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Storm Surge and Street-Level Inundation Modeling in New York City During Hurricane Sandy

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Hampton Roads Adaption Forum , February 23, 2015

WILLIAM & MARY
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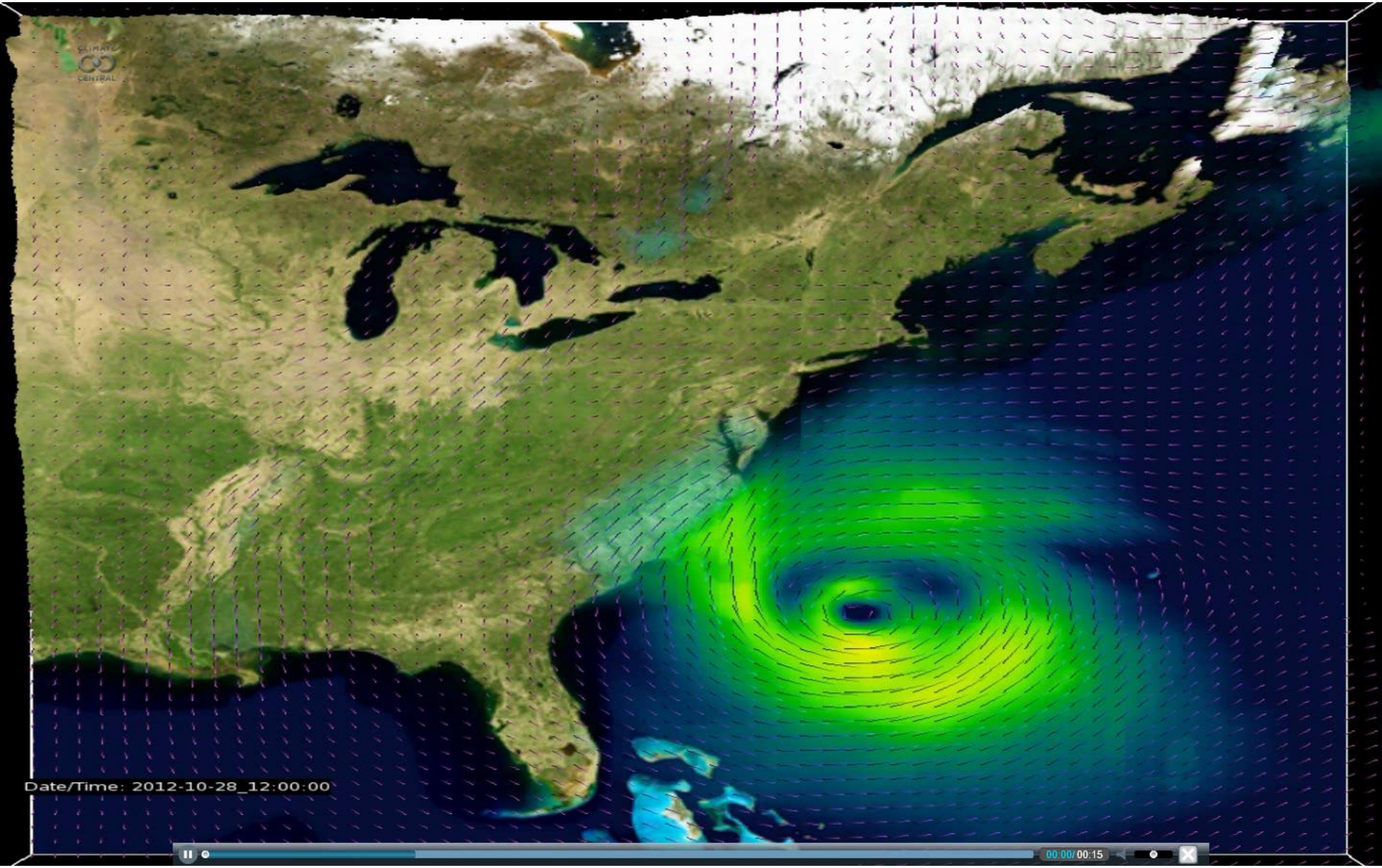
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Motivation

Outline

- Large scale storm tide and wind wave modeling using un-structured grid model SCHISM

- Vey 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/

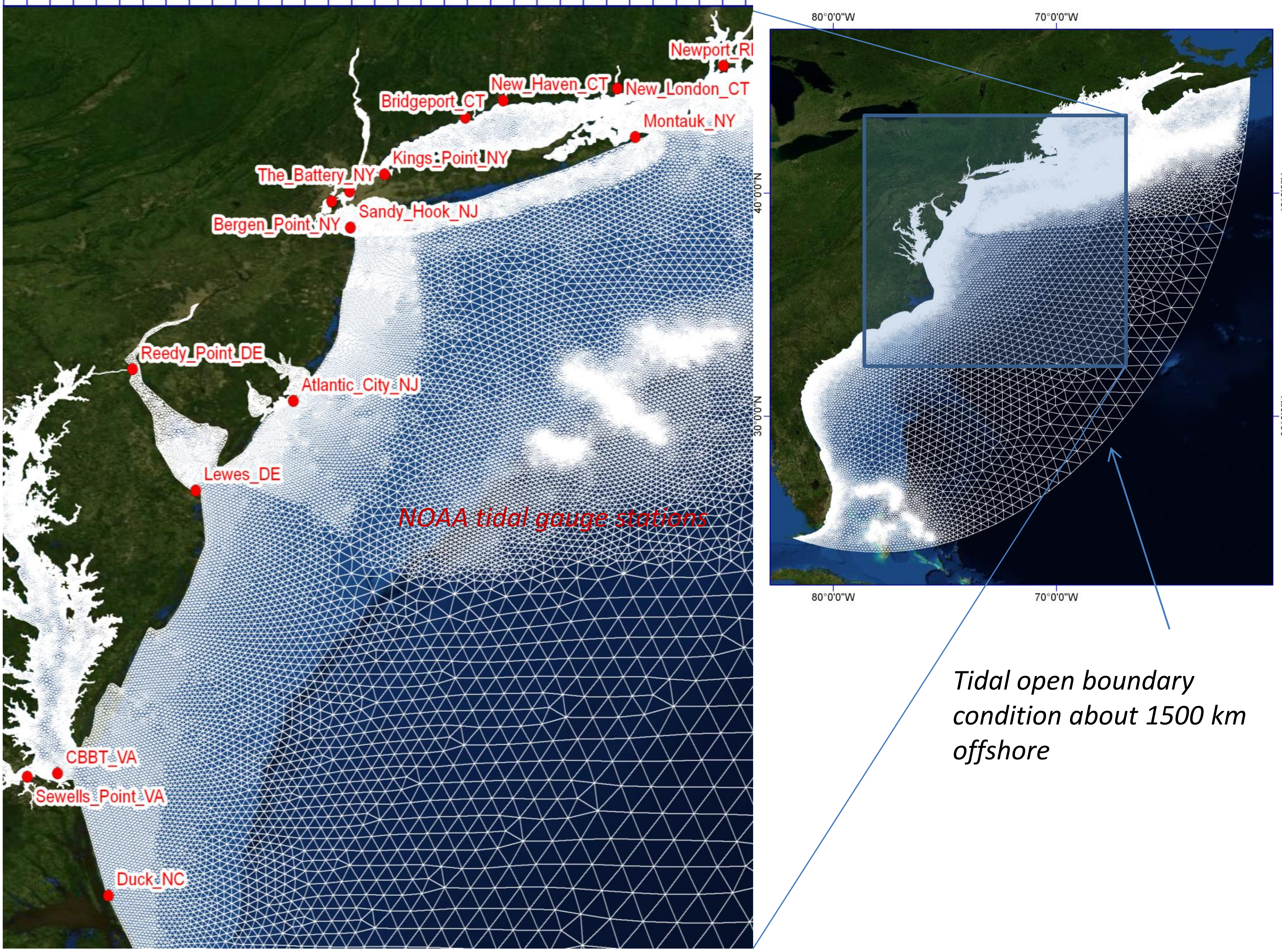
Key Features:

- **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.**


Newport_RI
New_Haven_CT
New_London_CT
Bridgeport_CT
Montauk_NY
Kings_Point_NY
The_Battery_NY
Sandy_Hook_NJ
Bergen_Point_NY
Reedy_Point_DE
Atlantic_City_NJ
Lewes_DE
NOAA tidal gauge stations
CBBT_VA
Sewells_Point_VA
Duck_NC
80°0'0"W
70°0'0"W
40°0'0"N
30°0'0"N
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

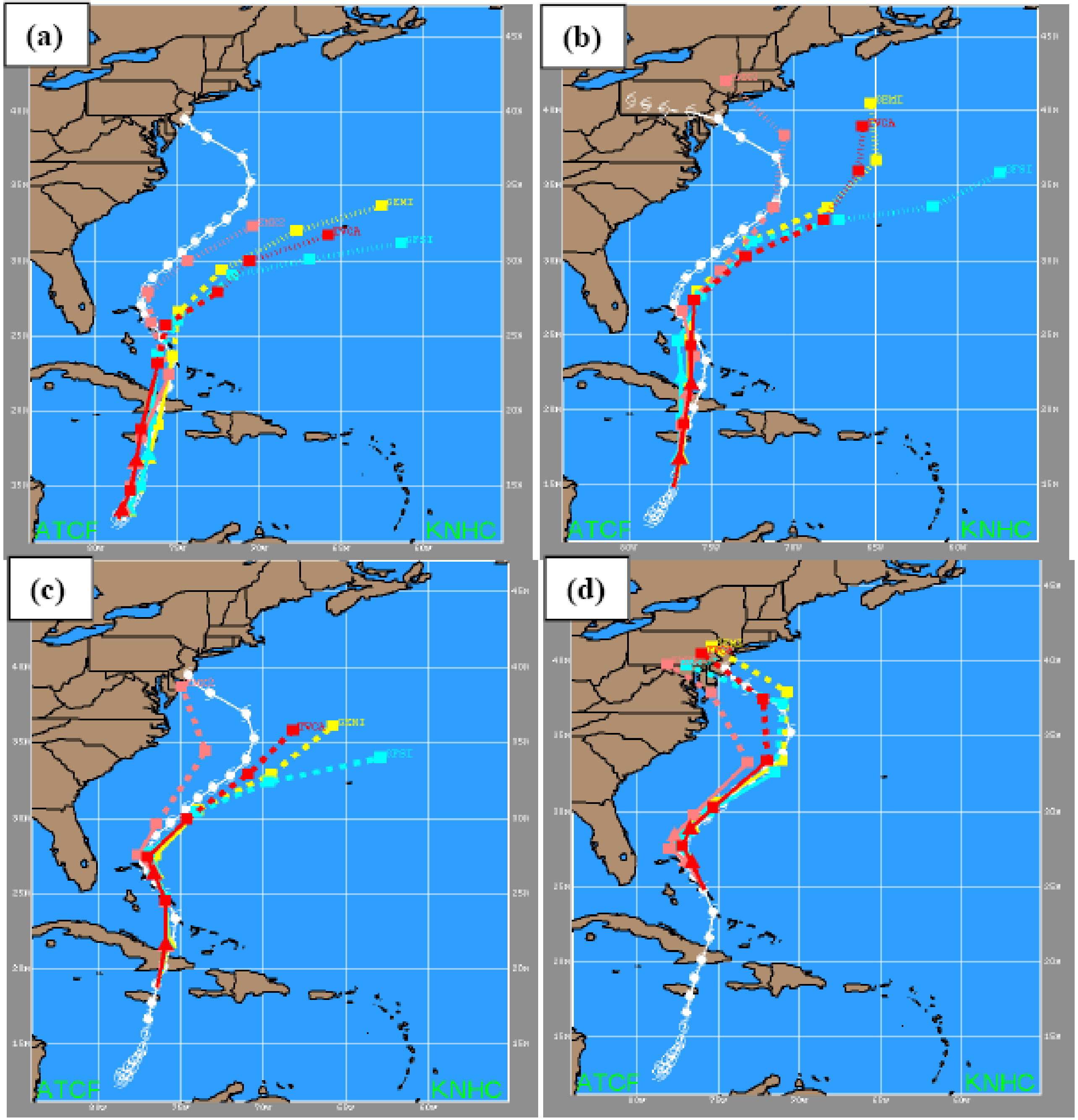


Figure 31: Model forecast tracks for Sandy at 0000 UTC 23 October (a), 000 UTC 24 October (b), 000 UTC October 25 (c), and 000 UTC 26 October, (d).

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

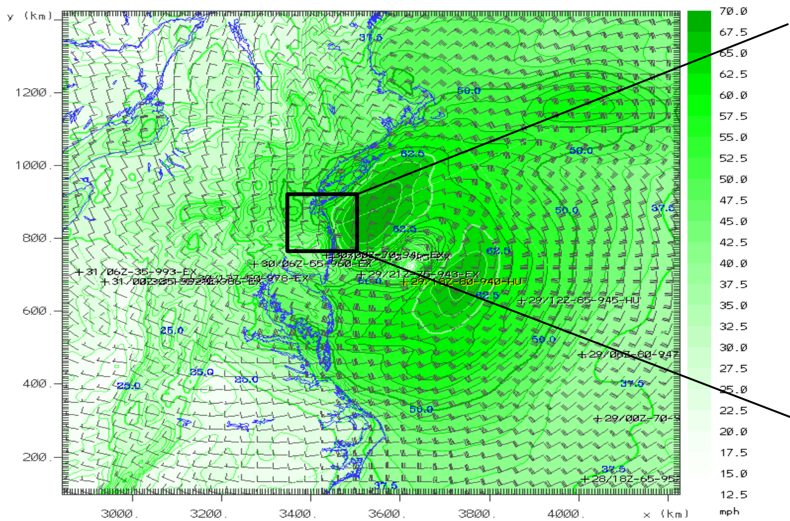
From: Blake, Eric, et al. (2013): Tropical Cyclone Report: Hurricane Sandy, National Hurricane Center,

The Impact of Winds on Storm Surge and Inundation

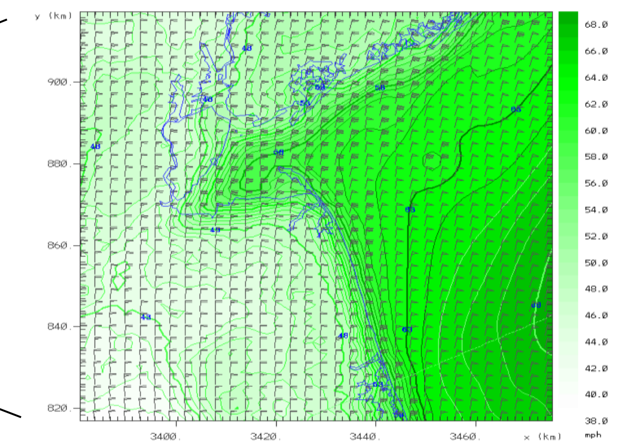
- Standardization allows assimilation of a larger number of high quality observations
- Gridded model reanalysis (RAMS/4DDA (past) --> GSI/WRF (future))
- Nested grids
    - Basin: 6-12 km depending on initializing analysis
    - Storm: 3km
    - Coastal zone: 1km or less

- 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

StormPrint



		grid 1			
z = 9.7 m	2012–10–29–1900.00 UTC	min	max	inc	lab*
contours	open field wind speed (mph)	13.88	69.95	2.500	1e 0
barbs	staff 4 m/s flag 20 m/s	2.670	27.07		

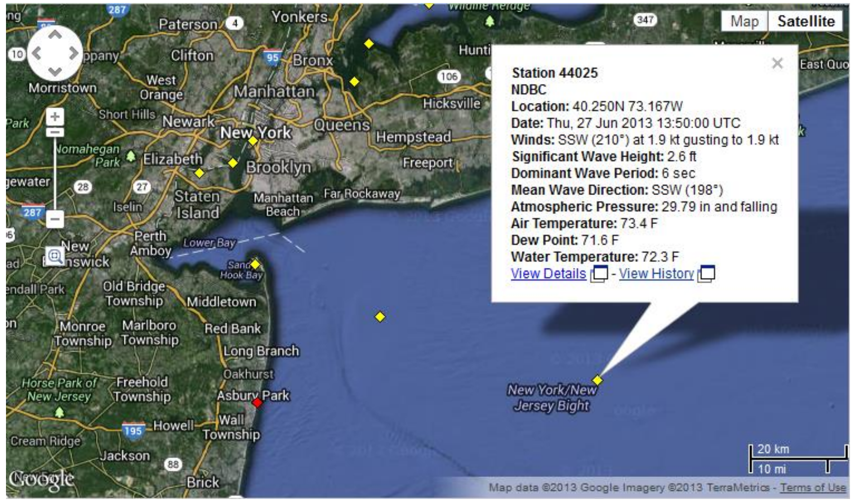


		grid 2			
z = 9.7 m	2012–10–29–1900.00 UTC	min	max	inc	lab*
contours	open field wind speed (mph)	38.93	68.51	1.000	1e 0
barbs	staff 4 m/s flag 20 m/s	7.696	26.47		

WeatherFlow
Better Data. Better Decisions.

Wind field comparisons at 18 stations: NOAA observations (Blue) vs NAM/WF** (Red)

New York area

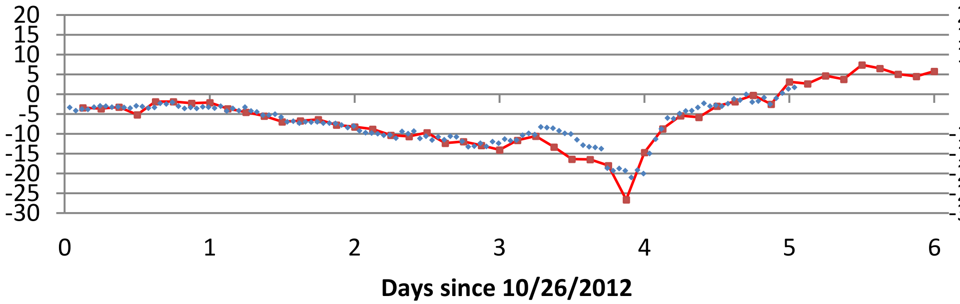


**WF: RMAS (Regional Atmospheric modeling System) carried out by Weather Flows Inc.

NAM

WF

u



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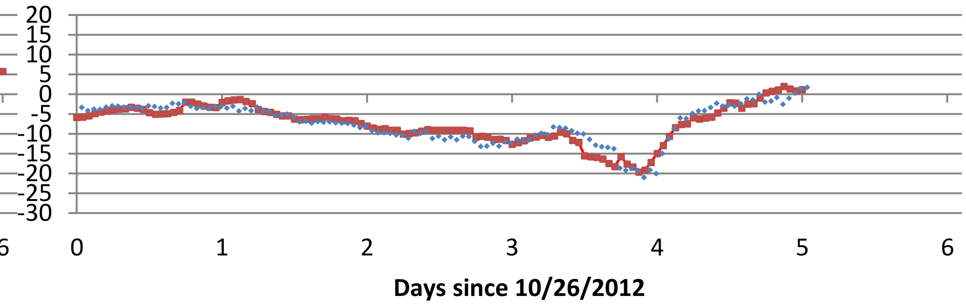
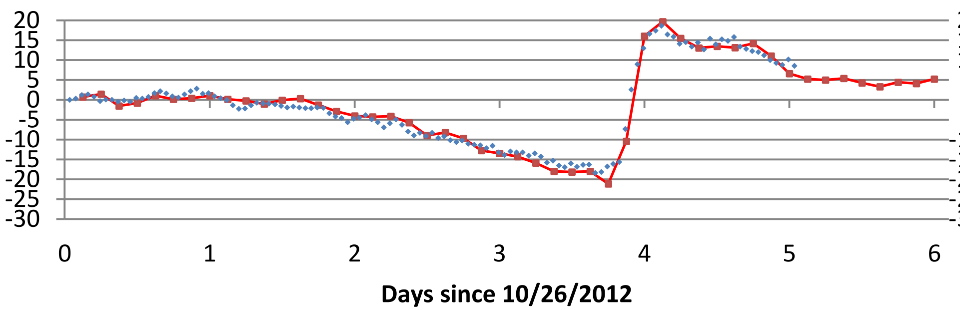
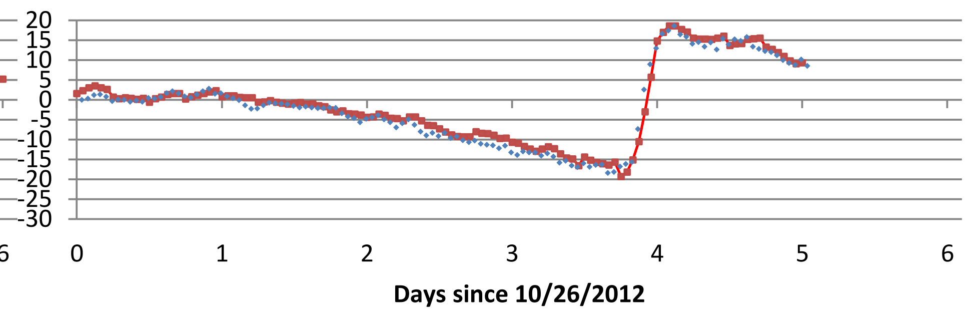


v

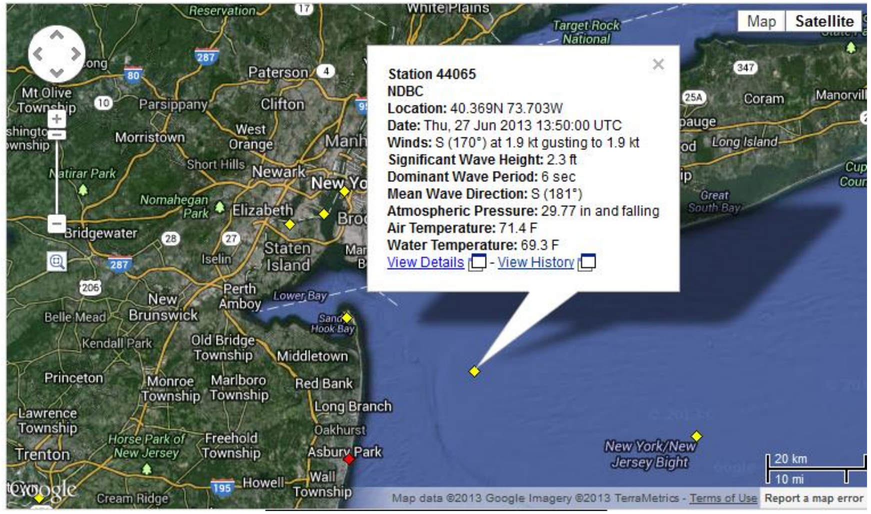


v



Wind field comparisons at 18 stations: NOAA observations (Blue) vs NAM/WF (Red)

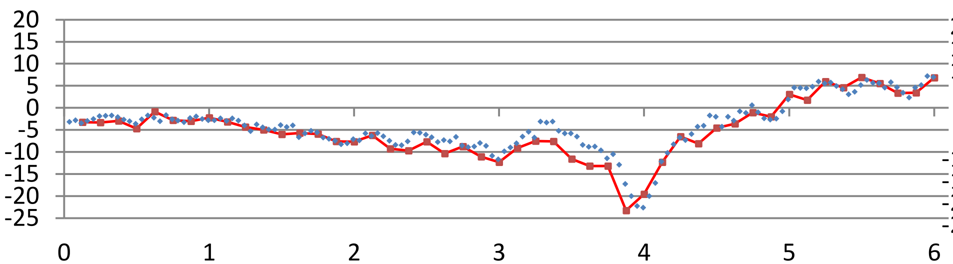
New York area



NAM

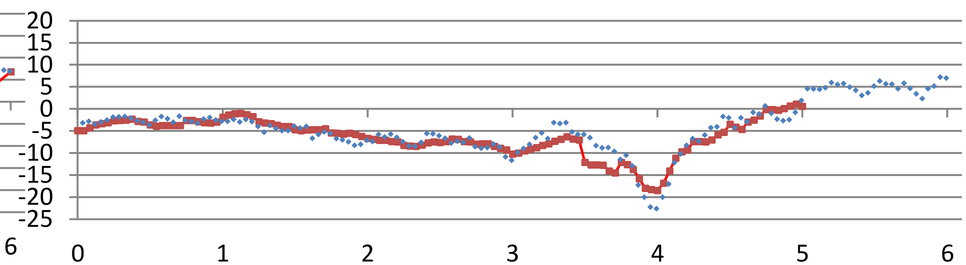
WF

u



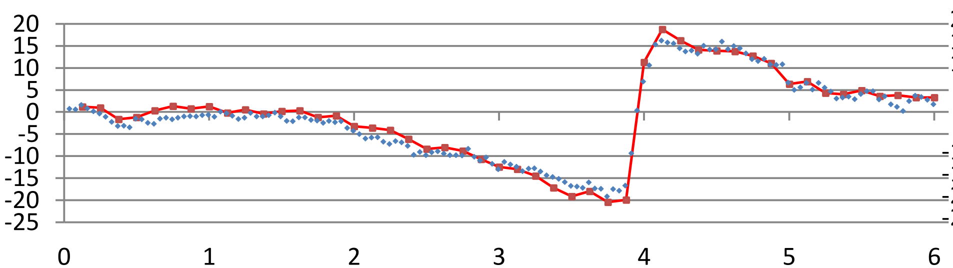
Days since 10/26/2012

u



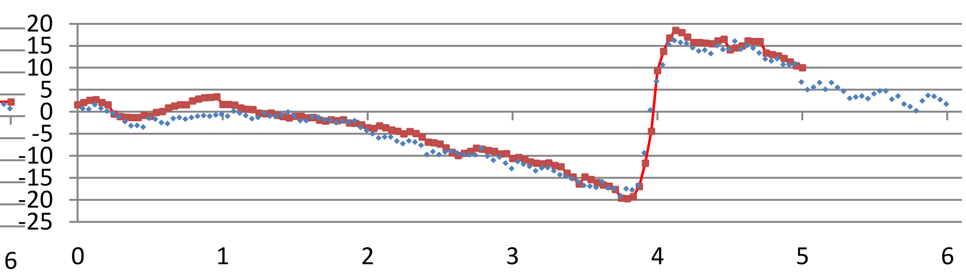
Days since 10/26/2012

v



Days since 10/26/2012

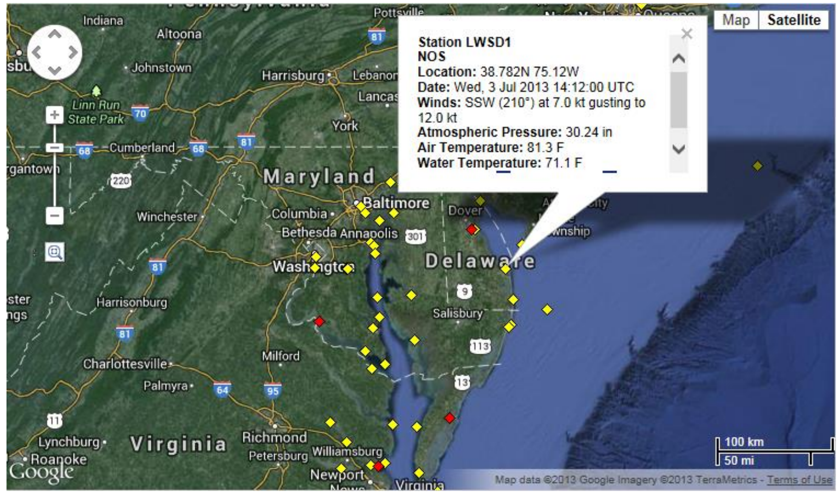
v



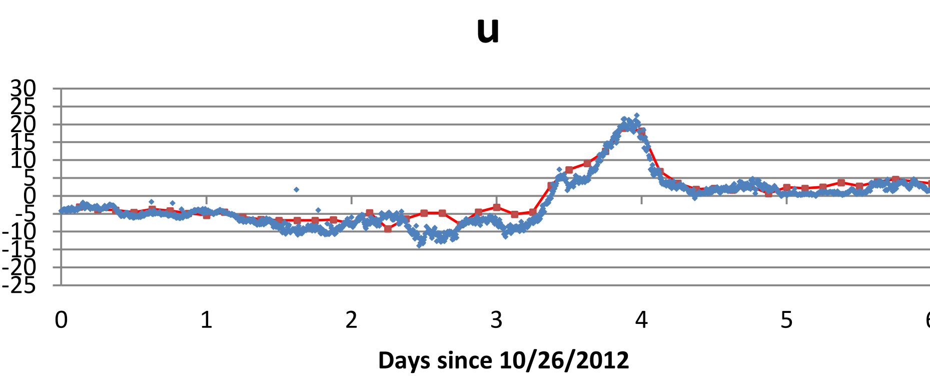
Days since 10/26/2012

Wind field comparisons at 18 stations: NOAA observations (Blue) vs NAM/WF (Red)

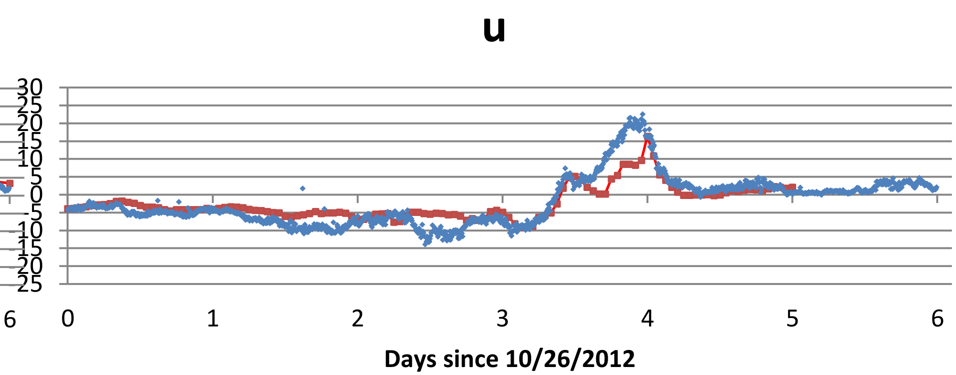
Delaware coast

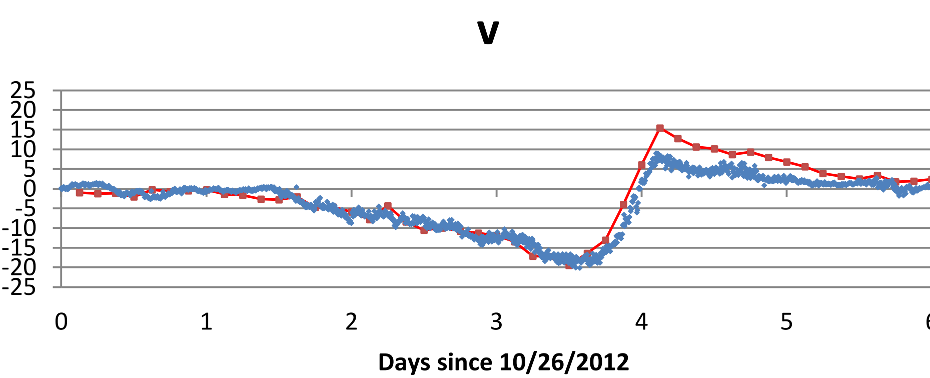


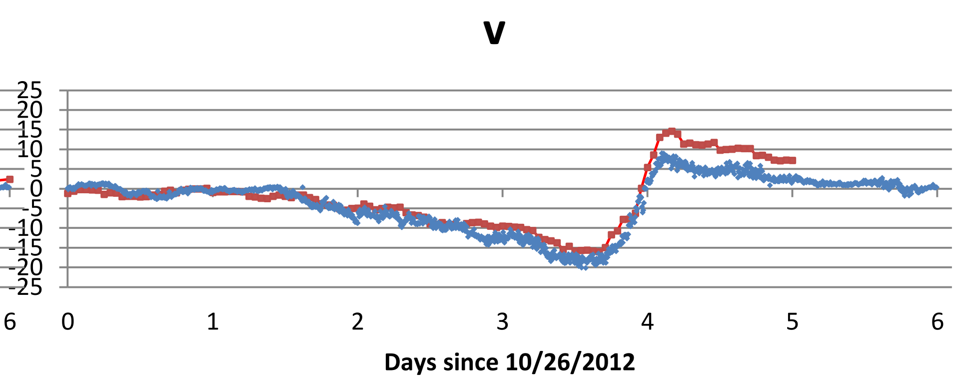
NAM



WF

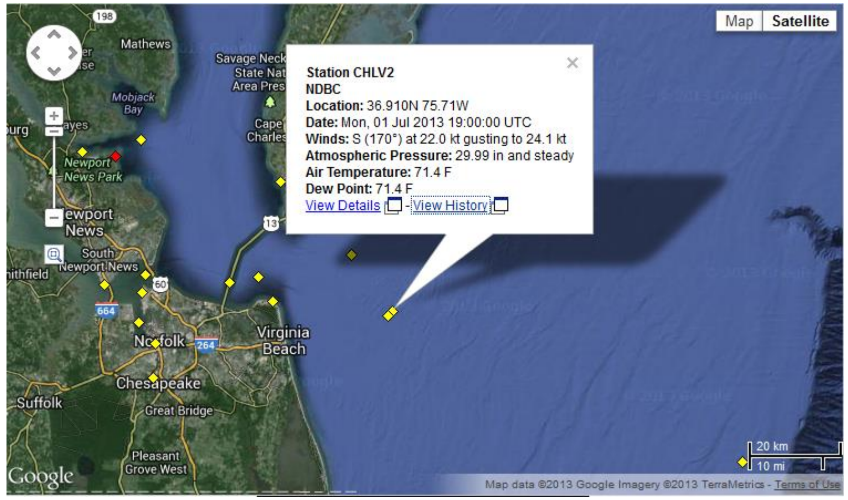






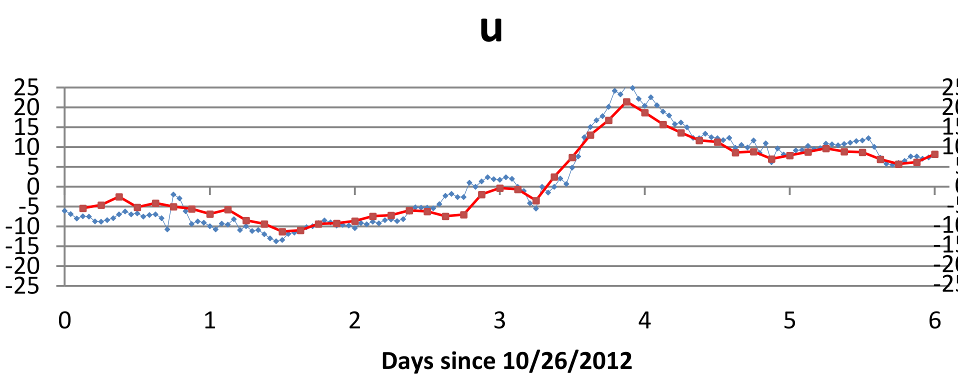
Wind field comparisons at 18 stations: NOAA observations (Blue) vs NAM/WF (Red)

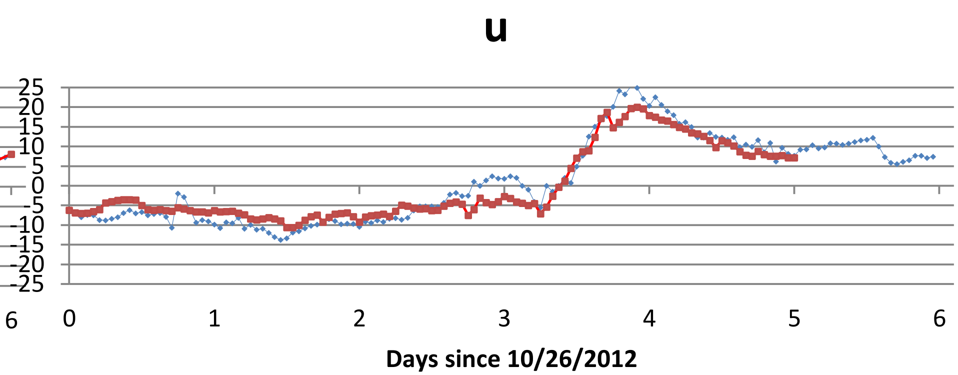
Chesapeake Bay

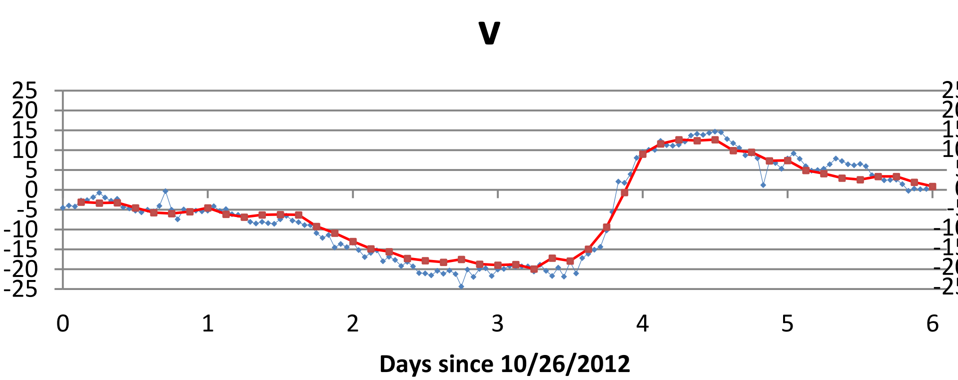


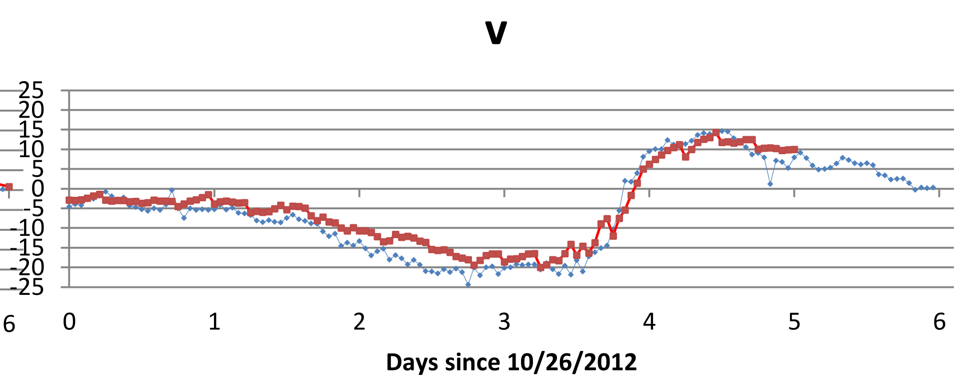
NAM

WF







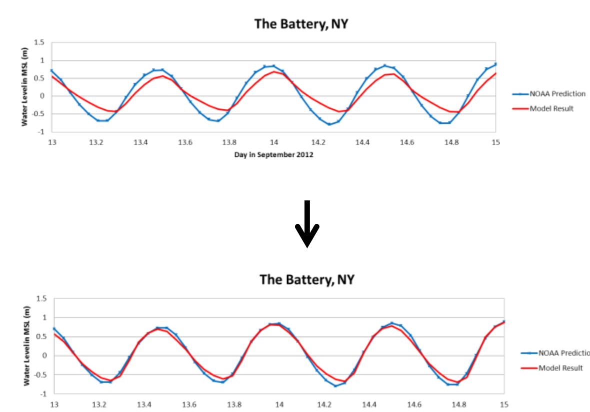


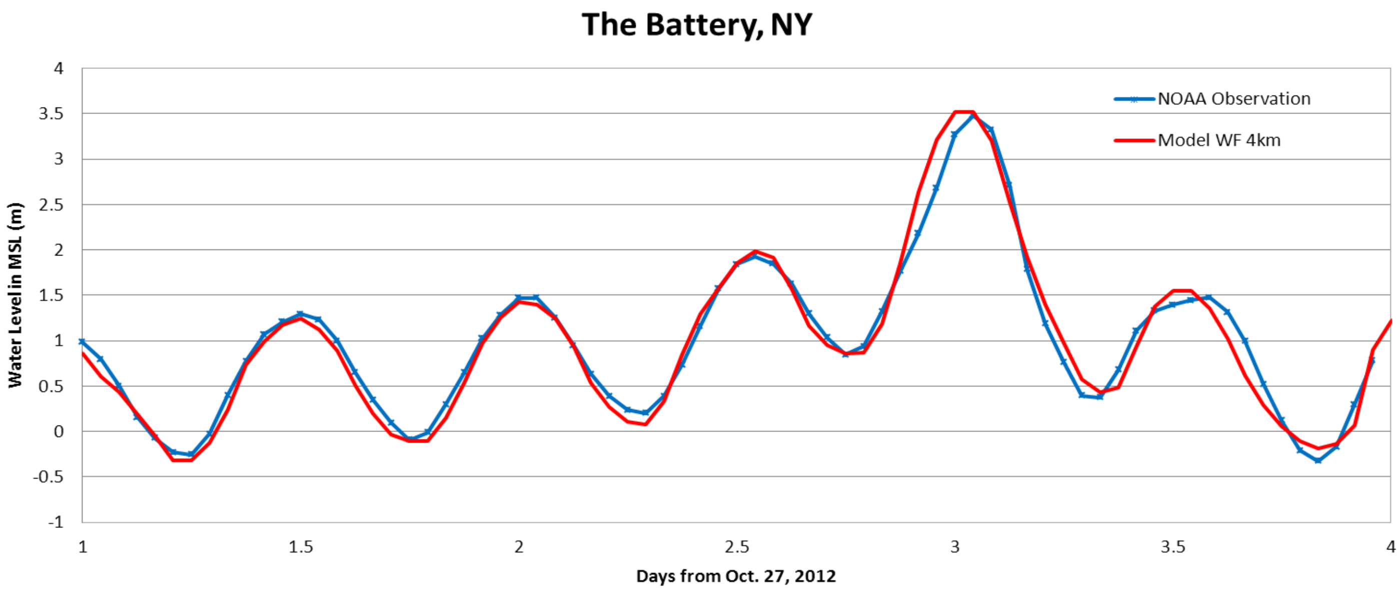
Friction formulation using Manning coefficient

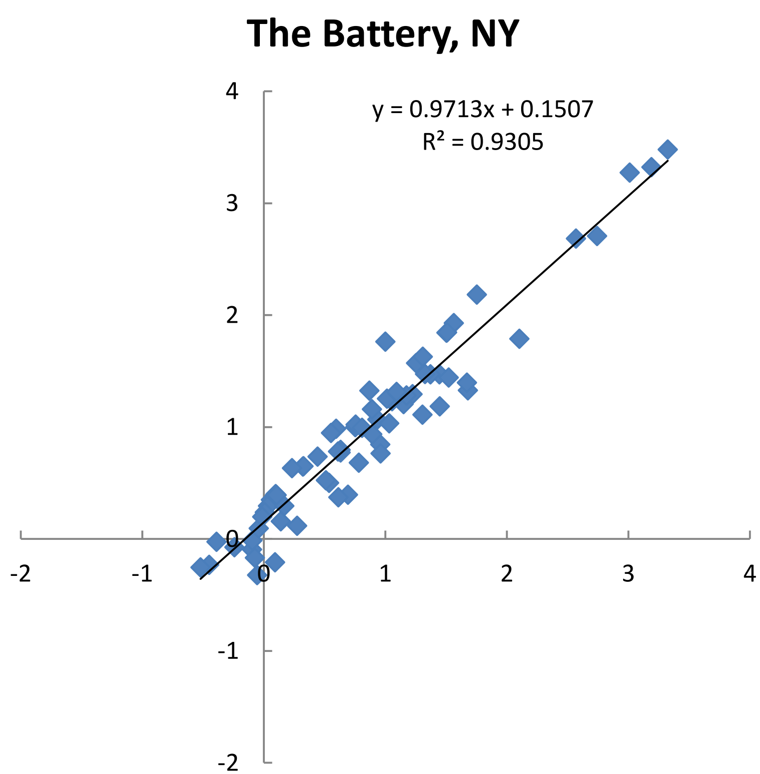
Manning n = 0.025 everywhere except

(1) New York Harbor n=0.010

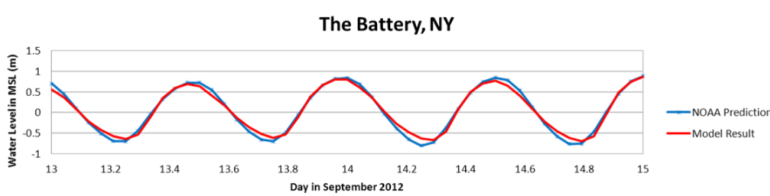
(2) East and Harlem Rivers n= 0.045

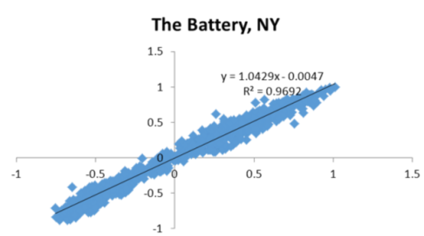


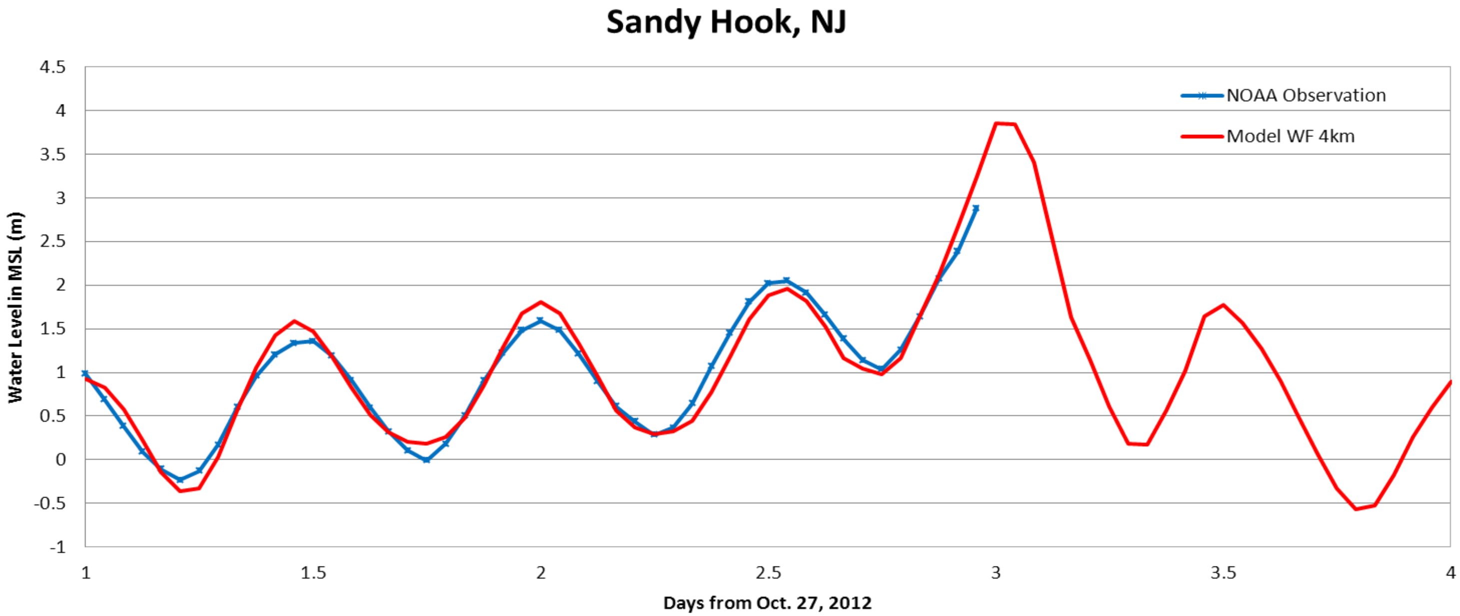

The Battery, NY
NOAA Observation
Model WF 4km
Water Level in MSL (m)
Days from Oct. 27, 2012
4
3.5
3
2.5
2
1.5
1
0.5
0
-0.5
-1
1
1.5
2
2.5
3
3.5
4

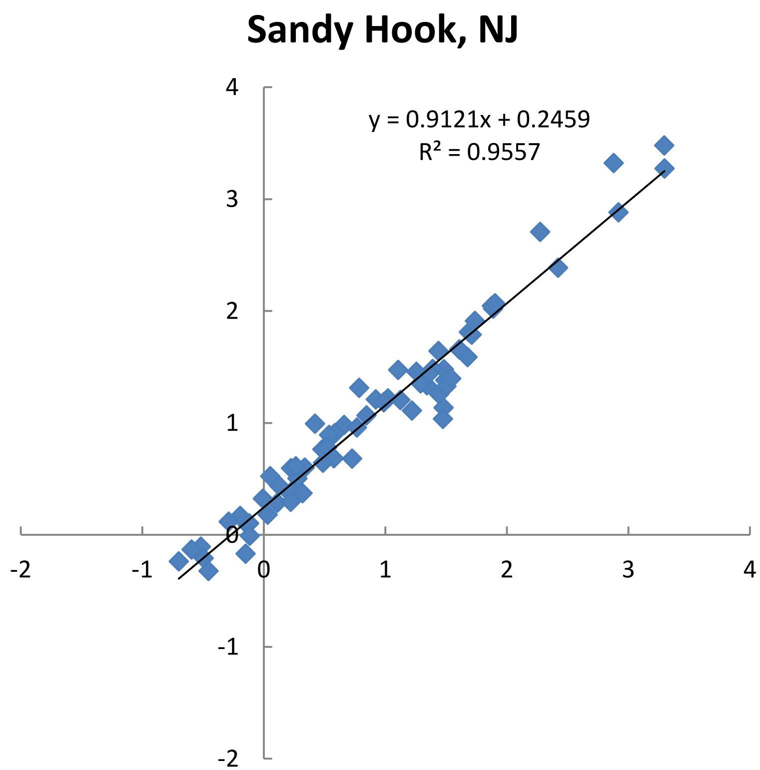

The Battery, NY
y = 0.9713x + 0.1507
R² = 0.9305
4
3
2
1
0
-1
-2
-2
-1
0
1
2
3
4

Tide only

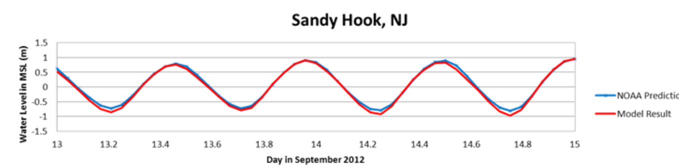

The Battery, NY
Water Level in MSL (m)
NOAA Prediction
Model Result
Day in September 2012
1.5
1
0.5
0
-0.5
-1
13
13.2
13.4
13.6
13.8
14
14.2
14.4
14.6
14.8
15

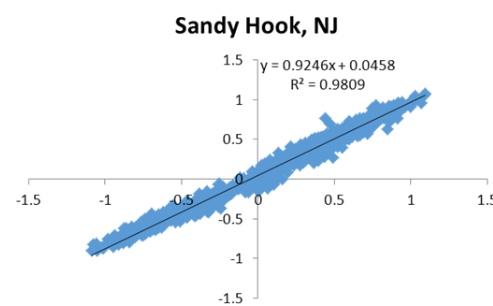

The Battery, NY
y = 1.0429x - 0.0047
R² = 0.9692
1.5
1
0.5
0
-0.5
-1
-1
-0.5
0
0.5
1
1.5

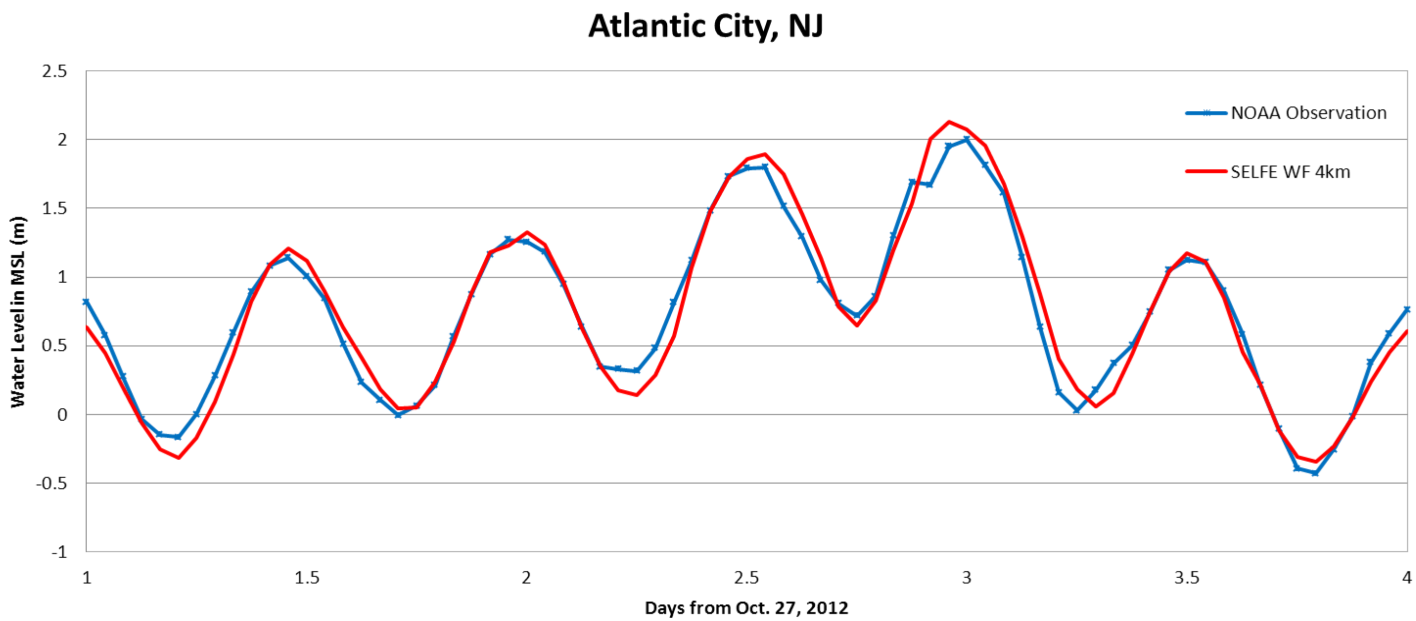

Sandy Hook, NJ
NOAA Observation
Model WF 4km
Water Level in MSL (m)
Days from Oct. 27, 2012

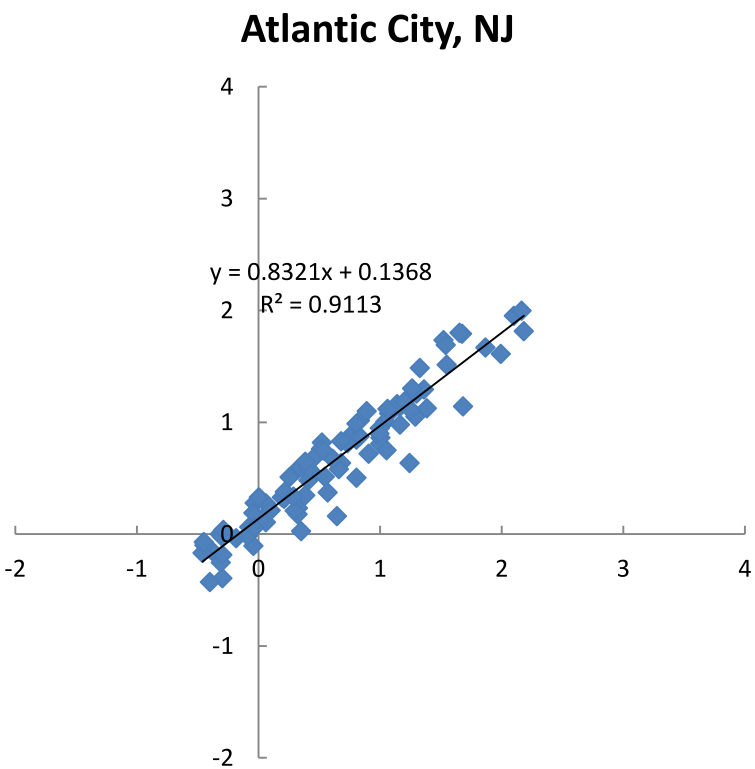

Sandy Hook, NJ
y = 0.9121x + 0.2459
R² = 0.9557

Tide only

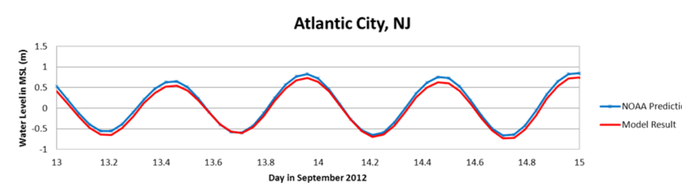

Sandy Hook, NJ
NOAA Prediction
Model Result
Water Level in MSL (m)
Day in September 2012

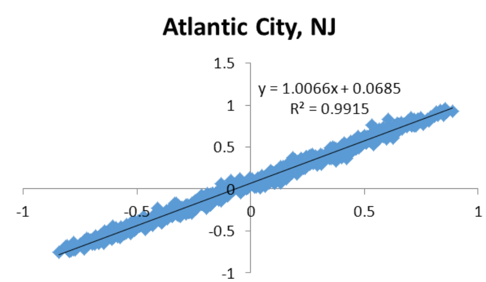

Sandy Hook, NJ
y = 0.9246x + 0.0458
R² = 0.9809

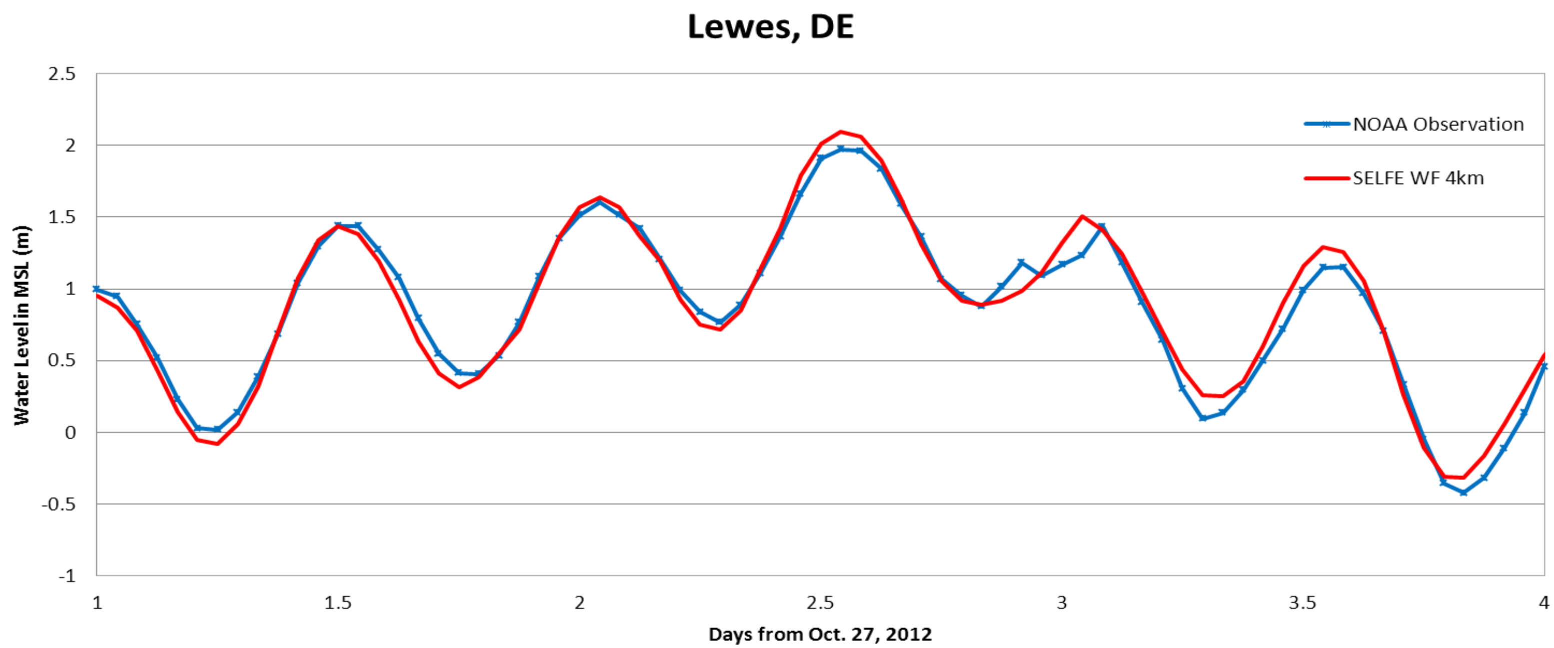

Atlantic City, NJ
NOAA Observation
SELFE WF 4km
Water Level in MSL (m)
Days from Oct. 27, 2012

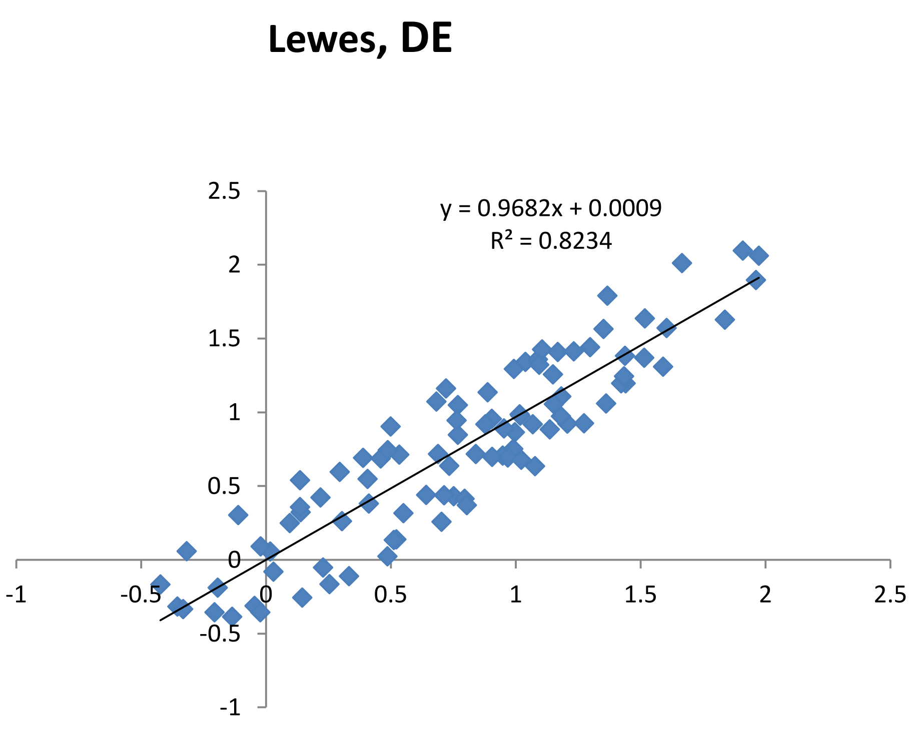

Atlantic City, NJ
y = 0.8321x + 0.1368
R² = 0.9113

Tide only

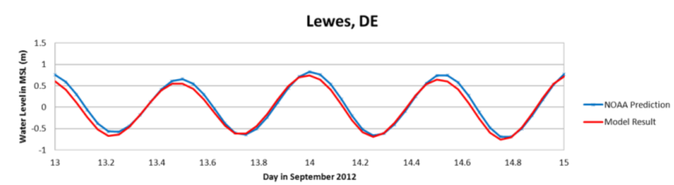

Atlantic City, NJ
NOAA Prediction
Model Result
Water Level in MSL (m)
Day in September 2012

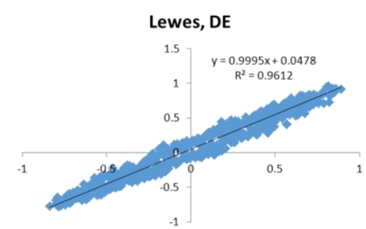

Atlantic City, NJ
y = 1.0066x + 0.0685
R² = 0.9915


Lewes, DE
NOAA Observation
SELFE WF 4km
Water Level in MSL (m)
Days from Oct. 27, 2012
2.5
2
1.5
1
0.5
0
-0.5
-1
1
1.5
2
2.5
3
3.5
4

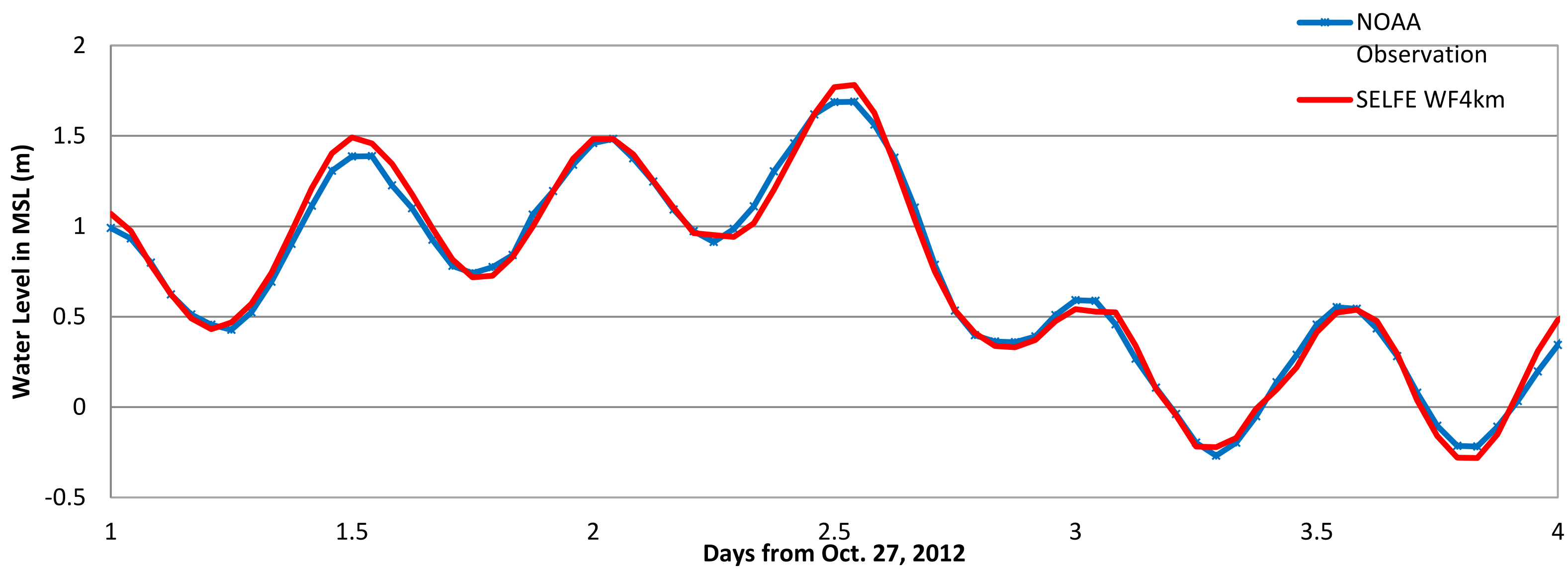

Lewes, DE
y = 0.9682x + 0.0009
R² = 0.8234
2.5
2
1.5
1
0.5
0
-0.5
-1
-1
-0.5
0
0.5
1
1.5
2
2.5

Tide Only

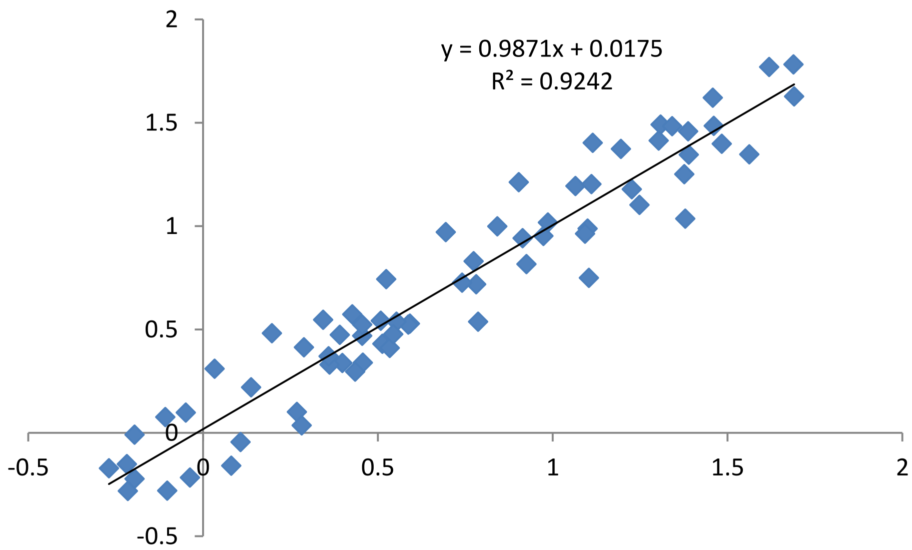

Lewes, DE
NOAA Prediction
Model Result
Water Level in MSL (m)
Day in September 2012


Lewes, DE
y = 0.9995x + 0.0478
R² = 0.9612

CBBT, VA



CBBT, VA



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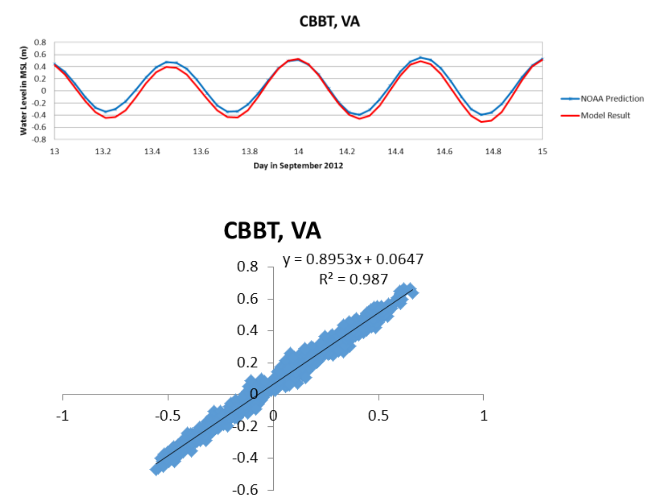
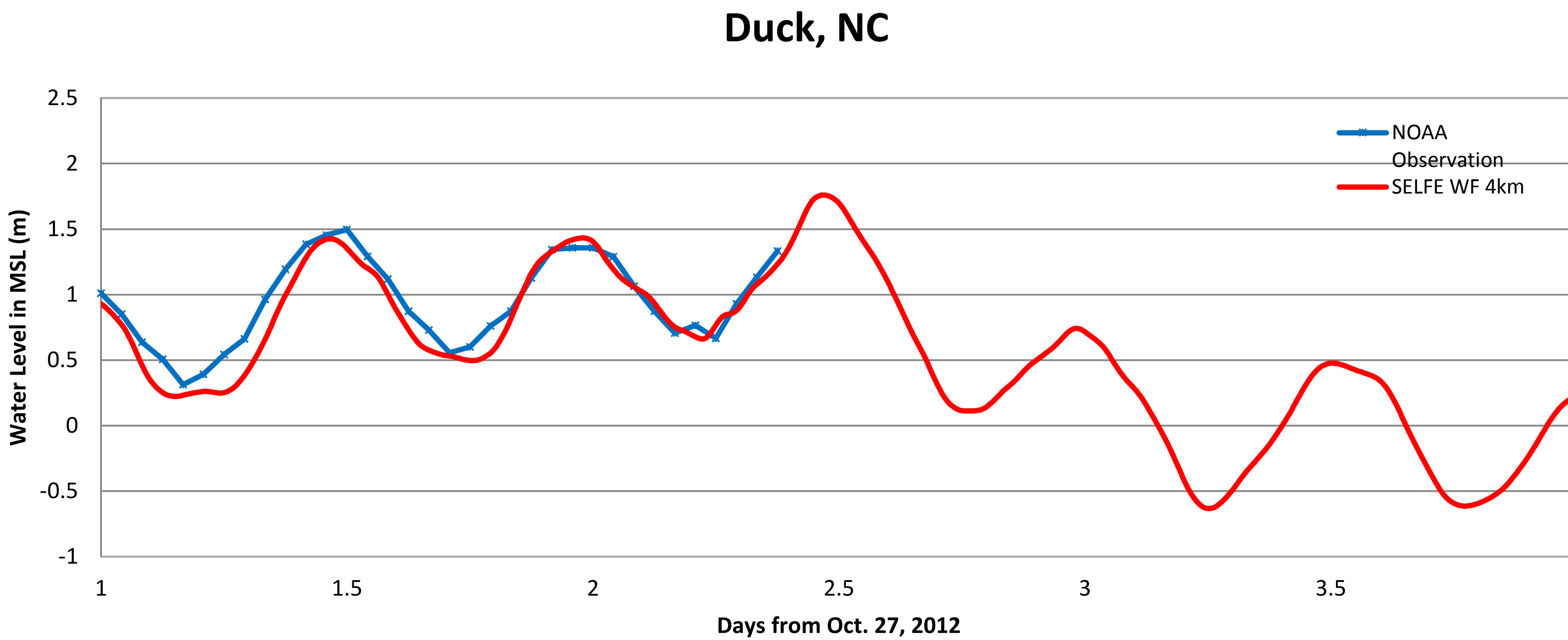
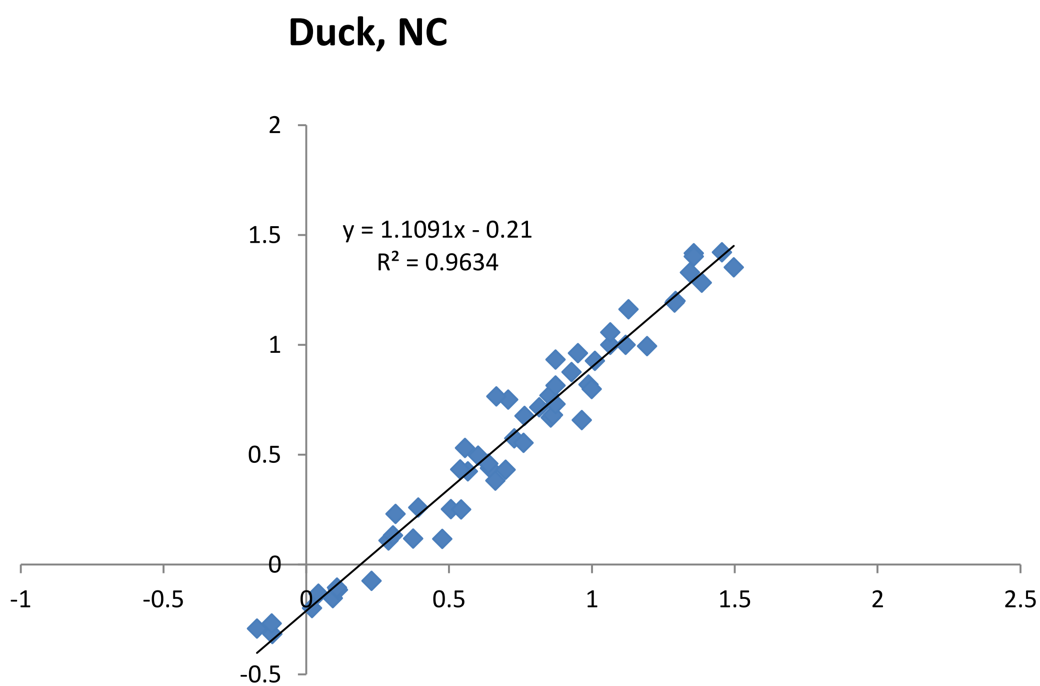


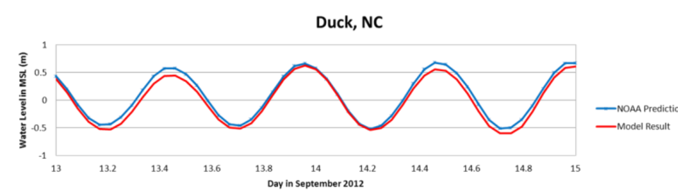


Duck, NC
Water Level in MSL (m)
Days from Oct. 27, 2012
NOAA Observation
SELFE WF 4km
2.5
2
1.5
1
0.5
0
-0.5
-1
1
1.5
2
2.5
3
3.5
4

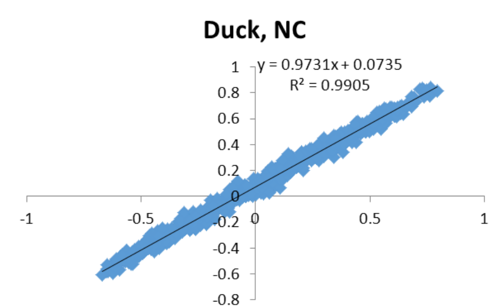


Duck, NC
y = 1.1091x - 0.21
R^2 = 0.9634
2
1.5
1
0.5
0
-0.5
-1
0.5
1.5
2.5

Tide only

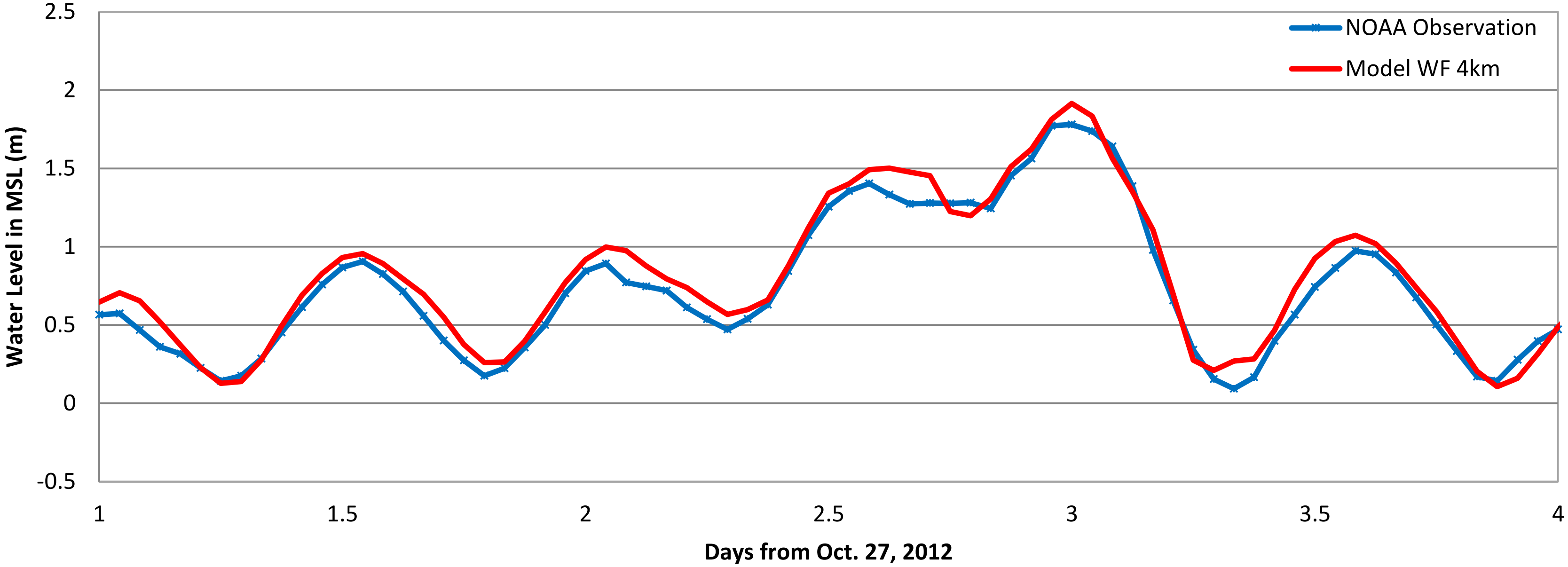


Duck, NC
Water Level in MSL (m)
Day in September 2012
NOAA Prediction
Model Result

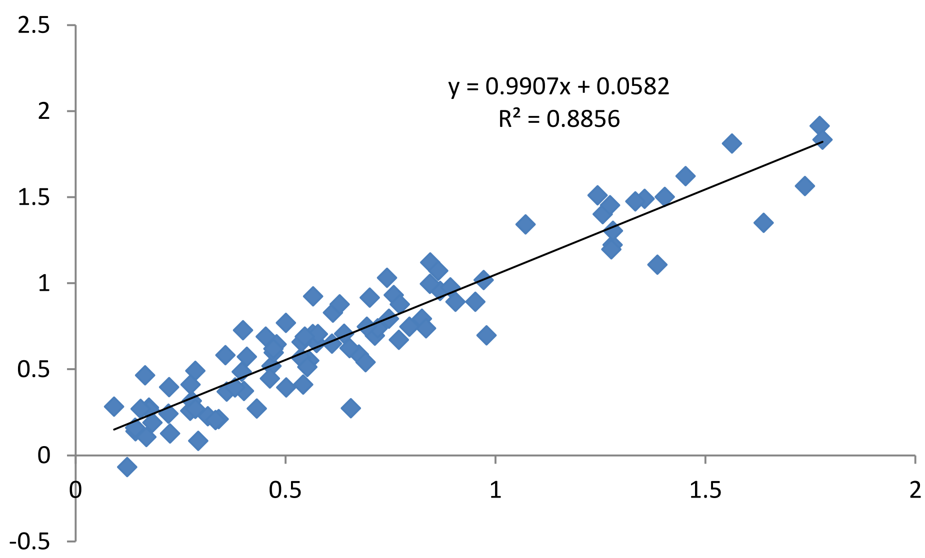


Duck, NC
y = 0.9731x + 0.0735
R^2 = 0.9905

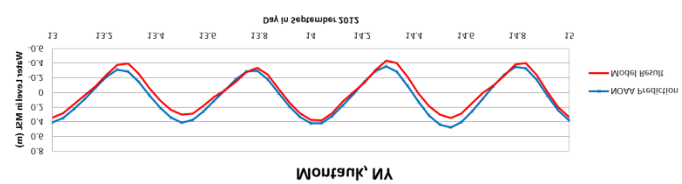
Montauk, NY

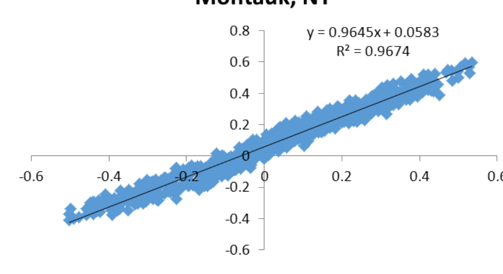


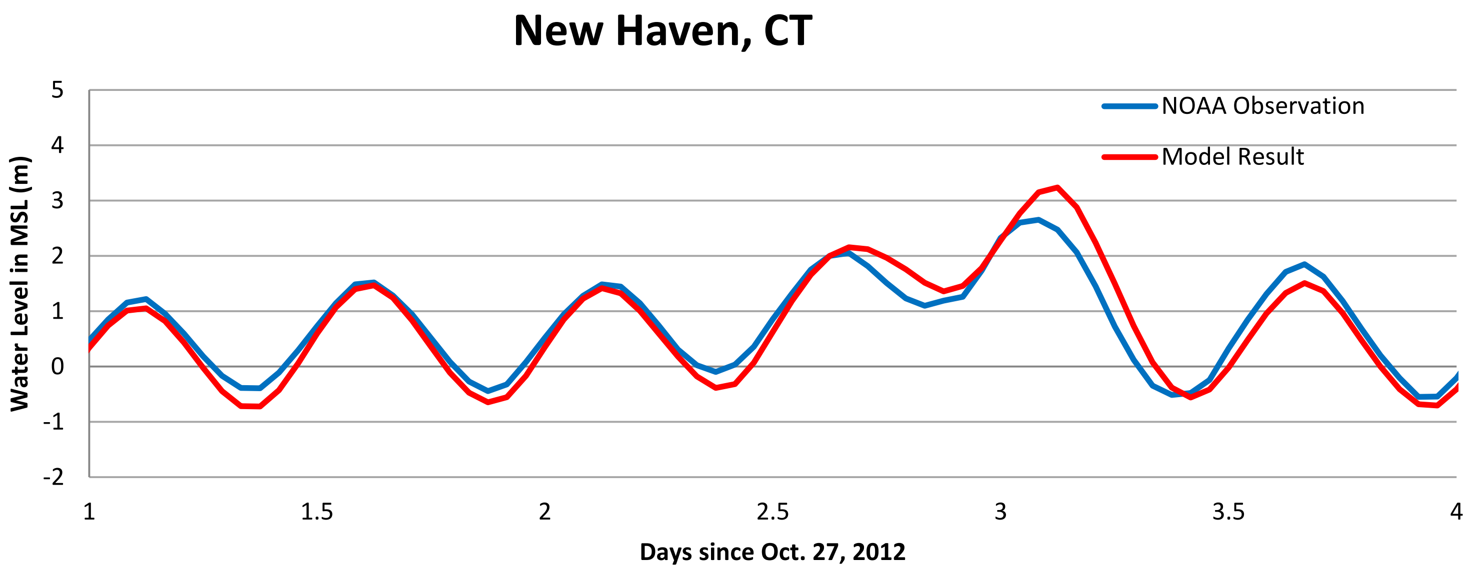
Montauk, NY

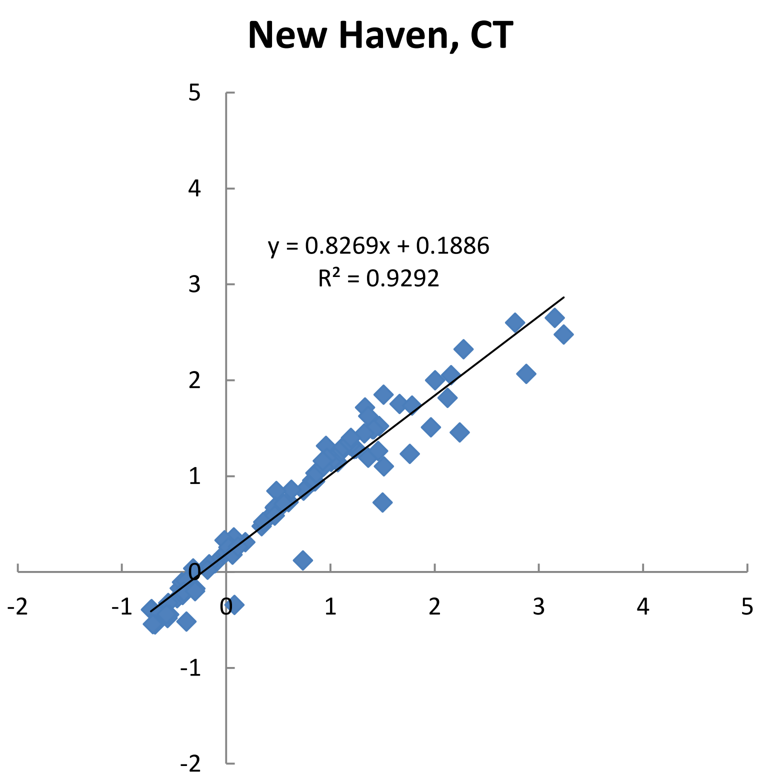


Tide only

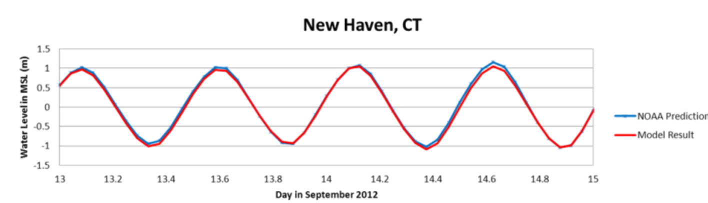


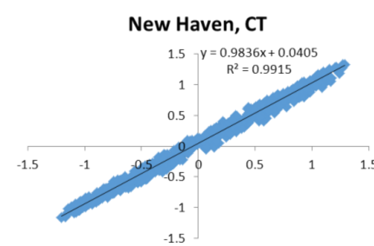


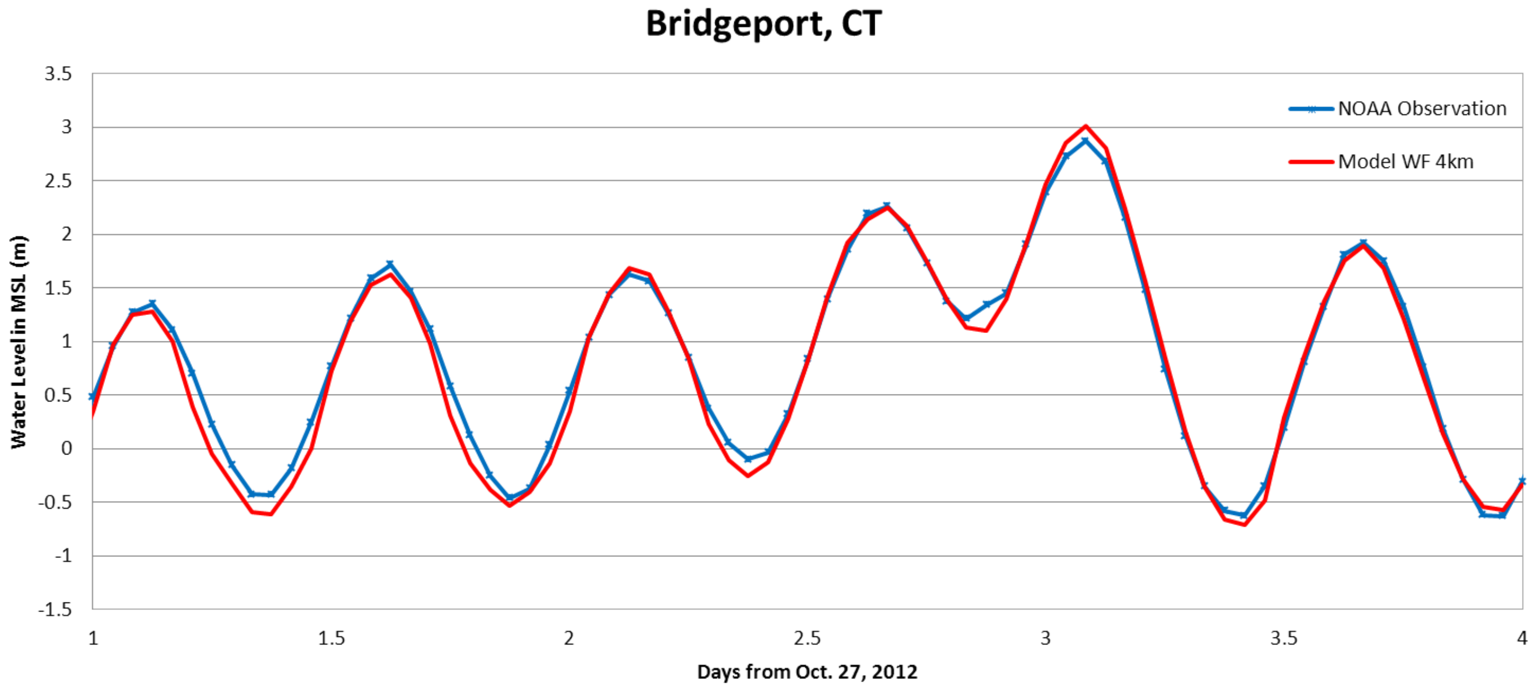

New Haven, CT
NOAA Observation
Model Result
Water Level in MSL (m)
5
4
3
2
1
0
-1
-2
1
1.5
2
2.5
3
3.5
4
Days since Oct. 27, 2012

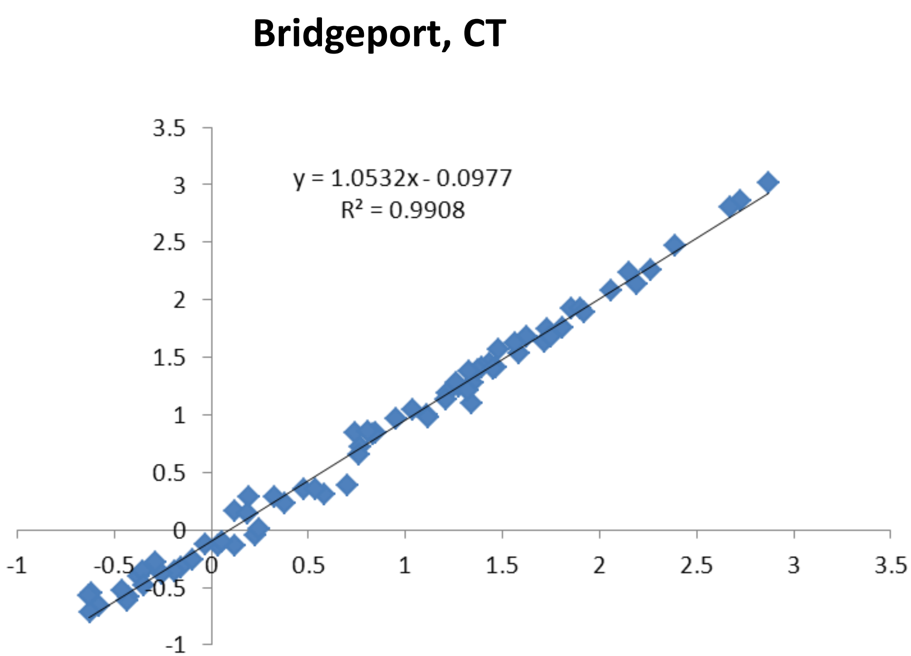

New Haven, CT
y = 0.8269x + 0.1886
R² = 0.9292
5
4
3
2
1
0
-1
-2
-2
-1
0
1
2
3
4
5

Tide only

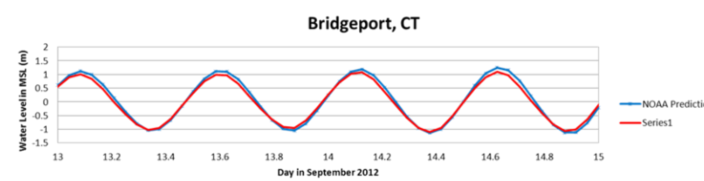

New Haven, CT
NOAA Prediction
Model Result
Water Level in MSL (m)
Day in September 2012

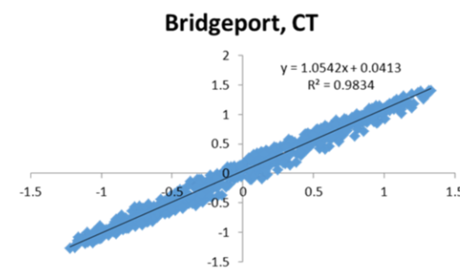

New Haven, CT
y = 0.9836x + 0.0405
R² = 0.9915

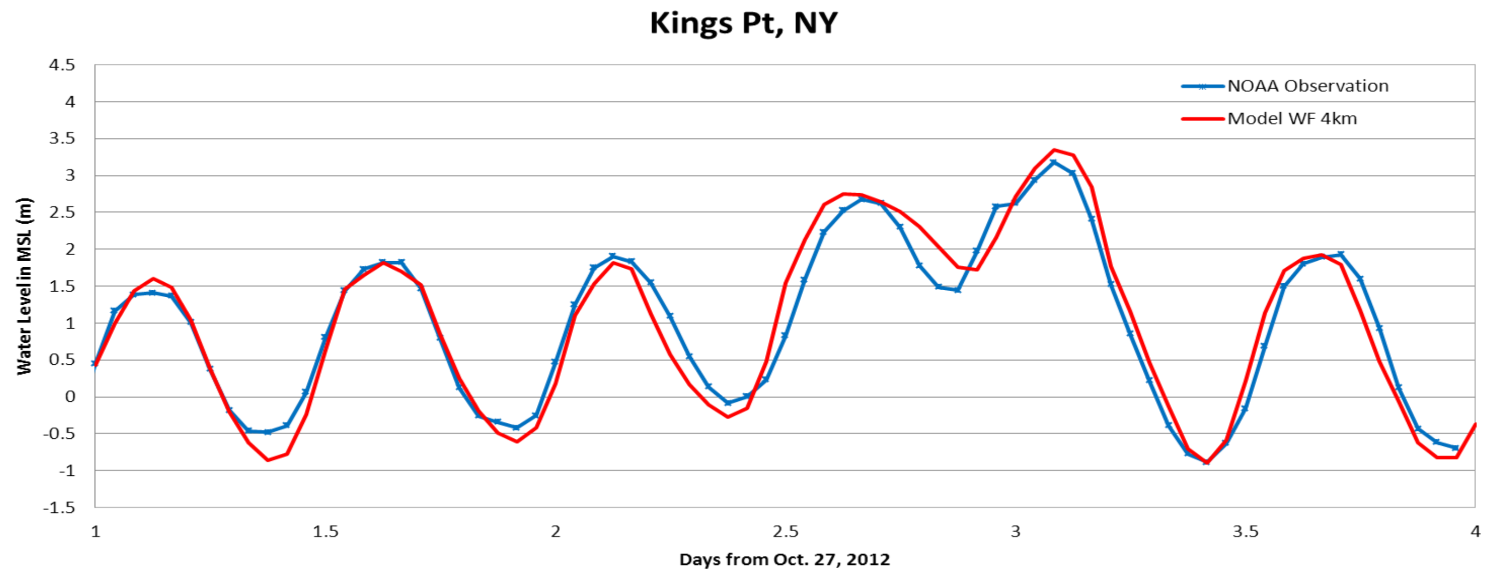

Bridgeport, CT
NOAA Observation
Model WF 4km
Water Level in MSL (m)
Days from Oct. 27, 2012

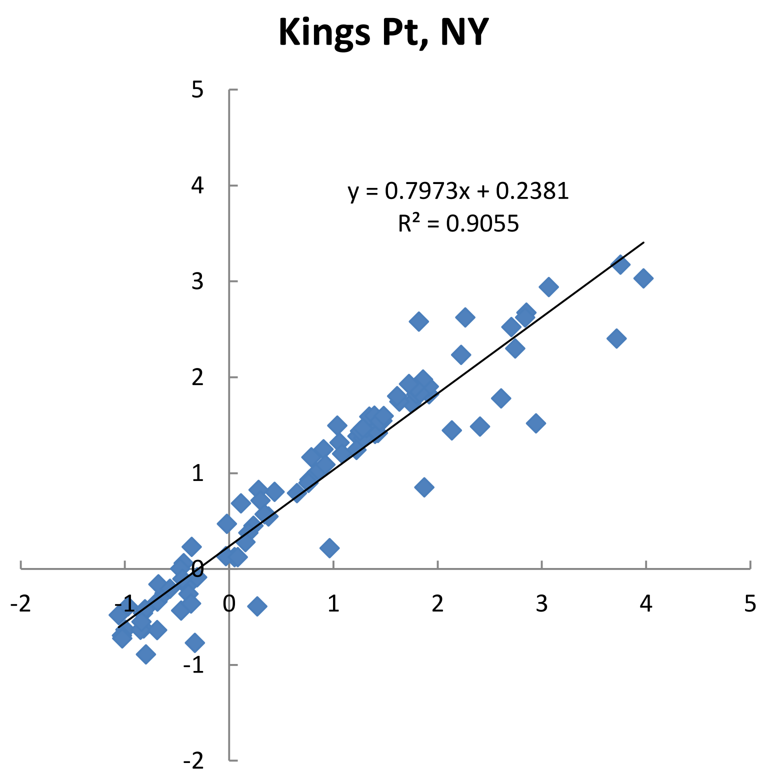

Bridgeport, CT
y = 1.0532x - 0.0977
R² = 0.9908

Tide only

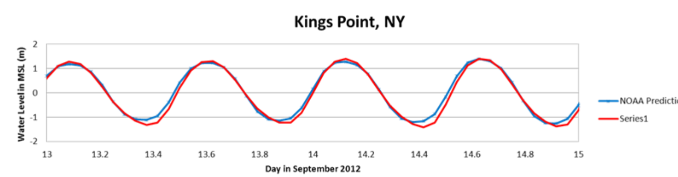

Bridgeport, CT
Water Level in MSL (m)
NOAA Prediction
Series1
Day in September 2012

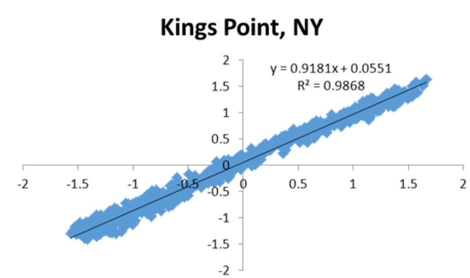

Bridgeport, CT
y = 1.0542x + 0.0413
R² = 0.9834


Kings Pt, NY
NOAA Observation
Model WF 4km
Water Level in MSL (m)
Days from Oct. 27, 2012
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
-0.5
-1
-1.5
1
1.5
2
2.5
3
3.5
4


Kings Pt, NY
y = 0.7973x + 0.2381
R² = 0.9055
5
4
3
2
1
0
-1
-2
-2
-1
0
1
2
3
4
5

Tide only

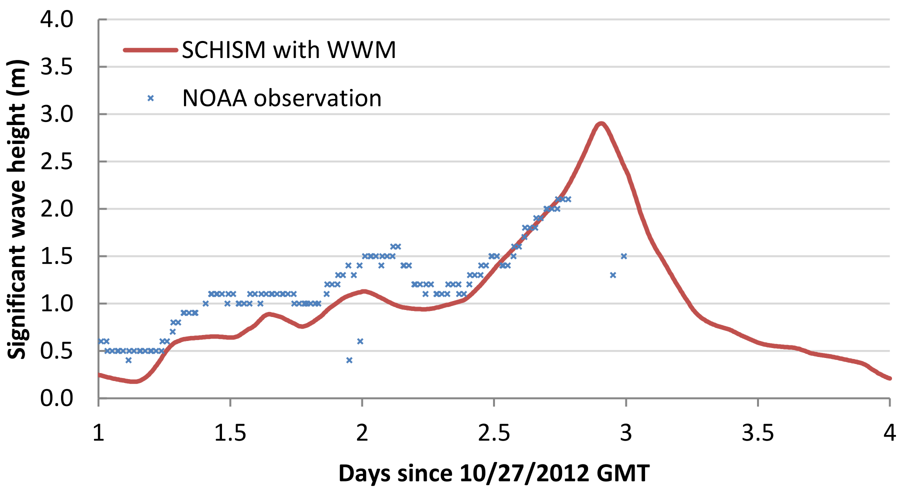

Kings Point, NY
Water Level in MSL (m)
Day in September 2012
NOAA Prediction
Series1
13
13.2
13.4
13.6
13.8
14
14.2
14.4
14.6
14.8
15


Kings Point, NY
y = 0.9181x + 0.0551
R² = 0.9868
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2

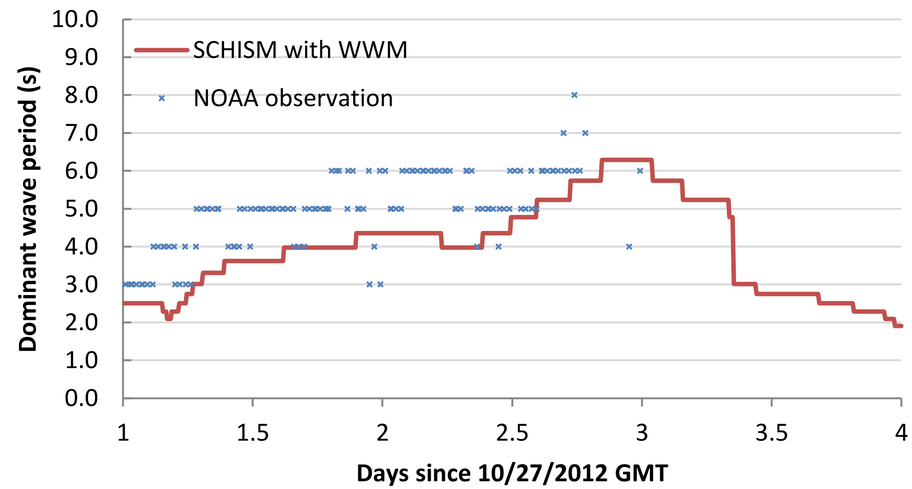
Significant wave height (m)

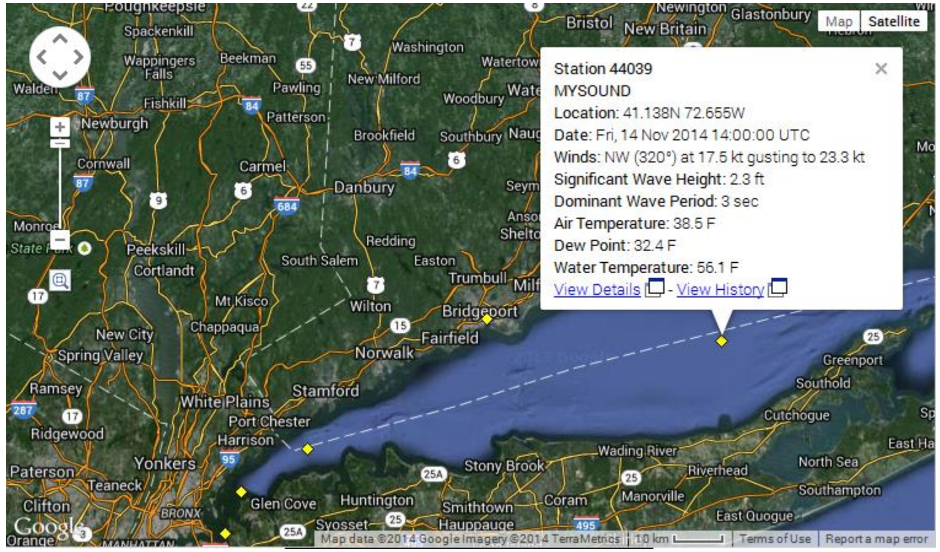
Dominant peak period (s)

Station 44040



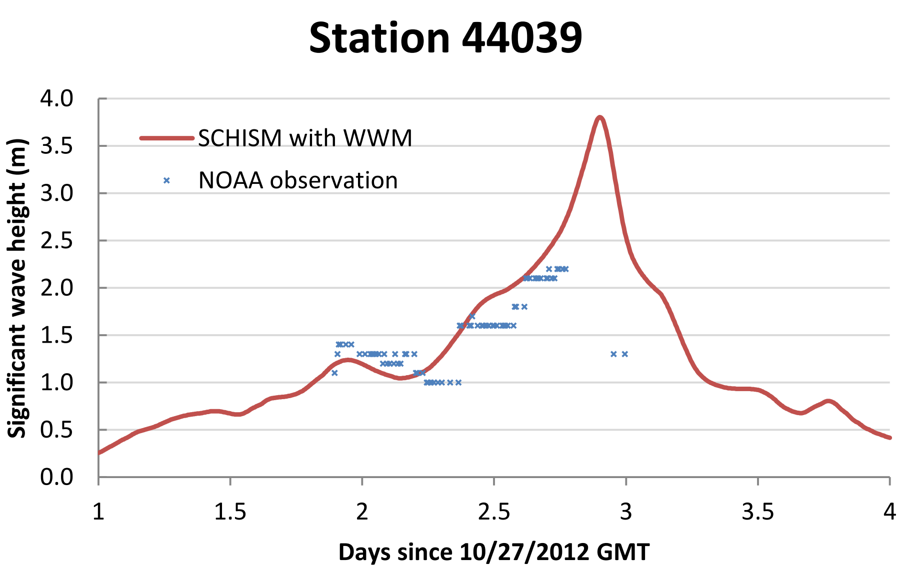
Station 44040

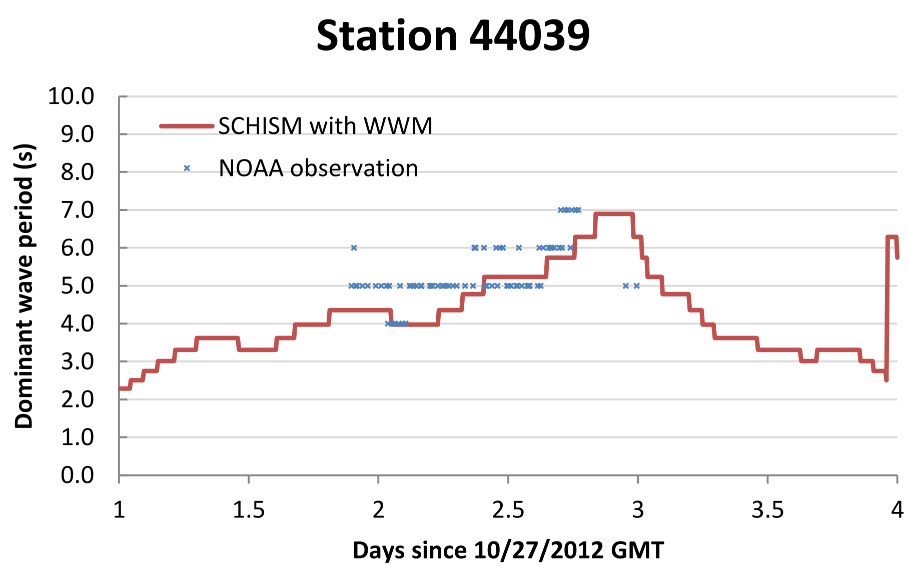


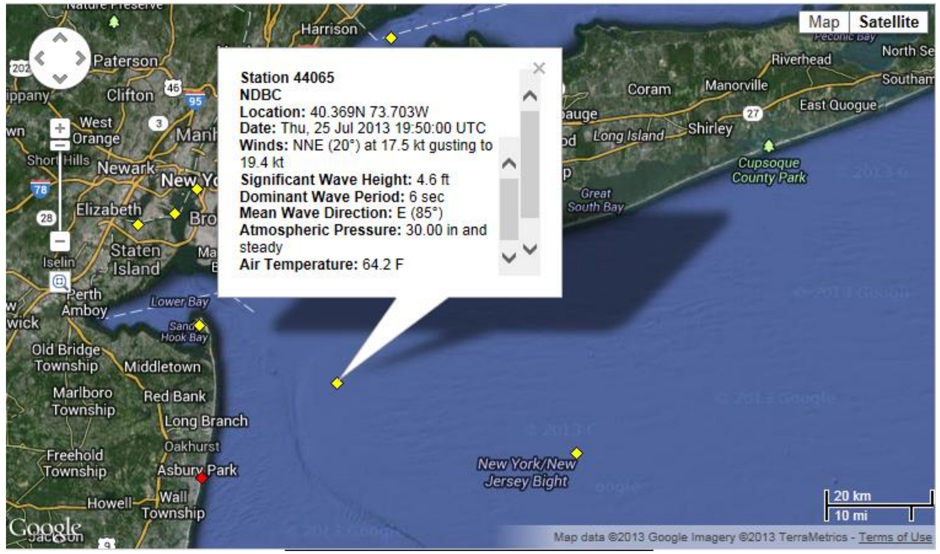


Significant wave height (m)

Dominant peak period (s)

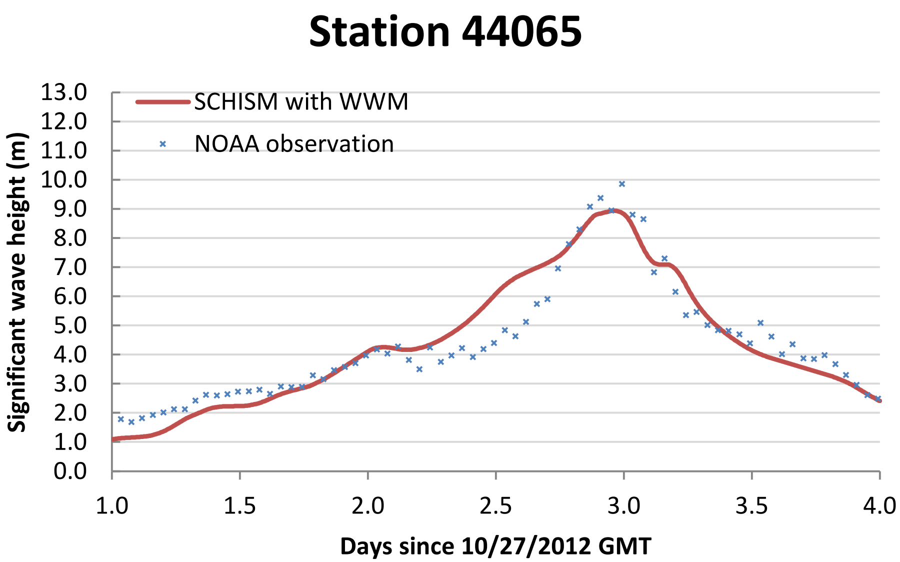


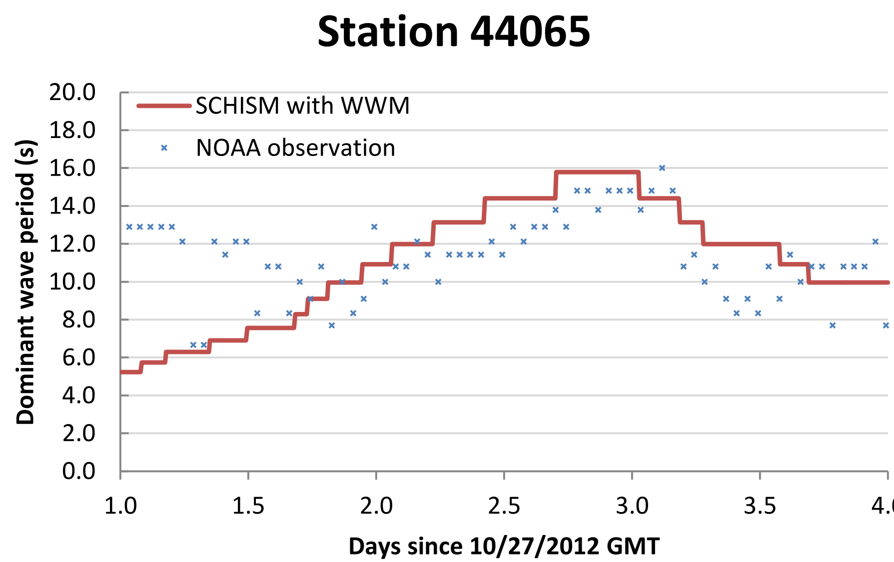


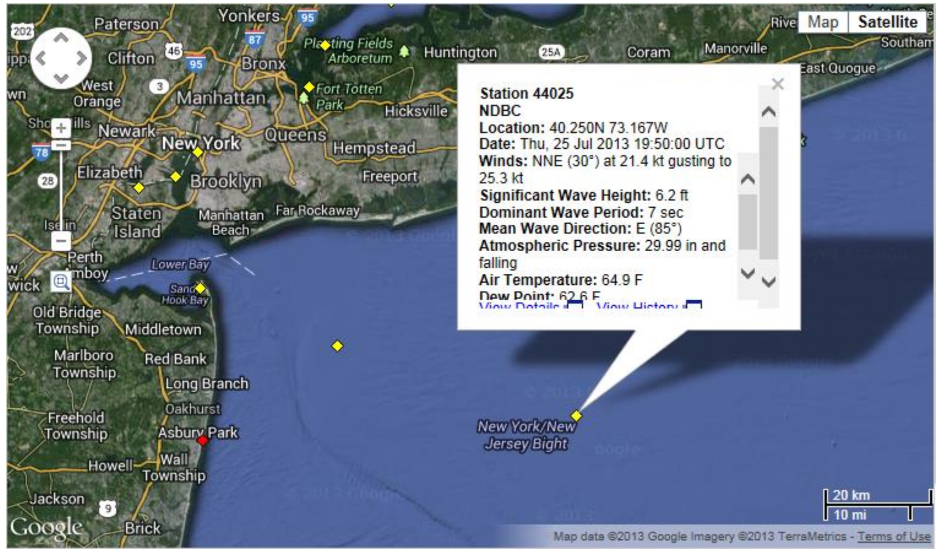


Significant wave height (m)

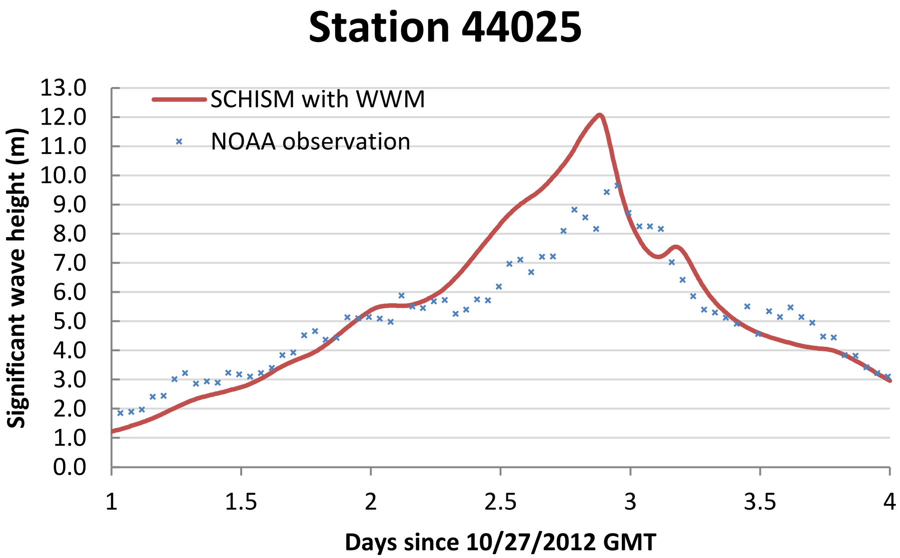
Dominant peak period (s)



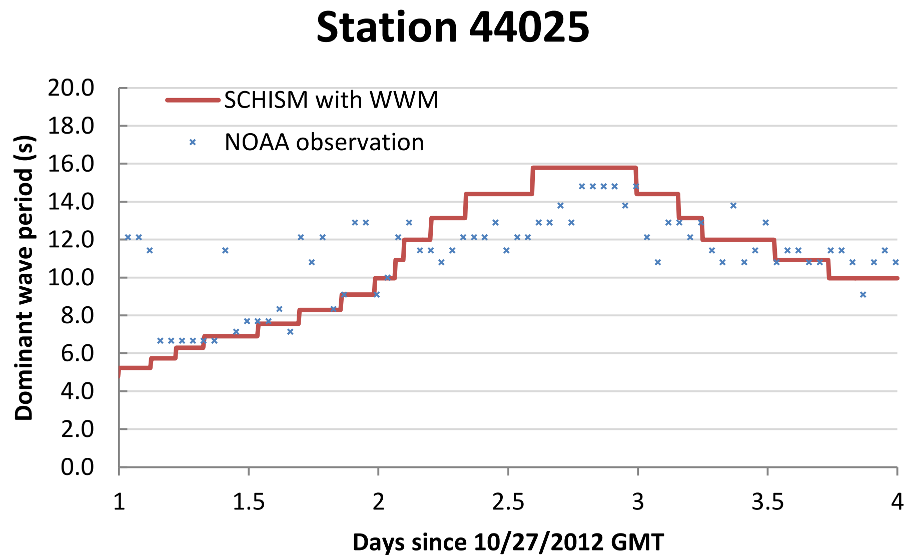




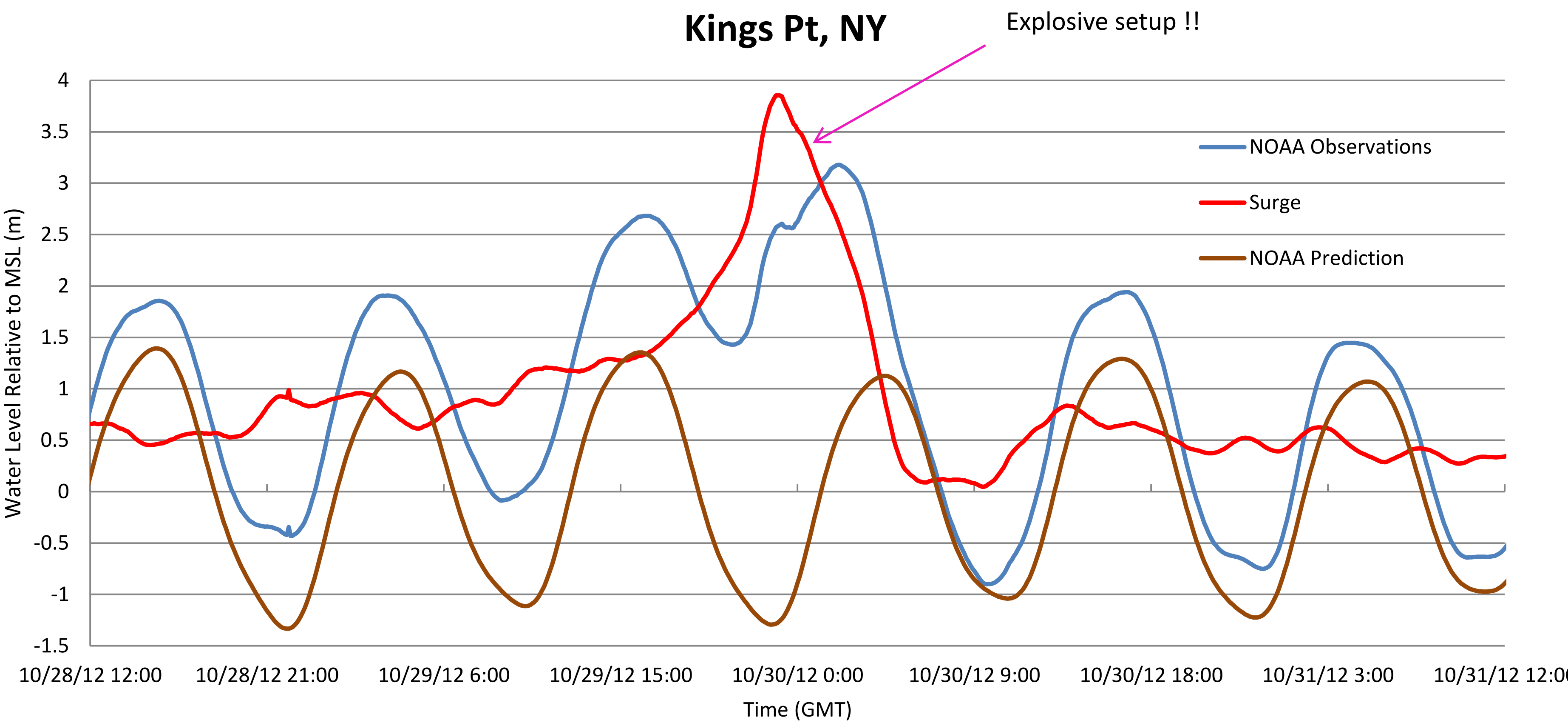
Significant wave height (m)



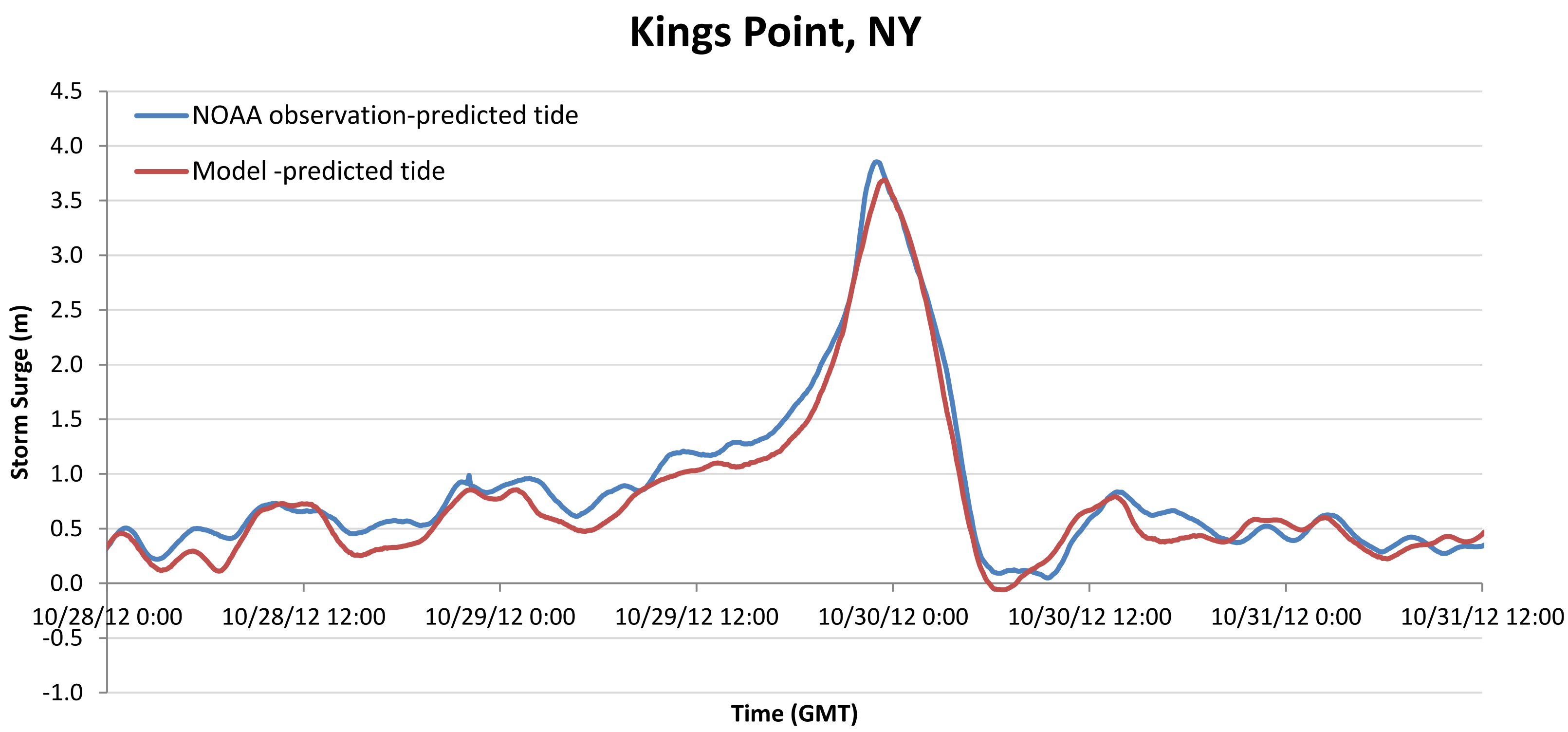
Dominant peak period (s)



Observation of explosive surge setup in Long Island Sound



Modeled explosive non-tidal surge



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.*

*Casulli V. and Stelling, G. S (2011): Semi-implicit subgrid modelling of three-dimensional free-surface flows. International Journal for Numerical Methods in Fluids, Vol, 67, p441-449.

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:

$$V(\eta) + T\eta = b$$

η is determined iteratively by a converging Newton type method

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

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 $cf = g\, n^2/\ h^{1/3}$

$$\longrightarrow \quad \frac{DU}{Dt} + g\frac{\partial \zeta}{\partial x} + g\frac{U\|U\|}{\Omega^2} = 0$$

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

$$\boxed{U = \Omega\sqrt{\varsigma_x}} \quad \text{or} \quad \boxed{\frac{U^2}{\Omega^2} = \varsigma_X}$$

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

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

Introduce cell average velocity U where

$$\|U\| = \frac{\sum_{j=1}^{J} h_j \|u_j\|}{\sum_{j=1}^{J} h_j} \quad \Longrightarrow \quad \left(\frac{\|u_j\|}{\Omega_j}\right)^2 = constant\,\forall j$$

- Then

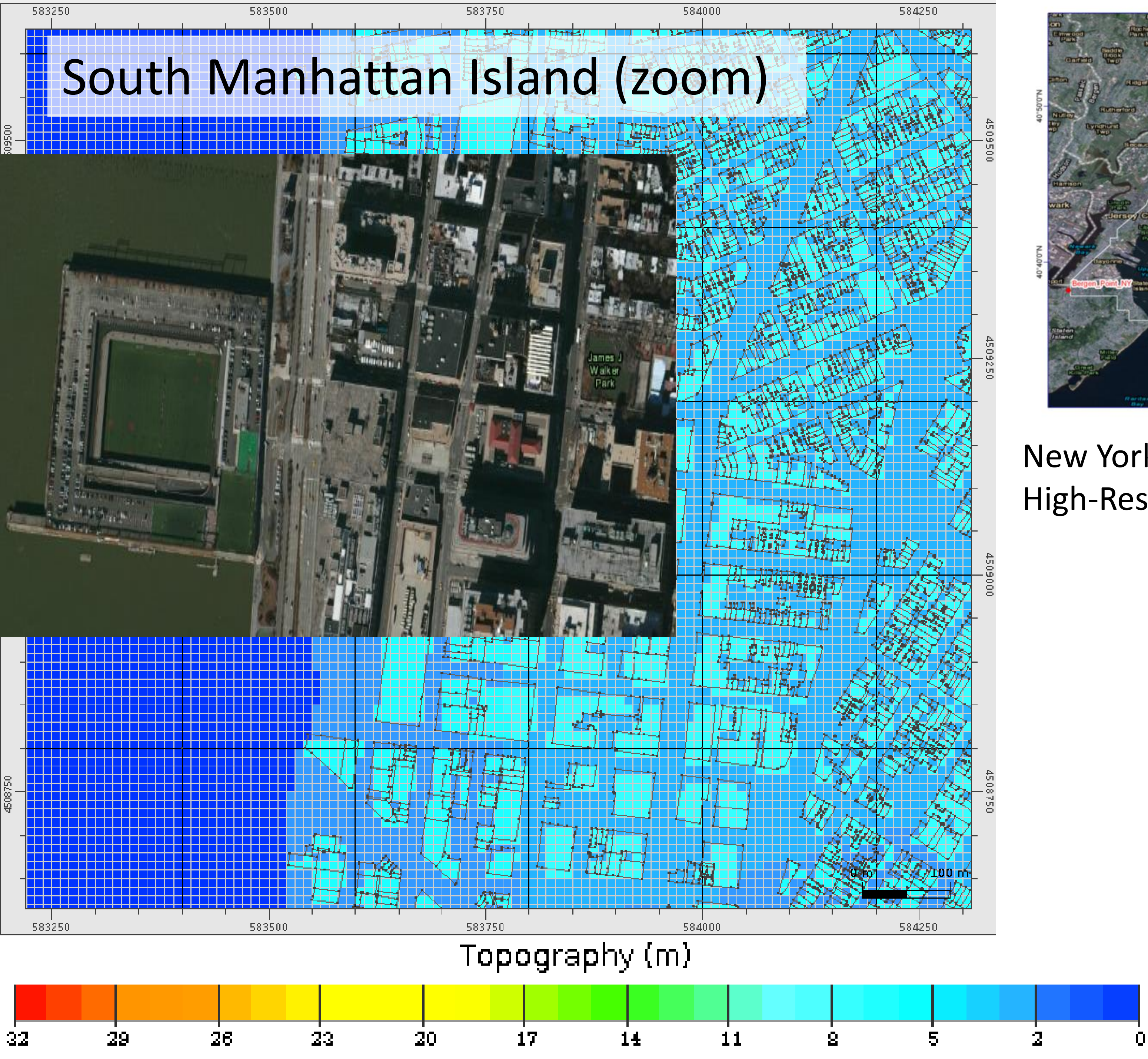
$$\boxed{\frac{\|u_j\|}{\Omega_j} = \frac{\|U\|}{\Omega}\ \forall j \quad \text{or} \quad \|u_j\| = \Omega_j \frac{\|U\|}{\Omega}}$$

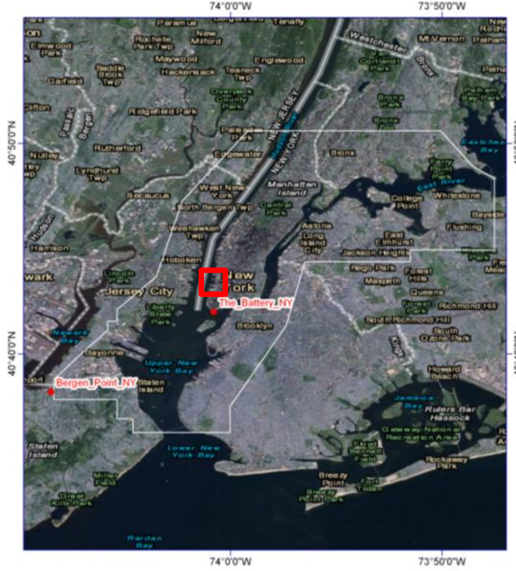
where

$$\Omega = \frac{\sum_{j=1}^{J} h_j \Omega_j}{\sum_{j=1}^{J} h_j}$$

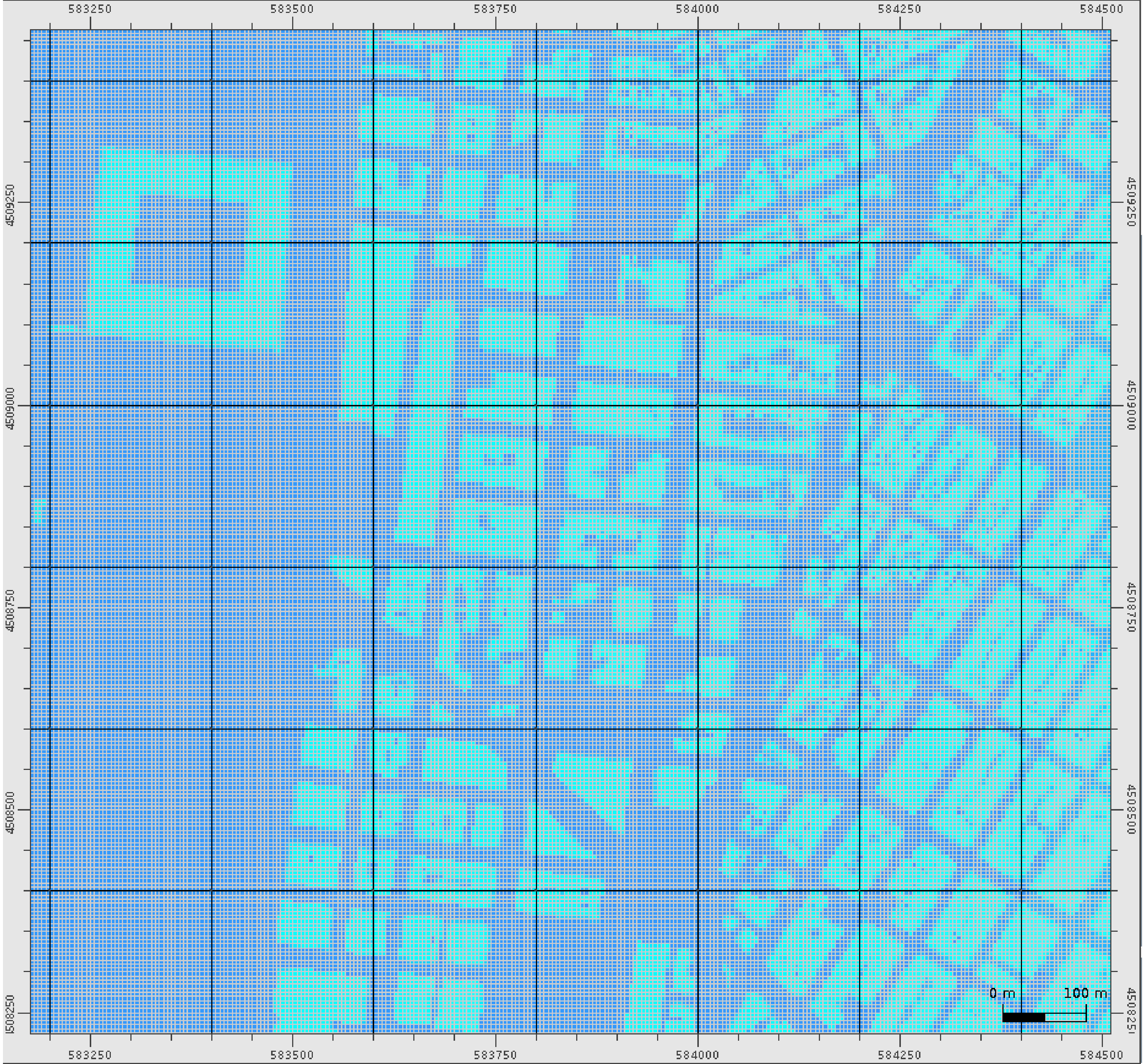
High resolution, local inundation dynamic model on sub-grid scale

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





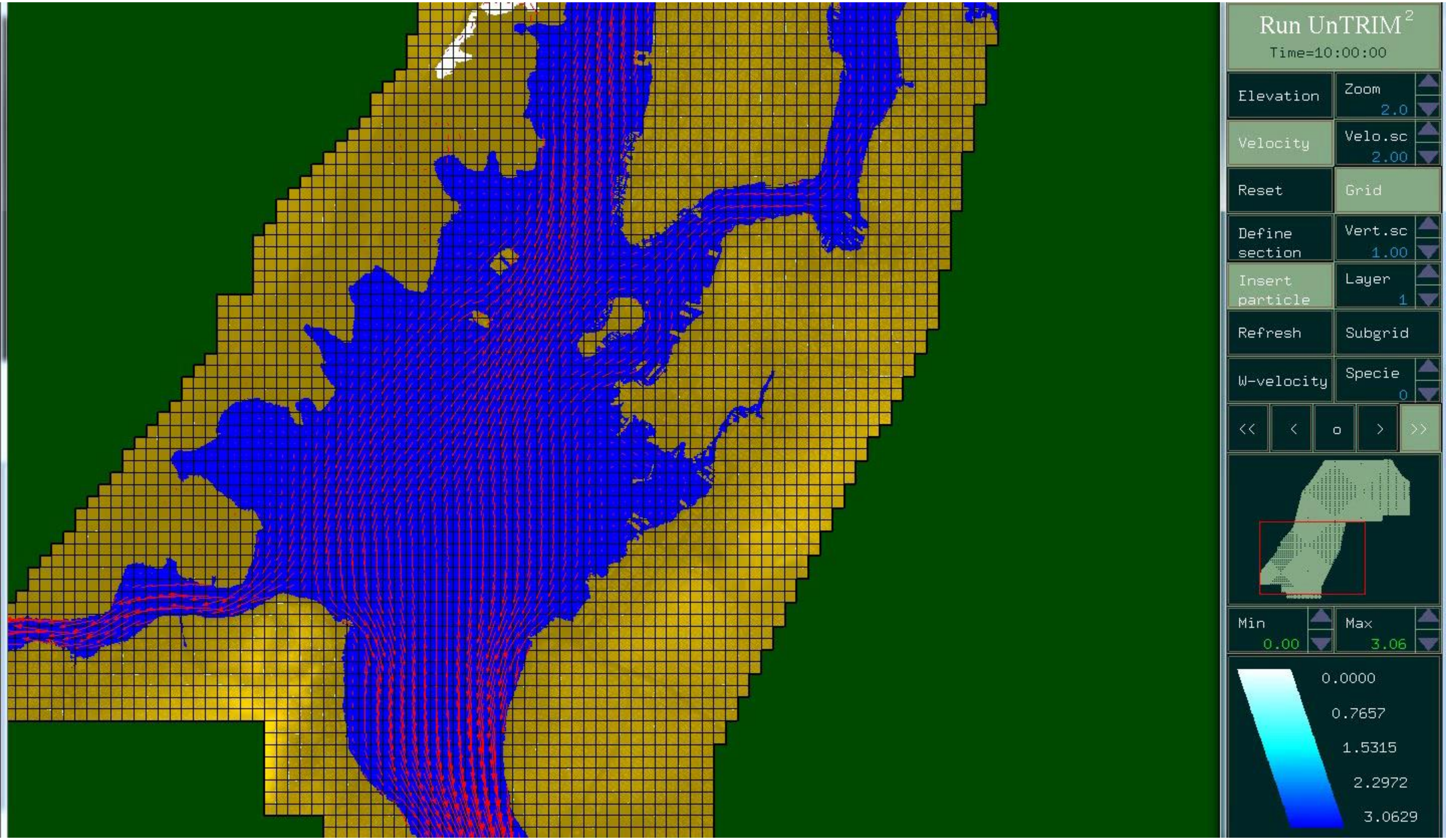
New York City Sub-Grid High-Resolution Domain



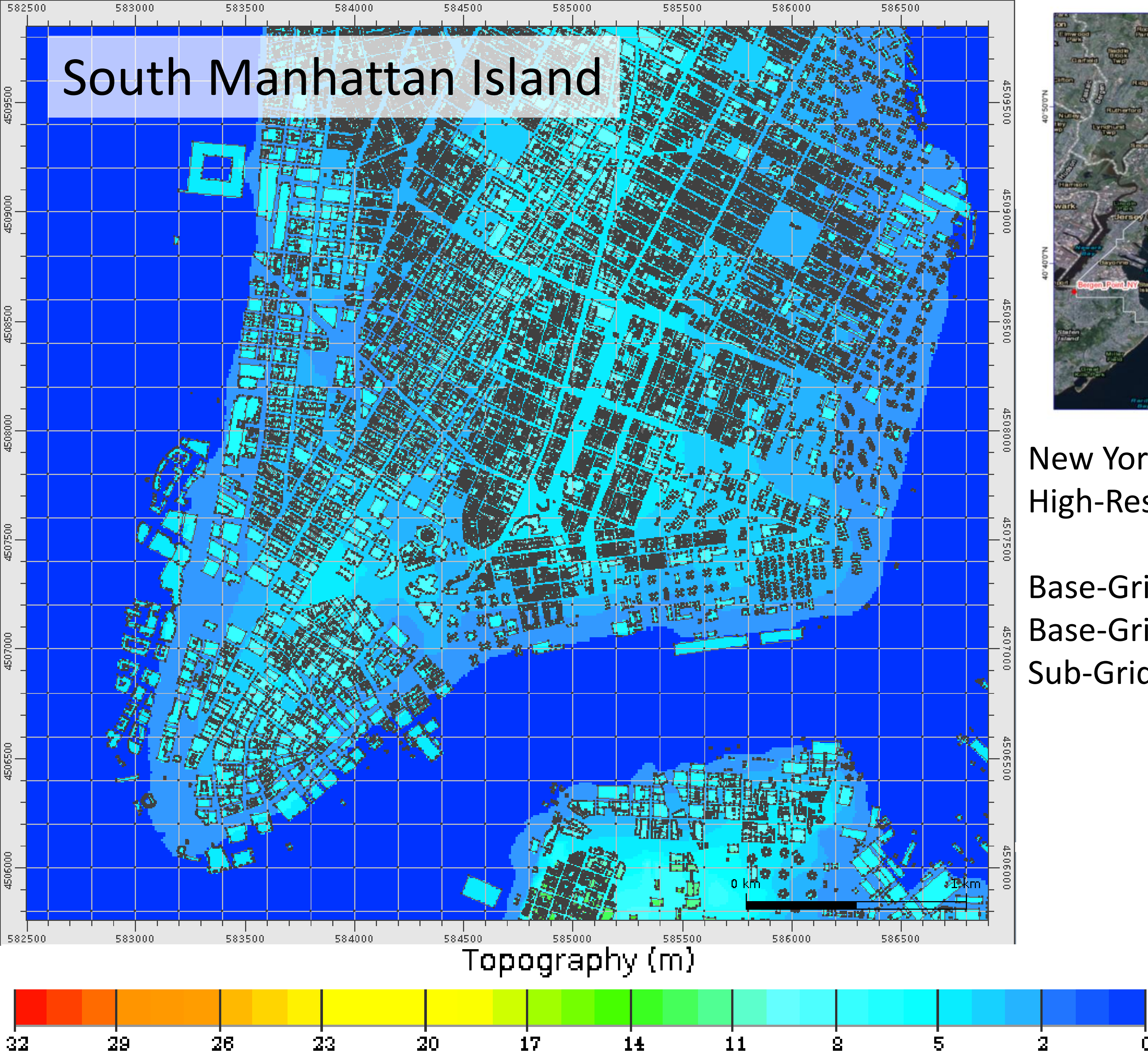
583250
583500
583750
584000
584250
584500
4509250
4509000
4508750
4508500
4508250
0 m
100 m

UNTRIM^2 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



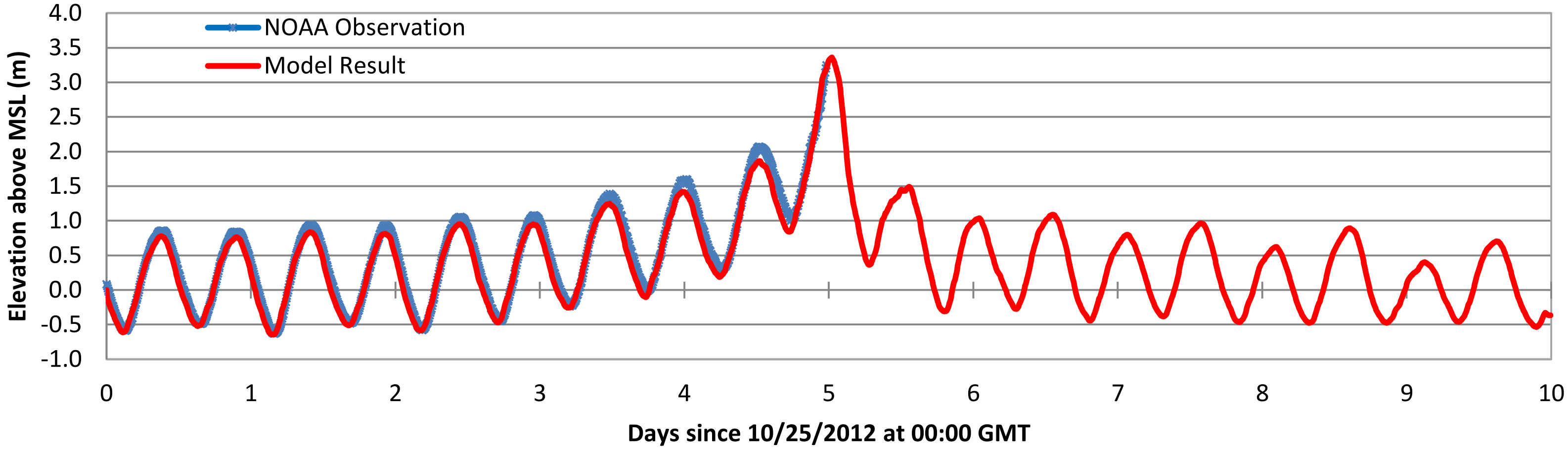
Run UnTRIM 2
Time=10:00:00
Elevation
Zoom
2.0
Velocity
Velo.sc
2.00
Reset
Grid
Define section
Vert.sc
1.00
Insert particle
Layer
1
Refresh
Subgrid
W-velocity
Specie
0
<<
<
o
>
>>
Min
0.00
Max
3.06
0.0000
0.7657
1.5315
2.2972
3.0629

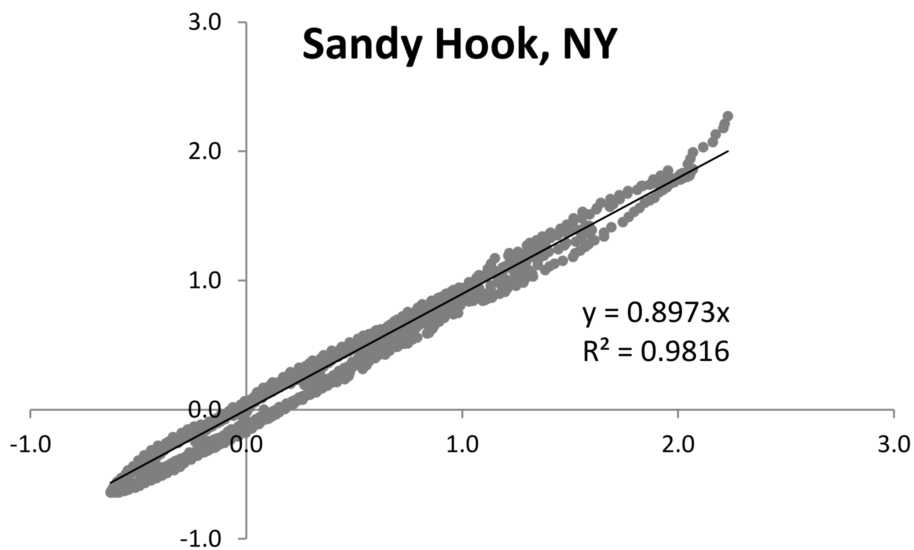


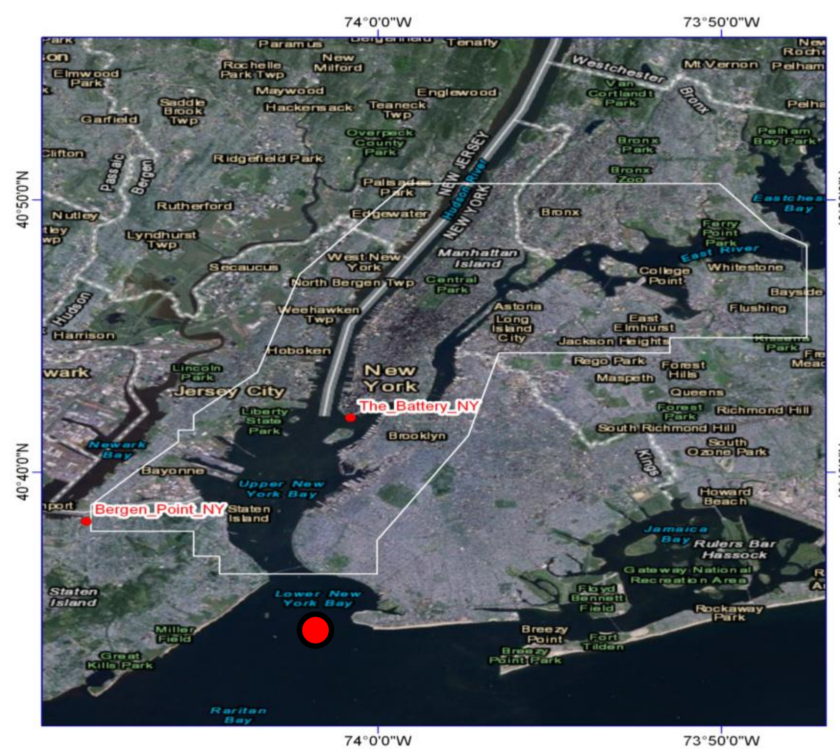
New York City Sub-Grid
High-Resolution Domain

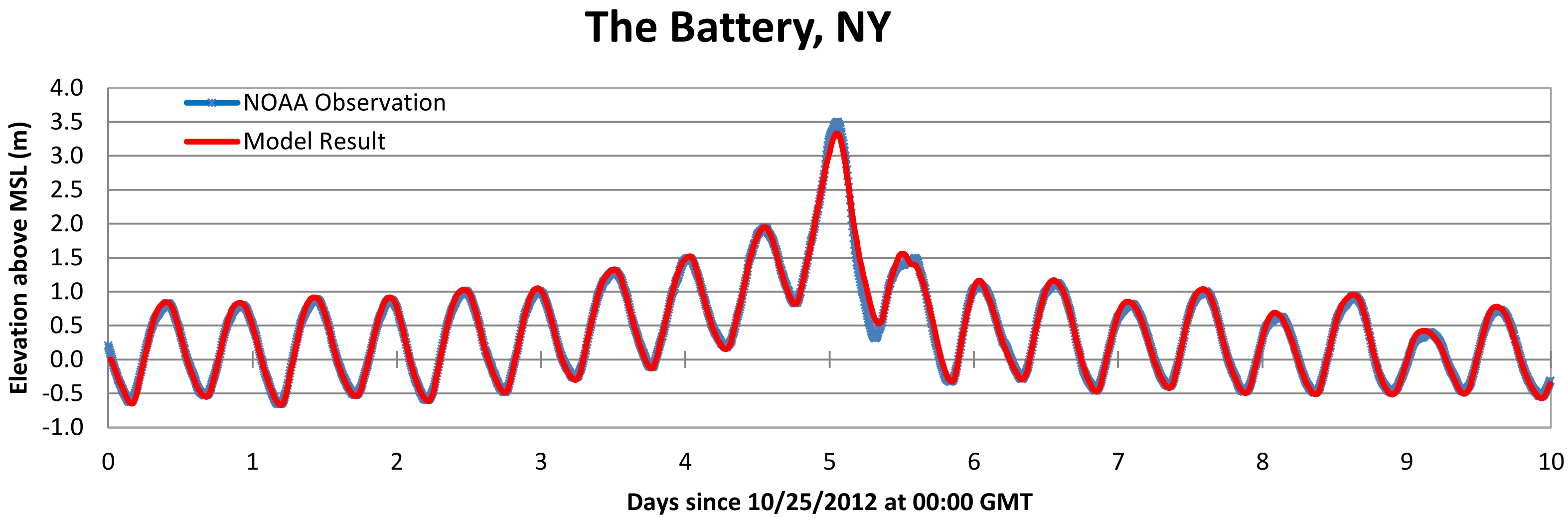
Base-Grid Nodes:	9,946
Base-Grid Cells:	9,663
Sub-Grid Cells:	3,865,200

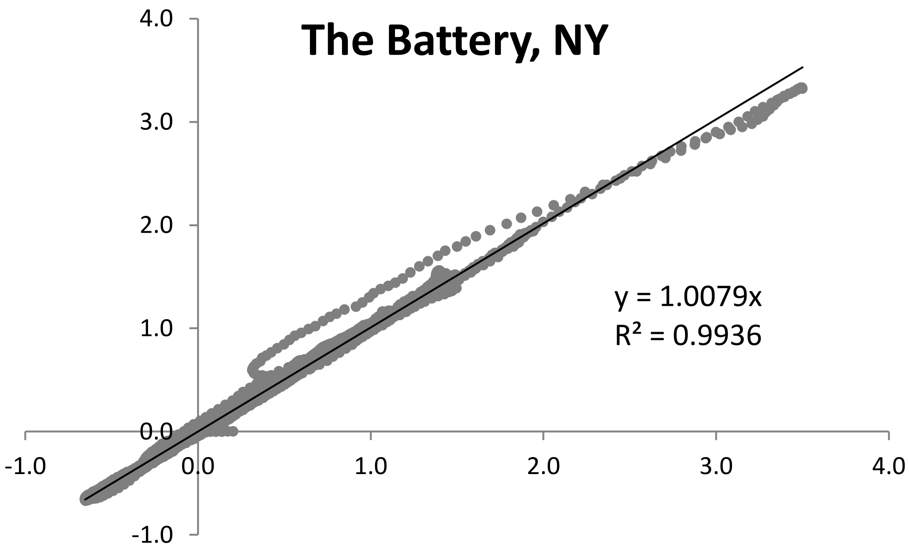
Sandy Hook, NY



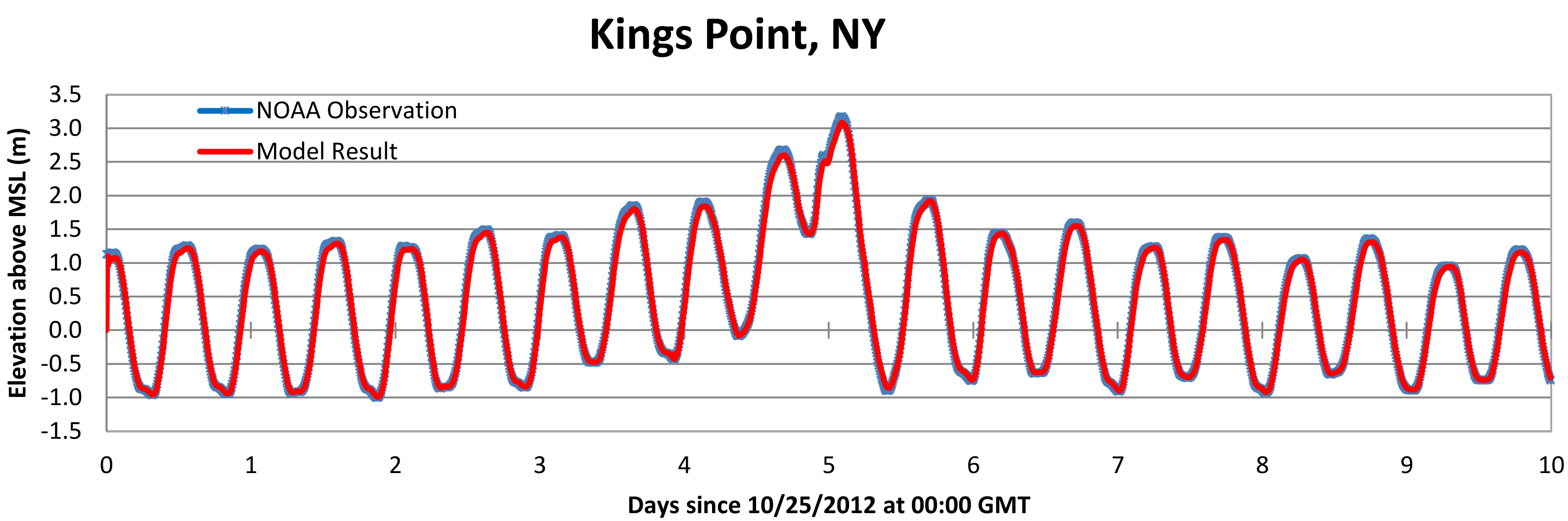


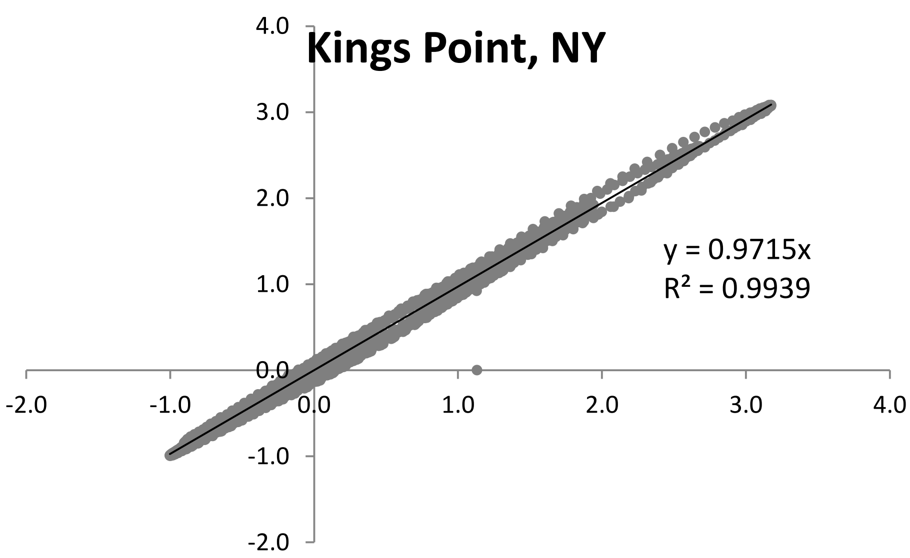



The Battery, NY
NOAA Observation
Model Result
Elevation above MSL (m)
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
-0.5
-1.0
0
1
2
3
4
5
6
7
8
9
10
Days since 10/25/2012 at 00:00 GMT


The Battery, NY
y = 1.0079x
R^2 = 0.9936
4.0
3.0
2.0
1.0
0.0
-1.0
-1.0
0.0
1.0
2.0
3.0
4.0

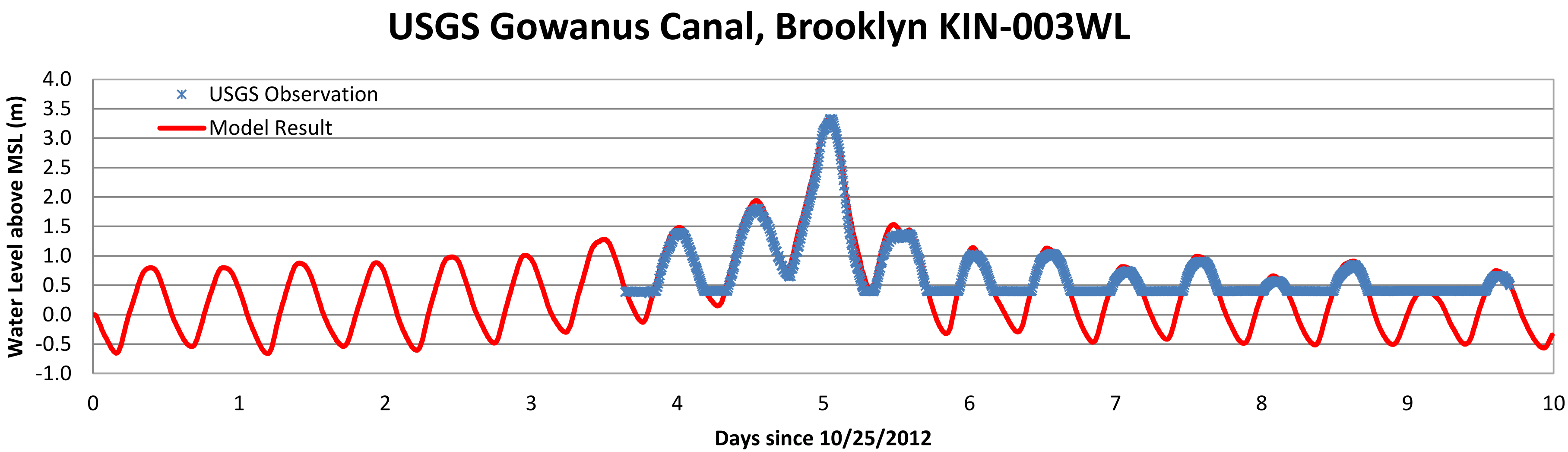

74°0'0"W
73°50'0"W
40°50'0"N
40°40'0"N
The_Battery_NY
Bergen_Point_NY
New York
Jersey City
Brooklyn
Manhattan Island
Bronx
Hoboken
Bayonne
Upper New York Bay
Lower New York Bay
Staten Island
Queens
Flushing
Jamaica Bay
Raritan Bay

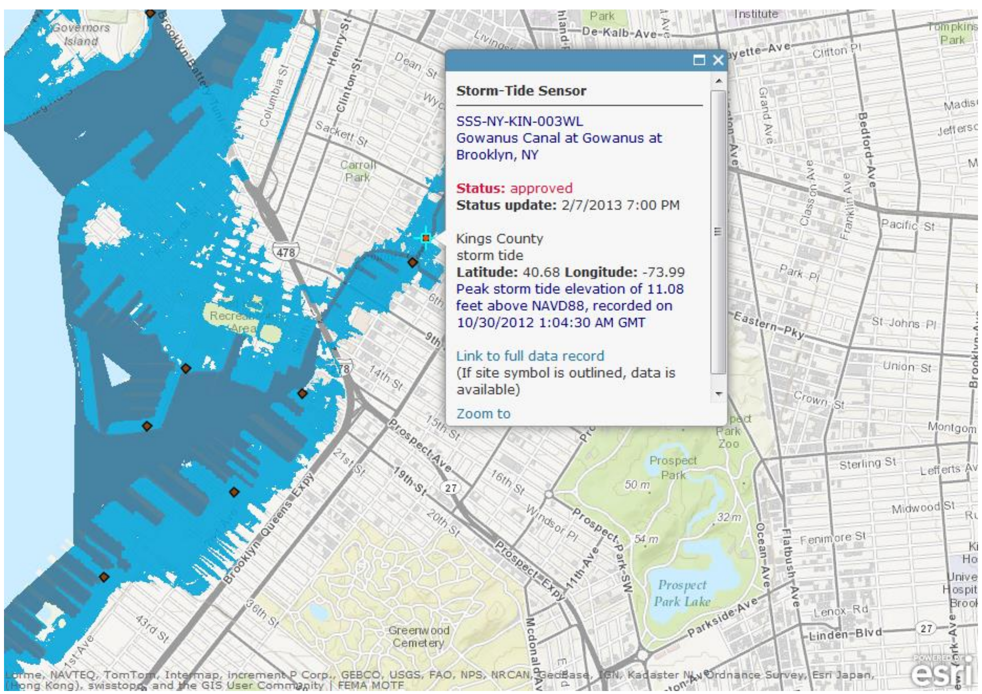

Kings Point, NY
NOAA Observation
Model Result
Elevation above MSL (m)
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
0
1
2
3
4
5
6
7
8
9
10
Days since 10/25/2012 at 00:00 GMT


Kings Point, NY
4.0
3.0
2.0
1.0
0.0
-1.0
-2.0
-2.0
-1.0
0.0
1.0
2.0
3.0
4.0
y = 0.9715x
R² = 0.9939


74°0'0"W
73°50'0"W
40°50'0"N
40°40'0"N
New York
Jersey City
Manhattan Island
Brooklyn
Bronx
The_Battery_NY
Bergen_Point_NY
Upper New York Bay
Lower New York Bay
Staten Island
Jamaica Bay
East River
Hoboken
Queens

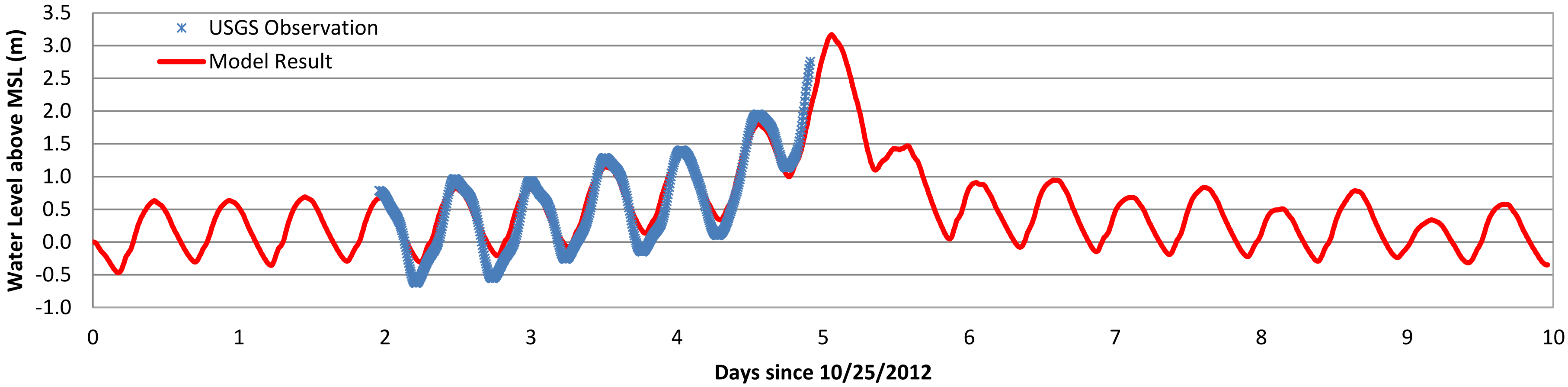
USGS Rapid Deployment Gauge Comparison

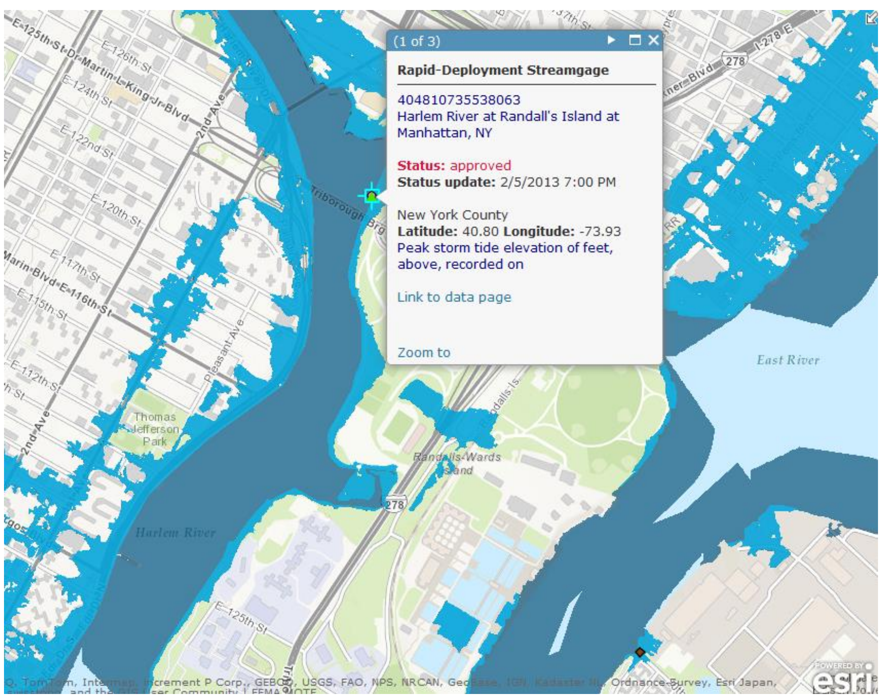




USGS Rapid Deployment Gauge Comparison

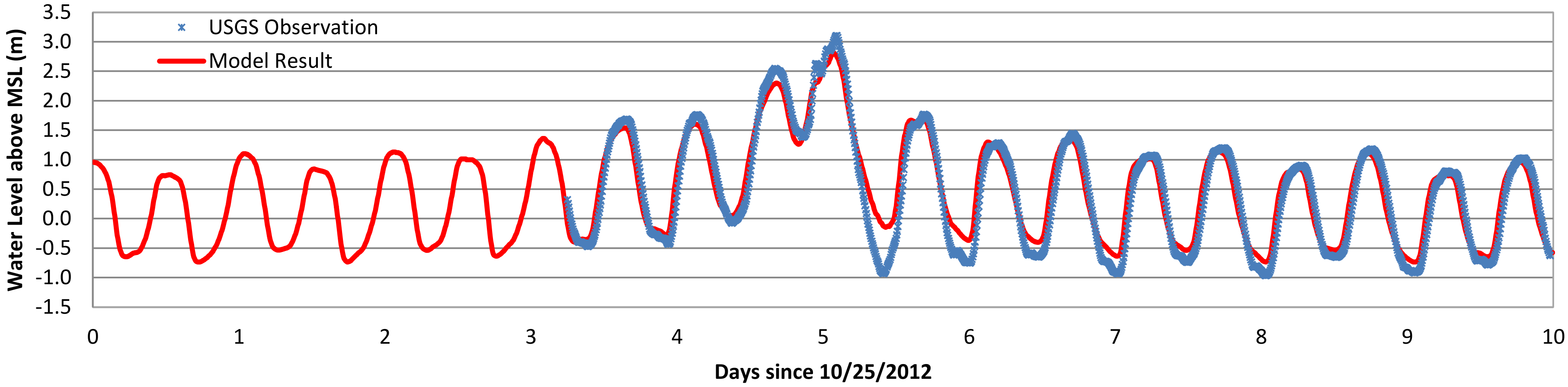
USGS Station #404810735538063 at Harlem & East River

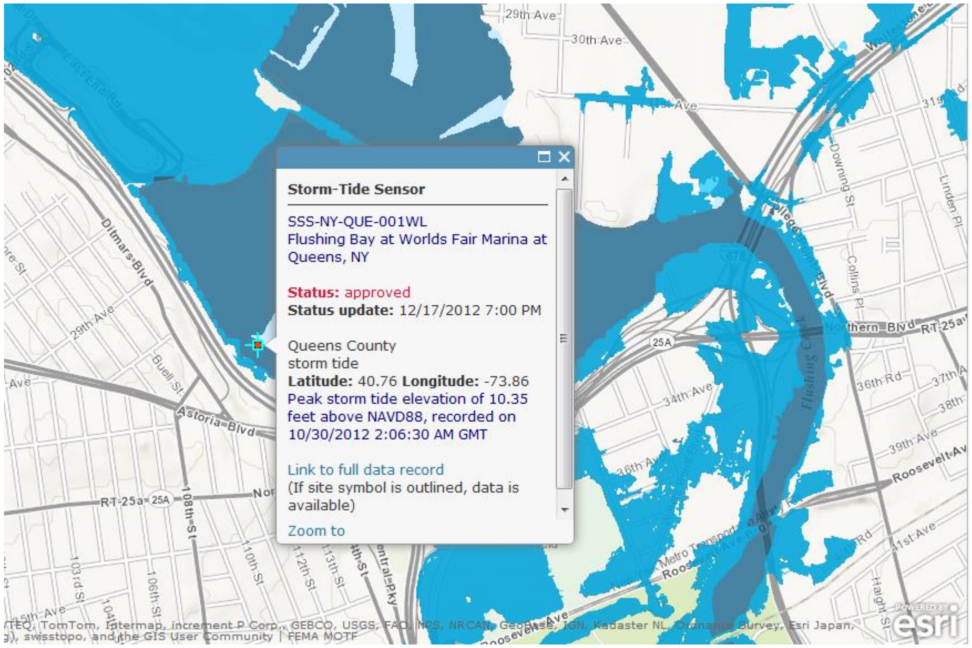


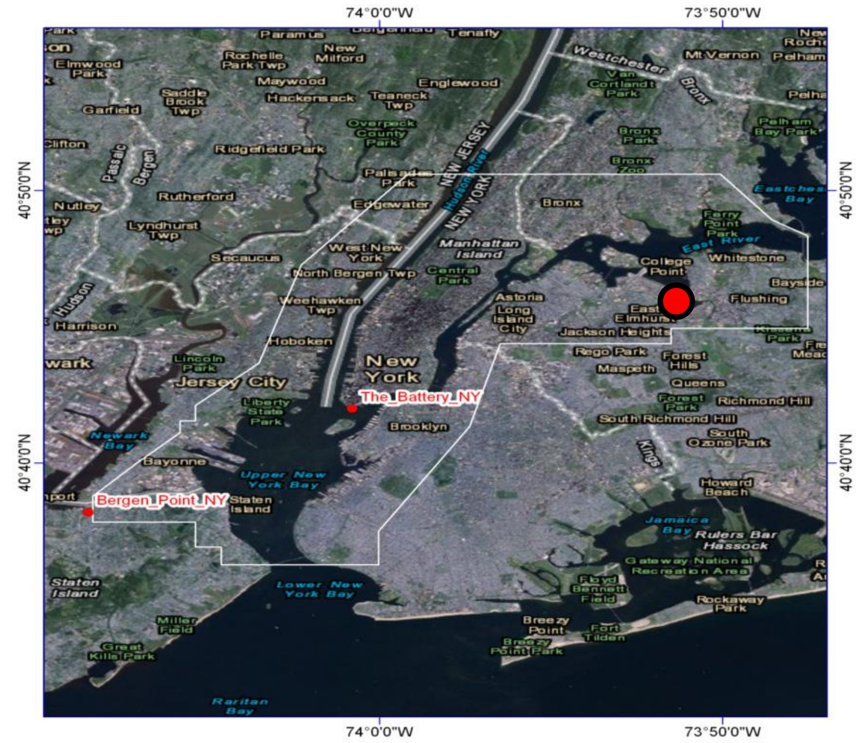


USGS Rapid Deployment Gauge Comparison

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

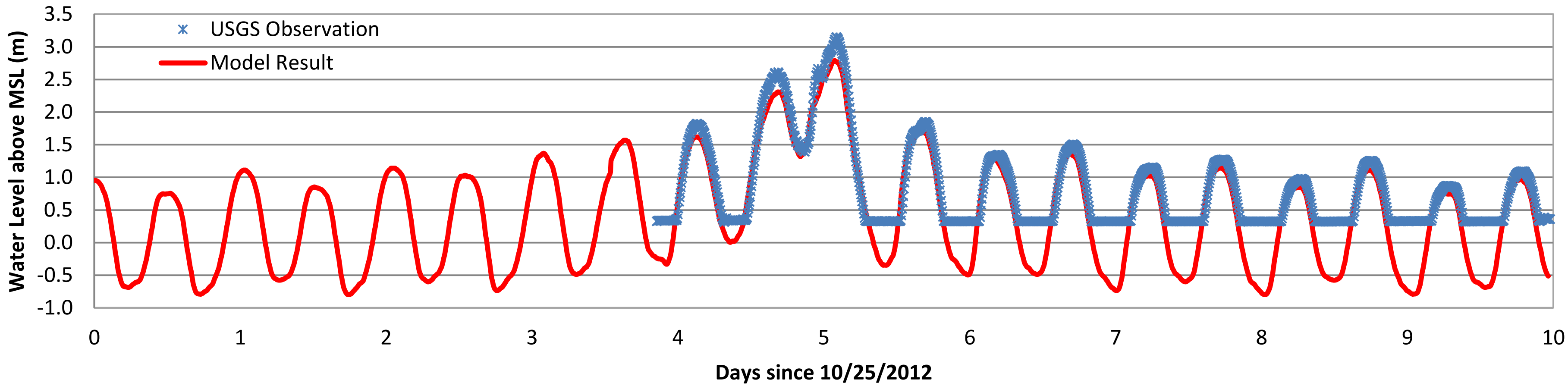


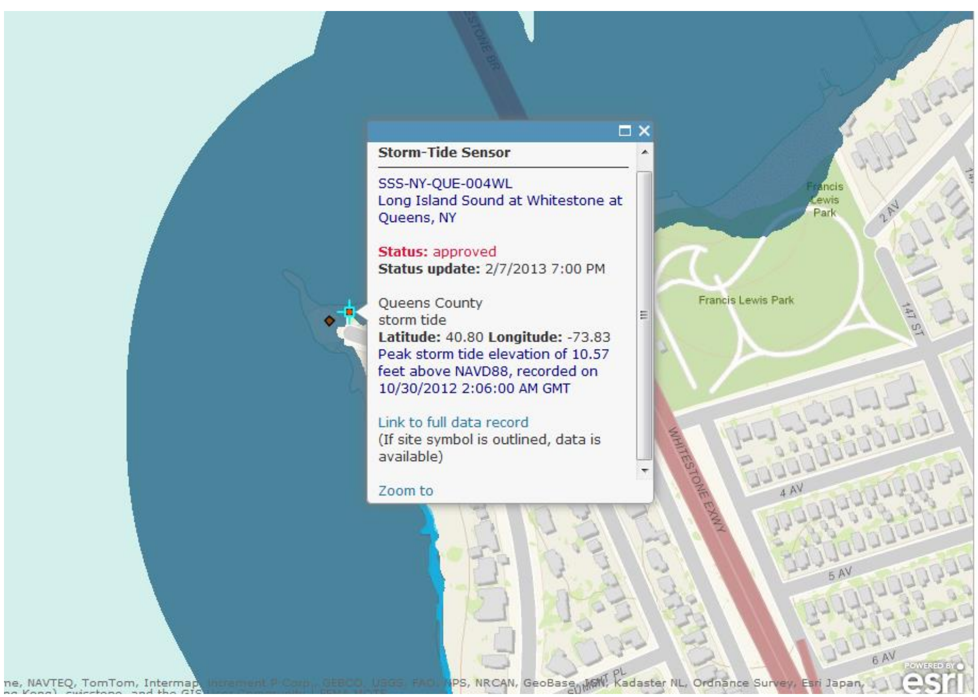


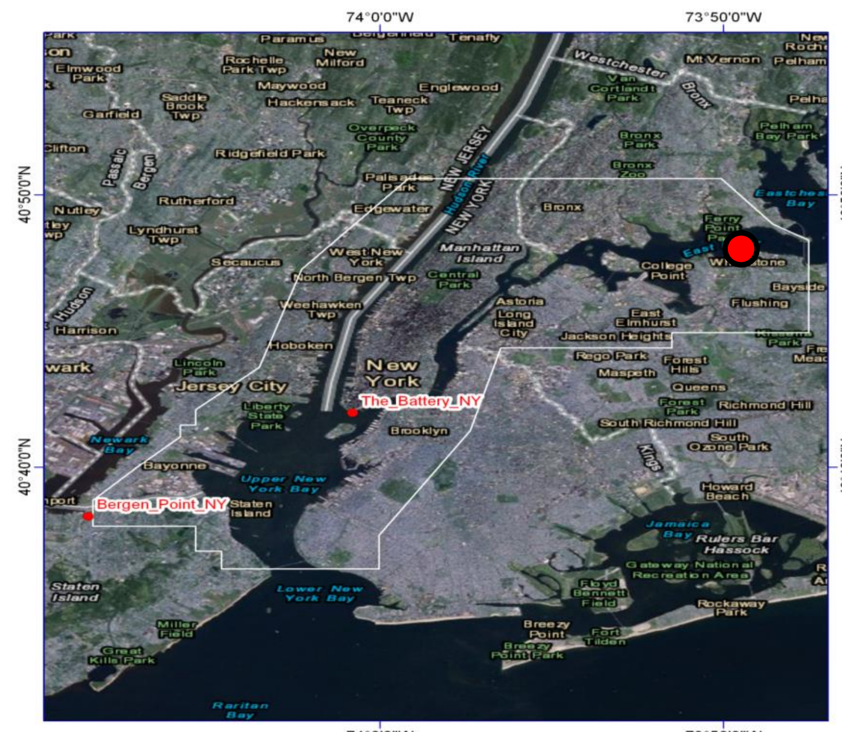


USGS Rapid Deployment Gauge Comparison

USGS Whitestone, Queens QUE-004WL





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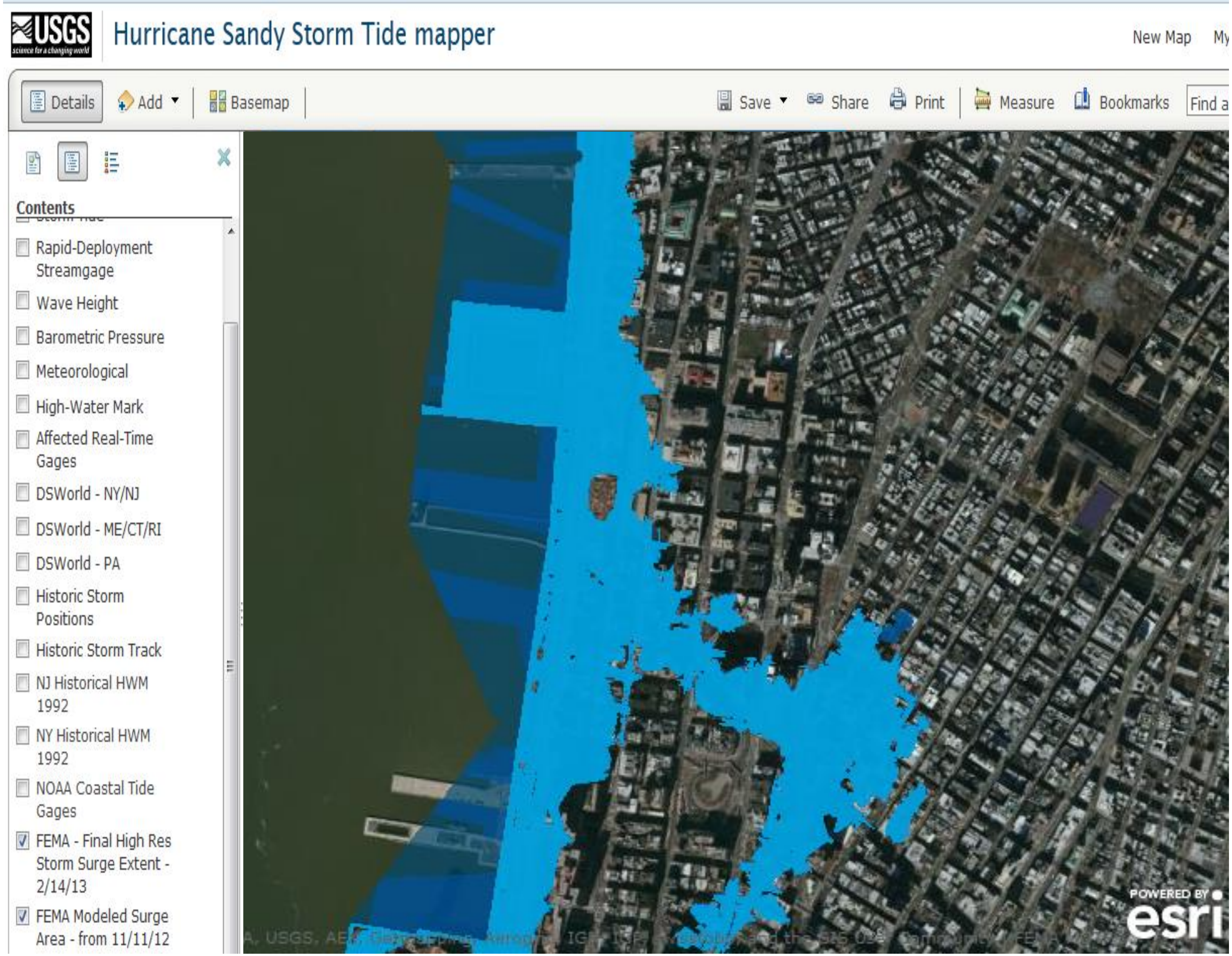
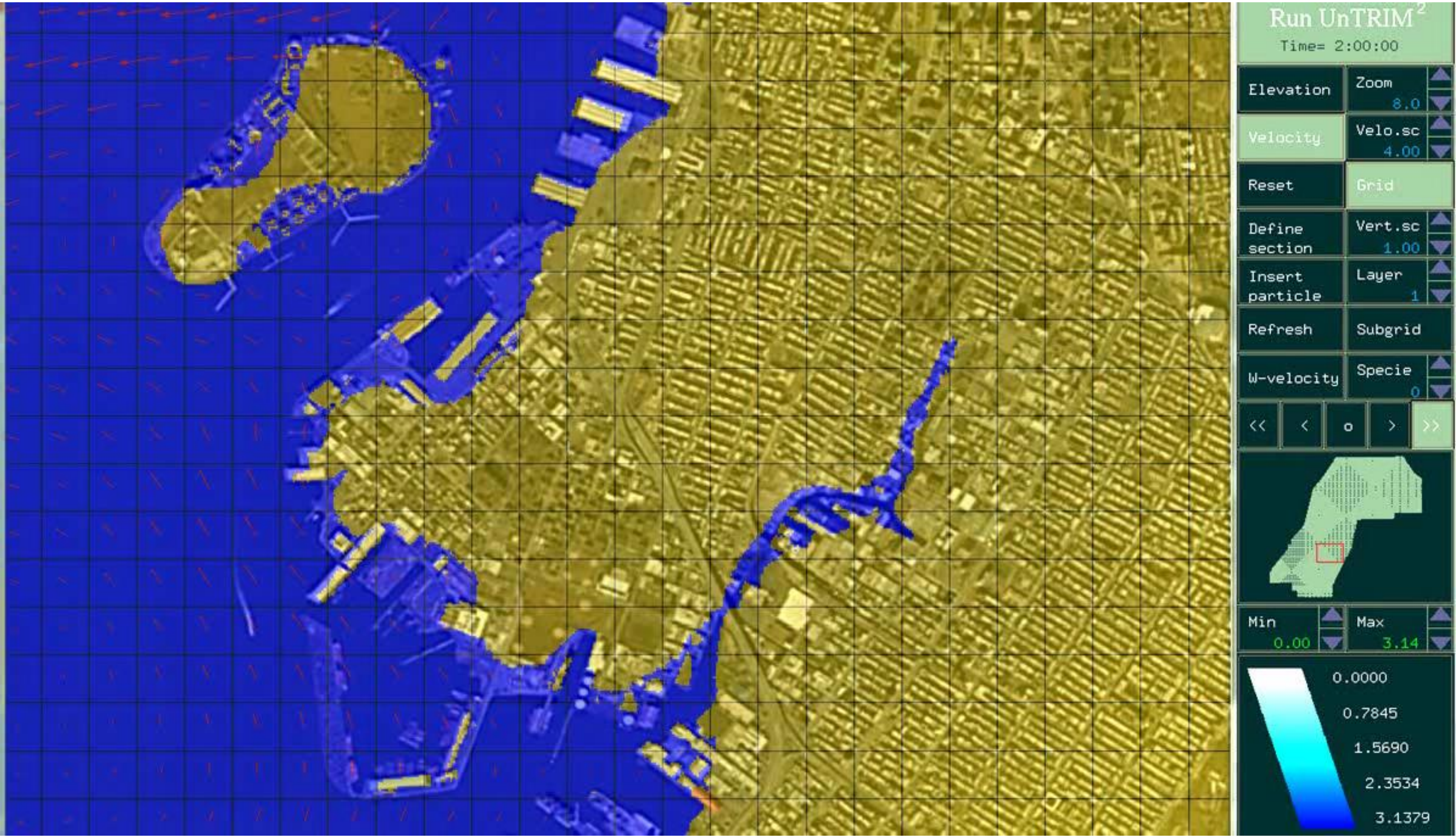
Elevation
Zoom
16.0
Velocity
Velo.sc
4.00
Reset
Grid
Define section
Vert.sc
1.00
Insert particle
Layer
1
Refresh
Subgrid
W-velocity
Specie
0
<<
<
o
>
>>
Min
0.00
Max
3.14
0.0000
0.7845
1.5690
2.3534
3.1379


USGS
science for a changing world
Hurricane Sandy Storm Tide mapper
New Map
My
Details
Add
Basemap
Save
Share
Print
Measure
Bookmarks
Find a
Contents
Rapid-Deployment Streamgage
Wave Height
Barometric Pressure
Meteorological
High-Water Mark
Affected Real-Time Gages
DSWorld - NY/NJ
DSWorld - ME/CT/RI
DSWorld - PA
Historic Storm Positions
Historic Storm Track
NJ Historical HWM 1992
NY Historical HWM 1992
NOAA Coastal Tide Gages
FEMA - Final High Res Storm Surge Extent - 2/14/13
FEMA Modeled Surge Area - from 11/11/12
POWERED BY
esri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Zoom
8.0
Velocity
Velo.sc
4.00
Reset
Grid
Define section
Vert.sc
1.00
Insert particle
Layer
1
Refresh
Subgrid
W-velocity
Specie
0
<<
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o
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Min
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Max
3.14
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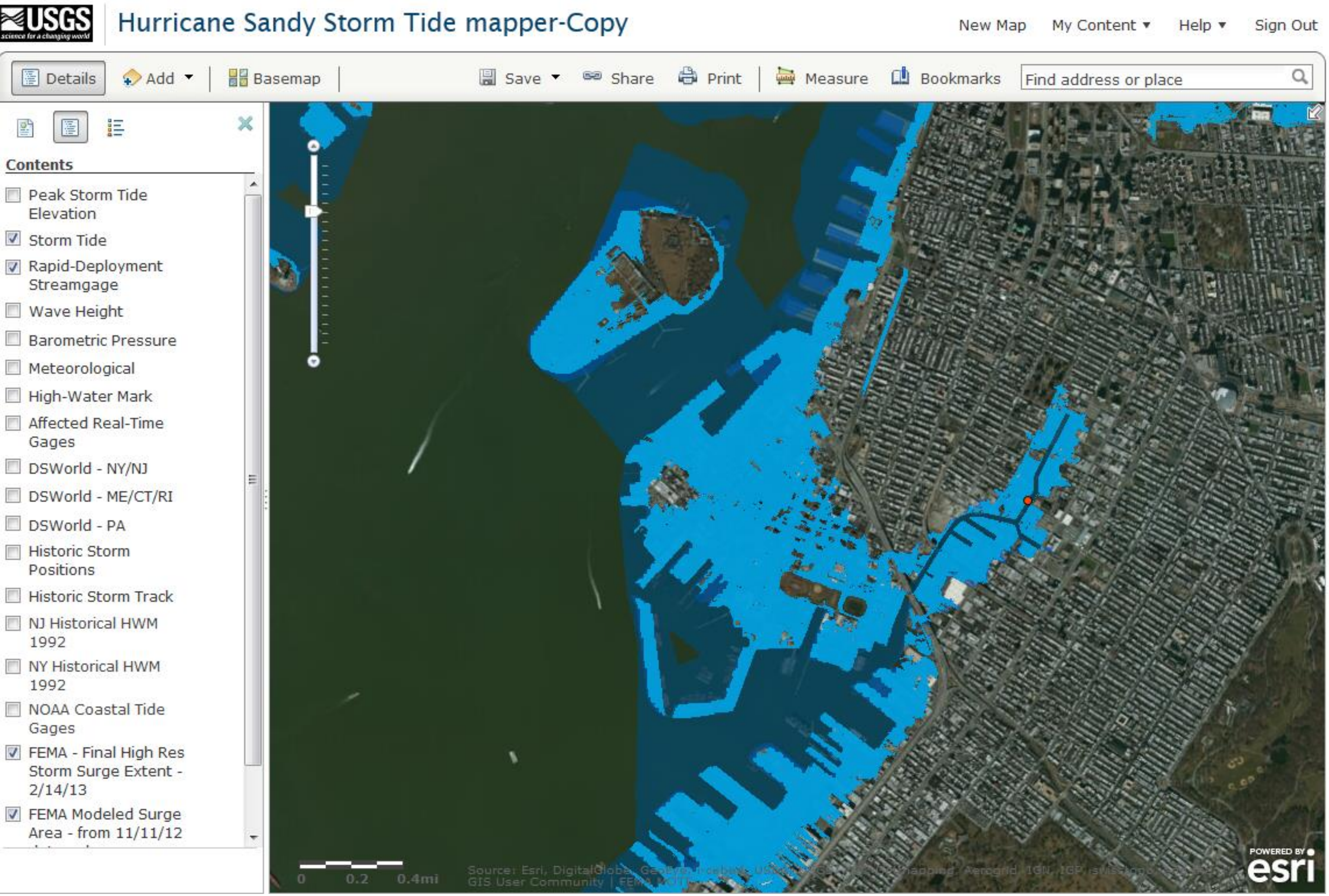
1.5690
2.3534
3.1379


USGS
science for a changing world
Hurricane Sandy Storm Tide mapper-Copy
New Map
My Content
Help
Sign Out
Details
Add
Basemap
Save
Share
Print
Measure
Bookmarks
Find address or place
Contents
Peak Storm Tide Elevation
Storm Tide
Rapid-Deployment Streamgage
Wave Height
Barometric Pressure
Meteorological
High-Water Mark
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DSWorld - NY/NJ
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Historic Storm Positions
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NJ Historical HWM 1992
NY Historical HWM 1992
NOAA Coastal Tide Gages
FEMA - Final High Res Storm Surge Extent - 2/14/13
FEMA Modeled Surge Area - from 11/11/12
0
0.2
0.4mi
POWERED BY
esri

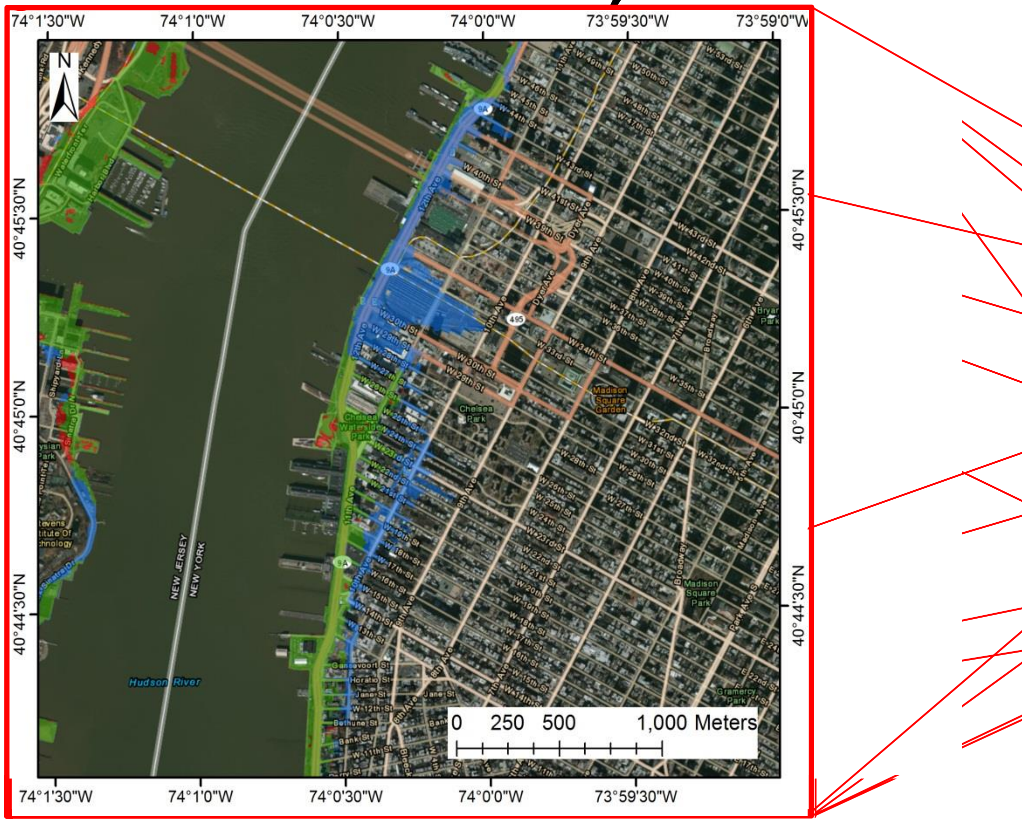
III. Model results comparison with USGS Hurricane Sandy Mapper

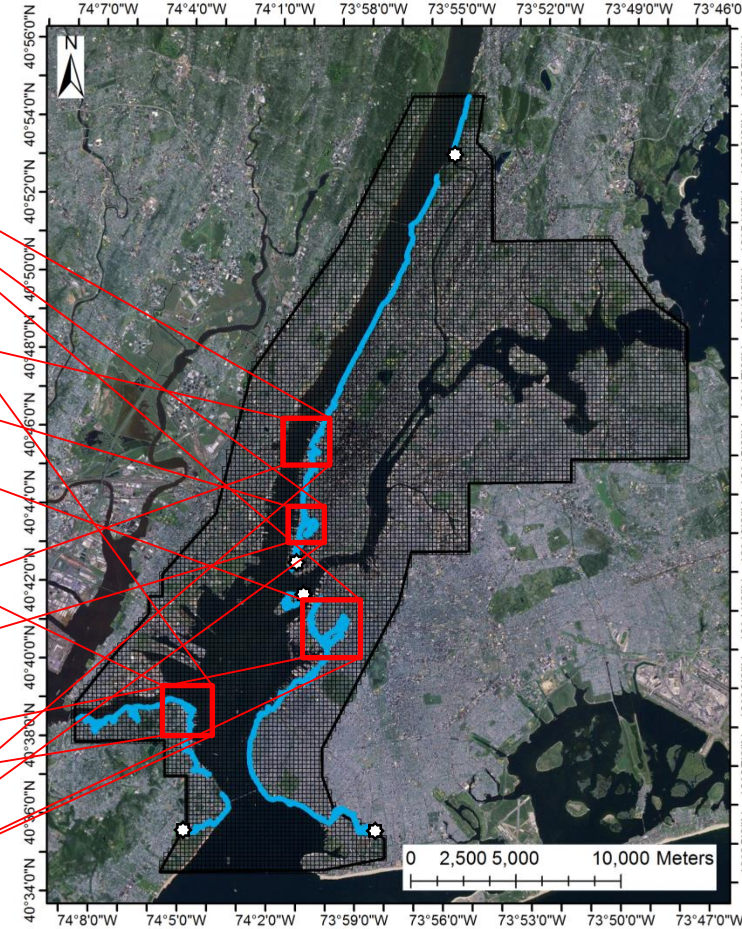
(http://54.243.149.253/home/webmap/viewer.html?webmap=c07fae08c20c4117bdb8e92e3239837e)

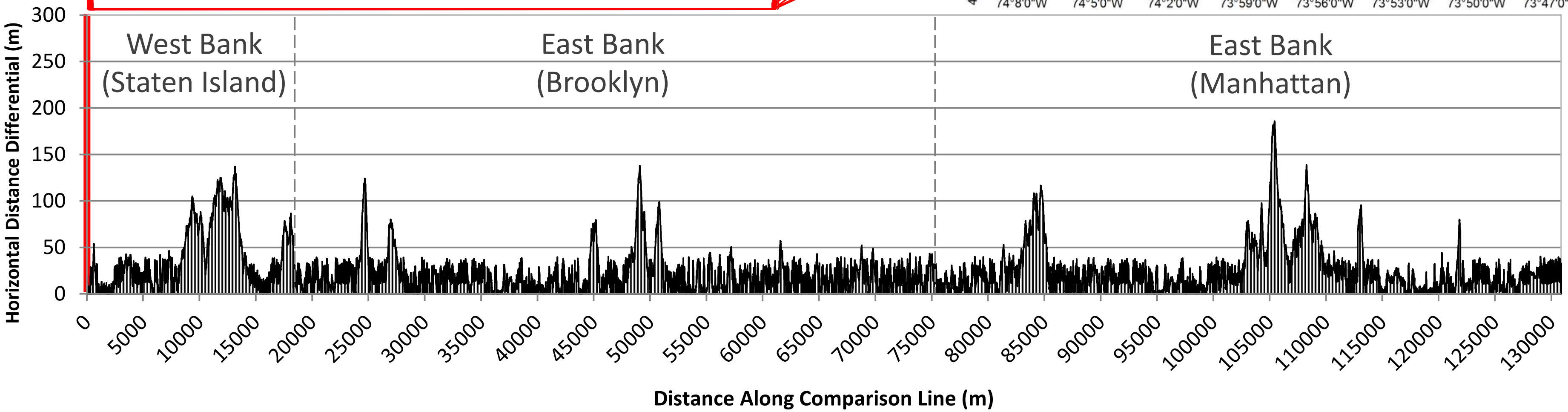
New York City Inundation comparison method:

1. Distance comparison
2. Area comparison

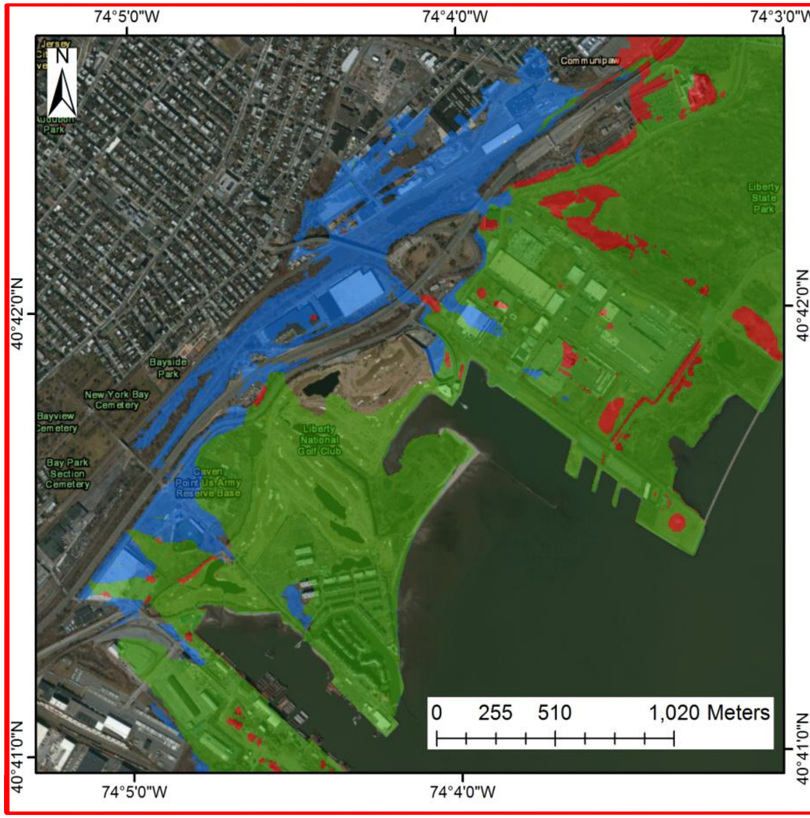
Hudson River, NY

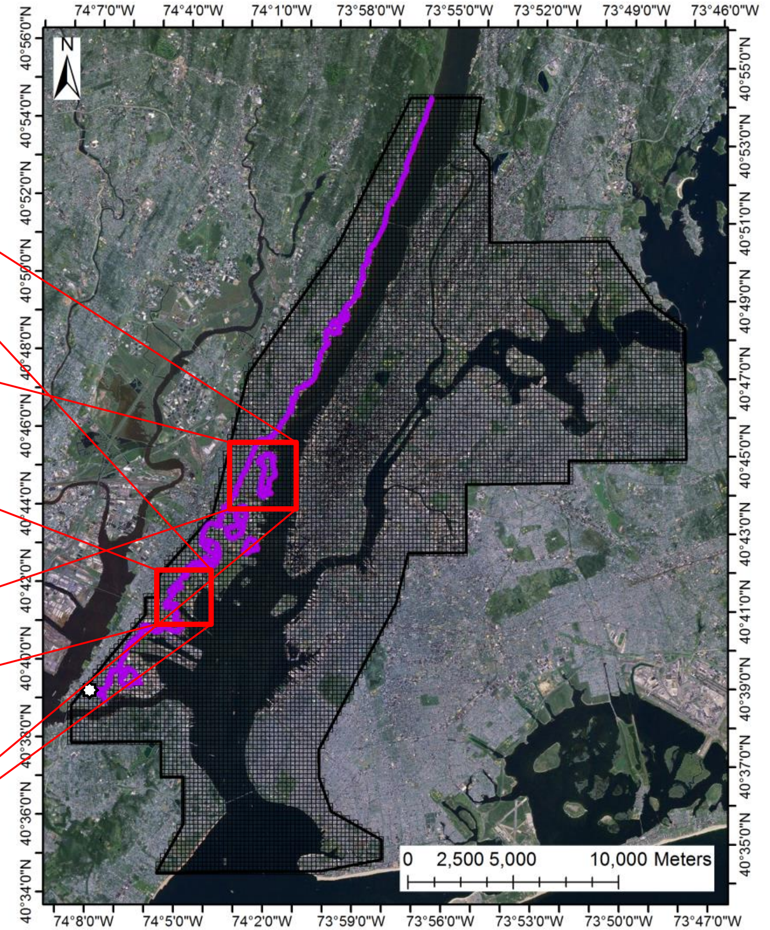


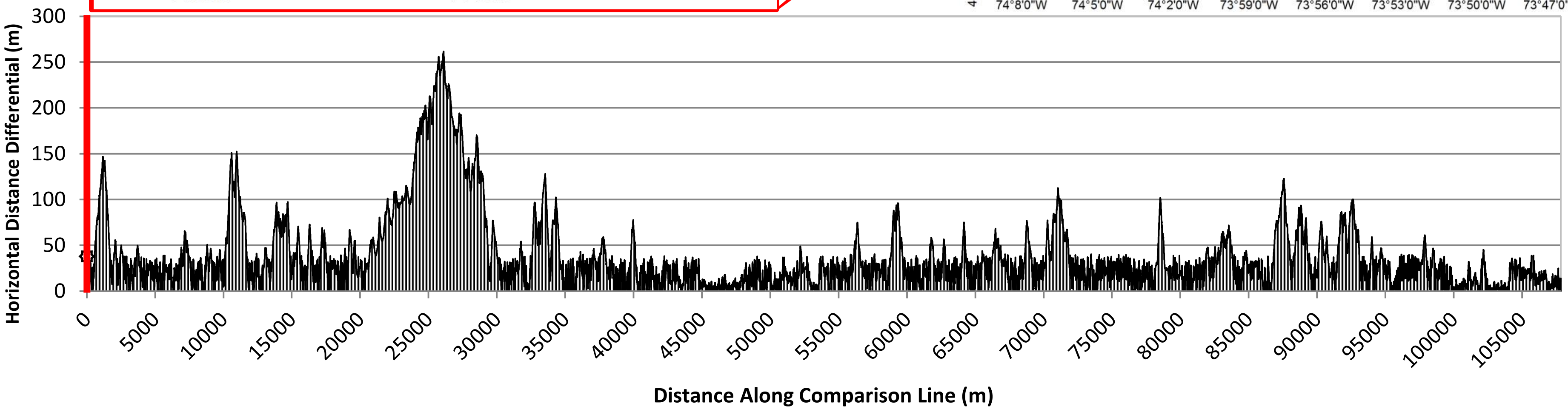




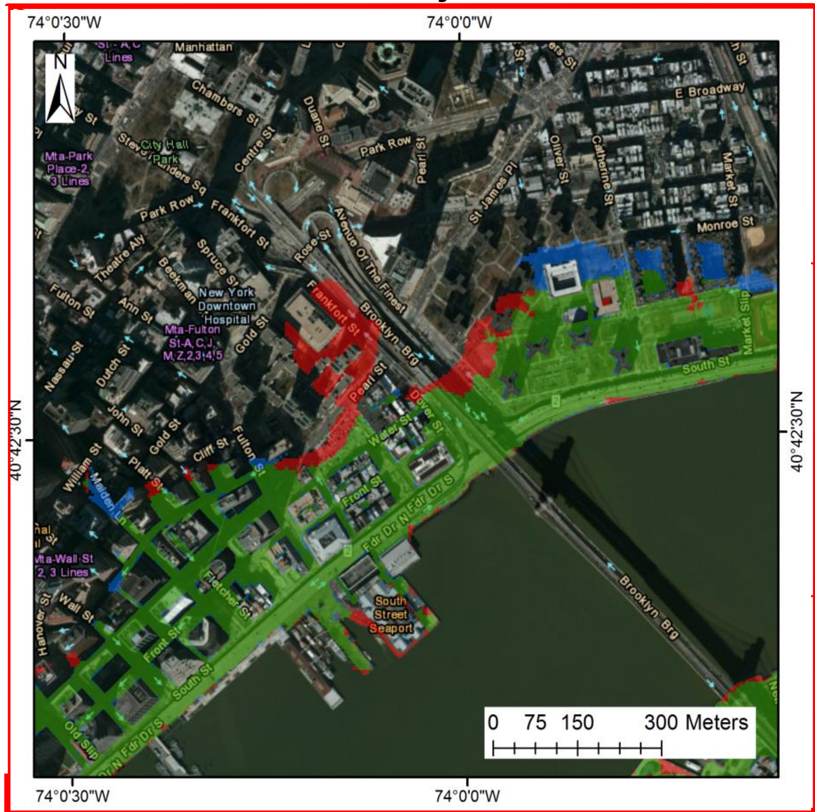
Hudson River, NJ

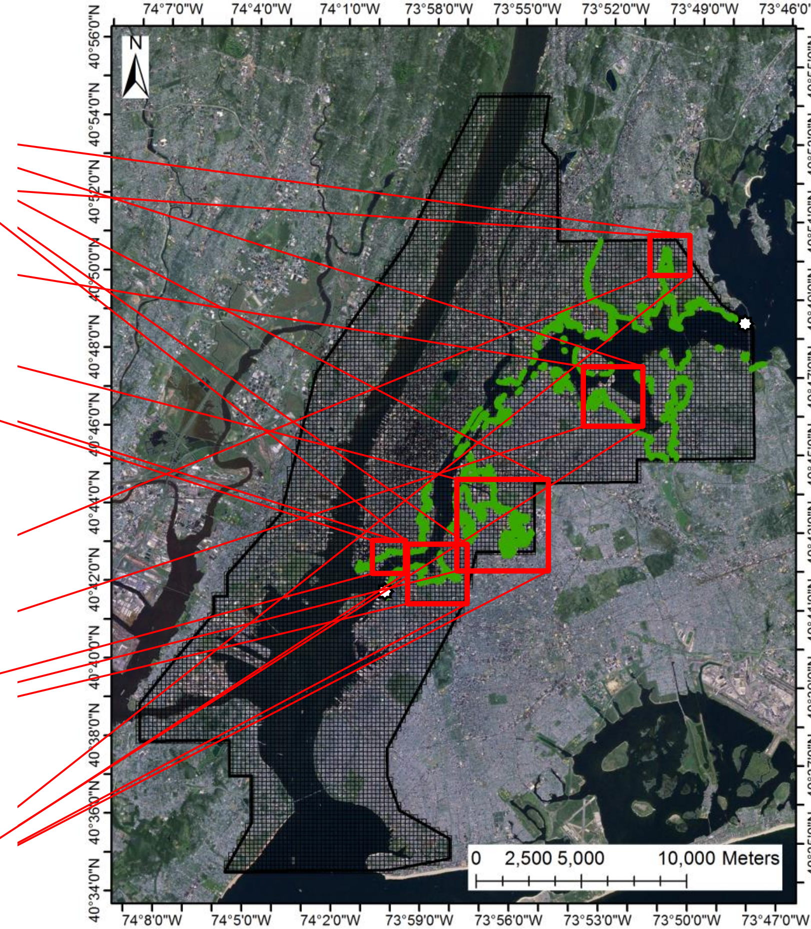


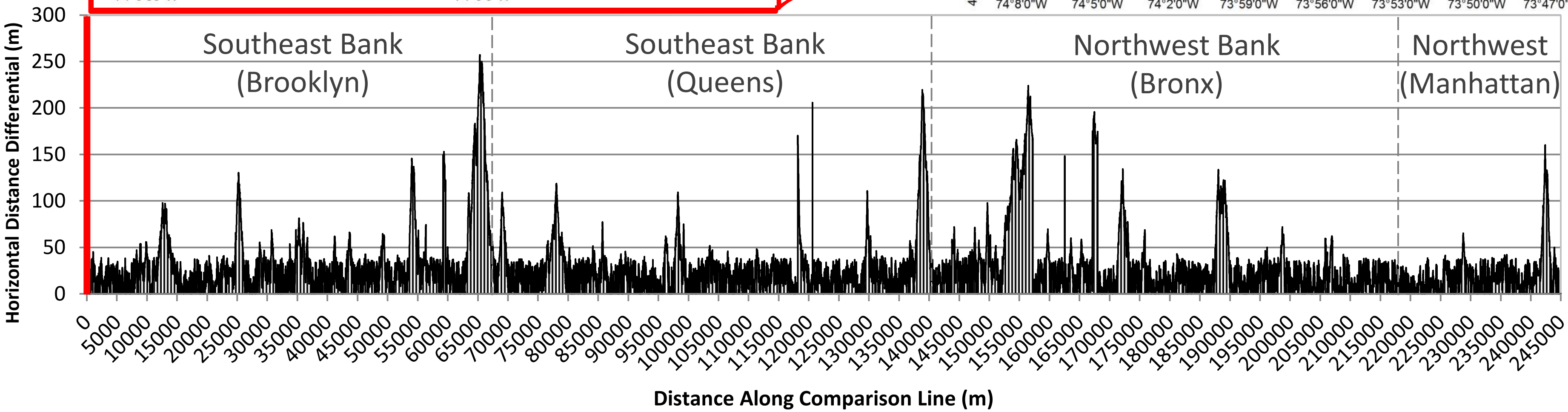




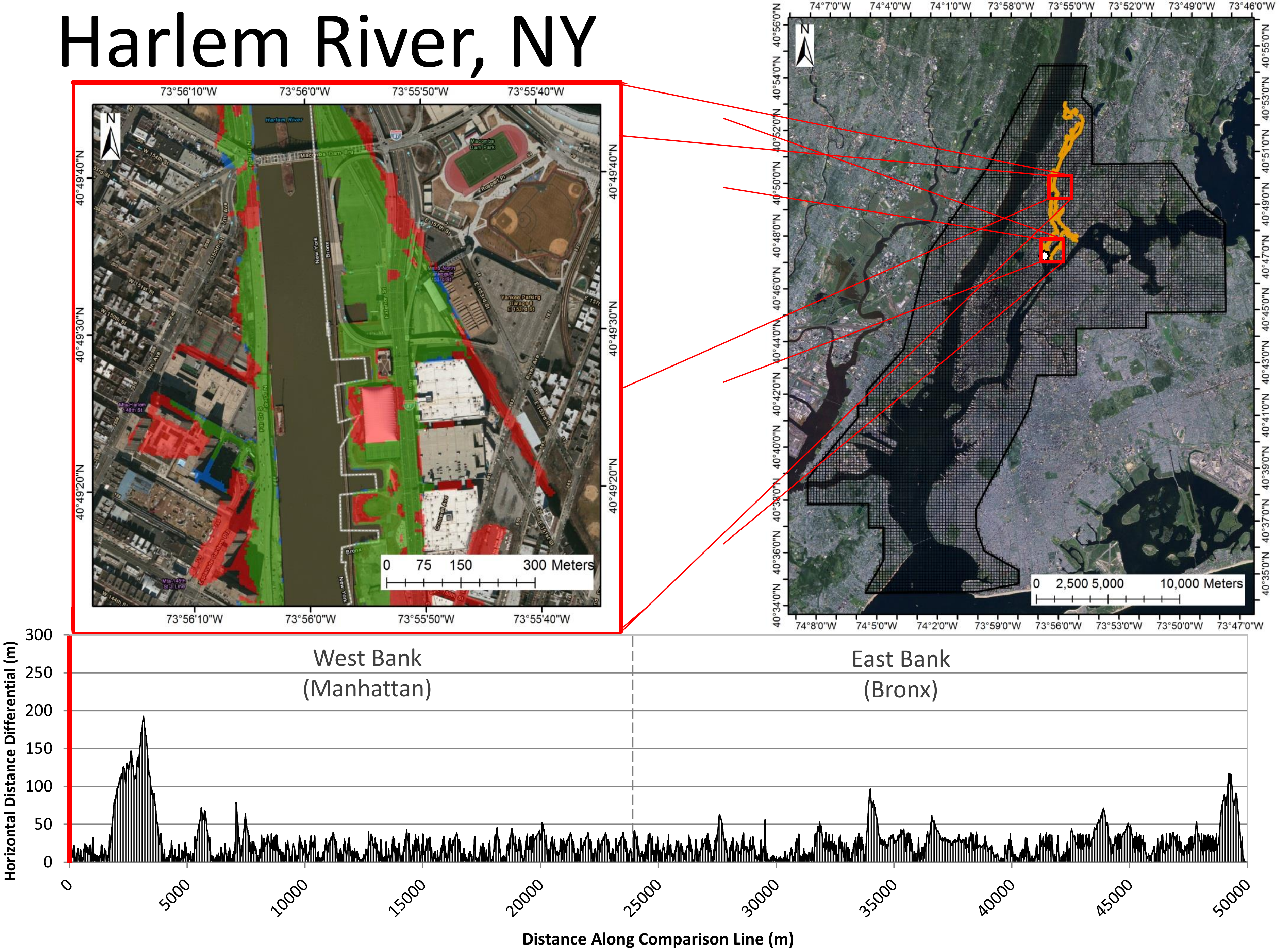
East River, NY







Harlem River, NY



Distances with 40m Max Difference Adjustment

Survey Region	**# of Points**	**Abs. Mean Dist.**	**(Diff.)**	**Std. Deviation**	**(Diff.)**
New York					
East River NY	47,283	19.907	*26.9*	12.984	*45.3*
Harlem River NY	9,673	18.616	*25.6*	12.564	*44.1*
Hudson River NY	21,492	16.484	*12.4*	9.840	*17.2*
All New York	78,448	18.336	*21.6*	11.796	*35.5*
New Jersey					
Hudson River NJ	16,396	24.079	*12.8*	13.048	*17.3*
All New Jersey	16,396	24.079	*12.8*	13.048	*17.3*
All Hudson River	37,888	20.281	*12.6*	11.444	*17.3*
Total Across Domain	94,844	21.207	*17.2*	12.422	*26.4*

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

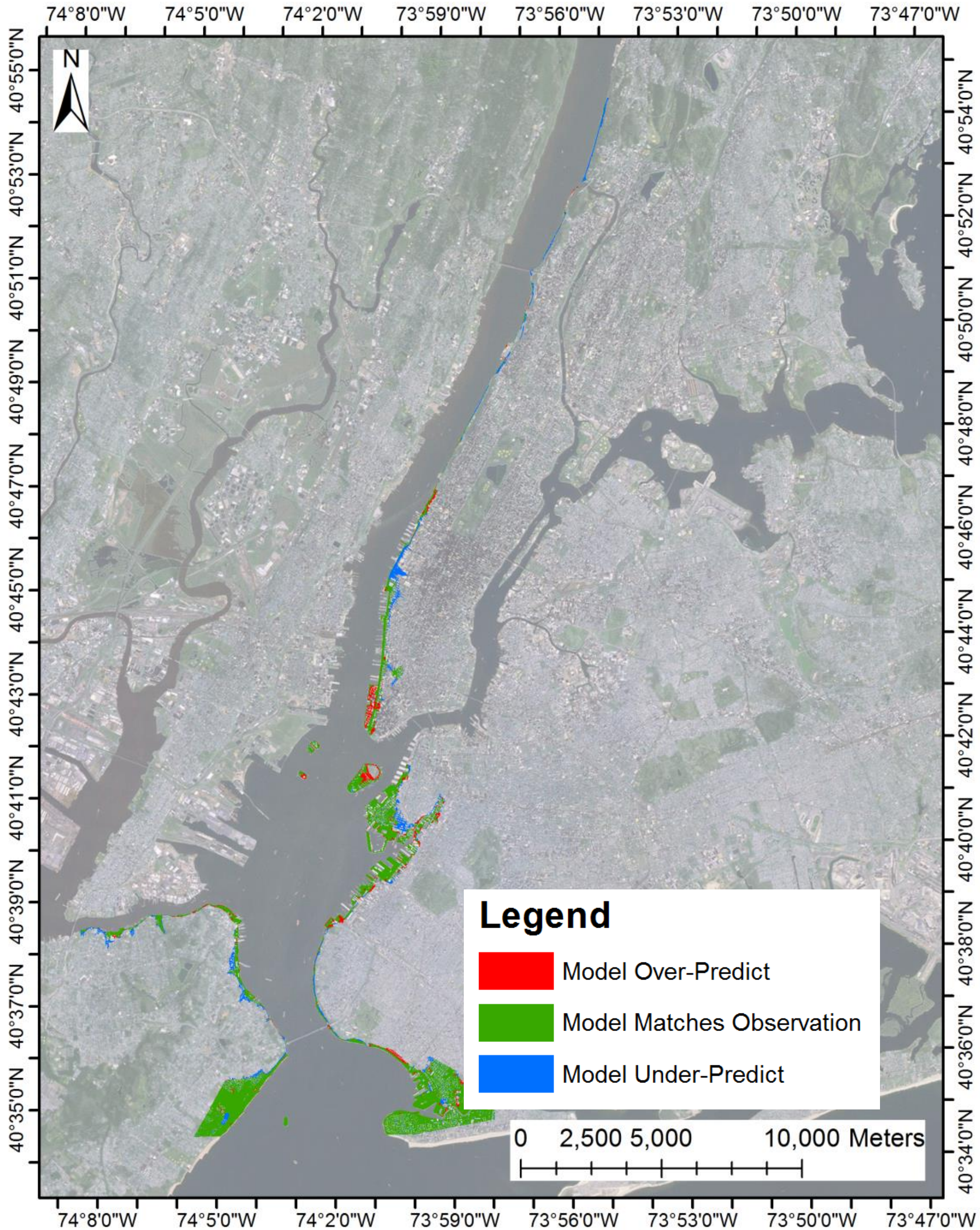
The sub-grid model prediction of flood extent is within 1/2 of a foot fall field accuracy, when comparing with observation conducted by USGS.

2. Area Comparison

(a) Hudson River, NY

Survey Region	Hudson River NY
Over-Predict	1,234,304
(%)	*7.44*
Match	13,076,031
(%)	*78.80*
Under-Predict	2,283,797
(%)	*13.76*
Total	**16,594,132**

(b) Hudson River, NJ
(c) East River, NY
(d) Harlem River, NY



Areas After 40m Max Difference Adjustment

Survey Region	Match	(%)	Under-Predict	(%)	Over-Predict	(%)	Total
New York							
East River NY	14,180,524	*83.55*	1,245,757	*7.34*	1,545,862	*9.11*	16,972,143
Harlem River NY	4,457,765	*83.14*	383,500	*7.15*	520,177	*9.70*	5,361,442
Hudson River NY	13,076,031	*88.04*	1,073,436	*7.23*	703,736	*4.74*	14,853,203
All New York	31,714,320	*85.28*	2,702,693	*7.27*	2,769,775	*7.45*	37,186,788
New Jersey							
Hudson River NJ	17,539,367	*84.95*	1,499,683	*7.26*	1,606,951	*7.78*	20,646,001
All New Jersey	17,539,367	*84.95*	1,499,683	*7.26*	1,606,951	*7.78*	20,646,001
All Hudson River	30,615,398	*86.24*	2,573,119	*7.25*	2,310,687	*6.51*	35,499,204
Total Across Domain	49,253,687	*85.17*	4,202,376	*7.27*	4,376,726	*7.57*	57,832,789

Area-wise, the sub-grid model prediction of flood extent covers 85% of the area, when comparing with the observation conducted by USGS.

3D Animations

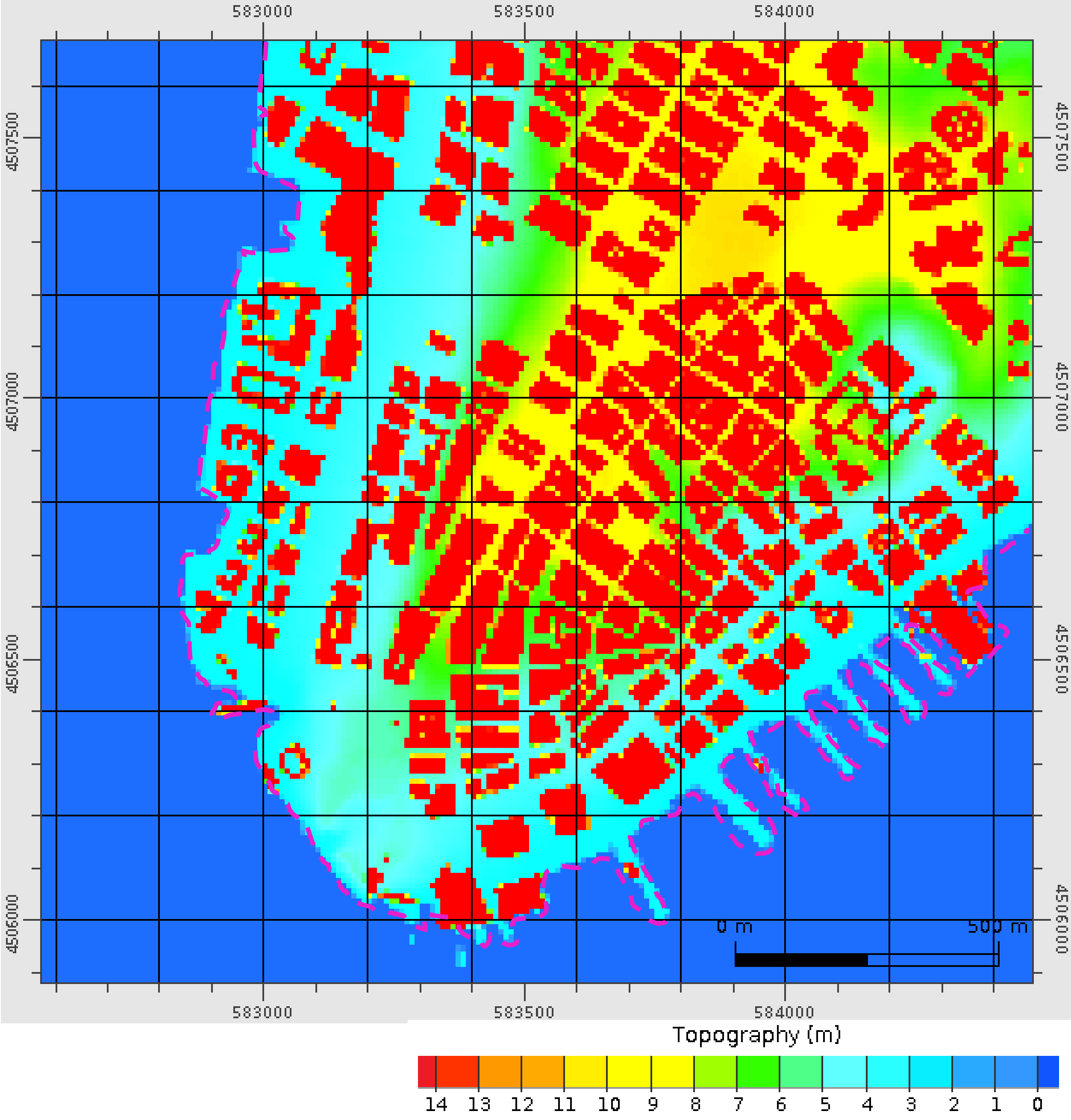
WILLIAM & MARY
VIMS
VIRGINIA INSTITUTE OF MARINE SCIENCE
SCHOOL OF MARINE SCIENCE

Sensitivity Test With and Without Sub-Grid Refinement

Grid Resolution

200m Base Grid

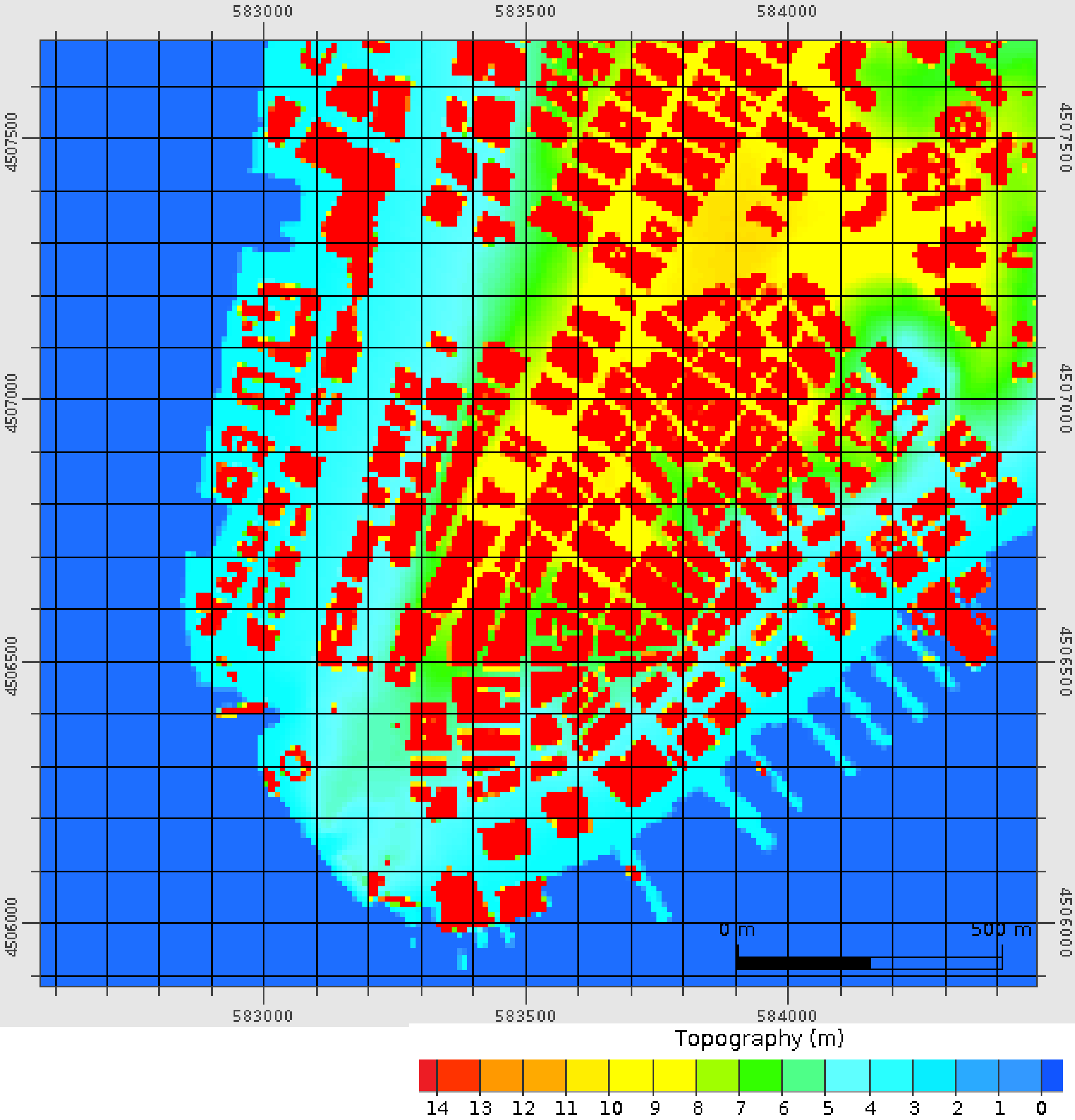
5m Sub-Grid



Grid Resolution

100m Base Grid

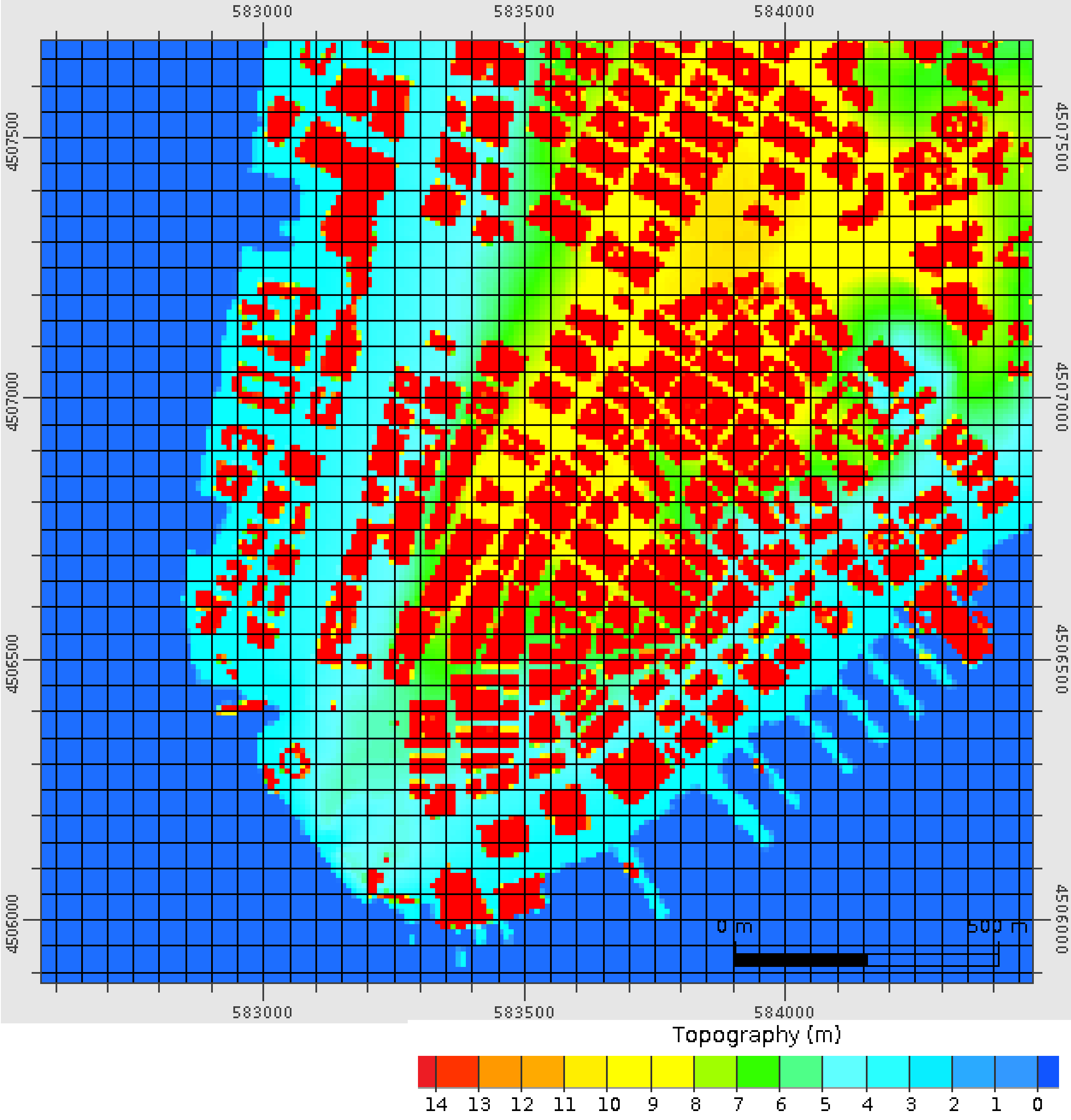
5m Sub-Grid

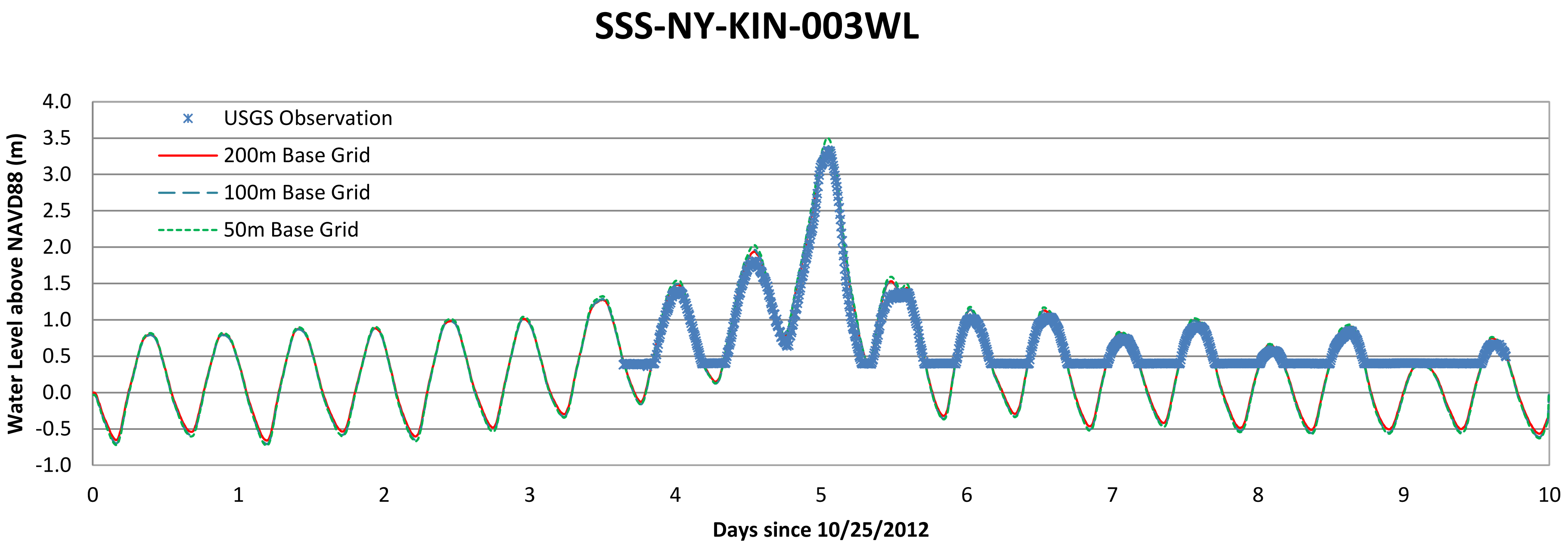


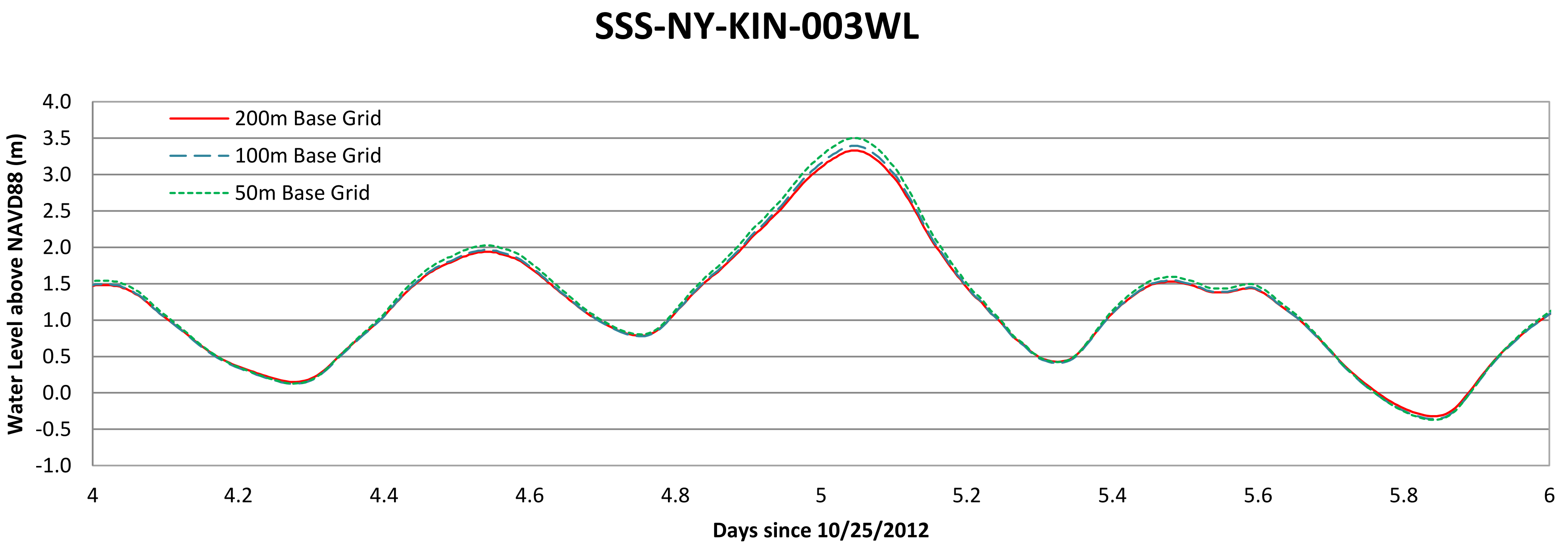
Grid Resolution

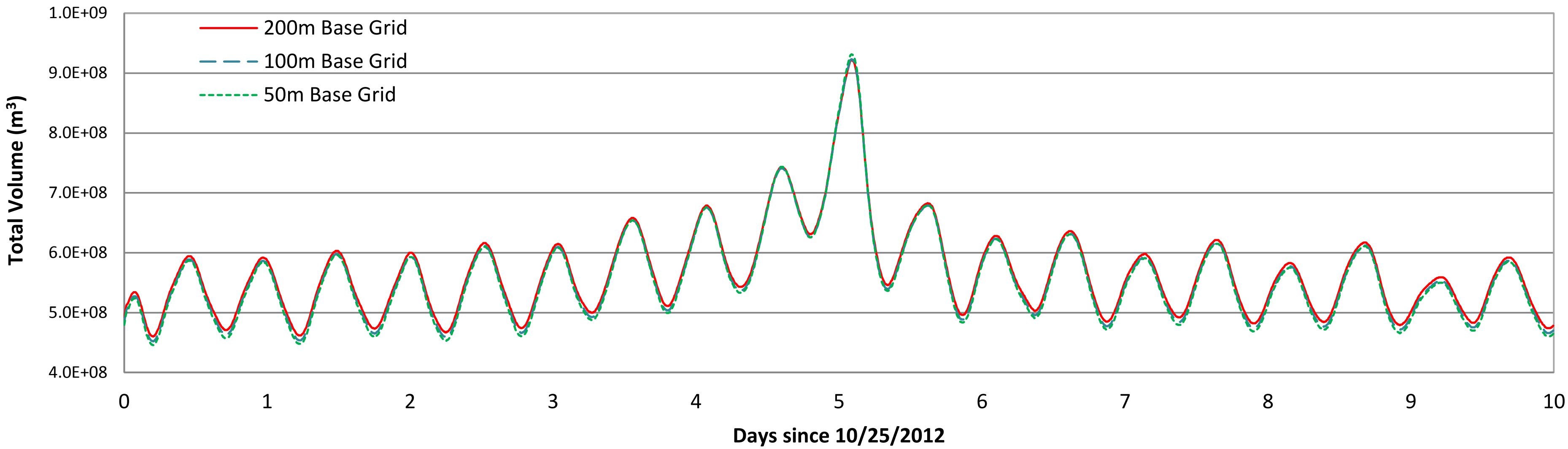
50m Base Grid

5m Sub-Grid

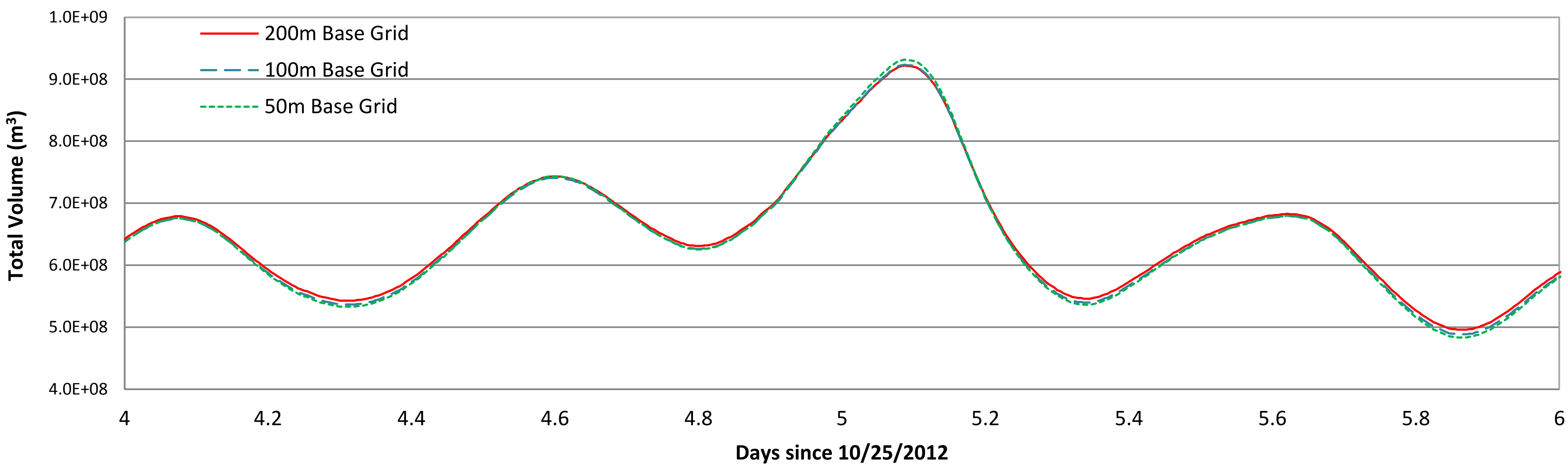



SSS-NY-KIN-003WL
USGS Observation
200m Base Grid
100m Base Grid
50m Base Grid
Water Level above NAVD88 (m)
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
-0.5
-1.0
0
1
2
3
4
5
6
7
8
9
10
Days since 10/25/2012


SSS-NY-KIN-003WL
200m Base Grid
100m Base Grid
50m Base Grid
Water Level above NAVD88 (m)
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
-0.5
-1.0
4
4.2
4.4
4.6
4.8
5
5.2
5.4
5.6
5.8
6
Days since 10/25/2012



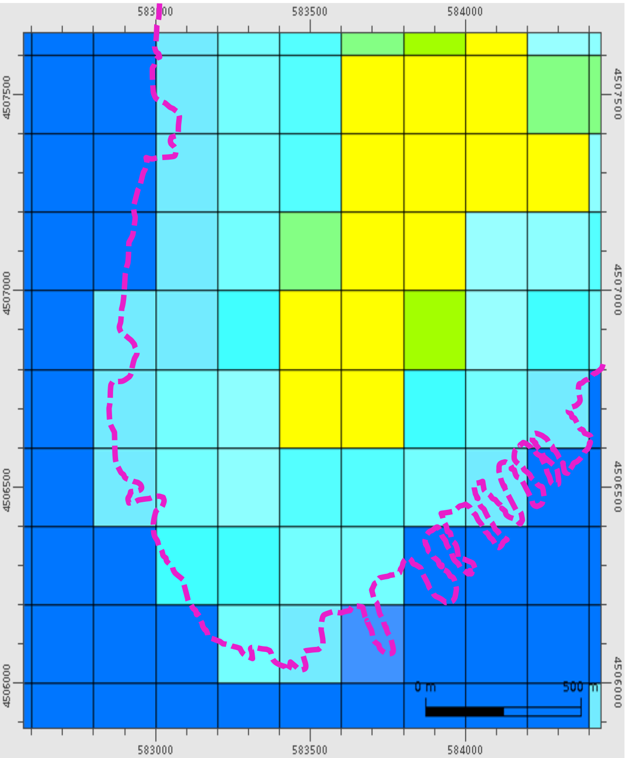
1.0E+09
9.0E+08
8.0E+08
7.0E+08
6.0E+08
5.0E+08
4.0E+08
Total Volume (m³)
200m Base Grid
100m Base Grid
50m Base Grid
0
1
2
3
4
5
6
7
8
9
10
Days since 10/25/2012



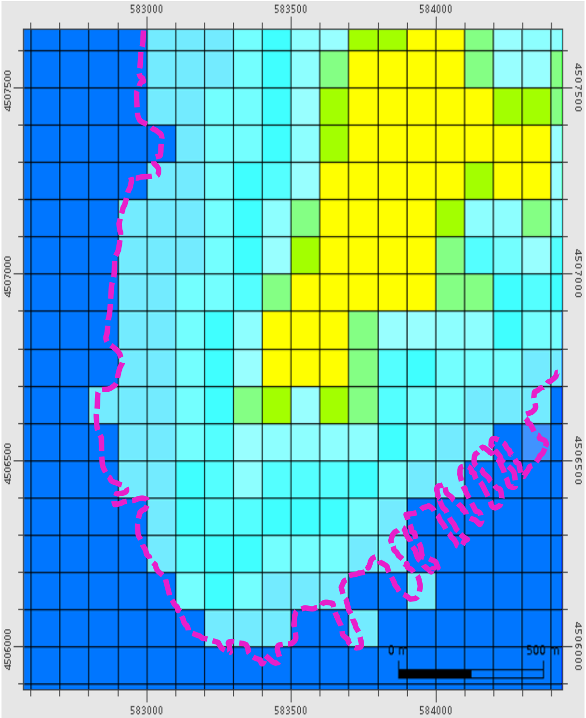
1.0E+09
9.0E+08
8.0E+08
7.0E+08
6.0E+08
5.0E+08
4.0E+08
Total Volume (m³)
200m Base Grid
100m Base Grid
50m Base Grid
4
4.2
4.4
4.6
4.8
5
5.2
5.4
5.6
5.8
6
Days since 10/25/2012

Without Sub-Grid Refinement

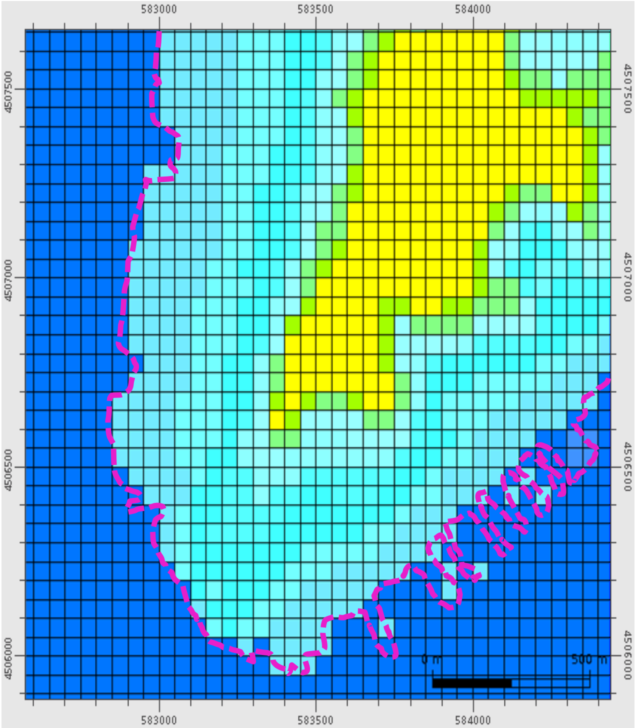
200 m base grid

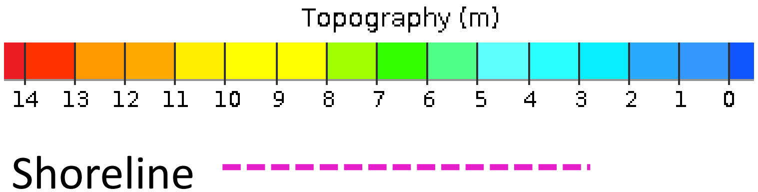


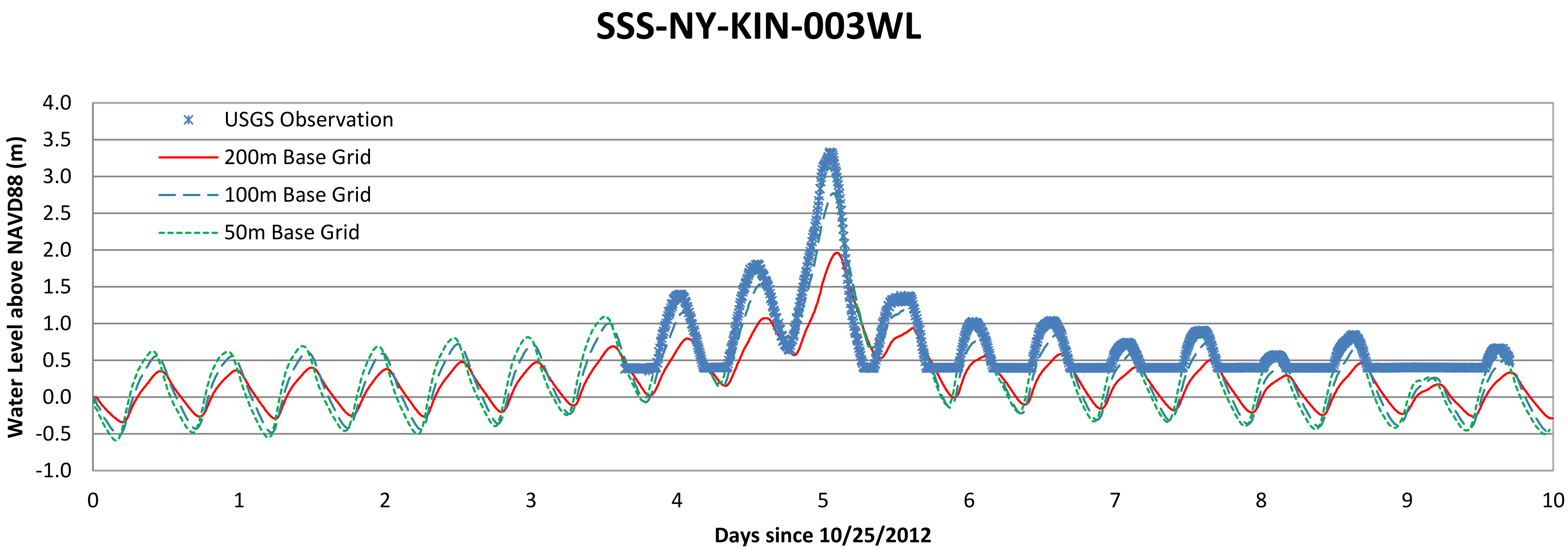
100 m base grid

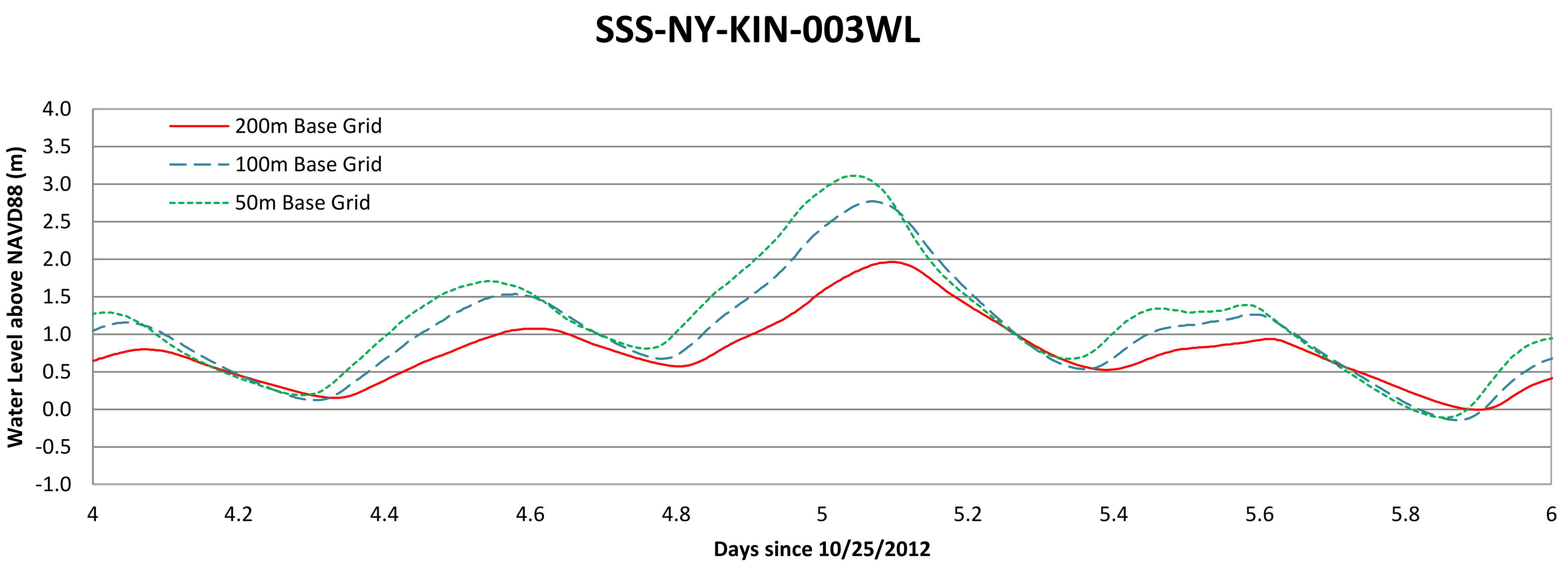


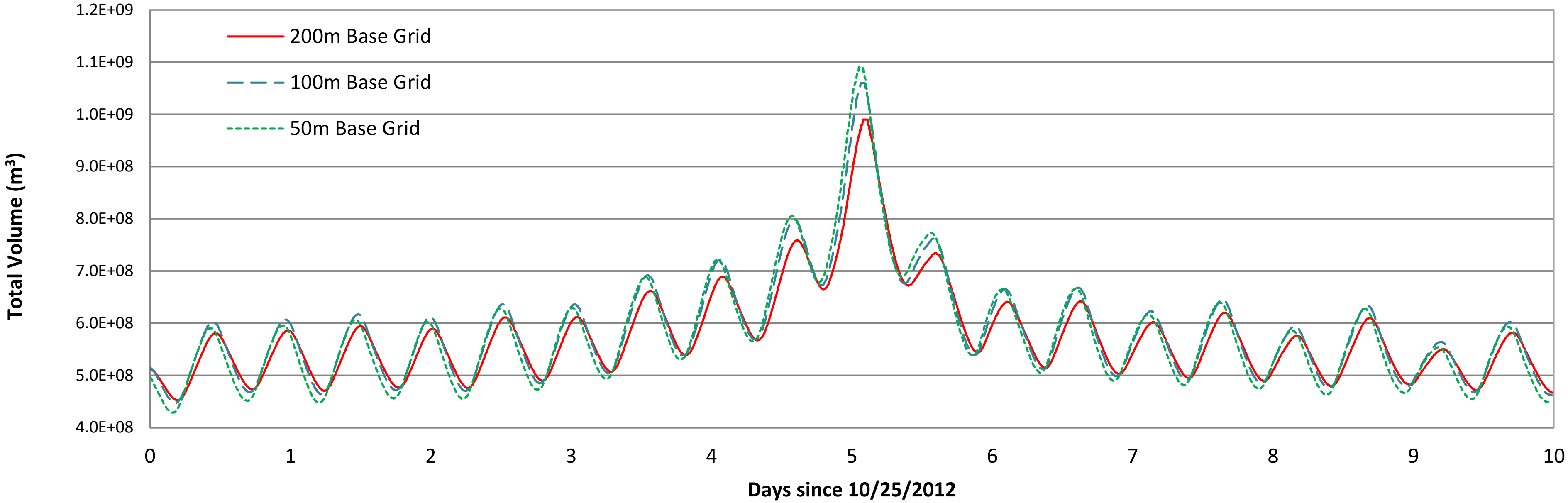
50 m base grid

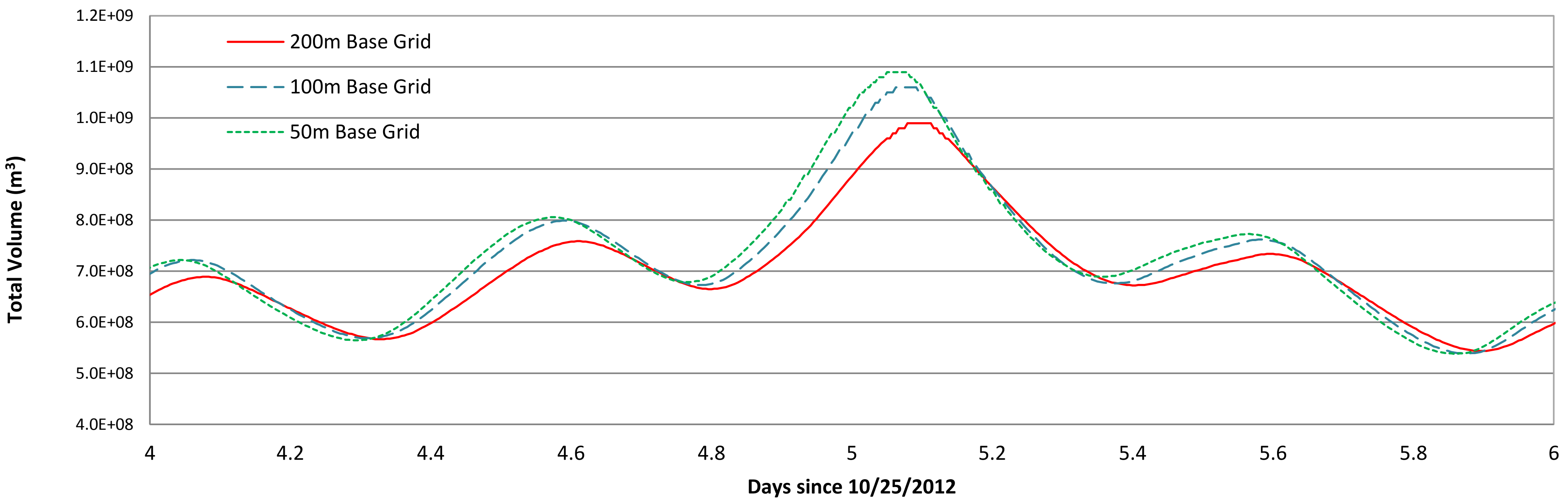





SSS-NY-KIN-003WL
USGS Observation
200m Base Grid
100m Base Grid
50m Base Grid
Water Level above NAVD88 (m)
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
-0.5
-1.0
0
1
2
3
4
5
6
7
8
9
10
Days since 10/25/2012


SSS-NY-KIN-003WL
200m Base Grid
100m Base Grid
50m Base Grid
Water Level above NAVD88 (m)
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
-0.5
-1.0
4
4.2
4.4
4.6
4.8
5
5.2
5.4
5.6
5.8
6
Days since 10/25/2012


200m Base Grid
100m Base Grid
50m Base Grid
Total Volume (m³)
Days since 10/25/2012


200m Base Grid
100m Base Grid
50m Base Grid
Total Volume (m³)
Days since 10/25/2012

Recent relevant publications:

1. Harry Wang, J. D. Loftis, Z. Liu, D. Forrest and J. Zhang (2014):"The storm surge and sub-grid inundation modeling in New York City during Hurricane Sandy". *Journal of Marine Science and Engineering, p 226-246, doi:10.3390/jmse201062.*

2. Loftis, J.D., Wang, H.V., Hamilton, S.E., and Forrest, D.R. (2014). Combination of Lidar Elevations, Bathymetric Data, and Urban Infrastructure in a Sub-Grid Model for Predicting Inundation in New York City during Hurricane Sandy. *Computers, Environment, and Urban Systems.* (Submitted) http://www.vims.edu/people/loftis_jd/storm_surge2/index.php

3. Loftis, J.D., Wang, H.V., DeYoung, R.J., and Ball, W.B. (2014). Integrating Lidar Data into a High-Resolution Topo-bathymetric DEM for Use with Sub-Grid Inundation Modeling at Langley Research Center. *Journal of Coastal Research, Special Issue.* (In Review) http://www.vims.edu/people/loftis_jd/storm_surge2/index.php

4. Roland, Aron, Yinglong. Zhang, Harry. V. Wang, Yanqiu Meng, Yi-cheng Teng, Vladimir Maderichd, Igor Brovchenkod, Mathieu Dutour-Sikirice and Ulrich Zankea (2012): "A fully coupled 3D wave-current interaction model on unstructured grids". *JGR – Oceans, Vol. 117, C00J33, doi:10.1029/2012JC007952*

5. Kyoung-Ho Cho, Harry Wang Jian Shen, Arnoldo Valle-Levinson and Yi-cheng Teng (2012): "A modeling study on the response of the Chesapeake Bay to Hurricane Events of Floyd and Isabel" *Ocean Modeling, Vol. 49-50, p22-46.*

JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 117, C00J33, doi:10.1029/2012JC007952, 2012

A fully coupled 3D wave-current interaction model on unstructured grids

Aron Roland,[1] Yinglong J. Zhang,[2,4] Harry V. Wang,[3] Yanqiu Meng,[3] Yi-Cheng Teng,[3] Vladimir Maderich,[5] Igor Brovchenko,[5] Mathieu Dutour-Sikiric,[6] and Ulrich Zanke[1]

Received 31 January 2012; revised 13 August 2012; accepted 21 August 2012; published 29 September 2012.

[1] We present a new modeling system for wave-current interaction based on unstructured grids and thus suitable for very large-scale high-resolution multiscale studies. The coupling between the 3D current model (SELFE) and the 3rd generation spectral wave model (WWM-II) is done at the source code level and the two models share same sub-domains in the parallel MPI implementation in order to ensure parallel efficiency and avoid interpolation. We demonstrate the accuracy, efficiency, stability and robustness of the coupled SELFE-WWM-II model with a suite of progressively challenging benchmarks with analytical solution, laboratory data, and field data. The coupled model is shown to be able to capture important physics of the wave-current interaction under very different scales and environmental conditions with excellent convergence properties even in complicated test cases. The challenges in simulating the 3D wave-induced effects are highlighted as well, where more research is warranted.

Ocean Modelling 85 (2015) 16–31

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journal homepage: www.elsevier.com/locate/ocemod

ELSEVIER

A new vertical coordinate system for a 3D unstructured-grid model

CrossMark

Yinglong J. Zhang[a,*], Eli Ateljevich[b], Hao-Cheng Yu[d], Chin H. Wu[c], Jason C.S. Yu[d]

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[b] California Department of Water Resource, 1416 Ninth St Rm 215-4, Sacramento, CA 95814, USA
[c] College of Engineering, Department Civil & Environmental Engineering, University of Wisconsin – Madison, 1415 Engineering Dr, Madison, WI 53706, USA
[d] Dept. of Marine Environment and Engineering, National Sun Yat-Sen University, 70 Lien-Hai Road, Kaohsiung 80424, Taiwan

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SELFE
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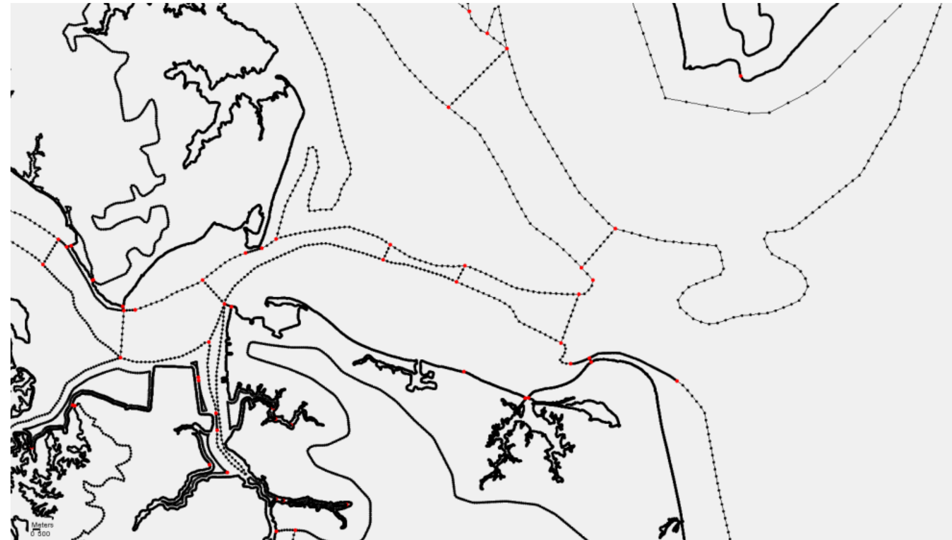
Great Lakes
Taiwan

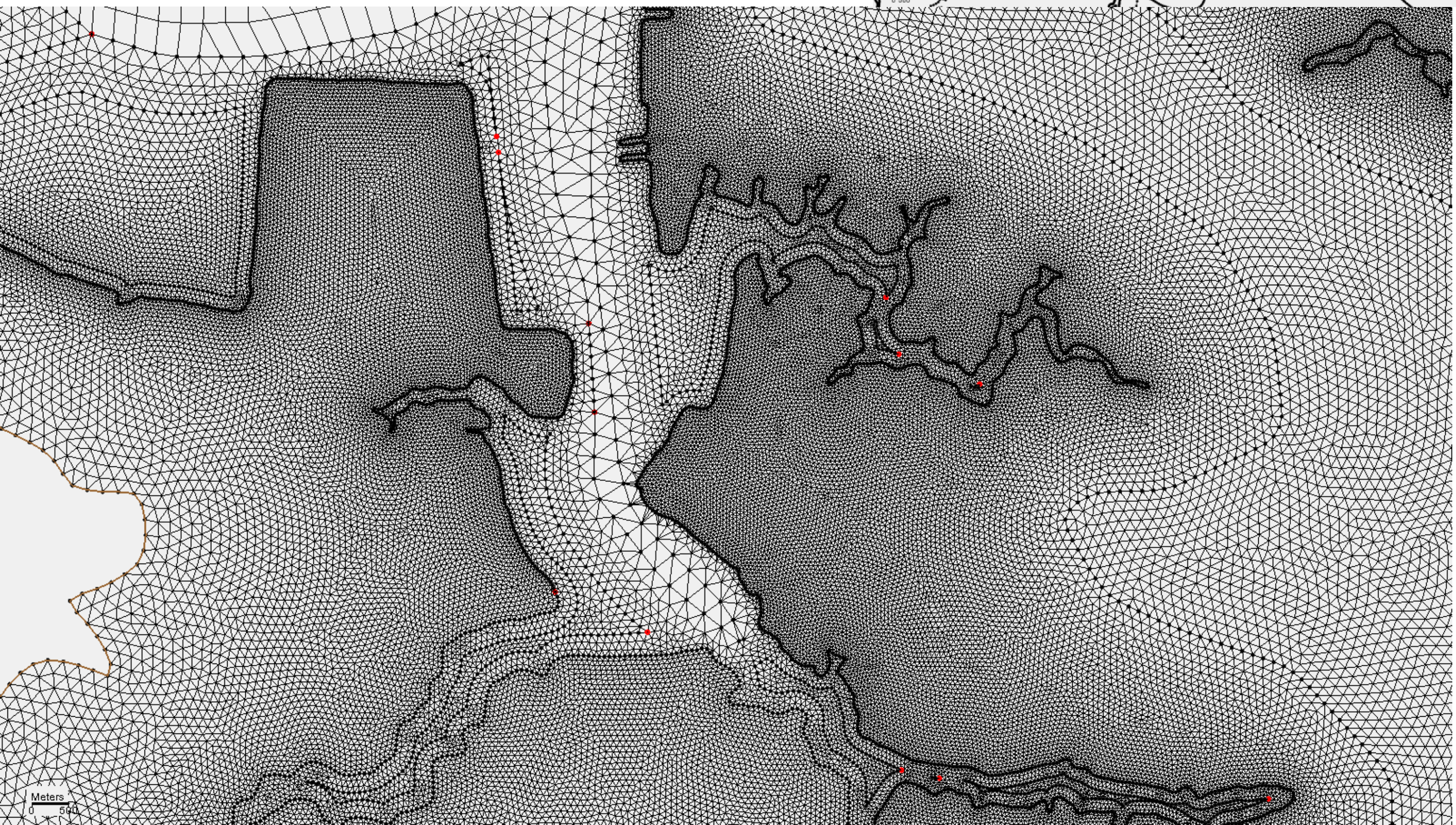
ABSTRACT

We present a new vertical coordinate system for cross-scale applications. Dubbed LSC^2 (Localized Sigma Coordinates with Shaved Cell), the new system allows each node of the grid to have its own vertical grid, while still maintaining reasonable smoothness across horizontal and vertical dimensions. Furthermore, the staircase created by the mismatch of vertical levels at adjacent nodes is eliminated with a simple shaved-cell like approach using the concept of degenerate prisms. The new system is demonstrated to have the benefits of both terrain-following and *Z*-coordinate systems, while minimizing their adverse effects. We implement LSC^2 in a 3D unstructured-grid model (SELFE) and demonstrate its superior performance with test cases on lake and ocean stratification.

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.



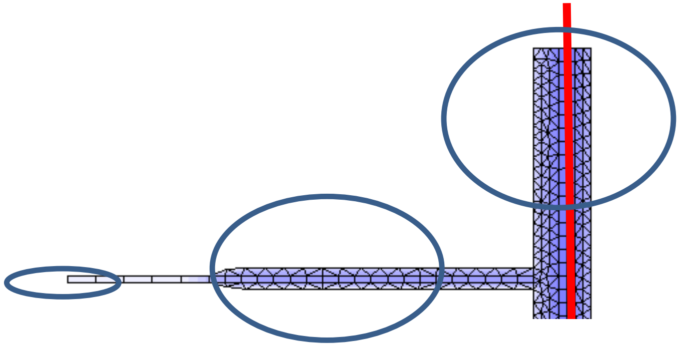


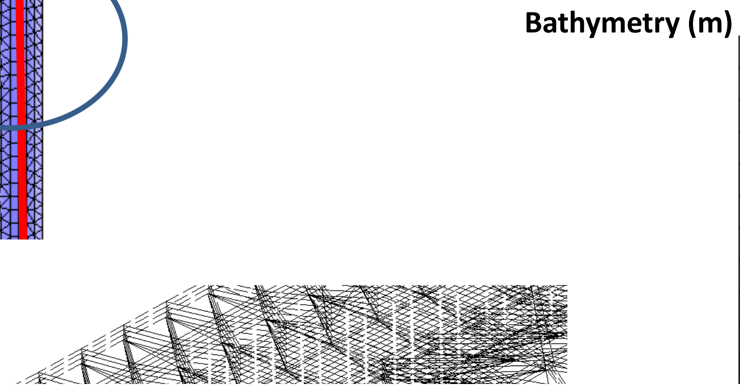
Using SMS to divide ship channels, embayment, overland before generating the model grid

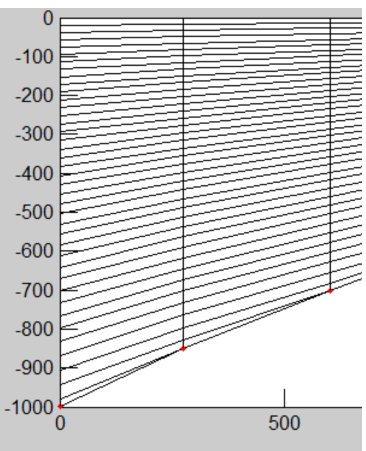
Ocean Modelling 85 (2015) 16-31

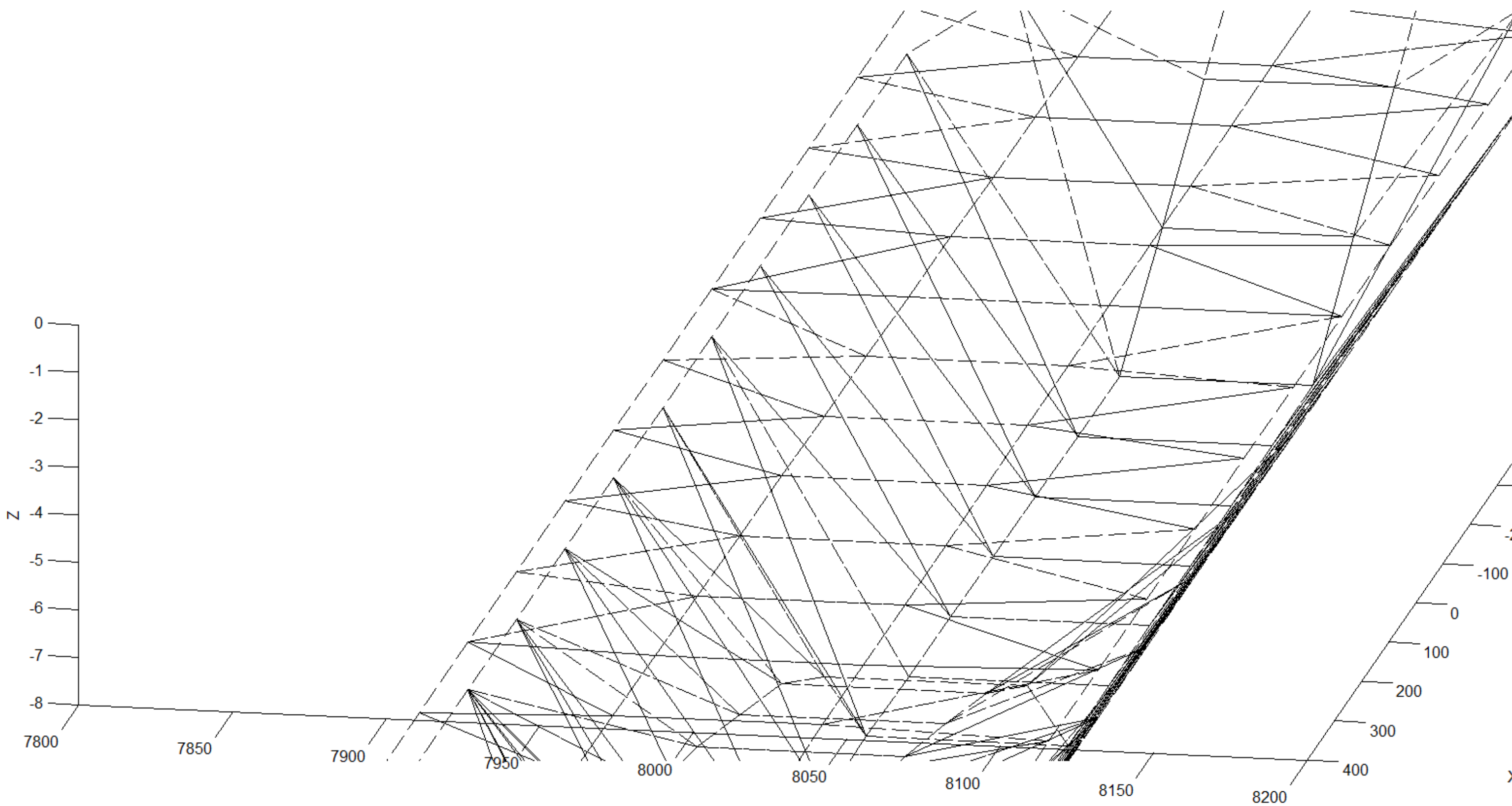
A new vertical coordinate system for a 3D unstructured-grid model
Yinglong J. Zhang , Eli Ateljevich , Hao-Cheng Yu , Chin H. Wu, Jason C.S. Yu

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 [§]

www.JCRonline.org

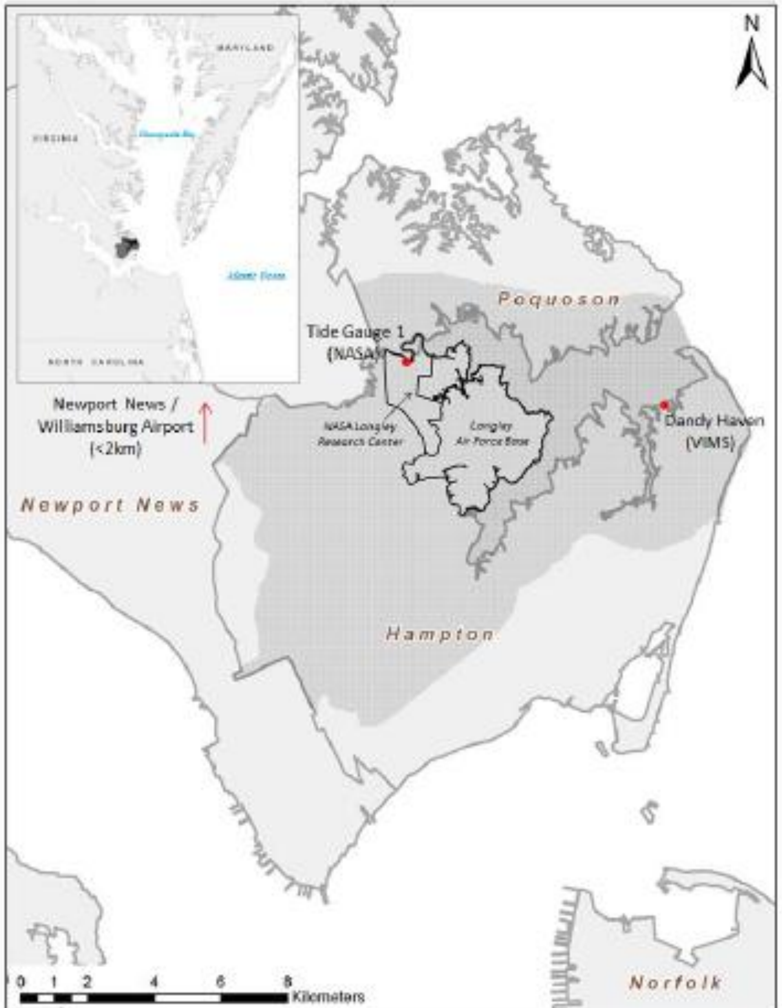


Figure 1. Study area showing 50m resolution model grid (in grey) aligned with the Back River watershed with two tide gauges in red.

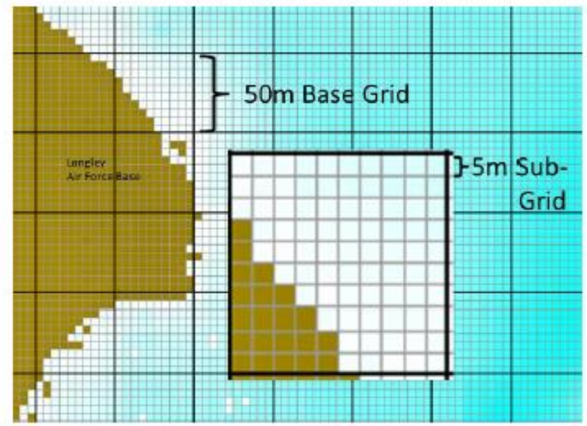


Figure 2. Model grid structure depicting a 50m base grid with a 10×10 nested 5m sub-grid showing the northeast tip of Langley Air Force Base with partially wet (blue) and partially dry (brown) grid cells.

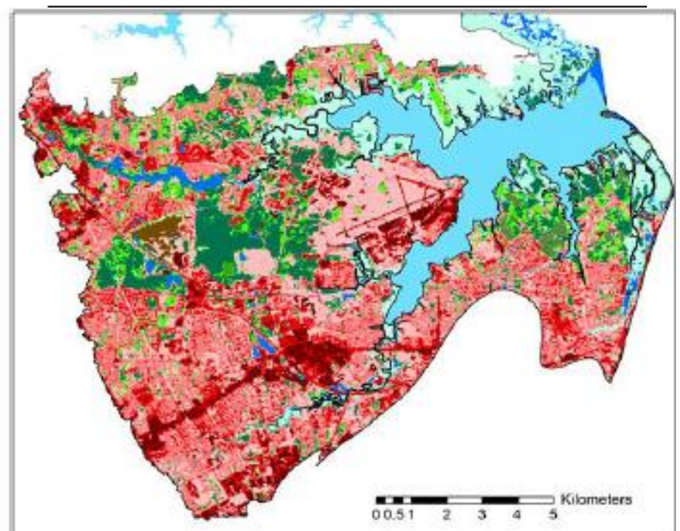


Figure B. Land use map for precipitation and infiltration calculation

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

U.S. DEPARTMENT OF COMMERCE
National Oceanic and Atmospheric Administrat
NATIONAL WEATHER SERVICE

10009 General Mahone Highway
Wakefield, Virginia 23888-2742

August 29, 2011

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

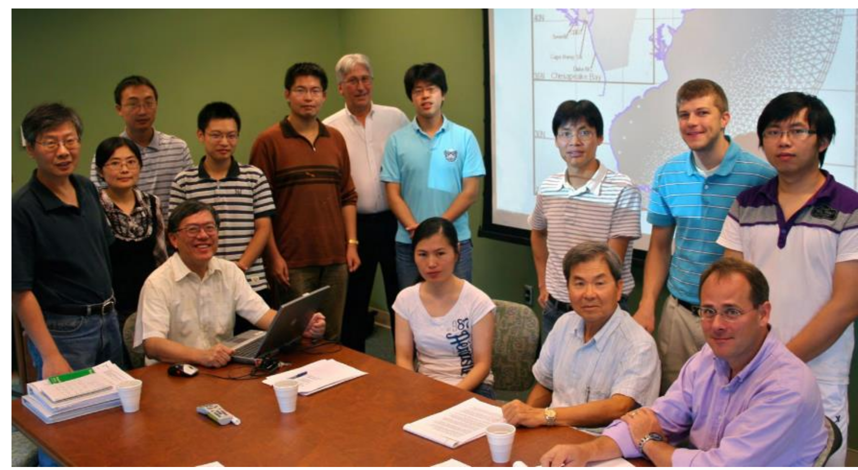
Dear Dr. Wells:

We at the National Weather Service would like to express our appreciation for all of 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 forecast 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,

VIMS ECM group won 2011 Governor's Innovative technology award



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.