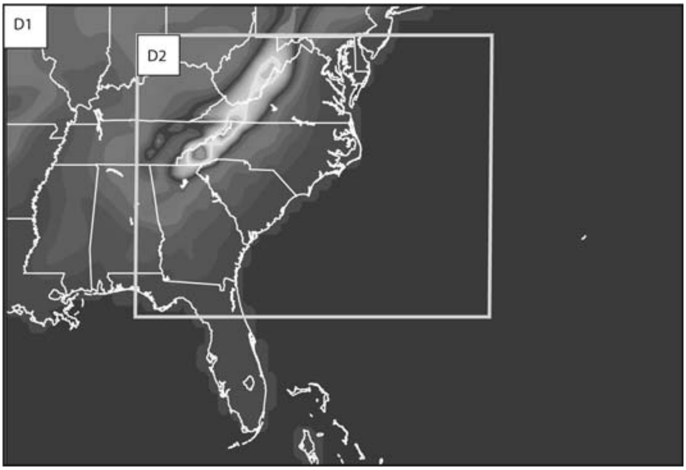

Fig. 1 MM5 domain configuration used in this study (Elevation data is shaded). The outer domain, D1, has a horizontal grid spacing of 15 km. The inner domain, D2, has a grid spacing of 5 km

system, please refer to Grell et al. (1995). Both simulations are initialized using the NCEP Eta212 (40 km) model grid, archived by the National Center for Atmospheric Research. Additionally, both simulations were initialized at 12 UTC 17 September and integrated for 48 h through 12 UTC 19 September 2003. The only difference between the two simulations is the SST data used to specify the lower boundary. The Control Simulation is initialized with the NCEP 50 km climatological SST data, while the Experimental Simulation uses high-resolution (1.44 km) SST observations obtained from NOAA's Coastwatch dataset. The Coastwatch SST data is updated 4 times a day using sensors from the advanced very high resolution radiometer (AVHRR) satellite.

Temperature difference (C) between the Experimental Simulation's SST initialization and Control Simulation's SST initialization is shown in Fig. 2. The shaded black line in Fig. 2 represents the observed track of Hurricane Isabel as the storm approached the coast of North Carolina. The Control Simulation is initialized with SST data provided by NCEP with a grid spacing of 50 km. This data is identical to the data being used operationally by the NCEP Eta model, and is based on a weekly, climatologically based analysis. The Experimental Simulation is initialized with SST data provided by NOAA's Coastwatch dataset with a grid spacing of 1.44 km. This data is derived from AVHRR satellite scans, and is updated every 4 h. Several interesting features of SST differences can be seen. First, positive anomalies are present in a region 50–100 km off the coast of North Carolina. The high-resolution (1.44 km) Coastwatch SST data was 3–5°C warmer than the more coarse (50 km) NCEP SST data. This region of high SST's is likely associated with the Gulf Stream current, often positioned at a distance less than 100 km off the coast of North Carolina throughout the year. Another interesting difference between the

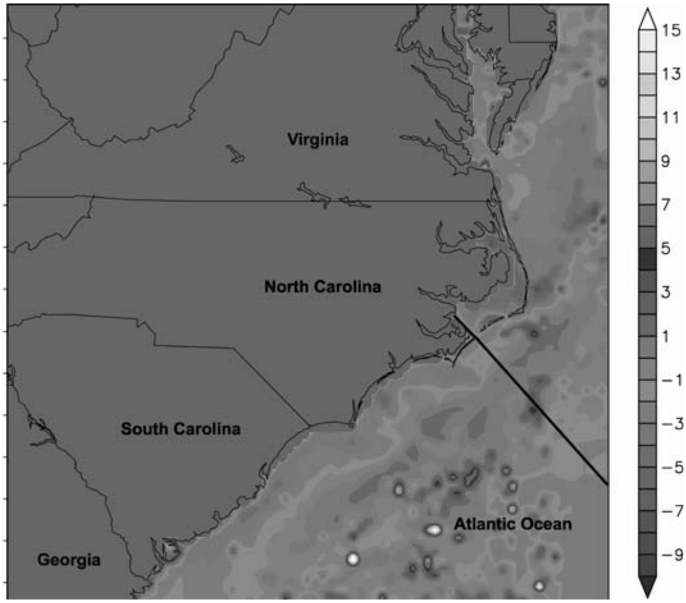

Fig. 2 Sea surface temperature (C) difference between the Experimental simulation and the Control simulation

Experimental and Control SST composites is over Pamlico and Albemarle Sounds, where there are pronounced negative SST anomalies. The high resolution near real time SSTs are 2–4°C cooler than the coarse climatological values used in the Control Simulation. This is likely a result of the persistent upwelling present over the North Carolina Outer Banks during late summer 2003 (Childs and Raman 2004). The high resolution SST data in the Experimental Simulation has stronger horizontal gradients than the coarser, climatologically based SST data in the Control Simulation.

4 Results

Model-simulated tracks of Hurricane Isabel for the two experiments are compared with the Tropical Prediction Center's (TPC) best track data in Fig. 3. The TPC best track is shown in diamonds while the Control and Experimental simulated tracks are shown in circles and squares, respectively. The Experimental Simulation agrees more closely with observed track than that of the Control Simulation. The Control Simulation is approximately 20 km south of the observed landfall, while the Experimental Simulation is virtually identical to the observed. The Experimental simulation agrees very closely with the observed track over water as well. However; after landfall, the Experimental track deviates from the observed track and follows the track simulated by the Control experiment. Several possibilities regarding the superior track forecast by the Experimental Simulation will be discussed in greater detail in subsequent sections.

Model-simulated central pressure (hPa) time series of Hurricane Isabel compared with the observed central pressure reported by the TPC valid 12 UTC 17 September through 12 UTC 19 September 2003 is shown in Fig. 4. The observed central pressure is shown in squares, while the Control and Experimental simulated pressures

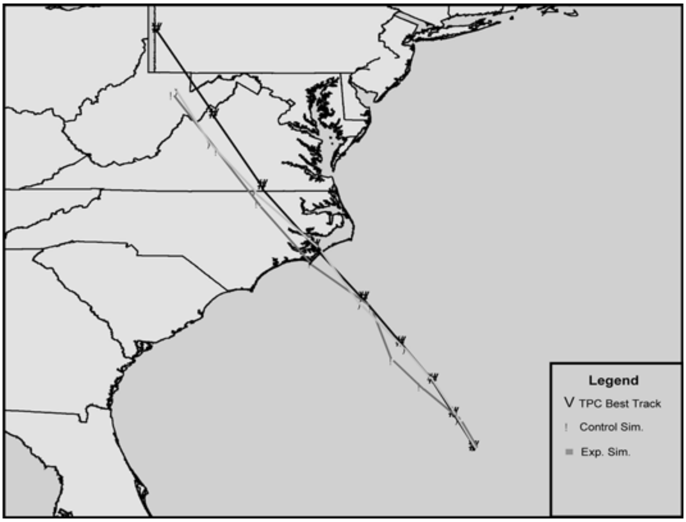

Fig. 3 MM5 simulated Hurricane Isabel tracks valid 12 UTC 17 September through 12 UTC 19 September 2003. The Control simulated track is shown in circles, while the Experimental simulated track is shown in *squares*. The Tropical Prediction Center best track data is shown in *triangles*

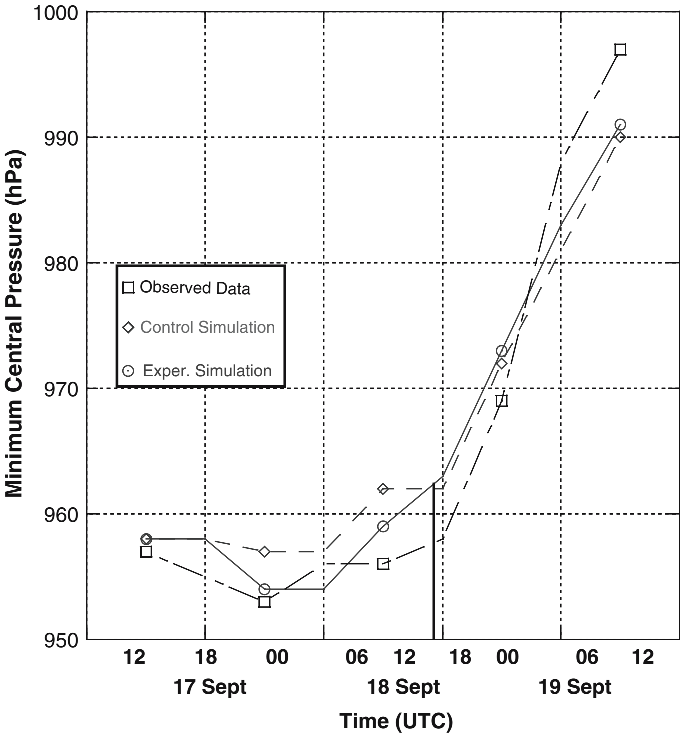

Fig. 4 Model simulated minimum central pressure (hPa) of Hurricane Isabel valid 12 UTC 17 September through 12 UTC 19 September 2003. The Control simulated minimum pressure is shown in *diamonds*, while the Experimental is shown in *circles*. The Tropical Prediction Center's observed pressure is shown in squares. The *solid black line* indicates landfall over eastern North Carolina

are presented in diamonds and squares, respectively. Both the Control and the Experimental simulations represent the *trends* in surface pressure reasonably well; however, the Experimental simulation values agreed more closely with the observations. Both the Control and the Experimental Simulations initialized the tropical cyclone vortex at 958 hPa at 12 UTC 17 September 2003. While the Control experiment simulated a near constant intensity of Isabel between the initialization time and landfall, 30 h later, the simulated hurricane on the Experimental Simulation has a drop in central pressure to 954 hPa between 00 UTC and 06 UTC on 18 September 2003. This trend is in agreement with surface observations from the Tropical Prediction Center, which indicate a surface pressure between 954 and 955 hPa at this time. Isabel traversed the Gulf Stream waters between 22 UTC 17 September and 10 UTC 18 September, with an increase in surface heat fluxes as a result of the presence of warmer waters. This increase in surface heat flux likely contributed to the observed vortex deepening during this period.

Storm total precipitation (in) (12 UTC 17 September through 12 UTC 19 September 2003) from the NCEP MesoEta model is shown in Fig. 5a, while the *Control Simulation's* precipitation forecast is shown in Fig. 5b. Observed precipitation values for this period are shown in Fig. 5c, showing more than 6 in (15.2 cm) of rain over eastern North Carolina. The MesoEta model predicted significantly lower total

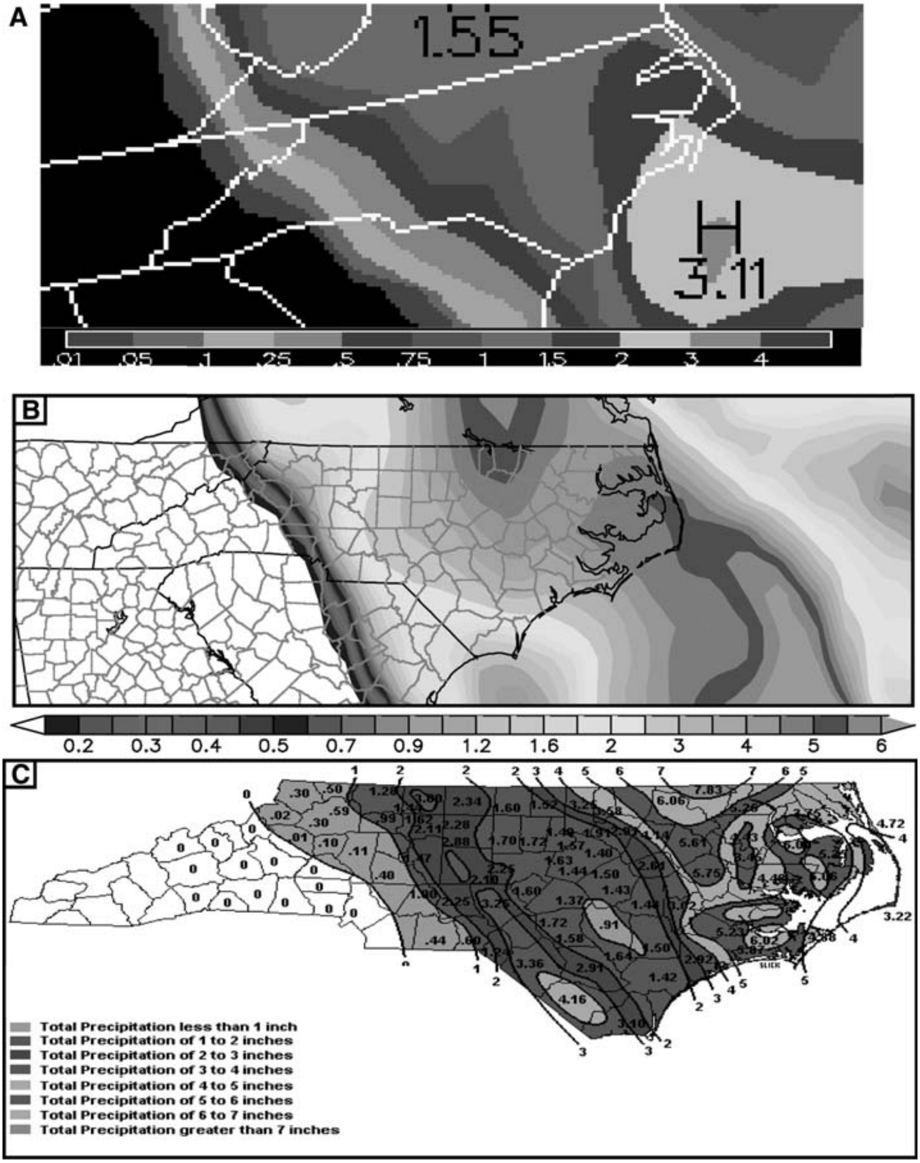

Fig. 5 MesoEta forecasted storm total precipitation (in) valid 12 UTC 17 September through 12 UTC 19 September 2003 is shown in 5a. Control simulated storm total precipitation is shown in 5b, while observed precipitation is shown in Figure 5c

precipitation, less than 2 in (5 cm), over much of this region. The Control Simulation predicts between 4 and 5 in (10.2 and 12.7 cm) of precipitation over much of eastern North Carolina, in general agreement with the observations. The Control Simulation predicts 3–4 in (7.62–10.2 cm) of precipitation over much of Central North Carolina where only 1–2 in (2.54–5.08 cm) is observed. The MesoEta simulated less than 1 in (2.54 cm) of precipitation over Central North Carolina. A secondary precipitation maximum of 2–4 in (5–10.2 cm) was observed over parts of southeastern North Carolina extending westward through west-central North Carolina. Forecasted precipitation from MesoEta shows less than 1 in (2.54 cm) over this region, while the Control Simulation shows between 2 and 3 in (5 and 7.62 cm) of precipitation. Even though the Control Simulation rainfall values agree closely with observations for this secondary maximum, it fails to produce the observed precipitation distribution.

As previously discussed, simulated storm total precipitation (12 UTC 17 September through 12 UTC 19 September 2003) from the NCEP MesoEta model is shown in Fig. 5a; while observed precipitation values are presented in Fig. 5c. Precipitation forecast with the Experimental Simulation is shown in Fig. 6. As stated previously, the MesoEta model predicts precipitation values too low over much of North Carolina. Observations indicate that more than 6 in (15.2 cm) of precipitation fell over portions of eastern North Carolina, while the Experimental Simulation predicts between 4 and 6 in (10.2–15.2 cm) over much of this region. The Experimental Simulation indicates a precipitation maximum near the landfall location along with a precipitation maximum over extreme Northeastern North Carolina agreeing closely with the observed precipitation distribution. Moreover, the Experimental Simulation shows a relative minimum in precipitation over portions Central North Carolina with an enhancement in precipitation to the west of this region. Between 0.8 and 2 in (2–5 cm) of precipitation is simulated over Central North Carolina while between 1.2 and 2 in (3–5 cm) is predicted to the west of this region. The simulated distribution is also similar to observations, although the amounts in the western regions are too low in the Experimental Simulation.

Several differences are apparent when comparing the simulated precipitation distribution between the Control and the Experimental models. The Control Simulation predicted a larger portion of central and eastern North Carolina receiving 3–5 in (7.62 and 12.7 cm) of precipitation. For example, the Control Simulation predicts over 3 in (7.62 cm) of precipitation at Raleigh-Durham International Airport (RDU), while the Experimental Simulation predicts 2 in (5 cm). Observations from RDU indicate that 1.57 in (4 cm) of precipitation fell during this period. Additionally, the Experimental Simulation predicts a relative minimum in precipitation over portions of Central North Carolina with an enhancement in precipitation to the west. The Control Simulation does not show this precipitation distribution; rather the entire region is in the 2–4 in (5–10.2 cm) range. The Experimental Simulation predicts between 0.8 and 2 in (2–5 cm) of precipitation over Central North Carolina, while 1.2–2 in (3–5 cm) is predicted to the west of this region. Surface observations

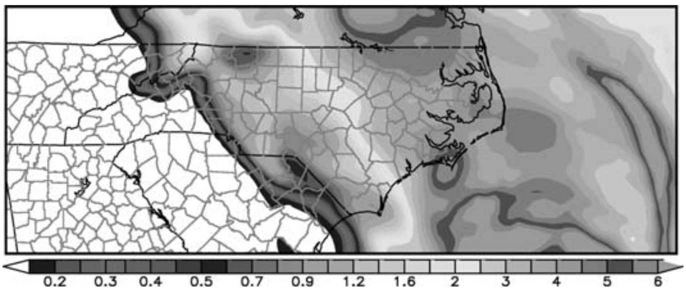

Fig. 6 Experimental simulated storm total precipitation (in) valid 12 UTC 17 September through 12 UTC 19 September 2003

show a similar precipitation distribution across the region, although amounts in the western regions are too low in the Experimental Simulation. In comparison, the Experimental Simulation's precipitation fields agree better with observations than the Control Simulation. This is likely a result of a more accurate storm track and intensity prediction associated with the Experimental Simulation.

Tropical cyclones are essentially flux driven systems; meaning their energy is derived from surface heat fluxes. Latent heat release is the primary energy source driving tropical cyclones (Schade and Emanuel 1999). Surface heat fluxes peak sharply just outside and under the eyewall and are partially responsible for the vertical motion patterns observed in tropical cyclones. Figure 7 shows the difference in surface latent heat flux (W/m^{-2}) between the Experimental and Control simulations of Hurricane Isabel valid 10 UTC (06 LT) 18 September 2003. During this time period, Isabel was crossing the warm, Gulf Stream waters. Large differences in surface latent heat fluxes are evident around the inner core of the simulated tropical cyclone vortex. Surface latent heat fluxes simulated by the Experimental configuration of the model is about 350 W/m^{-2} larger than that by the Control simulation around the eyewall of Isabel. With greater simulated latent heat fluxes, a more defined inner core structure often results. Increased latent heat fluxes likely led to better organized eye wall convection, and may have resulted in a better-simulated track of Hurricane Isabel in the Experimental Simulation. Differences between the Control and Experimental simulated latent heat fluxes are likely a result of the differences in the prescribed lower boundary conditions or, more specifically, SST.

5 Summary and conclusions

Results from this study show that both simulations (with coarse and fine resolution SST) predict the track of Isabel over North Carolina reasonably well, although the

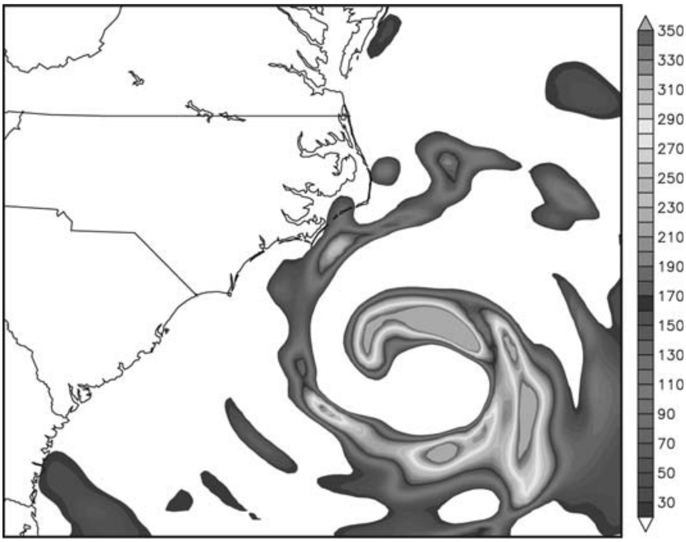

Fig. 7 Difference between the Control simulated surface latent heat flux and the Experimental simulated surface latent heat flux valid 10 UTC 18 September 2003. Fluxes are shown in W/m2

track predicted by the Experimental Simulation agrees more closely with observations from the Tropical Prediction Center. The Experimental Simulation more closely agrees with observations of the intensity of Isabel as indicated by central pressure tendencies. The simulated minimum central pressure from the Experimental Simulation is more realistic when compared with the observations from the Tropical Prediction Center. Both the Control and Experimental Simulations predicted precipitation amounts more accurately than the NCEP MesoEta model. However, the Experimental Simulation predicted the precipitation amounts and spatial distribution better than the Control Simulation. This is especially apparent over portions of central North Carolina, where the Control Simulation predicted 4–6 in (10.2–15.2 cm) precipitation, while less than 2 in (5.08 cm) of rainfall was actually recorded. The Experimental Simulation predicted between 1 and 3 in (2.54–7.62 cm) of precipitation over this region, more in line with observations.

The Experimental configuration simulates increased surface latent heat fluxes (about 350 W m^{-2} higher) as compared to the Control configuration around the eyewall of Hurricane Isabel. With greater simulated latent heat fluxes, a more defined inner core structure often results. The increased latent heat fluxes likely led to more organized eyewall convection, and in turn might have altered the simulated track of Isabel in the Experimental Simulation. The differences between the Control and Experimental simulated latent heat fluxes are obviously the result of the differences in the prescribed SSTs. The differences between the Control and Experimental SST data (more realistic) over the Gulf Stream region likely resulted in differences in the simulated surface latent heat fluxes between the two model configurations. The larger latent heat fluxes in the Experimental Simulation likely resulted in a stronger, more defined eyewall structure. The effects of the more realistic SST data in the Experimental Simulation were also present inland, as the Experimental simulated track deviated from the Control simulated track even after landfall in North Carolina.

Additional case studies with varying tropical cyclone tracks and intensities are needed to fully understand the importance of high-resolution SST data on tropical cyclone simulations.

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