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# NAVY NEARSHORE OCEAN PREDICTION SYSTEMS

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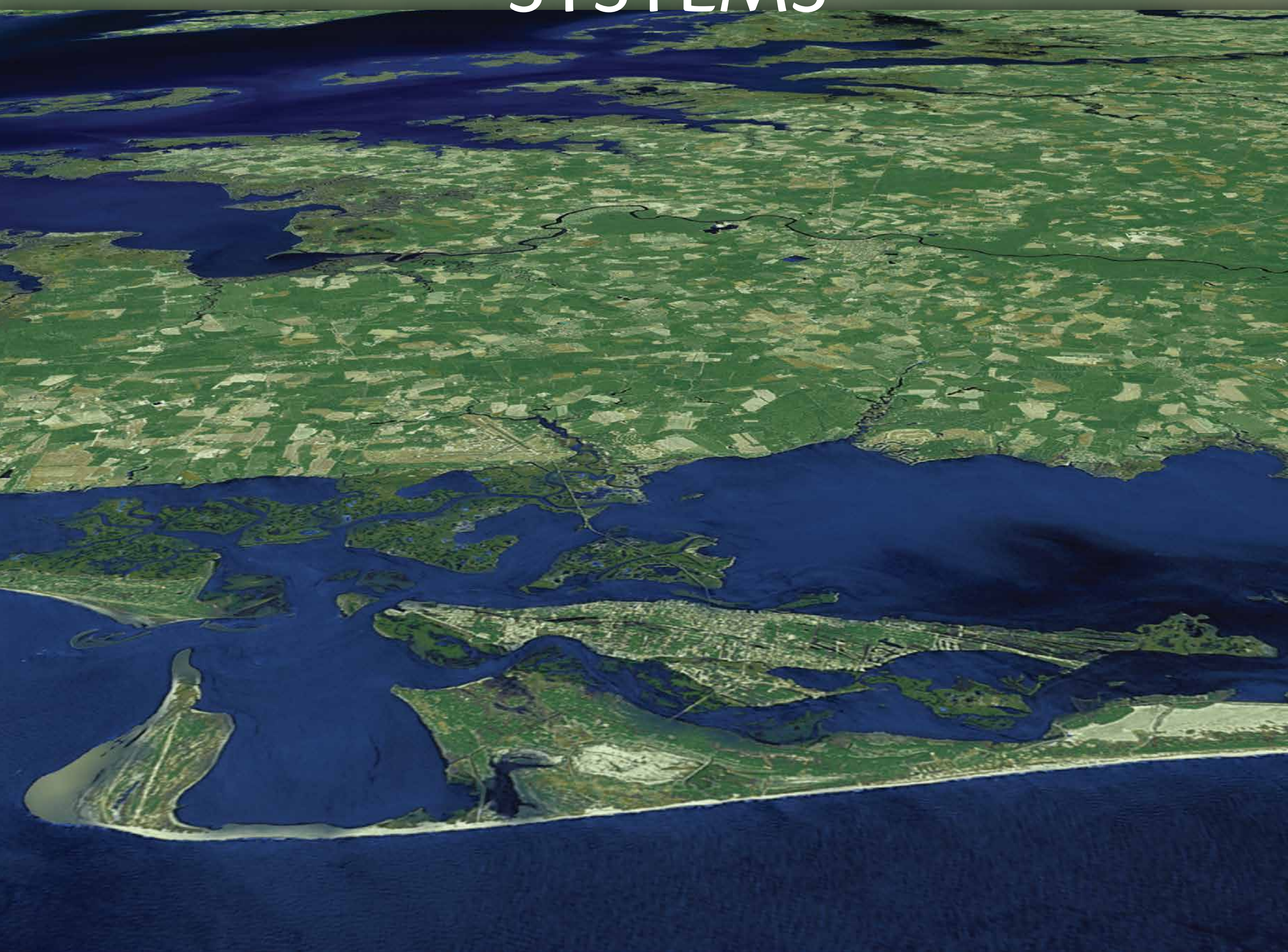

Chincoteague Island, VA. *Credit: NASA/Goddard Space Flight Center Scientific Visualization Studio.*

**ABSTRACT.** Knowledge of the nearshore ocean environment is important for naval operations, including military and humanitarian applications. The models used by the US Navy for predicting waves and circulation in the coastal regions are presented here. The wave model of choice for coastal regions is the Simulating WAves Nearshore (SWAN) model, which predicts wave energy as a function of frequency and direction. SWAN is forced by winds as well as waves at the offshore boundaries. For coastal circulation, Delft3D, composed of a number of different modules that can be coupled with each other, is presently used. Most applications for daily operational predictions use only the Delft3D-FLOW module, which predicts currents, mean water levels, temperature, and salinity. Inputs to the model include winds, tides, general ocean circulation, waves, daily river discharges, temperature, and salinity. Delft3D-FLOW is coupled with the Delft3D-WAVE module for areas where wave effects are of importance. A four-dimensional variational assimilation (4DVar) system based on SWAN, the SWANFAR system, is under development for nearshore wave predictions. It will improve wave predictions by using regional wave observations. We present several case studies that illustrate the validation and diverse applications of these models. All operational systems are run at the Naval Oceanographic Office.

## INTRODUCTION

Predicting the dynamics of the nearshore environment is important to many different aspects of naval operations, including military and humanitarian applications. It is important to Expeditionary Warfare for planning and executing insertions/extractions. Wave and current conditions, along with local geological conditions, can determine the extent of mine burial, which can impact both commercial and military activities. Low-lying coastal regions are at risk from storm surge and coastal inundation as demonstrated by recent storms such as Hurricanes Katrina (2005), Ike (2008), Irene (2011), and Sandy (2012) along the US Gulf and East Coasts; Cyclone Nargis (2008) along the coast of Myanmar; and Typhoon Haiyan (2013) that impacted Philippines and other parts of Asia, to name just a few. It is critical to provide accurate and timely forecasts of coastal inundation for both emergency planners and post-event humanitarian aid efforts.

Wind, waves, tides, river discharge, and the general ocean circulation impact the dynamics in the nearshore region. Compared to the deeper ocean, the nearshore length scales are much smaller (from a few meters to a few hundred meters), which means that typical resolutions needed for modeling these flows are much finer than is possible for global or even regional models. In addition, the different physical processes, such as depth-limited wave breaking, nonlinear triad interactions, and wave-driven currents, must also be represented in the models used for nearshore predictions.

## OVERVIEW OF MODEL SUITES

The US Navy uses a number of different models for forecasting conditions in coastal and nearshore regions. Here, we briefly describe the relevant systems and models, including the Simulating WAves

Nearshore (SWAN) model, Delft3D, and the SWANFAR system. See Allard et al. (2014, in this issue) for a discussion on the ocean-wave component in the Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS), which is being transitioned to operations at the Naval Oceanographic Office.

## SWAN

Waves in the nearshore region are typically forecast using the wave model SWAN (Booij et al., 1999), which solves the wave action balance equation to predict the evolution of the wave energy spectra in both the physical (x/y or latitude/longitude) and the spectral (frequency/direction) space in coastal regions. Using the action balance equation facilitates inclusion of the Doppler shift induced by ambient currents. Waves are propagated into the domain if wave spectra are specified at the boundaries. Winds force generation of waves inside the domain, and energy is transferred between frequencies and directions via approximations of nonlinear interactions (triads and quadruplets). Energy dissipates from the waves due to white capping in deeper water and bottom friction and depth-limited breaking in shallow water.

Typical inputs to the model include currents from a circulation model such as Delft3D-FLOW (described below) or the Navy Coastal Ocean Model (NCOM; Martin, 2000; Barron et al., 2006; Kara et al., 2006), bathymetry, wind from a meteorological model, and spectra from a global or regional wave model, such as WAVEWATCH III (WW3; Tolman, 2009), at the open boundary if significant wave energy is expected to propagate into the domain via the open boundaries. Daily forecasts are provided for over 350 domains worldwide, of which about one-third are for nearshore/coastal domains.

## Delft3D

Delft3D (Stelling, 1996) is a modeling suite designed for computations in coastal, estuarine, and river areas. It can be used to compute velocities, surface elevations, waves, temperature, salinity, water quality, and morphological changes in these regions over time and length scales greater than those of individual waves. It consists of a number of modules coupled together using a common interface that can be executed independently or in combination with each other. For Navy operations, the modules Delft3D-FLOW (FLOW for short) and Delft3D-WAVE (WAVE for short) are typically used.

The FLOW module, which can be run in two- or three-dimensional mode, solves the Navier-Stokes equations for an incompressible fluid, assuming shallow water conditions and with the Boussinesq assumption. The model can be set up in z-coordinates (fixed layer depths) or σ-coordinates (terrain following layers). In the σ-coordinate setup, hydrostatic flow is assumed, whereas the z-coordinate setup can be used for nonhydrostatic flow as well. Different types of boundary conditions can be prescribed, including water levels, velocities, or a combination of the two. Tides can be specified as boundary conditions in terms of water levels and/or velocities. For partially or fully enclosed bodies of water, tidal potentials can be included to enable generation of tides in the domain. In addition, the model can be forced by waves, wind, river discharge, temperature, and salinity. Bottom drag is calculated using the Chezy formula (Roberson and Crowe, 1993), using either a specified constant value for the friction coefficient in the computational domain or spatially varying coefficients. A number of wind drag parameterizations are available (Condon and Veeramony, 2012), and wind drag is computed with the user-specified wind drag coefficients depending on the formula chosen.

The WAVE module, which is typically run coupled with the FLOW module, consists of a wrapper that creates the input files to run SWAN as well as a SWAN executable. The WAVE module can obtain water levels, surface velocities, wind field, and bathymetry from FLOW, and in turn provide FLOW with wave forces (based on either radiation stress or dissipation) and wave orbital velocities.

For daily operations, coastal domain grids are set up using tools provided with Delft3D software, and model simulations are run in either two- or three-dimensional mode. The Naval Oceanographic Office (NAVOCEANO)

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provides daily forecasts to Navy users for approximately 40 locations worldwide. In most cases, FLOW is run in stand-alone mode because Delft3D with coupled FLOW and WAVE both running in parallel execution mode is a recent development that is still being tested and validated. Boundary conditions are prescribed using a combination of sea surface elevations, current velocities, wind (velocities and pressure), wave spectra, and freshwater fluxes at river mouths. In some instances, water level and current velocity forcing at the boundaries are provided by output from lower resolution NCOM. When density-driven currents are required, temperature and salinity fields from NCOM are prescribed. Surface wind and air temperature parameters are taken either from the COAMPS (Hodur, 1997; Doyle, 2002) or from the Navy Operational Global Atmospheric Prediction System (NOGAPS; Hogan and Rosmond, 1991) model fields provided by the Fleet Numerical Meteorology and Oceanography Center (FNMOC). The NAVy Global Environmental Model (NAVGEM; Hogan et al., 2014, in this issue) has recently replaced NOGAPS. Model runs are automated using command scripts running on Linux or Windows operating systems, and boundary conditions are updated automatically on a daily basis. Model forecasts up to 72 hours are provided to Navy users via Web downloads.

For event-driven forecasting such as storm surge and inundation, the domains are set up using the open source Delft DashBoard, part of the open-source initiative OpenEarth (de Boer et al., 2012), which allows quick model setup for different areas in the world. The model domain is typically set up in nested mode, with the outermost nest large enough to cover the entire region affected by the event and inner nests progressively refined to cover the area of interest. Tidal boundary conditions for the open ocean boundaries of the outer nest are determined using the TOPEX7.2 tidal atlas (Egbert and Erofeeva, 2002). For the inner nests, water surface elevation and currents are obtained from the outer nest. For a typical storm surge forecast, winds are generated by blending the current forecast to the best track available in HURDAT2 format (Sampson and Schrader, 2000). The wind field is a function of the azimuthal angle and the radial distance from the center of the storm, calculated using multivariate interpolation of the values provided by the forecast (Condon and Veeramony, 2012). This allows preservation of the shape of the wind field while retaining the ability to be quickly constructed for use in forecasts. The momentum transfer from the atmosphere to the ocean is calculated using the drag coefficient as described by Powell et al. (2012). The wave field is generated in the domain by the wind field, and no wave spectra are prescribed at the open boundaries.

> "COMPARED TO THE DEEPER OCEAN, THE NEARSHORE LENGTH SCALES ARE MUCH SMALLER (FROM A FEW METERS TO A FEW HUNDRED METERS), WHICH MEANS THAT TYPICAL RESOLUTIONS NEEDED FOR MODELING THESE FLOWS ARE MUCH FINER THAN IS POSSIBLE FOR GLOBAL OR EVEN REGIONAL MODELS."

### SWANFAR

The SWANFAR system is a four-dimensional variational (4Dvar) data assimilation system (Bennett, 2002) that uses wave data, available as a function of time at discrete locations in the model domain, to improve model predictions in the entire domain. The system is built around a discrete numerical adjoint to the structured version of SWAN (Flampouris et al., 2013; Orzech et al., 2013), which is composed of a collection of adjoint subroutines, each individually constructed from a corresponding subroutine in the original forward SWAN (Orzech et al., 2013). The adjoint propagates the model-data errors back in time and space to the initial time and to the boundaries. A perturbation tangent-linear SWAN that includes a corresponding collection of modified SWAN subroutines, each of which has been linearized and recast to propagate perturbations in wave action and other parameters, is used to determine the model-data errors at the observation locations for the next iteration. A "cost function," which is the square of the deviations between model and data weighted by the errors in the system, is used to determine whether the model-data errors fall within an acceptable limit. The weights are the inverse of the error covariances, which are assumed based on knowledge of the dynamical system. Determination of the weights is ongoing research, and currently we use the identity matrix (assume all errors are equally important and localized). The iterations are performed until the cost function is minimized. The system can assimilate complete frequency-directional wave spectra at multiple locations and times.

## CASE STUDIES

In this section, we present a number of case studies that demonstrate how the models described in the previous section are used in Navy applications. The first three cases are in locations that are of interest to the Navy because of the presence of a number of naval installations in the region. At Kaena Point, Hawaii, we use SWAN to forecast daily wave conditions. At Chesapeake Bay, Delft3D is used for daily forecasts in a bay/estuarine environment, and we show the typical products that are output for use by Navy customers. At the Mississippi Bight, we illustrate the same for the northern Gulf of Mexico, near the mouth of the Mississippi River. The fourth case, Hurricane Ike, shows the application of Delft3D in forecasting surge and inundation due to hurricanes/tropical storm systems. Finally, in the fifth case, Trident Warrior 2013, we apply the SWANFAR system to show improvement in wave prediction with the use of a wave data assimilation system.

### Kaena Point, Hawaii

Kaena Point is located on the western tip of the island of Oahu, Hawaii. The area typically has high wave energy in the winter, coming primarily from the north and leading to ocean conditions dangerous for human activity. The model domain is forced with meteorological winds from NAVGEM and waves from global predictions using WW3. Figure 1 shows the significant wave heights and directions in the region forecast for March 28, 2014, at 00 UTC (Coordinated Universal Time). Waves coming from the west refract/diffract around Kaena Point, leading to milder wave conditions farther south along the coastline (illustrated by the blue colored areas in the figure). Wave energy variability in the alongshore direction, defined by changes in wave height, is well illustrated, and this variability can potentially cause dangerous undertow and rip currents.

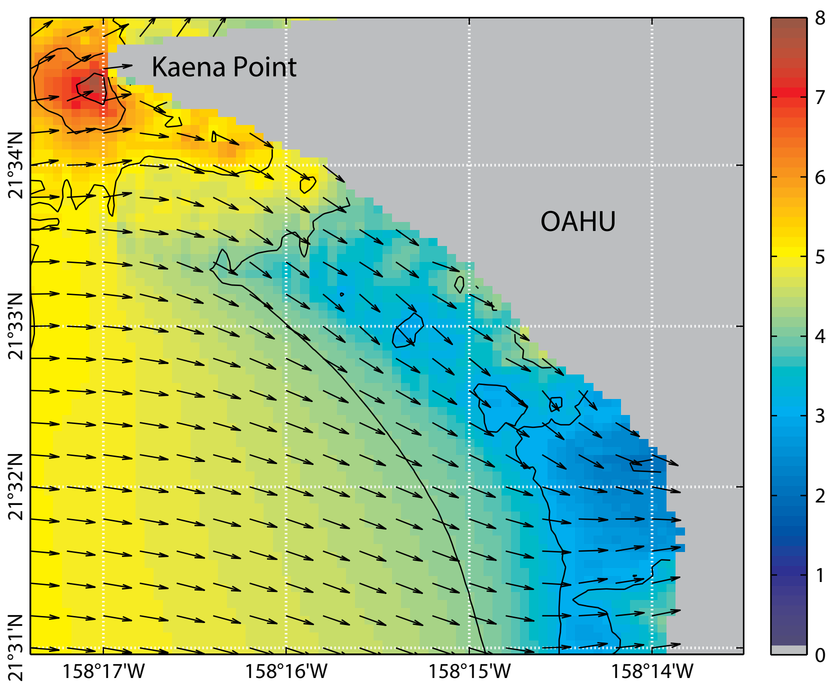

Figure 1. Wave height (feet) and direction (degrees) forecast for March 28, 2014, 00 UTC at Kaena Point, Oahu, Hawaii.

### Chesapeake Bay

Chesapeake Bay is a large estuary where ocean tides and currents, riverine discharge, and winds influence dynamics. The estuary is partially mixed, with net flow seaward in a surface layer and net flow in the opposite direction in a bottom layer (Goodrich and Bloomberg, 1991). The tidally averaged residual flow is around 0.1 m $s^{-1}$. River discharge heavily influences salinity distribution, and both winds and tides significantly impact flow in the domain (Carter and Pritchard, 1988). Many different models have been used to study this region's dynamics, including the Princeton Ocean Model (POM; Guo and Valle-Levinson, 2007), the US Army Corp of Engineers model Curvilinear Hydrodynamics in 3 Dimensions (CH3D; Johnson et al., 1993), and the Regional Ocean Modeling System (ROMS; Li et al., 2005).

The Delft3D model in this region is set up for high-resolution modeling near the mouth of Chesapeake Bay (Figure 2). The regional NCOM model provides boundary conditions for the Delft3D domain. The NCOM model includes monthly averaged river discharges from US Geological Survey (USGS) monitoring systems and is forced by COAMPS wind fields from FNMOC. The NCOM model output provides the water levels and velocities at the open boundaries to force the Delft3D simulation. Surface wind stress at the surface boundary is taken from COAMPS model fields provided by FNMOC. The Delft3D grid has resolutions ranging from 60–430 m and uses eight σ layers to describe the vertical variation in the domain. Temperature and salinity constituents are not included in this particular model configuration.

Figure 3 compares the Delft3D forecasts to the observed data. The left panel compares the water levels predicted by Delft3D to observed data over a 10-day period in December 2010 at two stations in lower Chesapeake Bay (Sewell's Point and Bay Bridge tunnel; see Figure 2). As expected, tides dominate the flow, and the Delft3D simulation captures the magnitude and phase accurately with biases of 0.003 m at Sewell's Point and 0.005 m at the Bay Bridge tunnel, root-mean-square (RMS) errors of 0.08 m and 0.03 m and mean absolute dispersion (MAD) of 0.062 m and 0.063 m, respectively. There is a small low-frequency modulation in the data that is underestimated by the model. The magnitude of surface velocity prediction at York Spit is typically smaller than the observations and has a bias 0.01 m $s^{-1}$, RMS error 0.18 m $s^{-1}$, and MAD 0.16 m $s^{-1}$. The predicted directions show a bias of 14°, RMS error of 16°, and MAD of 37.6°. For these simulations, the FLOW module is run without accounting for the influence of waves. Increased accuracy in the velocity magnitudes is achievable by increasing the vertical resolution of the model and by including waves; however, this compromises the time to completion for the model forecasts.

## Mississippi Bight

The Mississippi Bight is a highly dynamical shelf-break region where the dynamics are forced by a number of processes such as local and remote winds, river discharges, cyclonic eddies generated by the clockwise Loop Current in the Gulf of Mexico basin, and inertial oscillations in the Gulf of Mexico. As a result, all circulation models that do not assimilate data have difficulty reproducing the region's dynamics (Smith and Ngodock, 2008). Even though Delft3D as currently set up in this region does not use data to improve predictions, we see that it performs reasonably well in comparison to data because the boundary conditions come from NCOM, which does assimilate data.

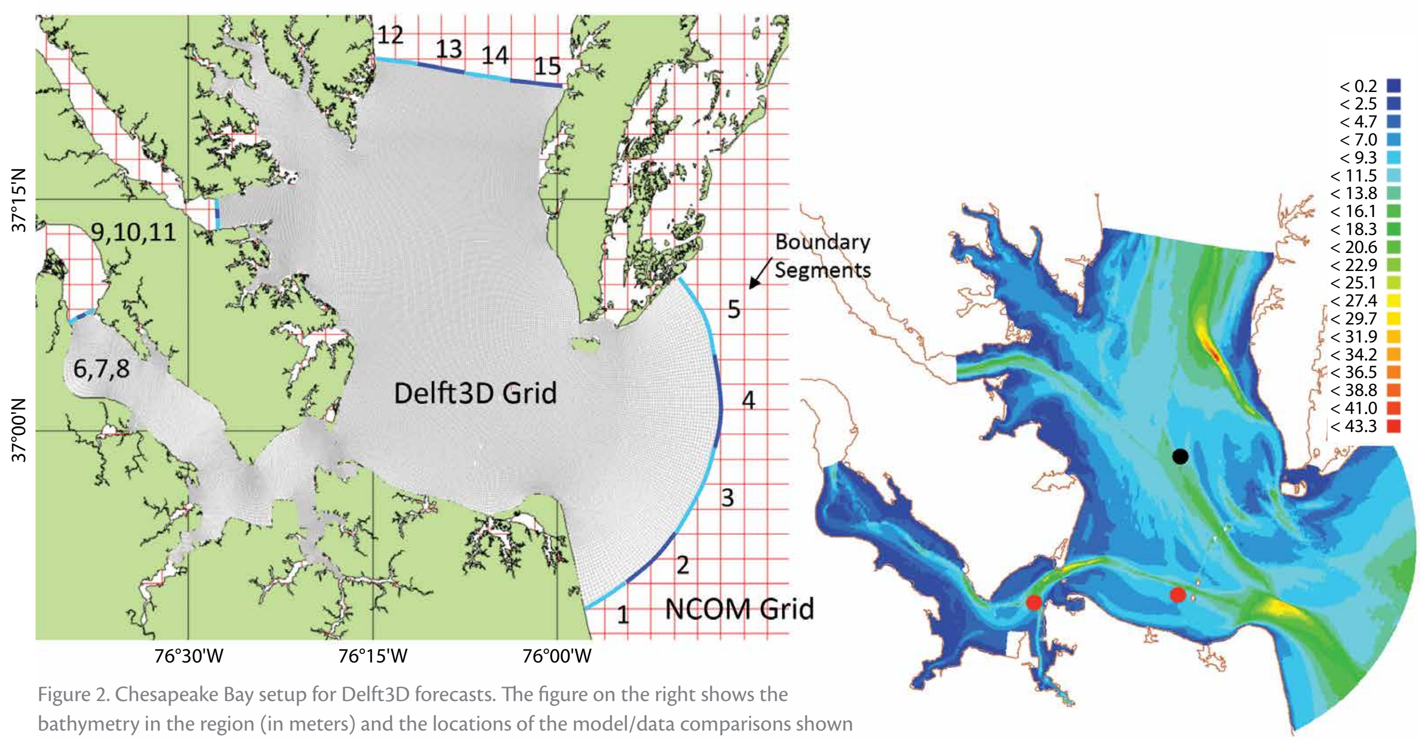


Figure 2. Chesapeake Bay setup for Delft3D forecasts. The figure on the right shows the bathymetry in the region (in meters) and the locations of the model/data comparisons shown in Figure 3. The black circle is York Spit (velocity comparisons in Figure 3), and the red circles locate the Figure 3 elevation comparisons (Sewell's Point at left and Bay Bridge Tunnel at right).

Figure 4 shows the model domain. The model grid is curvilinear, with approximately 54,000 points in the horizontal and 20 z-levels; resolution in the horizontal ranges from 200–1,350 m. Similar to the Chesapeake Bay region, the regional NCOM simulations provide water levels and currents along the open boundaries. Temperature and salinity fields from NCOM, as well as freshwater outflow from various rivers obtained from the USGS, are included. River discharges are updated daily prior to model forecast simulations. Wind forcing is obtained from the NOGAPS model. The results for December 1–15, 2010 (see Figure 5), show that the water levels predicted by the model are in agreement with the data (Mobile Bay: Bias = –0.002 m, RMSE = 0.083 m, MAD= 0.065 m. Gulfport: Bias = –0.001 m, RMSE = 0.083 m, $R^2$ = 0.916, MAD = 0.067 m.). The model captures the lowering of water level by offshore winds December 12–15, 2010. Again, there is a low-frequency component that is not predicted by the model. The magnitude of the surface velocity missed several peaks, most of which are believed to be associated with the horizontal movement of eddies spun off by the Loop Current. As a result, the statistical measures (Velocity magnitude: Bias = 0.008 m $s^{-1}$, RMSE = 0.076 m $s^{-1}$, MAD = 0.071 m $s^{-1}$. Direction: Bias = –25.659°, RMS = 40.890°, MAD = 65.074°.) are worse than for elevation. As in the Chesapeake Bay simulations, waves were not included in the forecast model.

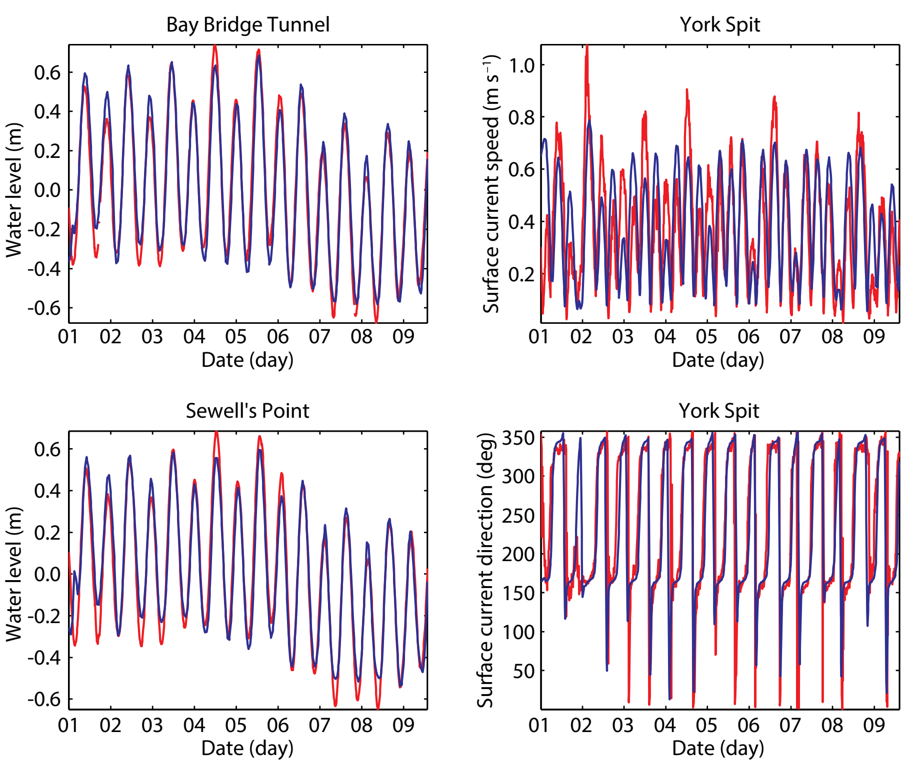


Figure 3. Comparison of water levels (in meters) at two stations (left panels) and surface velocity magnitude in m $s^{-1}$ (right panel, top) and direction in degrees (right panel, bottom) between Delft3D forecast (blue lines) and National Oceanic and Atmospheric Administration (NOAA) data (red lines) from December 1, 2010 to December 10, 2010.

## Hurricane Ike

The US Navy currently uses Delft3D for predicting nearshore circulation when inundation is not the primary concern, and uses PCTides (Posey et al., 2008) for worldwide coastal surge and inundation. However, PCTides does not include waves or other global ocean circulation and is also limited to a maximum resolution of approximately 1 km, which is insufficient for inundation predictions (Hope et al., 2013). While the omission of the global ocean circulation is likely to have minor impact on the surge and inundation levels, the omission of waves has a significant effect on water levels (Hope et al., 2013). The Delft3D modeling system (FLOW and WAVE) uses multiple nests to capture large, basin-scale circulation as well as coastal circulation and tightly couples waves and circulation at all scales. Prior to being used operationally, the Delft3D system was tested for a number of different storms. Below, we compare results from Delft3D with that of data from Hurricane Ike.

Ike was named as a tropical storm on September 1, 2008, when it was located just west of the Cape Verde Islands (US National Hurricane Center, 2010). Late on September 3, it reached hurricane strength, and by 0600 September 4, Ike was a major category four hurricane (track depicted in Figure 6). Ike's strength would fluctuate over the following days before emerging from the Cuban coast as a category one hurricane. The storm finally made landfall on September 13 at 0700 along the northern portion of Galveston Island on the Texas coast as a 95 kt, strong category two hurricane. As Ike moved inland, it weakened and was downgraded to a tropical storm by 1800 on September 13.

Ike serves as an ideal test case for validating models for surge and inundation because of the large storm surge and inundation it produced along the Texas and Louisiana coastlines. In addition, approximately 24 hours prior to landfall, the storm generated a large forerunner surge (Kennedy et al., 2011). Data were collected by a number of National Ocean Service (NOS) tide stations located throughout the northwestern Gulf of Mexico as well as by USGS water level stations. In addition, there were a number of National Data Buoy Center (NDBC) Coastal-Marine Automated Network (CMAN) buoys that recorded wave and wind data. To illustrate the model capability, we also show comparisons between the USGS surge station data and the model.

A total of five domains were used (Figure 6) in the model setup. The large-scale domain covered the Gulf of Mexico (GoM) with a resolution of 0.1° (approximately 10 km). Nested within the GoM domain was a nearshore domain that covered much of the northern Gulf (NG) from the Texas coast to the mouth of the Mississippi River with a resolution of 0.02° (approximately 2 km). Within the nearshore domain were three coastal domains with a resolution of 0.004° (approximately 400 m). These coastal domains covered Galveston Bay (GB), the Port Arthur area along the Texas-Louisiana border (PA), and the Vermillion Bay area of Louisiana (VB). The simulation period for the GoM domain begins on September 5, 2008, at 12:15 UTC and ends on September 14, 2008, at 23:15 UTC. The open boundaries in the inner nests are specified as Riemann time-series (Durran, 1999) boundaries, where the Riemann conditions are obtained from the water levels and currents from the immediate outer nest. For the simulations, an initial water level of 0.11 m was imposed, corresponding to seasonal sea level trends throughout the Gulf of Mexico for the month of September. Over open water, a spatially varying friction coefficient determined as a function of the water depth was used. Over land, the friction coefficient depends on the type of ground cover (e.g., amount of grass cover, tree cover, buildings). Such data were obtained from the National Land Cover Database (NLCD), courtesy of the USGS, and converted to a corresponding friction coefficient value based on the tables in Mattocks and Forbes (2008). The values around the coast are generally small but increase inland and in urban areas.

Figure 7 compares the model and data. The surge during Ike influenced a large area of the Texas and Louisiana coasts. In validating the storm surge

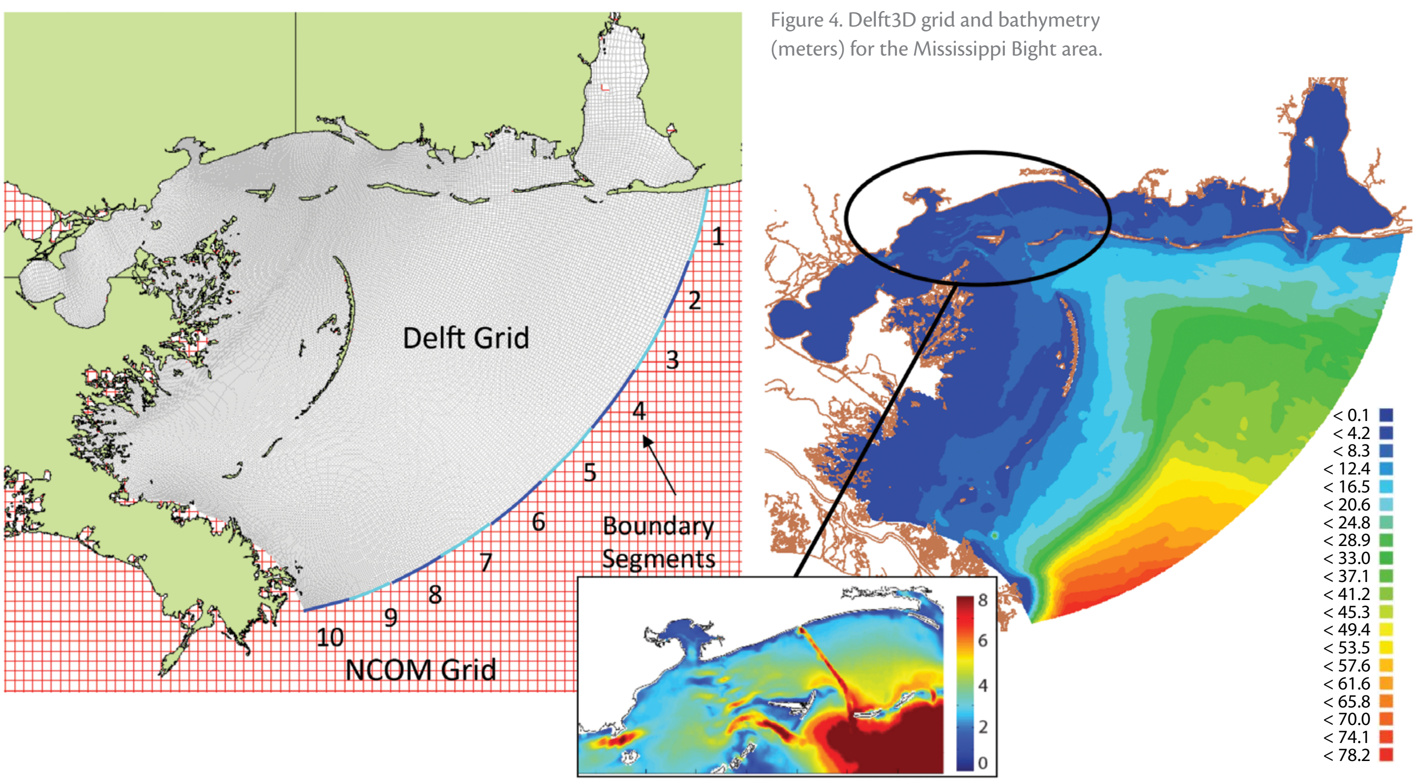


Figure 4. Delft3D grid and bathymetry (meters) for the Mississippi Bight area.

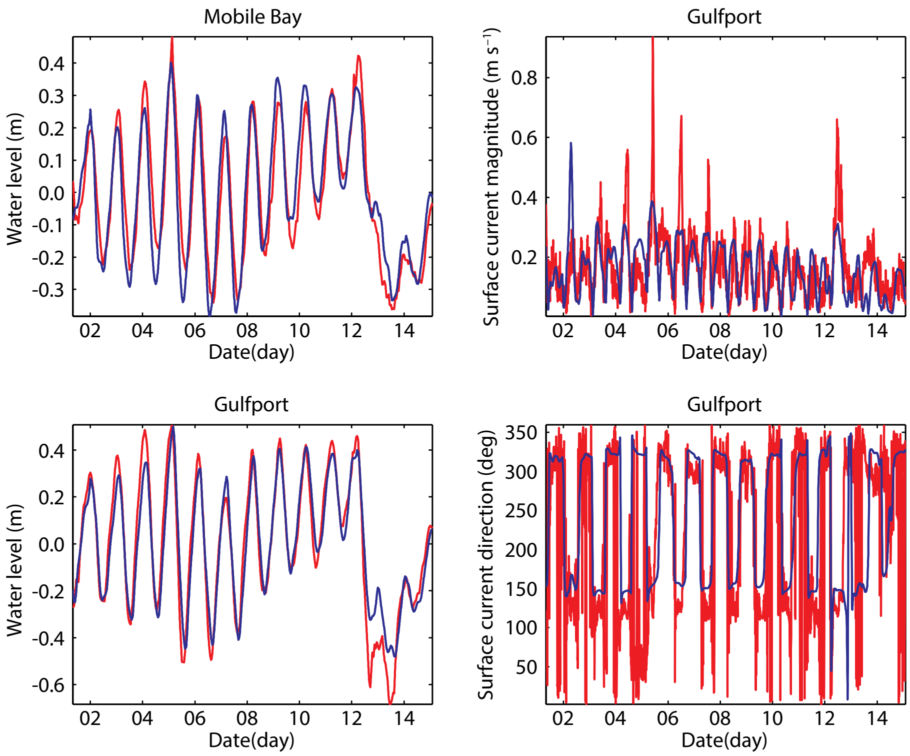


Figure 5. Comparisons of water levels (in meters) at two stations (left panels) and surface velocity magnitude in m $s^{-1}$ (right panel, top) and direction in degrees (right panel, bottom) between Delft3D forecast (blue lines) and NOAA data (red lines) from December 1, 2010, to December 15, 2010.

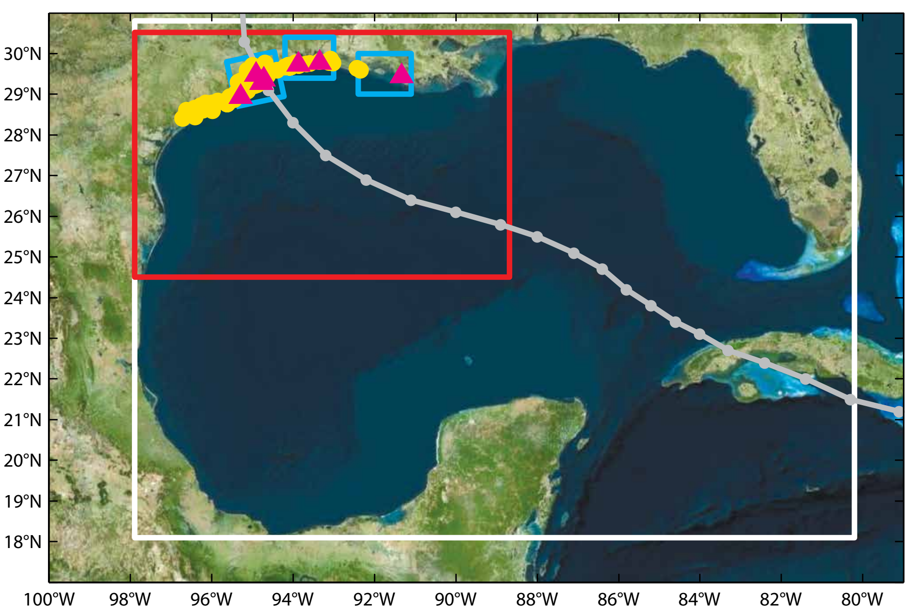


Figure 6. Domains used for Hurricane Ike studies. The white box outlines the 0.1 Gulf of Mexico domain, the red box the 0.02 nearshore domain, and the blue boxes the 0.004 coastal domains.

and inundation prediction system, there are two different components in terms of surge and flooding. First, the model must be able to accurately predict the water level at the NOS stations free of interactions with land (Figure 7, left panel). We see that the model reproduced the surge with good accuracy over the domain (Bias = 0.075 m, RMSE = 0.335 m, MAD = 0.350 m). In addition, it must accurately simulate the overland flooding that results from the surge. This task is especially difficult due to large and abrupt changes in topography and flood control structures that cannot be included in the models at this resolution. Also, land roughness values are averaged over the grid cells, which would lead to localized under/over estimations of the inundation, depending on how representative the averaged roughness is compared to reality. Comparison between model and USGS data (Figure 7, right panel) shows considerably larger variation (Bias = –0.478 m, RMS = 0.506 m, MAD = 0.615 m) than for the NOS stations. We can see that the higher resolution (0.004°) domain does predict better than the low resolution (0.02°) GoM domain (Bias = –0.775 m, RMS = 0.556 m, MAD = 0.663 m). However, there is still a lot of variability in the results that can be attributed to the reasons mentioned above.

## Trident Warrior 2013

The Trident Warrior exercise took place in July 2013 off Norfolk, Virginia, and included measurements of ocean temperatures, salinities, and currents as well as samples of offshore wave climatology. Here, we concentrate on the wave measurements and the use of wave data to improve predictions inside the

SWANFAR domain. For a more in-depth description of the exercise and for predictions of the circulation, see Allard et al. (2014, in this issue).

Boundary wave spectra were available from four nearby NDBC buoys and from regional-scale simulations conducted with WW3. Directional wave spectra in the interior of the domain were measured by five tethered mini-buoys and one free-floating mini-buoy. Although the buoys are designed to operate in a free drifting mode, evaluation of their performance while moored was one goal of the effort. Tension in the mooring line was found to influence the low-frequency energy content of the buoys, resulting in an erroneous low-frequency energy peak, which was removed through a simple high-pass filter (retaining only energy for f > 0.07 Hz).

In the following scenarios, the curvilinear domain (not shown) is roughly 80 km by 100 km, with grid spacing of 0.0025 deg (~ 250 m) and approximately 150,000 grid points. Modeled spectra at each location have 25 frequency and 36 directional bins. Assimilations are run in a "strong constraint" format in which only boundary conditions are corrected; measurements and model physics are assumed to be without error.

### *Stationary Assimilation, Five Fixed Locations*

For 0000 on July 14, 2013, the SWANFAR system is initialized with WW3-estimated boundary spectra and tasked with assimilating data from all five tethered mini-buoy locations. Dominant waves at the offshore boundary are from the southeast, with a significant wave height of about 2.5 m. For this time period, tether line effects on the mini-buoy data appear to be relatively small. Without assimilation, SWAN predicts significantly higher spectral densities at all observation locations (150% larger, on average), likely as a result of the WW3 boundary spectra overestimating the wave energy in the relatively shallow (20–40 m) water depths.

The system effectively assimilates the observed spectra in the vicinity of three mini-buoy locations (mb274, mb276, and mb277), reducing higher estimated total energy to be within 25% of observed levels and shifting estimated spectral shapes to better match observed distributions (e.g., Figure 8, top two rows). Errors in significant wave height are reduced by 70%, and errors in mean direction are reduced by 50%. In contrast, model-estimated spectra at the two remaining buoy locations (mb272 and mb273) are essentially unchanged by the assimilation. As mentioned earlier, SWANFAR assumes localized errors, so assimilation results affect only solutions near the observations, and the impact of estimated corrections decreases with distance from observation locations.

### *Nonstationary Assimilation, One Moving Location (Free-Floating Scripps Mini-Buoy)*

SWANFAR is run for a 15 hr period on July 19, 2013, assimilating hourly spectra from the single free-floating mini-buoy between 0200 and 1700. Because the buoy position changes over time, a nonstationary assimilation is required for this data set. The free-floating mini-buoy does not display the artificial low-frequency peak seen in the tethered buoy data, but like the moored buoys, it does often indicate significantly lower wave energy levels than those estimated by SWAN from the WW3 boundary spectra. In this case, the assimilation consistently reduces SWAN's original estimates of total energy, moving them closer to observed values (Figure 8, third row). However, in contrast to the stationary scenario, the post-assimilation spectral shapes are not shifted toward the observed spectral shapes, retaining instead the same shape as the original estimate (Figure 8, bottom row). Mean wave height error is reduced by 50%, while errors in mean period and

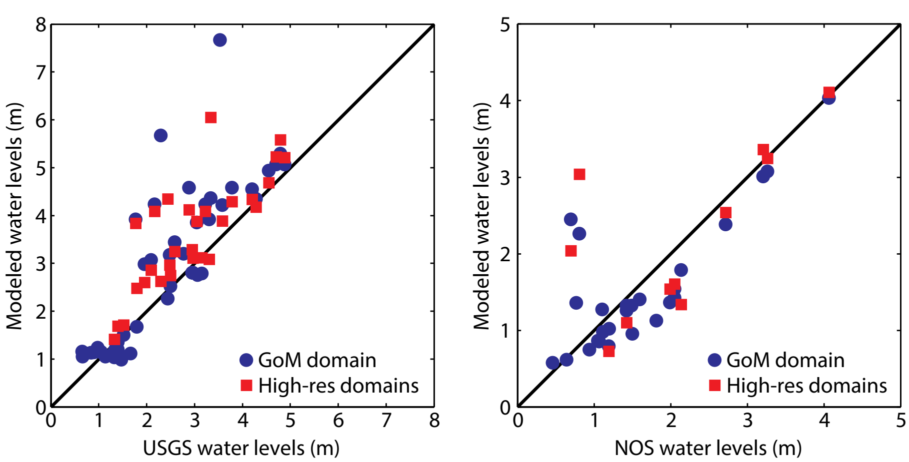


Figure 7. Surge (NOS stations) and inundation (US Geological Survey stations) comparisons between model (y-axis) and data (x-axis). The different colored symbols (blue = Gulf of Mexico domain, red = coastal domains) represent output from different model resolutions.

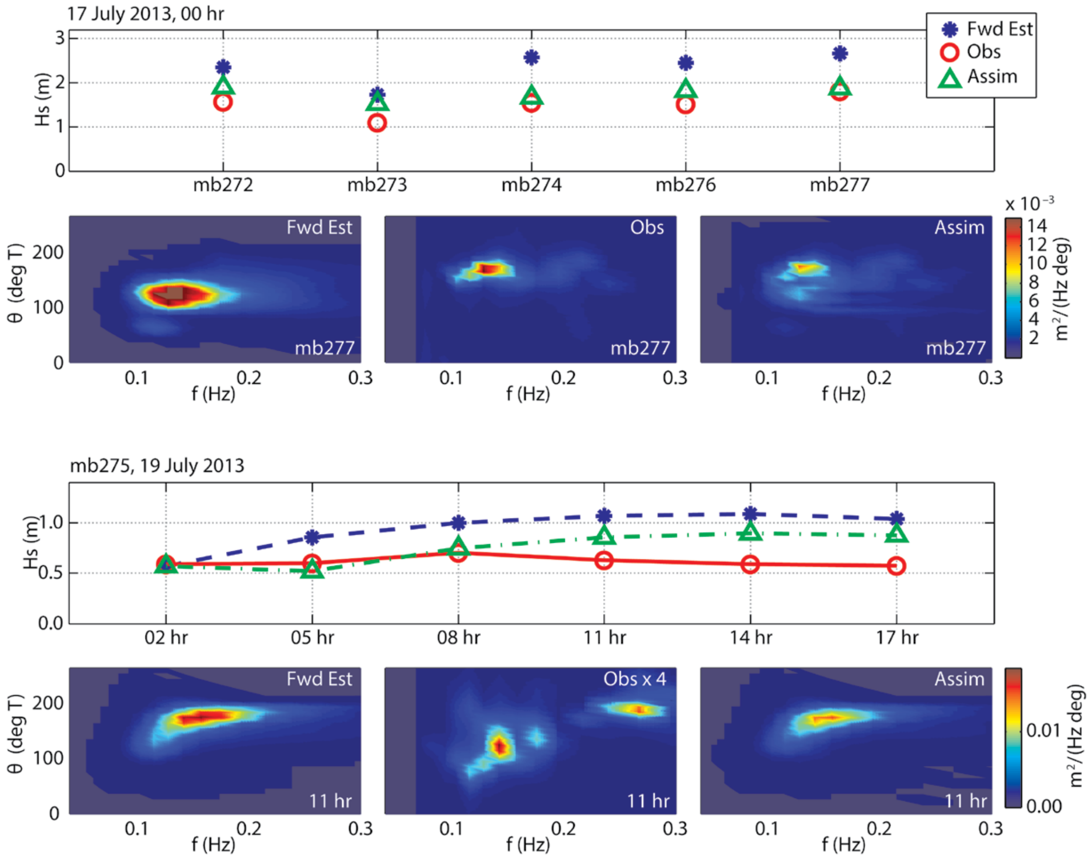


Figure 8. (top row) Estimated, observed, and post-assimilation significant wave heights for stationary simulation with five tethered Scripps mini-buoys, 00 hr on July 17, 2013. (second row) Example spectra of each type from mb277 results. The post-assimilation spectrum is much closer to the observed spectrum in both shape and magnitude. (third row) Estimated, observed, and post-assimilation significant wave heights for six locations from nonstationary simulation with untethered Scripps mini-buoy 275, July 19, 2013. (bottom row) Example spectra of each type from 11 hr results. Observed spectrum values are multiplied by four; all panels have the same color scale range.

direction increase slightly. This result should improve substantially with the application of error covariances in time and space.

## SUMMARY AND FUTURE PLANS

The Naval Oceanographic Office currently runs the Delft3D system for daily predictions of coastal ocean circulation. The surge and inundation validation was recently completed and is being tested under operational conditions. The system is expected to become operational in 2015. The SWANFAR system will soon incorporate covariance multipliers; it is expected to transition to operations by December 2014. Enhancements are presently being made to NCOM for nearshore applications. A wetting and drying algorithm has been implemented in NCOM based on the work of Oey (2005, 2006). In addition, a roller model that acts to delay the transmission of momentum in the nearshore surf zone from the waves to the currents is being added to NCOM. This mechanism is needed to move the peak longshore currents closer to the shoreline, as observed in laboratory and field experiments (Ruessink et al., 2001), which is necessary to improve the wave-driven circulation in the surf zone.

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