Research papers

Skill assessment of a real-time forecast system utilizing a coupled hydrologic and coastal hydrodynamic model during Hurricane Irene (2011)


A R T I C L E   I N F O

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A B S T R A C T

Due to the devastating effects of recent hurricanes in the Gulf of Mexico (e.g., Katrina, Rita, Ike and Gustav), the development of a high-resolution, real-time, total water level prototype system has been accelerated. The fully coupled model system that includes hydrology is an extension of the ADCIRC Surge Guidance System (ASGS), and will henceforth be referred to as ASGS-STORM (Scalable, Terrestrial, Ocean, River, Meteorological) to emphasize the major processes that are represented by the system. The ASGS-STORM system incorporates tides, waves, winds, rivers and surge to produce a total water level, which provides a holistic representation of coastal flooding. ASGS-STORM was rigorously tested during Hurricane Irene, which made landfall in late August 2011 in North Carolina. All results from ASGS-STORM for the advisories were produced in real-time, forced by forecast wind and pressure fields computed using a parametric tropical cyclone model, and made available via the web. Herein, a skill assessment, analyzing wind speed and direction, significant wave heights, and total water levels, is used to evaluate ASGS-STORM’s performance during Irene for three advisories and the best track from the National Hurricane Center (NHC). ASGS-STORM showed slight over-prediction for two advisories (Advisory 23 and 25) due to the over-estimation of the storm intensity. However, ASGS-STORM shows notable skill in capturing total water levels, wind speed and direction, and significant wave heights in North Carolina when utilizing Advisory 28, which had a slight shift in the track but provided a more accurate estimation of the storm intensity, along with the best track from the NHC. Results from ASGS-STORM have shown that as the forecast of the advisories improves, so does the accuracy of the models used in the study; therefore, accurate input from the weather forecast is a necessary, but not sufficient, condition to ensure the accuracy of the guidance provided by the system. While Irene provided a real-time test of the viability of a total water level system, the relatively insignificant freshwater discharges precludes definitive conclusions about the role of freshwater discharges on total water levels in estuarine zones. Now that the system has been developed, on-going work will examine storms (e.g., Floyd) for which the freshwater discharge played a more meaningful role.

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1. Introduction

Since the devastating effects of Hurricanes Katrina, Rita, Ike and Gustav in the Louisiana and the northern Gulf of Mexico region, the development of a high-resolution, real-time, total water level prototype forecast system has been accelerated: the development and assessment of such a system is the subject of this manuscript. It produces a holistic representation of the coastal flooding through development of a total water level product (defined herein to be tides + waves + rivers + surge + precipitation).

Over the last several years, the ADCIRC Coastal Circulation and Surge Model, which forms the backbone of the system described...
herein, has been used in many hurricane studies, in particular, the Interagency Performance Evaluation Task Force to study Hurricane Katrina (Link et al., 2006), and evaluations of the hindcasts of Hurricanes Gustav (Forbes et al., 2010) and Rita (Dietrich et al., 2010). As part of this process, a wave component (Dietrich et al., 2010) was added and there has been continued development of a parametric tropical cyclone model following Holland (1980) and Mattocks et al. (2006). In addition, a real-time system has been developed, the ADCIRC Surge Guidance System (ASGS), to automate the use of ADCIRC in forecast applications (Fleming et al., 2008). The model system described in this paper demonstrates a further extension of ASGS to include a hydrologic model, capturing both coastal and inland total water levels associated with tropical and extratropical storms. This model system is herein referred to as ASGS-STORM (ASGS-Scalable, Terrestrial, Ocean, River, Meteorology). A parallel, collaborative effort with NOAA (National Oceanic and Atmospheric Administration) through their CI-FLOW (Coastal Inland-Flood Observation and Warning) project is reported in Van Cooten et al. (2011), which documents the history of the system’s development and its initial testing.

In some coastal storm events, the surge and wave components play the most significant role; while for others, the freshwater component from upstream river flow is the dominant component. An event that illustrated the need to incorporate the upstream freshwater component in the coupled model system was Hurricane Floyd. The North Carolina watersheds saw only a small surge (≈3 m) during Hurricane Floyd, but inland main stem river reaches and their tributaries experienced record precipitation that produced historical flooding (comparable to the 500-year flood levels on the Tar/Pamlico River) (Tromble et al., 2011). Hurricane Dennis preceded Floyd and alleviated the drought conditions in the North Carolina coastal areas; however, it also set up the antecedent conditions that brought about massive flooding during Hurricane Floyd. Thus, in order to accurately represent the coastal flood inundation caused by both the upstream flooding and storm surge, a system is needed that incorporates not only the tides, waves, winds and atmospheric pressure differences due to the storm but also the antecedent conditions, precipitation and riverine flows. Events such as these have spurred the development of a total water level product, which has been the focus of both DHS (Department of Homeland Security) and NOAA projects. Thus, herein, we describe progress towards the development of a modeling system to produce high-resolution, total water level forecasts for coastal, near-shore and inland areas.

Previous studies have looked at real-time systems; however, none of these previous systems have coupled a hydrologic and hydrodynamic model in a real-time framework. Blain et al. (2002) documented a real-time tidal modeling system designed to integrate meteorological information from different scale meteorological models. However, this system did not include waves, hydrological components, or the ability to develop the meteorological forcing from tropical cyclone advisories. Mattocks et al. (2006) developed a system that provided real-time coastal modeling utilizing ADCIRC and a new parametric tropical cyclone model. This system included the tidal effects; however, it did not include the waves and hydrological models. Modern cyberinfrastructure tools were applied to ADCIRC by Ramakrishnan et al. (2006) to develop a real-time modeling capability that could

Fig. 1. Schematic of ASGS-STORM for predicting total water inundation in coastal North Carolina; upper boxes illustrate model components in the coupled system, lower boxes illustrate output products, and arrows and text boxes indicate data flow.
ingest information from several different locations. The cyberinfrastructure developed in this study was utilized in the initial test of the coupled model system for Hurricane Earl. Fleming et al. (2008) describes an automated surge guidance system that was initially developed for use in Lake Pontchartrain in Louisiana; however, as additional capabilities were added to the system, a more generalized format was added that allowed it to be utilized outside of Louisiana. This system evolved into the ADCIRC Surge Guidance System (ASGS). ASGS includes software automation, job control, fault tolerance and data flow services. The ASGS technology was implemented in ASGS-STORM for use after Hurricane Earl, to couple the hydrologic and hydrodynamic models. Lastly, Chu et al. (2009) developed a relocatable ADCIRC automation system that utilized a toolbox approach, which allowed the user to run the system in either an automated or manual fashion. It provided five modules that included system set up, data acquisition, model configuration, model run status, and product generation. The system was designed to be relocatable to areas of interest in a short period of time and was developed for the United States Navy.

NOAA utilizes several different models in operational settings in a non-coupled fashion to simulate water quantity (e.g., SLOSH: Sea, Lake, and Overland Surges from Hurricanes—Jelesnianski et al., 1992) and HL-RDHM (National Weather Service/Hydrology Laboratory—Research Distributed Hydrologic Model—Koren et al., 2004). NOAA runs a variety of hurricane meteorological models, such as HWRF (Hurricane Weather Research and Forecasting—Skamarock et al., 2008) and GFS (Global Forecast System—Environmental Modeling Center, 2003). However, none of the models or systems that NOAA runs in real-time currently couple the meteorological forcing, river inflows, tides, waves and storm surge into one complete system. The advantage of ASGS-STORM is that it can couple these components through physics-based models that produce a complete picture of the total water level.

The paper is divided into six sections: Section 1 discusses the motivation for the project and background on other real-time systems; Section 2 describes the components of ASGS-STORM and their development to produce the total water level response from a tropical or extratropical event; Section 3 gives information about Hurricane Irene; Section 4 presents the results from ASGS-STORM for Irene's winds, waves, and total water levels for three different advisories (Advisories 23, 25 and 28) and the best track; Section 5 provides some general observations about the system's performance; and Section 6 gives some concluding remarks on the coupled model system and directions for future work.

2. Background

2.1. Coupled model system—ASGS-STORM

Fig. 1 shows a schematic of ASGS-STORM, which can be utilized for both tropical and extratropical events (Tromble et al., 2011; Van Cooten et al., 2011). ASGS-STORM links precipitation, atmospheric, hydrologic, wave, and hydrodynamic models into an integrated system to produce routine predictions of total water levels, along with the significant wave heights and other information. The first test of ASGS-STORM occurred in the 2010 hurricane season with results being produced for Hurricane Earl; however, the system was not run in a real-time mode during the entire event. In June 2011, ASGS-STORM was run in a prototype, real-time mode and was utilized during Hurricane Irene to provide total water level information in the North Carolina area. A discussion of the system is given in Tromble et al. (2011) and Van Cooten et al. (2011): a summary of that discussion is provided in the following subsections for completeness.

2.1.1. Hydrologic model and precipitation—HL-RDHM and QPE/QPF

The hydrologic modeling component of the coupled model system, HL-RDHM (Koren et al., 2004), ingests precipitation information from QPFs1 and/or QPEs2 to produce riverine flows. QPEs are used as model inputs for current and past precipitation (required for model states), and QPFs are used for future time steps. Surface runoff generation is based on the original concepts of the Sacramento soil moisture accounting model (SAC-SMA-Burnash, 1995). These concepts are applied to each 4-km grid cell in the domain, and water is routed downstream using the kinematic wave equation. This model is the operational National Weather Service (NWS) distributed hydrologic model and is fixed on a 4-km grid based on the Hydrologic Rainfall Analysis Project (HRAP—Reed and Maidment, 1999), which allows for the direct integration of the QPE/QPF information. There are a total of 19 parameters and 6 state variables that control the behavior of the storages and fluxes in the model. A priori parameter settings for HL-RDHM have been estimated over the United States using readily available spatial maps of soil characteristics and land cover. The 19 parameters enable a great deal of flexibility for the model to be applied in diverse geographic and hydroclimatological settings. With this flexibility, however, comes the need to provide accurate estimates of parameter settings, which may be difficult to identify in order to optimize model performance for a broad range of scenarios (e.g., a land-falling hurricane with very dry initial conditions). Historical records of rainfall and runoff were used to manually calibrate the HL-RDHM model parameters in each sub-basin of the Tar/Pamlico and Neuse River basins. This process was completed efficiently by adjusting the routing parameters alone.

Computational resources allowed for a total of 128 riverine model simulations using HL-RDHM to be performed in real-time for each 6-hour update, corresponding to new QPFs issued by the HPC. These ensemble members were designed to encapsulate uncertainty in the rainfall forcing (estimated and forecast) and model parameters. The 128 ensemble included four different parameter sets (designated event-based, automatic, multiple basin, and a priori) with three of the parameter sets multiplied by 16 different rainfall multipliers that are uniformly distributed between 0.8 and 1.2. The last parameter set (a priori) was multiplied by 5 different rainfall multipliers, along with 16 channel routing perturbations. Thus, with the first three parameter sets there are 48 members of the ensemble with the last parameter set providing 80 members of the ensemble. A full discussion of the results from these 128 ensemble members can be found in Section 4.2.1.

Within ASGS-STORM, streamflow forecasts are produced every 6 hours in the Tar/Pamlico and Neuse River basins in North Carolina and, subsequently, passed to the ADCIRC hydrodynamic model to serve as river boundary conditions (a discussion on these locations can be found in Section 2.2). All forecast and observed rainfall above the location of the river boundary conditions for ADCIRC is accounted for by the hydrologic model and routed downstream. Rainfall occurring directly on top of the estuaries, or on the land surface below the boundary condition points, is neglected in the current configuration. The river boundary conditions for ADCIRC were chosen to be well upstream of locations where any tidal or storm surge effects would be experienced, as the routing component of HL-RDHM uses a kinematic wave equation, which cannot model backwater effects. Thus, any backwater effects caused by water moving up the estuaries must be
captured by the hydrodynamic model, ADCIRC. Results from HL-RDHM are produced at every 4-km grid point in the model domain, but results from the entire ensemble are stored only at gauge locations (for validation purposes) and boundary points of the hydrodynamic model.

2.1.2. Wind model—DAH

Two different atmospheric models are utilized in ASGS-STORM based on the type of event occurring in the area of interest. For tropical events, ASGS-STORM employs a parametric tropical cyclone model that is based on Holland (1980) and Mattocks et al. (2006). This captures the asymmetric nature of the wind field and is referred to as the Dynamic Asymmetric Holland (DAH) Model, while for non-tropical events, the results from the North American Mesoscale (NAM—Janjić et al., 2001) model drive the wind fields. Meteorological forcing presents a challenge to an operational modeling system that has limited computational resources due to the need for real-time, high-resolution spatial data. Data-assimilated meteorological fields provide the most accurate representation of the meteorological forcing; however, these types of products (e.g., H*Wind—Powell et al., 1998) typically are only produced after the event, sometimes days after the storm has already dissipated and the NOAA/NWS/National Hurricane Center (NOAA/NWS/NHC) has stopped issuing advisories. Therefore, data-assimilated wind fields cannot be utilized in a real-time environment because the data would not be available and the wind fields could not contain any information about future winds. NAM can provide gridded meteorological forcing, but only at a relatively coarse grid resolution (≈ 12 km grid resolution), which may not capture the hurricane wind field in an accurate manner. In turn, this could cause inaccuracies in the QPFs. However, during normal meteorological conditions, NAM can provide a gridded meteorological forcing with relatively good accuracy.

In many cases, parametric wind models (Holland, 1980; Houston et al., 1999; Mattocks et al., 2006) produce wind fields that capture storm surge in a reasonable manner (Forbes et al., 2010). These types of models require only a small amount of data in order to develop wind fields, produce information in a timely fashion as required by real-time operational systems, and provide information on wind stresses and pressures at any location.

2.1.3. Hydrodynamic model—ADCIRC

ADCIRC (2D, depth-integrated mode) serves as the hydrodynamic model in ASGS-STORM and ingests information from the hydrologic model at riverine boundaries (Tromble et al., 2012), while also taking information from the wind and wave models. ADCIRC utilizes the full nonlinear shallow water equations with the hydrostatic assumption and Boussinesq approximation. The model obtains the elevation changes from the Generalized Wave Continuity (GWC) equation (Kinnmark, 1986) and the velocities from the momentum equation. Spatially, it utilizes Galerkin finite elements with equal-order interpolating functions (linear $C^0$)

Fig. 2. Example of the CERA website during Hurricane Irene. Results are shown for Advisory 28 for the maximum water elevation. The track of the hurricane appears on the figure, along with the location of the hurricane at the time of the advisory, denoted by the black hurricane symbol.
triangular element). Temporally, ADCIRC uses a semi-implicit, three-time level approximation (centered at \( k \)) for the GWC equation and a lumped, two-time level approximation (centered at \( k + \frac{1}{2} \)) for the momentum equation; the nonlinear terms are evaluated explicitly. Conversely, the equations can be evaluated in fully explicit mode, thus improving the scalability of the model (Tanaka et al., 2010), which is utilized within this system. The solution utilizes exact quadrature rules, but the advective terms are approximated with \( L_2 \) interpolation. The full development of the model and equations can be found in Kinnmark (1986), Luettich et al. (1992) and Kolar et al. (1994).

ADCIRC has been used extensively for many applications over its 25-year history, such as hurricane storm surge modeling (Blain et al., 1994, 1998; Westerink et al., 2008; Bunya et al., 2010; Dietrich et al., 2010), Lagrangian particle transport, for both chemical and biological applications (Luettich et al., 1999; Reynolds et al., 2006; Oliveira et al., 2006; Dietrich et al., 2012), tidal and wind-driven circulation (Westerink et al., 1994; Blain et al., 2002), and density-driven circulation (Blain et al., 2010, 2012). Recent advances have included a more accurate representation of the land use/land cover by incorporating Manning’s resistance formula, the reduction of the wind drag coefficient due to changes in the land cover, inclusion of the air–sea interaction (Bunya et al., 2010), and the coupling of the wave interaction in the model (Dietrich et al., 2011b), which is further discussed in Section 2.1.4.

2.1.4. Wave model—SWAN

The wave model utilized in ASGS-STORM is the Simulating Waves Nearshore (SWAN) model, which was recently expanded to utilize unstructured meshes in both the nearshore areas and in deep water (Zijlema, 2010). The SWAN model employs the wave action balance equation given in Booij et al. (1999) and includes wave propagation in space and time, wave refraction and diffraction, as well as shifting of the wave frequency with the change in water depth or current. It takes into consideration bottom friction, whitecapping of waves and their loss of energy, nonlinear effects due to changes from deep to shallow regions, and surf breaking. Specifics on the model and its solution scheme can be found in Booij et al. (1999).

The SWAN model has been dynamically coupled to ADCIRC in recent years (Dietrich et al., 2011b), thus allowing the two models to pass information during run time. The tight coupling of the two models is facilitated by using the same domain and grid in their solution. During a simulation, the ADCIRC model passes the wind forcing, water levels and currents to the SWAN model, which in
turns uses that information to calculate the wave radiation stresses over the entire domain. The wave radiation stresses are then used to calculate their gradients, which are subsequently passed back to the ADCIRC model. The models use an explicit “leap frog” algorithm to pass information between each other; the time between staggered steps is a user-defined parameter, set at 20 minutes for results herein. This coupling interval is similar to what has been used in other studies with the tightly coupled ADCIRC and SWAN model (e.g., 10 min intervals in Dietrich et al. (2011b) and Dietrich et al. (2011a)). For other loosely coupled hydrodynamic-wave models, the coupling interval has been set to 15 or 30 min, respectively (Slinn, 2008; Bunya et al., 2010). In addition, the convergence behavior of SWAN for the advisories analyzed herein shows that it converged within 5 or 6 iterations, which is well before the 20 iterations specified, indicating that the wave results from the SWAN model did not change more than the convergence criteria between the iterations during the coupling interval. Thus, a coupling interval of 20 min seems appropriate for this application.

2.1.5. Distribution to end-users

Results from ASGS-STORM are shown in real-time in various forms on three different web locations. One of these is the NSSL CI-FLOW web page, which shows hydrographs and maximum inundation figures in real-time. Second, results in kmz format are provided on an OPENDAP server from the Renaissance Computing Institute (RENCI) in North Carolina. Third, the Coastal Emergency Risks Assessment (CERA) website is an interactive interface, which was developed by Louisiana State University. The CERA website (http://nc-cera.renci.org) provides several different layers of results (e.g., water elevation, water inundation, significant wave heights, wave periods, and wind speed). Fig. 2 illustrates an example CERA product for the water elevation.

2.2. Domain and area of interest

The study domain for HL-RDHM is shown in Fig. 3. The region falls completely within the area of responsibility of the NWS Southeast River Forecast Center (SERFC). The total basin area modeled by HL-RDHM is 14,426 km². HL-RDHM produces outputs at every 4-km grid cell, but time series and statistical analyses are produced only at USGS stations, where there are observed discharges. HL-RDHM also records output at four locations that provide the upper river boundary conditions to ADCIRC. These four locations are shown in Fig. 3 and correspond to the four major tributaries that impact the estuaries (as determined by a study of historical storms): the Tar/Pamlico and Neuse Rivers and Courtennea and Fishing Creeks. As stated above, these four handoff points were chosen, based on historical records, to be above zones of tidal and surge influence.

The entire ADCIRC domain is shown in Fig. 4(a), with zooms of the North Carolina area shown in Fig. 4(b) and (c). ADCIRC utilizes
3. Hurricane Irene

Hurricane Irene became the ninth named storm of the 2011 season and the first to make landfall in the United States since Hurricane Ike in 2008. The storm tracked through the Caribbean Islands of Puerto Rico, Hispaniola, Dominican Republic, Haiti, Bahamas, and the Turks and Caicos before heading to the East Coast of the United States. Irene peaked as a Category 3 in the Bahamas, and it made its initial landfall in the United States along the Outer Banks of North Carolina near Cape Lookout as a Category 1 hurricane on August 27 at 1200 UTC, bringing with it 39 m/s wind speeds. It then made a second United States landfall on August 28 at 0935 UTC in New Jersey and was downgraded to a tropical storm near New York City. It caused damage in many areas of the United States and the Caribbean, with estimates of monetary damage ranging from 10 to 15 billion dollars. ASGS-STORM provided guidance during Hurricane Irene, starting with Advisory 14 and concluding with Advisory 35, the last advisory of NOAA/NWS/NHC (Avila and Cangialosi, 2011). In advisories prior to number 14, the path of the storm did not approach the North Carolina area, thus, ASGS-STORM did not provide guidance for these advisories.

3.1. Track of storm from advisories

Fig. 5 shows the forecast tracks from 16 different advisories, along with the post-analysis “best track” developed by the NOAA/NWS/NHC of Hurricane Irene. As can be seen in Fig. 5, the advisory tracks of Hurricane Irene were close to the actual track of the hurricane, even for early advisories. Advisory 15 through 19 show the hurricane just skirting the tip of the Outer Banks of North Carolina (east of the actual track of the storm), while the other advisories (20–30) show a path similar to the best track, with some of the advisories predicting that the storm’s path would pass slightly to the west or east of the actual track. In their Irene report, Avila and Cangialosi (2011) indicated that the track forecast was better than average, which is evident in the advisory tracks passing close to the best track.

3.2. Intensity of storm from advisories

The intensity of Hurricane Irene peaked at a Category 3 and decreased to a Category 1 storm as it made landfall in the United States. However, the forecast intensity of the storm at landfall varied from a Category 3 to Category 1, with the forecast of the correct intensity occurring as the storm made landfall. Fig. 6 shows three of the advisories from Irene. Each of these advisories predicted a different storm intensity as Irene made landfall. Fig. 6(a) shows the track and intensity associated with Advisory 23, while Fig. 6(b) shows Advisory 25 and Fig. 6(c) shows Advisory 28. The intensity of Irene was over-predicted in the early advisories. As will be shown in Sections 4 and 5, these intensity errors (and track errors to a lesser extent because they were more consistent for Irene) manifest themselves as surge prediction errors.

4. Comparison to real-time data

As mentioned above, Fig. 6 shows three different advisory forecasts, with the strength of Hurricane Irene shown by the dots along the path of the storm. These three advisories were chosen due to their different strengths and tracks. The strength of the storm forecasted by NOAA/NWS/NHC for these different advisories changed significantly as the storm approached the coast of North Carolina. Advisory 23 (shown in Fig. 6(a)) predicted a Category 3 hurricane upon landfall in North Carolina, while Advisory 25 (shown in Fig. 6(b)) showed a decrease to Category 2, and Advisory 28 (shown in Fig. 6(c)) predicted a further decrease to a Category 1, which Irene was at landfall. The path of the storm forecasted by NOAA/NWS/NHC for the three different advisories varied to a certain extent as the storm approached the coast of North Carolina. The predicted track of Advisory 23 took the storm into the inland areas of North Carolina, while Advisory 25 showed the storm track over the estuarine area of the North Carolina coast, and Advisory 28 predicted the storm track over the outer banks of the North Carolina coast. The best track of Irene, developed in the post-analysis of the storm, showed it falling between the tracks of Advisories 25 and 28.

The results from ASGS-STORM shown in this manuscript will compare the wind, wave and total water levels during the three advisories shown in Fig. 6, along with the wind, wave and total water levels for the best track. These results will then be compared to observations taken from National Ocean Service (NOS) water.
level stations, National Data Buoy Center (NDBC) buoys, and USGS gauge locations. Table 1 gives the longitude and latitude location of the stations analyzed herein. Model results are presented in the following subsections with an initial discussion of the results and a more thorough discussion occurring in Section 5.

4.1. Wind and waves

Fig. 7 shows the location of the NDBC buoy stations that are utilized to evaluate the wind and wave performance of ASGS-STORM, along with the forecast tracks for three different

Fig. 6. Forecast information of the track and storm intensity (shown by the color of the dots along the track) for three different advisories: a) Advisory 23, b) Advisory 25, and c) Advisory 28. The legend shows the storm strength and the track information, along with the predicted maximum water surface elevation. The cone of uncertainty is also shown in each figure by the gray areas on either side of the official forecast track. Storm position is shown by the black hurricane symbol. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this article.)
advisories (Advisories 23, 25 and 28) and the best track. The stations used to compare the wind performance are shown in the left panel of Fig. 7, while the wave stations are shown in the right panel.

4.1.1. NOAA National Data Buoy Center—Wind

Fig. 8 presents the wind speed results from ASGS-STORM for stations along coastal North Carolina. Wind direction results were also evaluated, and they are presented in Fig. 9. The wind speed plots for the three different advisories are shown in Fig. 8, with the line types matching the track lines as shown in Fig. 7, along with the best track result and the observations from the NDBC buoy stations. Wind results show that the earlier advisories had wind speeds that were larger than actual speeds recorded during the storm due to the over-prediction of the strength of the hurricane. The best track, as well as Advisory 25, capture the passing of the eye of the hurricane (denoted by the sudden decrease of wind speeds to a rapid increase in winds) over the area for many of the stations analyzed. In both cases, the results tend to capture the trend of the wind speeds, but there is an over-estimation of the actual peaks of the wind speeds, with Advisory 25 showing a greater over-prediction due to the over-estimation in the strength of the storm. In all the advisories and the best track results, the wind speeds are above the actual observed wind speeds after the storm passes. This leads to the water levels remaining high after the storm passes through the area. This over-estimation of the wind speeds is being investigated as part of improving future operations.

The wind direction results indicate that for the different advisories and the best track many of the changes in direction are captured well. At some of stations (DUKN7 and CLKN7), the direction changes faster than those of the observed due to the easterly path of the storm and the location of the eye of the storm.

4.1.2. NOAA National Buoy Data Center—Waves

Fig. 10 presents the results for significant wave heights from ASGS-STORM for stations along coastal North Carolina. Similar to the wind results, the wave height plots show results from the three different advisories shown in Fig. 6, with the line types matching the track lines shown in Fig. 7, along with the best track and the observations from the NDBC buoy stations. Results are only shown here for the significant wave heights; however, the wave periods and direction present similar patterns. The wave heights were over-predicted in most of the advisories due to the over-estimation of the strength of the hurricane. This over-estimation leads to increases in the wind speeds, which translates to the increase in the heights of the waves. The best track and Advisory 28 results show only a slight over-prediction of the wave heights. Improvements in the prediction of the wind speeds should translate to better prediction in the significant wave heights along the coastal areas.

4.2. Water levels

4.2.1. USGS gauge stations—HL-RDHM

Fig. 11 shows four snapshots of ensemble predictions from HL-RDHM produced during the hurricane event for the Tar/Pamlico River at Tarboro, North Carolina. This site is in close proximity to one of the ADCIRC boundary condition locations; as such, it is

<table>
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<th>Station</th>
<th>Latitude (° N)</th>
<th>Longitude (° E)</th>
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<td>−71.960</td>
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<tr>
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<tr>
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critical to have accurate flows to pass to the ADCIRC domain. The mean of the forecast streamflows is derived from the 128-member ensemble (discussed in Section 2.1.1), and the ensemble mean streamflow is provided to ADCIRC at the four hand-off locations shown in Fig. 3. At gauged locations, the best member, which performed best compared to observed streamflow, as measured by the Nash–Sutcliffe Coefficient of Efficiency (Nash and Sutcliffe, 1970) and bias in the last 24 h, is highlighted in the red dashed line. In short, this best member assimilates observed streamflow into its selection. It should be cautioned that this member only has relevance when the gauge observes event-based streamflow (e.g., the rising limb of hydrograph); during base flow conditions, the ensemble approach has difficulty identifying a best member.

Fig. 11(a) shows that the forecast peak flow from the ensemble mean is in close agreement with the observed streamflow. The simulation at this stage in the forecast cycle was driven purely by forecast rainfall, providing a lead time of 3 days prior to the maximum observed streamflow. It can also be seen that the best member (in the red dashed line) overestimates the observed peak flow because there is very little time-varying data to assimilate in streamflow observations within the past 24 h. Fig. 11(b) shows similar performance from both the ensemble mean and the best member due to base flow conditions dominating the 24-hour period. At this point in the simulation, the rainfall hyetograph indicates approximately half of the rainfall forcing comes from estimated radar plus gauge rainfall from QPE, while the other half is from QPF. The simulations at later time in Fig. 11(c) and (d) are all forced with QPE rainfall estimates. Once the response due to the event is observed at the gauging station, the assimilation technique and selection of the best member is able to provide more accurate forecasts (cf. red dashed and blue dotted lines in Fig. 11c). In Fig. 11d, the accuracy of the best member finally exceeds that of the ensemble mean.

A post-event analysis was conducted, which utilized the full observed hydrograph for the Tar/Pamlico River at Tarboro to quantify the relative skill of the best member vs. the ensemble mean. Fig. 12 illustrates the results of this skill assessment. It shows the peak water level error (observed-predicted) for the ensemble mean and the member with streamflow assimilation are plotted as a function of lead time. This summary plot demonstrates that the ensemble mean performed quite well, with errors of approximately 20% when the precipitation forcing was from forecasts alone. As the forcing became dominated by radar plus gauge rainfall, errors were generally less than 10%. Overall, the performance of the HL-RDHM ensemble can be judged as accurate for this high-impact event, thus giving confidence to our procedure of using the ensemble mean at ADCIRC handoff
points where gauge information is lacking. Future work will analyze performance at additional stations and provide comparative results to operationally produced forecasts from the SERFC.

4.2.2. NOAA NOS Stations—ADCIRC

Fig. 13 (left panel) shows the location of the NOS water level stations that are utilized to evaluate the performance of ASGS-STORM, along with the forecast tracks for three different advisories (Advisories 23, 25 and 28) and the best track. As can be seen in Fig. 13, the best track of Irene (solid black line in the figure) changed directions several times during its forward progression toward landfall.

Fig. 14 shows results from six different NOS stations along the North Carolina, Virginia and New York coasts. The figures include the total water level predicted from the three different advisories presented previously, with the line types matching the track lines shown in Fig. 13, along with the observations from the NOS stations. Total water level results from four stations along the North Carolina coast are shown in the first four panels, with the last two panels providing results from the real-time system in Virginia and New York, which are outside the focus area of the project. Results are shown in relation to MSL (the ADCIRC datum).

In both Advisories 23 and 25, ASGS-STORM over-predicts the storm surge due to the over-estimation of the strength of the hurricane in the advisories. In most of the cases, the timing of the water levels peaks are captured, but water levels are higher than that recorded. For example, results from Advisory 23 for Duck Pier show the over-prediction of the storm surge due to the estimated category 2 strength of the storm; however, it also displays that the timing of the peaks coincides with the actual peaks. In Advisory 28 and the best track results, ASGS-STORM captures the surge and peaks of the storm surge; however, the best track does better at obtaining the duration of flooding and reproducing the receding water levels after the storm versus Advisory 28. An example of this can be seen in the Oregon Inlet buoy (cf., solid black line and gray dots in Fig. 14). Future improvements in the prediction of the wind and wave information during the storm may lead to further improvements in capturing the flooding that occurs in the coastal areas. In particular, improvements in these two areas may lead to a more accurate representation of the secondary peak that occurs in the Oregon Inlet area that is currently missed by ASGS-STORM.

4.2.3. USGS gauge stations—ADCIRC

The panel on the right side of Fig. 13 shows the location of the two USGS gauge stations that are utilized to evaluate the performance of ASGS-STORM, along with the forecast tracks for three different advisories (Advisories 23, 25 and 28) and the best track.
Fig. 15 provides the total water results for the two USGS gauge stations shown in Fig. 13 (right panel). The figures include the total water level predicted from the three different advisories presented previously, with the line types matching the track lines shown in Fig. 13, along with the observations from the USGS gauge stations. The New Bern station resides on the Neuse River, while the Washington station is on the Tar/Pamlico River, thus providing an initial test of the ASGS-STORM as a whole. However, Irene did not have a significant freshwater discharge component associated with it; therefore, it is not currently possible for us to make conclusions about the role of freshwater discharges on total water levels in estuarine zones. On-going work will examine historical storms, such as Floyd, where the freshwater discharge played a significant role.

Advisories 23 and 25 both over-predicted the water levels at these two USGS stations, and for Advisory 23, the predicted peak is delayed slightly (cf. long-dashed line in Fig. 15). The over-prediction of the water levels is related to the over-estimation of the strength of the storm, while the delayed peak for Advisory 23 is related to the more westerly track of the storm. In contrast, for Advisory 28, the predicted track of the storm is easterly, which leads to the peak occurring slightly earlier than the actual timing of the peak at both USGS gauge stations. The best track results show that in both stations the peak is slightly higher than the actual recorded peak, but the best track results are accurately capture the receding water levels after the storm. Currently, model resolution in riverine areas may be limiting its ability to capture the timing and magnitude of the peaks accurately. This is an area that is being investigated to improve future operations.

4.2.4. High water marks—total water levels

Fig. 16 shows the difference between high-water marks (HWMs), collected after Hurricane Irene by the USGS and other partners in North Carolina, and the total water level results from ASGS-STORM using the best track for Irene. There are 74 HWM locations utilized in this comparison. Results show that, in most areas of coastal North Carolina, the differences between the two range from $\pm 0.5$ to $\pm 1.0$ m, with only a few areas showing a greater than $\pm 1.5$ m difference. In particular, 81% of the HWMs are within $\pm 0.5$ m difference, while 16% and 3% of the HWMs are within $\pm 1.0$ m and $\pm 1.5$ m, respectively. Most of the large differences between the HWMs and ADCIRC results occur in areas where more grid resolution may be needed. Previous studies in Louisiana (Bunya et al., 2010) have shown that increased grid resolution can provide improvement in the accuracy of the model. Additionally, the best track information does not incorporate the data-assimilated wind products for the hurricane. Thus, improved skill may be seen when evaluating the data-assimilated wind.
A full study of the wind model, as compared to the data-assimilated wind products, is the subject of an upcoming paper.

Fig. 17 provides scatterplots of the measured to predicted total water levels for the NOS and USGS stations in the coastal North Carolina area, along with the HWMs for the three different advisories and the best track for Hurricane Irene. As can be seen in this figure, the results show an improvement with each advisory as the track and intensity of the storm start to approach the actual storm track and intensity. For each of the advisories and the best track results, a root mean square error (RMSE) was calculated using the following formula:

\[
RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^{n} (y_i - \bar{y})^2}
\]

where \(y_i\) are the modeled values, \(\bar{y}\) are the observed values and \(n\) represents the number of predictions. The RMSE improved (decreased towards zero) through all three of the advisories, with the best track providing the lowest RMSE. It can be seen in Fig. 17 that the spread of the points decreases with each advisory, and the early advisories show over-prediction of peak water levels, with many of the points residing above the one-to-one line. The best track results show the least amount of scatter and provide results that are slightly under-predicted compared to the observed peak water levels.

It should be noted that there are two possible sources of errors in the water levels: errors within the hydrologic/hydrodynamic models themselves or errors in the weather forecast that serve as forcing to the models. The latter is not within our control and
Fig. 13. Location of the NOS water level stations (left panel) and USGS gauge stations (right panel) for comparison of the total water level results, along with the tracks for three different advisories and the best track: long dashed line – Advisory 23, dotted line – Advisory 25, dot-dashed line – Advisory 28, and black line – best track. Note that for the NOS stations, Station 8510560 is not shown on the figure in the left panel, as it is located further north in latitude than is available in the figure. Actual longitude and latitude locations can be found in Table 1.

Fig. 14. Results for the total water levels from ASGS-STORM for Hurricane Irene. The different panels show result from the modeling system for the NOS water level stations, which are shown in Fig. 13 for three advisories and the best track: long dashed line – Advisory 23, dotted line – Advisory 25, dot-dashed line – Advisory 28, black line – best track, and gray dots - NOS observations.
Fig. 15. Results for the total water levels from ASGS-STORM for Hurricane Irene. The different panels show results from the modeling system at USGS gauge station locations, which are shown in Fig. 13 for three advisories and the best track: long dashed line – Advisory 23, dotted line – Advisory 25, dot-dashed line – Advisory 28, black line – best track, and gray dots – USGS observations.

Fig. 16. Plot of the differences between High Water Mark (HWMs) collected after Irene by the USGS and other partners in North Carolina and the total water level results for the best track of Irene from ASGS-STORM. Scale is shown in the figure.

Fig. 17. Scatterplots of the measured and predicted total water levels for NOS stations along the Outer Banks of North Carolina (shown in the left panel of Fig. 13), the two USGS stations (shown in the right panel of Fig. 13), and the HWMs shown in Fig. 16 for three advisories and the best track of Hurricane Irene: (a) Advisory 23, (b) Advisory 25, (c) Advisory 28, and (d) Best track.
tends to produce larger errors with the earlier advisories and lower errors with the later advisories. The errors within the models themselves are something that can be controlled and is usually constant over time. Thus, if the majority of the error is in the forecast, then the guidance should approach the measured values over the course of each advisory as the weather forecast improves. Results herein have shown that as the forecast of the advisories improves, so does the accuracy of the models used in the study.

5. General observations

Several observations can be made from the results presented in Section 4:

- Results from Advisory 23, the long-dashed lines in Figs. 8, 9, 10, 14, 15, show over-prediction of the wind speeds, significant wave heights, and surge at all the stations due to the over-estimation of the strength of the storm upon landfall (cf., predicted 54 m/s vs. observed 38 m/s Avila and Cangialosi, 2011), along with a more westerly track of the storm than the actual track of Irene. The more westerly track of the storm, combined with the error in the intensity, alters the timing and response in the coastal areas.

- Results from Advisory 25, the dotted line in Figs. 8, 9, 10, 14, 15, show over-prediction of the wind speeds, significant wave heights, and surge at some of the stations also due to the over-estimation of the strength of the storm (cf., predicted 46 m/s vs. observed 38 m/s Avila and Cangialosi, 2011). However, these results did capture the duration of the peak storm surge, because the forecast track was closer to the actual track of Irene.

- Results from Advisory 28, the dot-dashed line in Figs. 8, 9, 10, 14, 15, show that ASGS-STORM accurately captures the peak surge at most of the stations and only slightly over-predicts the wind speeds and significant wave heights, primarily due to the differences in the strength of the storm (cf., predicted 40 m/s vs. observed 38 m/s Avila and Cangialosi, 2011). However, the more easterly track of the storm decreased the predicted duration of the peak storm surge.

- Results from the best track of Hurricane Irene, the black line in Figs. 8, 9, 10, 14, 15, show that, given the actual track of the hurricane, ASGS-STORM shows good skill in capturing the peak surge and wind speeds measured along the coast, with only slight over-prediction in the significant wave heights.

Overall, ASGS-STORM did well at faithfully reproducing the measured surge along the coast and in the major estuarine/river systems in North Carolina, provided the NOAA/NWS/NHC advisories accurately captured the actual hurricane strength and path. It should also be noted that, while ASGS-STORM only provides high-resolution and hydrologic modeling in the North Carolina study area, it also showed skill at other Mid-Atlantic stations. For example, the bottom two plots in Fig. 14 show the results from the same three forecast advisories for NOS stations near Montauk, New York and Chesapeake, Virginia. As can be seen, the later advisories, along with the best track, provide an accurate representation of the surge in these areas. ASGS-STORM also does a decent job of capturing the wind speeds and wind direction. However, the wind model does seem to have trouble with dissipating winds after the storm passes through the North Carolina area (note the tail of the wind speeds shown in Fig. 8). The over-prediction of the waves may be due to errors in the wind fields, or they may indicate model errors. Possible sources of the latter are that the parameters used in ADCIRC may need further calibration.

As mentioned in Section 4.2.4, two possible sources of errors exist in the water levels: errors within the models themselves, which are under our control and consistent over time, or errors in the weather forecast, which are not under our control and can produce significant errors. Results from ASGS-STORM have shown that as the forecast of the advisories improves, so does the accuracy of the models used in the study; therefore, accurate input from the weather forecast is a necessary, but not sufficient, condition to ensure the accuracy of the guidance provided by the system.

6. Some concluding remarks and future work

Hurricane Irene provided a rigorous initial test of ASGS-STORM for real-time operations. Total water level products were produced every 6 hours during the storm, with the results capturing the water levels with good skill. Wind results show slight over-prediction of the wind speeds ahead of the hurricane and after the hurricane passes through the area. Wind direction results indicate that ASGS-STORM captures the changes accurately. Lastly, the significant wave heights are consistently over-predicted from ASGS-STORM; however, this over-prediction is most likely due to the wind fields. Additionally, as mentioned earlier Irene provided a good real-time test of the ASGS-STORM system; however, Irene did not produce significant freshwater discharges. Thus, definitive conclusions about the role of freshwater discharges on total water levels in the estuarine zones cannot be determined from Irene. Future work will examine storms, such as Floyd, for which the freshwater discharge played a meaningful role with the ASGS-STORM system to determine the role of freshwater discharges on total water levels.

Since Irene, ASGS-STORM has continued to run 24 hours-a-day, 7 days-a-week and produces updates to the websites as results become available. Improvements to the modeling system are ongoing, with changes being related to every aspect of the system. For example, there will be upgrades to the hydrologic and hydrodynamic models. We are improving the data exchange between the two models. As a specific ADCIRC example, modifications are currently addressing the precipitation input over the ADCIRC portion of the coastal plains. Further analysis of the coupled modeling system for Hurricane Irene will entail analyzing the performance of HL-RDHM at additional stations, as well as comparing these results to the operationally produced forecasts from the SERFC of NOAA NWS. Additional analysis of the ADCIRC and SWAN results will look at the total water level and wave height outputs from simulations with data-assimilated wind products.

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