Development of Extratropical Surge and Tide Operational Forecast System (ESTOFS)

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ABSTRACT

The Coast Survey Development Laboratory (CSDL) of the National Ocean Service (NOS) and the Environmental Modeling Center (EMC) of the National Centers for Environmental Prediction (NCEP) have collaborated to establish an Extratropical Surge and Tide Operational Forecast System (ESTOFS) for the Western North Atlantic basin. The hydrodynamic model employed for ESTOFS is the ADvanced CIRCulation (ADCIRC) finite element model.

The ESTOFS will be implemented operationally by NCEP Central Operations (NCO) to provide forecasts of surge with tides, astronomical tides, and sub-tidal water levels (the isolated surge) throughout the domain. The ESTOFS combines the surge with tides and utilizes unstructured grids which can provide higher resolution at the coast. The ESTOFS is also designed to provide the surge with tides to WAVEWATCHIII® (WW3) for coupling waves with coastal water levels. Therefore, ESTOFS set-up is designed to follow WW3: it uses the same Global Forecast System (GFS) forcing and has the same forecast cycle and length, and will run concurrently at NCO.

The model results are compared with observations at 62 stations using NOS' standard skill assessment software. The skill assessment focuses on the performance of the model in simulating water levels in two model run scenarios: the hindcast, and the semi-operational forecast. As the results of skill assessment, the model's water level forecasts are of sufficient accuracy for operational implementation.

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INTRODUCTION

Impacts of extratropical storm surge can be far-reaching and catastrophic along the east coast of United States. The National Weather Service (NWS) Extratropical Storm Surge (ETSS) system developed by Meteorological Development Laboratory (MDL) is being successfully used by Weather Forecast Offices for extratropical storm surge forecasts (http://www.weather.gov/mdl/etsurge/). However, the coarse grid resolution and the lack of astronomical tide can cause a technical challenge in producing accurate storm surge forecasts. Thus an enhanced model would be valuable for local weather offices to more effectively prepare and respond to extratropical storm surge. Additionally, a model that produces water level fields is needed to couple to coastal wave models. Finally, an extratropical storm surge model that simulates surge and tides could be advantageous for providing boundary conditions to coastal wave and hydrodynamic models.

In order to meet these needs the Coast Survey Development Laboratory (CSDL) of the National Ocean Service (NOS) and the Environmental Modeling Center (EMC) of the National Centers for Environmental Prediction (NCEP) have collaborated to establish an Extratropical Surge and Tide Operational Forecast System (ESTOFS) for the Western North Atlantic basin. The hydrodynamic model employed for the ESTOFS is the ADvanced CIRCulation (ADCIRC) finite element model (Luettich et al. 1992; Luettich and Westerink 2004). The ADCIRC hydrodynamic model has several beneficial features for this system and has been demonstrated to be effective at predicting tidal circulation and storm surge propagation in complex coastal systems. Its unstructured grid methodology allow for the propagation of storm surges from offshore, across the shelf, and inland. This grid can also readily and accurately represent irregular shorelines including barrier islands, rivers and waterways.

The ESTOFS will be implemented operationally by NCEP Central Operations (NCO) to provide forecasts of surge with tides, astronomical tides, and sub-tidal water levels (the isolated surge) throughout the domain. The ESTOFS will provide NWS with a second extratropical surge system in addition to the ETSS that currently is based on the Sea Lake and Overland Surge from Hurricanes (SLOSH) model (Jelesnianski et al. 1992). The ESTOFS provides surge with tides and utilizes unstructured grids which are beneficial for efficiently resolving coastal features. This capability serves the needs of NCEP's Ocean Prediction Center (OPC) and the National Hurricane Center's Tropical Analysis and Forecast Branch (NHC/TAFB), who are responsible for providing offshore marine forecasts. It also meets the needs of Weather Forecast Offices for putting out coastal inundation forecasts. The ESTOFS is also designed to provide surge with tides to the WAVEWATCHIII® (WW3) wave model for coupling these systems. Therefore, its set-up is designed to mimic WW3: it uses the same Global Forecast System (GFS) forcing and has the same forecast cycle and length, and will run concurrently on NCEP's Central Computing System (CCS).

The final step in the transition to operational implementation is to assess the performance of the model. This was done for ESTOFS by using standard NOS skill assessment criteria (Hess et al. 2003). NOS developed a software tool in order to perform model skill assessment according to these criteria (Zhang et al 2006), and the ESTOFS results are analyzed using this tool. Skill assessment score tables are compiled for each location where observations are available, and these tables are used to demonstrate the model is prepared for transition to an operational environment.

This paper is broken into 5 sections, the first of which is this introduction. Section 2 focuses on an overview of ESTOFS including a brief description of ADCIRC, the model grid for this application, the forcing products, the operational set-up and output files. Comparisons of NOS/Center for Operational Oceanographic Products and Services (CO-OPS) observations with model a hindcast and a semi-operational forecast are summarized in Section 3. Lastly, the skill of the model is examined using the skill assessment criteria in Section 4. Section 5 presents a summary of the ESTOFS skill assessment.

MODEL SYSTEM OVERVIEW

ADCIRC Hydrodynamic Model

The ADCIRC model was developed to perform high resolution simulations of coastal hydrodynamics (Luettich et al. 1992; Luettich and Westerink 2004). This model is a system of computational algorithms that solve time-dependent, free surface circulation and transport problems in two and three dimensions. The ADCIRC Two-Dimensional Depth Integrated (2DDI) version, used in the ESTOFS, is the barotropic version of the model. ADCIRC utilizes the finite element method in space, taking advantage of highly flexible, irregularly spaced grids. Numerous studies have shown this model to be accurate for computing the variation in water levels throughout the Western North Atlantic and Gulf of Mexico regions (Luettich et al. 1994; Mukai et al. 2001; Westerink et al. 2008)

ADCIRC solves the fully nonlinear governing shallow water equations through use of the generalized wave continuity equation formulation (Kolar et al. 1992). This formulation benefits from minimal existence of spurious oscillations without relying on excessive non-physical dissipation by propagating the shortest resolved ("so-called $2\Delta x$") waves. For efficient computation, the two dimensional depth-integrated form of the model is applied since surge and tide propagation consists of barotropic waves captured therein. ADCIRC uses a second order Galerkin finite element method to solve the governing equations to take advantage of an unstructured grid technique. While the semi-implicit time stepping scheme requires relatively small time steps that satisfy the Courant condition, extensive use of the model on multiple platforms has led to efficient coding and solution techniques. Furthermore, the model has been parallelized using the Message Passing Interface, demonstrating linear speed-up proportional to the number of processors.

Model Grid

The unstructured grid used in the ESTOFS for the Western North Atlantic domain is the East Coast 2001 tidal database (EC2001) grid version 2e (Mukai et al. 2001). The EC2001 uses a grid consisting of 254,565 nodes (Figure 1). Coastal resolution generally averages about 3 km. The open-ocean boundary is located at the 60^{o} W meridian, where harmonic tidal constituents from a global tidal model are used to specify tidal water surface fluctuations. The performance of EC2001 for astronomical tides was verified using tidal elevation data from over 100 observation stations throughout the domain (Mukai et al. 2001). The EC2001 grid was also used by CSDL to produce an updated tidal database, EC2001_NOS, which updated the boundary condition forcing as well as calculated CO-OPS standard suite of 37 tidal constituents from a 1 year simulation (versus the original calculation of 7 constituents over a 90 day simulation). CO-OPS observation stations used in this paper to compare to ESTOFS results are shown in Figure 1.

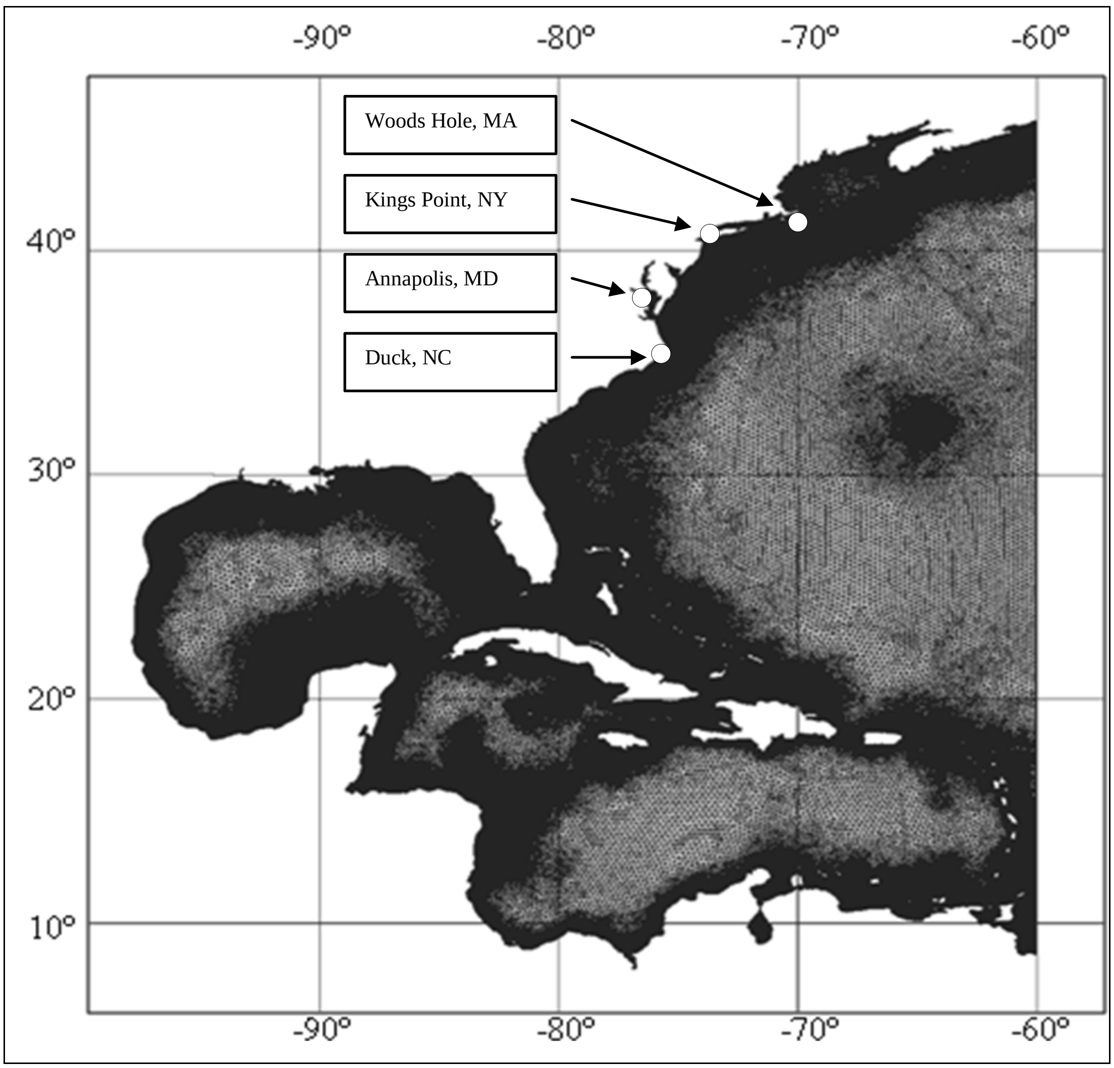

Figure 1. The EC2001 grid and CO-OPS observation stations.

Model Forcing Products

Global Forecast System (GFS)

The Global Forecast System (GFS) is a global numerical weather prediction computer model run by NOAA/NCEP (http://www.emc.ncep.noaa.gov/GFS/). The GFS is run four times a day and produces forecast guidance out to 16 days. The model provides two types of results: the first has a higher (0.5 degree) resolution and goes out to 180 hours (7 days) in the future, and the second runs from 180 to 384 hours (16days) at a lower (1.0 degree) resolution. It produces output for every 3 hours for the first 180 hours; after that output is produced every 12 hours. ESTOFS' surface forcing consists of wind velocities and atmospheric pressure, and is provided from GFS every 3 hours. GFS output of the east and north wind 10 m above ground and pressure reduced to Mean Sea Level are interpolated onto the ESTOFS grid.

Oregon State University Global Inverse Tidal Model (TPXO 6.2)

ESTOFS uses the Oregon State University Global Inverse Tidal Model (TPXO 6.2) for the open-ocean boundary forcing and the Newtonian tidal potential and corrections (Egbert and Erofeeva 2002). TPXO 6.2 is a global model of ocean tides, which best-fits, in a least-squares sense, the Laplace Tidal Equations. The tides are provided as complex amplitudes of earth-relative sea-surface elevation for eight primary (M2, S2, N2, K2, K1, O1, P1 and Q1), two long period (mf and Mm), and 3 non-linear (M4, MS4 and MN4) harmonic constituents, on a 0.25 degree resolution full global grid. ESTOFS uses eight primary and two long period harmonic constituents for the open-ocean boundary forcing. The Newtonian tidal potential terms for the 8 primary constituents are forced within the ESTOFS domain (Reid 1990).

Operational Implementation and Output

ESTOFS will operate normally as an automated job on the NCEP CCS. Since ESTOFS is designed to be coupled with WW3, it has the same run cycle (4 times per day) and length (6 hour nowcast followed by 180 hour forecast) as WW3. Hot start files are recorded every 6 hours during the run, and one is written upon completion of the 6 hour nowcast that is used to initialize the next forecast cycle simulation. Output is being provided in two formats: 2.5 km GRIB2 files, and NetCDF files that contain the native EC2001 grid. Figure 2 shows the CONUS and Puerto Rico GRIB2 grids overlaying the EC2001 domain. MDL will also deliver output on the website at stations which provide ETSS predictions (http://www.weather.gov/mdl/etsurge/). All output files are currently being disseminated experimentally via NCEP's developmental NOMADS server (http://nomad1.ncep.noaa.gov/pub/raid2/estofs/). This will be transitioned to the operational NOMADS server at NCEP one the model becomes fully operational in 2012. An archive of ESTOFS will be stored by the National Coastal Data Development Center.

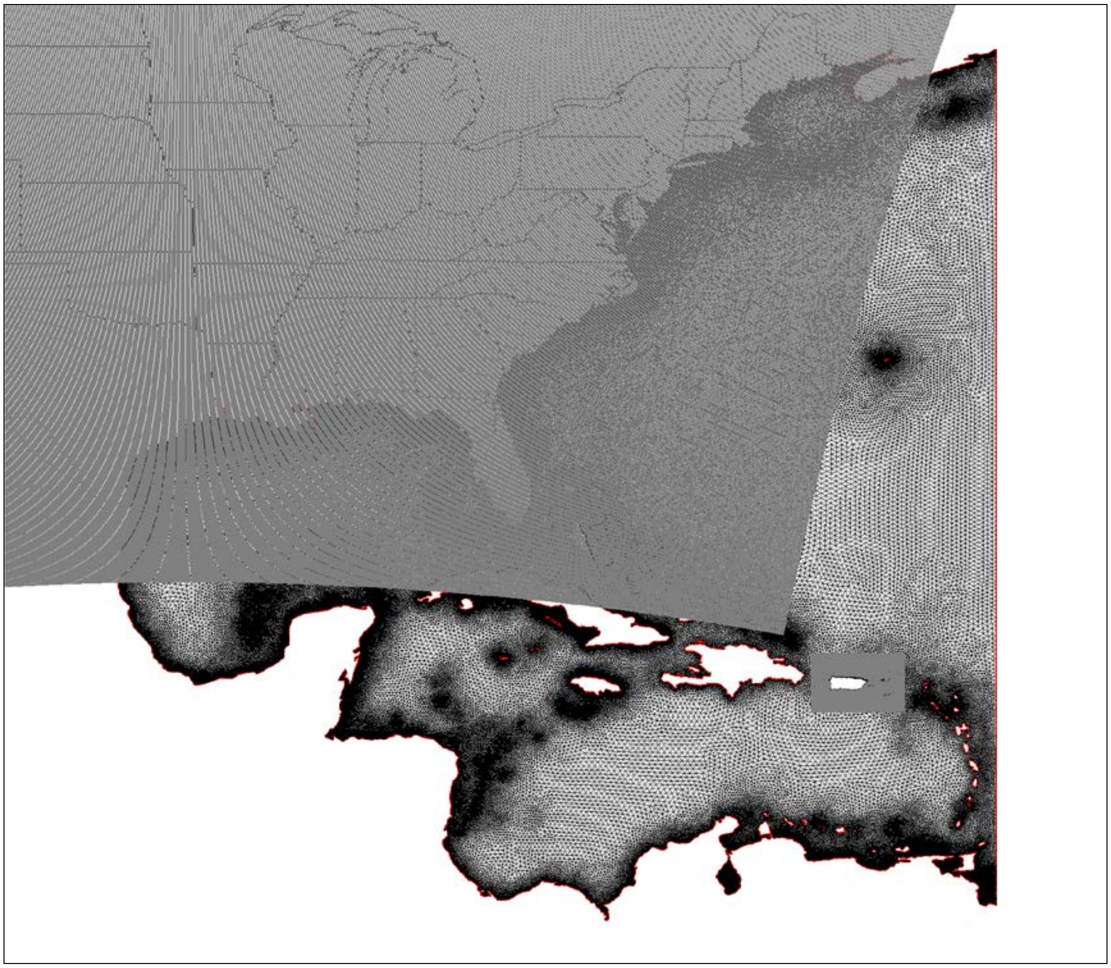

Figure 2. The NDFD CONUS and Puerto Rico grids overlaying the EC2001 domain.

MODEL VALIDATION

Hindcast Simulation for the entire year of 2009

As part of the model evaluation, ESTOFS was run for the entire year of 2009 due to significant storm surge events (i.e. Hurricane Ida and the November 2009 Mid-Atlantic nor'easter). In this simulation, the open-ocean boundary forcing and Newtonian tidal potential were derived from TPXO 6.2, and the surface forcing was provided from GFS, every 6 hours. There were no river discharge inflows and seasonable adjustments. The November 2009 Mid-Atlantic nor'easter (from November 11, 2009 to November 17, 2009) was a good meteorological event to test extratropical storm surge prediction. It was a powerful nor'easter that formed from the remnants of Hurricane Ida that created 70 mph (31 m/s) wind gusts in the mid-Atlantic. It caused severe flooding due to storm surge in much of the region

Figure 3 and 4 show a comparison of the CO-OPS observation and ESTOFS combined water level at Duck, NC and Annapolis, MD (see Figure 1). The comparison indicates that the combination of tidal amplitude, phase, and storm surge, known as the combined water level in ESTOFS, are well represented.

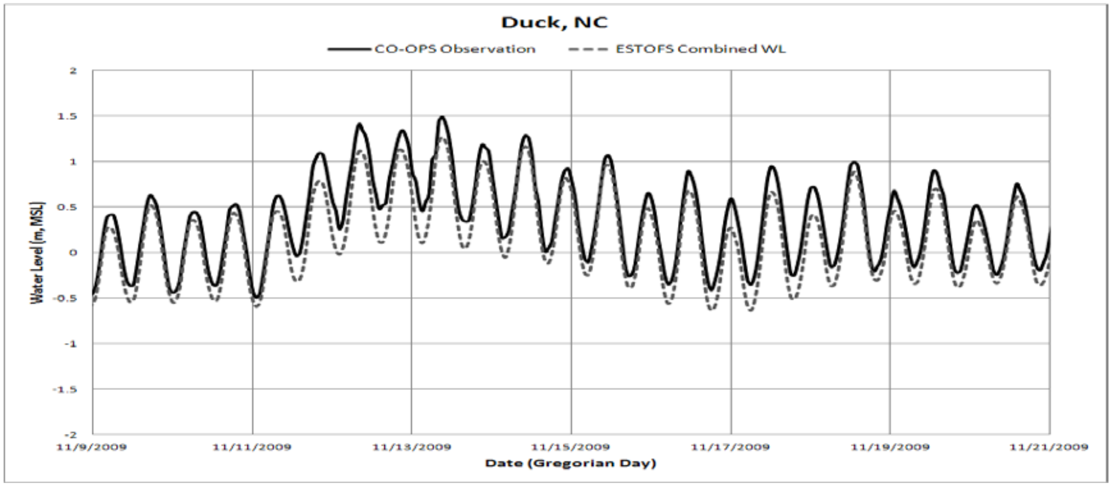

Figure 3. Water level comparison at Duck, NC.

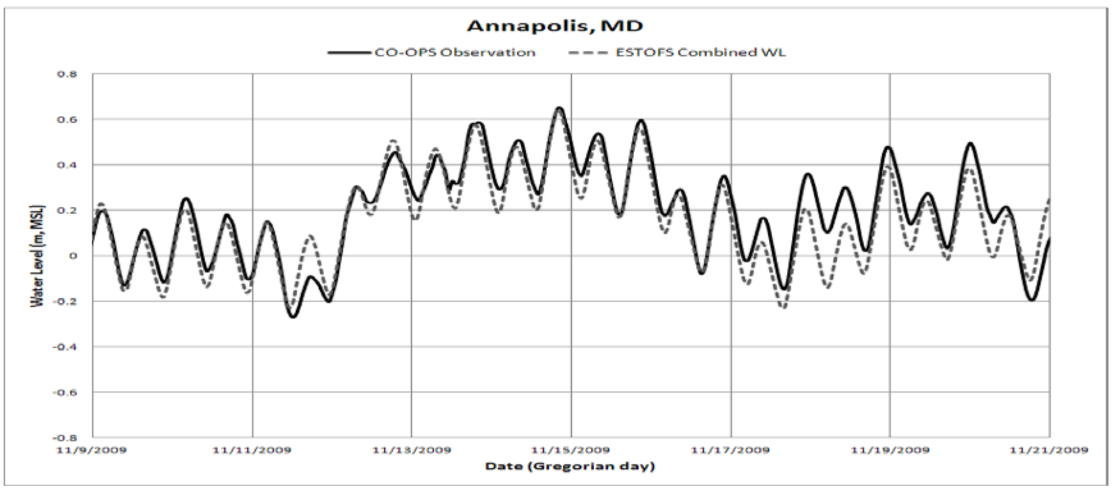

Figure 4. Water level comparison at Annapolis, MD.

Semi-Operational Forecast Simulation

In this simulation, the model forcing was created from real-time operational forecast guidance from the GFS models. Initial conditions were generated from the nowcast. This run tested the ability of the model in an operational environment by using the operational implementation. This simulation was made for the two weeks from October 25 to November 8 2010.

Semi-Operational Forecast Simulation for Hurricane Irene 2011

ESTOFS ran semi-operationally during Hurricane Irene (August 20 – 29, 2011). Hurricane Irene produced large surges and caused flooding along Mid-Atlantic coast lines. Stations from New York City, NY to Woods Hole, MS, had maximum storm surge value between 1.0 m and 1.5 m above predicted tidal levels. Figure 5 and 6 shows a comparison of the CO-OPS observation and ESTOFS combined water levels at Kings Point, NY and Woods Hole, MA from both the 00Z August 25 and the 00Z August 26 cycles, which were two day and one day before Irene made landfall. The peak surge from the 00Z August 25th cycle was shifted a half-day late due to uncertainty of GFS forecasts. However, ESTOFS predicted the peak surge well for the 00Z August 26th cycle. These results illustrate that water level forecasts are sensitive to GFS forecasts.

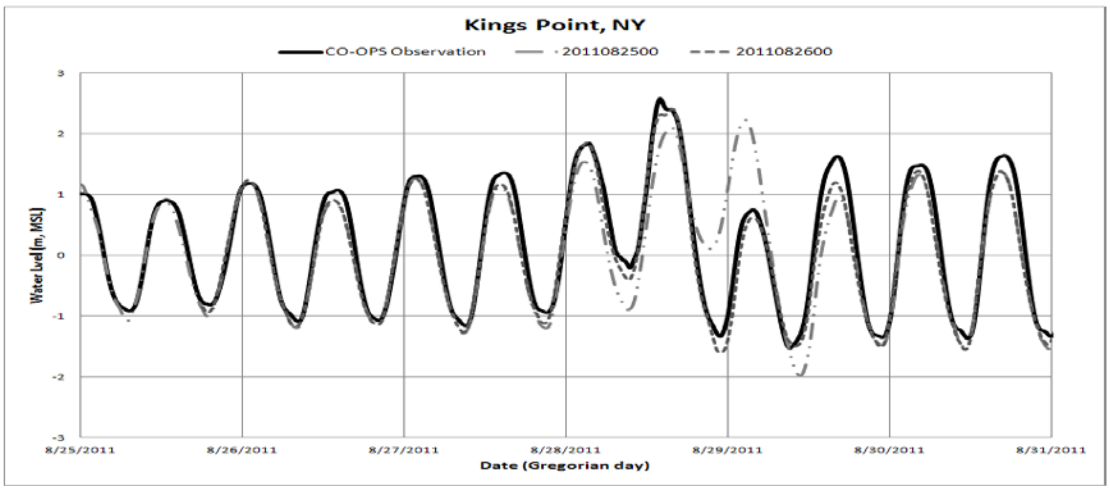

Figure 5. Water level comparison at Kings Point, NY.

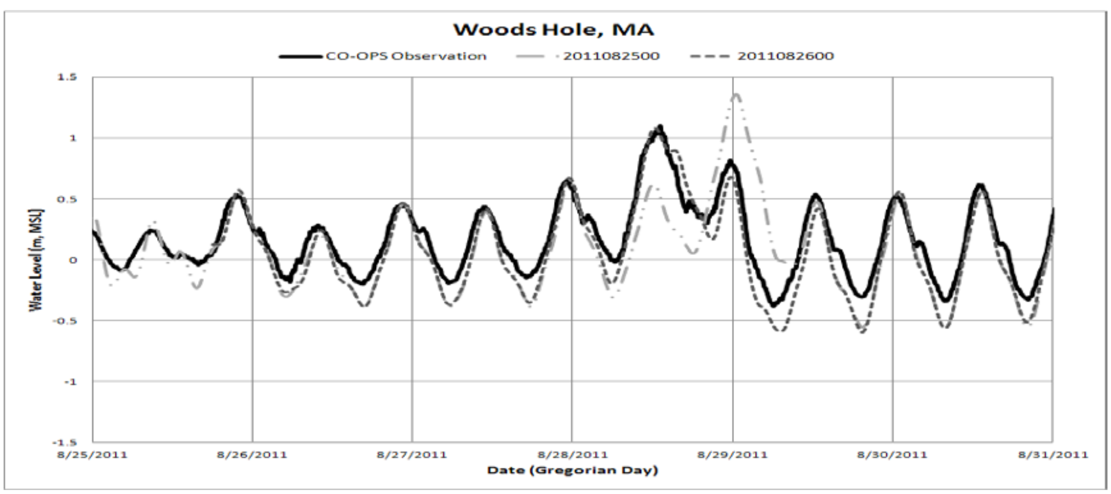

Figure 6. Water level comparison at Woods Hole, MA.

SKILL ASSESSMENT

Skill assessment is an objective measurement of the performance of a model when systematically compared with observations. NOS skill assessment criteria were created for evaluating the performance of circulation models (Hess et al. 2003), and a software package was subsequently developed to evaluate these criteria using standard file formats output from the models (Zhang et al. 2006). The software can compute the skill assessment automatically using files containing observations, predictions, and model results. In this report, skill assessment scores were computed for water levels at 62 stations along the Atlantic and Gulf coasts of the United States.

Hindcast

The hindcast simulation was made for the entire year of 2009, and water level time series were saved at hourly interval at locations where observations were available. Figure 7 shows the plot of the Root Mean Square (RMS) errors. The RMS errors vary from 1.15 m at Philadelphia, PA to 0.14 m at Newport, RI. A total of 14 stations have RMS errors larger than 0.20 m, which are located mainly on upper rivers or behind barrier islands and inlets where the grid does not cover or have enough resolution. Since the model selects the nearest element as the model observation locations, it's difficult to fit the observation. Thus these stations are eliminated from ESTOFS observation locations until there is an upgrade of the model grid to provide higher resolution around these areas.

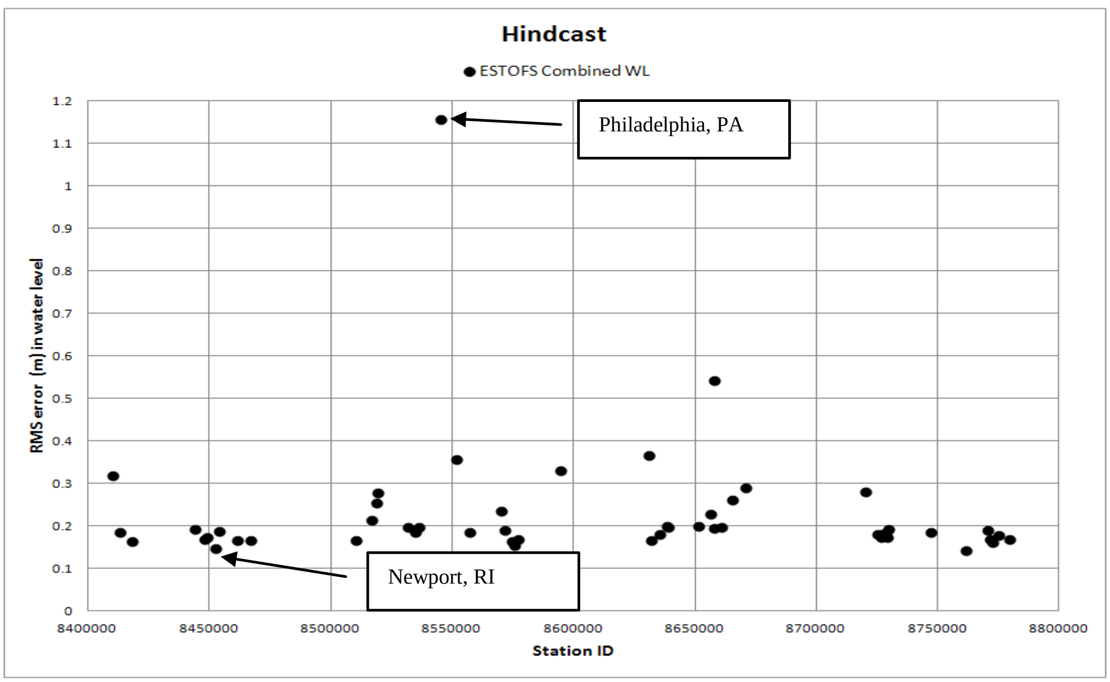

Figure 7. RMS errors in the combined water level from the hindcast.

Semi-Operational Forecast

Semi-operational forecasts were made from October 25 2010 to November 8 2010. ESTOFS applied the same NCO implementation set-up and ran 4 times per day to make 180 hour forecasts and store water levels at 6 min intervals at observation locations. The 180 hour simulations were concatenated into a continuous time series for skill assessment analysis. The ESTOFS forecasts are compared to CO-OPS preliminary real-time water level observations, which are not quality-controlled data. Due to the standards for NOS skill assessment, only the first 96 hour of the forecasts are used to compute skill assessment scores.

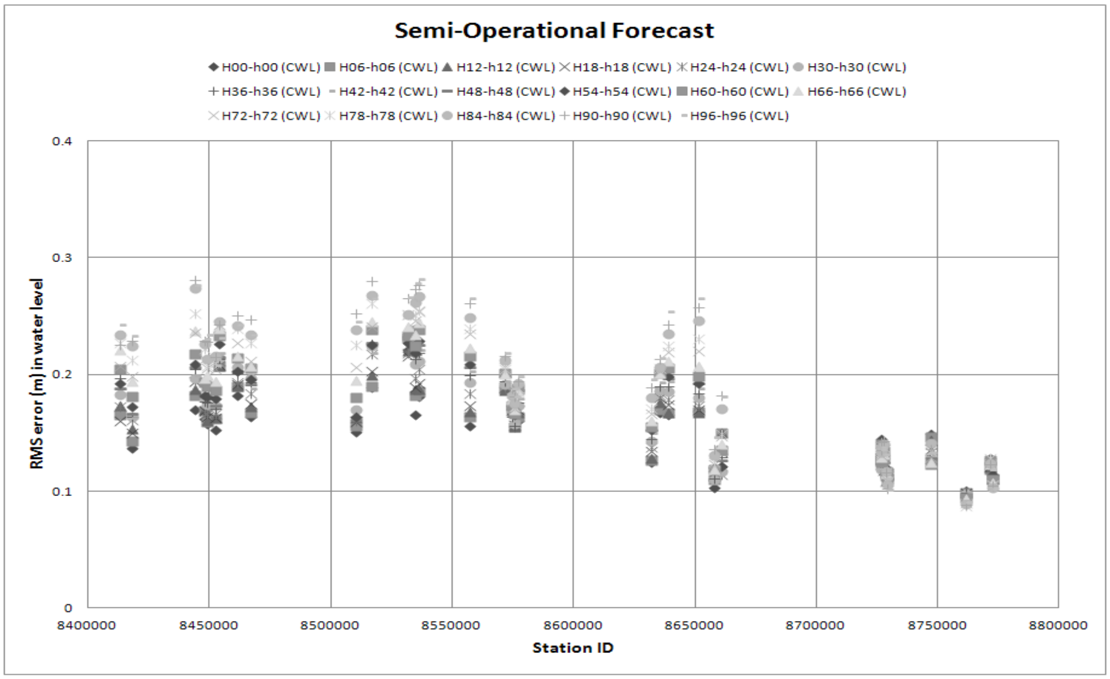

Figure 8. RMS errors in the semi-operational forecast; the forecast water level (H) is compared the observed water level (h).

The plots of the RMS errors, except for the 14 stations that are unresolved by the grid, are shown in Figure 8. The RMS errors slightly increase as the forecast progresses due to the increase in meteorological forecast uncertainty. However, the difference in RMS errors between the beginning of the forecast (H00-h00 forecasts) and after 96 hours (H96-h96 forecasts) appears to be a relatively small increase. These results show that the ESTOFS has the capability to provide skillful water level forecasts.

CONCLUSIONS

As part of the establishment of ESTOFS, CSDL has evaluated an application of the ADCIRC hydrodynamic model on the Western North Atlantic basin which will be implemented to perform operational 180-hour forecasts. The model results are compared with the observations at 62 stations using the NOS standard skill assessment software. The skill assessment focused on the performance of the model in simulating water levels in two scenarios: hindcast and semi-operational forecast.

The skill assessment for the hindcast simulation, shown that the skill scores for combined water levels satisfy the NOS criteria except for some stations which are located in complex geometries where the model grid doesn't have enough resolution. As a result of the skill assessment, the poorly performing stations were deemed unsuitable as locations for ESTOFS to provide water level forecasts in the operational implementation.

The semi-operational forecast is close to meeting the NOS criteria of 0.2 m RMSE. Although the NOS criteria were designed for coastal forecast model with higher resolution, the reason the criteria aren't met might be attributed to a couple of reasons. First is the lack of river discharge inflow. River discharges can have an important impact on coastal water levels. Considering the model domain resolution, it is difficult for the ESTOFS to specify river discharge locations. Second could be the variation in water levels due to baroclinic effects. Unfortunately ESTOFS does not incapable to incorporate baroclinic effects. The model's water level forecasts are of sufficient accuracy for operational implementation.

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