Real-Time Forecasting and Visualization of Hurricane Waves and Storm Surge Using SWAN+ADCIRC and FigureGen

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Abstract Storm surge due to hurricanes and tropical storms can result in significant loss of life, property damage, and long-term damage to coastal ecosystems and landscapes. Computer modeling of storm surge is useful for two primary purposes: forecasting of storm impacts for response planning, particularly the evacuation of vulnerable coastal populations; and hindcasting of storms for determining risk, development of mitigation strategies, coastal restoration, and sustainability. Model

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results must be communicated quickly and effectively, to provide context about the magnitudes and locations of the maximum waves and surges in time for meaningful actions to be taken in the impact region before a storm strikes.

In this paper, we present an overview of the SWAN+ADCIRC modeling system for coastal waves and circulation. We also describe FigureGen, a graphics program adapted to visualize hurricane waves and storm surge as computed by these models. The system was applied recently to forecast Hurricane Isaac (2012) as it made landfall in southern Louisiana. Model results are shown to be an accurate warning of the impacts of waves and circulation along the northern Gulf coastline, especially when communicated to emergency managers as geo-referenced images.

Keywords Hurricane waves • Storm surge • Hurricane Isaac (2012) • ASGS • SWAN • ADCIRC • FigureGen

1 Introduction

Storm surge is primarily a competition between wind and wave forcing and frictional resistance. As hurricanes approach the coast, water is driven inland and can cause significant flooding, loss of life, and damage to property and coastal ecosystems. Predicting and understanding the magnitude and geographic extent of surge is critical to emergency managers in the event of an impending landfall, and to longer-term efforts to protect and sustain coastal environments. Computer models of storm surge are central to these efforts.

The modeling of hurricane waves and storm surge has advanced significantly in the last decade, motivated by the active seasons of 2004 (Charley, Frances, Ivan), 2005 (Katrina, Rita), 2008 (Gustav, Ike), and 2012 (Isaac), all of which caused significant flooding along the U.S. Gulf of Mexico coastline from Texas to Florida. To simulate the waves and surge caused by these storms, model advancements have included the improved representation of wind stress forcing, incorporation of dynamic inflows from major waterways, such as the Atchafalaya and Mississippi Rivers, and better parameterizations of input and boundary conditions. Tighter coupling between the wave and circulation models has also improved the simulation of these processes, notably within the coupling of the Simulating WAves Nearshore (SWAN) and ADvanced CIRCulation (ADCIRC) models [14, 15]. The resulting SWAN+ADCIRC model simulates hurricane waves and storm surge from deep water to the nearshore in a manner shown to be both accurate and efficient [17].

The SWAN+ADCIRC model benefits from improvements in the computational meshes that describe the Gulf Coast. Complex coastal regions contain channels, levees, raised roads, and other internal barriers that must be included in a description of the model domain, since they either enhance or impede inland flow. The computational domain is discretized using triangular finite elements, to better represent complex coastal features, barrier islands, and internal barriers, and to allow for gradation of the mesh that increases feature detail in moving from the

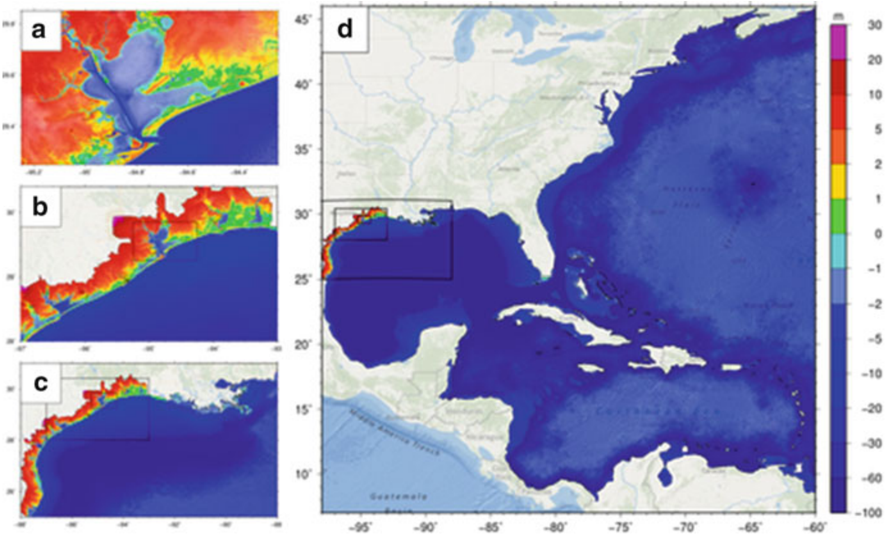

Fig. 1 Details of the bathymetry/topography (m) in the TX2008r35h mesh, with panels at successive zoom levels indicated by *black rectangles*. The depth/elevation contour range is identical in all panels. The panels depict the geographic regions of: (**a**) Galveston Bay, (**b**) the north Texas coast, (**c**) the Louisiana-Texas continental shelf, and (**d**) the entire computational domain

deeper ocean, onto the continental shelf, into estuaries and marshes, and over low-lying coastal floodplains. These meshes have evolved and been validated for storm applications in southeastern Louisiana [8, 15, 40] and Texas [10, 22]. Recent meshes contain millions of triangular elements and feature mesh spacings that range from 4–6 km in the deeper Gulf, 500–1,000 m on the continental shelf, 200 m within the coastal floodplains, and downward to 20 m within the fine-scale natural and manmade channels and levees. In Fig. 1, the multiple scales are illustrated within a high-resolution mesh of the Texas coastline. These high-resolution meshes provide accurate representations of the waves and circulation characteristics within the coastal environment, but their effective use requires numerical algorithms that are efficient in parallel computing environments [17, 36].

The coupled SWAN+ADCIRC models are applied in real time to generate forecasts of hurricane waves and storm surge via their implementation in the ADCIRC Surge Guidance System (ASGS) [33, 34]. The ASGS was created initially in 2006 to provide guidance to the U.S. Army Corps of Engineers following the construction of gates along the rainwater outfall canals on the north side of New Orleans after Hurricane Katrina; the operation of the new gates depended on the timing and severity of wind speed and storm surge within Lake Pontchartrain as storms approached [18]. The ASGS has been adapted continuously to allow for portability to disparate computing environments, geographical relocation to different computing sites, and flexible postprocessing. The ASGS parses storm parameters from official forecast/advisories issued at 6-h intervals from the National

Hurricane Center (NHC) and provides them to ADCIRC's asymmetric vortex model [20, 27] to generate meteorological forcing throughout the model domain. Commitment of computational resources at a level appropriate to the ADCIRC mesh resolution (higher resolution requires more computational resources) allows the ASGS to provide high-resolution predictions of waves and surge during the storm's approach to the coast.

Within the ASGS, the tightly coupled SWAN+ADCIRC models generate a variety of output files to describe their simulated results. Even in compressed formats, these output files can be as large as 5–10 GB, especially when they contain days of information for a simulation using a high-resolution mesh. These large output files must be postprocessed to provide meaningful results that can be interpreted quickly by emergency managers to understand the magnitudes of the wave heights and storm surge, as well as the locations of their maximum values. Thus it is essential to visualize and geo-reference the SWAN+ADCIRC results in an efficient manner. Examples of forecast visualization are provided by the Coastal Emergency Risks Assessment group (CERA, http://coastalemergency.org/), which contours the maximum predicted surge within a Google Maps Web service for storms with predicted landfall locations in North Carolina or the north-central Gulf. These maps are interactive, but their content is fixed, and thus the user cannot include additional layers of visualization from other sources.

Another visualization tool is FigureGen, which has been developed for illustration of the input and output files that describe SWAN+ADCIRC simulations (http://www.caseydietrich.com/figuregen/). FigureGen creates illustrations of unstructured meshes, bathymetry/topography, input parameterizations such as Manning's n values, and computed quantities such as water levels and significant wave heights. It can be implemented in a parallel computing environment, so that the cores work together to illustrate multiple time frames from an output file, and so that the output files can be processed immediately as they are written by the wave and circulation models. FigureGen creates publication-quality images in raster graphics formats including TIFF, JPG, and PNG, and it also geo-references images for use with software packages such as Esri's ArcGIS and Google Earth. The open-source FORTRAN code is available for all applications of SWAN+ADCIRC, and the simplicity of its execution and parameter file format mean that it is easily scriptable. As a result, the generation of visualizations with FigureGen offered a simple addition to the flexible postprocessing facility of the ASGS.

An example of the forecasting application occurred during Hurricane Isaac (2012), which crossed the Gulf of Mexico during late August before making landfall in southeastern Louisiana as a Category 1 storm. The storm's projected track was uncertain, especially as it moved through the Caribbean Sea. The predicted landfall location shifted along the Florida coastline, appeared to stabilize on the Florida panhandle near Pensacola, and then moved to southeastern Louisiana less than 48 h before the eventual landfall. Because of this track uncertainty, there was intense concern about the storm from forecasters throughout the Gulf. In particular, the lead authors of the present study were tasked with providing forecast guidance to the Texas State Operations Center (SOC), and these results were shared with the

National Weather Service Southern Region Headquarters in Fort Worth, Texas, as well as local NWS Forecast Offices in Tallahassee and Miami, Florida. To make the best use of available computing resources, these forecasts were performed on a coarsely resolved mesh with coverage of the entire Gulf. As will be shown below, these forecast results provided an efficient approximation of the waves and surge along the Gulf coastline, especially when communicated with geo-referenced images created by FigureGen.

The following sections describe components of the ASGS and the results of operational support using ASGS during Isaac. Section 2 summarizes the SWAN and ADCIRC models for waves and circulation, including references to detailed descriptions of their numerics, input, and boundary conditions; the unstructured meshes are also described. Section 3 describes the FigureGen tool, including its input file types, the software tools it uses to generate its images, its implementation in parallel computing environments, and the options for geo-referenced output products. Finally, Sect. 4 describes the implementation of these models for real-time forecasting of Isaac, with an emphasis on large-scale validation and examples of the output products that were shared with weather forecasters and emergency managers during the event.

2 Models of Waves and Circulation in the Gulf of Mexico

2.1 Tight Coupling of SWAN+ADCIRC

In large-scale applications, it can become inefficient to resolve the phases of individual waves, and thus the SWAN and other phase-averaged wave models consider the evolution of action density $N(t,\lambda,\varphi,\theta,\sigma)$ in time t, geographic space (λ,φ), and spectral space with directions θ and frequencies σ [5]. The action density N can be integrated to determine properties of the wave environment, such as significant heights and mean periods. Wave energy is generated, propagated, and dissipated via source terms that represent wave growth by wind; action lost due to whitecapping, surf breaking, and bottom friction; and action exchanged between spectral components due to nonlinear effects in deep and shallow water. The source term parameterizations used herein are identical to those in recent studies [15, 17].

SWAN employs the finite difference method, with a third-order upwind scheme for the advection terms in geographic space [35] and a diffusive correction for the "garden-sprinkler" effect [4]. A Gauss–Seidel iterative technique is employed to update the action densities in geographic space, by ordering the vertices and then sweeping through them in opposite directions. This solution method is implicit and thus unconditionally stable. Detailed descriptions of the SWAN solution method are available [5]. This method was extended recently to utilize unstructured meshes with triangular elements [41], so mesh resolution can be improved in regions with large gradients in input parameters (e.g., bathymetry) or the computed solution.

The ADCIRC model has been validated using tide gauges and field measurements for several hurricanes in southern Louisiana [8, 13, 40], and it has been used extensively by the U.S. Army Corps of Engineers (USACE), the Federal Emergency Management Agency (FEMA), and local agencies to design flood control systems and to evaluate hurricane flooding risk.

ADCIRC computes water levels ζ and depth-averaged currents (U,V) via solution of modified forms of the shallow-water equations (SWE) [9, 23, 25, 40]. The model applies the continuous-Galerkin, finite-element method with linear C_0 triangular elements to discretize and solve the SWE on unstructured meshes. Water levels ζ are determined from the Generalized Wave Continuity Equation (GWCE), which is a combined and differentiated form of the continuity and momentum equations, and which is discretized over three time intervals, so that the solution for the future water level requires knowledge of the present and past water levels. Current velocities (U,V) are determined from the vertically integrated momentum equations, which are discretized explicitly for all terms except the Coriolis force, which uses an average of the present and future velocities [36].

ADCIRC utilizes boundary conditions and input parameterizations to simulate effectively the circulation in coastal regions. The specific details of these parameters are contained in other publications, and thus they are only referenced herein. Large rivers with significant impacts on the coastal circulation, such as the Mississippi and Atchafalaya Rivers in Louisiana, are forced with an inflow boundary condition that prevents surge and tidal waves from reflecting back into the computational domain [26,40]. Tidal constituents are forced along the open-ocean boundary in the Atlantic Ocean, and tidal potential functions are forced within the model domain [24, 28]. Bottom friction is parameterized with Manning's n values that vary spatially based on representative land-cover data [1, 2, 7, 8]. Wind stresses are computed using a quadratic drag law [19] with adjustments based on storm sector [15, 31, 32]. Wind stresses are corrected in overland regions depending on upwind roughness and the presence of tree canopies [40]. Overland regions are allowed to flood or dry as the storm surge inundates or recedes, respectively [12].

The SWAN and ADCIRC models are coupled tightly so that they run as the same executable and on the same unstructured meshes [14, 17]. Coupling information is passed through local memory/cache without the need for interpolation between heterogeneous meshes. ADCIRC passes wind velocities, water levels, current velocities, and friction roughness lengths to SWAN, while SWAN passes wave radiation stress gradients to ADCIRC. The coupling interval is taken to be the same as the SWAN time step, which is 20 min for the current simulations.

In a high-performance computing environment, the domain is decomposed into local subdomains for the computational cores [21]. Each core runs the coupled models on a local submesh, with an overlapping layer of elements that allows for intramodel communication between neighboring submeshes. However, the intermodel communication between SWAN and ADCIRC is still intracore via local memory/cache, because there is no need to interpolate values over the network. Thus the tight coupling is highly efficient. SWAN+ADCIRC maintains the excellent

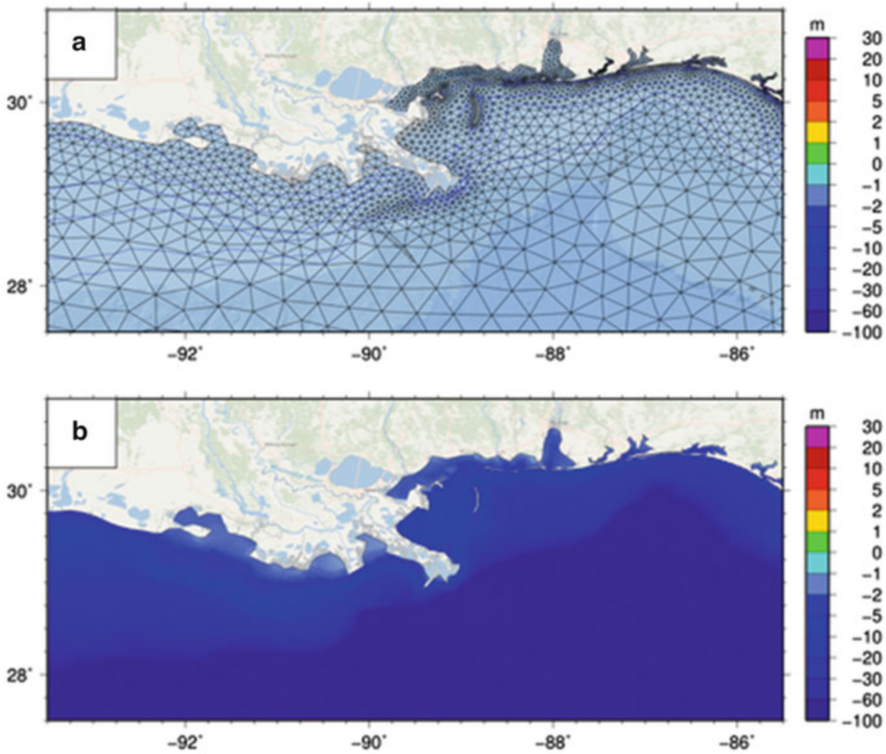

Fig. 2 Details of the EC95d mesh in the north-central Gulf of Mexico, with panels of (**a**) unstructured mesh and (**b**) bathymetry and topography relative to NAVD88 (2004.65). Note that the full computational mesh extends through the Gulf of Mexico and Caribbean Sea and to 60°W longitude in the Atlantic Ocean

scalability of its component models, and provides high-resolution simulations of hurricane waves and storm surge in less than 10 min per day of simulation [17, 36].

2.2 Unstructured Meshes

The SWAN+ADCIRC models have been validated on unstructured meshes within the Gulf of Mexico region, with varying levels of resolution, for applications ranging from tidal databases to hurricane forecasts. Examples of coarsely and finely resolved meshes are shown in Figs. 2 and 3, respectively.

The Eastcoast 1995 (EC95d) mesh was developed for the generation of a tidal database in the Western North Atlantic Ocean, based on earlier studies for mesh generation for tidal computations [38,39]. The EC95d mesh contains 31,435 vertices and 58,369 triangular elements, and it includes coverage of the entire western North

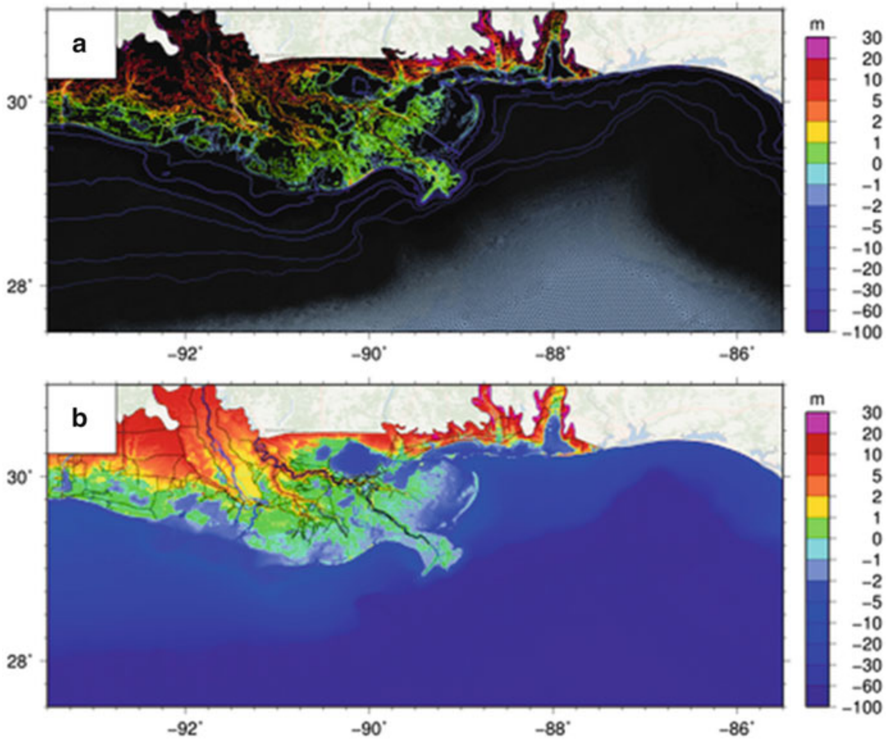

Fig. 3 Details of the SL16v31 mesh in the north-central Gulf of Mexico, with panels of (**a**) unstructured mesh and (**b**) bathymetry and topography relative to NAVD88 (2004.65). Note that the full computational mesh extends through the Gulf of Mexico and Caribbean Sea and to 60°W longitude in the Atlantic Ocean

Atlantic Ocean, Caribbean Sea, and Gulf of Mexico. Its coarse spatial resolution ranges upward to element sizes of 100 km, and it does not include any coastal floodplains (Fig. 2). In the northern Gulf, the mesh spacings range downward to 5–10 km on the continental shelf and 1–2 km along the coastlines of Mississippi and Alabama. Thus, although the EC95d mesh contains sufficient levels of mesh resolution to propagate the tides into the Gulf, it was not designed for application to nearshore hurricane waves and surge. However, its coarse mesh resolution allows faster forecasts when storms are located far from the coastline of interest.

This mesh was improved and refined, and its boundary was extended inland to allow for coastal inundation, resulting in a series of meshes with progressively greater spatial resolution [8, 28, 40]. SWAN+ADCIRC was validated recently on the Southern Louisiana (SL16v31) mesh for high-resolution hindcasts of the recent storms to impact the northern Gulf, including Katrina and Rita (2005) and Gustav and Ike (2008) [15, 17]. The SL16v31 mesh contains 5,035,113 vertices and 9,945,623 elements, and thus it is roughly 160 times the size of the EC95d mesh. It contains mesh spacings of 20–25 km in the Caribbean Sea and Atlantic

Ocean, 4–6 km in the Gulf of Mexico, 500–1,000 m on the continental shelf, and 200 m or smaller in the coastal floodplains of southern Louisiana, Mississippi, and Alabama (Fig. 3). The mesh spacings range downward to 20 m in natural and manmade channels such as the distributaries of the Mississippi River Delta. When applied on this mesh, SWAN+ADCIRC has been shown to provide highly accurate hurricane simulations throughout the northern Gulf, and it has also been shown to be highly efficient, provided that enough computational cores are utilized to maintain a problem size of less than 10,000 mesh vertices per 1 MB of share cache [17]. Thus, the SL16v31 mesh can be employed with SWAN+ADCIRC in a real-time production framework if it is allotted an appropriate commitment of computational resources.

3 FigureGen

The tightly coupled SWAN+ADCIRC models generate a variety of output files in formats including ASCII text, binary, and the Network Common Data Form (NetCDF, http://www.unidata.ucar.edu/software/netcdf/). However, even in compressed formats, output files can be 10 GB or larger, especially when they contain information covering simulated days of model computations using high-resolution meshes. These large output files must be postprocessed to extract meaningful results targeted for emergency managers to understand the threats posed by the magnitudes of the wave heights and storm surge, as well as the locations of their maximum values. Thus it becomes essential to visualize the SWAN+ADCIRC results. This visualization must geo-reference accurately the results within the coastal environment, to provide context for the end user. And this visualization must be efficient, to deliver illustrations in a timely manner. For these reasons, the FigureGen visualization tool was developed to provide high-quality illustrations of SWAN+ADCIRC results.

FigureGen is a FORTRAN program that acts as an interface between the SWAN+ADCIRC simulation files and the resulting illustrations (http://www.caseydietrich.com/figuregen/). The unstructured mesh can be illustrated in terms of its triangular elements and/or contours of mesh spacings or bathymetry, as in Figs. 2 and 3. Vertex-based input parameterizations, such as Manning's n values and directional wind reduction factors, can also be contoured spatially. For parallel computing applications, the domain decomposition can be visualized to show the local submeshes. Background images can be underlaid to show satellite imagery or previous simulation results.

FigureGen also visualizes the SWAN+ADCIRC output files in ASCII and NetCDF formats. ADCIRC produces files with global data sets of water levels, current velocities, atmospheric pressures, wind velocities, and wave radiation stress gradients [36]. SWAN produces files with global data sets of significant wave heights, peak and mean wave periods, and mean wave directions [14]. Scalar and vector data can be plotted with filled and/or linear contours, and vector data can also be overlaid on a regular grid. FigureGen can also visualize the locations of conservative tracers, such as the simulated oil transport following the destruction of the Deepwater Horizon platform in the Gulf [16].

To create the illustrations, FigureGen relies on the Generic Mapping Tools (GMT, http://gmt.soest.hawaii.edu/). GMT is an open-source collection of Unix-based command-line tools for manipulating and visualizing geographic data sets [37]. The tools have undergone more than 20 years of continuous development with support from the National Science Foundation. The GMT suite processes data on structured and unstructured meshes; performs operations such as filtering, trend fitting, and coordinate projection; and produces illustrations with filled and linear contours, vectors, etc., in two or three dimensions.

GMT requires input data in specific gridded formats, and thus FigureGen converts the ADCIRC input and output files before passing them to GMT. FigureGen develops files containing the scalar or vector quantities to be plotted at the locations of the mesh vertices, the vertex connectivity information, the color palettes, etc. Then these files are passed to the GMT command-line tools. It is noted that the FigureGen implementation does not alter the source code of GMT, but rather communicates with the GMT tools via external files, and thus it can be extended to future GMT releases as they become available. At the same time, FigureGen does not require any knowledge of GMT by its user, because the interaction is handled automatically.

In a parallel computing environment, FigureGen uses the Message Passing Interface (MPI) to divide the work among the computational cores. The first core coordinates the overall effort by assigning new images to be produced by the other cores. The visualization cores read the SWAN+ADCIRC files, convert the data into appropriate formats, and then call the GMT tools to generate contours, vectors, etc. In this way, an output file containing numerous discrete time frames can be visualized in parallel, with the work shared by the computational cores. Workflow acceleration is limited only by the number of available cores. FigureGen can also be coupled loosely with SWAN+ADCIRC, by running concurrently and querying the output files for the next time step. As the data is written by the coupled models, it is read and visualized by FigureGen. In this way, the illustrations are ready for the user as the simulation reaches the final time step.

FigureGen creates illustrations in raster image formats such as TIFF, JPG, GIF, and PNG. It can also geo-reference the images for use in other software packages such as Esri's ArcGIS and Google Earth. For example, to output files for use with Google Earth, the image is simplified by removing the labeling around the data frame and moving the contour and vector scales into separate image files. A text file is written in the Keyhole Markup Language (KML), and then everything is compressed into a zipped format (KMZ). These KMZ files allow emergency managers to overlay the SWAN+ADCIRC visualizations on satellite and aerial imagery and other geo-referenced data sets prepared for use in Google Earth. FigureGen can also create vector-based graphics such as encapsulated postscript (EPS) and postscript (PS). These formats are ideal for portable document format (PDF) publications.

4 Hurricane Season 2012

4.1 ASGS Forecasting

Forecast modeling of hurricane waves and storm surge requires a real-time system that is fully automated and resilient, especially within a shared high-performance computing environment. The system must monitor and detect when new data describing meteorological and riverine forcings become available, and download and convert them into formats appropriate for input to the wave and circulation models. It must preprocess the input files and decompose the domain into localized problems for the computational cores. It must submit and monitor each simulation within the batch queue on the computing resource. And it must detect when each simulation finishes, so that the model results can be visualized and shared. For all of these processes, the system should detect and work around errors when possible. In addition, the system should be extensible to a variety of computing environments, to provide redundancy in model forecasts.

For these reasons, the ASGS was developed to automate the use of SWAN+ADCIRC in real-time forecasting environments [18,33,34]. The ASGS has been employed for hurricane applications including Irene (2012) along the North Carolina coastline [3], as well as forecasting during the oil spill resulting from the destruction of the Deepwater Horizon drilling platform in the Gulf [16]. The ASGS accepts meteorological forcing in several formats. Under normal conditions, the system uses gridded wind and pressure files such as the model output from the NOAA National Centers for Environmental Prediction's (NCEP) North American Mesoscale (NAM) model. When a hurricane threatens a coastline, the system downloads the forecast advisories from the NHC, and the storm parameters are used as inputs to generate wind fields using an asymmetric vortex model [20,27]. Riverine influxes are downloaded from the NOAA National Severe Storms Laboratory (NSSL) and used as boundary conditions when necessary. Tidal input and boundary conditions are also developed automatically. The ASGS suite of Perl scripts operates on the front end of a computing cluster, downloads and preprocesses simulation files, monitors the progress of simulations as they run, and produces visualizations of the model results.

The ASGS produced results used by several teams during the 2012 hurricane season. Forecasters from the University of North Carolina (UNC) implemented the system on high-performance computing clusters at the Renaissance Computing Institute (RENCI, http://www.renci.org/), the U.S. Army Engineer Research and Development Center (ERDC, http://www.erdc.hpc.mil/), and other locations. The UNC team focuses primarily on storms with projected impacts along the Carolina coastline. As the lead developers of the ASGS, the UNC team also supports other forecasters using the system, including those at Louisiana State University (LSU), where the focus is primarily on storms with projected impacts along the north-central Gulf coastline. Both teams use the system on high-resolution meshes representing the barrier islands, bays and estuaries, and coastal floodplains in their respective regions of interest. Among other output products, the UNC and LSU teams provide forecast guidance via the CERA (http://coastalemergency.org/), which incorporates the model results within a Google Maps web service.

At the University of Texas at Austin (UT), the lead authors of the present study were tasked with providing forecast guidance to the Texas SOC for storms with projected impacts along the Texas coastline. This forecast modeling is performed typically on a high-resolution mesh (Fig. 1) representing the broad continental shelf, barrier islands, and coastal floodplains ranging from Port Isabel to Port Arthur, Texas; SWAN+ADCIRC has been validated extensively on this mesh for waves and surge during Ike (2008) [10, 22]. The UT team implemented the ASGS at the Texas Advanced Computing Center (TACC http://www.tacc.utexas.edu/). Because of the needs of the UT team and its local partners, the ASGS results for Texas were not posted publicly online, but rather were shared as raster and geo-referenced images. An automated notification system supported the rapid dissemination of images to support decision-makers preparing for storm impacts. In particular, the KMZ files from FigureGen allowed emergency managers to work with the computed results within Google Earth applications, where they can be visualized and overlaid with other data in similar formats. Examples of these output products are shown in subsequent sections.

4.2 Hurricane Isaac

Isaac (2012) differed from other recent storms that made landfall in southeastern Louisiana, such as Katrina (2005) and Gustav (2008), in that it was relatively weaker and slower moving. Isaac passed over Hispaniola and Cuba as a tropical storm, and it was expected to strengthen to a hurricane shortly after it moved into the Gulf. However, although its central pressure reached a minimum of 968 mbar (typical of a Category 2 hurricane on the Saffir–Simpson scale), its core did not become well organized until just before it made landfall, and thus it approached the Louisiana coastline as a Category 1 hurricane. Isaac made initial landfall at 2012/08/28/2345 UTC near the western tip of the Mississippi River Delta, moved offshore near Barataria Bay, and then made a second landfall at 2012/08/29/0700 UTC near Port Fourchon, Louisiana [6, 30]. Slow storm movement caused significant amounts of rainfall, including reports of 20 in within the New Orleans area. And the storm's counterclockwise rotation pushed surge along the Louisiana–Mississippi continental shelf, including reports of 3.4 m of surge measured by a tide gauge near Shell Beach on Lake Borgne east of New Orleans [29]. This storm surge threatened the protection system around New Orleans and caused extensive flooding in communities, such as Braithwaite, Louisiana, exposed outside of the protective coastal infrastructure.

The storm's projected track was uncertain, especially as the storm moved westward through the Caribbean Sea. The predicted landfall location varied along the Florida coastline and then appeared to stabilize on the Florida panhandle near

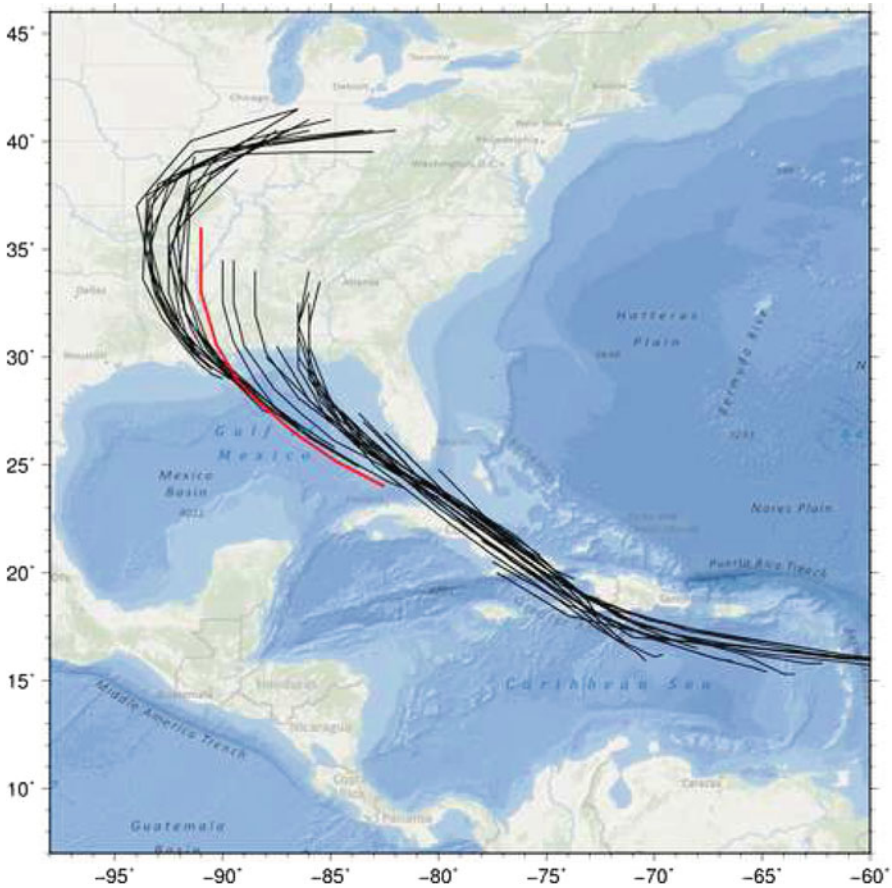

Fig. 4 Consensus 84-h forecast tracks for Isaac (2012) issued by the National Hurricane Center for advisories 1–38. The predicted landfall location was the Florida panhandle for advisories 13–20, but it shifted to Louisiana by advisory 24 (shown in *red*), which was issued 2012/08/27/0300 UTC, or less then 2 days before the initial landfall. Colors refer to figure as printed online

Pensacola, notably during NHC advisories 13–20 (issued over 2 days, August 24–26). As shown in Fig. 4, the projected landfall location shifted westward during August 26 and settled on southeastern Louisiana by NHC advisory 24 (which was issued 2012/08/27/0300 UTC). Because of this track uncertainty, there was intense concern from storm forecasters throughout the Gulf, including the SWAN+ADCIRC modeling teams using the ASGS. The LSU/UNC teams provided guidance based on a high-resolution mesh of southern Louisiana. The lead authors of the present study provided guidance based on the coarsely resolved EC95d mesh.

In the Texas SOC in Austin, an activation of the Governor's Emergency Management Council for Isaac was supported by the UT team. Although Isaac represented a threat primarily to coastal areas in Louisiana and Mississippi, teams of first responders from Texas state agencies, including Texas Task Force 1 search-and-rescue teams, deployed to locations in Louisiana before landfall to assist local responders. The forecast guidance products generated by ASGS and illustrated by FigureGen were used during periodic briefings of the Governor's Emergency Management Council to update agency representatives about changes in the magnitude of impacts to areas offshore and along the coastline. Descriptions of the impacts were recorded in situation reports issued by the Texas Division of Emergency Management to the media, emergency managers, and public officials. In addition, the UT team worked closely with National Weather Service meteorologists at the NWS Southern Region Headquarters in Fort Worth and in local forecast offices in Miami with responsibility for warnings covering the Florida Keys and in Tallahassee with responsibility for Apalachee Bay. ASGS forecast products were transmitted to the NWS offices using KMZ and PNG files along with narrative descriptions that highlighted the results. Feedback received during the event from NWS indicated that the ASGS results were very useful in the preparation of their guidance to emergency managers.

In the sections that follow, the forecast performance on the EC95d mesh is assessed using comparisons with measured time series of significant wave heights and water levels. Then hindcasts are performed on the EC95d and SL16v31 meshes using wind fields generated from the best-track analysis from NHC. It is shown that the EC95d mesh provides an economical approximation of the hurricane waves and storm surge, but higher levels of mesh resolution are required to determine the details of threats posed to specific coastal areas.

4.2.1 Forecasts on the EC95d Mesh

Each advisory requires two simulations: (1) a "nowcast" run using known storm parameters to update the ADCIRC+SWAN simulation state since the end of the last nowcast; and (2) a "forecast" run combining the freshly updated nowcast state and the parameters from the latest official forecast advisory to predict the waves and storm surge 5 days into the future. To accomplish this, the model domain must be decomposed into local subdomains for the computational cores, each of which uses the ADCIRC asymmetric vortex model and the storm parameters provided by the ASGS to generate wind fields in parallel and in real time. When the forecast is finished, the results must be postprocessed and visualized. This process is completed quickly when the ASGS is employed on the EC95d mesh as a result of its modest size. The EC95d mesh resolution requires a relatively small total of 120 cores, and thus these computational jobs may be submitted to the development queue on the TACC Lonestar system, where they will execute immediately, without queue-related delays. The Isaac advisories required an average duration of 26.3 min, of which only 50 s was required by FigureGen to create the Google KMZ visualization products. In summary, the forecast guidance was available within 30 min after each advisory was posted by the NHC when running the EC95d mesh via the ASGS.

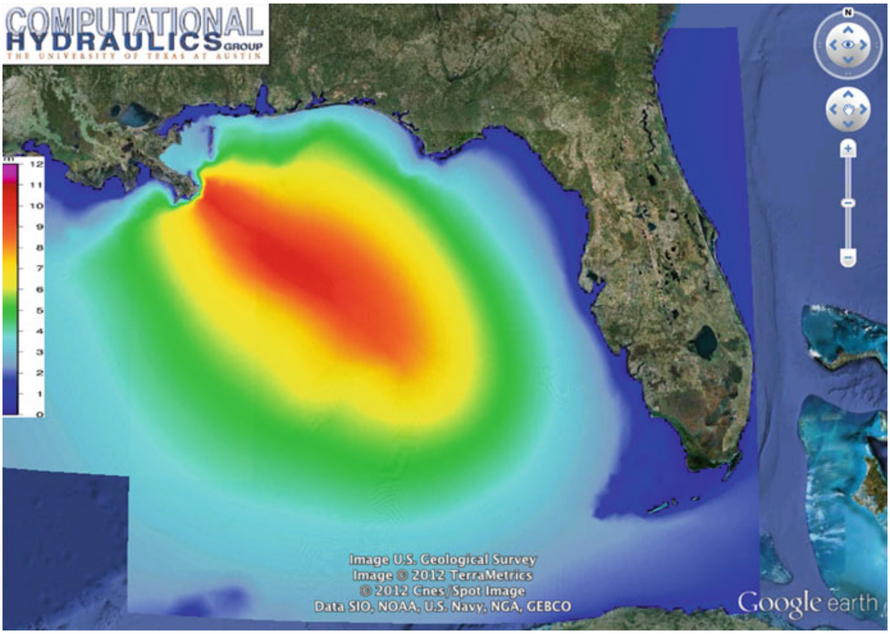

Fig. 5 FigureGen visualization within Google Earth of maximum SWAN-computed significant wave heights on the EC95d mesh for NHC forecast advisory 28, which was issued 2012/08/28/0300 UTC

An example output product is shown in Fig. 5, in which the maximum significant wave heights for NHC forecast advisory 28 are visualized within a Google Earth application. This advisory was issued at 2012/08/28/0300 UTC, or less than 24 h before the storm's initial landfall within the Mississippi River Delta. Isaac was centered within the Gulf at (87.0°W, 27.1°N), or due south from Pensacola and due west from Cape Coral, Florida. As the storm moved along its predicted track toward Louisiana, the SWAN-computed waves had significant heights with maxima of 9–10 m along the storm track and 5 m or larger throughout a large section of the northern Gulf. These forecast products were shared in real time with the NWS Forecast Offices in Tallahassee and Miami.

The variability in official forecast tracks and storm intensities caused significant differences in the ADCIRC-computed surge across the forecasts, including NHC forecast advisories 20, 24, and 28 in the days leading to landfall. Advisory 20 (Fig. 6a) was the last forecast with a predicted landfall location in the Florida panhandle. Had the storm followed this track, Louisiana would have been located on its weaker western side, and thus the predicted surge levels were minimal along its coastline. By Advisory 24 (Fig. 6b), the predicted landfall location had moved to Louisiana. However, at this time, the storm had just moved into the Gulf, and it was expected to intensify more than actually happened. For this reason, the predicted surge levels were larger than 4 m in Lake Borgne east of New Orleans.

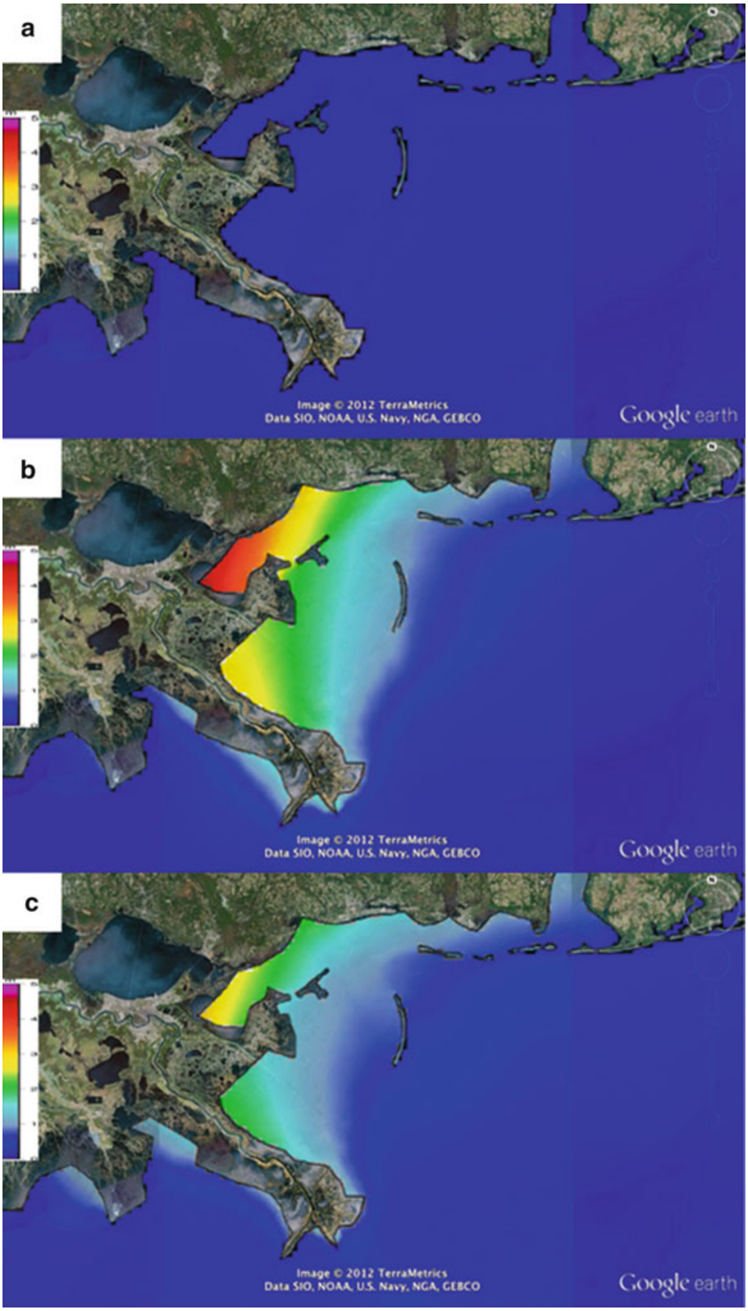

Fig. 6 Maximum ADCIRC-computed water levels on the EC95d mesh for NHC forecast advisories (**a**) 20, issued 2012/08/26/0300 UTC and with a predicted landfall in the Florida panhandle; (**b**) 24, issued 2012/08/27/0300 UTC and with a predicted landfall near Grand Isle; and (**c**) 28, issued 2012/08/28/0300 UTC, or less than 24 h before the initial landfall. The contour range is the same in all three panels and has a maximum of 5 m

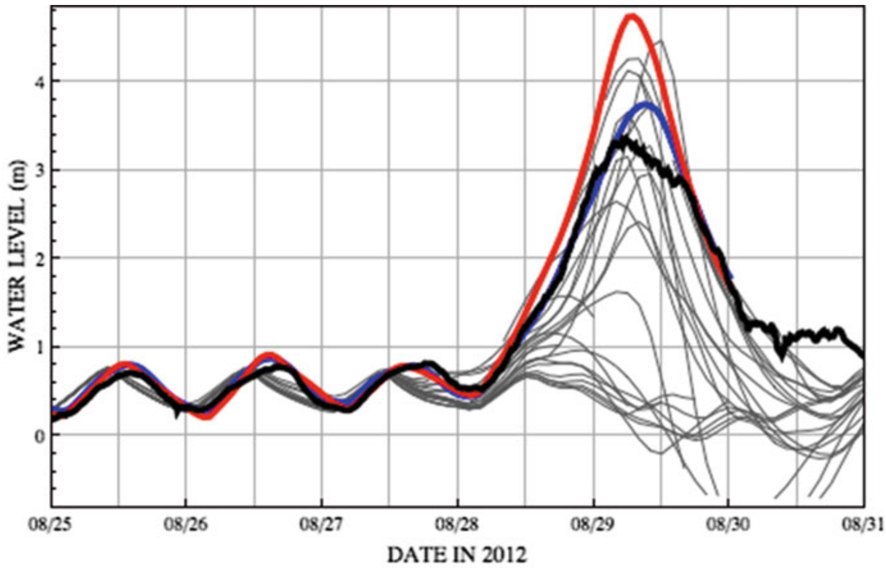

Fig. 7 Hydrographs at NOAA station 8761305 near Shell Beach, Louisiana. Water levels are shown in different colors for the measurements (*black*), EC95d forecasts (*gray*), EC95d hindcast (*red*) and SL16v31 hindcast (*blue*). ADCIRC-computed water levels have been adjusted to the MLLW datum used by the NOAA measurements. Colors refer to figure as printed online

When advisory 28 (Fig. 6c) was issued the next day, the predicted storm intensities lessened, and the maximum surge was predicted to reach a maximum of about 3 m in Lake Borgne.

This forecast guidance was reasonable, especially considering the relatively modest resources used to compute it. Figure 7 shows the time series of measured and computed water levels at the NOAA station 8761305 near Shell Beach, Louisiana. This station is located on the southern shoreline of Lake Borgne just east of metropolitan New Orleans, and it experienced the large surges that threatened the protection system surrounding the city and its neighboring communities. The peak surge was measured at 3.4 m at this location. It should be noted that the NOAA station near Shell Beach lies approximately 22 km from the western side of Lake Borgne, which experienced the highest surge levels during Isaac. The predicted surges from the EC95d forecasts show a range of peak values, from about 1.5 m to about 4.4 m, reflecting the uncertainty in the landfall location and intensity as the storm evolved.

Thus, the SWAN+ADCIRC wave and circulation models were employed within the ASGS to provide forecast guidance. The predicted maxima for significant wave heights and water levels were visualized with FigureGen and shared as KMZ files for use within Google Earth, allowing the user to control the zoom level, overlay other forecast products, add user-defined layers, etc. However, this guidance was limited to the open water, since the coarsely resolved EC95d mesh does not represent the coastal floodplains of southeastern Louisiana.

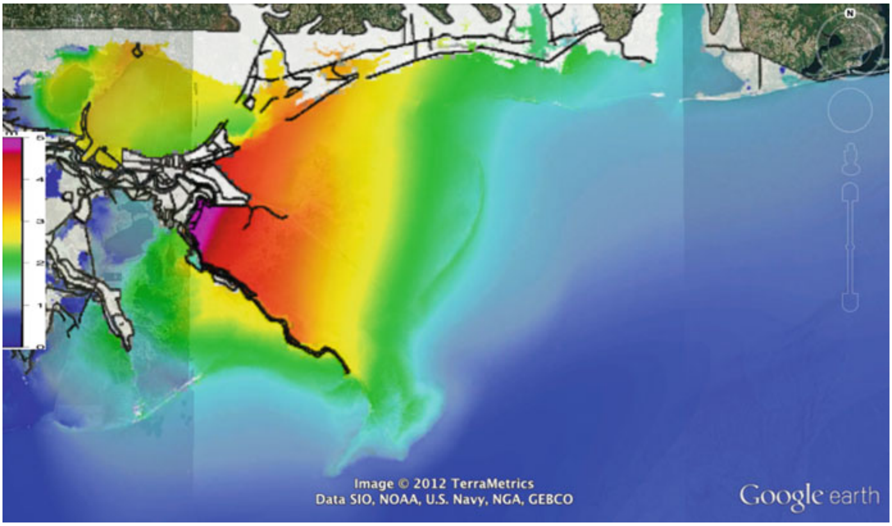

Fig. 8 Maximum ADCIRC-computed water levels on the SL16v31 mesh for the NHC best-track analysis. The contour range is the same as Fig. 6 and has a maximum of 5 m. *Gray colors* indicate regions that were not wetted within the ADCIRC simulation. Colors refer to figure as printed online

4.2.2 Hindcast on the SL16v31 Mesh

After the event, the storm parameters within the NHC best-track analysis were used to create an asymmetric wind field using the same methodology as that used during the forecasts [20, 27], and then hindcasts were performed on the EC95d and SL16v31 meshes. The EC95d hindcast produced too much surge on the Louisiana–Mississippi continental shelf and within the marshes to the east of New Orleans. At the Shell Beach station (red line in Fig. 7), the peak surge is about 4.75 m, and thus larger than the peak surges from the measurements or any of the forecasts.

Much of the error can be attributed to the coarse resolution of the EC95d mesh. The computed surge is appropriately smaller in the SL16v31 hindcast, including by as much as 1 m smaller at the Shell Beach station (blue line in Fig. 7). The increased resolution in the SL16v31 mesh allows for a better representation of the continental shelf, the wave-breaking zones, the coastal floodplains, and the natural and manmade channels that convey surge into the inland lakes and estuaries. This behavior is evident in Fig. 8, which shows the maximum ADCIRC-computed water levels for the SL16v31 hindcast. Surge is pushed into the Biloxi and Caernarvon marshes and against the earthen levees near Braithwaite. Compared to the results from EC95d, which limits the surge to the coastline, these high-resolution hindcast results are a better representation of the flooding caused by Isaac.

These Isaac hindcasts can be further improved through the refinement of wind fields with assimilated measurements of atmospheric pressures and wind speeds. Detailed validation studies are forthcoming, and they will examine the forecast performance on the high-resolution meshes utilized by the LSU/UNC team during the event, as well as the differences in SWAN+ADCIRC responses when forced with a variety of forecast winds.

5 Conclusions

Hurricane forecasts require hydrodynamic models that represent the generation of waves and storm surge and their propagation toward the coastline. These models should be employed on computational meshes with appropriate resolution to represent details of the complex coastal environment, including the coastal floodplains and fine-scale channels. During the 2012 hurricane season, the tightly coupled SWAN+ADCIRC models were employed within the ASGS to provide forecast guidance on several meshes for delivery to several stakeholders. These forecasts must be visualized efficiently and shared in formats that geo-reference the model results.

The FigureGen postprocessing tool was developed for visualization of simulation files from SWAN+ADCIRC. FigureGen visualizes input data such as bathymetry and vertex-based attributes such as Manning's n values and directional wind reduction factors, as well as computed output data such as significant wave heights and water levels. Scalar and vector data can be plotted with filled and/or linear contours, and vector data can also be overlaid on a regular grid. In a parallel computing environment, FigureGen uses MPI to divide the work, and the accelerated workflow is limited only by the number of computational cores. Illustrations can be georeferenced for use in other geospatial software.

FigureGen was incorporated within the ASGS, and it was used to visualize forecast guidance during Hurricane Isaac (2012). Uncertainties in the track and intensity caused significant differences in the forecasts as the storm approached the northern Gulf coastline. On a coarsely resolved EC95d mesh, the computed peak surges ranged from 1.5 m to 4.4 m at a NOAA station east of New Orleans that had a measured peak value of about 3.4 m. However, when the storm was hindcasted using a high-resolution SL16v31 mesh and winds generated from the NHC best-track analysis, the computed peak surge was within 0.5 m of the field measurements coinciding with the actual landfall of Isaac. Future work will explore the ASGS forecast performance on higher-resolution meshes.

The forecast guidance was visualized in KMZ format for use within Google Earth, allowing the user to control the zoom level, overlay additional forecast products, and add user-defined layers. As Isaac crossed the northwestern Caribbean and Gulf of Mexico, the results of the ASGS forecasts were relayed as visualization products (KMZ and PNG files) to the NWS Southern Region Headquarters and NWS forecast offices in Miami and Tallahassee. In the Texas SOC, the ASGS forecast products were used to brief the Governor's Emergency Management Council, and descriptions of the results appeared in situation reports published by the Texas Division of Emergency Management. The rapid delivery of updated information about potential storm impacts following the release of each NHC forecast advisory offered an excellent new source of accurate guidance to weather forecasters and emergency managers in the path of Isaac. Future work will tighten the coupling between FigureGen and SWAN+ADCIRC. Model results will be visualized as they become available, and thus the illustrations will be ready for the user when the simulation finishes.

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