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4.6 Establishing a Community-Based Extratropical Storm Surge and Tide Model for NOAA's Operational Forecasts for the Atlantic and Gulf Coasts

Jesse Feyen[1]
NOAA/NOS/OCS/CSDL
Silver Spring, MD

Yuji Funakoshi
UCAR at NOAA/NOS/OCS/CSDL
Silver Spring, MD

André van der Westhuysen
UCAR at NOAA/NWS/NCEP/EMC/MMAB
College Park, MD

Steven Earle
NWS/NCEP/CO/PMB
College Park, MD

Christine Caruso Magee
NWS/NCEP/CO/PMB
College Park, MD

Hendrik Tolman
NOAA/NWS/NCEP/EMC/MMAB
College Park, MD

Frank Aikman III
NOAA/NOS/OCS/CSDL
Silver Spring, MD

1. INTRODUCTION

Impacts of extratropical storm surge can be far-reaching and catastrophic along the east coast of United States. The National Weather Service's (NWS) Extratropical Storm Surge (ETSS) system (NOAA, 2013) is being successfully used by Weather Forecast Offices for extratropical storm surge forecasts.

However, the lack of astronomical tide can cause challenges in producing accurate water level forecasts during storms. 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 that includes surge and tides 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 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 allows 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 was implemented operationally in September 2012 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 therefore provides 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 can provide better resolution at the coast. 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 issuing coastal inundation forecasts. The ESTOFS is also designed to provide surge with tides to the WAVEWATCH III® wave model (hereafter WW3, Tolman et al. 2002) and the Nearshore Wave Prediction System (NWPS, Van der Westhuysen et al. 2013) 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 runs concurrently on NCEP's Central Computing System.

The final step in the transition to operational implementation was to assess the performance of the model against water level observations from NOS's

[1] Corresponding author address: Jesse Feyen, NOAA/NOS/OCS/CSDL, Silver Spring, MD 20910; e-mail: Jesse.Feyen@noaa.gov

Center for Operational Oceanographic Products and Services (CO-OPS) stations. 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).
The structure of this paper is the following: Section 2 provides an overview of ESTOFS and its operational setup, including the model grid and the various input files. Section 3 describes the validation of the system via the NOS hindcast skills assessment. Section 4 illustrates the system's performance for the field case of Superstorm Sandy. Section 5 closes the paper with conclusions.

2. MODEL SYSTEM OVERVIEW

2.1 *The ADCIRC model*

The ESTOFS system is built around the unstructured grid, hydrodynamic community model ADCIRC (Luettich et al. 1992; Luettich and Westerink 2004). ADCIRC was developed to perform high resolution simulations of coastal hydrodynamics, and solves 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. 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).

2.2 *Model grid and boundary conditions*

The unstructured grid used in the Atlantic and Gulf of Mexico implementation of ESTOFS 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 the Oregon State University Global Inverse Tidal Model (TPXO 6.2, Egbert and Erofeeva 2002) 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 the CO-OPS standard suite of 37 tidal constituents from a 1-year simulation (versus the original calculation of seven constituents over a 90 day simulation).

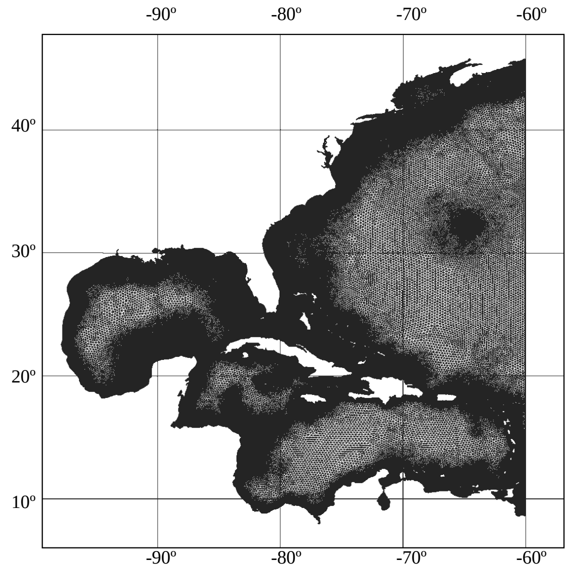

Figure 1: The EC2001 grid applied in the ESTOFS Atlantic system.

2.3 *Input files and operational setup*

The underlying ADCIRC model run is defined by two basic input files, namely the model grid and boundary condition file (fort.14) and the parameter and periodic boundary conditions file (fort.15). The former defines the unstructured grid (node locations, elevations, and element connectivity) and specifies various boundary conditions (e.g. land, river, and ocean). The latter file contains the majority of parameters required to run the model, as well as the inputs for the tidal harmonic forcing.
Meteorological forcing is specified in the fort.22 input file. Fields of wind velocity at 10 m elevation and sea level pressure are taken from NCEP's Global Forecast System (GFS), input every 3 hours from the 00z, 06z, 12z and 18z forecast cycles. System continuity is ensured by the use of the pair of ADCIRC hotfiles fort.67.nc and fort.68.nc.
The ESTOFS is run four times a day, at the 00z, 06, 12z and 18z cycles. Each run starts with a 6 h nowcast, followed by a forecast out to 180 h (time step of 5 s), mirroring the regime of WW3. During each model run, a harmonic tidal simulation is first completed, followed by a tide plus atmospheric forcing simulation. This enables the production of three water level components, namely the tide, the total water level, and the surge component (difference of the previous two). This provides forecasters the opportunity to adjust surge levels where required and subsequently add them back to the tidal fields.

2.4 *System output*

In agreement with the above, ESTOFS delivers three types of water level output:

- *Combined Water Level (CWL):* output of the combined surge and tide simulation
- *Harmonic Tidal Prediction (HTP):* Astronomical tides
- *Subtidal Water Level (SWL):* the surge-only component, computed as SWL = CWL – HTP

These results are produced both as water level fields (hourly) and point output (6 min). The field output is generated both on the ADCIRC native unstructured grid (NetCDF) and interpolated onto the structured NDFD grid 251 (Coastal Ocean Forecast System Grid - North Atlantic Region, in GRIB2). These outputs are distributed in the following ways:

- Via NCEP's production model output ftp site: http://www.ftp.ncep.noaa.gov/data/nccf/com/estofs/prod/
- Via NCEP's NOMADS model output distribution site: http://nomads.ncep.noaa.gov/
- GRIB2 files will be delivered via the Satellite Broadcast Network (SBN) to NWS's Advanced Weather Interactive Processing System (AWIPS) in 2013 Q3.

3. HINDCAST SKILL ASSESSMENT

NOS created a set of skill assessment criteria and software for evaluating the performance of circulation models, including the root-mean-squared (RMS) error, standard deviation, duration of positive and negative outliers, etc. (Hess et al. 2003; Zhang et al. 2006). Most of these skill assessment statistics have criteria which are a benchmark for the acceptance of a modeling system into NOS operational use.
To evaluate the performance of ESTOFS, two hindcast runs (harmonic tide; combined tide and surge) and a semi-operational forecast were completed. Skill assessment scores were computed for modeled and observed water level time series at NOS's Center for Operational Oceanographic Products and Services (CO-OPS) stations along the U.S. Atlantic and Gulf coasts. A total of 48 of these stations fall within the ESTOFS model grid, and were therefore included in the comparison. Figure 2 shows an example of the RMS error at the CO-OPS stations for the combined water level (CWL) hindcast spanning the year 2009. Wind velocity and atmospheric pressure fields obtained from GFS analysis output for 2009, available every 6 hours,

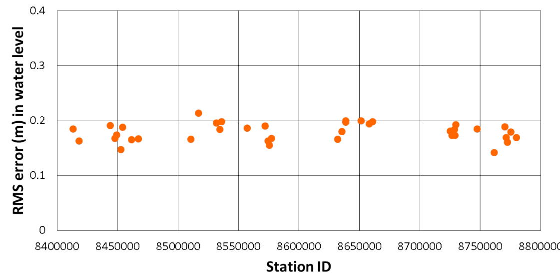

Figure 2: RMS errors in the combined water level for a one year (2009) hindcast evaluated at 48 NOS/CO-OPS water level stations.

were fed to the model. NOS's recommended criterion for the RMS error of a coastal operational model is 0.15 m. However, ESTOFS has difficulty in meeting these criteria, since they were designed for higher resolution, local scale, three-dimensional coastal forecast systems. Considering ESTOFS's large scale, an error level not exceeding 0.20 m is considered acceptable for operational implementation. Figure 2 shows that all stations except one (8516945) meet this adjusted criterion.
Note that although ESTOFS applies unstructured grid along the coast line, the grid does not have enough coastal resolution to incorporate sufficient reaches of rivers, small tributaries, and barrier island lagoons (see below). Therefore, a total of 14 CO-OPS stations (IDs 8410140, 8516945, 8518750, 8519483, 8545240, 8551910, 8570283,8594900, 8631044, 8656483, 8658120, 8665530, 8670870, and 8720030) fall outside of the model grid, and are not included in the present assessment. The extension of the model grid to include these output points is a high priority for future development.

4. SUPERSTORM SANDY FIELD CASE

Next we consider the performance of ESTOFS in predicting coastal surges during the landfall of Superstorm Sandy (2012). Sandy was a tropical cyclone that transitioned to a very large, strong post-tropical storm. ESTOFS was designed primarily to model extraptropical storm surges because of two reasons. First, the 0.5 degree GFS fields used do not presently contain sufficient resolution to adequately resolve cyclone structure. Second, considering the uncertainties in hurricane track and intensity, probabilistic approaches are preferred for tropical cyclone prediction. Since ESTOFS is driven by the output of a single deterministic GFS run, it is currently best suited to extratropical applications. Nonetheless, as a tropical cyclone approaches landfall, the uncertainties in track and intensity decreases significantly, so that single forecast fields become

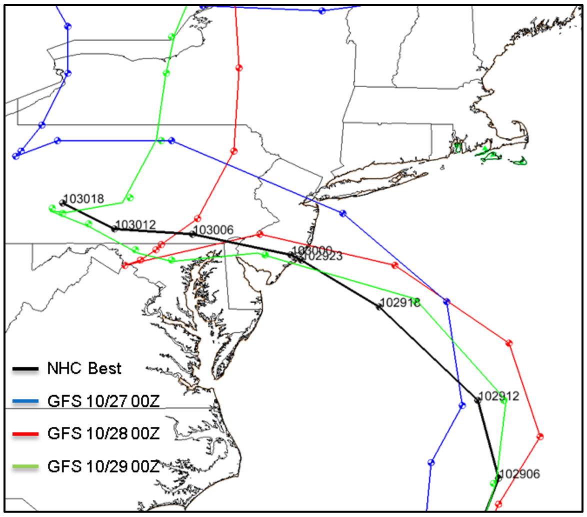

Figure 3: Various forecast tracks from GFS for the three days leading up to Superstorm Sandy landfall, as well as the NHC best track.

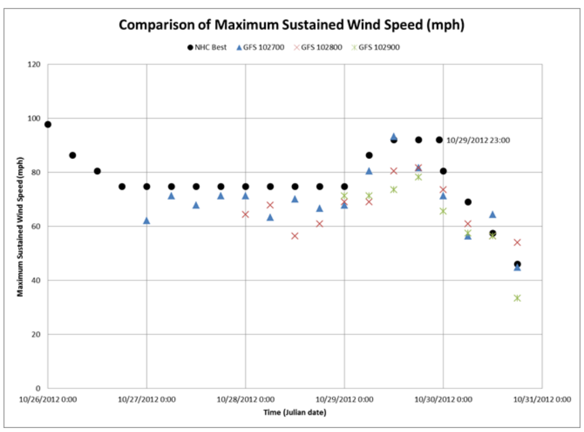

Figure 4: Comparison of maximum sustained wind speed produced by GFS for the three days leading up to Superstorm Sandy landfall, as well as the NHC best estimate.

more reliable. Despite these reservations, we will show here that ESTOFS, being forced by a series of GFS forecast prior to landfall, yields accurate surge forecasts, and that these improve proportional to the decrease in uncertainty in the wind forcing fields.

Figure 3 shows the cyclone tracks produced by GFS in the three daily 00z forecasts leading up to the October 29 landfall of Superstorm Sandy near Atlantic City, NJ. Also shown is the best track issued by NHC for this event. It can be seen that the track prediction skill of GFS improves as the lead time to landfall

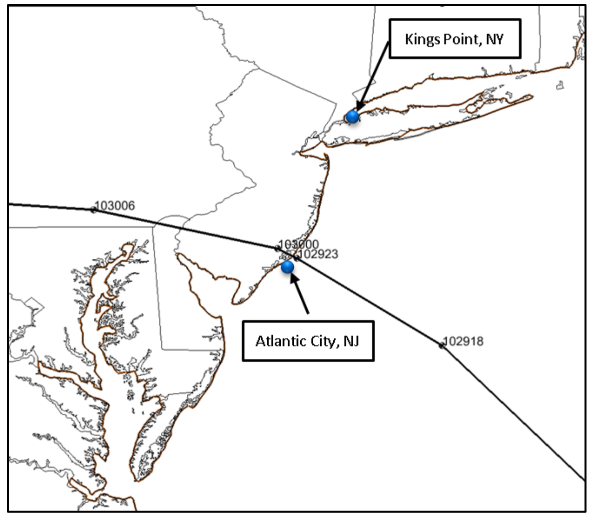

Figure 5: Coastal analysis locations relative to the NHC best track. Thick line indicates the model boundary of the ESTOFS unstructured grid, and thin line the actual coastline.

decreases, as expected. Figure 4 compares the maximum sustained wind speed predictions produced by GFS ahead of landfall with the NHC best estimate. Again, the GFS wind speed predictions improve closer to the time of landfall, as expected.

Figure 5 shows the location of two water level stations along the NY/NJ coast relative to the NHC best track, namely Kings Point, NY, at the western end of Long Island Sound, and Atlantic City, NJ. Note also in this figure that the ESTOFS grid does not include all features of the coastline, due to limited extent and resolution. Notice, in particular, Upper New York Harbor are excluded from the ESTOFS grid at present.

Figures 6 through 9 compare the ESTOFS results at Kings Point and Atlantic City against the observed water levels from these CO-OPS stations. In each case, the results are divided into the surge only component (combined water level minus harmonic tide, Figures 6 and 8), and the combined water level (Figures 7 and 9). In all of these cases, the accuracy of the ESTOFS water level predictions (surge and combined) consistently improves as the time to landfall reduces. As such, the forecast run of 10/29/2012 00z shows very good agreement with the observed water levels, for both the surge and combined levels.

From these results it can be concluded that ESTOFS performed well during Superstorm Sandy, provided that the uncertainty in the meteorological forcing fields was low, as was typically the case near landfall.

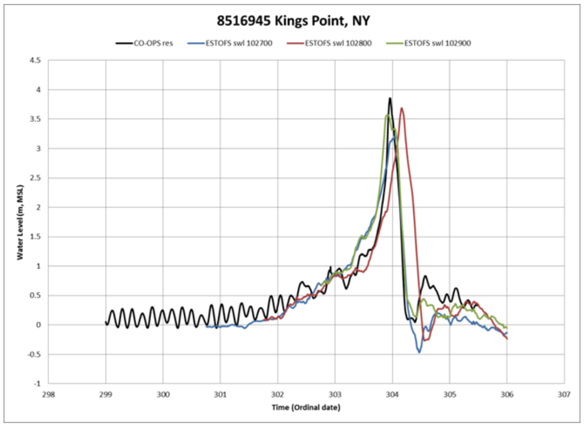

Figure 6: ESTOFS Subtidal Water Level at Kings Point, NY, for one forecast cycle for each of the 3 days leading up to landfall

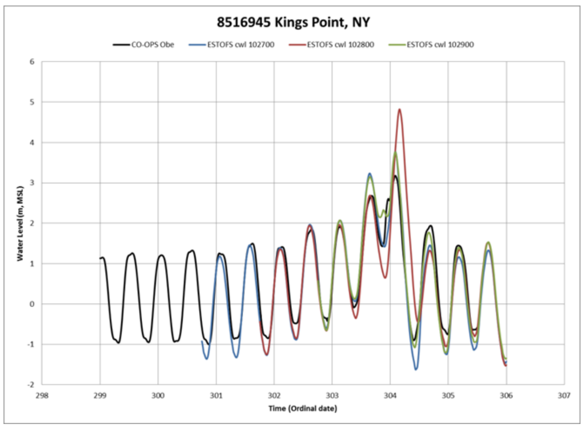

Figure 7: ESTOFS Combined Water Level at Kings Point, NY, for one forecast cycle for each of the 3 days leading up to landfall.

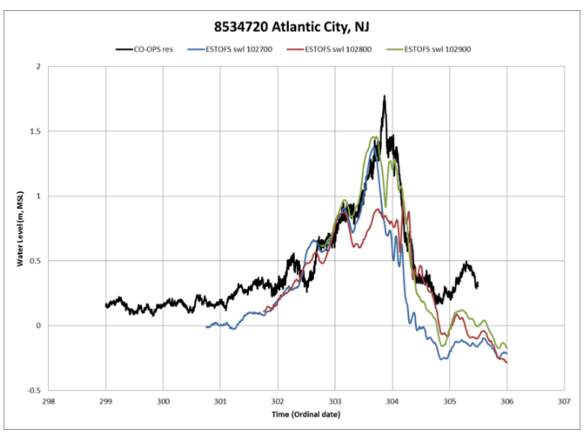

Figure 8: ESTOFS Combined Water Level at Atlantic City, NJ, for one forecast cycle for each of the 3 days leading up to landfall.

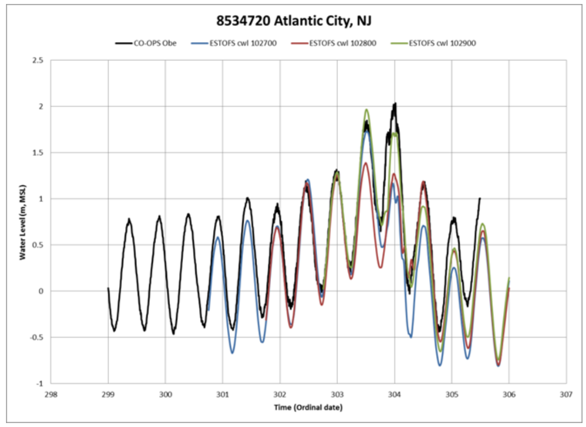

Figure 9: ESTOFS Combined Water Level at Atlantic City, NJ, for one forecast cycle for each of the 3 days leading up to landfall.

5. CONCLUSION

This paper described the establishment of ESTOFS, an operational extratropical surge and tide model based on the community model ADCIRC. The modeling system has been implemented operationally over the U.S. Atlantic and Gulf of Mexico coasts using the EC2001 grid. Based on the hindcast assessments carried out, the following can be concluded:

- ESTOFS yields a satisfactory performance against the NOS skill assessment criteria (e.g. an RMS error in total water level of less than 0.20 m), and is therefore considered suitable as operational forecast guidance.
- Even though ESTOFS is has been designed for extratropical application (due to its use of deterministic input), the system performed well for the Superstorm Sandy case, particularly as the storm became post-tropical as it approached landfall.

Future plans for ESTOFS include the expansion of the system to the Pacific coast, including the U.S. West Coast, Alaska and Hawaii, which is currently under development. In addition, the nearshore coverage and resolution of the current Atlantic and Gulf of Mexico implementation will be increased in order to provide reliable estimates of surge levels in smaller bays and harbors. Finally, additional ensemble members which are driven by different wind forcing will be added to enable forecasters to assess uncertainty in model guidance and improve predictions.

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