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ADAPTATION OF THE ADVANCED HURRICANE WRF FOR DRIVING A STORM SURGE PREDICTION MODEL

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1. INTRODUCTION

A wide spectrum of tropical cyclone surface wind fields has been used to drive storm surge prediction models, ranging from parametric wind models, to steady-state dynamic PBL models, to inner-core kinematic analyses, to sophisticated non-hydrostatic NWP models (Cardone and Cox 2009). Though parametric wind models have distinct operational advantages that maximize the number of hours of forecast utility (direct coupling to ocean models, extreme computational efficiency, minimal data I/O), they cannot reproduce far-field winds that generate "precursor" or "forerunner" surges with a high degree of accuracy or replicate unbalanced/fine-scale features such as supergradient radial inflow or spiral rainbands. On the other hand, extreme care must be exercised when interpolating NWP model gridded wind fields to storm surge model finite-element mesh nodes in both space and time. Otherwise, errors can be introduced that cause along-track elliptical distortions in the shape of the isotachs, resulting in an artificially weak representation of the storm, especially for fast-moving tropical cyclones. To obtain more accurate storm surge predictions, these wind generation methods are now being combined. GWAVA (gradient wind asymmetric vortex analysis) wind model fields and H*Wind analyses (Powell et al. 1998) are being assimilated into the Advanced Hurricane WRF model. The winds are simulated at high horizontal resolution (1 km), output at high frequency (10-60 minutes), then interpolated to the ADCIRC coastal ocean model's grid domain to run storm surge simulations.

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2. NUMERICAL MODEL BLEND

The GWAVA wind model, used in the OLAS (Ocean Land Atmospheric Simulation) forecast system (Mattocks and Forbes 2008), is based on Holland (1980), with the added feature that the radius of maximum winds varies azimuthally around the cyclone to capture asymmetry in the shape of the storm. A cross-isobar inflow angle and a directional surface roughness parameterization that modulates the wind speed at a given location based on the types of land cover encountered upwind are applied to represent surface friction. These parametric winds, generated on-the-fly from NHC forecast advisory and best track information in a computationally efficient manner, are available at exact analytical resolution. Thus, they can be directly coupled to an atmosphere/ocean/climate model at every time step and grid point while the model is running. GWAVA's numerics and physics have been extensively upgraded since the model was first utilized in ADCIRC for generating real-time, event-triggered forecasts of storm surge beginning with the 2006 hurricane season. Hindcasts of recent storms (Fig. 1) demonstrate that this wind forcing produces realistic estimates of storm surge.

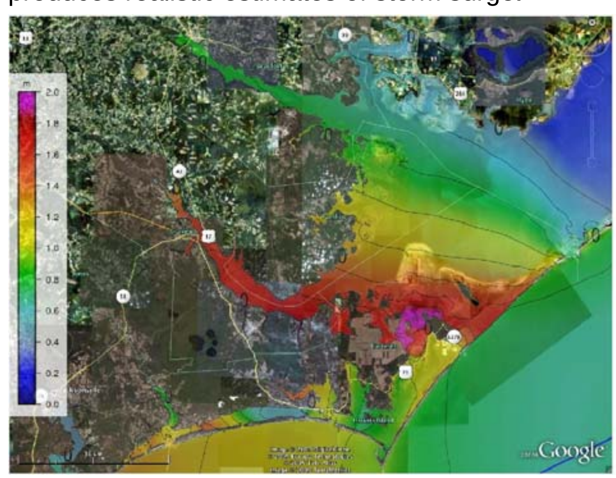

FIG. 1. Maximum water elevation (m) over Pamlico Sound, NC during Hurricane Ophelia (2005), as simulated by the ADCIRC storm surge prediction model driven by winds from the GWAVA wind model.

The Advanced Hurricane WRF (AHW) (Davis et al. 2008) is a moving-nest, vortex-tracking version of WRF-ARW that includes drag saturation at high wind speeds and a one-dimensional columnar, mixed-layer ocean model, with the horizontal distribution of mixed-layer depth provided by the HYCOM ocean model, to more accurately simulate vertical momentum/heat exchange. AHW simulations were run with both the WRF-default coarse-resolution (50 km) real-time global (RTG) SST analyses and temporally varying high-resolution (1 km) MODIS SST analyses provided by the Short-term Prediction Research and Transition (SPoRT) project (Darden et al. 2007, Jedlovec et al. 2006) at NASA-Marshall Space Flight Center. The latter have been shown to capture the diurnal variability of the vertical heat and moisture fluxes from the ocean that drive the formation of low-level clouds and precipitation over the ocean (LaCasse et al. 2007, Case et al. 2008a,b).

ADCIRC (Luettich et al. 1996) is a finite-element hydrodynamic model used to simulate wind-driven storm surge, tides, riverine flow and inundation. The unstructured triangular grid includes all waters in the western Atlantic, Caribbean and Gulf of Mexico. Several high-resolution (30 m) grid meshes are available, with computational points draped across inlets and waterways, aligned with shoreline and elevation contours. The unstructured-mesh version of the SWAN (Simulating WAves Nearshore) spectral wave model has recently been integrated with ADICRC (Dietrich et al. 2009). Wave-circulation interactions were included in the simulations for this study.

3. RESULTS

Storm surge predictions are extremely sensitive to track error, as demonstrated by comparing results from ADCIRC+SWAN simulations of Hurricane Ike (2008) driven by GWAVA winds with a shift of 0.1 degree in track to the southwest (left Ike) and northeast (right Ike) relative to the Best Track (Fig. 2). This departure was chosen because it corresponds to the location reporting precision in NHC forecast advisories. The difference in surface water elevation is highly dependent on coastline geometry, local bathymetry, and wind direction. The “left Ike” simulation produces large amplification in the eastern half of Galveston Bay, with peak differences higher than 7 m to the northeast of Galveston Bay, while the “right Ike” simulation produces much more isolated, but larger differences of greater than 12 m far from the storm center.

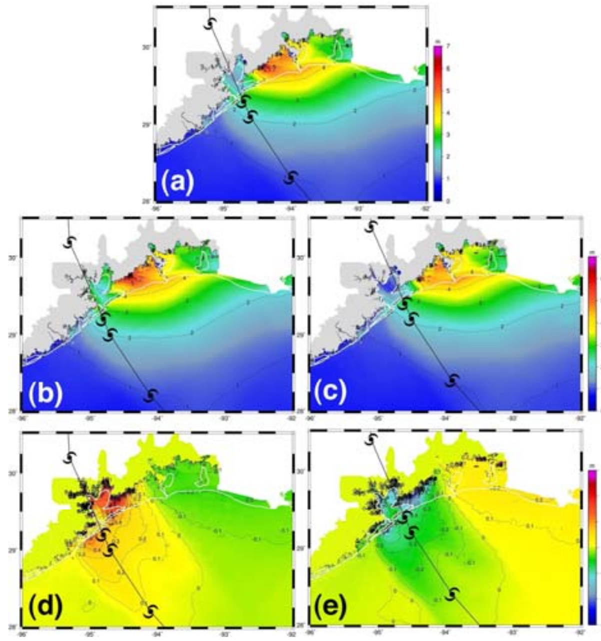

FIG. 2. Maximum water surface elevation (m) for Hurricane Ike (2008) generated by the ADCIRC+SWAN storm surge prediction model forced by winds from the GWAVA wind model using National Hurricane Center Best Track storm parameters: (a) NHC Best Track, (b) track shifted to the left 0.1 degrees in latitude and longitude, (c) track shifted to the right 0.1 degrees in latitude and longitude, (d) difference in maximum elevation (m) between the left-shifted track and Best Track, and (e) difference in maximum elevation (m) between right-shifted track and Best Track.

It is well documented that numerical model predictions of hurricanes suffer from significant track and intensity errors (Franklin 2008). Our experience bears this out. Attempts to generate accurate 84-hour AHW hindcast simulations of Hurricane Ike (2008) initialized with 12 km NAM analyses resulted in the tracks shown in Fig. 3. Note the substantial southwest track bias of approximately 50-100 km that persist in these simulations. AHW simulations were run with several different cloud microphysics (MP) schemes (Morrison, Thompson, WDM6, Lin, Milbrandt) to try to reduce the track error. The most consistent track with the least overall error was produced with the Lin scheme. The best performance at landfall was achieved using the Milbrandt scheme, which caused the track to suddenly veer to the right 6-7 hours prior to landfall. This track sensitivity to cloud microphysics scheme is in agreement with WRF simulations of hurricanes conducted by other investigators (Fovell and Su 2007, Fovell et al. 2009, Fovell et al. 2010) which showed that scheme-dependent cloud-radiative feedback (CRF) formulations, specifically the longwave radiation absorption and emission coefficients, play a major role in tropical cyclone vortex motion. Indeed these track variations have been used to construct cloud physics-based forecast ensembles (Fovell and Boucher 2009) but this is beyond the focus of the current effort, which is to obtain the best deterministic forecast possible. As of yet, there is no general solution to this problem. Deactivating CRF makes storms more compact, their convective asymmetry more pronounced, and their intensities considerably stronger. Since the WRF microphysics schemes vary substantially in the quantity and species apportionment of condensate, each has a different radiative response. Much work remains to be done on this topic.

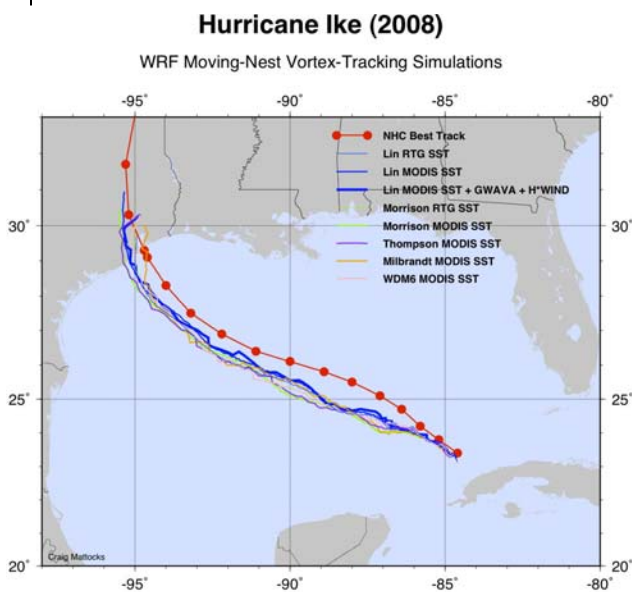

FIG. 3. Hurricane Ike tracks from AHW simulations using various microphysics schemes, SSTs and surface nudging: NHC Best Track (red line with dots), AHW simulations with RTG (Real Time Global) 50 km SST and Lin microphysics (thin blue line), with NASA MODIS 1 km SST and Lin microphysics (thicker blue line), with NASA MODIS 1 km SST and Lin microphysics and nudging to GWAVA and H*Wind analyses (thick blue line), with RTG SST (thin green line) and Morrison microphysics, with NASA MODIS 1 km SST and Morrison microphysics (thick green line), with NASA MODIS 1 km SST and Thompson microphysics (purple line), with NASA MODIS 1 km SST and Milbrandt microphysics (orange line), and NASA MODIS 1 km SST and WDM6 microphysics (pink line).

One of the most widely used techniques developed to remedy errors in track and intensity is the insertion of a three-dimensional "bogus" symmetric Rankine or Holland vortex into the initial state of the atmosphere. The vorticity, geopotential height and velocity perturbations associated with the previously analyzed location of the tropical cyclone are removed in a process known as "vortex relocation" prior to insertion of the new idealized bogus vortex into the flow field. However, as noted by Rhome et al. (2004), this axisymmetric spinup procedure can inadvertently destroy the environmental wind shear upstream, allowing a storm to intensify unrealistically. Since we had no problems spinning up a tropical cyclone of adequate intensity using the 12 km NAM initial conditions, we adopted a more gentle approach for mitigating errors in storm track/intensity, while avoiding the problems caused by vortex relocation/insertion. We incorporated temporally interpolated high-resolution SST composites into the initial and boundary conditions, then assimilated H*Wind analyses and hourly GWAVA snapshots into AWH using surface nudging (Newtonian relaxation).

The impact of incorporating the 1-km SPoRT MODIS SSTs (Fig. 4) in the AWH simulations is promising.

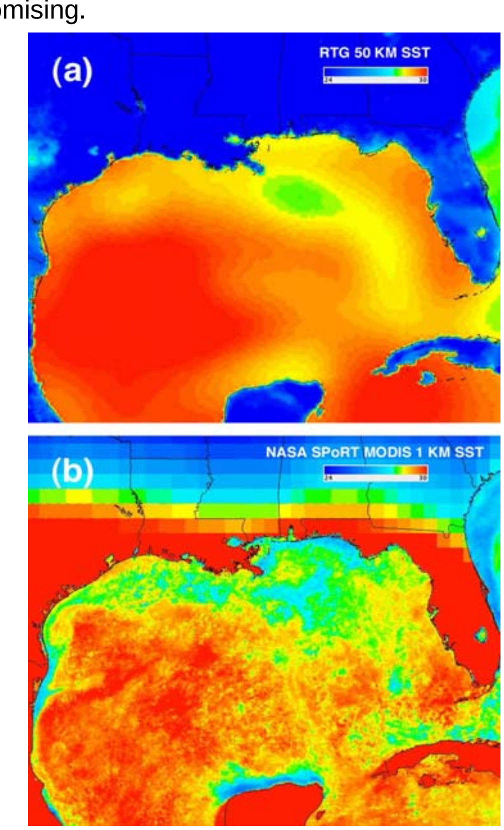

FIG 4. SST analysis at 06 UTC 10 September 2008 from (a) RTG (Real Time Global) 50 km resolution, and (b) NASA-Marshall Space Flight Center SPoRT MODIS 1 km resolution products.

The traces of central pressure (Fig. 5a) show a significant improvement (reduction) in the pressure deficit of approximately 12 mb for the Morrison scheme (green) and 9 mb for the Lin scheme (blue) immediately after landfall due to the high-resolution SSTs.

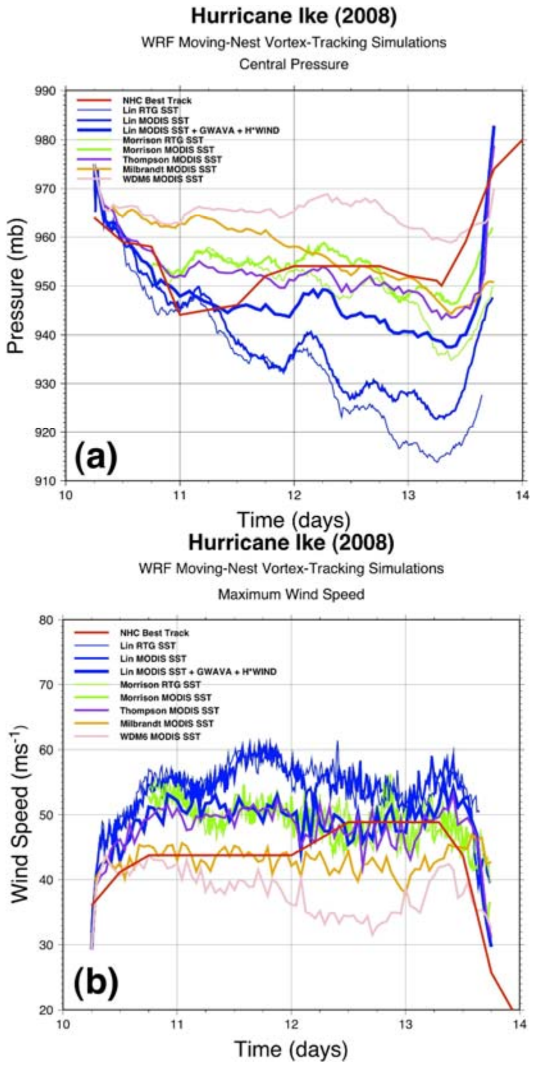

FIG 5. (a) Central pressure (mb) and (b) maximum wind speed (kts) from AHW simulations of Hurricane Ike using various microphysics schemes, SST and surface nudging: NHC Best Track (red line with dots), AHW simulations with RTG (Real Time Global) 50 km SST and Lin microphysics (thin blue line), with NASA MODIS 1 km SST and Lin microphysics (thicker blue line), with NASA MODIS 1 km SST and Lin microphysics and nudging to GWAVA and H*Wind analyses (thick blue line), with RTG SST (thin green line) and Morrison microphysics, with NASA MODIS 1 km SST and Morrison microphysics (thick green line), with NASA MODIS 1 km SST and Thompson microphysics (purple line), with NASA MODIS 1 km SST and Milbrandt microphysics (orange line), and NASA MODIS 1 km SST and WDM6 microphysics (pink line).

The Lin scheme generates the best simulations of central pressure early in the simulation when the pressure drop is steepest, while the Milbrandt, Thompson and Morrison simulations are more accurate in the latter half of the simulation when the pressure tendency levels off. Surface wind nudging, only performed for the Lin scheme thus far, improves the simulated central pressure at landfall by an additional 14 mb.

A comparison of time series of maximum wind speed (Fig. 5b) is less definitive regarding the impact of the high-resolution MODIS SST. Assimilation of the H*Wind analyses and hourly GWAVA wind snapshots within the lowest 100 mb using the WRF-default nudging parameters significantly improves the simulated maximum sustained wind speed. In general, the Milbrant MP scheme produces the best predictions of wind speed early in the simulation, while the Morrison, Thompson and nudged-Lin MP schemes converge to within ±5 ms^{-1} of each other and produce the best estimates in the latter part of the simulations.

Snapshots of four different types of surface wind fields at landfall are shown in Fig. 6.

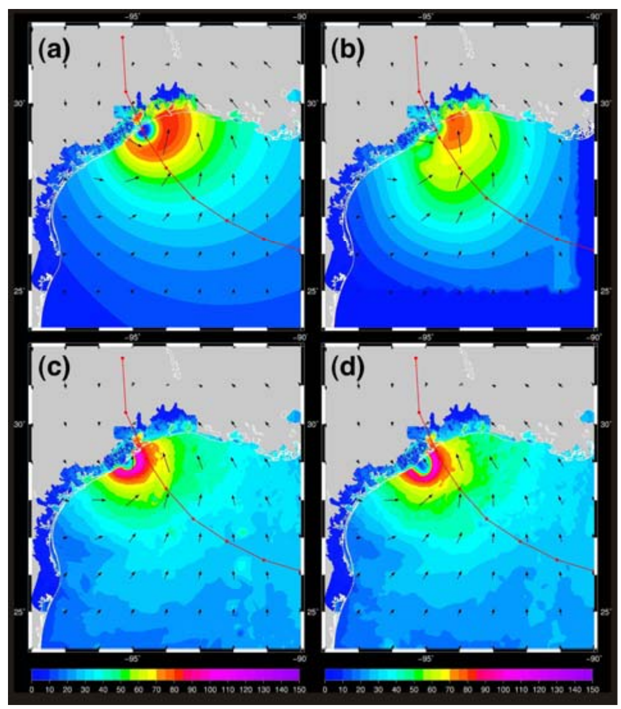

FIG. 6. Hurricane Ike's winds (kts) at landfall produced by (a) the GWAVA wind model using National Hurricane Center Best Track storm parameters, (b) H*Wind analyses, (c) AHW simulation with Lin microphysics and MODIS SST, and (d) AHW simulation with Lin microphysics and MODIS SST, plus surface nudging to H*Wind analyses and GWAVA wind fields.

The GWAVA parametric winds (Fig. 6a) are idealized and smooth, but are exactly on track at the correct Best Track intensity. In contrast, the left side of the storm in the H*Wind analysis (Fig. 6b) exhibits an elongated, open vortex structure and smaller area of hurricane force winds. The AHW renditions of the wind fields there are quite similar. Both the AHW Lin + MODIS SST (Fig. 6c), and the AHW Lin + MODIS SST + nudging (Fig. 6d) winds are characterized by more realistic banded structures outside the radius of maximum winds, but are plagued by a track error of approximately 40 km at landfall. Surface wind nudging increases the eye diameter and elongates the vortex towards the southeast. In the AHW simulation that uses the Milbrant MP scheme (Fig. 7), Hurricane Ike suddenly jogs close to the Best Track just hours prior to landfall. We are currently investigating why this occurs and whether it is related to the CRF formulation.

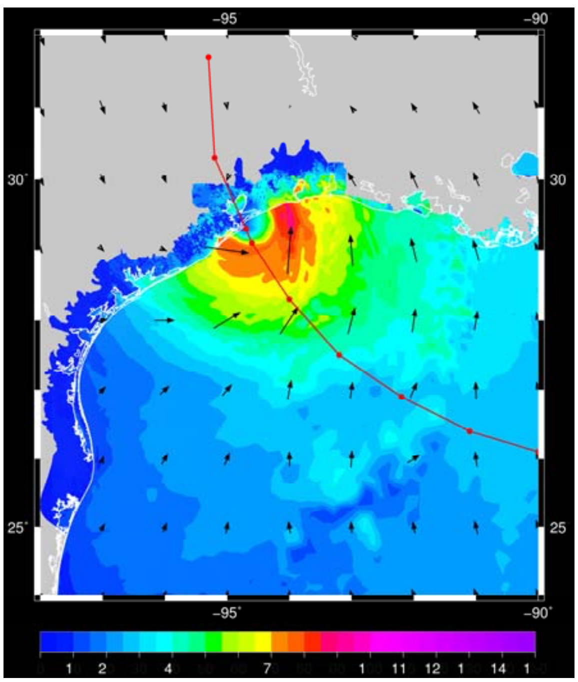

FIG. 7. As in Fig. 6, but for the Milbrandt double-moment cloud microphysics scheme.

A time series comparison between wind measurements from 3 NOAA/NDBC stations and the ADCIRC wind forcing at station locations, both time-averaged to 10-minutes and adjusted to a height of 10 meters, is displayed in Fig. 8. Typical of most gradient wind models, GWAVA overestimates the wind speed near the radius of maximum winds and underestimates the intensity far from the center of the storm. Nevertheless, it replicates the observations remarkably well at Morgan's Point. In general, the H*Wind traces are closer to the recorded observations than the GWAVA wind traces when a station falls into the area covered by the moving H*Wind 8° by 8° gridded analysis domain. Due to the southwest track bias in the AHW wind fields, there are no eyewall traversals in any of the AHW Lin + MODIS SST wind time series; the right side of the storm passes over the stations. Therefore, the wind speeds are overestimated (underestimated) in the trailing (leading) portion of the wind time series. Surface nudging begins to carve out eyewall signature in the wind trace at Morgan's Point because the eye diameter is expanded. The one improvement the AHW winds provide is a better rendition of both the wind speed and direction in the far field, especially in the leading edge of the hurricane. The H*Wind and GWAVA wind direction traces are similar and turn abruptly during eyewall traversals, while the AHW directions change more gradually due to the southwesterly track error.

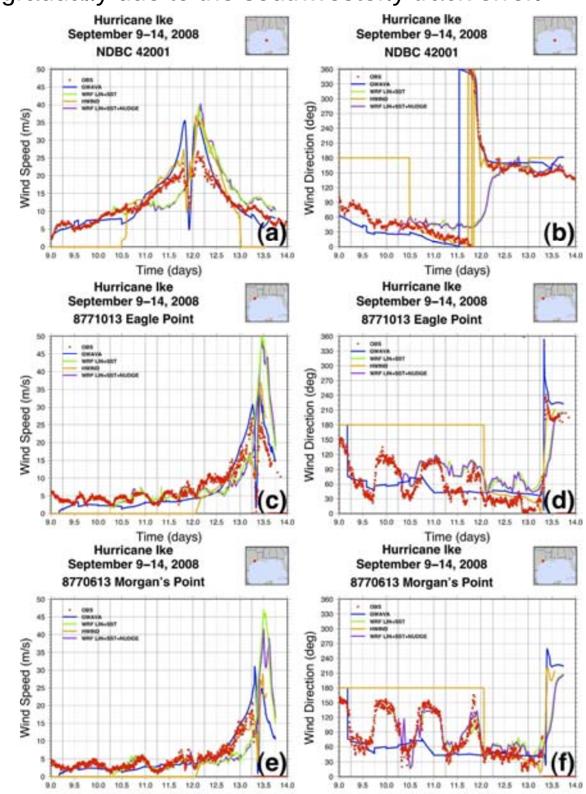

FIG. 8. Comparison of wind speed (ms^{-1}) and direction (deg) from AHW model simulations and observations from (a) NDBC buoy 42001 wind speed and (b) direction, (c) NOAA station Eagle Point wind speed and (d) direction, and (e) NOAA station Morgan's Point wind speed and (f) direction. Observations are indicated by red dots and model results by lines: GWAVA wind model (blue), AHW with Lin microphysics and MODIS SST (green), H*Wind analyses (orange), AHW with Lin microphysics and MODIS SST plus surface nudging to GWAVA winds and H*Wind analyses (purple).

Maximum surface water elevations produced by ADCIRC+SWAN storm surge simulations driven with four different sources of wind forcing are shown in Fig. 9. The GWAVA wind-forced (Fig. 9a) and H*Wind analysis-forced (Fig. 9b) simulations generate water elevations that are similar in magnitude and areal extent. The H*Wind results are a bit broader and lower in height, especially along the shoreline east of Galveston Bay. The aforementioned track error in the WRF-forced simulations (Figs. 6c,d) has an enormous deleterious impact on the simulated storm surge (Figs. 9c,d). The strongest winds are shifted to the southwest and focused on the entrance of Galveston Bay, which creates an erroneous surge of 4-5 m at Galveston and drives water across the bay, up Trinity Bay into the low-lying lake areas northeast, and northwest into the Houston suburbs. WRF surface wind nudging pushes this aberrant surge northeastward along the shoreline, reducing the water levels at northwest of Galveston, but it cannot overcome the large track error, so the surge distribution remains largely the same.

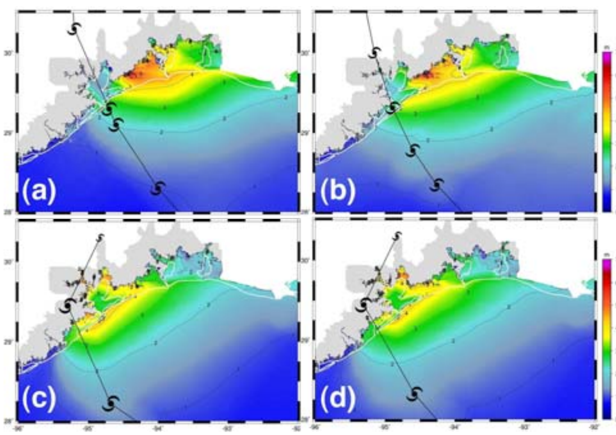

FIG. 9. Maximum water surface elevation (m) for Hurricane Ike generated by the ADCIRC+SWAN storm surge prediction model forced by winds from (a) the GWAVA wind model using National Hurricane Center Best Track storm parameters, (b) H*Wind analyses, (c) AHW simulation with Lin microphysics and MODIS SST, (d) AHW simulation with Lin microphysics and MODIS SST plus surface nudging to H*Wind analyses and GWAVA wind fields.

The maximum water surface elevation from ADCIRC+SWAN produced by wind forcing from the Milbrandt AHW simulation is shown in Fig. 10. The storm track correction immediately prior to landfall markedly improves the quality of the simulated storm surge. The horizontal distribution of the water elevations is similar to those in Figs. 9a (GWAVA forcing) and 9b (H*Wind forcing), but are slightly lower in amplitude.

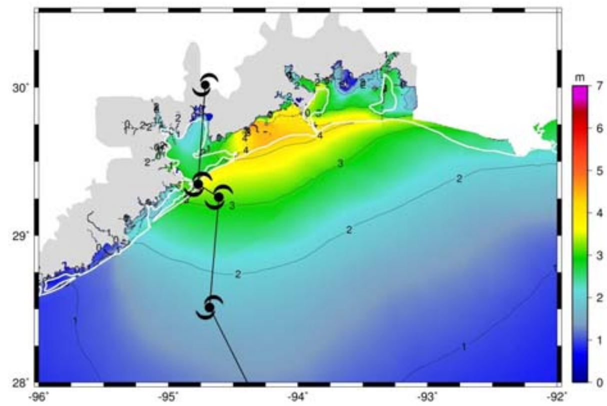

FIG. 10. As in Fig. 9, but with wind forcing provided by an AHW simulation with the Milbrandt microphysics scheme.

4. SUMMARY

Attempts to improve storm surge predictions through the use of far-field winds from the Advanced Hurricane WRF model remains a challenge due to significant track biases in the AHW simulations. Incorporation of high-resolution MODIS SST composites and nudging to a combination of GWAVA surface wind snapshots and H*Wind analyses were partially successful in producing more realistic renditions of central pressure and maximum sustained wind speed, but these measures could not overcome the persistent track error in the simulations. Much work needs to be done on the cloud radiative feedback formulations in the WRF cloud microphysics schemes to correct predictions of tropical cyclone vortex motion before these wind fields can be used reliably as forcing to drive storm surge prediction models.

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