UTILIZING A MESOSCALE MODEL FOR SHORT-TERM FORECASTING DURING HURRICANE ISABEL

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ABSTRACT

Hurricane Isabel caused considerable damage across the National Weather Service (NWS) Wakefield, Virginia county warning area (CWA), including major storm surge damage along parts of the Chesapeake's western shore and major tributaries. In addition, thousands of trees were downed from strong wind gusts. Site surveys conducted by the Wakefield office indicated that several areas within the CWA had greater damage than others. This locally enhanced damage could be attributed to a combination of storm surge, wave action, and high wind gusts. An examination of the performance of the workstation Eta (WSEta) model [1] during Hurricane Isabel was conducted, using model output up to 24 hours before Isabel affected the Wakefield CWA, to identify mesoscale features that contributed to greater damage. Wind direction and speed were examined to assess the duration and fetch of winds over open water and to determine the potential impact of wave heights on storm surge. Atmospheric stability was also examined to evaluate when gust potential was maximized as Isabel moved through the area. The passage of a coastal front was studied to assess further the mixing of higher wind speeds to the ground. The results of this study will be used to suggest a method of how to use mesoscale models effectively before hurricane landfall to assess potential impacts.

INTRODUCTION

Hurricane Isabel caused extensive damage across the Wakefield county warning area (CWA; Figure 1), including areas along the Chesapeake Bay and its tributaries. Surveys of damage caused by Isabel revealed mesoscale structure to the damage with some locations receiving substantially more damage than others. Various meteorological factors contributed to this damage pattern. Specifically, prolonged winds directed up tributaries on the western Chesapeake combined with over-water trajectories of 32 to 97 km (20 to 60 miles), increasing the storm surge and producing higher waves on top of this surge. Although emergency managers, through training and experience, know that significant storm surge augmented by wave action will occur in this situation, more specific information and advanced warning as the storm develops and moves through the area will enhance their ability to respond to the storm effectively. While real-time observations and radar data provide some specifics, this information offers limited value beyond short-term forecasts (1 to 2 hours from observation time). This study examines the Workstation Eta's ability to provide detailed, small-scale information on Isabel's wind, temperature, and precipitation substructures that can improve storm surge and wind forecasting several hours before damage occurs.

MATERIALS AND METHODS

WSEta model output for 00:00 UTC, 06:00 UTC, and 12:00 UTC on 18 September 2003 were examined. The WSEta runs the full physics of its larger-scale parent Eta model [2, 3] with 39 vertical levels, initial conditions through an interpolation of isobaric GRIB data from the Eta or GFS model [1], and lateral boundary conditions supplied by the Eta or the Global Forecast System (GFS) [4,

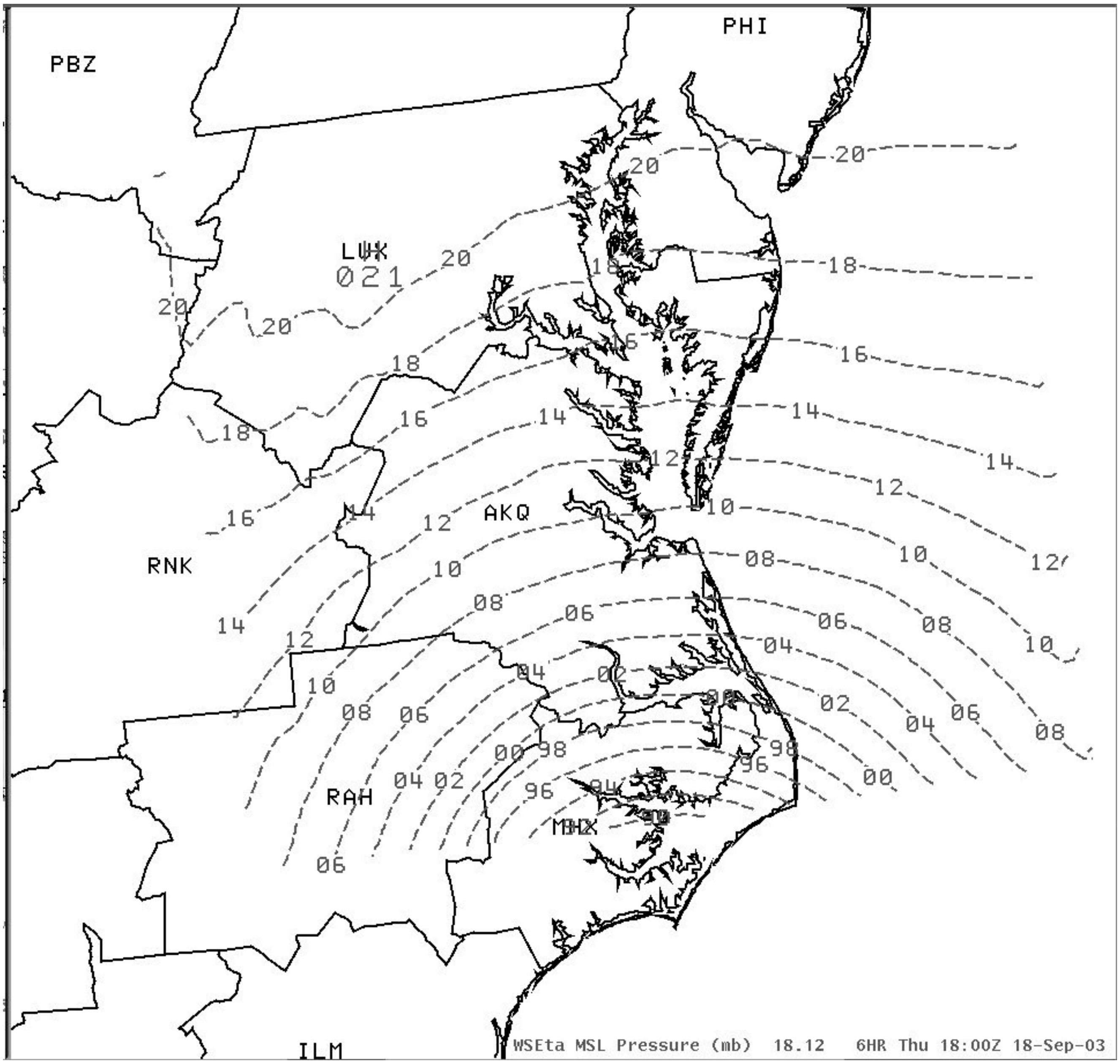


Figure 1. Forecast mean sea level pressure (mslp) contoured every 2 hPa (dashed) from the 12:00 UTC WSEta run, valid at 18:00 UTC on 18 September 2003. Three-letter identifier AKQ is located in the middle of the Wakefield, VA CWA (middle of figure). Area covered by contours of mslp shows the domain of the WSEta.

5]. The model was run initially over a larger, outer (coarse) grid of 15-km grid spacing with a Kain-Fritsch convective scheme [6]. A nested run was then made over a much smaller grid with a spacing of only 5 km (Figure 1). Various runs used different configurations over the inner (nested) grid. These different configurations were evaluated to determine which one best simulated wind, temperature, and precipitation substructures that appeared to be associated with the enhanced damage.

The Kain-Fritsch convective parameterization was always used on the outer domain. Explicit convection was used over the inner domain, except for one run for which the Kain-Fritsch parameterization was also applied to the inner grid. Weisman et al. [7] showed that explicit convective schemes can be used at 4 km, but not at 8 km (no testing was conducted at intermediary resolutions). Since the inner grid resolution (5 km) was close to this threshold, it warranted trying an explicit convection scheme. All runs were hydrostatic, except for one run (Eta initial/boundary conditions and explicit convection over nested grid) for which non-hydrostatic equations were used over the inner grid.

RESULTS AND DISCUSSION

Evaluation of WSEta Output

The various configurations of the WSEta were evaluated with runs at 00:00 UTC, 06:00 UTC and 12:00 UTC on 18 September 2003 using the Weather Event Simulator (WES) [8], which mimics the Advanced Weather Interactive Processing System (AWIPS) graphical display system, to determine if any mesoscale features—frontal boundaries, banded structures, and small-scale wind trajectories and speed maximums—were present and forecasted by the model runs. Any identified features were then examined to determine the impact they had on potential damage.

While the run using the GFS initial/boundary condition had a better overall track and intensity for Isabel when compared to runs with Eta initial/ boundary conditions, the broader grid spacing in the GFS caused a loss of the finer detail that this study was attempting to capture. Though using the Eta to provide initial and lateral boundary conditions produced varying tracks and intensity for Isabel (depending on initialization time), these were generally less accurate than those from runs initialed from the GFS. The Eta did, however, provide more detail about the storm's structure. Figure 2 shows this detail through two distinct bands of ascent at 700 hPa in the run using the Eta for boundary conditions; the WSEta run using GFS initial/boundary conditions has one large area of ascent at 700 hPa over southeast Virginia.

The run using Kain-Fritsch convective parameterization on the nested grid provided less structure than runs using explicit convection. A non-hydrostatic run over the nested grid using the Eta boundary conditions, Kain-Fritsch scheme on the initial run and explicit on the nested grid showed slightly more structure. It was felt, however, that the small run time and the barotropic nature of the main feature of interest would make the difference between non-hydrostatic and hydrostatic runs over the 5-km domain small. The slight gain in detail was sufficiently substantial to outweigh the increased runtime (runtime more than doubled, from an average of just shy of 2 hours using hydrostatic equations to over 4 hours using non-hydrostatic equations). The best runs to use for the purpose of this study, therefore, were those

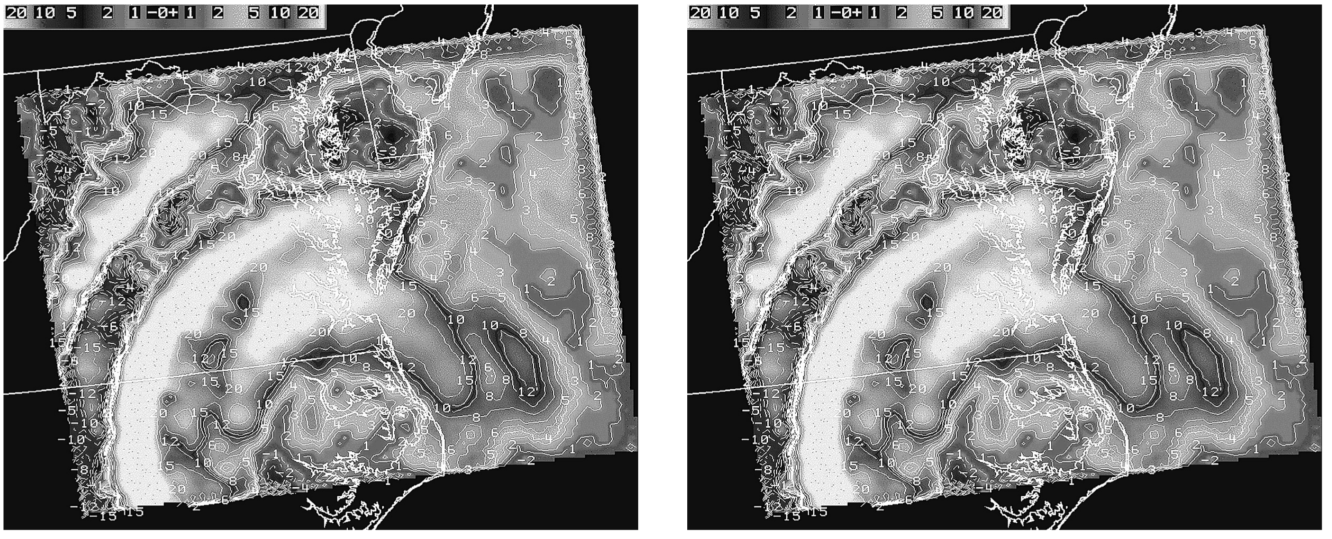
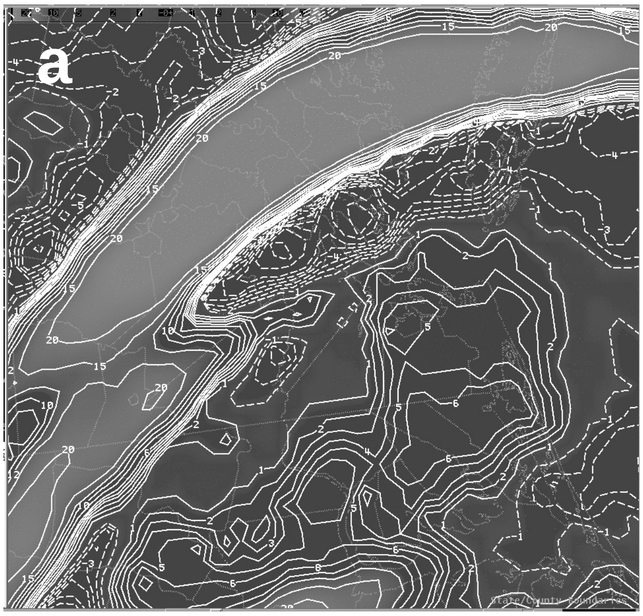
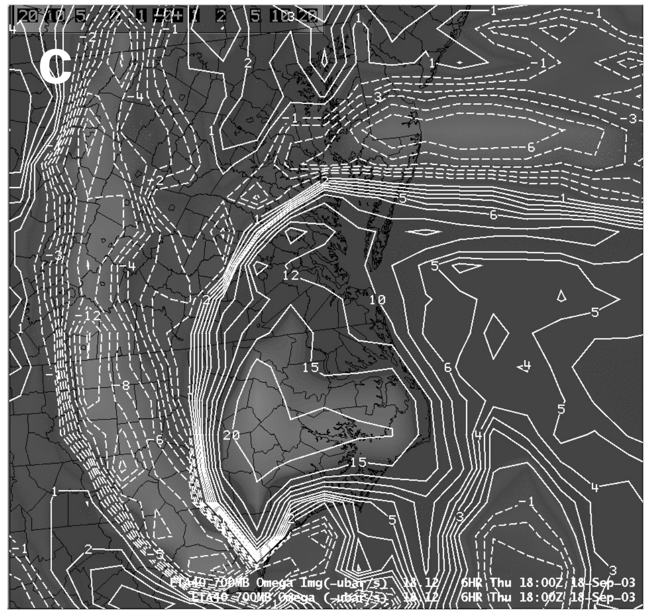


Figure 2. Forecast 700 hPa vertical motion from the 00:00 UTC WSEta run with the Eta boundary conditions (left) and GFS boundary conditions (right), valid at 22:00 UTC 18 September 2003.





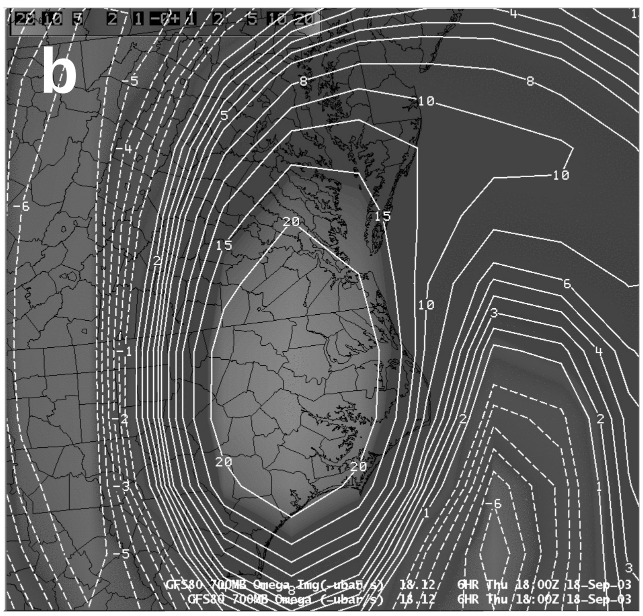


Figure 3. Forecast 700 hPa vertical motion at 18:00 UTC, from WSEta (a), Eta (b), and GFS (c) (respectively) run at 12:00 UTC 18 September 2003. Solid contours represent upward vertical motion; dashed contours represent downward vertical motion. The brighter whites indicate the strongest upward vertical velocity where the stronger bands in a tropical system are expected.

incorporating Eta boundary conditions with hydrostatic equations and explicit convection over the inner grid. This configuration provided detailed output, while enabling more efficient use of limited computer resources. These advantages outweighed any advantage gained by having a more realistic storm track and intensity.

Finally, a comparison of the best configuration and the two operational models (Eta and GFS) was made. As expected given the differences in resolution, a comparison of the WSEta output (5-km resolution) with that of the Eta (20-km resolution in AWIPS) and GFS (about 80-km resolution in AWIPS), the WSEta showed much more detail about the hurricane's banded structure. The Eta depicted some structure (not as much or as detailed as the WSEta) and the GFS indicated only a broad area of ascent with little or no structure evident. Figures 3a through 3c show areas of 700 hPa ascent (and descent) for the three models respectively. The following subsections explore some of the findings from WSEta runs using the configuration as specified above.

Frontal Boundary. The WSEta model runs depicted a low-level boundary, which is well portrayed in a plot of surface theta-e and surface wind barbs (Figure 4) from the 00:00 UTC run of the WSEta. This boundary indicated a tight gradient of theta-e across interior southeast Virginia, with north winds blowing parallel to the theta-e gradient along and on the cool side of the boundary and northeast winds on the warm side of the boundary. This setup

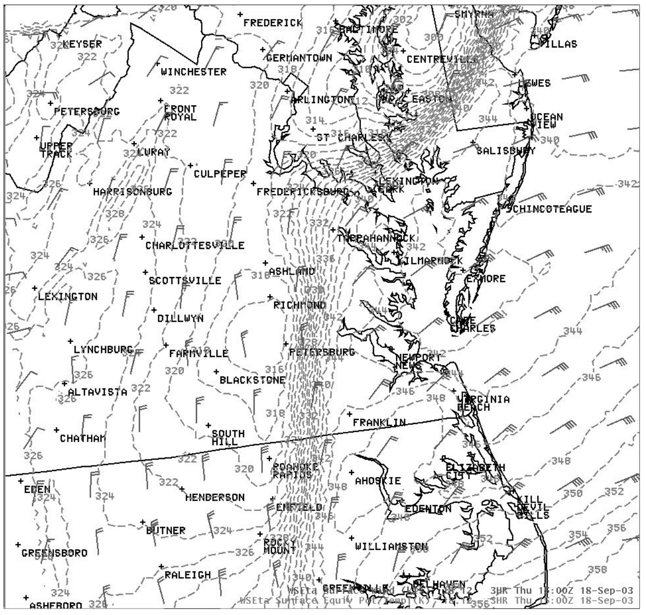


Figure 4. Forecast theta-e at 4K intervals (gray) and surface wind (gray barbs) from the 06:00 UTC WSEta run, valid 15:00 UTC.

is typical of conditions for an inland-moving coastal front over the Mid-Atlantic region. This coastal front delineates a relatively unstable maritime tropical airmass to its south and east and a relatively stable continental polar airmass to its north and west, associated with high pressure area to the north pushing drier air into the Mid-Atlantic states on 17 September 2003. The coastal front moved slowly inland over the coastal plain during the day on 18 September 2003 and was shown by Millet and Billet [9] to substantially affect the timing of stronger winds from Isabel reaching the ground.

WSEta soundings from Roanoke Rapids, North Carolina and Norfolk, Virginia (Figure 5) indicate the depth of this boundary aloft. In Figure 5a, the inversion extends to about 875 hPa, with the inversion preventing the downward mixing of the stronger winds above this layer [9]. Figure 5b indicates a more unstable airmass, however, with the potential to mix down stronger winds from aloft. This stability difference at the two locations is also demonstrated by the CAPE (convective available potential energy) increasing from 50 Jkg^{-1} near Roanoke Rapids to around 500 Jkg^{-1} near Norfolk at 15:00 UTC (not shown). The winds below 950 hPa on the sounding show more northerly winds at Roanoke Rapids, while winds at Norfolk have a more easterly, onshore component. This pattern is typical of a coastal front that has recently moved through one station (Norfolk) and is approaching another (Roanoke Rapids). Wind speeds at 950 hPa are comparable at both locations, providing similar gust potentials, but surface wind gusts are much lower near Roanoke Rapids in the sounding. Real-

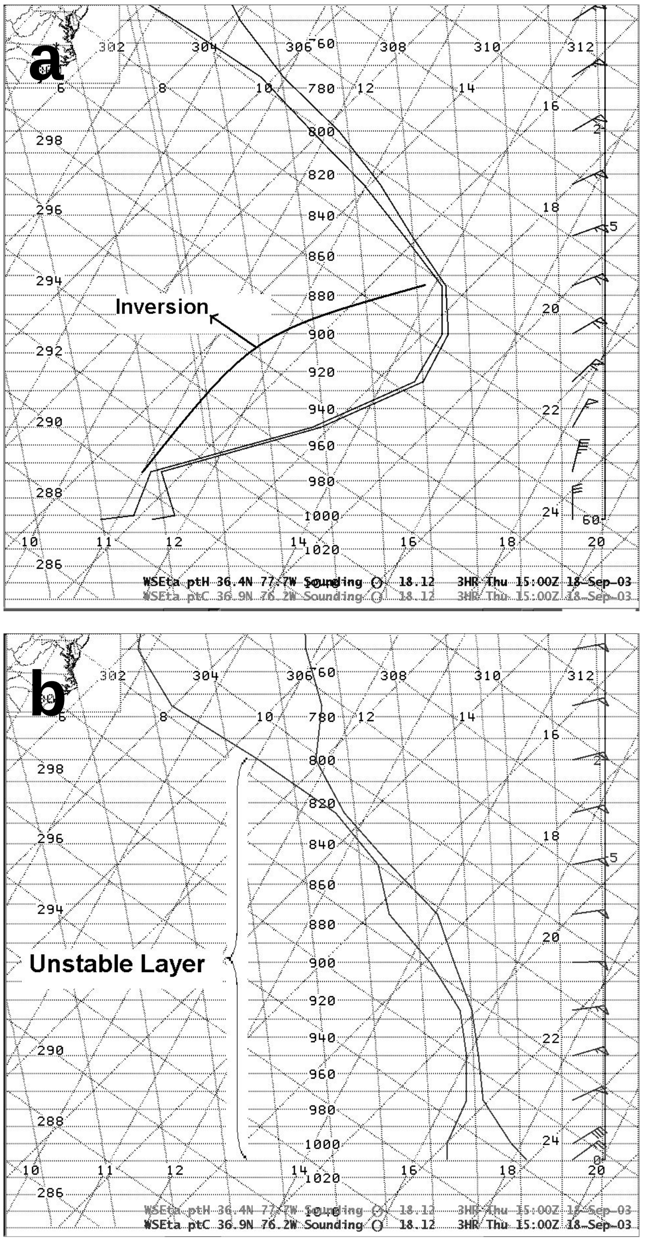


Figure 5a. a) WSEta Sounding at Roanoke Rapids, NC from 12:00 UTC WSEta run valid at 15: 00 UTC 18 September 2003; b) WSEta Sounding at Norfolk, VA from 12:00 UTC WSEta run valid at 15:00 UTC 18 September.

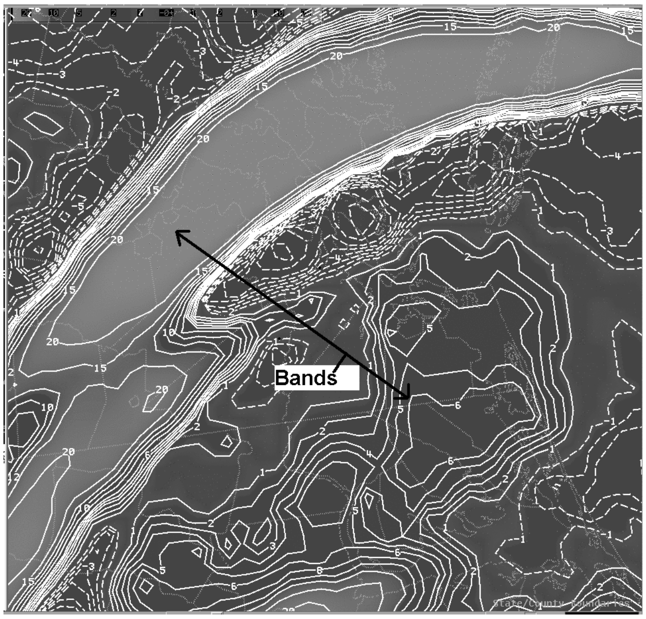


Figure 6. Identical to Figure 2a.

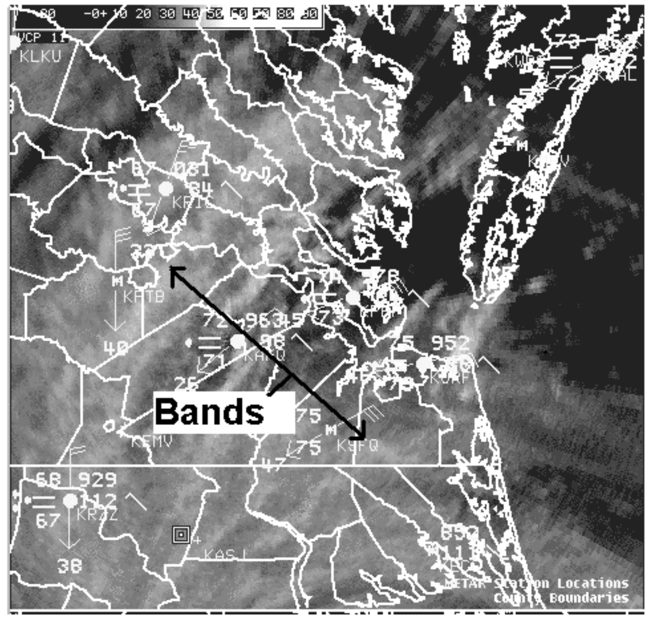


Figure 7. Wakefield, Virginia WSR-88D 0.5-degree, 8-bit reflectivity at 17:57 and 18:00 UTC observations.

time observations show the validity of these model soundings since winds at 2500 ft (762 m) (925 mb) were depicted by radar at approximately 74 kts at both locations near 15:00 UTC, but winds at the surface near 15:00 UTC only peaked at 33 kts at Roanoke Rapids and 52 kts at Norfolk [0].

Banded Structures. Vertical motion at 700 hPa has long been used to diagnose the location of convection from numerical weather prediction models. Examination of the vertical motion forecast from the WSEta valid at 18:00 UTC (Figure 6) indicates a banded structure to the convection (upward vertical motion), with a primary band stretching from the Virginia Eastern Shore, across the Chesapeake Bay, and southwest into south-central Virginia. A second, though weaker, band occurs from southeast Virginia into northeast North Carolina, with a region of sinking air between the two bands. The NWS Wakefield Doppler radar at 17:57 UTC (Figure 7) indicated similar structure and strength to the two bands, with a minimum of activity in between and corresponding to the area of descending vertical motion in Figure 6.

Further comparison of Figure 6 and Figure 7 suggests that the model bands were similar to radar observations, including the shape narrowing with time as the bands propagated further from the center. The behavior of the bands when looping model output was similar to their behavior while looping an extended radar or enhanced IR satellite loop. This ability of the WSEta to replicate the general structure and behavior of the bands shows the validity of using the model to gather meaningful detail about these bands as they move about the storm. In other words, the WSEta produced a detailed and realistic storm-relative picture of Isabel's banded structure.

While the location of the bands in the model corresponded well with the actual location of the bands, this situation was not always the case. The primary reason may be that the WSEta, as a consequence of using Eta boundary conditions, did not always provide accurate motion, and hence instantaneous location, for Isabel. Because the WSEta does capture the storm-relative essence of the structure, strength, and motion of individual bands, however, meaningful information can still be derived from its output—even when the physical location and/or intensity of the storm in the WSEta differed from what actually occurred or was forecast. By translating the model location for Isabel (and all associated detail) to the corresponding location (in space and time) along

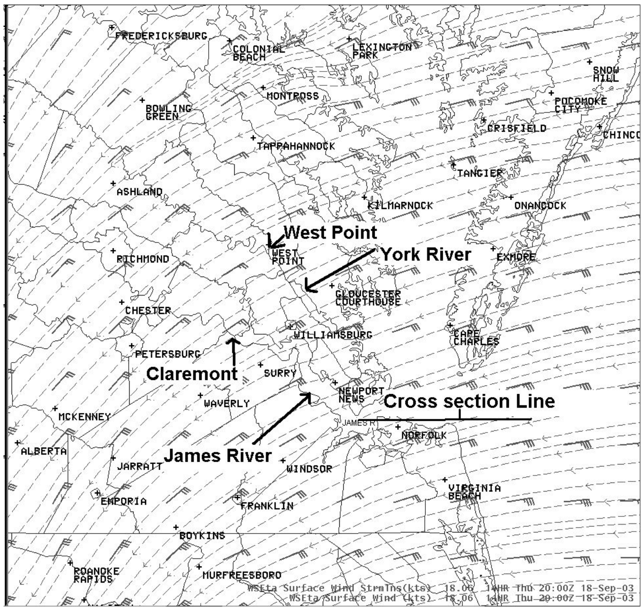


Figure 8. Forecast surface wind barbs and stream-lines from the 12:00 UTC WSEta run valid 18:00 UTC, 18 September 2003.

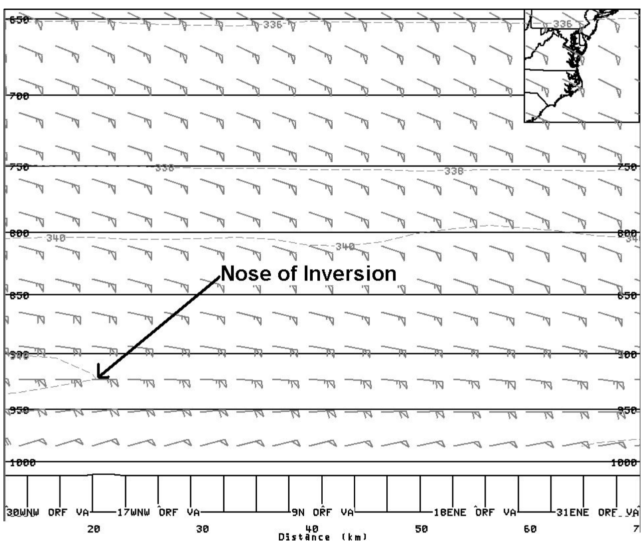


Figure 9. Cross-section of wind and theta-e dashed from 1000 to 650 hPa along an east-west line in Figure 8.

the National Hurricane Center track for the storm, the bands ended up close to where they were observed.

The WSEta forecast of these bands was accurate up to 12 hours ahead of their actual occurrence. In addition, each successive run of the WSEta provided similar details and evolution of these bands, which helps forecaster confidence when providing this information to customers. The timing of these features can help emergency managers determine when particularly severe weather will move across their area. Possessing this specific information should enable them to better manage their short-term resources.

Wind Trajectories with Wave Setup. Some of the more extensive damage associated with Isabel occurred along the York and James rivers, particularly in the towns of West Point and Claremont, with storm surveys indicating the damage came from high storm surge and wave action. Real-time wind trajectories traveled over open water, which played a major role in causing this damage. Initially, winds had a long water trajectory pointing into the mouth of the Bay, which raised water levels and drove water into these rivers. As Isabel moved inland, winds became southeast and pushed water up the rivers, increasing storm surge. In addition, long trajectories over open water built waves to an estimated .37 m (1.2 ft) on the rivers, with waves of this height adding around .09 m (0.3 ft) to the storm surge where it came ashore. The WSEta wind fields provided a means of examining the over-water wind trajectories. Figure 8 shows long over-water wind trajectories forecast by the WSEta, which would support piling of water into the mouth of the Bay. These forecast wind trajectories were accurate in orientation and duration, with the WSEta depicting longer over-water wind trajectories up the James and York rivers, but surface wind speeds were significantly less than observed.

Figure 9 shows a cross-section, from the coastal waters into the mouth of the James River, from east of Norfolk to south of Newport News. The cross-section showed unidirectional winds greater than 50 kts to the east of the low-level inversion through 900 hPa, allowing the wind gusts to enhance the surface winds and resulting in increased wave action up the James River. The WSEta indicated that the winds would veer to the southeast late on 18 September 2003 (not shown), allowing the water piling into the mouth of the James and York rivers to be pushed further upriver. At the same time, high tide was occurring, increasing the amount of water flowing up the rivers on the west side of the Bay. This information could have been given to emergency managers as early as nine hours before the highest tides during Isabel on the evening of 18 September 2003. The advanced knowledge of these long-duration fetches of wind up the rivers on the Bay's west side would have been useful to emergency managers in planning for more water damage in specific areas. Predictions of the onset and duration of local maxima of storm surge and wave flooding and suggestions that storm surge and wave impact projections might be exceeded could have proved particularly useful.

CONCLUSIONS

The WSEta can be used in a real-time operational environment to examine mesoscale features. The best WSEta model configuration for depicting the coastal front, banded precipitation structures, and wind trajectories and wind speed maxima in this case was the use of explicit convection in the nested grid, Kain-Fritsch convective parameterization over the coarse domain, and hydrostatic equations. Several features relative to the impact of Isabel were provided in WSEta runs including coastal front depiction, convective band structure, and over-water wind trajectories. The strong theta-e gradient across the Wakefield CWA indicated a change in the ability to mix higher wind speeds from aloft to the surface. Convective band structure was present by the WSEta depiction of strong vertical velocities and provided a storm-relative frame to suggest when periods of more intense rains and higher wind gusts would occur, especially when combined with information on the coastal front location. Wind trajectories from the WSEta provided details on where the most significant waves might occur and information on where increased storm surges were possible.

Overall, the WSEta did a good job of indicating where increased storm surge and higher waves would combine to cause potentially greater damage once the location of features were translated to the projected NHC track for the storm. When properly interpreted output from the WSEta is relayed to customers, such information can guide planning for worsening conditions and indicate how long these conditions might last. Finally, since this study involves only one storm, its results should be used with care until additional research on other tropical systems is conducted.

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