Towards Predicting Street-Level Inundation: using Operational Forecast Modeling Techniques during 2011 Hurricane Irene

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INTRODUCTION

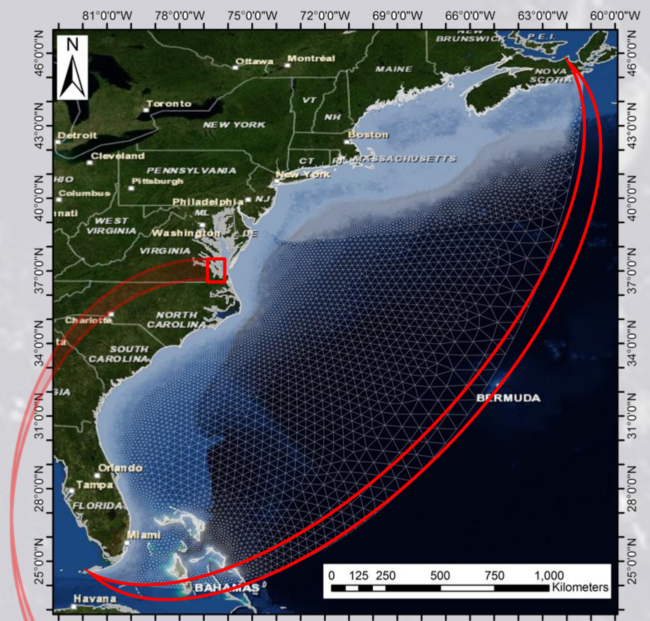
Coastal flooding initiated by storm surge and river discharge during hurricanes and Nor'easters along the U.S. East Coast is a substantial threat to residential properties, community infrastructure, and human life. Very high-resolution, accurate flooding prediction at the street-level is highly desirable.

The traditional methods for universally decreasing the scale of a model grid to achieve street-level resolution is constrained by computational limitations. As an ideal alternative that is well-suited for forecast predictions, the sub-grid modeling approach enables the model to cover a large domain with reasonable resolution while simultaneously allowing an embedded sub-grid to resolve fine-scale features efficiently. Key elements involved in this study are outlined below:

- Large-scale forecast simulations during 2011 Hurricane Irene were performed using the state-of-the-art open-source SCHISM model for the entire U.S. Eastern Seaboard and provided to emergency managers before the event.
- A fine-scale sub-grid model was driven using SCHISM model predictions at the mouth of the Elizabeth River Estuary.
- In order to increase accuracy of inundation simulation predictions:
  - The sub-grid model will be coupled with high-resolution Lidar-derived digital topography embedded within a 5m resolution sub-grid (Loftis, 2014; Wang *et al.*, 2015)
  - Buildings will be incorporated in the grid for the urban areas surrounding the Elizabeth River (Wang *et al.*, 2014; Loftis *et al.*, 2015)
- A general purpose wetting-and-drying scheme using an innovative nonlinear solver is incorporated in the sub-grid (Casulli, 2009; Casulli and Stelling, 2011).

STUDY SITES

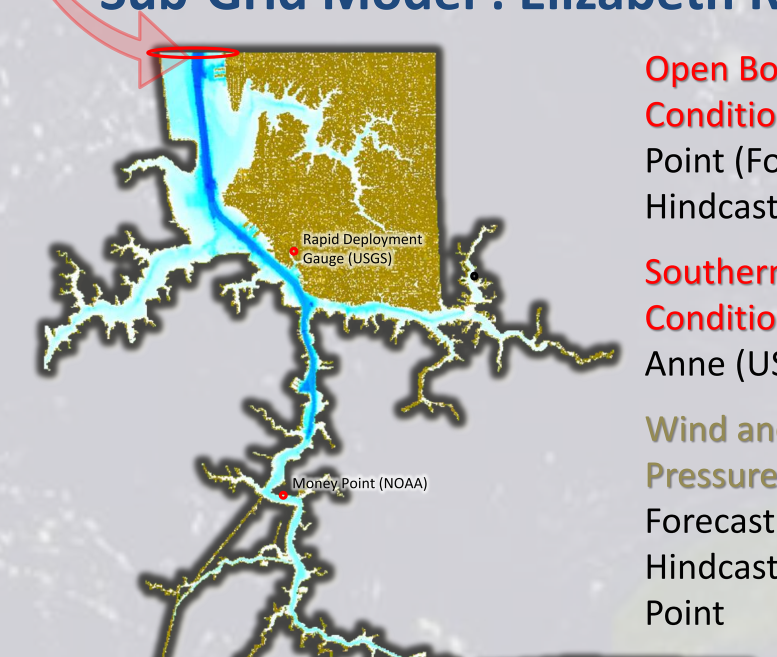
SCHISM Model Domain : U.S. East Coast



Open Boundary Condition Tidal Harmonics: M_2, S_2, N_2, K_2, O_1, P_1, K_1, Q_1, & M_4

Wind and Atmospheric Pressure Inputs from Forecast: National Weather Service Wakefield, VA GFS 12km spatial resolution; 3 hr temporal resolution Hindcast: Combined Inputs from Simulations

Sub-Grid Model : Elizabeth River



Open Boundary Condition at Sewells Point (Forecast: SCHISM Hindcast: NOAA)

Southern Flux Boundary Condition at Princess Anne (USGS)

Wind and Atmospheric Pressure Inputs from Forecast: SCHISM Hindcast: NOAA Sewells Point

ABSTRACT

Storm surge-induced coastal inundation poses numerous personal, commercial, industrial, and sociopolitical challenges for society. Flooding can be caused by the combination of storm surge and river-induced inland flooding in many locations throughout the coastal plain. The cross-disciplinary nature of the hydrodynamics involved (hydraulics, oceanography, and hydrology), coupled with the complexity of the atmospheric forcing, makes a numerical model the best approach for a comprehensive study of the dynamics of coastal inundation.

This study builds upon the lessons learned from forecast modeling experiences during 2011 Hurricane Irene in Tidewater Virginia, to ascertain the most effective way to approach predicting street-level inundation. During the storm event, a large-scale ocean model (SCHISM) was provided atmospheric forcing from the National Oceanic and Atmospheric Administration's Global Forecast System, updated every 6 hours to simulate 9 separate 30-hour simulations, which were provided to emergency managers and the National Weather Service in Wakefield, VA. Forecast water level predictions were evaluated at 5 stations near the Hampton Roads region in the Lower Chesapeake Bay to yield an aggregate RMSE=19.9 cm.

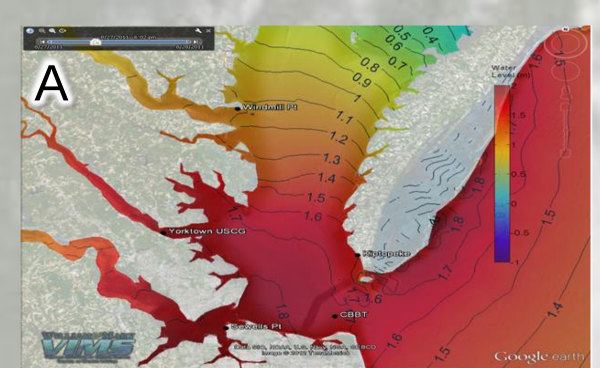
To accurately predict street-level inundation, water elevations at key points near the mouths of vulnerable tributaries can be used to drive a separate street-level high-resolution sub-grid model (UnTRIM) to simulate localized flooding events on the scale of 5-meter resolution. To this end, high-resolution Digital Elevation Models including building and roadway infrastructure were developed from Lidar-derived topography for the Hampton Roads Region of Virginia, and used to accurately predict flooding in low-lying areas of the Cities of Norfolk, Portsmouth, and Chesapeake along the Elizabeth and Lafayette Rivers. Additionally, grids were prepared for the City of Virginia Beach along the Lynnhaven River, and along Hampton, York, and Poquoson along the Back River. Tropical storm surge flood heights were validated via temporal comparison with water level observations from NOAA, the USGS, and NASA; aggregated to an average RMSE=0.18 cm. Spatial extent of flooding was evaluated using USGS data retrieved from high water marks and from rapid deployment overland water level gauges during Hurricane Irene to reveal favorable agreement with the model's inundation predictions.

METHODOLOGY

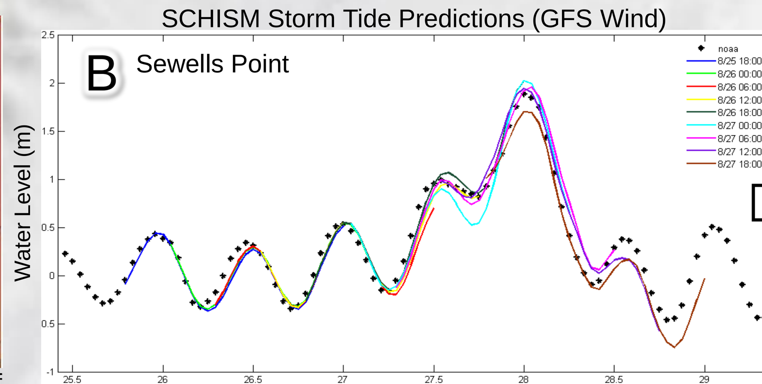
This study embodies a two-pronged approach to achieving street-level (≤ 5m resolution) forecast model results:

1) The large-scale SCHISM Model was used to run 9 successive 30-hour forecast simulations (6 hours apart; updating with latest forecast wind and pressure predictions) and pass the A) animated water level maps, and B) time series predictions and from each forecast to emergency managers

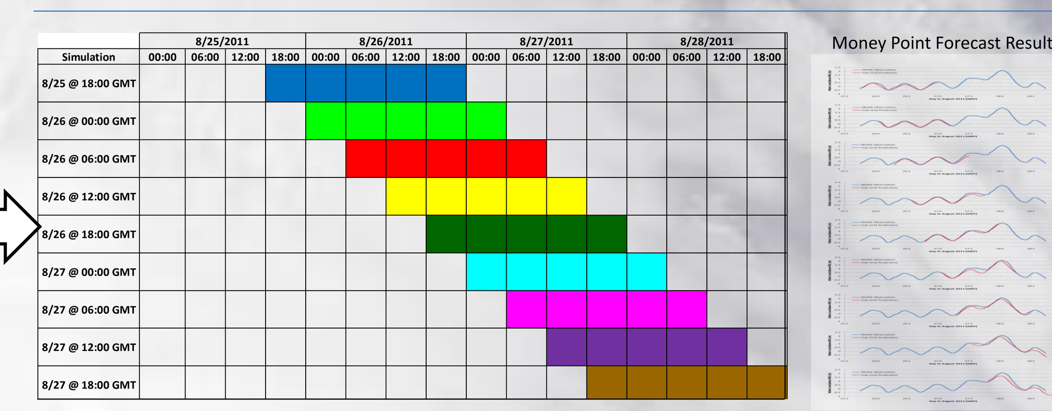
2) A Street-Level Sub-Grid Inundation Model was used to predict inundation at 5m spatial resolution throughout the Elizabeth River Estuary using modeled forecast results retrieved from Sewells Point in SCHISM



Google Earth Animation Still showing locations of 5 NOAA Gauges on 8/27/2011 at 6:02PM GMT



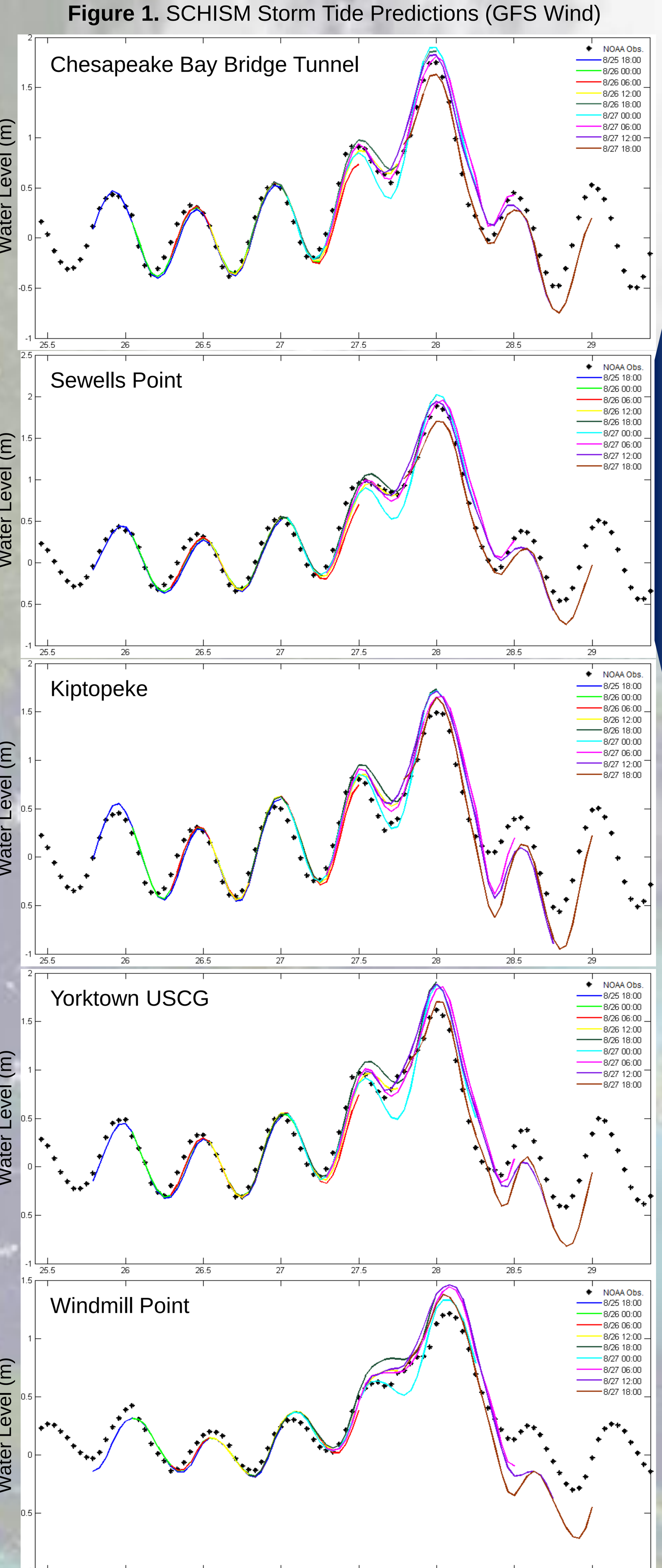
Day in August 2011 starting at 10:00 GMT



SCHISM Forecast Results used to drive Sub-Grid Predictions for Street-Level Inundation

RESULTS

Figure 1. SCHISM Storm Tide Predictions (GFS Wind)



Day in August 2011 starting at 10:00 GMT

Figure 2. Street-Level Inundation Model Results at Money Point driven via SCHISM's Sewells Point Forecast during 2011 Hurricane Irene

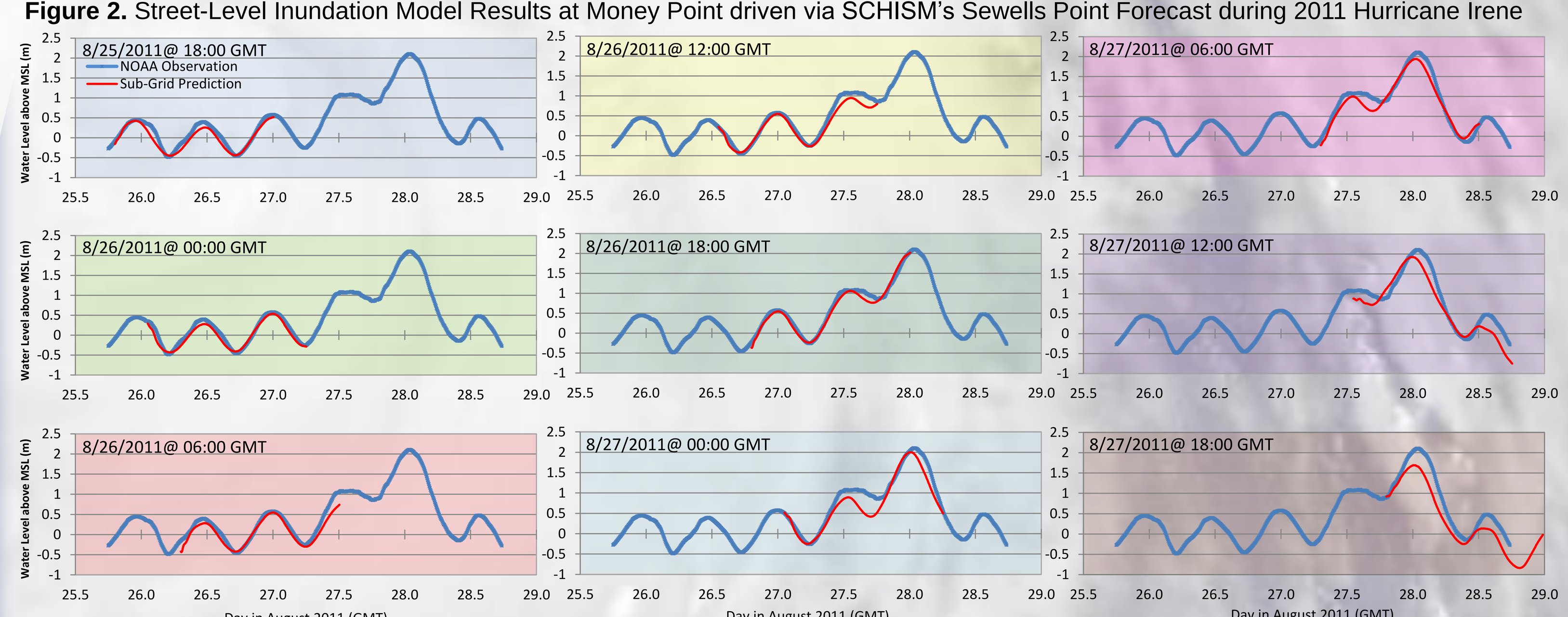
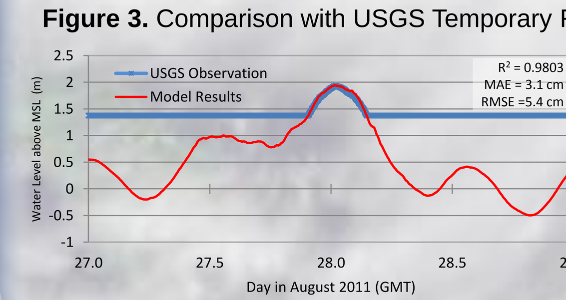


Figure 3. Comparison with USGS Temporary Rapid Deployment Gauge near the intersection of Fairfax Avenue and Mowbray Arch



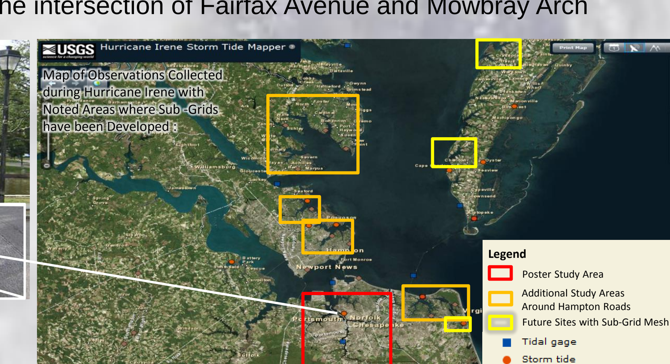


Figure 4. Still Frames of Flood Animations around Norfolk and Chesapeake

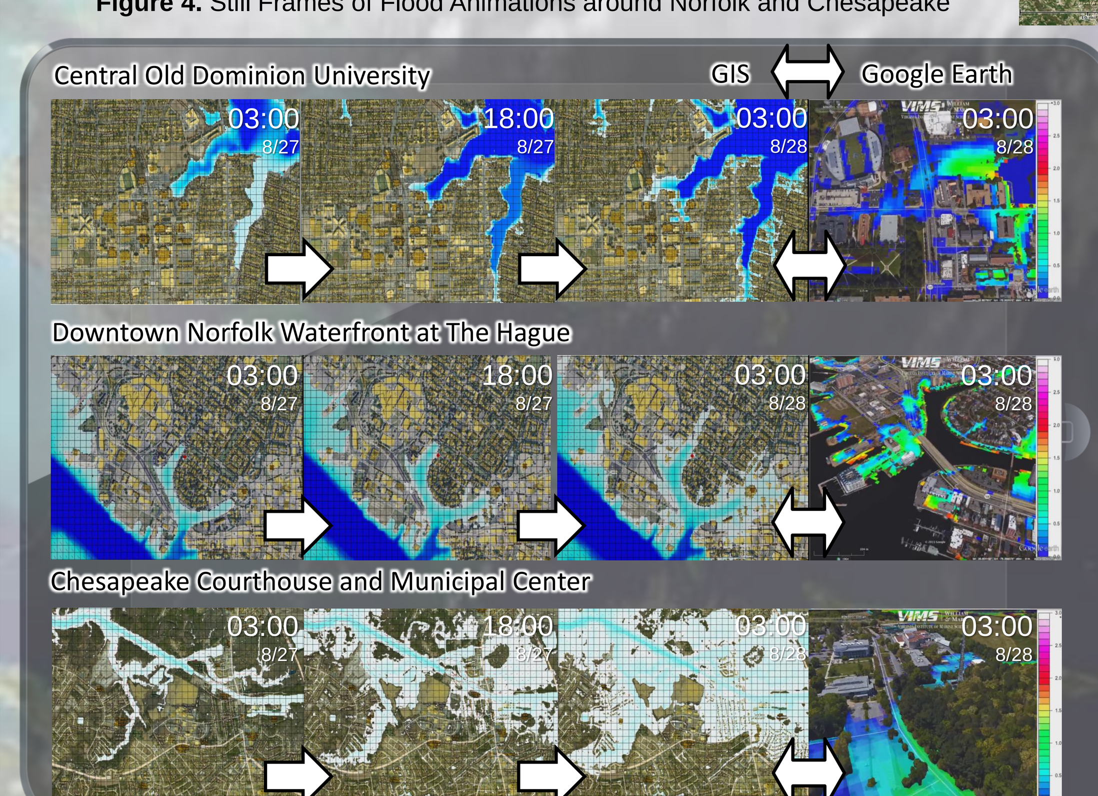


Figure 5. Computational Performance Metrics

SCHISM

Pre-Processing **(10 minutes)**
to download GFS atmospheric model results at 12km resolution to cover the model domain to use as SCHISM model forcing

Model Simulation **(40 minutes)**
to run SCHISM in 2D barotropic mode in parallel for each 30-hour forecast using 64 processors (Dell SC1435 chipset) available on the Typhoon sub-cluster of the SciClone heterogeneous high-performance computing platform at The College of William & Mary (in 2011).

Post-Processing **(25 minutes)**
to post-process zoom-able Google Earth maps and time-series results for 5 stations in the Lower Chesapeake Bay and send to emergency managers during the forecast event

Total SCHISM Time: ***75 minutes***

Street-Level Sub-Grid Model

Pre-Processing **(2 minutes)**
for Matlab scripts to extract hourly model results at Sewell's Point from SCHISM binary results and interpolate to 6-minute hydrodynamic and atmospheric inputs to drive Street-Level Sub-Grid Model on local PC

Model Simulation **(5 minutes)**
to run the Street-Level Sub-Grid Model for each 30-hour forecast on a Dell T3500 PC Workstation with Windows 7 Professional (64-bit edition) using an Intel Xeon Quad Core X5570 Processor (2.93GHz); with 24GB RAM

Post-Processing **(15 minutes)**
to post-process the time-series results for Money Point and Rapid Deployment Gauge site(s) along with zoom-able Google Earth and GIS inundation maps for Norfolk and the Elizabeth River

Total Street-Level Sub-Grid Model Time: ***22 minutes***

Overall Forecast Time: 97 minutes

DISCUSSION

SCHISM Storm Tide Predictions in the Lower Chesapeake Bay during 2011 Hurricane Irene

- Water Levels at 5 Ches. Bay Tide Gauges **(Table 1):**

Station Name	R^2	MAE (cm)	RMSE (cm)
Chesapeake Bay Bridge Tunnel	0.9102	9.1	12.6
Sewells Point	0.9356	6.5	9.7
Kiptopeke	0.8389	21.3	24.8
Yorktown USCG	0.8818	16.6	19.4
Windmill Point	0.8519	20.8	23.2
Average	0.8837	14.9	17.9
Std. Dev.	0.0401	6.8	6.6

Street-Level Inundation Model Predictions at Money Point during 2011 Hurricane Irene

- Water Levels driven via SCHISM Forecast **(Table 2):**

Simulation #	Timeframe Start	R^2	MAE (cm)	RMSE (cm)
1	8/25/2011@ 18:00 GMT	0.9377	7.3	11.6
2	8/26/2011@ 00:00 GMT	0.9619	4.2	9.3
3	8/26/2011@ 06:00 GMT	0.9428	10.1	14.5
4	8/26/2011@ 12:00 GMT	0.9827	9.9	13.1
5	8/26/2011@ 18:00 GMT	0.9849	6.4	9.7
6	8/27/2011@ 00:00 GMT	0.9308	20.3	24.2
7	8/27/2011@ 06:00 GMT	0.9530	13.0	17.3
8	8/27/2011@ 12:00 GMT	0.9056	22.8	27.6
9	8/27/2011@ 18:00 GMT	0.8801	29.7	35.2
	Average	0.9422	13.7	18.1
	Std. Dev.	0.0341	8.6	9.0

- These results (RMSE=18.1 cm) make this modeling method is ideal for piggybacking (+22 minutes) on large-scale forecasting operations (Figure 5).

CONCLUSION

- SCHISM is capable of producing accurate storm tide water level predictions over a large area in an operational capacity; RMSE=17.9 cm (Loftis *et al.*, 2015).
- Sub-grid modeling can be successfully used in conjunction with SCHISM as an efficient method to develop reliable street-level inundation predictions.
- This was verified (≤5m resolution) when compared with verified observation data (Figures 1-3).

ACKNOWLEDGEMENTS

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Finally, thank you to the Commonwealth of Virginia Innovative Technology Symposium for recognizing the merits of this research and awarding us with the Governor's Technology Award in Richmond in 2011:

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