Lessons Learned Forecast Modeling 2011 Hurricane Irene, and the Path to Predicting Street-Level Inundation

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VIMS | William & Mary
Virginia Institute of Marine Science
1940-2015 75 Years

Outline

I. Introduction

II. Large-Scale Storm Tide Forecast using SCHISM

   A. Model Setup

   B. Results

III. Street-Level Flood Forecasts via Sub-Grid Modeling

   A. Model Setup

   B. Results

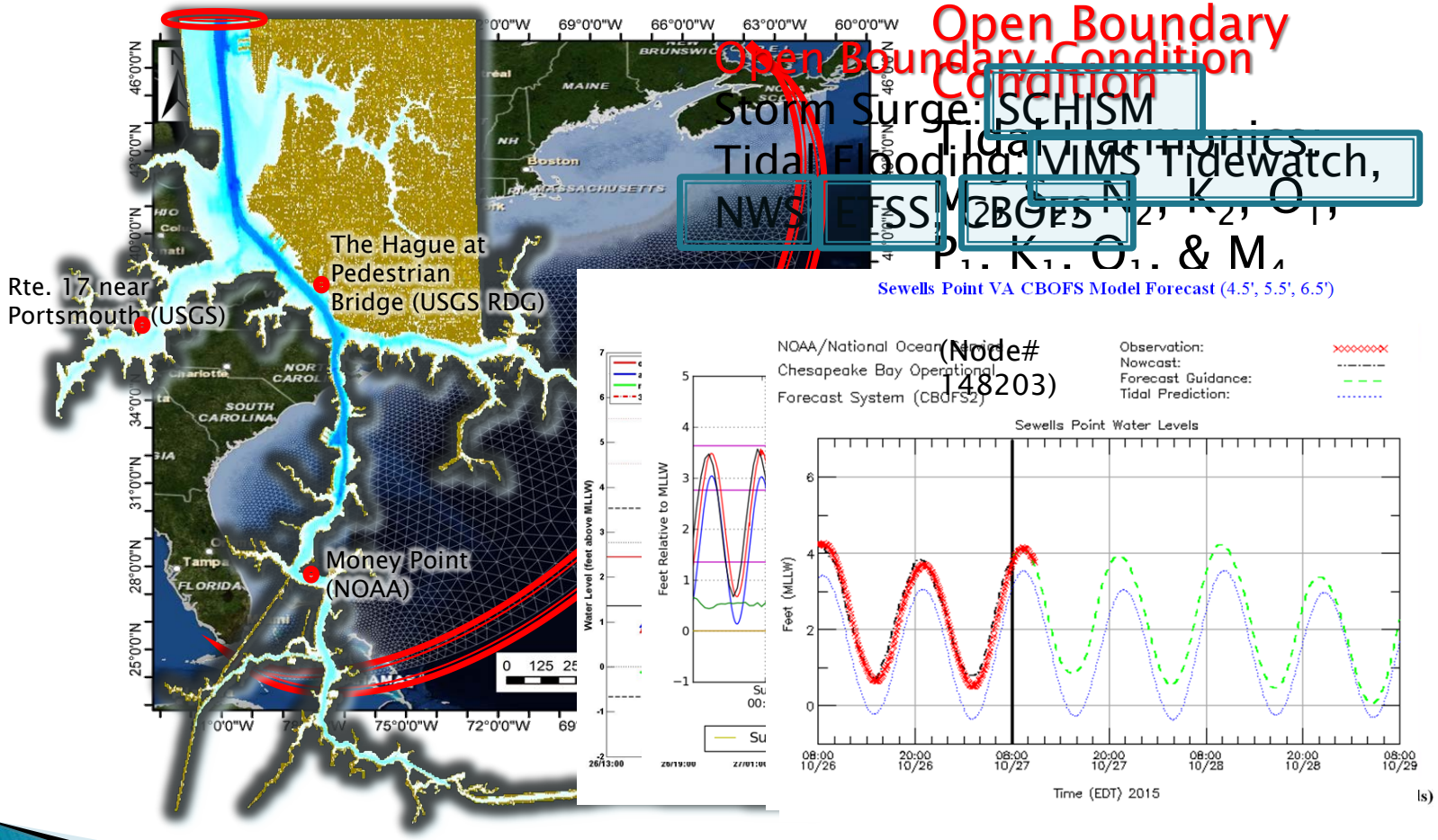
IV. Future Applications and Model Validation Methods

V. Conclusions

I. Introduction

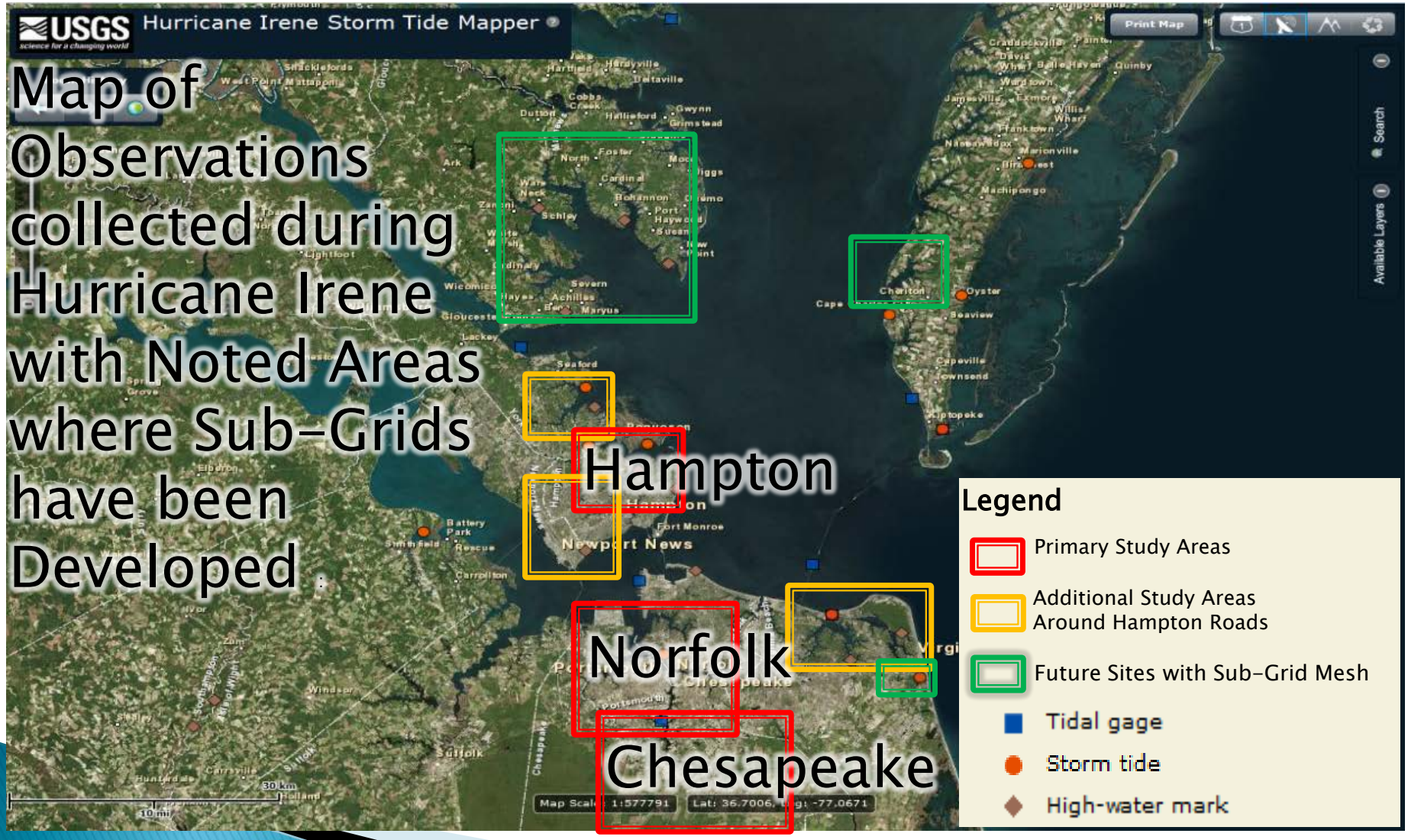
SCHISM-Coupled Domain Elizabeth River

SCHISM-Model Domain: U.S. East Coast



http://www.weather.gov/akq/SewellsPoint

I. Introduction

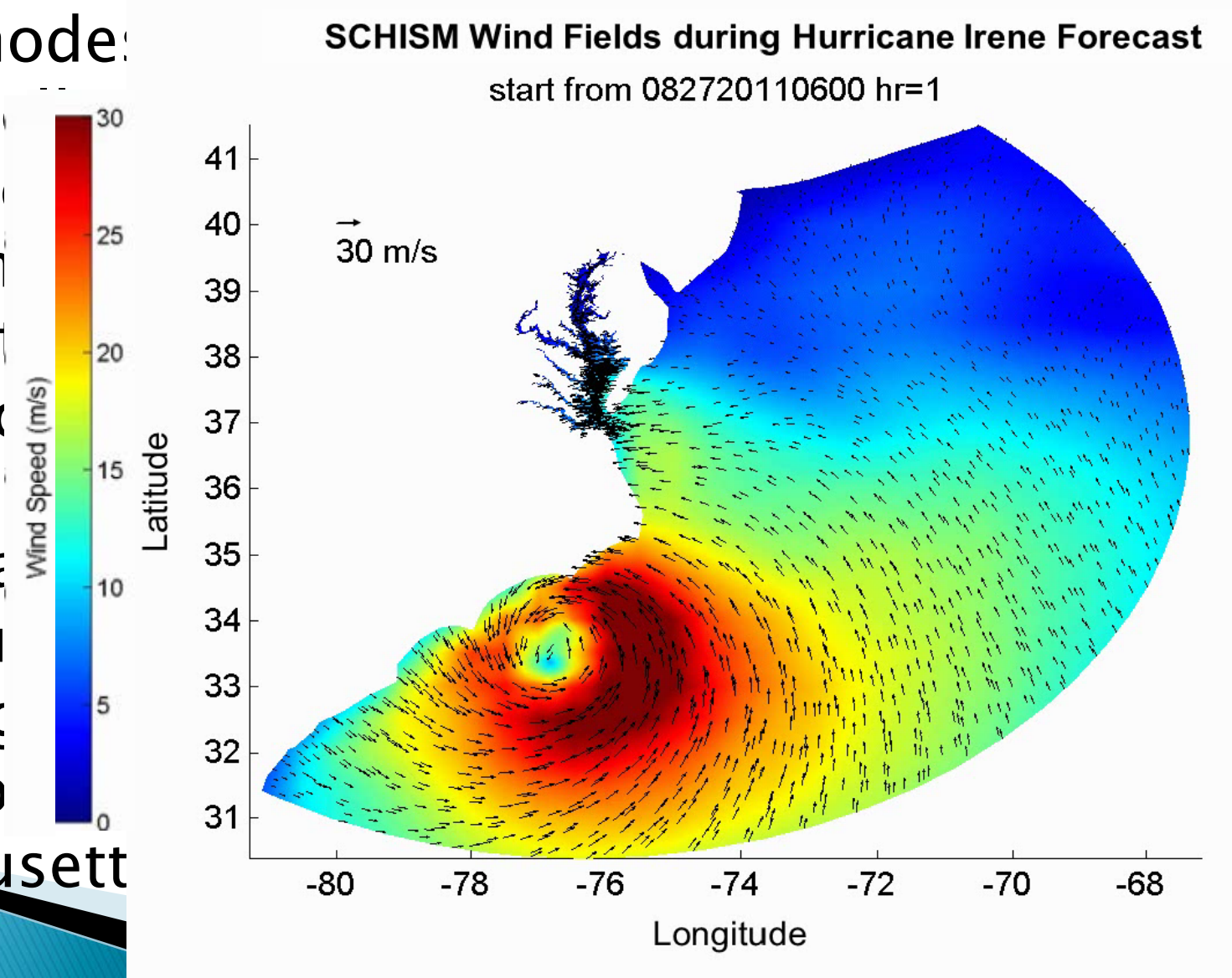


II. Large-Scale Storm Tide Forecast using SCHISM

- SCHISM (Semi-implicit Cross-scale Hydroscience Integrated System Model) is an open-source community-supported modeling system based on unstructured grids, designed for seamless simulation of 3D baroclinic circulation across creek-lake-river-estuary-shelf-ocean scales.
- Finite element/volume formulation
- Hydrostatic & non-hydrostatic options
- Unstructured mixed triangular/quadrangular grid in the horizontal dimension
- Hybrid SZ coordinates in the vertical dimension
- Semi-implicit time stepping (no mode splitting): no CFL stability constraints → numerical efficiency

A. SCHISM Large-Scale Domain

- 207,996 node
- 392,013 c
- Extends fr the U.S. sh line out in Atlantic Oc to 67°W
- Curvilinea open bou stretching Florida to Massachusett



SCHISM Model Inputs

- Nine separate 30-hour forecast simulations
- 6-hour update intervals starting on August 25, 2011 at 18:00 GMT as new Global Forecast Wind (GFS) products and pressure fields became available from the National Weather Service facility in Wakefield, VA
- Tide inputs were calculated separately for each 30-hour forecast via Xtide harmonic estimation and utilized as tidal boundary conditions for each unique forecast run for: M_2, S_2, N_2, K_2, O_1, P_1, K_1, Q_1, & M_4

Forecast #	Start Date	Start Time
1	8/25/2011	18:00 GMT
2	8/26/2011	00:00 GMT
3	8/26/2011	06:00 GMT
4	8/26/2011	12:00 GMT
5	8/26/2011	18:00 GMT
6	8/27/2011	00:00 GMT
7	8/27/2011	06:00 GMT
8	8/27/2011	12:00 GMT
9	8/27/2011	18:00 GMT

Surface and Bottom Stress

- Bottom Stress formulation

$$(\tau_{bx,}\tau_{by}) = \rho_0 C_{Db}\sqrt{u_b^2 + v_b^2}(u_b, v_b)$$

$$C_{Db} = \frac{gn^2}{h^{\frac{1}{3}}}$$

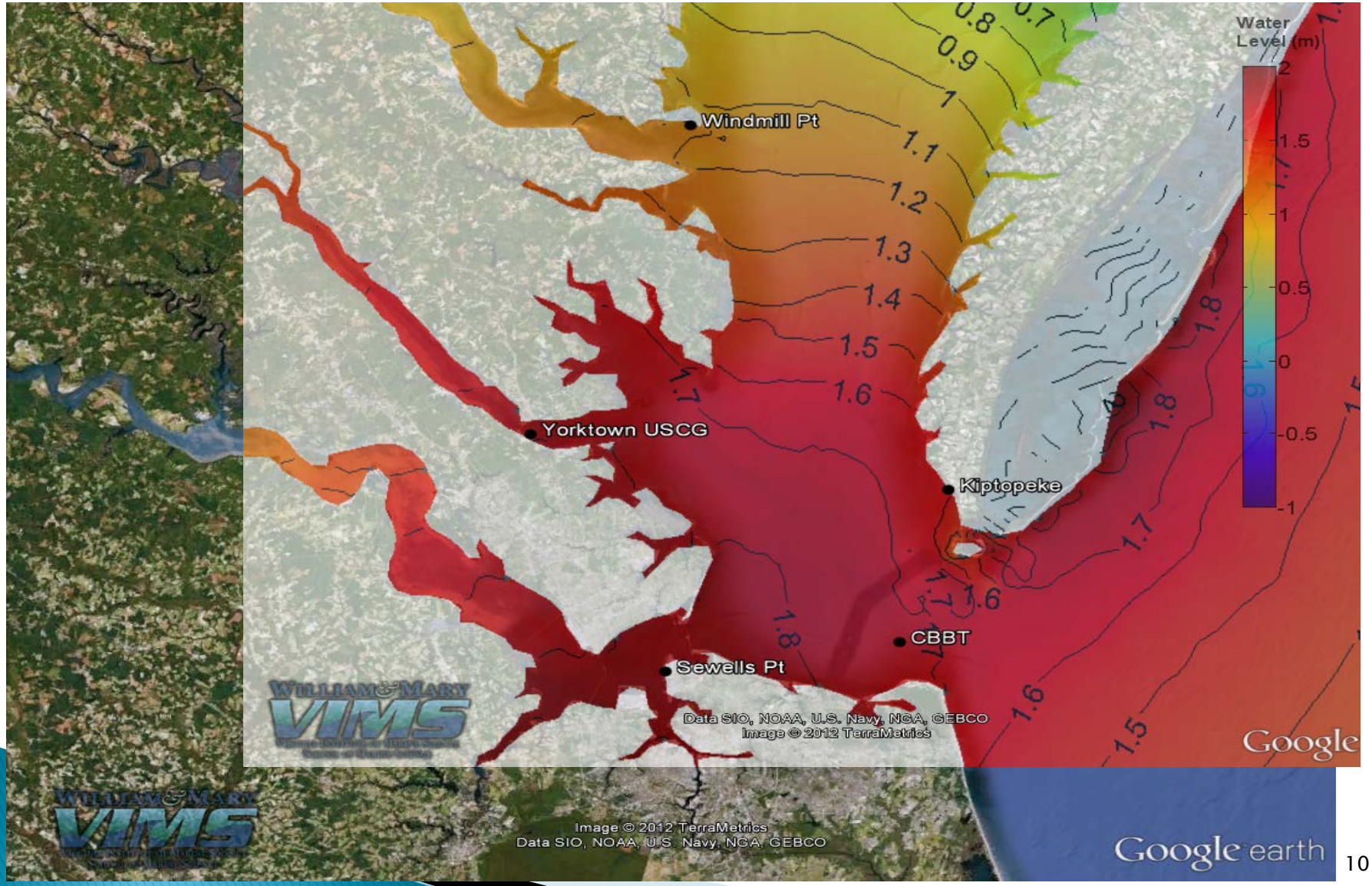
- Wind Stress formulation

$$(\tau_{Wx,}\tau_{Wy}) = \rho_a C_{Ds} |\overrightarrow{W}| (W_x, W_y)$$

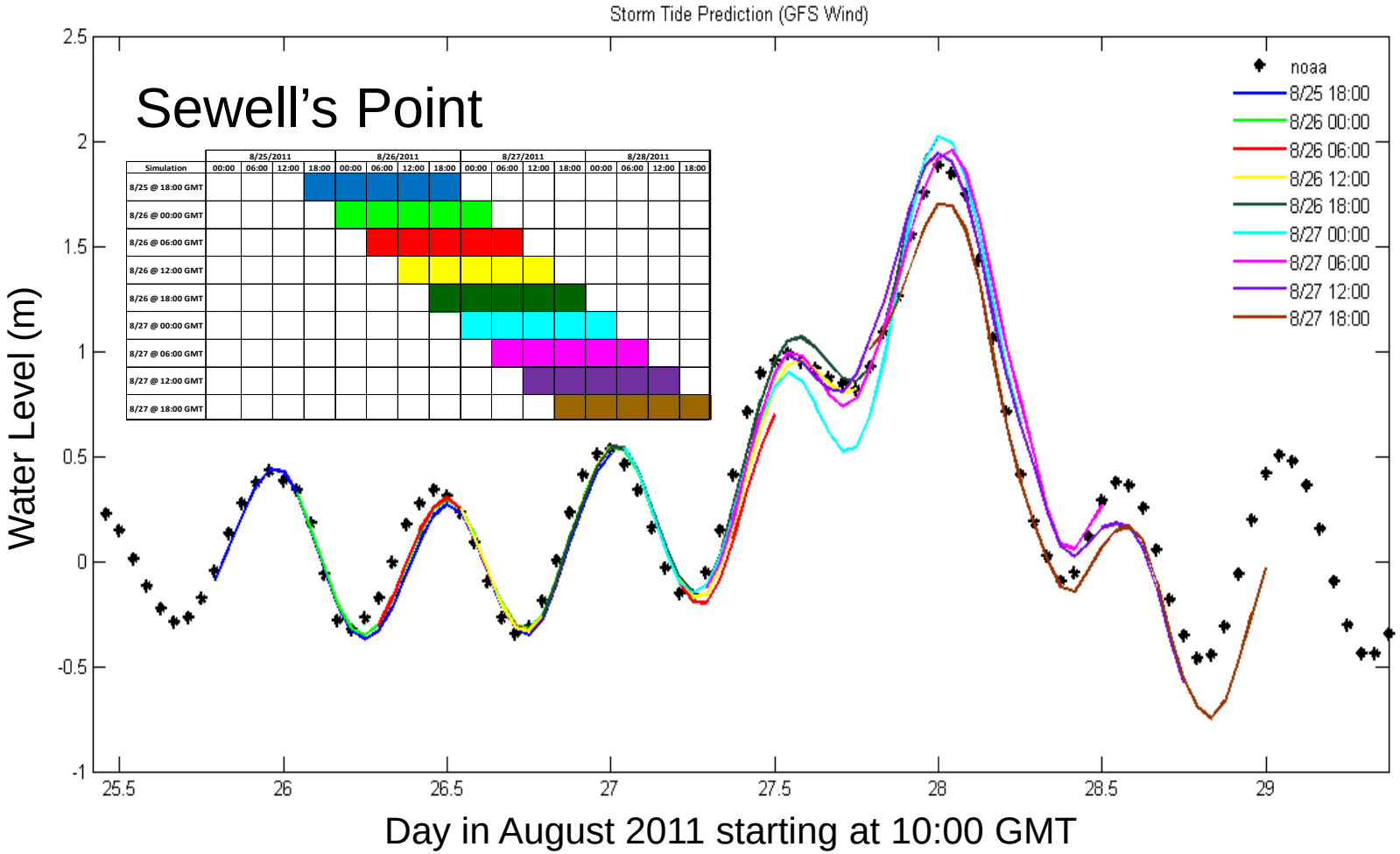
$$C_{Ds} = (0.49 + 0.065|\overrightarrow{W}|) \times 10^{-3}$$

$$(11m/s \le |\overrightarrow{W}| \le 33m/s)$$

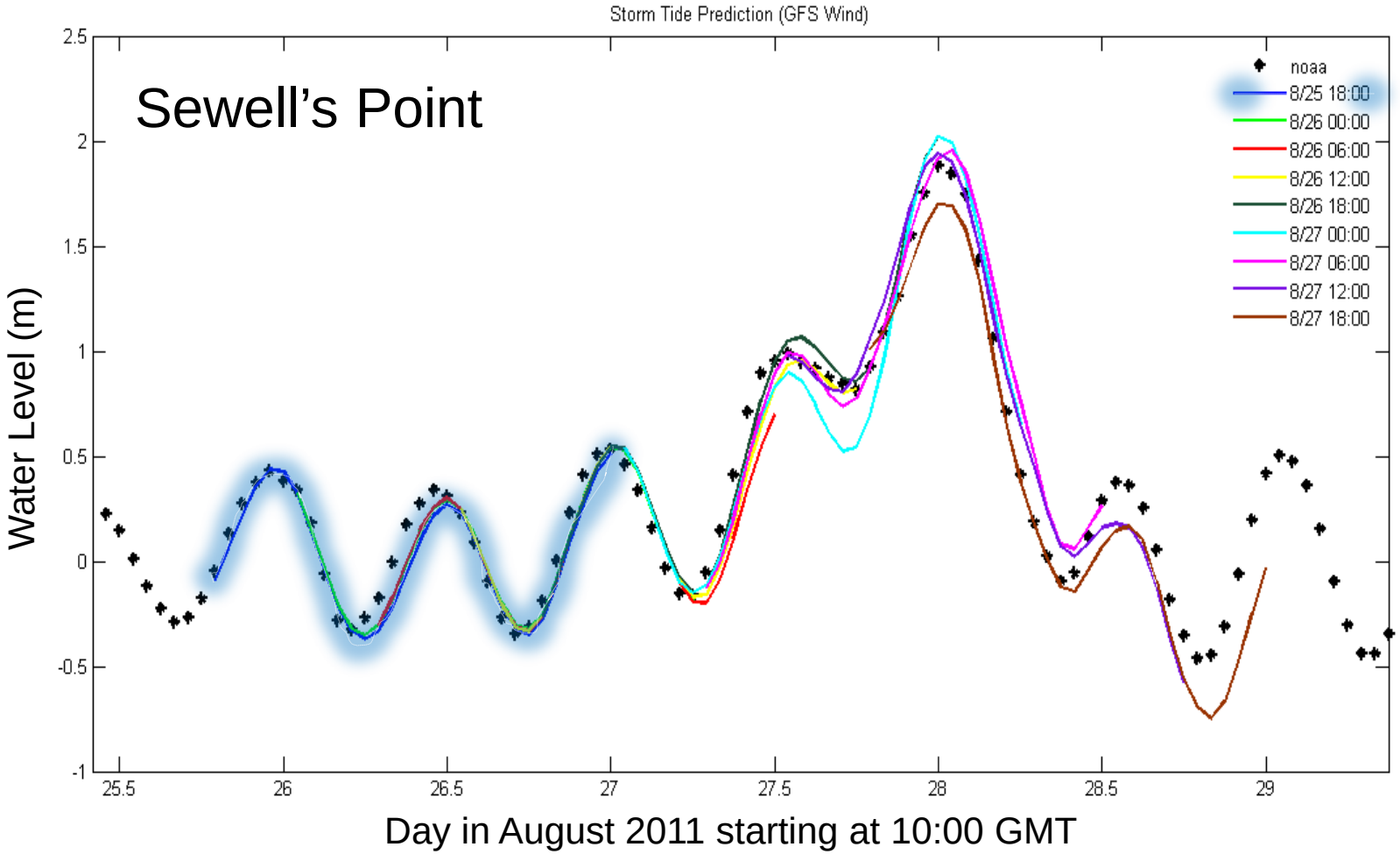
B. SCHISM Time Series Results



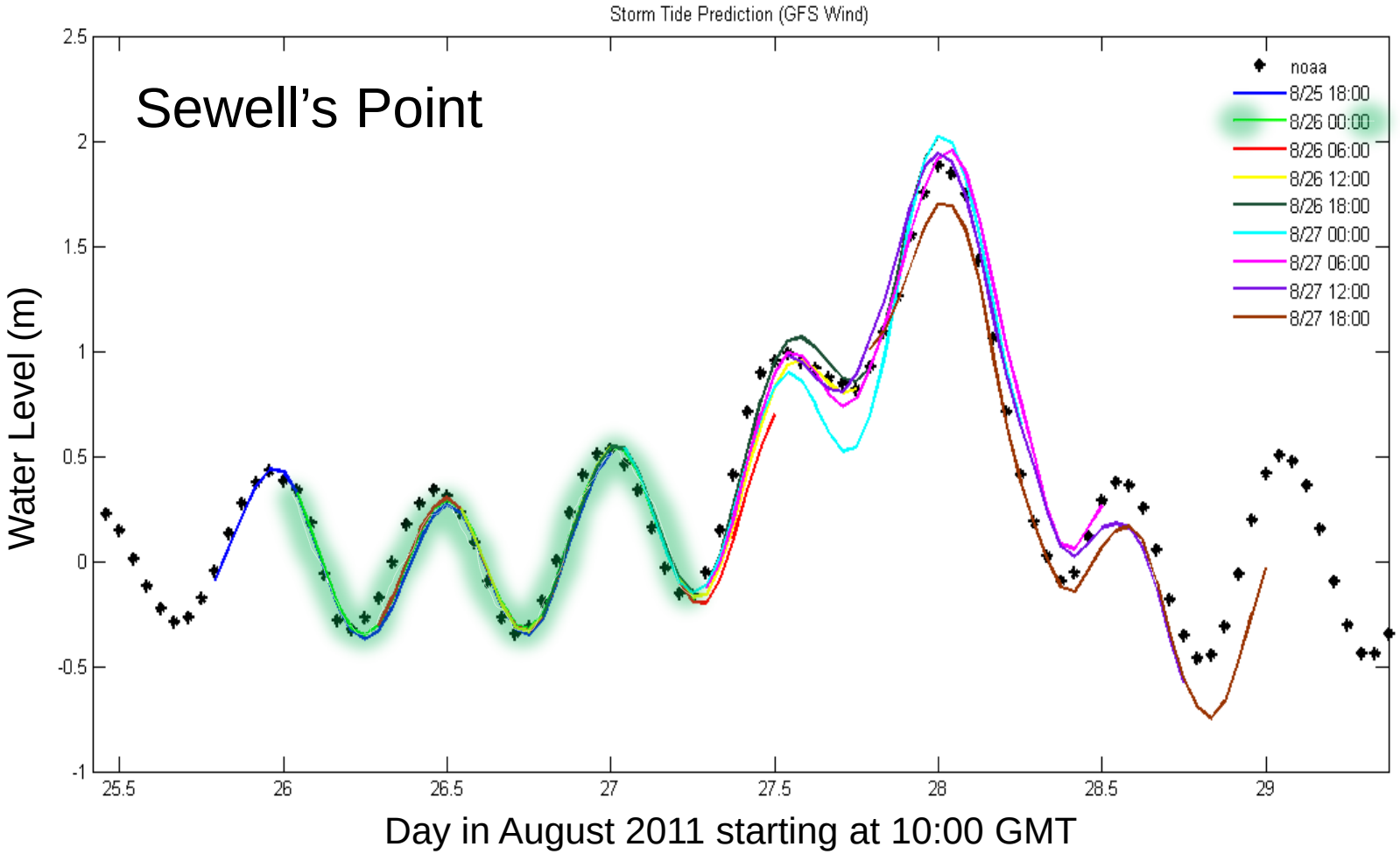
Hurricane Irene Forecast



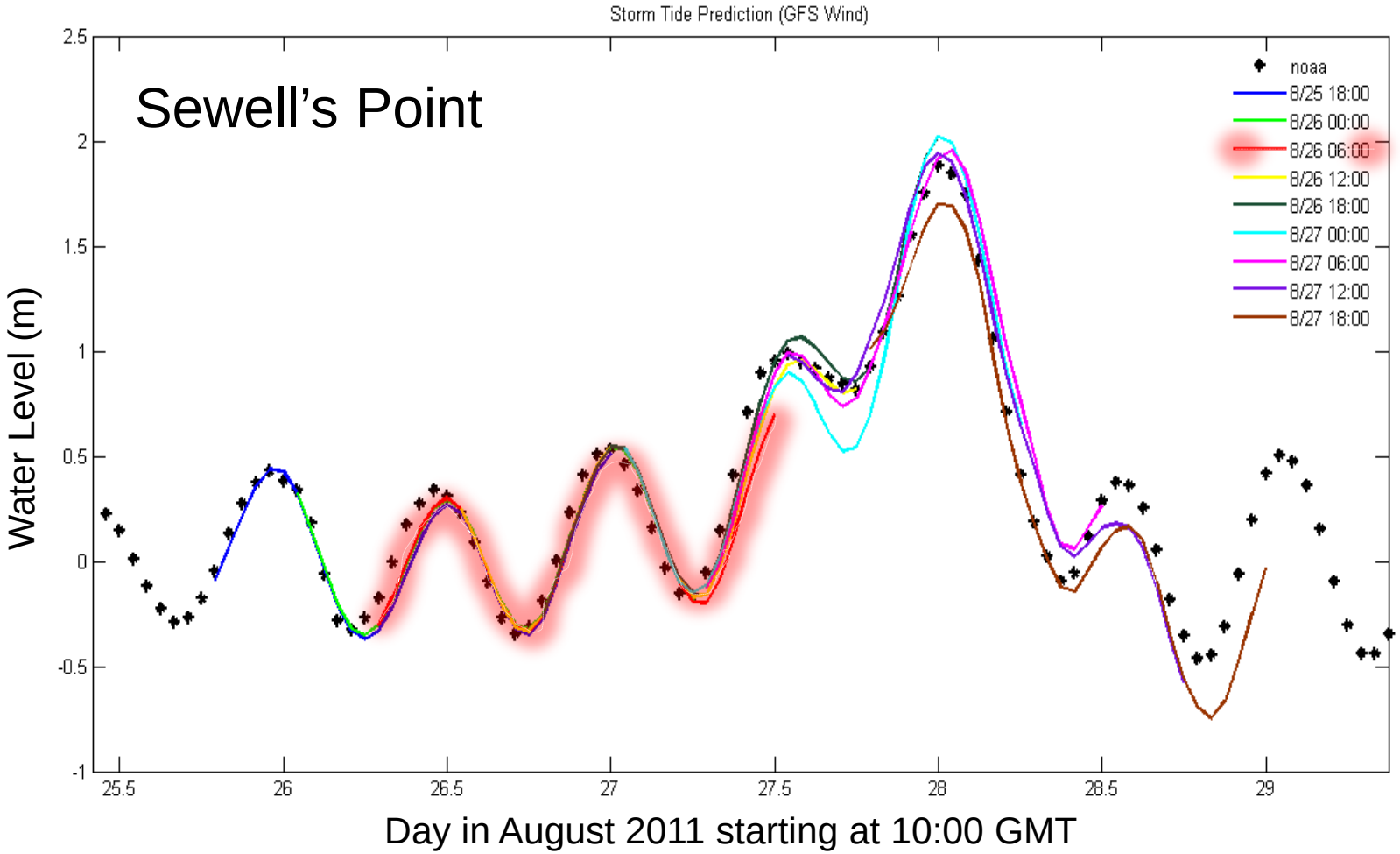
Hurricane Irene Forecast



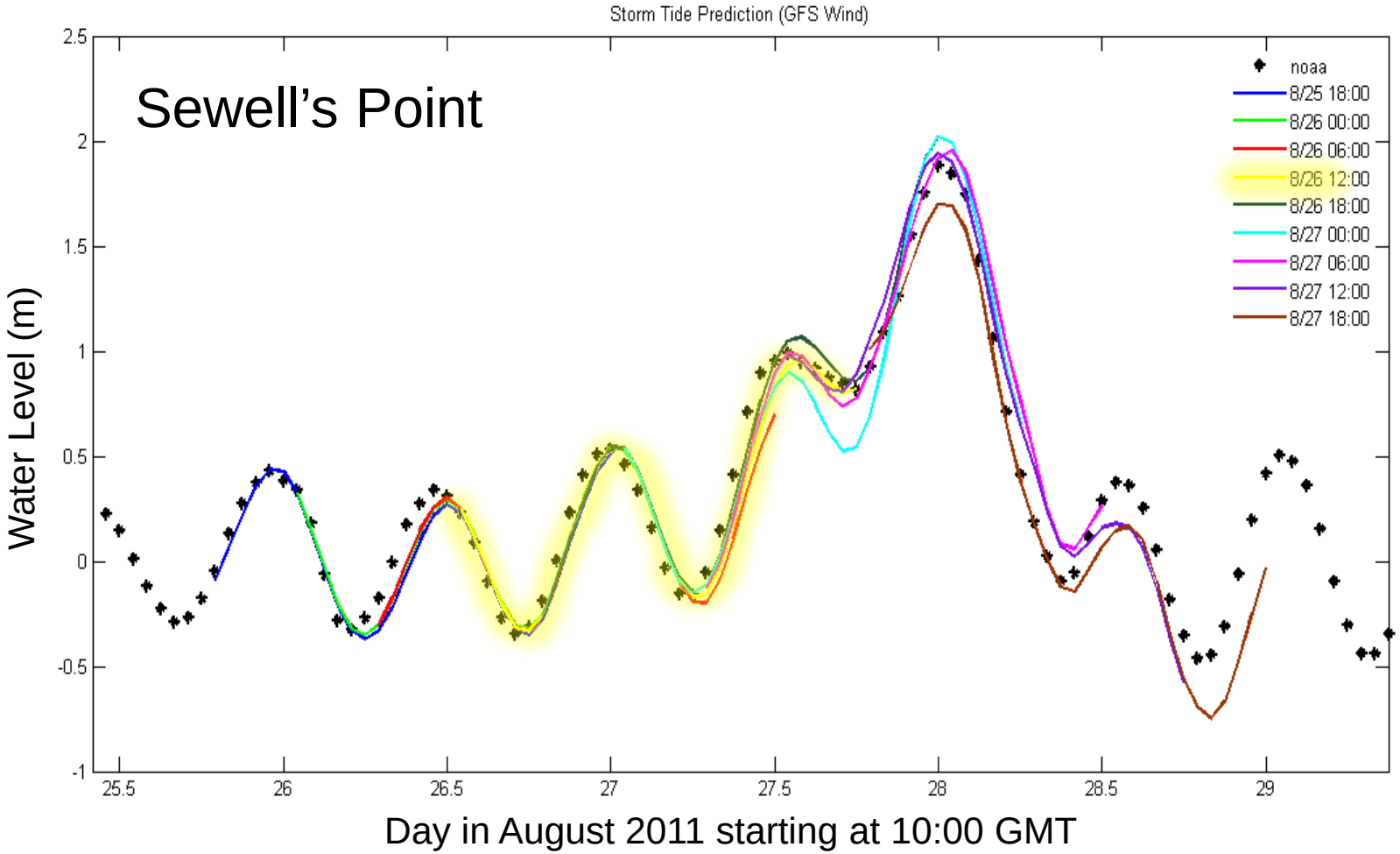
Hurricane Irene Forecast



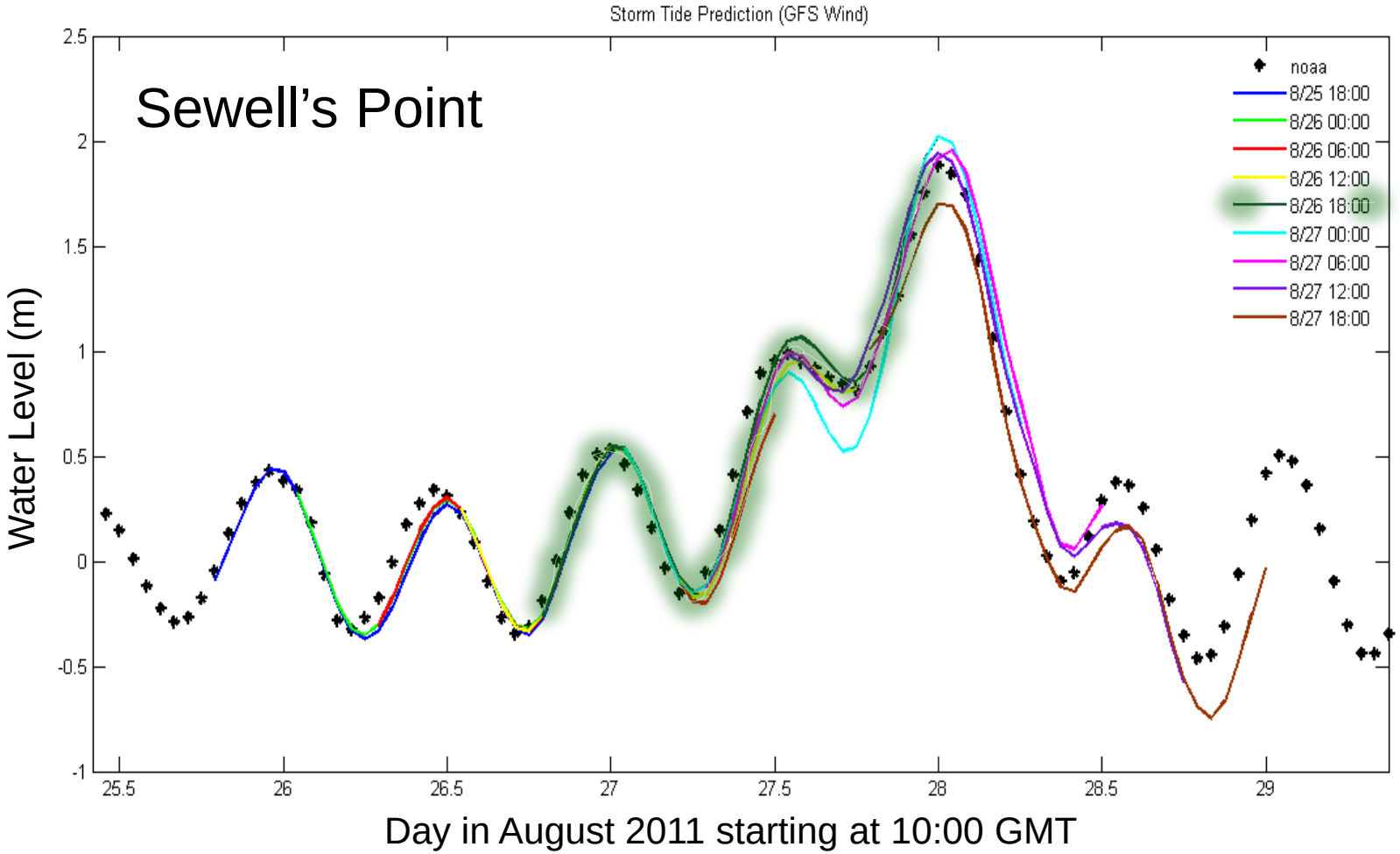
Hurricane Irene Forecast



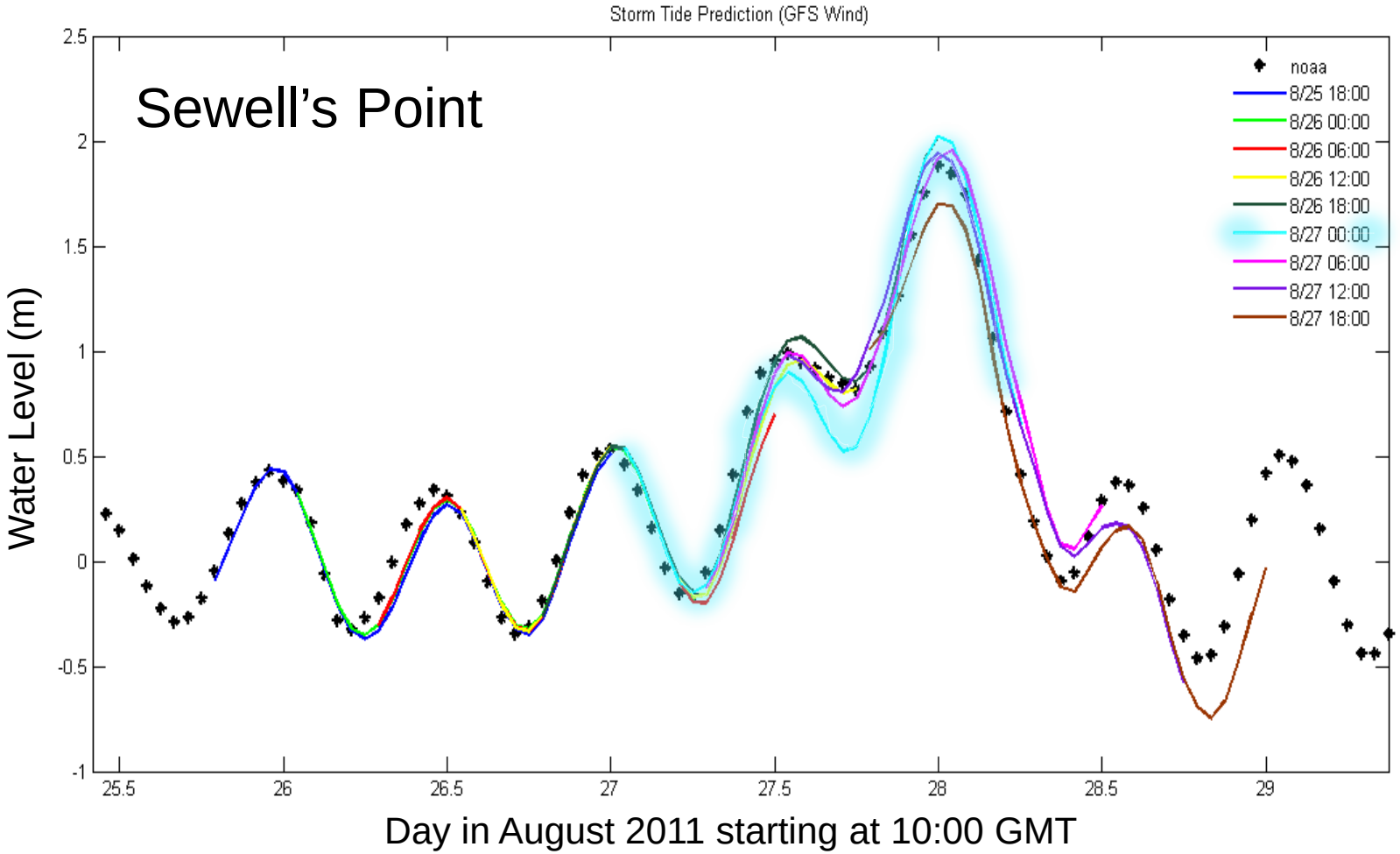
Hurricane Irene Forecast



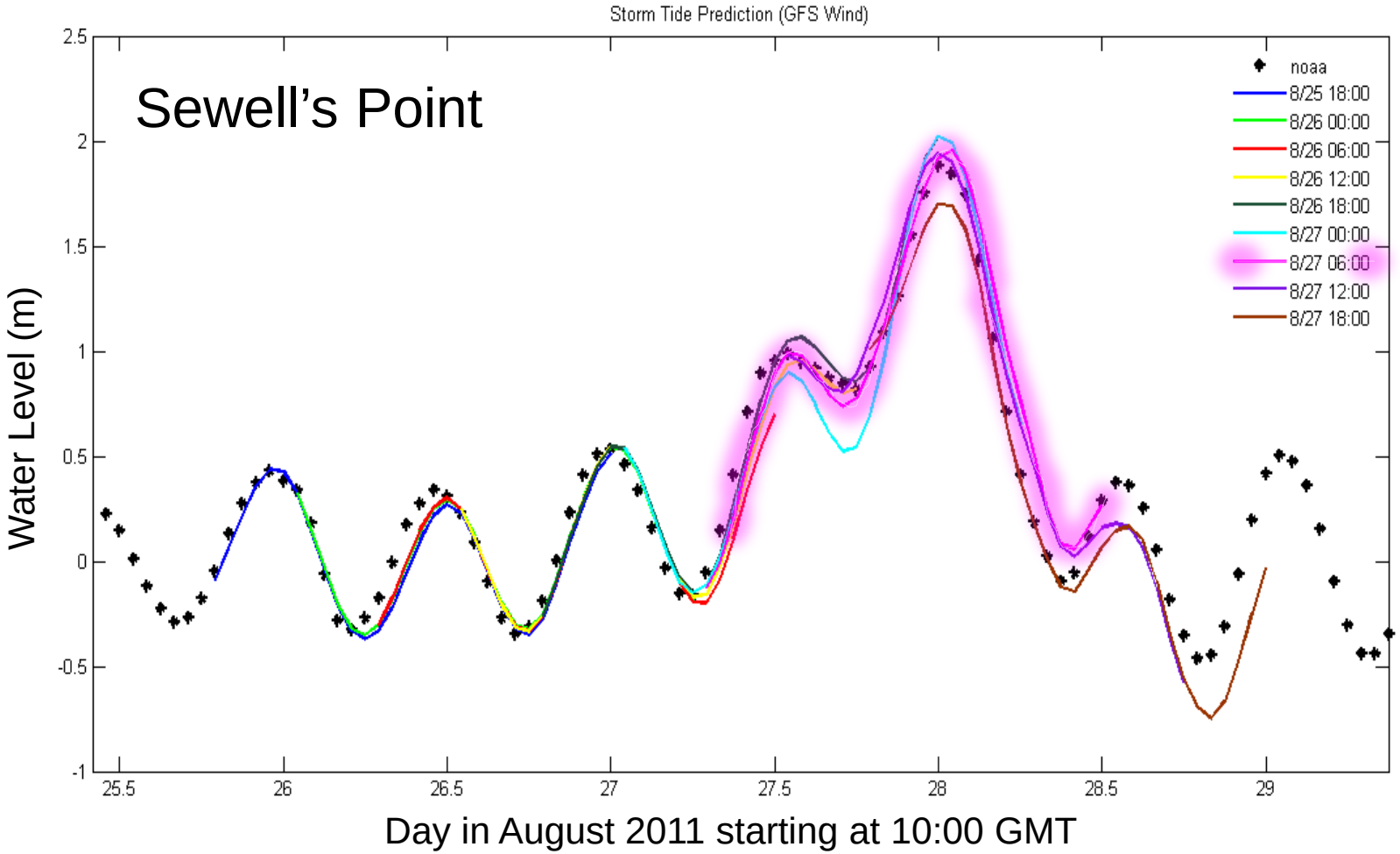
Hurricane Irene Forecast



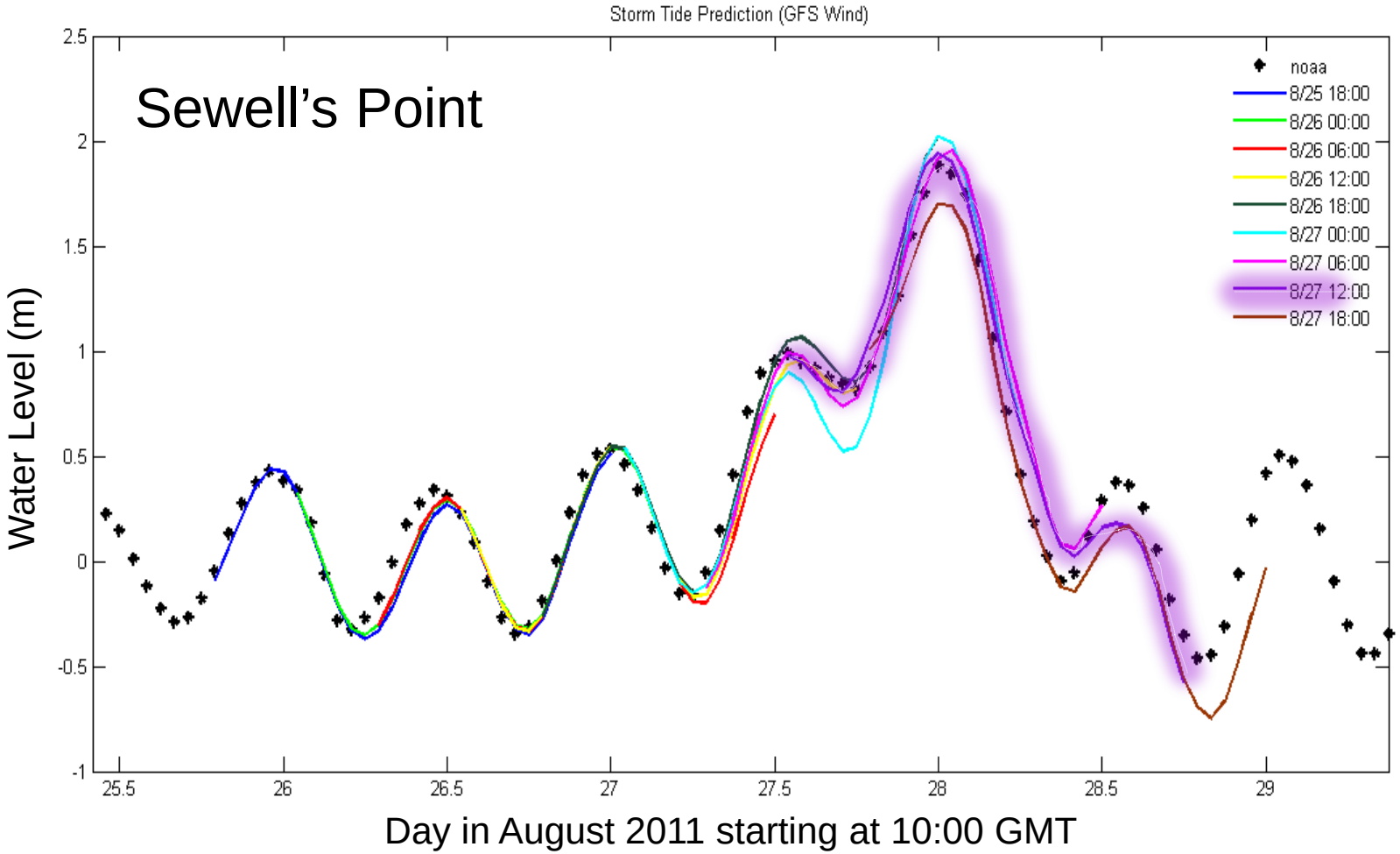
Hurricane Irene Forecast



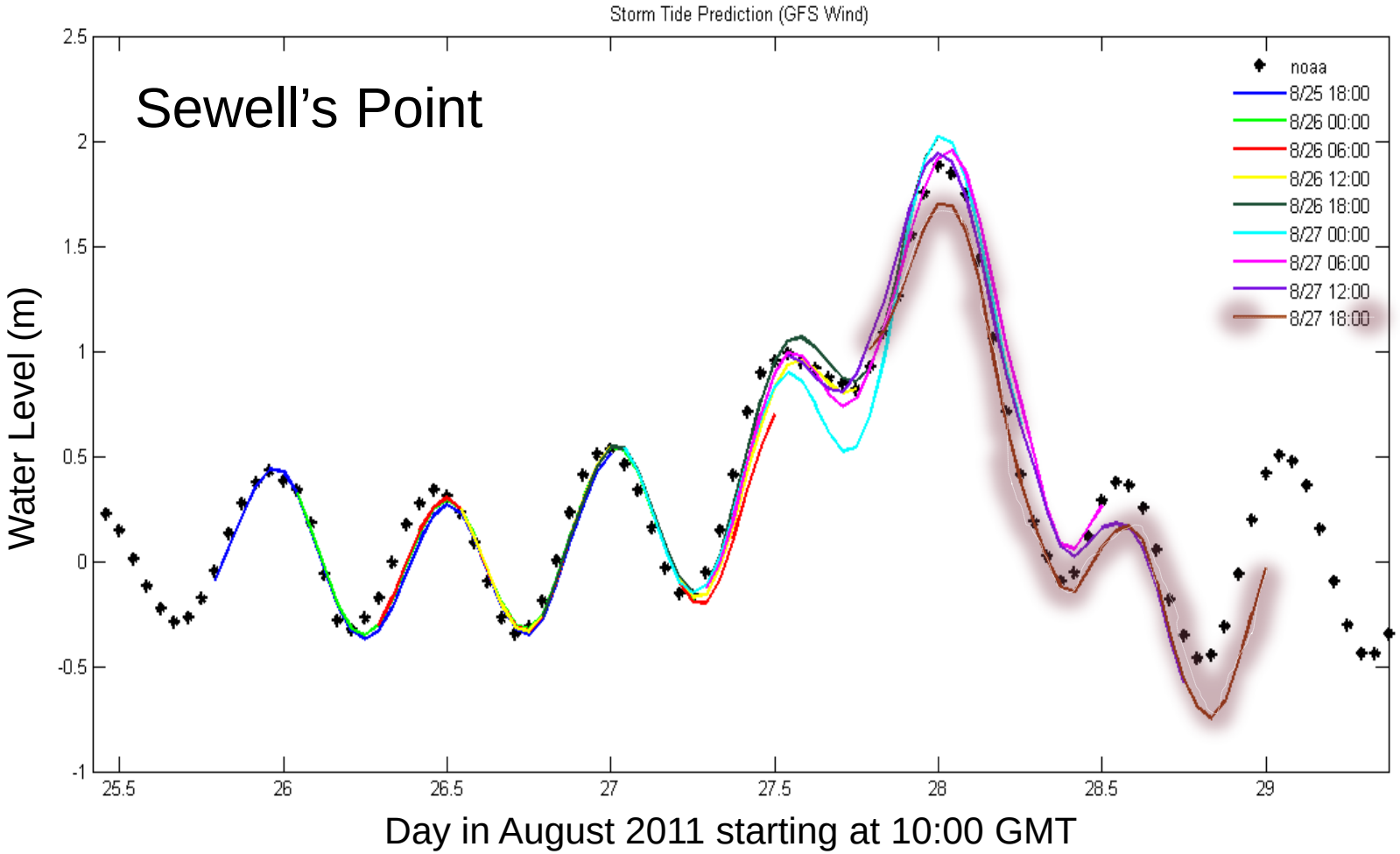
Hurricane Irene Forecast



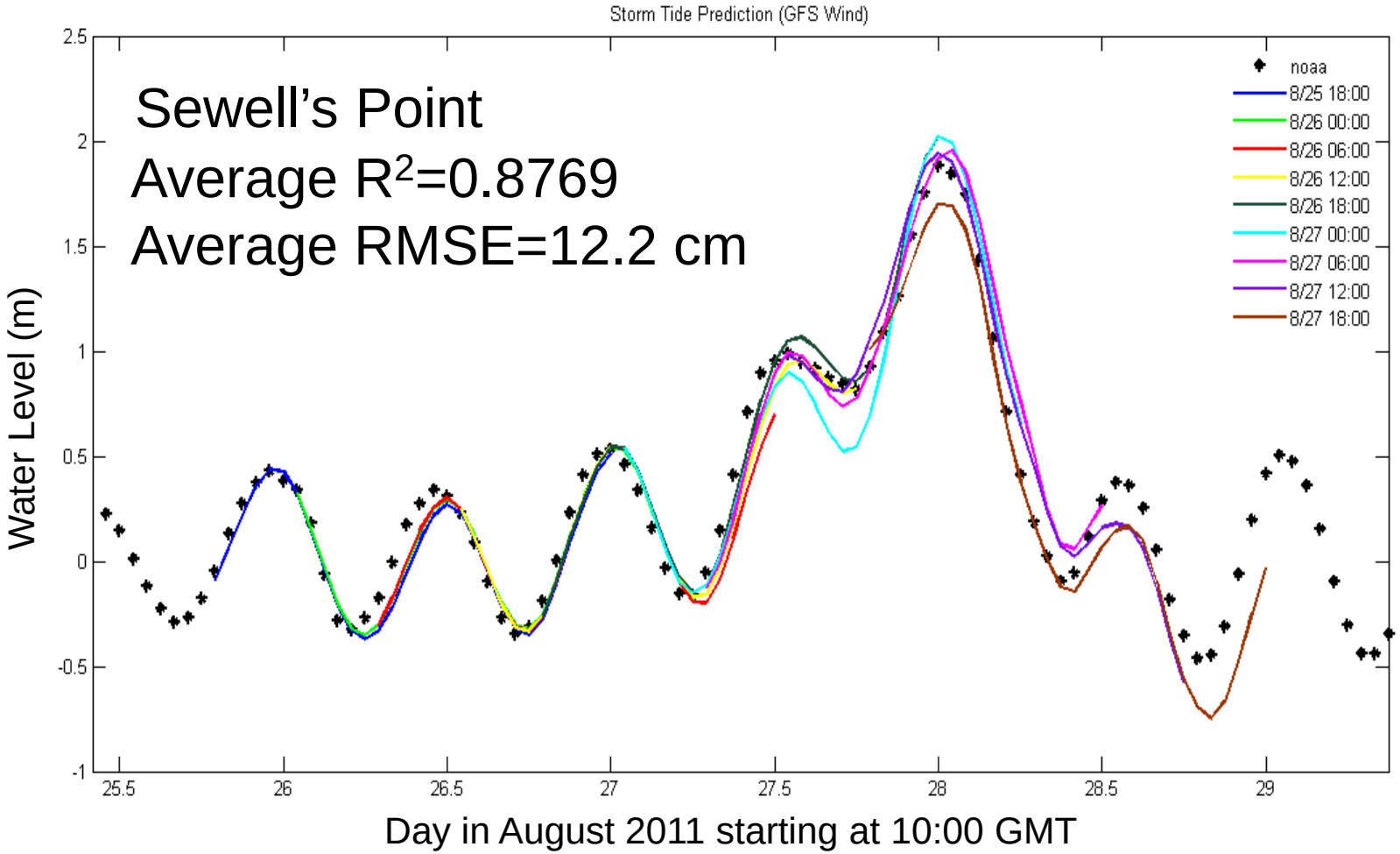
Hurricane Irene Forecast

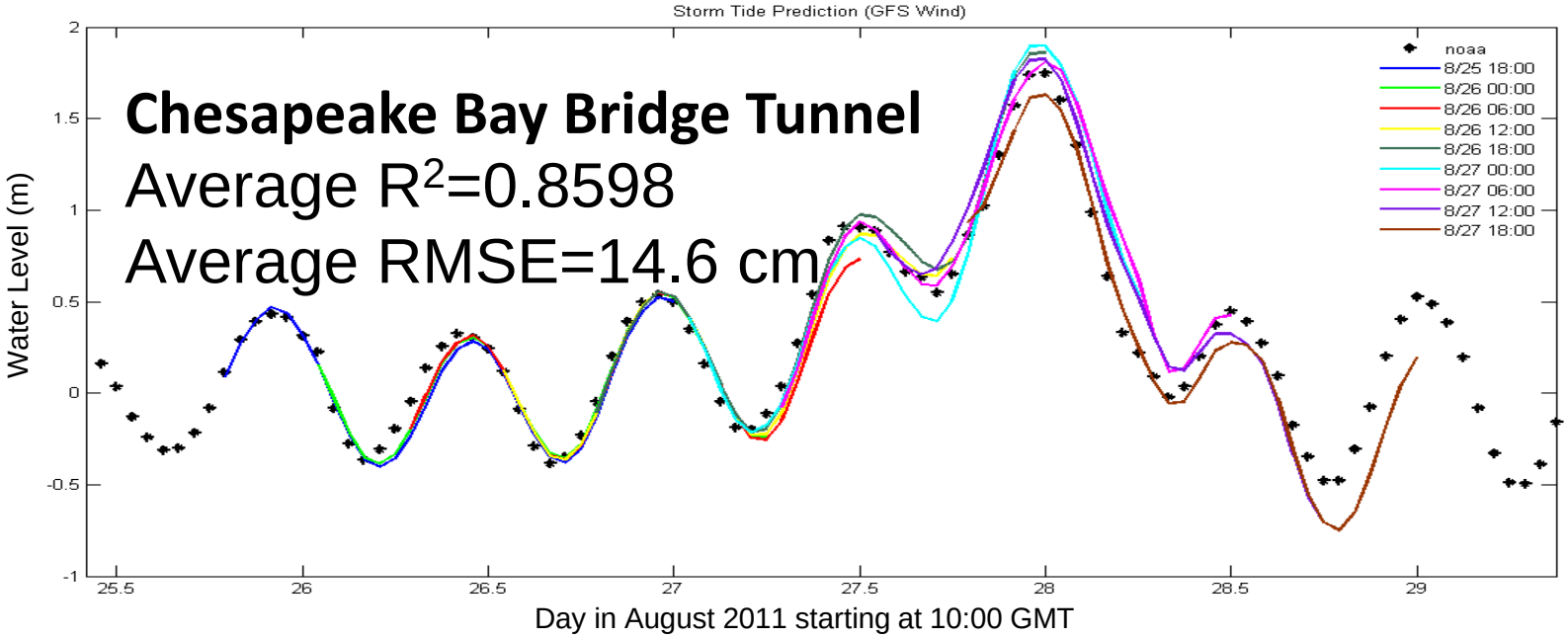


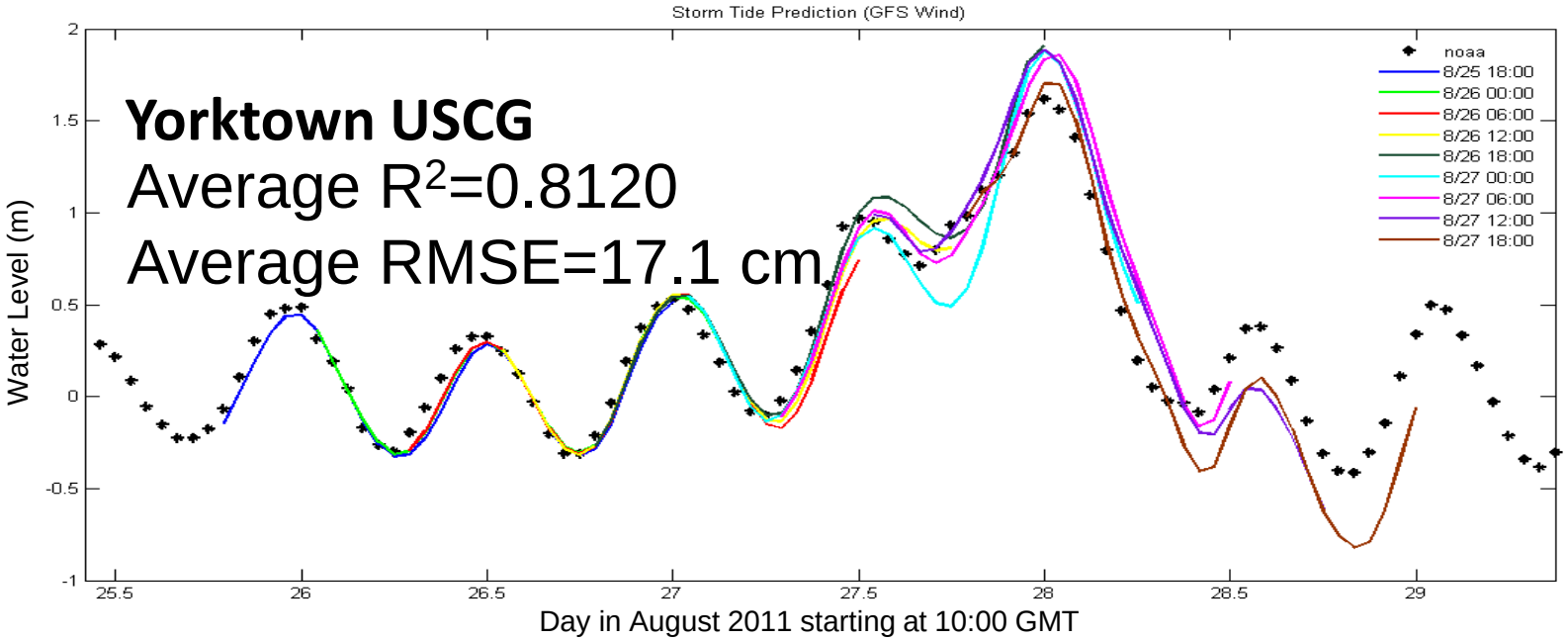
Hurricane Irene Forecast

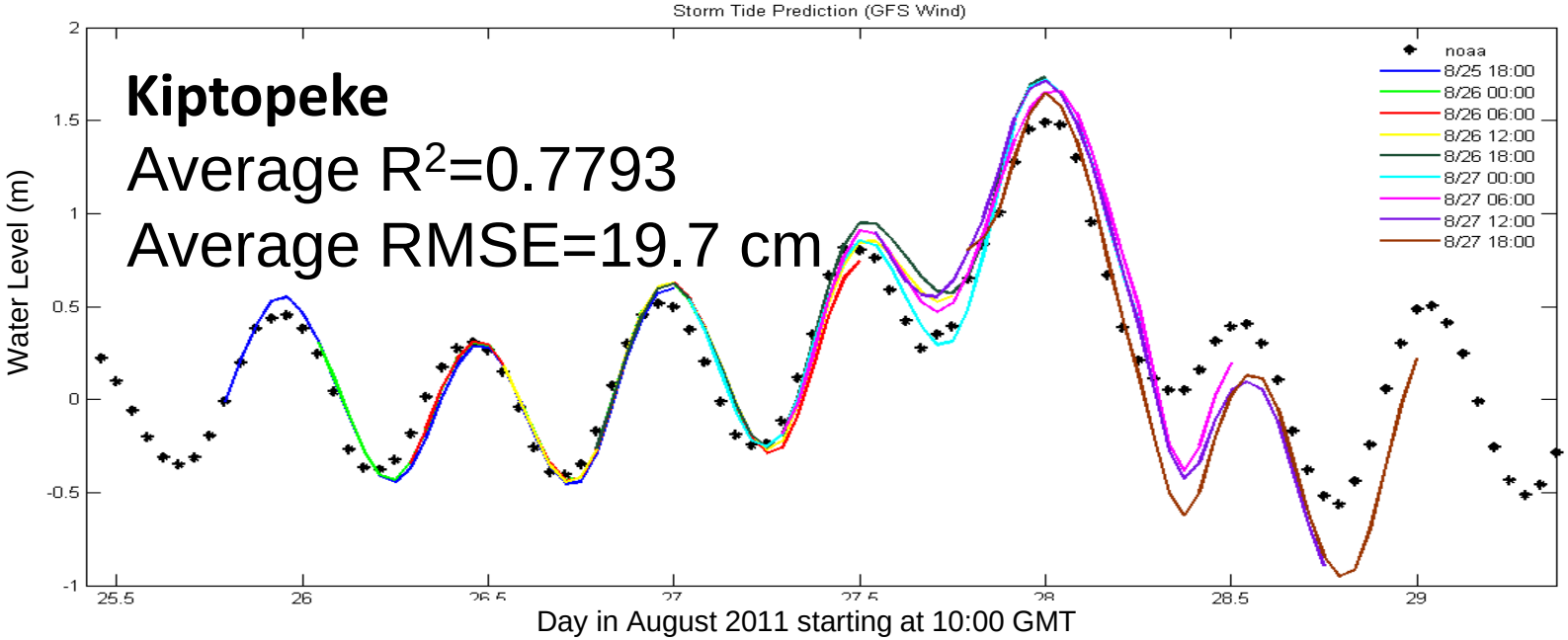


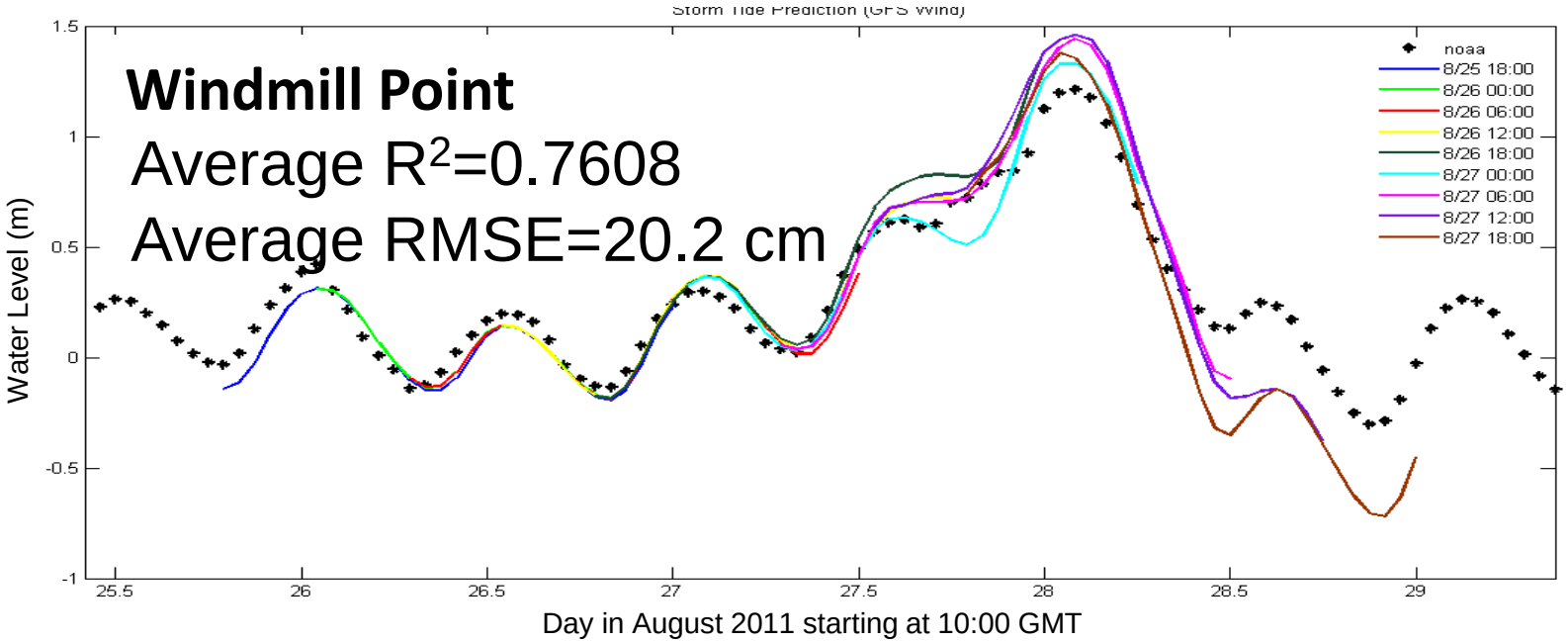
Hurricane Irene Forecast

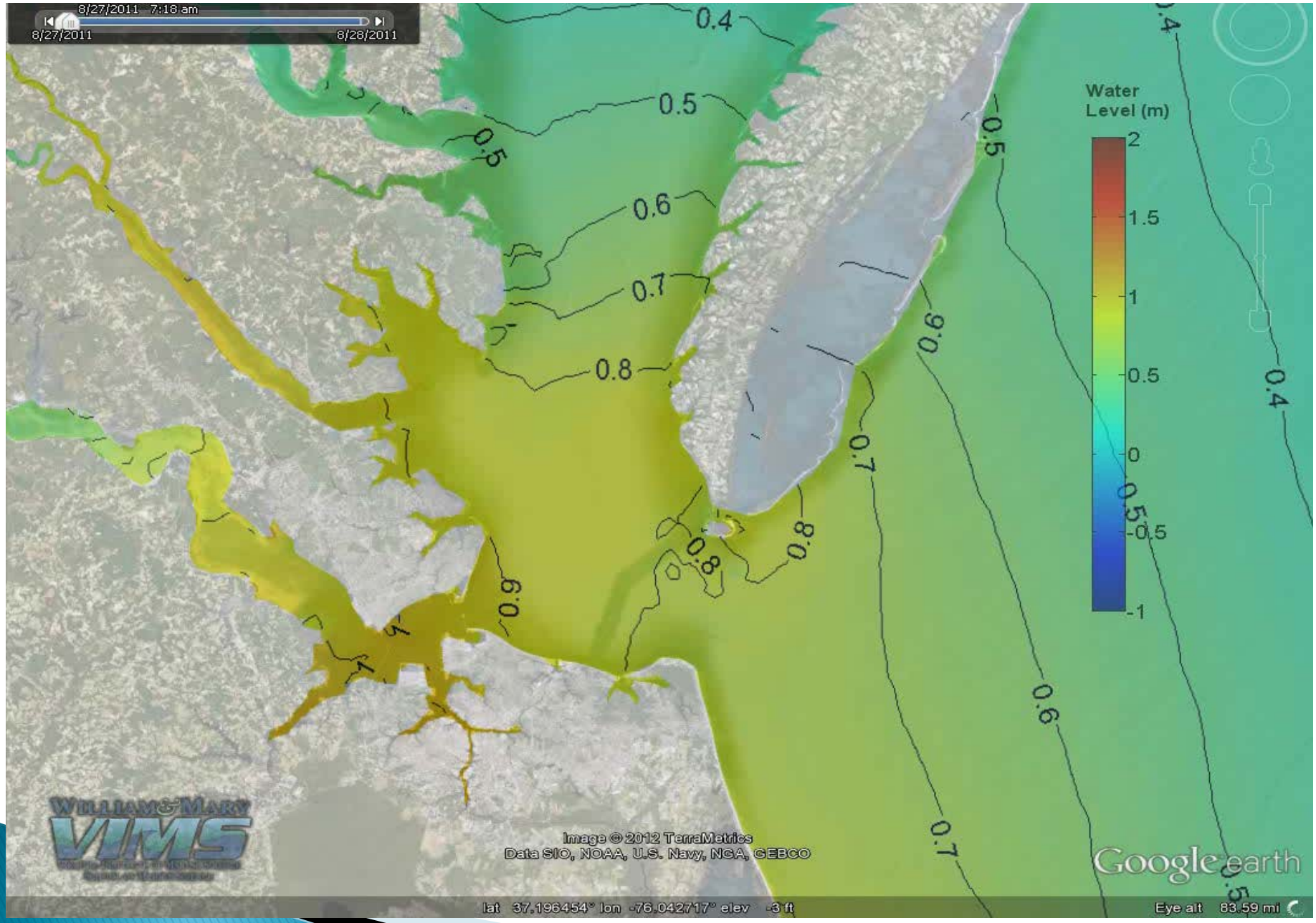



Storm Tide Prediction (GFS Wind)
Chesapeake Bay Bridge Tunnel
Average R²=0.8598
Average RMSE=14.6 cm
noaa
8/25 18:00
8/26 00:00
8/26 06:00
8/26 12:00
8/26 18:00
8/27 00:00
8/27 06:00
8/27 12:00
8/27 18:00
Water Level (m)
Day in August 2011 starting at 10:00 GMT


Storm Tide Prediction (GFS Wind)
Yorktown USCG
Average R²=0.8120
Average RMSE=17.1 cm
noaa
8/25 18:00
8/26 00:00
8/26 06:00
8/26 12:00
8/26 18:00
8/27 00:00
8/27 06:00
8/27 12:00
8/27 18:00
Water Level (m)
Day in August 2011 starting at 10:00 GMT


Storm Tide Prediction (GFS Wind)
Kiptopeke
Average R²=0.7793
Average RMSE=19.7 cm
Water Level (m)
Day in August 2011 starting at 10:00 GMT
noaa
8/25 18:00
8/26 00:00
8/26 06:00
8/26 12:00
8/26 18:00
8/27 00:00
8/27 06:00
8/27 12:00
8/27 18:00


Storm Tide Prediction (GFS Wind)
Windmill Point
Average R²=0.7608
Average RMSE=20.2 cm
Water Level (m)
Day in August 2011 starting at 10:00 GMT
noaa
8/25 18:00
8/26 00:00
8/26 06:00
8/26 12:00
8/26 18:00
8/27 00:00
8/27 06:00
8/27 12:00
8/27 18:00


8/27/2011 7:18 am
8/27/2011
8/28/2011
Water Level (m)
2
1.5
1
0.5
0
-0.5
-1
0.4
0.5
0.6
0.7
0.8
0.9
1
Image © 2012 TerraMetrics
Data SIO, NOAA, U.S. Navy, NGA, GEBCO
Google earth
lat 37.196454° lon -76.042717° elev -3 ft
Eye alt 83.59 mi

III. Street-Level Flood Forecasts via Sub-Grid Modeling

Journal of Coastal Research	SI	76	1–15	Coconut Creek, Florida	2015

Using Lidar Elevation Data to Develop a Topobathymetric Digital Elevation Model for Sub-Grid Inundation Modeling at Langley Research Center

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[‡] Science Directorate, NASA Langley Research Center, Hampton, VA 23681

[§] GIS Team Leader, NASA Langley Research Center, Hampton, VA 23681

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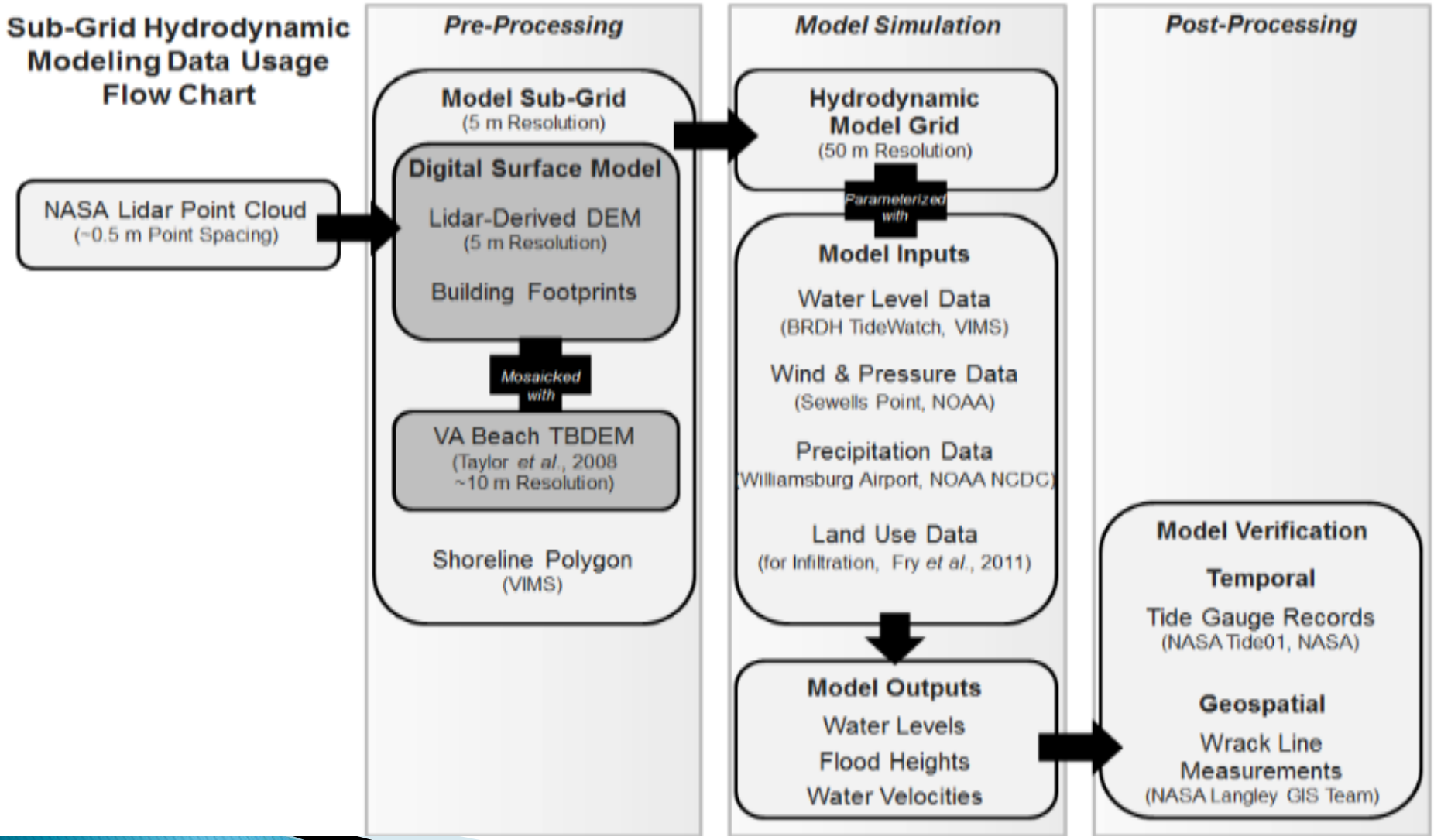
www.JCRonline.org

ABSTRACT

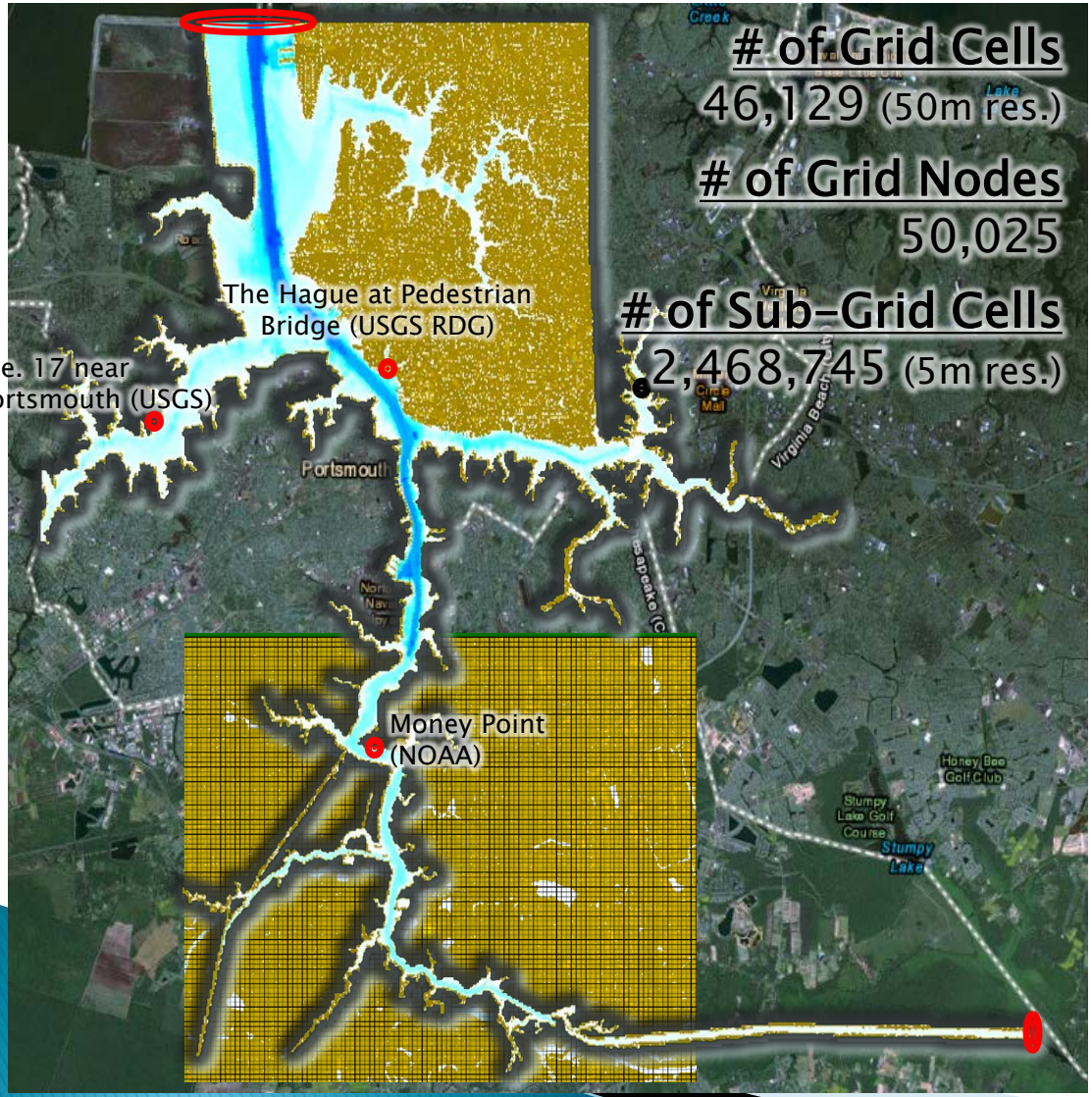
Loftis, J.D.; Wang, H.V.; DeYoung, R.J.; and Ball, W.B., 2015. Using Lidar Elevation Data to Develop a Topobathymetric Digital Elevation Model for Sub-Grid Inundation Modeling at Langley Research Center. *In*: Brock, J.C., Parrish, C.E., Gesch, D., Wright, C.W., and Rogers, J. (eds.), *Advances in Topobathymetric Mapping, Models, and Applications*. Journal of Coastal Research, Special Issue, No. 76, pp. 1–15. Coconut Creek (Florida), ISSN 0749-0208.

Technological progression in light detection and ranging permits the production of highly detailed digital elevation models, which are useful in sub-grid hydrodynamic modeling applications. Sub-grid modeling technology is capable of incorporating these high-resolution lidar-derived elevation measurements into the conventional hydrodynamic modeling framework to resolve detailed topographic features for inclusion in a hydrological transport model for runoff simulations. The horizontal resolution and vertical accuracy of the digital elevation model is augmented via inclusion of these lidar elevation values on a nested 5-m sub-grid within each coarse computational grid cell. This aids in resolving ditches and overland drainage infrastructure at Langley Research Center to calculate runoff induced by the heavy precipitation often accompanied with tropical storm systems, such as Hurricane Irene (2011) and Hurricane Isabel (2003). Temporal comparisons of model results with a NASA tide gauge during Hurricane Irene

A. Sub-Grid Model Setup



Norfolk and Chesapeake Sub-Grid Model Domain



# of Grid Cells
46,129 (50m res.)

# of Grid Nodes
50,025

# of Sub-Grid Cells
2,468,745 (5m res.)

Open Boundary Condition

Sewells Point (NOAA)
Forecast: SCHISM model for Storm Surge – or – VIMS TideWatch for tidal flooding)

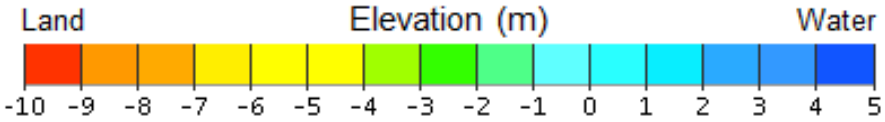
Southern Flux Boundary

Princess Anne (USGS)
Forecast: Empirical relationship with Sewells Point water level gauge

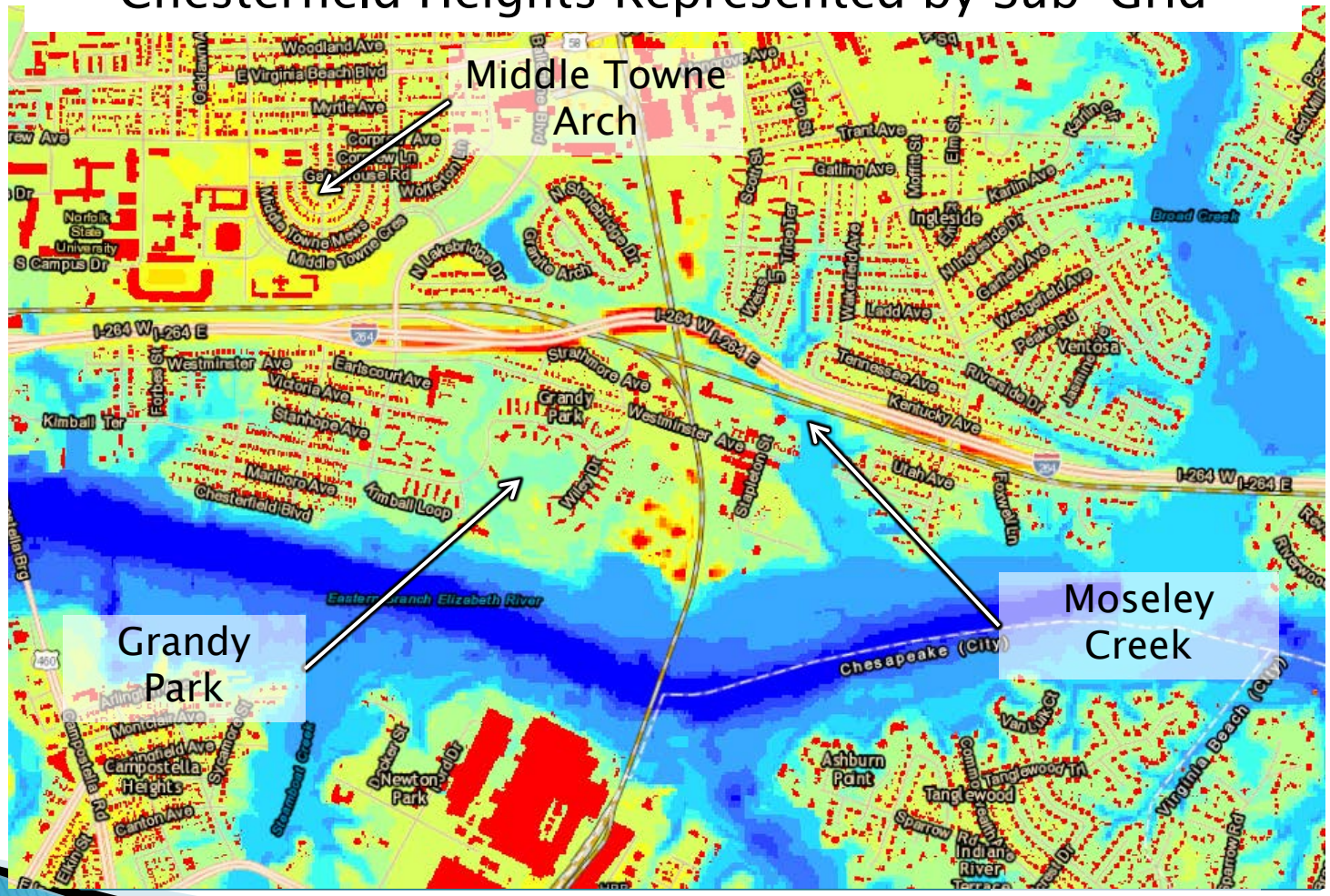
Wind and Atm. Pressure

Forecast: GFS or RAMS – or – NWS Prediction for Sewells Point

Model Grid Development with Lidar-Derived DEM

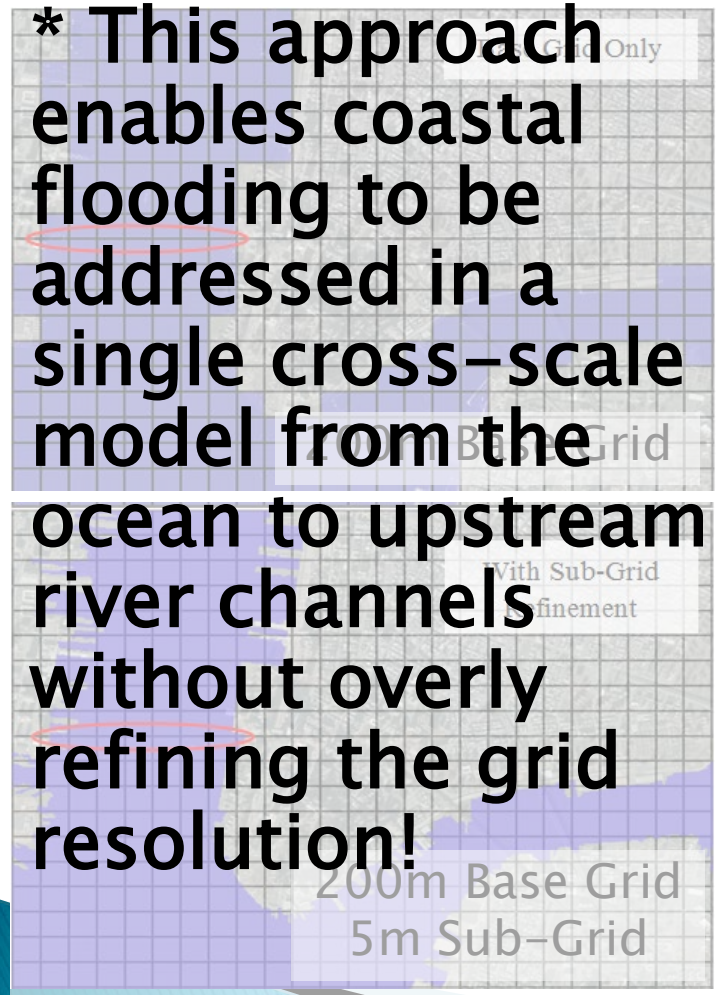


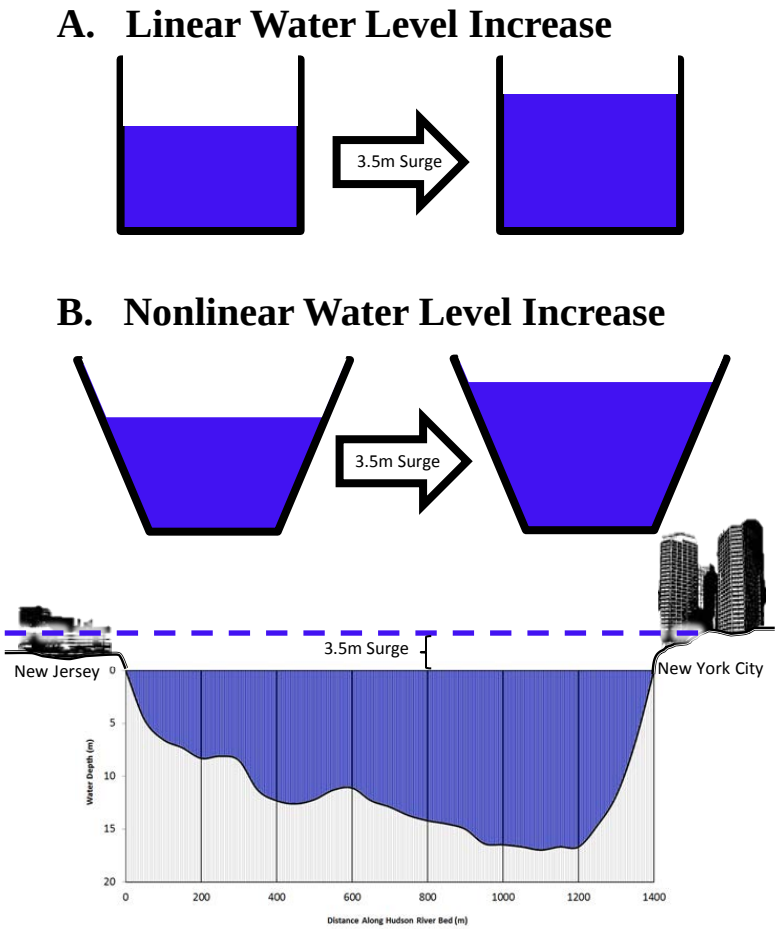
Chesterfield Heights Represented by Sub-Grid



Sub-Grid Modeling

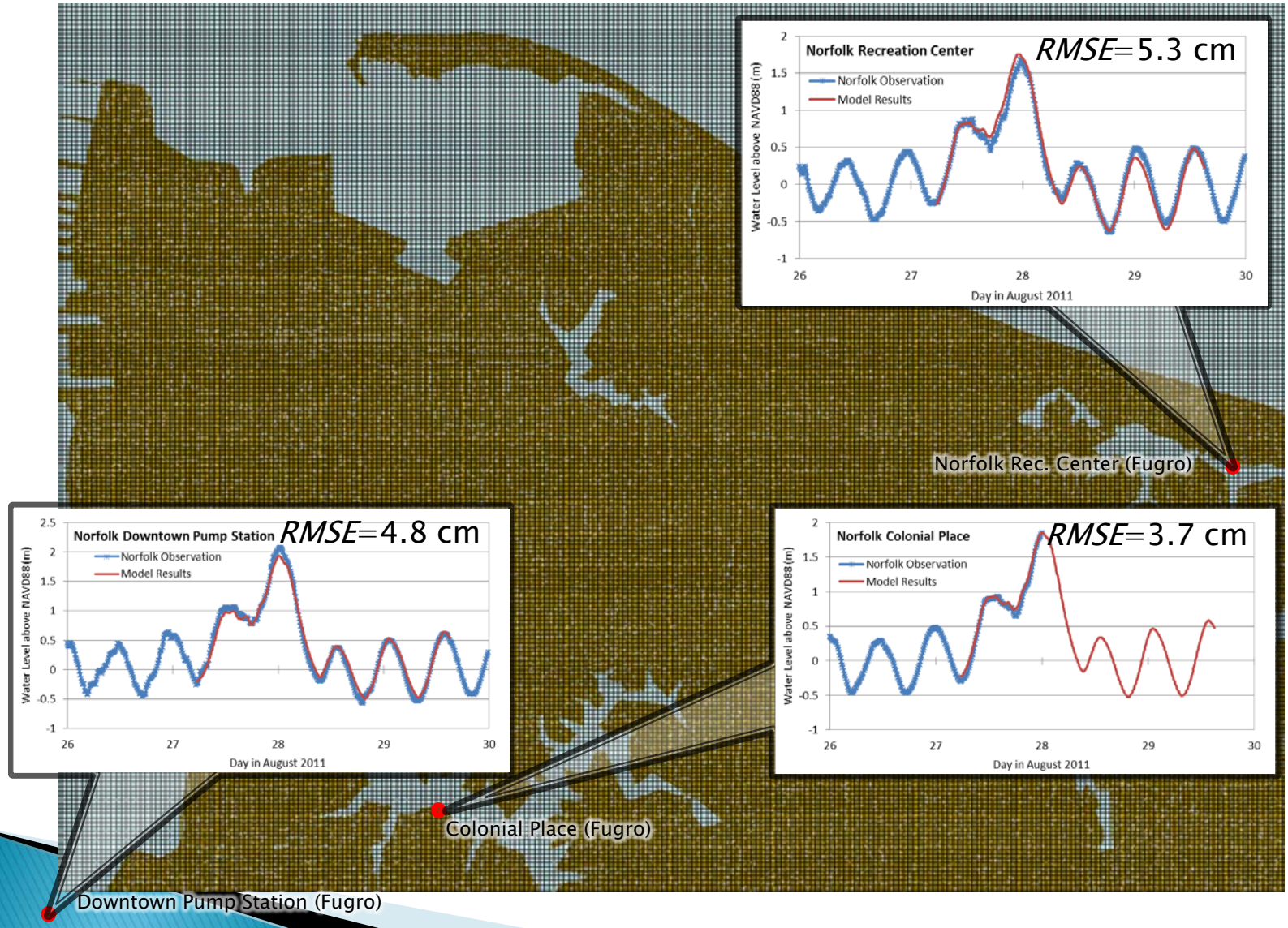
* This approach enables coastal flooding to be addressed in a single cross-scale model from the ocean to upstream river channels without overly refining the grid resolution!





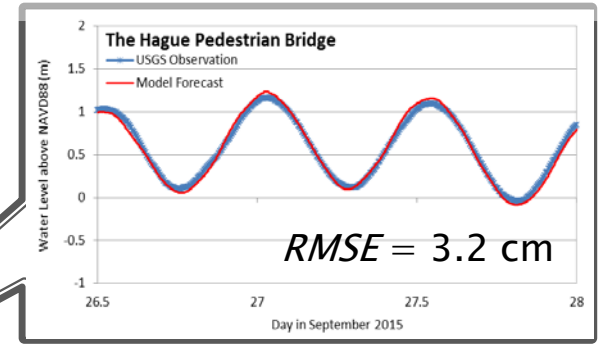
B. Sub-Grid Model Results

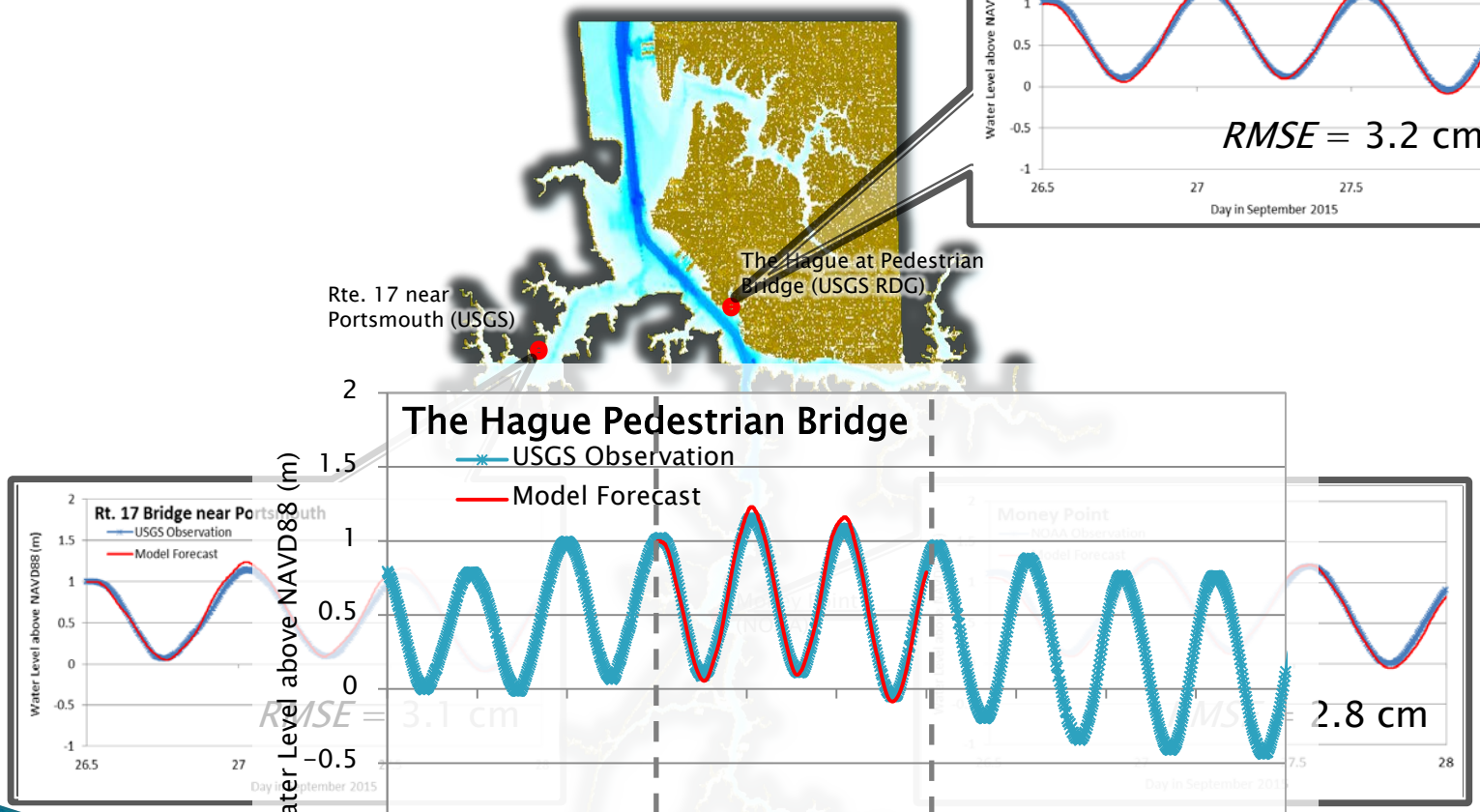
Forecast Model Forcing



IV. Future Applications and Model Validation Methods

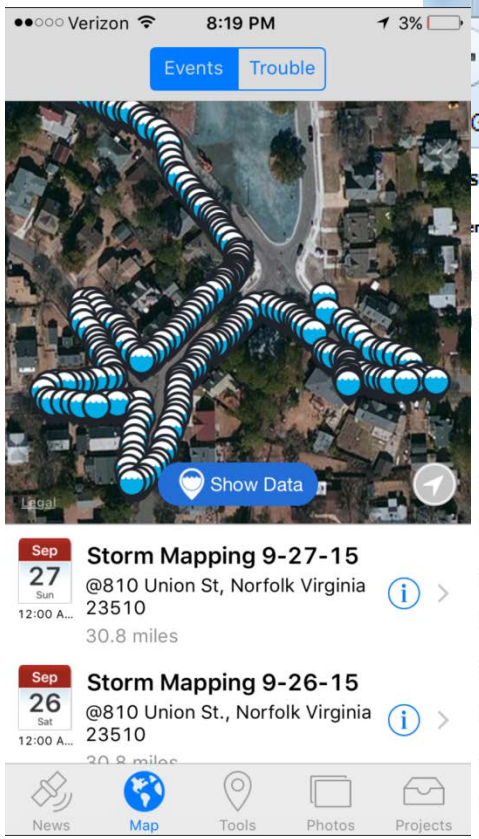
Time Series Comparison

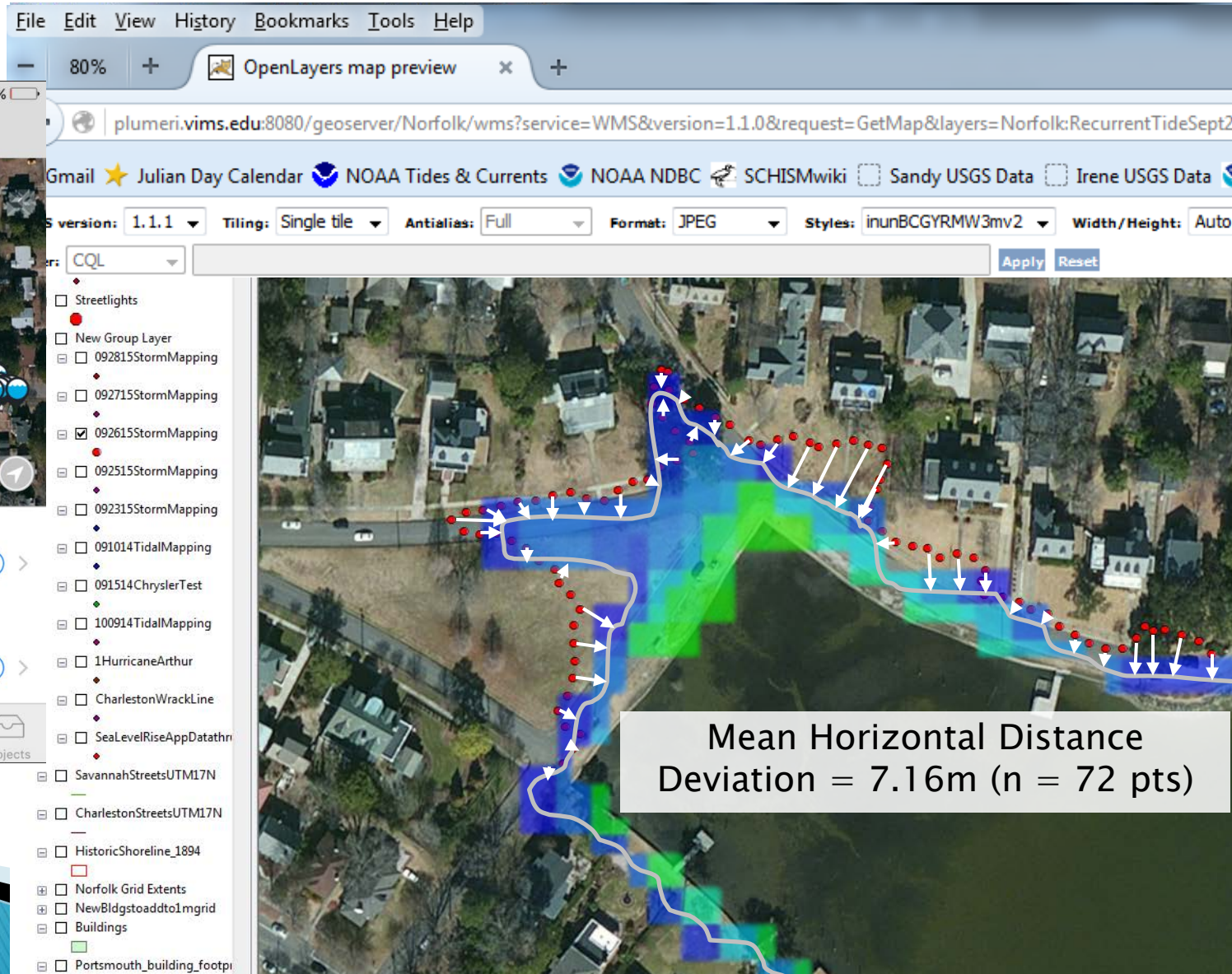




*36-hr forecast inundation simulations were executed in ≈17 min CPU time by a high-end PC with 24 processors, 256 GB RAM, and GPU-compatible graphics card (Perf. Speed ≈240:1 CPU-to-real time ratio)

Validating Maximum Flooding Extents via GPS using Sea Level Rise App





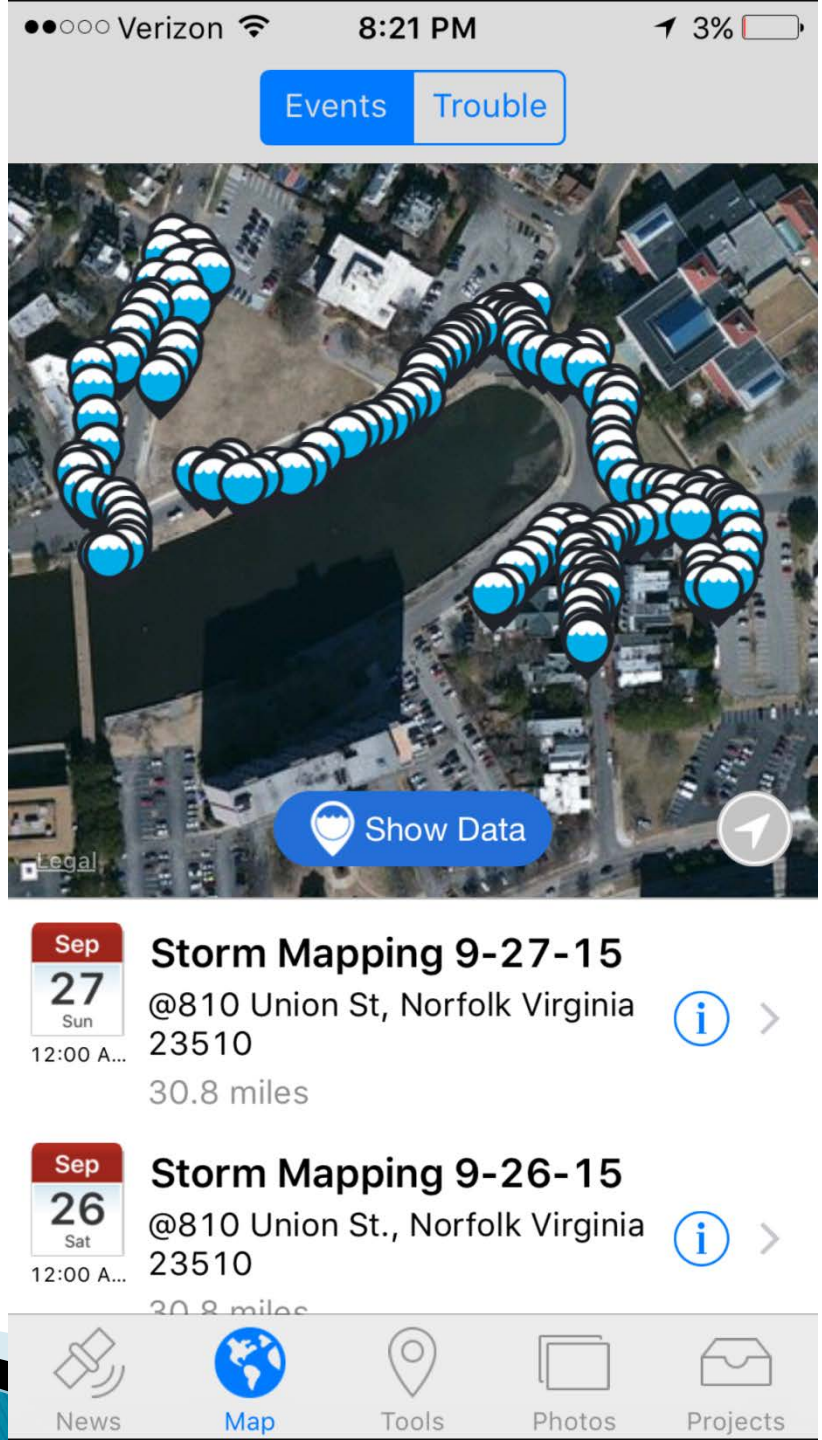
Site 1

The Hague

Sept. 27th, 2015

High Tide and Precipitation Floods

n = 156 points surveyed

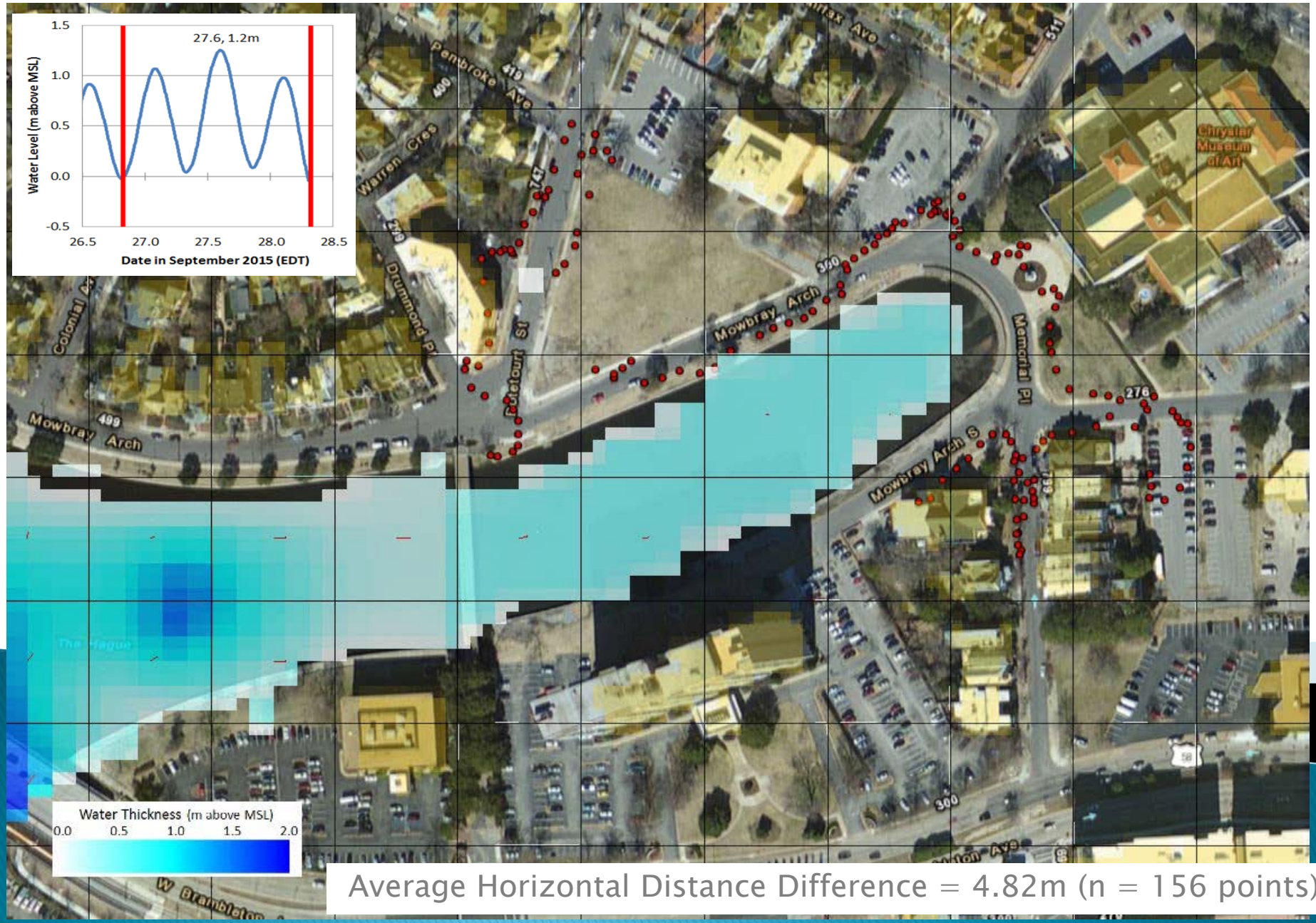


Crowd Sourced Maximum Inundation Extents from Sea Level Rise App

(available for iOS and Android devices)

Animation of Forecast Modeled Extents on September 27, 2015 in The Hague

Plotted with Maximum Inundation Extents from Sea Level Rise App



Average Horizontal Distance Difference = 4.82m (n = 156 points)

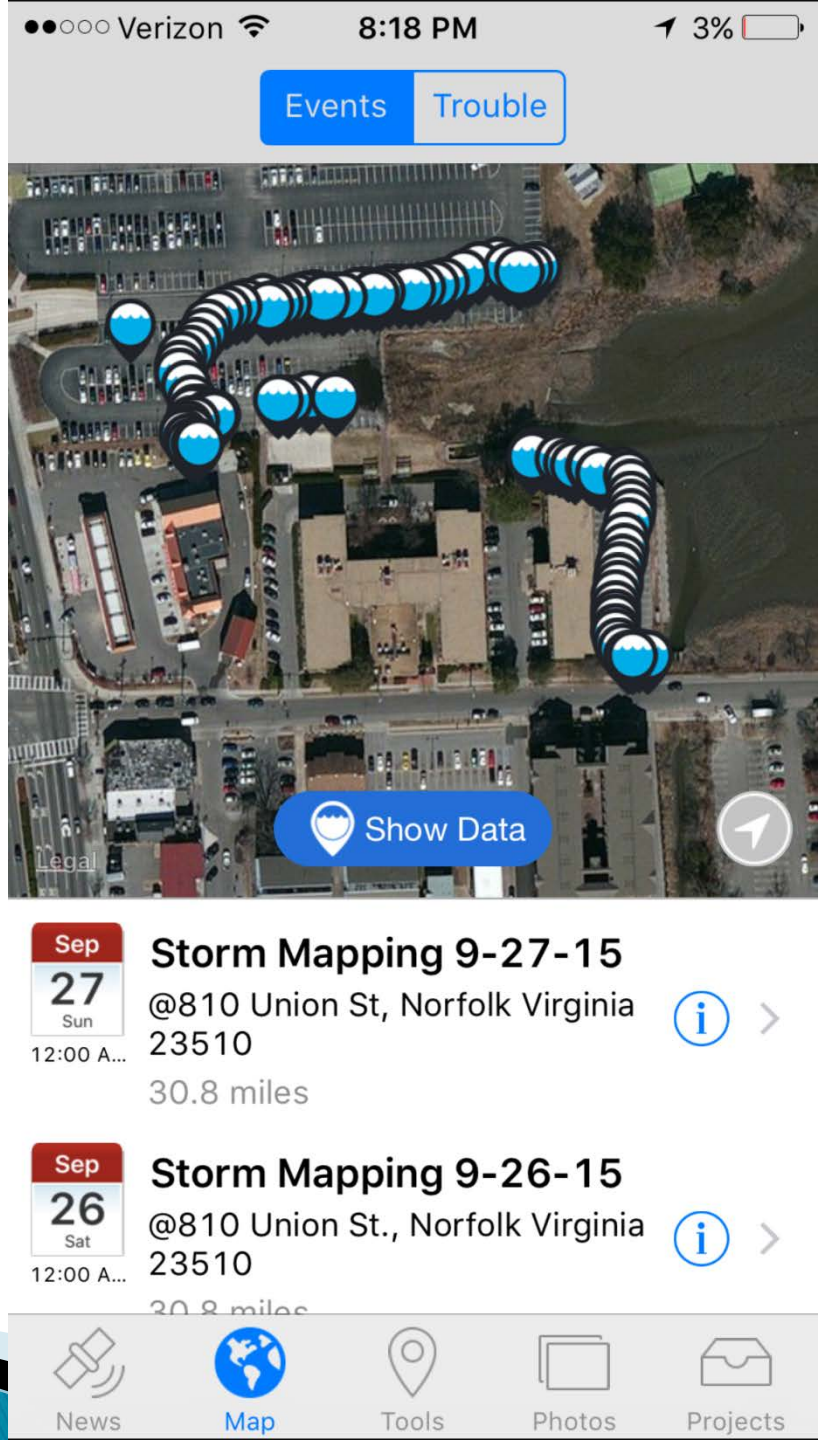
Site 2

ODU Parking Lot

Sept. 27th, 2015

High Tide and Precipitation Floods

n = 140 points surveyed

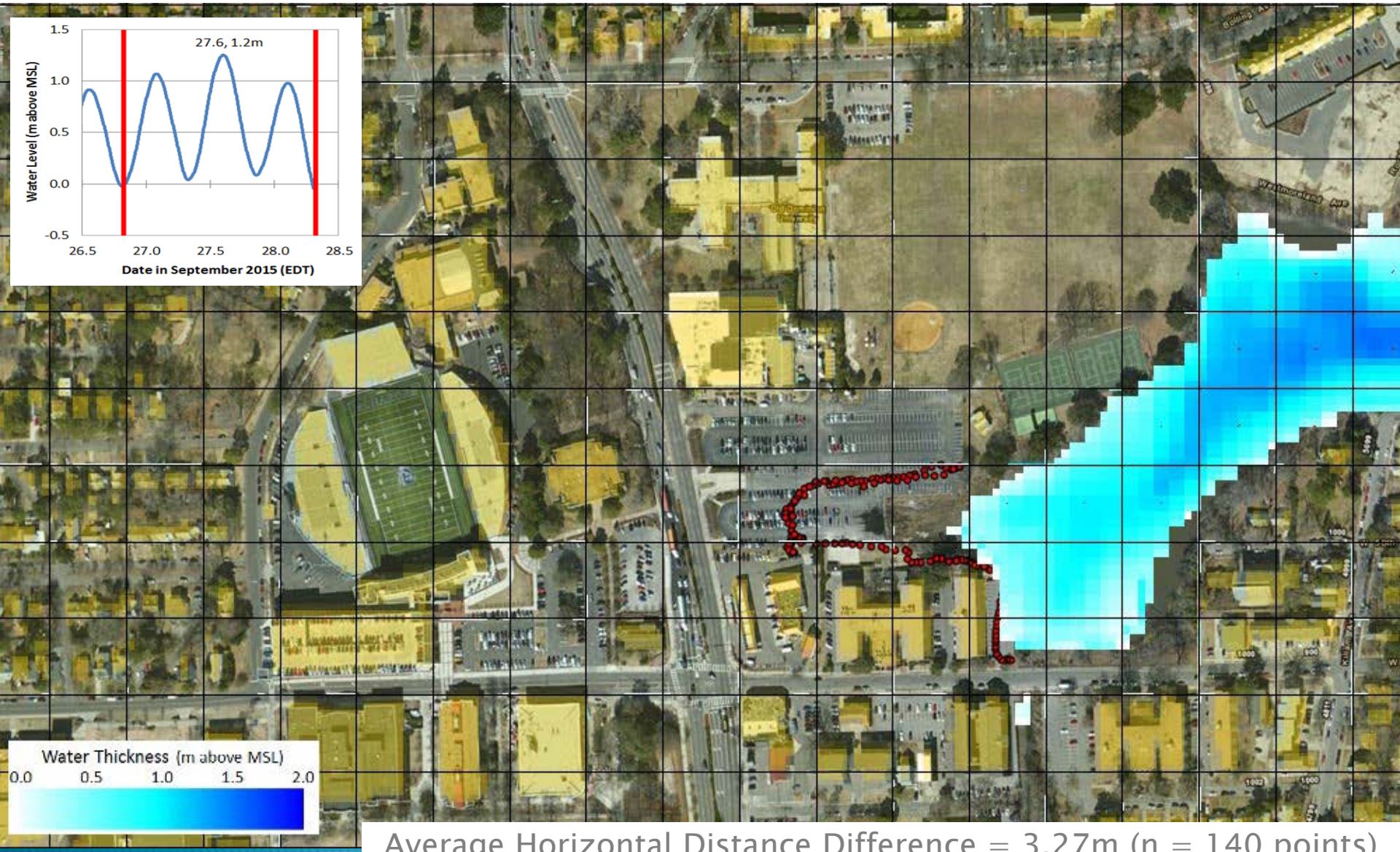


Crowd Sourced Maximum Inundation Extents from Sea Level Rise App

(available for iOS and Android devices)

Animation of Forecast Modeled Extents on September 27, 2015 on ODU Campus

Plotted with Maximum Inundation Extents from Sea Level Rise App



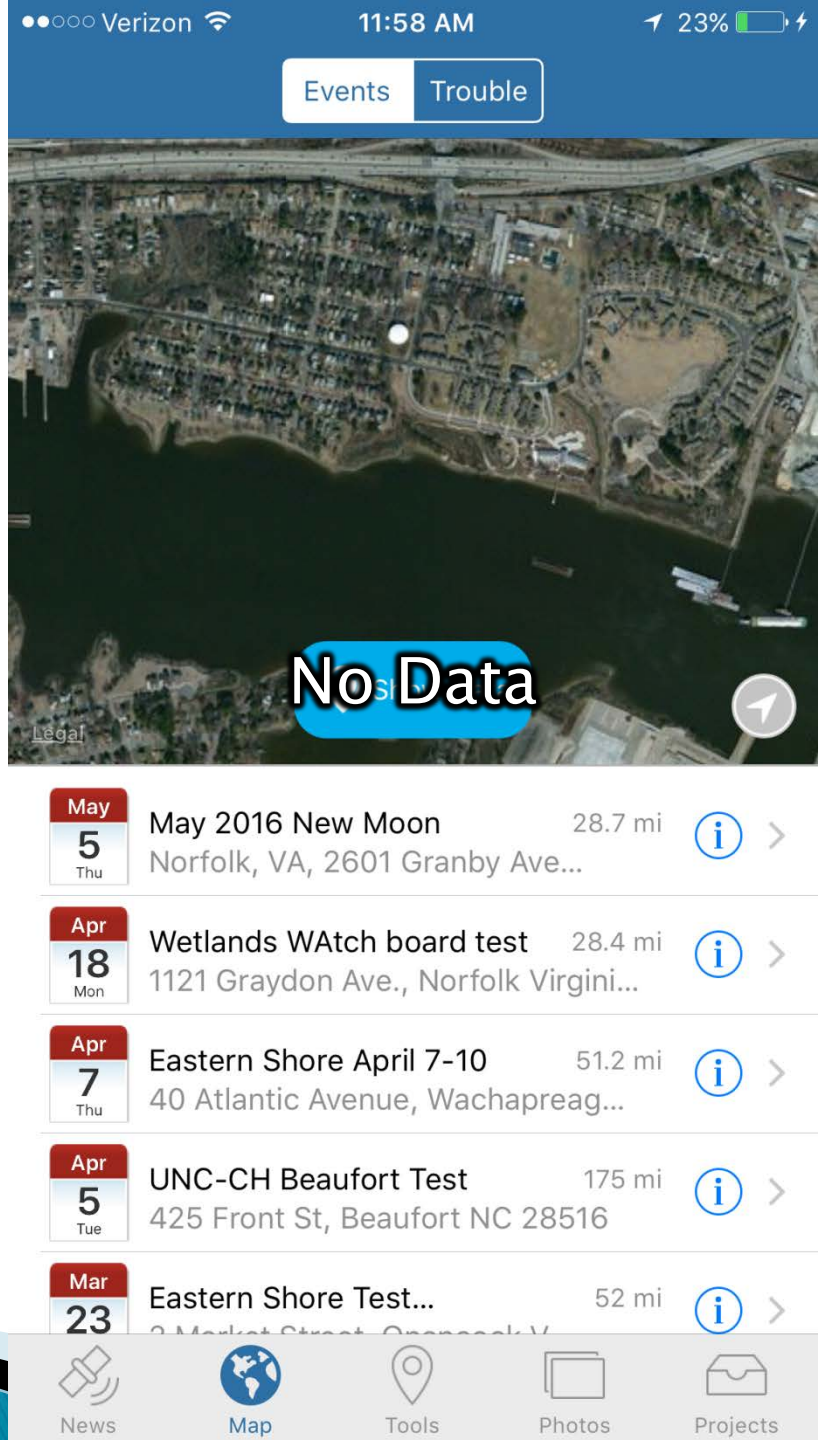
Average Horizontal Distance Difference = 3.27m (n = 140 points)

Site 3

Chesterfield Heights

Aug. 28th, 2011

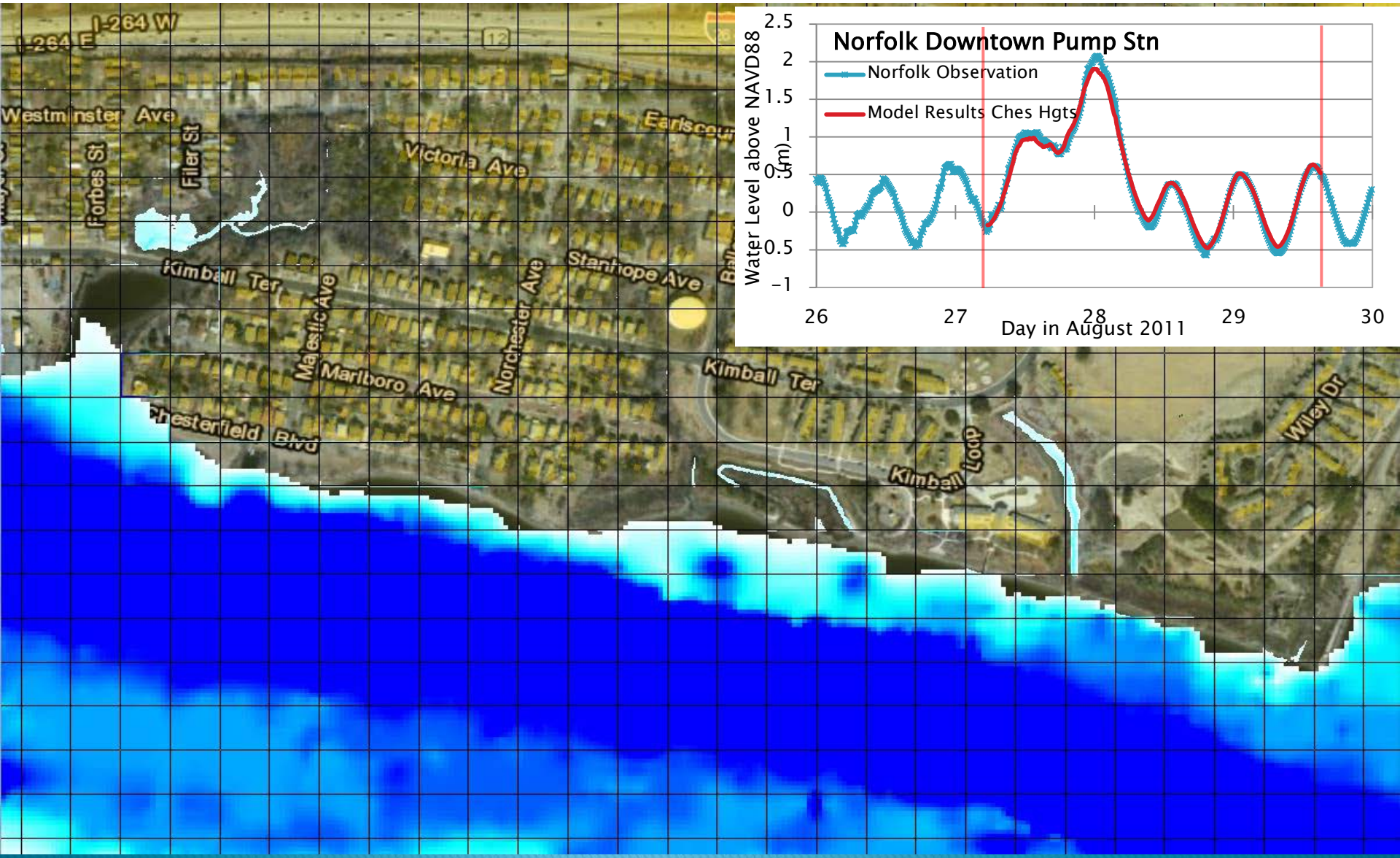
Storm Surge, Precipitation Flooding



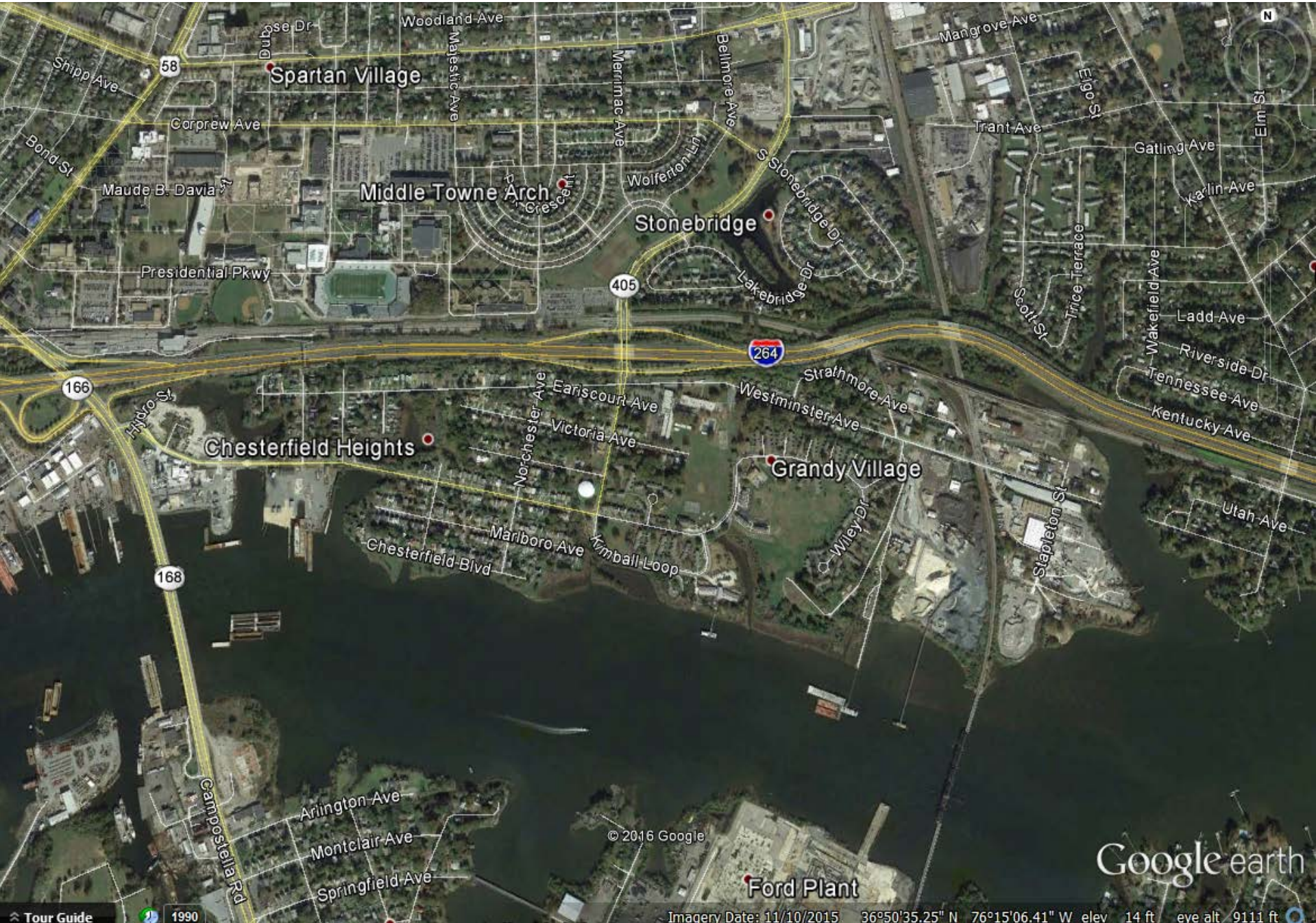
Crowd Sourced Maximum Inundation Extents from Sea Level Rise App

(available for iOS and Android devices)

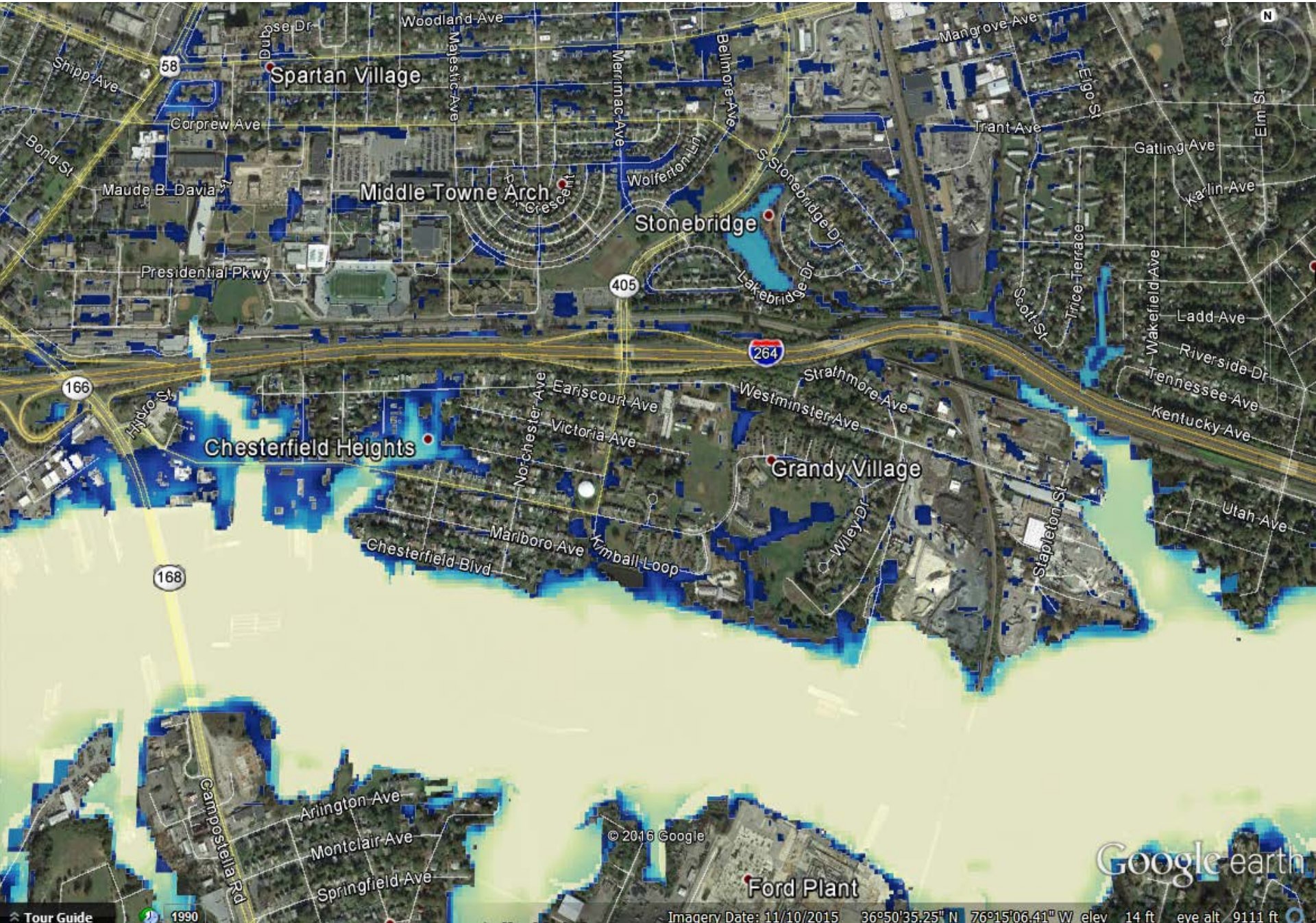
Animation of Hindcast Modeled Extents on August 28, 2011 in Chesterfield Heights



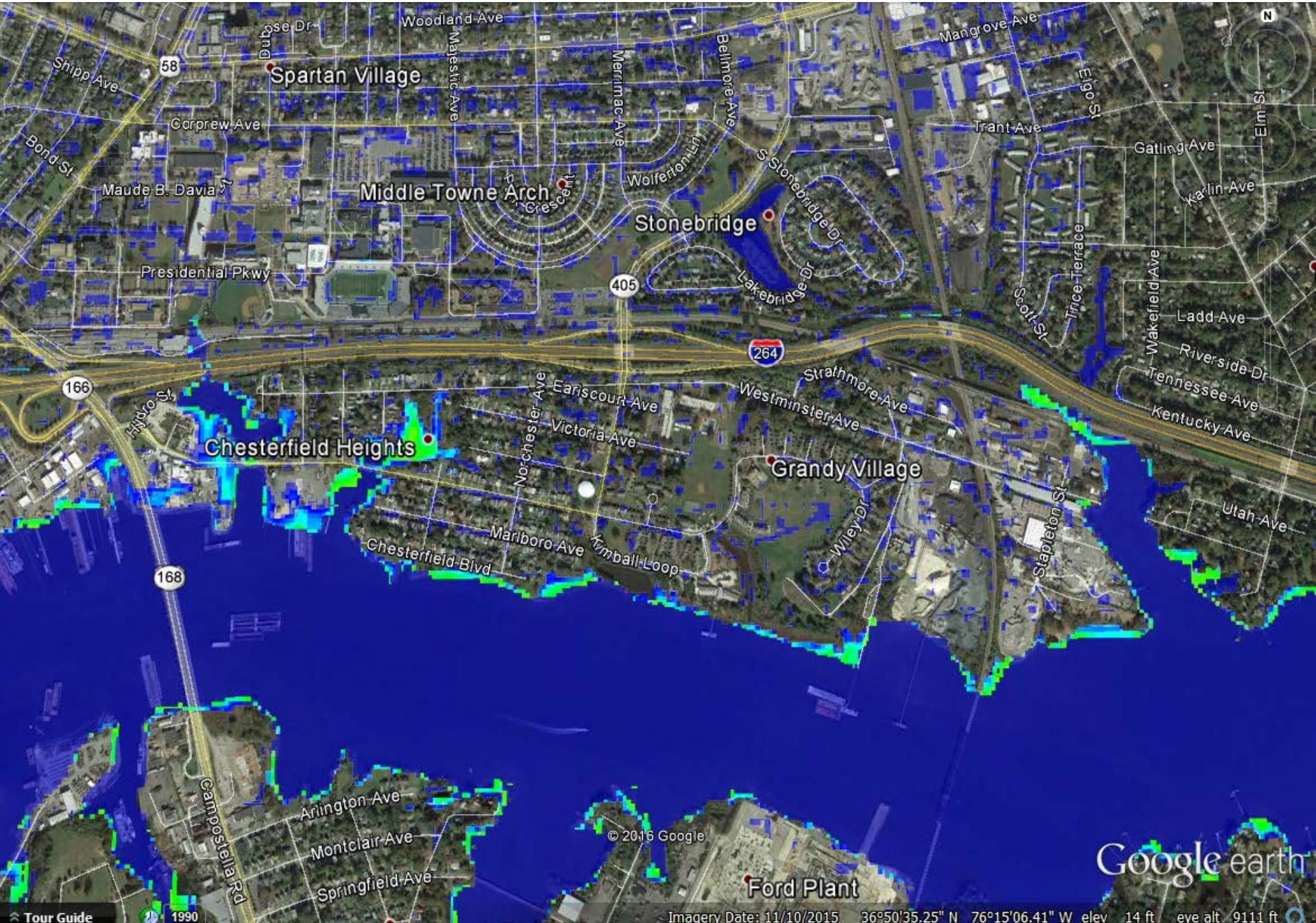
Chesterfield Heights and Grandy Village in Google Earth



Modeled Inundation from Hurricane Irene on August 28, 2011 in Chesterfield Heights



Modeled Inundation from Fall Tidal Flooding on Oct. 4, 2015 in Chesterfield Heights



Thank You!

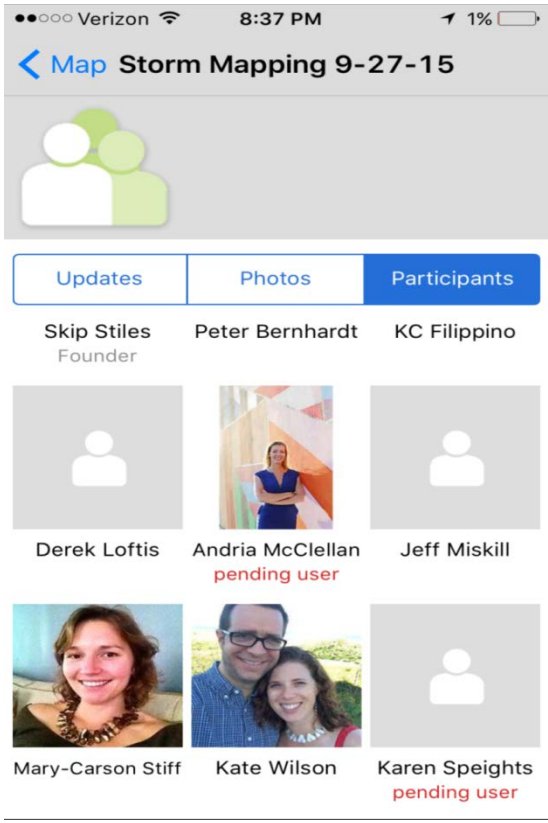
http://www.norfolk.gov/AgendaCenter/ViewFile/Item/1731?fileID=2346

V. Conclusions

1. The VIMS sub-grid hydrodynamic model has demonstrated that it is not only capable of resolving streets and buildings within the model grid, but it also considers variable friction parameters for the transition of fluid flow over river beds to flow over streets and through vegetation during inundation.
2. The street-level model was developed using a digital surface model built from lidar-derived elevation data with buildings added, and thus, should compute water level, momentum and volume of water movement with considerable accuracy.
3. The sub-grid model incorporates a non-linear solver to address the complex relationship between water level and the cross-section area of rivers, creeks, and streets that serve as conduits for fluid flow during inundation periods.

Conclusions (cont'd)

4. The model forecasted flood heights and extents during Hurricane Irene with considerable accuracy when compared with verified water level gauge observations collected by the USGS and NOAA with an average RMSE of 4.4 cm.
5. The sub-grid model forecasted tidal flooding in September 2015 and was validated via tide gauges and 'Sea Level Rise' App GPS extent data:
   Vertical Accuracy: aggregate *RMSE* of 3.19 cm (n=3; 432 ts each)
   Horizontal Accuracy: distance diff. of 9.35 m (n=1263 GPS pts)
6. In the future, these data validations may also serve as a platform where GPS flooding extent data entered by trained, registered users can be used for inter-comparison between different inundation models for the betterment of all.

Thank You!

- Thank you to the **City of Norfolk** for their open GIS data access to their building footprints and monument mapper datasets
- Thank you to **VIMS TideWatch, the USGS, NOAA, & NWS forecasts**
- Thank you to Skip Stiles, and the registered volunteers on the **Sea Level Rise App** who made the provisional model validation effort possible!