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Authors
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Storm Surge and Street-level Inundation Modeling in New York City during Hurricane Sandy

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Poquoson, VA 23662
757-868-5362

Hampton Roads Adaption Forum, February 23, 2015
Motivation
Outline

• Large scale storm tide and wind wave modeling using unstructured grid model SCHISM

• Very high resolution, local inundation street-level modeling directly coupling with LIDAR data

• Comparing inundation modeling results with USGS Sandy observation - mapper in the New York City

• Operational benchmark, software supports, and adaptation issues including sea level rise
I. Large-scale storm tide modeling

The model used is SCHISM (Semi-implicit, Cross-scale, Hydro-science Integrated System Model) http://ccrm.vims.edu/schism/

Key Features:

• Unstructured triangular and quadrilateral grid in the horizontal and hybrid SZ coordinates in the vertical dimensions, allowing cross-scale 1-D, 2-D, 3-D connection from ocean to the rivers

• Semi-implicit finite-element Eulerian-Lagrangian algorithm to solve the Navier-Stokes equations not constrained by CFL stability -> numerical efficiency.

• It is naturally incorporate simulation of wetting-and-drying process.

• The model was fully parallelized with domain decomposition method and MPI protocol.
Tidal open boundary condition about 1500 km offshore
SELFE model (an old version of SCHISM) setup for Hurricane Sandy

• Open boundary condition
  The model is forced by 8 tidal constituents: M2, S2, N2, O1, K1, Q1, P1, and K2, at the offshore open boundary.

• Time step: 6 minutes (using semi-implicit, Eulerian-Lagrangian scheme)

• Winds: Have trying NOAA NCEP NARR (24km), NAM (5km), for 3 hourly winds, and eventually the RAMS (2km) hourly wind, pressure fields provided by Weather Flows (free) was used. (The wind speed was adjusted upwards by 6%)

• Model Setup for 5 days spin-up from 10/20/2012 00 Z to 12/25/2012 00Z; hurricane simulation from 10/25/2012, 00Z to10/30/2012, 00Z.

• **CPU time: 180 time of real time on a infini-band Dell cluster with 128 processors. The 5 days simulation finished within 40 minutes.**

**Main assumptions: no precipitation, no infiltration, and no storm water drainage**
Figure 31: Model forecast tracks for Sandy at 0000 UTC 23 October (a), 000 UTC 24 October (b), 000 UTC October 25 (c), and 000 UTC 26 October, (d).

The ECMWF is in coral, the GFS ensemble in yellow, the GFS in cyan, and the TVCA model consensus is in red.

From: Blake, Eric, et al. (2013): Tropical Cyclone Report: Hurricane Sandy, National Hurricane Center,
The Impact of Winds on Storm Surge and Inundation

- Standardization allows assimilation of a larger number of high quality observations
- Gridded model reanalysis (RAMS/4DDA (past) --> GSI/WRF (future))
- Nested grids
  - Basin: 6-12 km depending on initializing analysis
  - Storm: 3km
  - Coastal zone: 1km or less

- Currently done operationally for tropical cyclone events (WeatherFlow StormPrint)
  - Could be done on a continuous basis
  - Forecast and hindcast modes
  - Climatological analyses and case studies
Wind field comparisons at 18 stations: NOAA observations (Blue) vs NAM/WF** (Red)

New York area

**WF: RMAS (Regional Atmospheric modeling System) carried out by Weather Flows Inc.
Wind field comparisons at 18 stations: NOAA observations (Blue) vs NAM/WF (Red)

New York area

NAM

WF

Days since 10/26/2012

Days since 10/26/2012

Days since 10/26/2012

Days since 10/26/2012
Wind field comparisons at 18 stations: NOAA observations (Blue) vs NAM/WF (Red)

Delaware coast

NAM

WF

Days since 10/26/2012

Days since 10/26/2012
Wind field comparisons at 18 stations: NOAA observations (Blue) vs NAM/WF (Red)

Chesapeake Bay

NAM

WF

Days since 10/26/2012

Days since 10/26/2012
Friction formulation using Manning coefficient

Manning n = 0.025 everywhere except

(1) New York Harbor  
n = 0.010

(2) East and Harlem Rivers  
n = 0.045
The Battery, NY

\[ y = 0.9713x + 0.1507 \]

\[ R^2 = 0.9305 \]
Sandy Hook, NJ

\[ y = 0.9121x + 0.2459 \]

\[ R^2 = 0.9557 \]
Atlantic City, NJ

\[ y = 0.8321x + 0.1368 \]

\[ R^2 = 0.9113 \]
Lewes, DE

\[ y = 0.9682x + 0.0009 \]

\[ R^2 = 0.8234 \]

Tide Only

Lewes, DE

\[ y = 0.9995x + 0.0438 \]

\[ R^2 = 0.9913 \]
CBBT, VA

Water Level in MSL (m)

Days from Oct. 27, 2012

CBBT, VA

\[ y = 0.9871x + 0.0175 \]

\[ R^2 = 0.9242 \]

Tide only

\[ y = 0.8953x + 0.0647 \]

\[ R^2 = 0.987 \]
Duck, NC

\[ y = 1.1091x - 0.21 \]
\[ R^2 = 0.9634 \]
Montauk, NY

\[ y = 0.9907x + 0.0582 \]
\[ R^2 = 0.8856 \]

Montauk, NY

\[ y = 0.9645x + 0.0583 \]
\[ R^2 = 0.9674 \]
New Haven, CT

Water Level in MSL (m)

Days since Oct. 27, 2012

-2 -1 0 1 2 3 4 5

NOAA Observation
Model Result

New Haven, CT

Tide only

y = 0.8269x + 0.1886
R² = 0.9292
Kings Pt, NY

\[ y = 0.7973x + 0.2381 \]
\[ R^2 = 0.9055 \]
Significant wave height (m)

**Station 44025**

- SCHISM with WWM
- NOAA observation

Dominant peak period (s)

**Station 44025**

- SCHISM with WWM
- NOAA observation
Observation of explosive surge setup in Long Island Sound

Kings Pt, NY

Explosive setup!!

Water Level Relative to MSL (m)

Time (GMT)

- NOAA Observations
- Surge
- NOAA Prediction
Modeled explosive non-tidal surge

Kings Point, NY

- NOAA observation-predicted tide
- Model-predicted tide
II. High-resolution, sub-grid inundation modeling

Synopsis:
While many global basin scale storm tide models focus primarily on waterways, it is our belief that the technology for predicting local inundation over land is equally important, if not more important.

• The goals for local inundation prediction:
  a. The maximum inundation extent
  b. The timing of the inundation
  c. The depth of the inundation
Fundamental Idea of “Subgrid Modeling”

- The availability of detailed bathymetry LIDAR data plugged within a coarse grid model can and should be used to further improve a model accuracy.

- The availability of super computing power... are useful tools but, alone, are still insufficient to faithfully account for complex topographic features.

The key features for sub-grid modeling* are:

- Nonlinear semi-implicit solver for wetting-and-drying

- A conveyance formulation (based on friction dominated flow) allows the effects of small features be more accurately represented without overly expensive computational cost.

A. Nonlinear semi-implicit solver for wetting-and-drying

- High resolution bathymetry data at sub-grid level allows the cross-sectional area and volume be calculated more accurately
- It allows mass balance in wet, dry, and partially-wet-and-dry region
- It does not require a threshold value for minimum water depth
- It generates accurate results with relatively coarse mesh and large time step by solving a mild nonlinear system:

\[ V(\eta) + T \eta = b \]

\( \eta \) is determined iteratively by a converging Newton type method

\[ \eta^{(m+1)} = \eta^{(m)} - \left[ P(\eta^{(m)}) + T \right] \left[ V(\eta^{(m)}) + T \eta^{(m)} - b \right] \]

fast, and efficiently implemented by use of a PCGM
B. Conveyance formulation on a sub-grid scheme

• A simplified 2D depth averaged momentum equation:

\[
\frac{DU}{Dt} + g \frac{\partial \zeta}{\partial x} + cf \frac{U\|U\|}{h} = 0
\]

where \( cf = g/Cz^2 \) or \( cf = g n^2/h^{1/3} \)

\[
\frac{DU}{Dt} + g \frac{\partial \zeta}{\partial x} + g \frac{U\|U\|}{\Omega^2} = 0
\]

If friction dominates, the main balance is the last two terms in each time step

\[
U = \Omega \sqrt{\zeta_x}
\]

or

\[
\frac{U^2}{\Omega^2} = \zeta_x
\]

Where \( \Omega = \sqrt{\frac{gh}{cf}} \) is conveyance velocity

• In 2D sub-grid, for each pixel \( \frac{cf_j}{gh_j} \|u_j\|^2 = \text{constant} \) (assume \( \zeta_x \) is constant)

Introduce cell average velocity \( U \) where

\[
\|U\| = \frac{\sum_{j=1}^{J} h_j \|u_j\|}{\sum_{j=1}^{J} h_j}
\]

\[
\left( \frac{\|u_j\|}{\Omega_j} \right)^2 = \text{constant} \forall j
\]

• Then

\[
\frac{\|u_j\|}{\Omega_j} = \frac{\|U\|}{\Omega} \forall j
\]

or

\[
\|u_j\| = \Omega_j \frac{\|U\|}{\Omega}
\]

where

\[
\Omega = \frac{\sum_{j=1}^{J} h_j \Omega_j}{\sum_{j=1}^{J} h_j}
\]
Kings Point NY

Base - Grid Nodes: 9,946
Base - Grid Cells: 9,663
Sub - Grid Cells: 3,865,200

High resolution, local inundation dynamic model on sub-grid scale
UNTRIM² Sub-grid model setup for Hurricane Sandy

• Open Boundary Forcing from NOAA Stations
  – West Boundary: Bergen Point, NY  NOAA Station #8519483
  – East Boundary: Kings Point, NY  NOAA Station #8516945
  – South Boundary: near Sandy Hook, NJ  NOAA Station #8531680

• Flux Boundary Forcing from USGS Station
  – North Boundary: Hudson River near Wappinger Falls
    USGS Station #01372500

• Model Setup for 10 days from 00:00, 10/25/2012 to 00:00, 11/04/2012

• Atmospheric pressure and wind data retrieved from Bergen Point, NY, at NOAA Station #8519483

• CPU time: 240 time of real time on Dell Precision T-3500
  with Intel Xeon W3670; Windows 7, 64-bit OS; 24 GB RAM
South Manhattan Island

New York City Sub-Grid
High-Resolution Domain

Base-Grid Nodes: 9,946
Base-Grid Cells: 9,663
Sub-Grid Cells: 3,865,200
Sandy Hook, NY

Elevation above MSL (m) vs. Days since 10/25/2012 at 00:00 GMT

- NOAA Observation: Blue line
- Model Result: Red line

Equation: $y = 0.8973x$

$R^2 = 0.9816$
The Battery, NY

y = 1.0079x
R² = 0.9936
Kings Point, NY

Elevation above MSL (m)

Days since 10/25/2012 at 00:00 GMT

y = 0.9715x
R² = 0.9939
USGS Rapid Deployment Gauge Comparison

USGS Gowanus Canal, Brooklyn KIN-003WL

Water Level above MSL (m)

- USGS Observation
- Model Result

Days since 10/25/2012

---

USGS Observation Model Result

USGS Observation

USGS Observation Model Result

---

Storm Tide Sensor

SSS-NY-KIN-003WL
Gowanus Canal at Gowanus at Brooklyn, NY

Status: approved
Status update: 2/7/2013 7:00 PM

Kings County
storm tide
Latitude: 40.69 Longitude: -73.99
Peak storm tide elevation of 11.08 feet above NAVD88, recorded on 10/30/2012 3:04:30 AM GMT

Link to full data record
(If site symbol is outlined, data is available)
Zoom to
USGS Rapid Deployment Gauge Comparison

USGS Station #404810735538063 at Harlem & East River

Water Level above MSL (m)

-1.0 -0.5 0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5

Days since 10/25/2012

x USGS Observation

Model Result

USGS Station #404810735538063 at Harlem & East River
USGS Rapid Deployment Gauge Comparison

USGS Worlds Fair Marina Flushing Bay, Queens QUE-001WL

Water Level above MSL (m)

Days since 10/25/2012

-1.5 -1.0 -0.5 0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5

0 1 2 3 4 5 6 7 8 9 10

USGS Observation

Model Result

Storm-Tide Sensor

55S-AW-QUE-001WL
Flushing Bay at Worlds Fair Marina at Queens, NY
Status: approved
Status update: 12/17/2012 7:00 PM
Queens County
storm tide
Latitude: 40.76 Longitude: -73.86
Peak storm tide elevation of 10.35 feet above NAVD88, recorded on 10/30/2012 2:66:39 AM GMT
Link to full data record
Zoom to

Map showing location of the gauge.
USGS Rapid Deployment Gauge Comparison

USGS Whitestone, Queens QUE-004WL

Water Level above MSL (m)

Days since 10/25/2012

-1.0
-0.5
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5

0
1
2
3
4
5
6
7
8
9
10

x USGS Observation

Red Model Result

Storm-Tide Sensor

SSS-NY-QUE-004WL
Long Island Sound at Whitestone at Queens, NY

Status: approved
Status update: 2/7/2013 7:00 PM
Queens County
Storm Tide
Latitude: 40.80 Longitude: -73.83
Peak storm tide elevation of 10.57 feet above NAVD88, recorded on 10/30/2012 2:10:00 AM GMT

Link to full data record
(If site symbol is outlined, data is available)

Zoom to
III. Model results comparison with USGS Hurricane Sandy Mapper

(http://54.243.149.253/home/webmap/viewer.html?webmap=c07fae08c20c4117bdb8e92e3239837e)

New York City Inundation comparison method:

1. **Distance comparison**
2. **Area comparison**
<table>
<thead>
<tr>
<th>Survey Region</th>
<th># of Points</th>
<th>Abs. Mean Dist.</th>
<th>Std. Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>New York</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>East River NY</td>
<td>48,921</td>
<td>46.779</td>
<td>58.306</td>
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<tr>
<td>Harlem River NY</td>
<td>9,978</td>
<td>44.222</td>
<td>56.696</td>
</tr>
<tr>
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<td>26,179</td>
<td>28.876</td>
<td>27.017</td>
</tr>
<tr>
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<td>78,448</td>
<td>39.959</td>
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<td>47,748</td>
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</tr>
<tr>
<td>Total Across Domain</td>
<td>100,017</td>
<td>38.430</td>
<td>38.858</td>
</tr>
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</table>

- **Southeast Bank (Brooklyn)**
- **Southeast Bank (Queens)**
- **Northwest Bank (Bronx)**
- **Northwest (Manhattan)**

**Distance Along Comparison Line (m)**

**Horizontal Distance Differential (m)**
<table>
<thead>
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</tbody>
</table>
## Distances with 40m Max Difference Adjustment

<table>
<thead>
<tr>
<th>Survey Region</th>
<th># of Points</th>
<th>Abs. Mean Dist.</th>
<th>(Diff.)</th>
<th>Std. Deviation</th>
<th>(Diff.)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>New York</strong></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>East River NY</td>
<td>47,283</td>
<td>19.907</td>
<td>26.9</td>
<td>12.984</td>
<td>45.3</td>
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<tr>
<td>Harlem River NY</td>
<td>9,673</td>
<td>18.616</td>
<td>25.6</td>
<td>12.564</td>
<td>44.1</td>
</tr>
<tr>
<td>Hudson River NY</td>
<td>21,492</td>
<td>16.484</td>
<td>12.4</td>
<td>9.840</td>
<td>17.2</td>
</tr>
<tr>
<td><strong>All New York</strong></td>
<td>78,448</td>
<td>18.336</td>
<td>21.6</td>
<td>11.796</td>
<td>35.5</td>
</tr>
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<tr>
<td><strong>All Hudson River</strong></td>
<td>37,888</td>
<td>20.281</td>
<td>12.6</td>
<td>11.444</td>
<td>17.3</td>
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<tr>
<td><strong>Total Across Domain</strong></td>
<td>94,844</td>
<td>21.207</td>
<td><strong>17.2</strong></td>
<td><strong>12.422</strong></td>
<td><strong>26.4</strong></td>
</tr>
</tbody>
</table>

(Diff.) is the difference from original distance calculation.

*The sub-grid model prediction of flood extent is within 1/2 of a foot fall field accuracy, when comparing with observation conducted by USGS.*
2. Area Comparison

(a) Hudson River, NY

<table>
<thead>
<tr>
<th>Survey Region</th>
<th>Hudson River NY</th>
</tr>
</thead>
<tbody>
<tr>
<td>Over-Predict</td>
<td>1,234,304</td>
</tr>
<tr>
<td>(%)</td>
<td>7.44</td>
</tr>
<tr>
<td>Match</td>
<td>13,076,031</td>
</tr>
<tr>
<td>(%)</td>
<td>78.80</td>
</tr>
<tr>
<td>Under-Predict</td>
<td>2,283,797</td>
</tr>
<tr>
<td>(%)</td>
<td>13.76</td>
</tr>
<tr>
<td>Total</td>
<td>16,594,132</td>
</tr>
</tbody>
</table>

(b) Hudson River, NJ

(c) East River, NY

(d) Harlem River, NY
## Areas After 40m Max Difference Adjustment

<table>
<thead>
<tr>
<th>Survey Region</th>
<th>Match (%)</th>
<th>Under-Predict (%)</th>
<th>Over-Predict (%)</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>New York</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>East River NY</td>
<td>83.55</td>
<td>7.34</td>
<td>9.11</td>
<td>16,972,143</td>
</tr>
<tr>
<td>Harlem River NY</td>
<td>83.14</td>
<td>7.15</td>
<td>9.70</td>
<td>5,361,442</td>
</tr>
<tr>
<td>Hudson River NY</td>
<td>88.04</td>
<td>7.23</td>
<td>4.74</td>
<td>14,853,203</td>
</tr>
<tr>
<td><strong>All New York</strong></td>
<td>85.28</td>
<td>7.27</td>
<td>7.45</td>
<td>37,186,788</td>
</tr>
<tr>
<td><strong>New Jersey</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hudson River NJ</td>
<td>84.95</td>
<td>7.26</td>
<td>7.78</td>
<td>20,646,001</td>
</tr>
<tr>
<td><strong>All New Jersey</strong></td>
<td>84.95</td>
<td>7.26</td>
<td>7.78</td>
<td>20,646,001</td>
</tr>
<tr>
<td><strong>All Hudson River</strong></td>
<td>86.24</td>
<td>7.25</td>
<td>6.51</td>
<td>35,499,204</td>
</tr>
<tr>
<td><strong>Total Across Domain</strong></td>
<td>85.17</td>
<td>7.27</td>
<td>7.57</td>
<td>57,832,789</td>
</tr>
</tbody>
</table>

*Area-wise, the sub-grid model prediction of flood extent covers 85% of the area, when comparing with the observation conducted by USGS.*
Sensitivity Test With and Without Sub-Grid Refinement
Grid Resolution
200m Base Grid
5m Sub-Grid
Grid Resolution
100m Base Grid
5m Sub-Grid
Grid Resolution
50m Base Grid
5m Sub-Grid
Total Volume (m$^3$) vs. Days since 10/25/2012

- 200m Base Grid
- 100m Base Grid
- 50m Base Grid
- 50m Base Grid (zoomed view)
Without Sub-Grid Refinement

200 m base grid

100 m base grid

50 m base grid

Shoreline
Total Volume (m$^3$)

Days since 10/25/2012

200m Base Grid
100m Base Grid
50m Base Grid
Recent relevant publications:


SCHISM’s new features:

1. SCHESM’s mixed quadrilateral and triangular grids allows for resolving ship channel and detail features such as major piers, Lafayette River, East Branch, West Branch, and southern Branch.

Using SMS to divide ship channels, embayment, overland before generating the model grid.
2. A cross-scale model grid, allowing 3D degenerate to 2D, 1D, to simulate from Rivers to the Ocean.
3. Addressing precipitation and infiltration

Integrating Lidar Data into a High-Resolution Topobathymetric DEM for Use with Sub-Grid Inundation Modeling at Langley Research Center

Jon Derek Loftis †, Harry V. Wang †, Russell J. DeYoung ‡, and William B. Ball §

Figure 1. Study area showing 50m resolution model grid (in grey) aligned with the Back River watershed with two tide gauges in red.

Figure 2. Model grid structure depicting a 50m base grid with a 10×10 nested 5m sub-grid showing the northeast tip of Langley Air Force Base with partially wet (blue) and partially dry (brown) grid cells.

Figure B. Land use map for precipitation and infiltration calculation
Operational Benchmark and software support

- Large scale storm tide model of ~200 k nodes used in Hurricane Sandy takes CPU time 180 time of real time on a infini-band Dell cluster with 128 processors. The 5 days simulation finished within 40 minutes (without wind wave).
- Commercial usage can be supported by Amazon cloud computing
- In a small cases, can be run under Windows 8 – 16 cores.
- The inundation model is executed on a window 7, 64 bit, 16 cores, 24 GB Ram. It takes 2.5 hour to run 10 days simulation with graphic user interface. Without graphic user interface, it takes 45 minutes to finish.
- Software supported by SMS pre- and post-processing. ACE tool is free-ware. For 3D supported by VisIT visualization.
- SCHISM is a community model supported by national and international community including: California Department of Water Resources, Oregon Department of Geology & Mineral Industries (DOGAMI), Helmholtz-Zentrum Geesthacht (Germany), Niedersachsischer Landesbetrieb fur Wasserwirtschaft, Kusten- und Naturschutz (Germany), The German Federal Institute of Hydrology (BfG), Central Weather Bureau (Taiwan), National Laboratory for Civil Engineering (Portugal) and Tsinghua Univ. (China).
Receiving award for conducting operational Forecast during Hurricane Irene

VIMS ECM group won 2011 Governor’s Innovative technology award

Dr. John Wells
Virginia Institute of Marine Science
P.O. Box 1346
Gloucester Point, Virginia 23062

Dear Dr. Wells:

We at the National Weather Service would like to express our appreciation for all the help and support provided by VIMS during Irene. Dr. Harry Wang contributed by producing 6 hourly runs of forecast storm surge. The details provided by his surge model enhanced the National Weather Service’s ability to provide critical forecast surge information to emergency managers. These forecasts were particularly useful when examining various bays and tributaries along the lower sections of the Chesapeake Bay. The COMET funded project with Dr. John Brubaker provided an excellent web site for use in observing real time water levels and forecasting location specific storm tide. The constant updating of the observations provided quick feedback allowing us to verify forecasts and monitor rapidly rising water levels as Irene approached. The comparison between the extratropical storm surge model and VIMS model with real time data provided quick feedback as to how forecasts were verifying compared to observational data.

It must be noted that these services were all provided without any funding highlighting VIMS’s commitment to applying research into operations. The services directly contributed to improved forecasts and information for Virginia residents which had an impact on the protection of life and property. Thank you for all the hard work which helped to better serve the public.

Sincerely,

[Signature]

August 29, 2011
Summary

1. Given recent advancement in the atmospheric modeling, VIMS have partnered with WeatherFlow to provides real-time large-scale meteorological forcing for driving the SCHISM/SELFE storm tide model.

2. The storm surge and tide model that covers the domain of entire US East Coast can be executed accurately, efficiently, reliably, with moderate computing resources, as demonstrated by the Hurricane Sandy simulation.

3. The large scale storm tide model is an unstructured finite element model with mixed quadrilateral and triangular grid and can be extended upstream from 3D, 2D to 1D for cross-scale modeling. It already couples with wind
wave model and can be coupled with rivers, small creeks and the sea level rise scenario in 3D manner.

4. The high resolution, sub-grid model using nonlinear solver, which directly incorporating LIDAR data into model proved to be capable of simulating street-level inundation robustly and accurately to 30 m and 85% coverage, as demonstrated by Hurricane Sandy application.

5. Going forward, future enhancements include the effects of precipitation, infiltration, urban storm water drainage, and coupling with ODU’s Gulf-stream-induced sea level rise scenario.