Towards a Predictive Storm Surge Modeling System for the Northeastern Seaboard, USA

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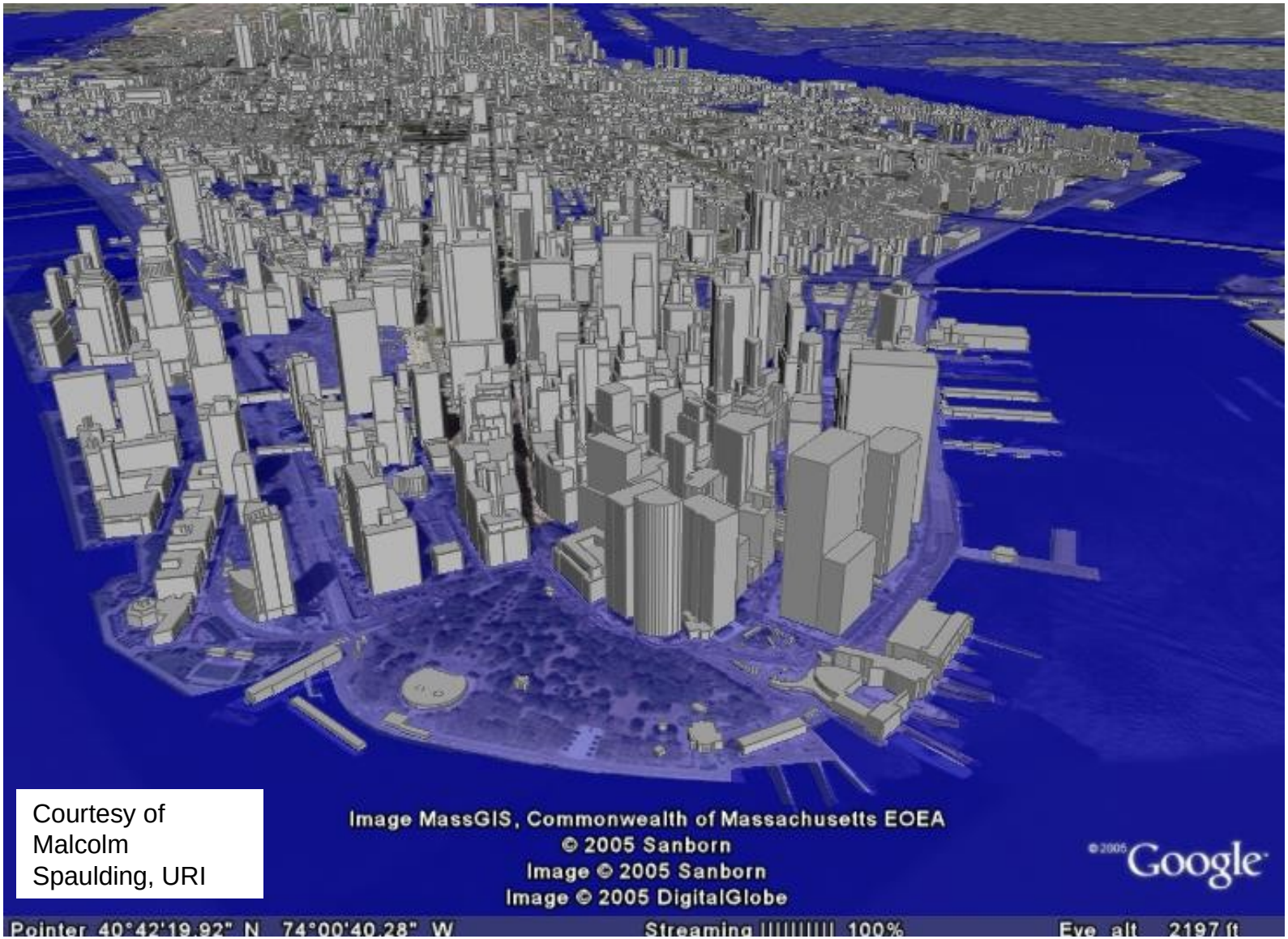
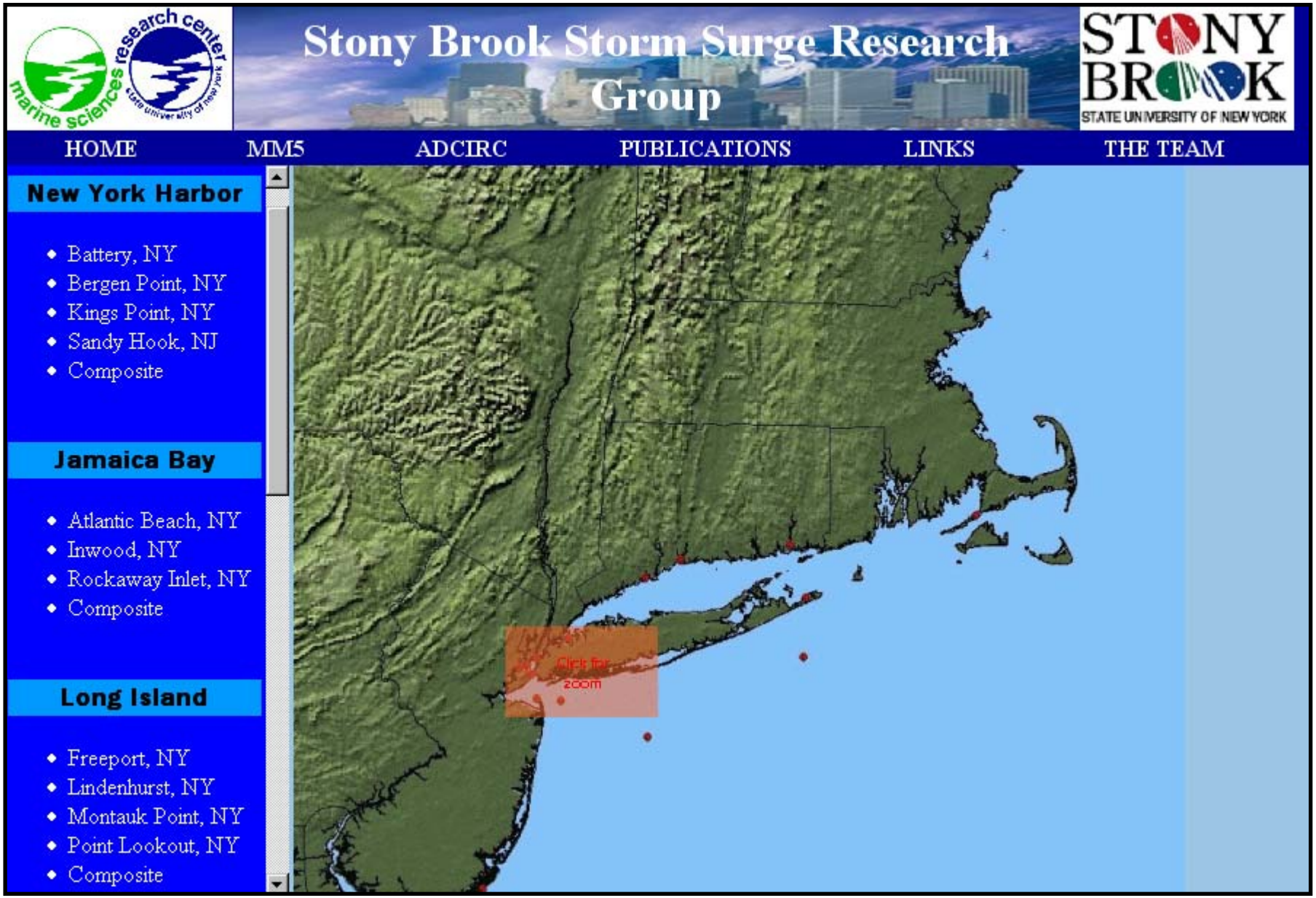
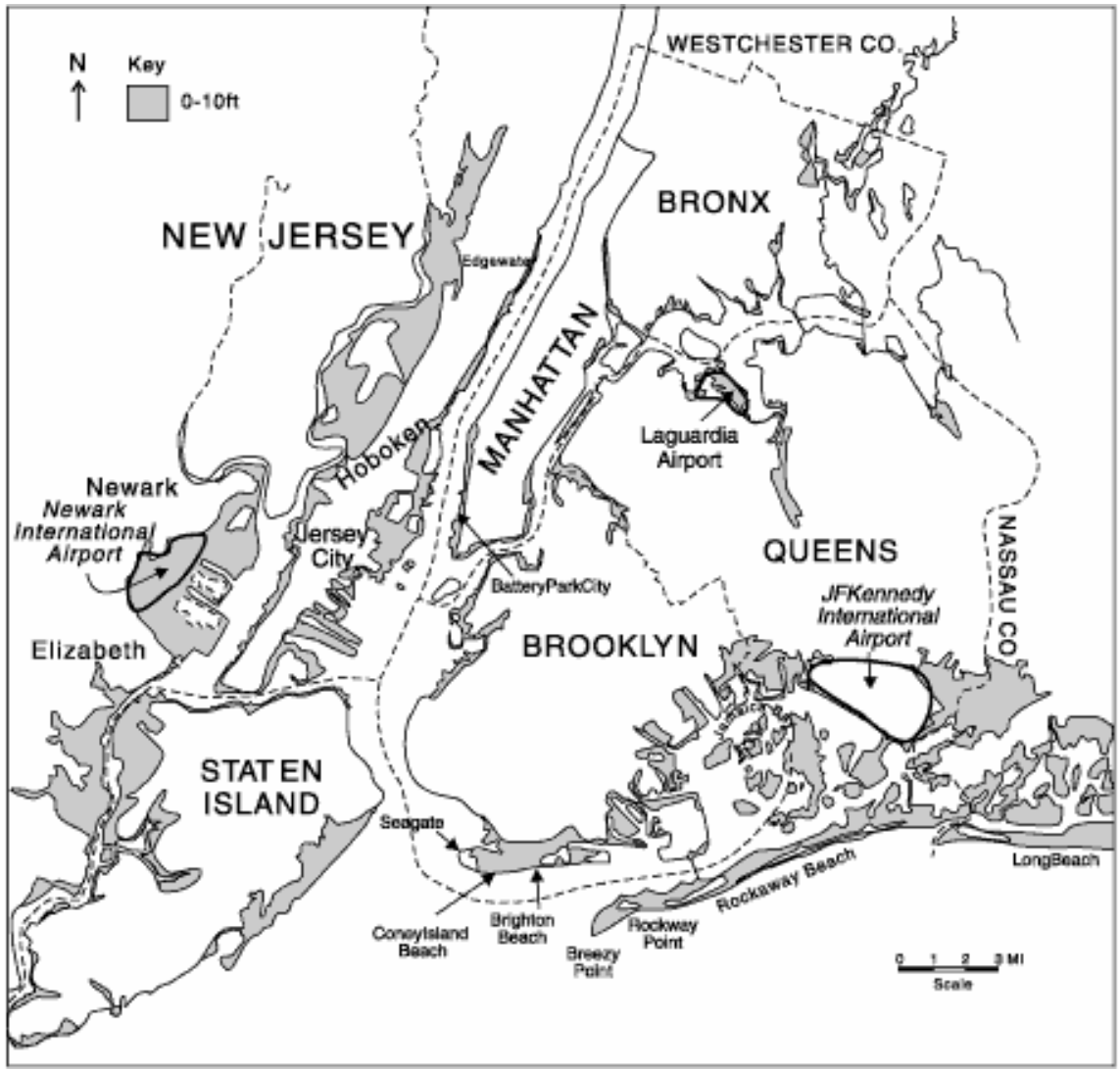


Or, New York's Katrina: science and beyond into engineering, public policy, politics, awakenings……

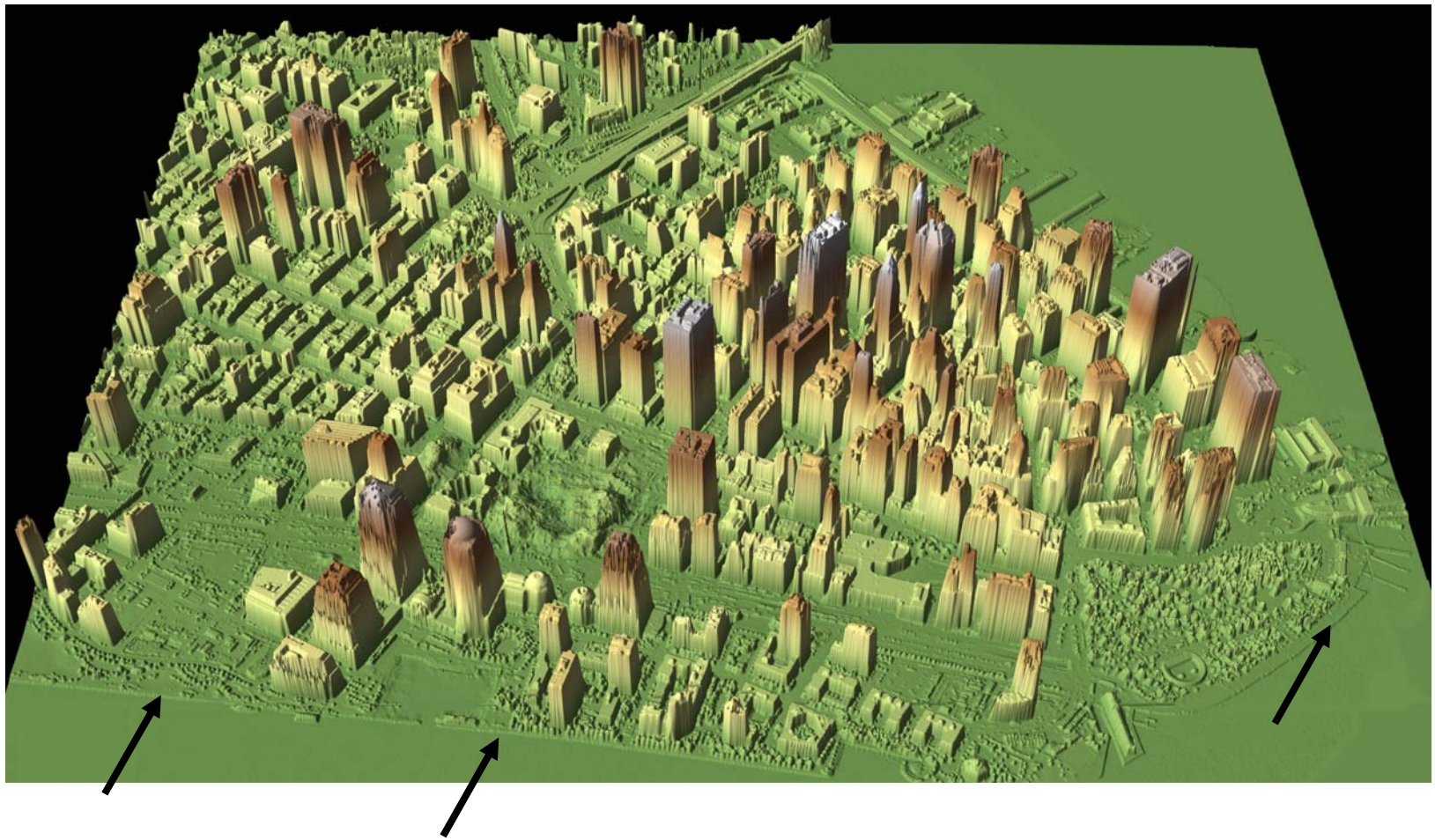


http://stormy.msrc.sunysb.edu/

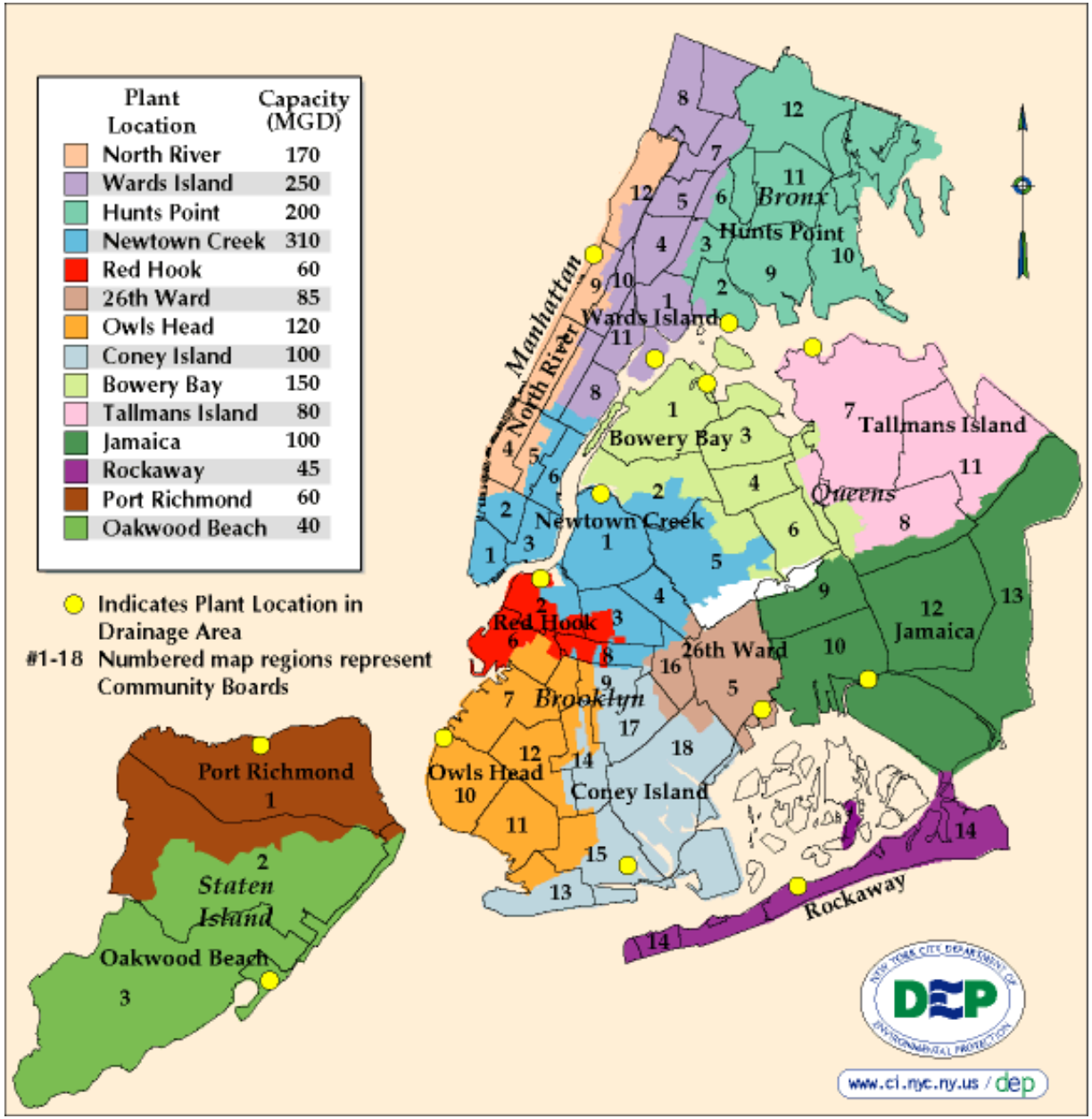
100-year Flood Zone



The 100-year flood at present mean sea level (from Gornitz, 2001)



Lidar image of business district of Manhattan showing seawall locations and elevation (arrows). The imager is flying above the Hudson River looking east.



New York City sewage districts: 14 major treatment stations, over 770 CSO's. Plus NJ's outflows.

Hog Island was hit by a category 2 hurricane on the night of 23 August 1893. By morning the island had largely disappeared.

http://en.wikipedia.org/wiki/Hog_Island_(New_York)

Hog Island Washed Away and the Edgemere in Danger.

WORK OF THE WIND AND TIDE.

Far Rockaway Bathing Houses Carried Away in Last Night's Storm and Much Damage Done—Call for Queens County's Democratic Primaries and Conventions — The Kissam-Clowes Wedding at Hempstead — Patchogue Votes $20,000 for Good Roads.

(Special to the Eagle.)

Far Rockaway, N. Y., September 10—While the damage done by last night's high tide and storm was pretty closely estimated the full amount of the wreck was not positively known until this morning, when the work of rescuing the floating bathing houses was in progress. Hog island is now a thing of the past, and with the first heavy sea and southeast storm the Hotel Edgemere will probably go also. The Far Rockaway Ferry and Improvement company was early at work

← Brooklyn Eagle. Part of a story from Sept. 10, 1896.

On the night of August 23, 1893, a terrifying Category 2 hurricane struck New York City. It hit land in the marshes that is JFK Airport today and began the erosion of the low-lying resort area.

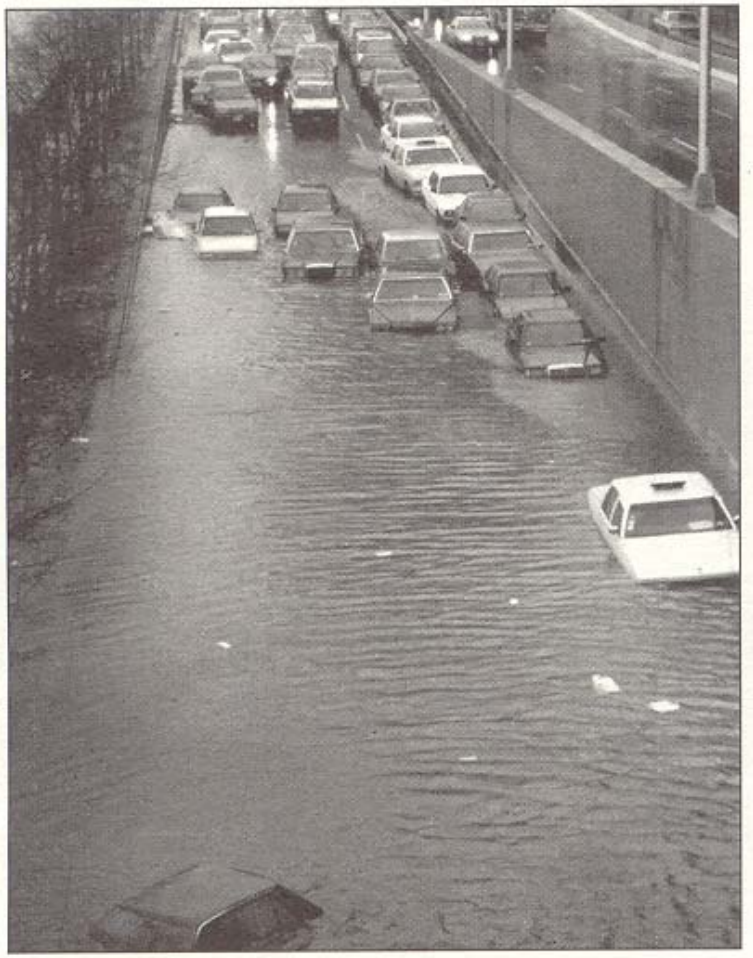
All six front-page columns of the August 25, 1893, New York Times were dedicated to the "unexampled fury" of the "West Indian monster."

The storm sunk dozens of boats and killed scores of sailors. Everything below Canal Street was under water.

Another major storm on Sept 9 finished the job.

21 Sept 1938 "Long Island Express" hurricane hit the south shore of Long Island

A severe storm in November 1950 caused extensive flooding of La Guardia airport (Bloomfield et al, 1999)

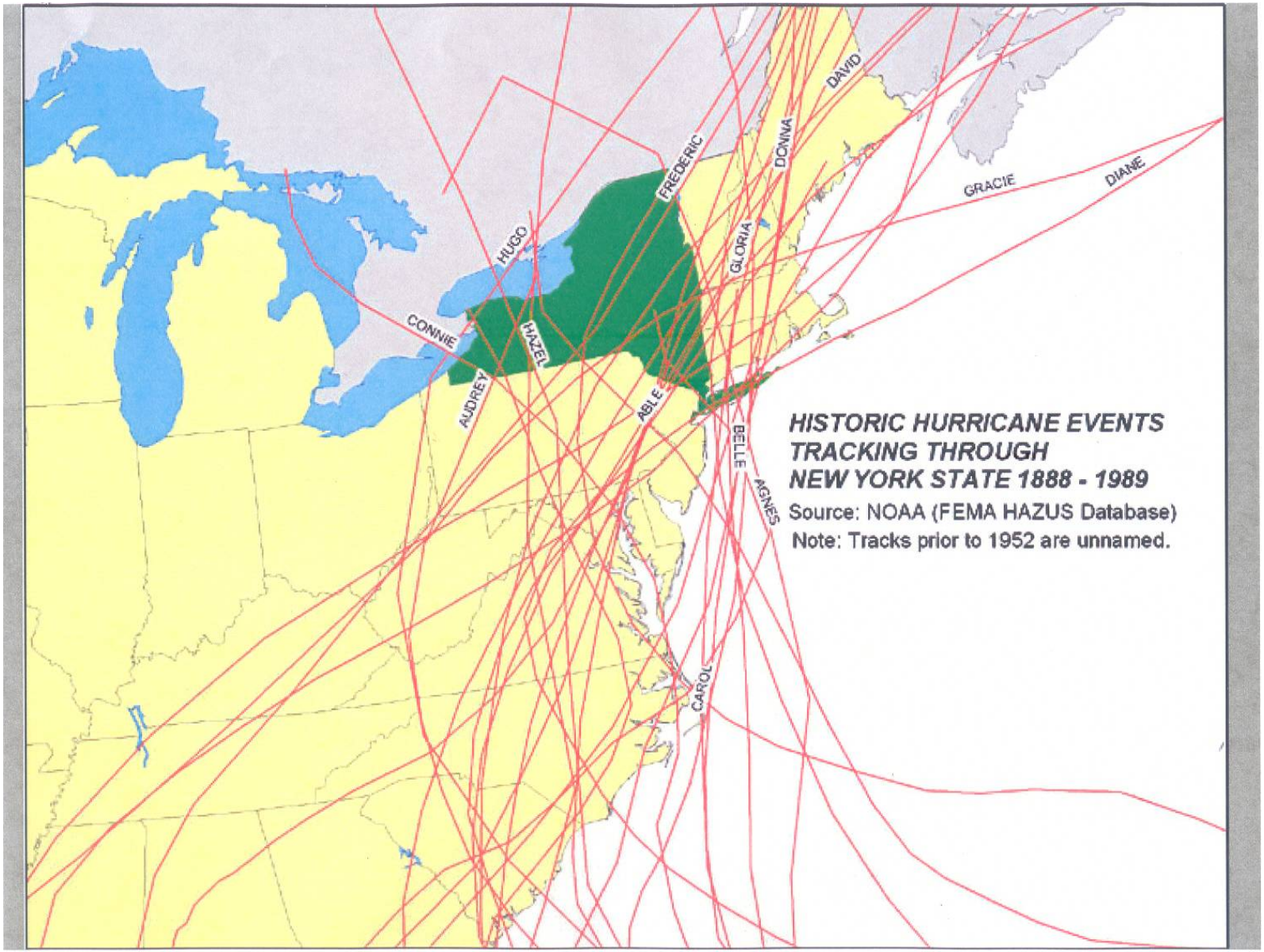


FDR Drive during the December 1992 nor'easter (Bloomfield et al, 1999)

Ref: Bloomfield, J., M. Smith and N. Thompson, 1999. *Hot Nights in the City*. Environmental Defense Fund, New York.

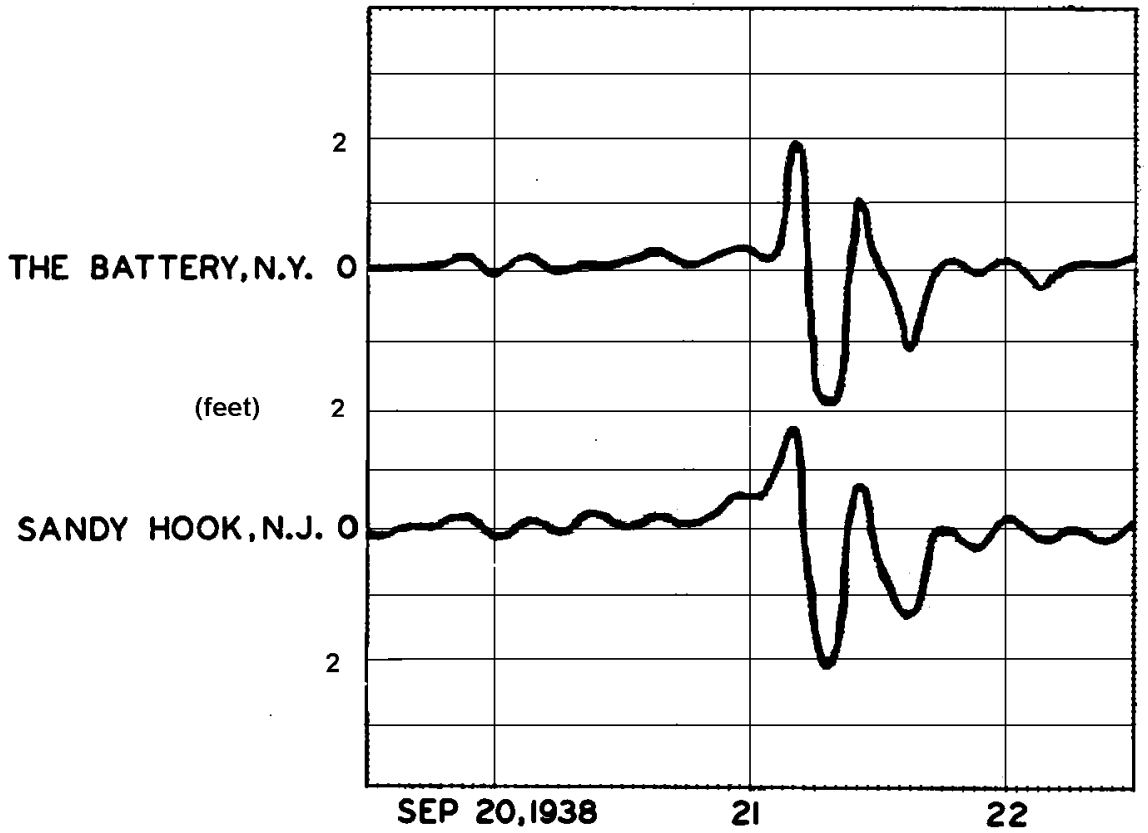
Hoboken NJ subway station, Dec '92 Nor'easter

Source: Metro New York Hurricane Transportation Study, 1995



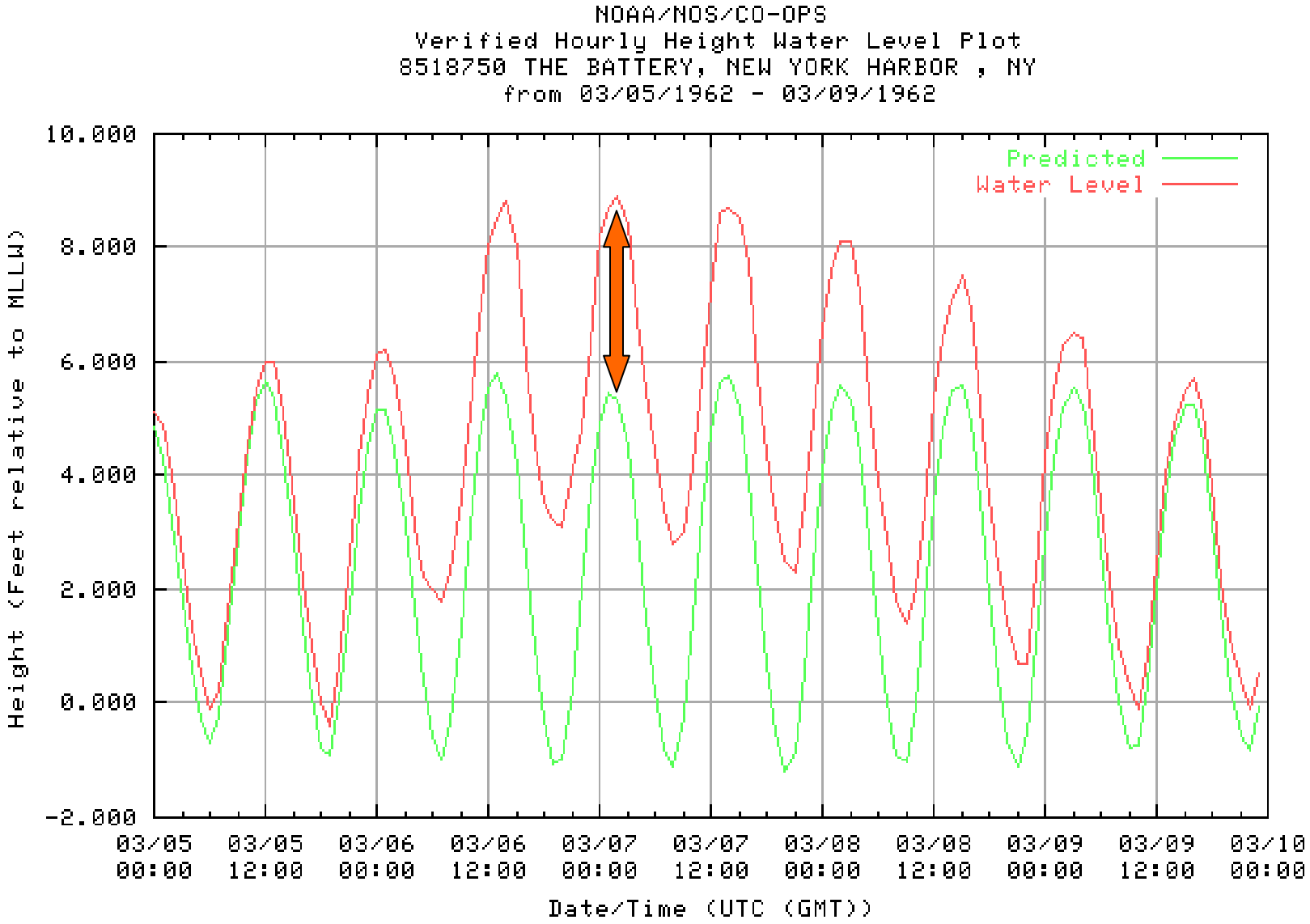
Courtesy K. Jacob.

Hurricane Storm Surge

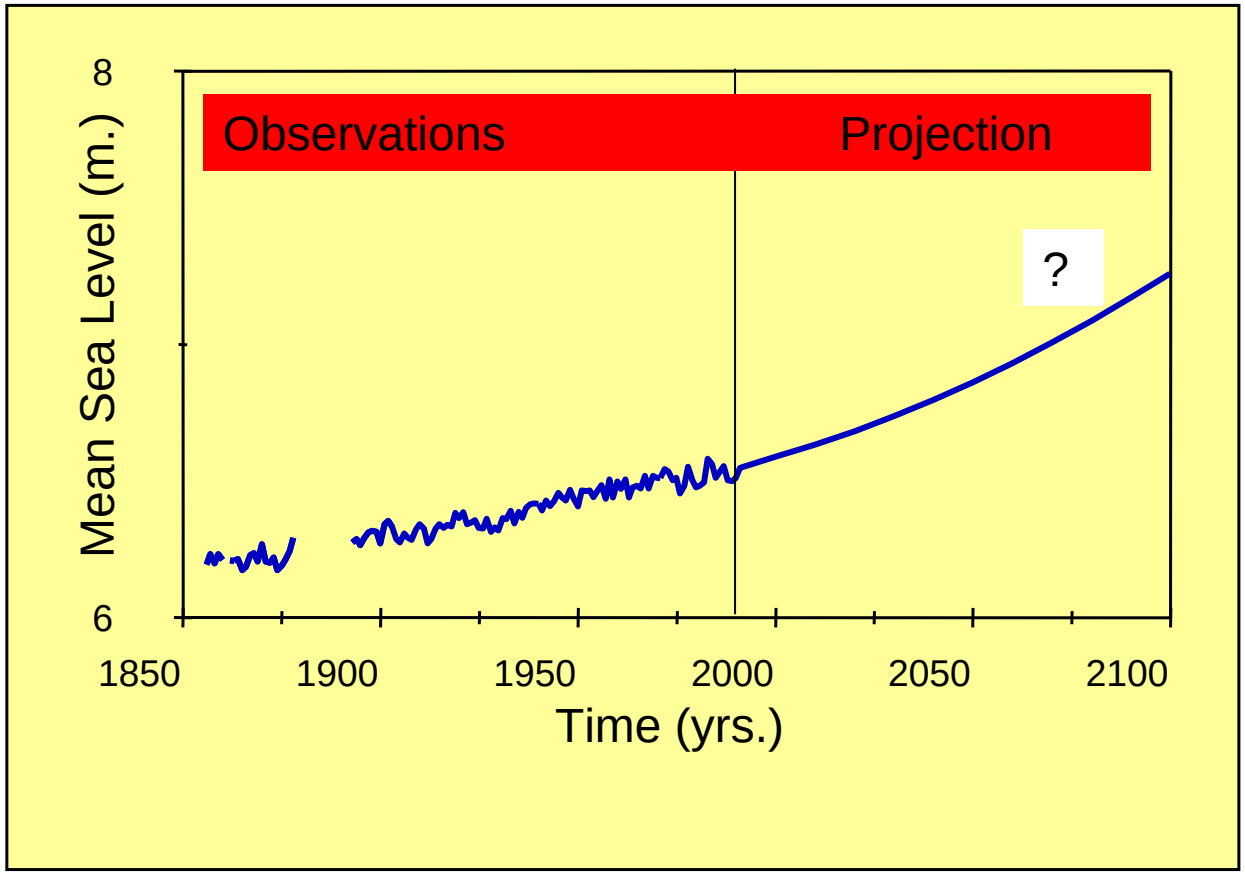


21-22 September 1938 hurricane
Source: N.A. Pore and C.S. Barrientos, Storm Surge, 1976

Nor'easter storm surge at the Battery, March 5-10, 1962



NYC Rise in Sea Level 1850 - 2100



(courtesy Robert J. Nicholls)

Stony Brook Storm Surge Model

Forecasting and Recent Developments

Overview of Modeling System

Incorporation of Ensemble Forecasts

Inclusion of the South Shore of Long Island

Modeling of Nearshore Wave Conditions

http://stormy.msrc.sunysb.edu

Stony Brook Storm Surge Research Group

STONY BROOK STATE UNIVERSITY OF NEW YORK

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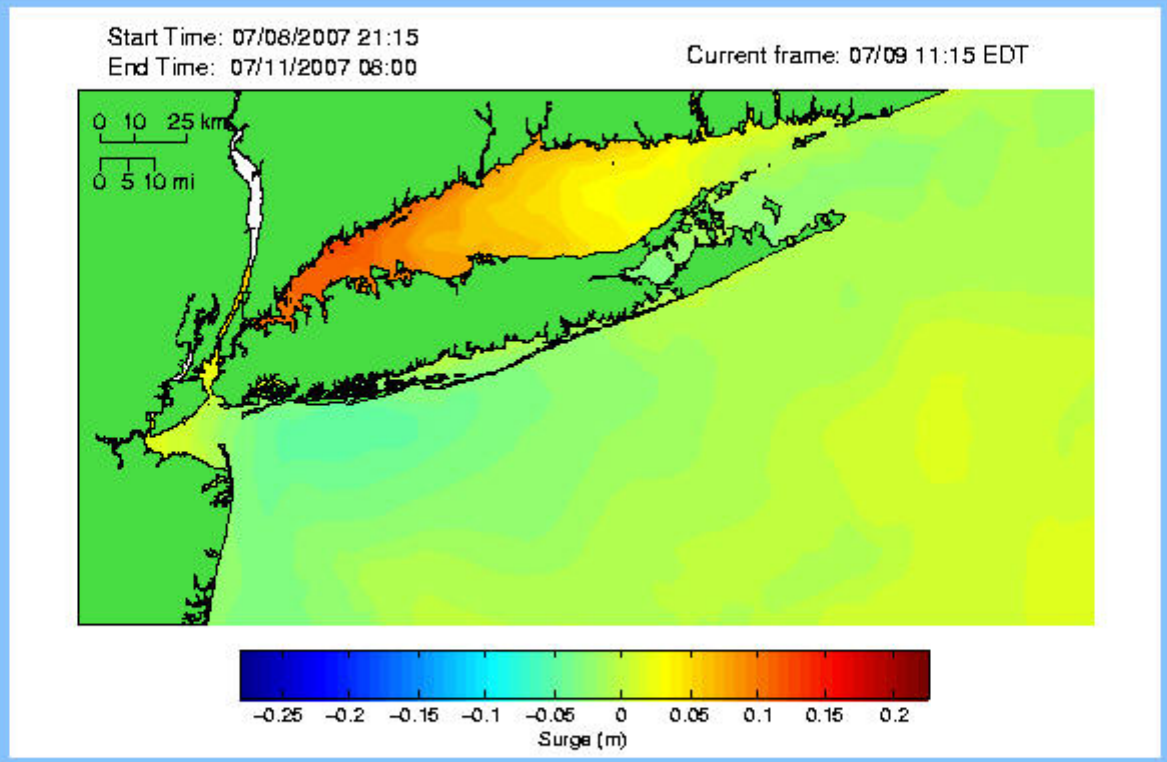
Stations

- New York Harbor
- LI South Shore
- LI Sound
- Southern Stations
- Buoy Stations
- Animations
  - Description
  - Metro New York
  - Regional
  - Eastern Seaboard
- Wave Heights

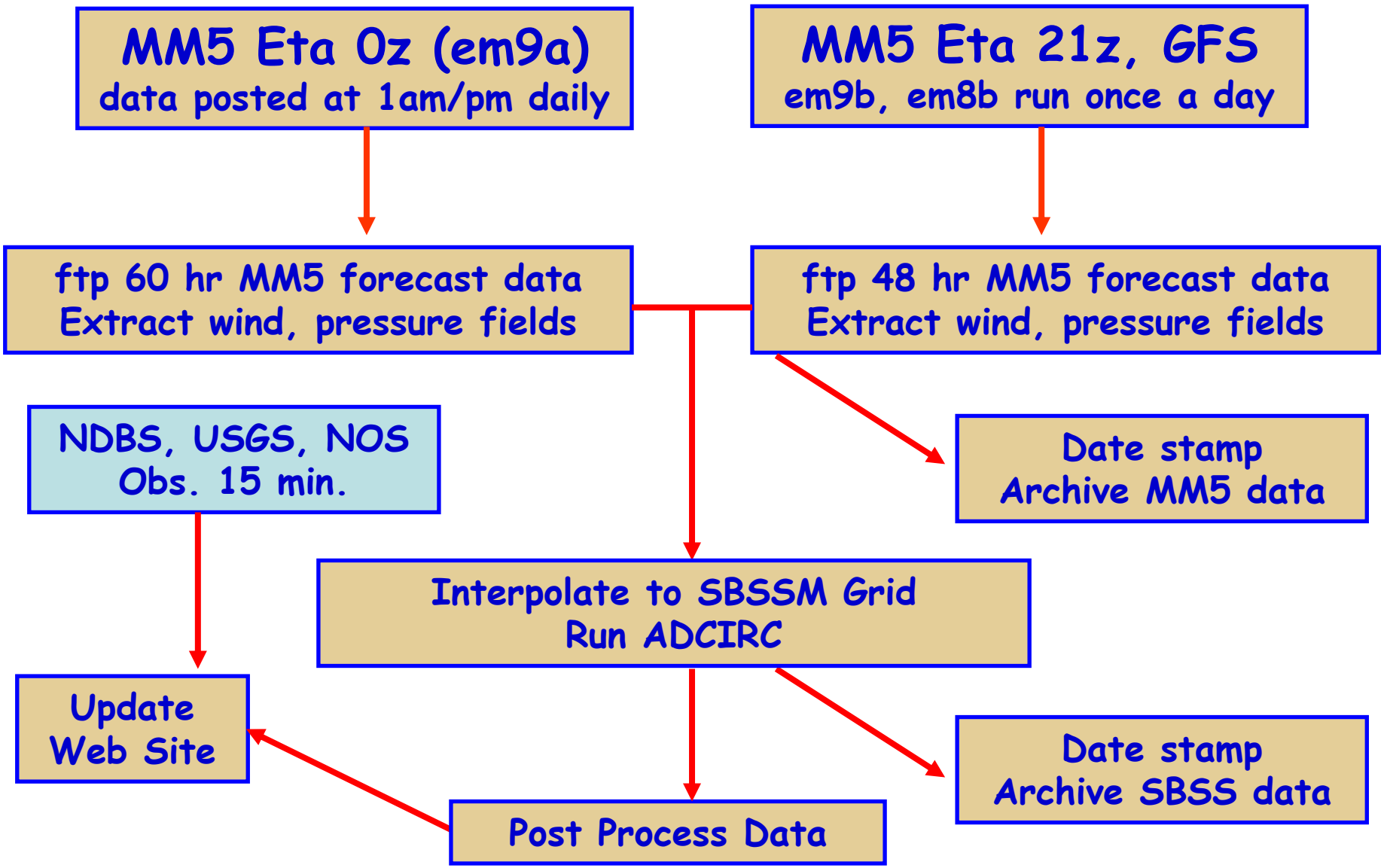


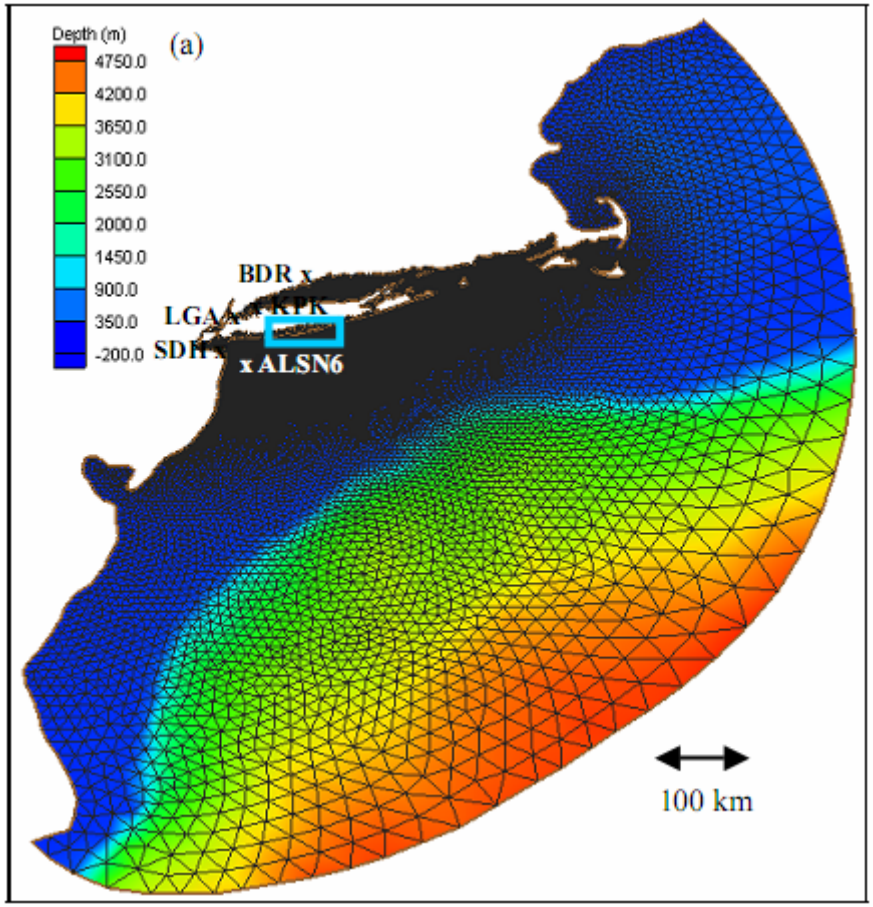
DEP | HydroQual | Sea Grant New York

The Eppley Foundation for Research, Inc.

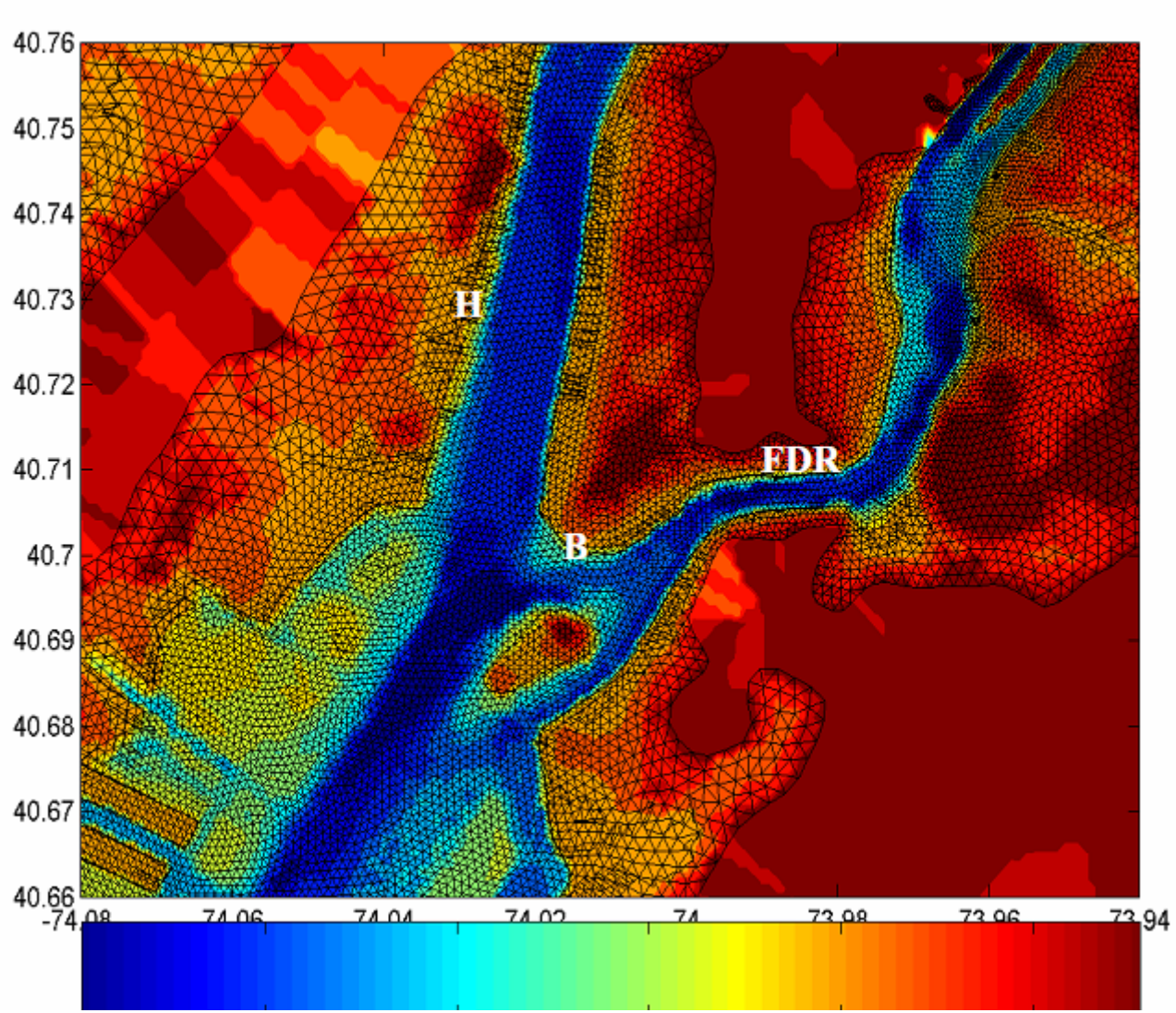
http://stormy.msrc.sunysb.edu

Incorporation of Ensemble Forecasts

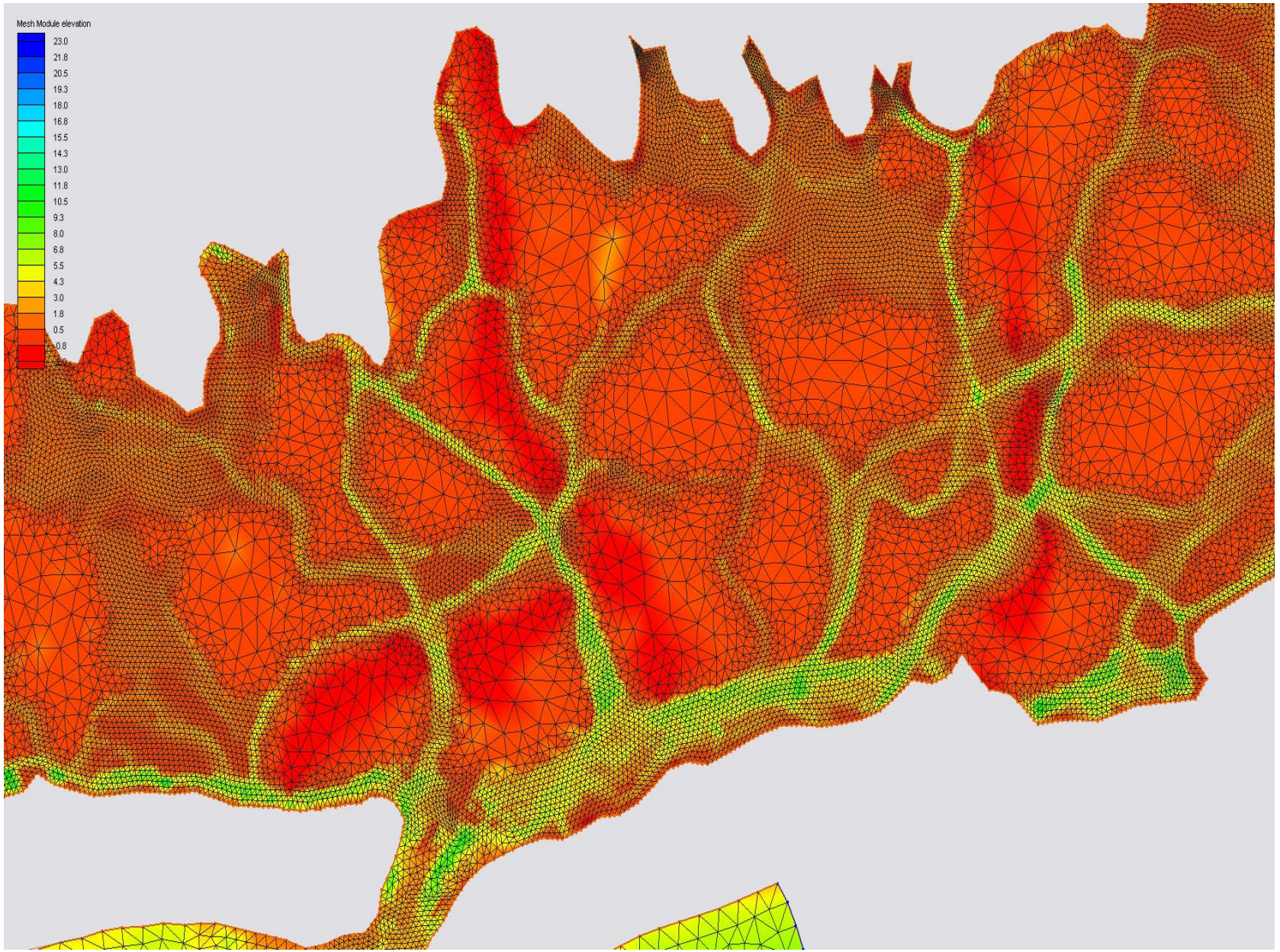




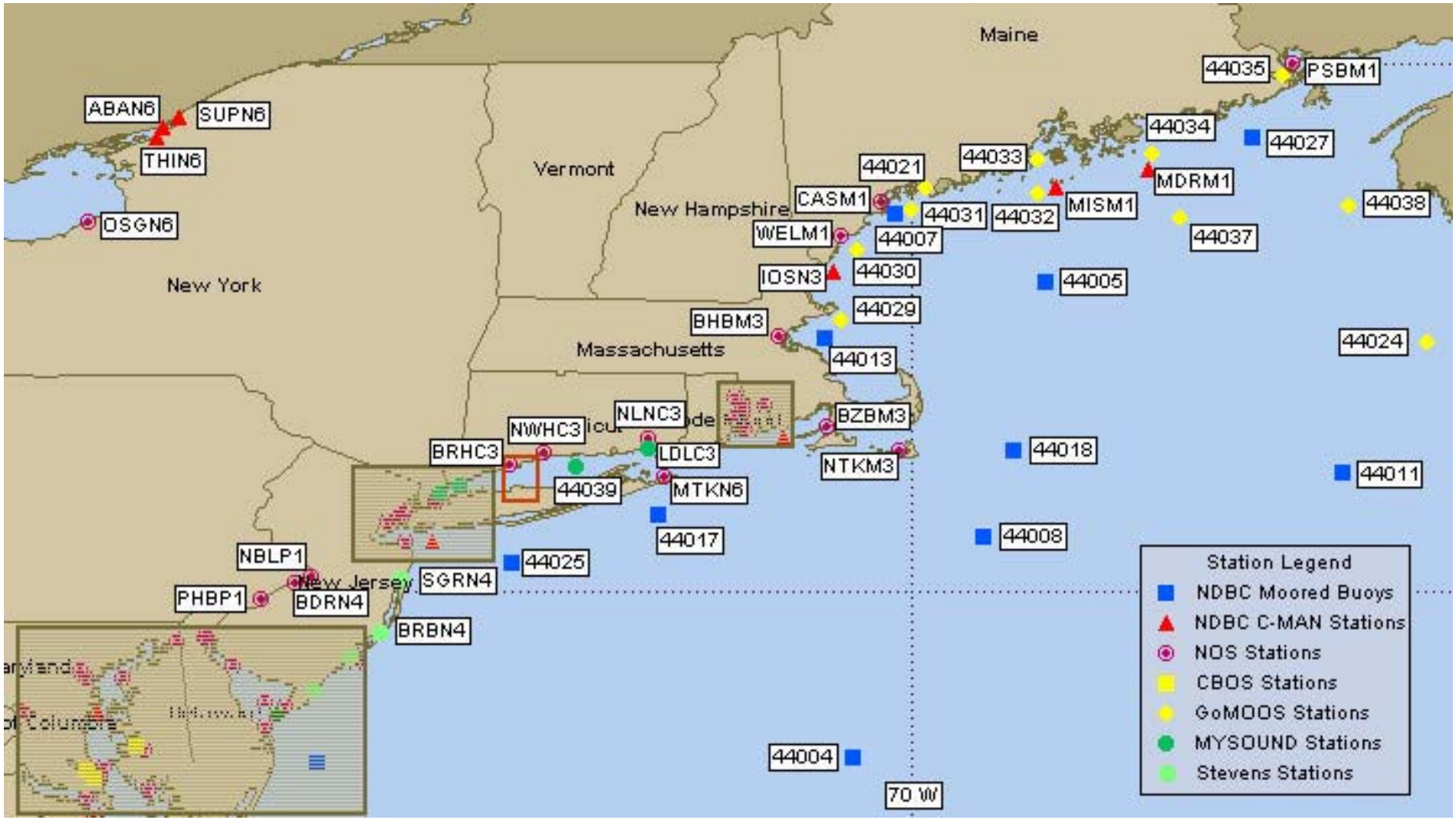
(a) Full domain used for the storm surge model (ADCIRC) showing the unstructured grid and bathymetry (color shaded in meters). The grid overlaps the 12-km MM5/WRF domain.



The triangular elements of ADCIRC grid are overlaid on the bathymetry and topography (color shaded in meters) for the region that surrounds Manhattan Island and parts of Brooklyn and New Jersey. The model is gridded up to the 8-m level above mean sea level to allow for the most serious coastal flooding. The locations of Hoboken, the Battery, and FDR Drive are given by H, B, and FDR, respectively.



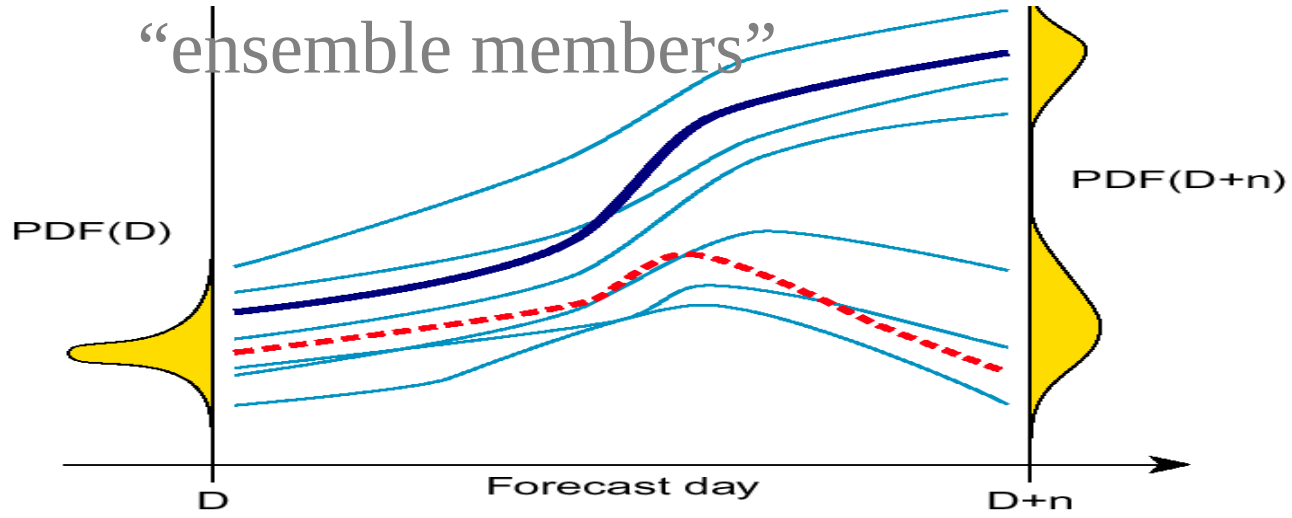
Unstructured computational grid and interpolated bathymetry in South Oyster Bay

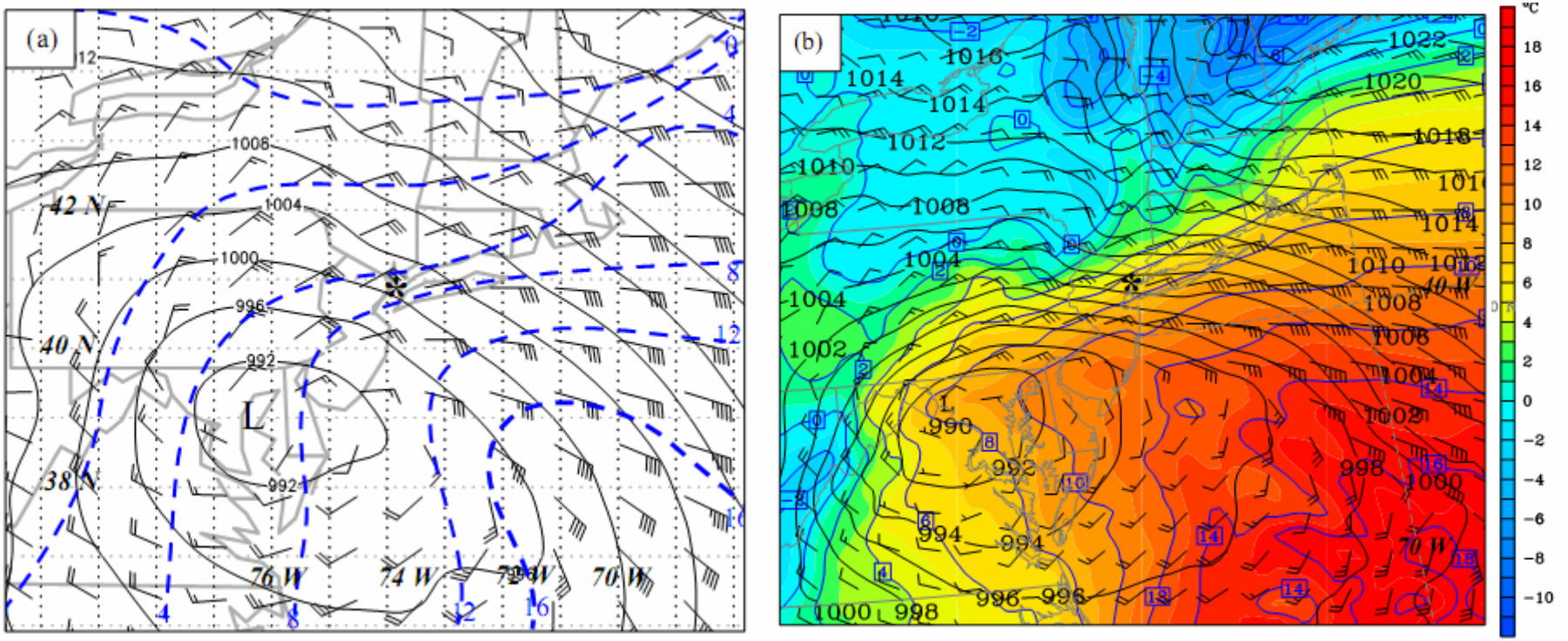

Maine
Vermont
New Hampshire
New York
Massachusetts
New Jersey
ABAN6
SUPN6
THIN6
OSGN6
PSBM1
44035
44034
44027
44033
44021
MDRM1
CASM1
MISM1
44038
44031
44032
WELM1
44007
44037
IOSN3
44030
44005
44029
BHBM3
44024
44013
NLNC3
BZBM3
NWHC3
BRHC3
LDLC3
NTKM3
44018
44039
MTKN6
44011
44017
44008
NBLP1
44025
SGRN4
PHBP1
BDRN4
BRBN4
44004
70 W
Station Legend
NDBC Moored Buoys
NDBC C-MAN Stations
NOS Stations
CBOS Stations
GoMOOS Stations
MYSOUND Stations
Stevens Stations

FACT:

Weather forecasts will *ALWAYS* Be Coupled with *varying* degrees of uncertainty ("*chaos" theory*)!

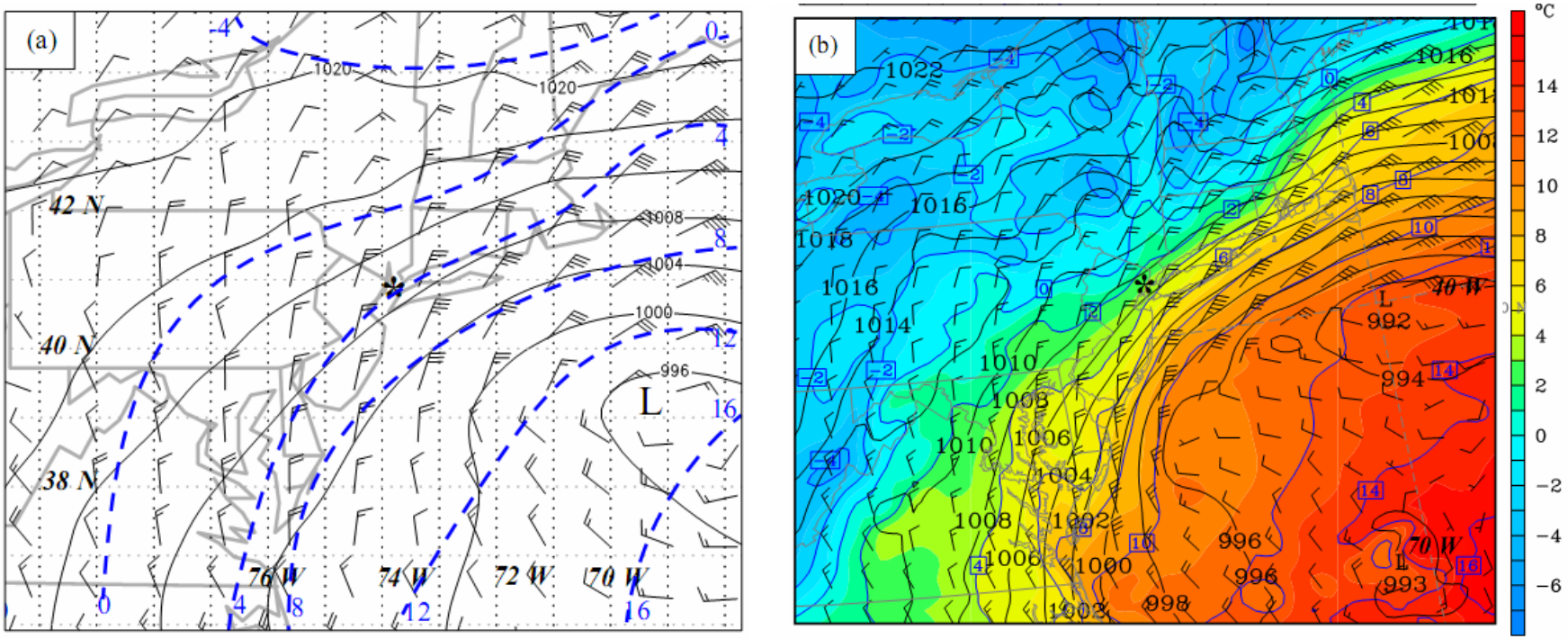
➔ Forecast process is inherently stochastic (probabilistic) in nature!!



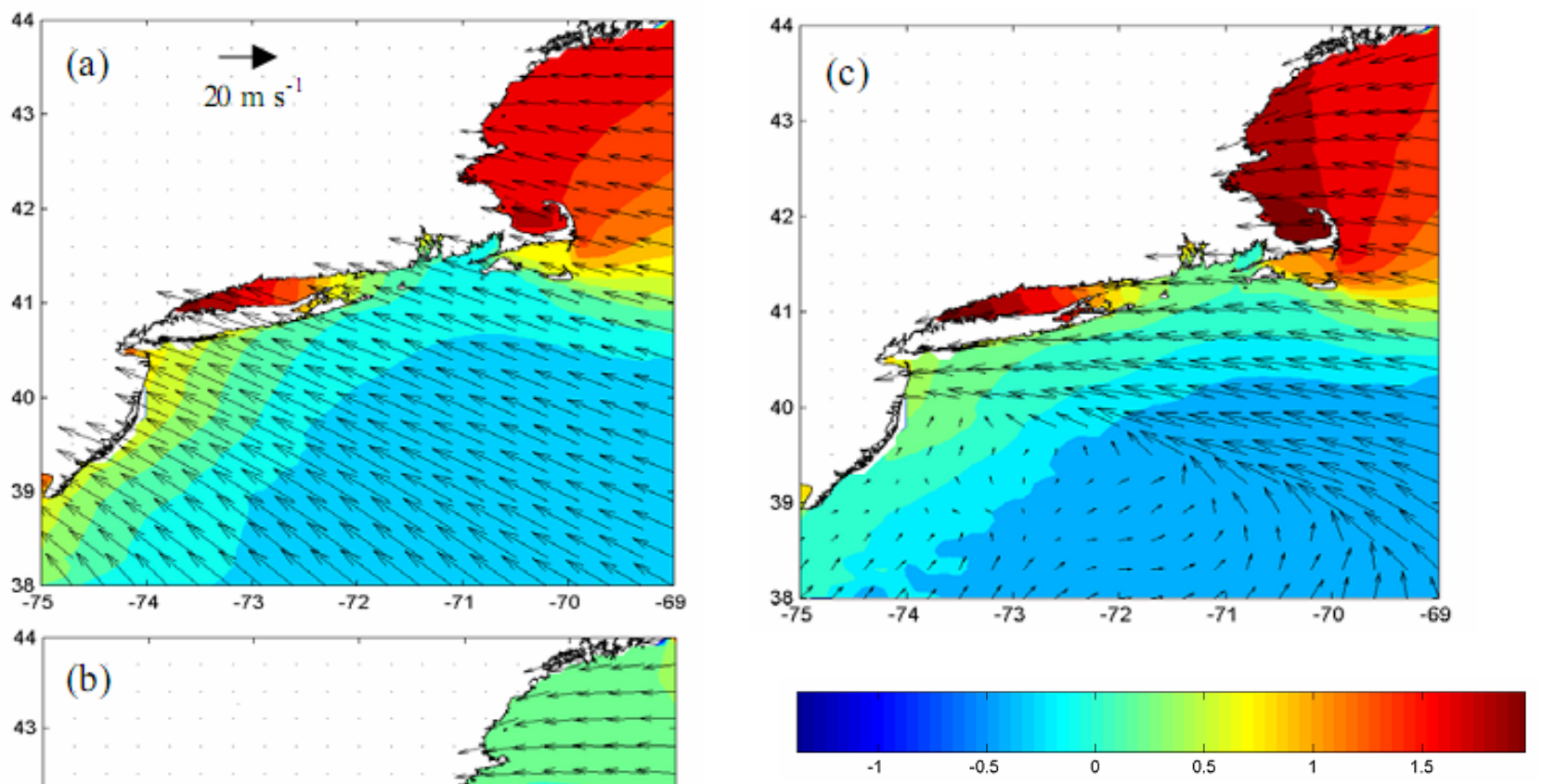


Dec 1992 storm. (a) NCEP regional reanalysis around the Northeast U.S. and Mid-Atlantic at 1200 UTC 11 Dec. 1992 showing sea-level pressure (solid black every 2 mb), surface temperature (blue every 4 °C) and winds (full barb = 10 kts).

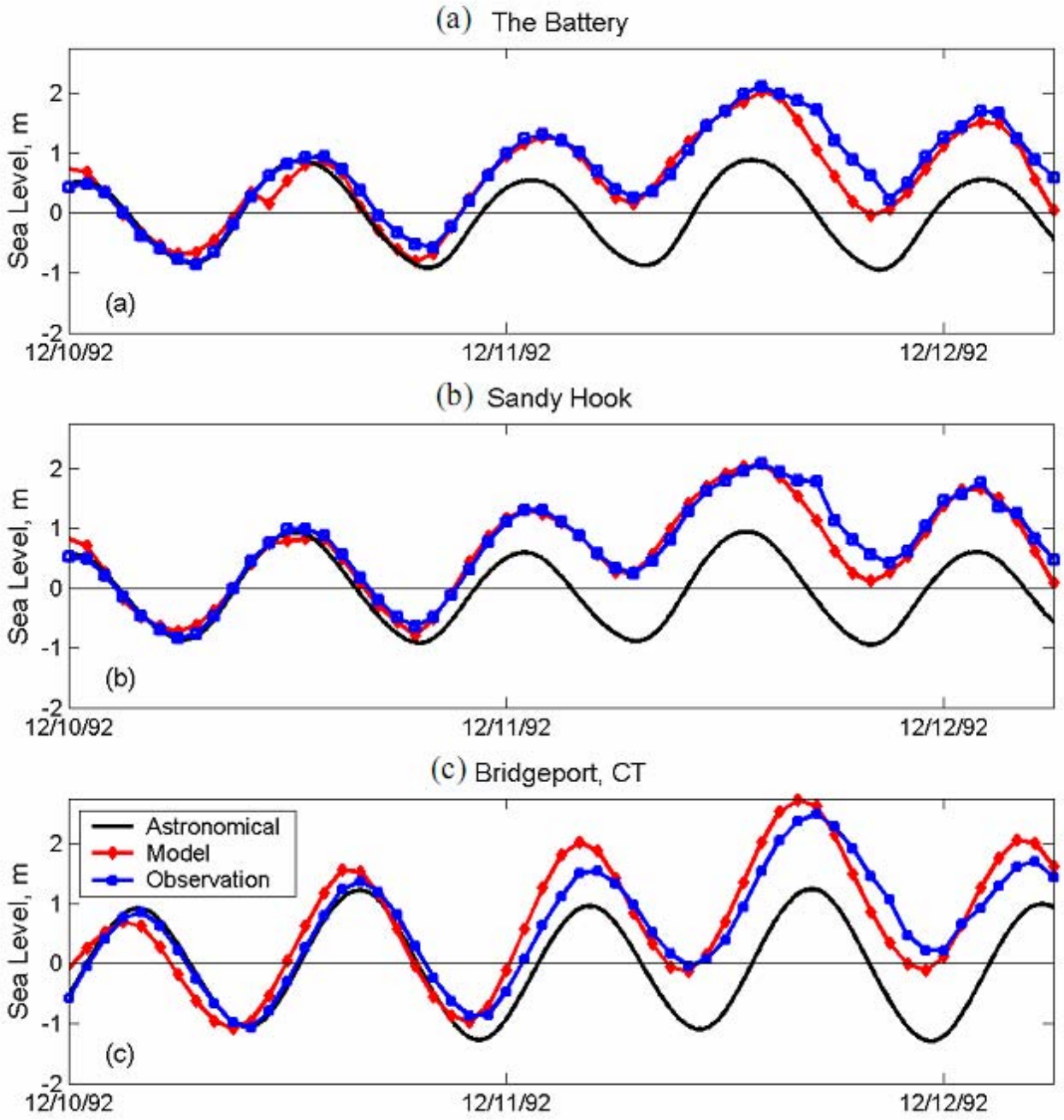
(b) MM5 12-h forecast from the 12-km grid valid at 1200 UTC 11 Dec. 1992 showing sea-level pressure (solid black every 2 mb), 2-m temperature (blue every 2 °C and shaded using scale), and winds (full barb = 10 kts).



Dec 1992 storm. Same as previous slide 5 except for 1200 UTC 12 Dec.



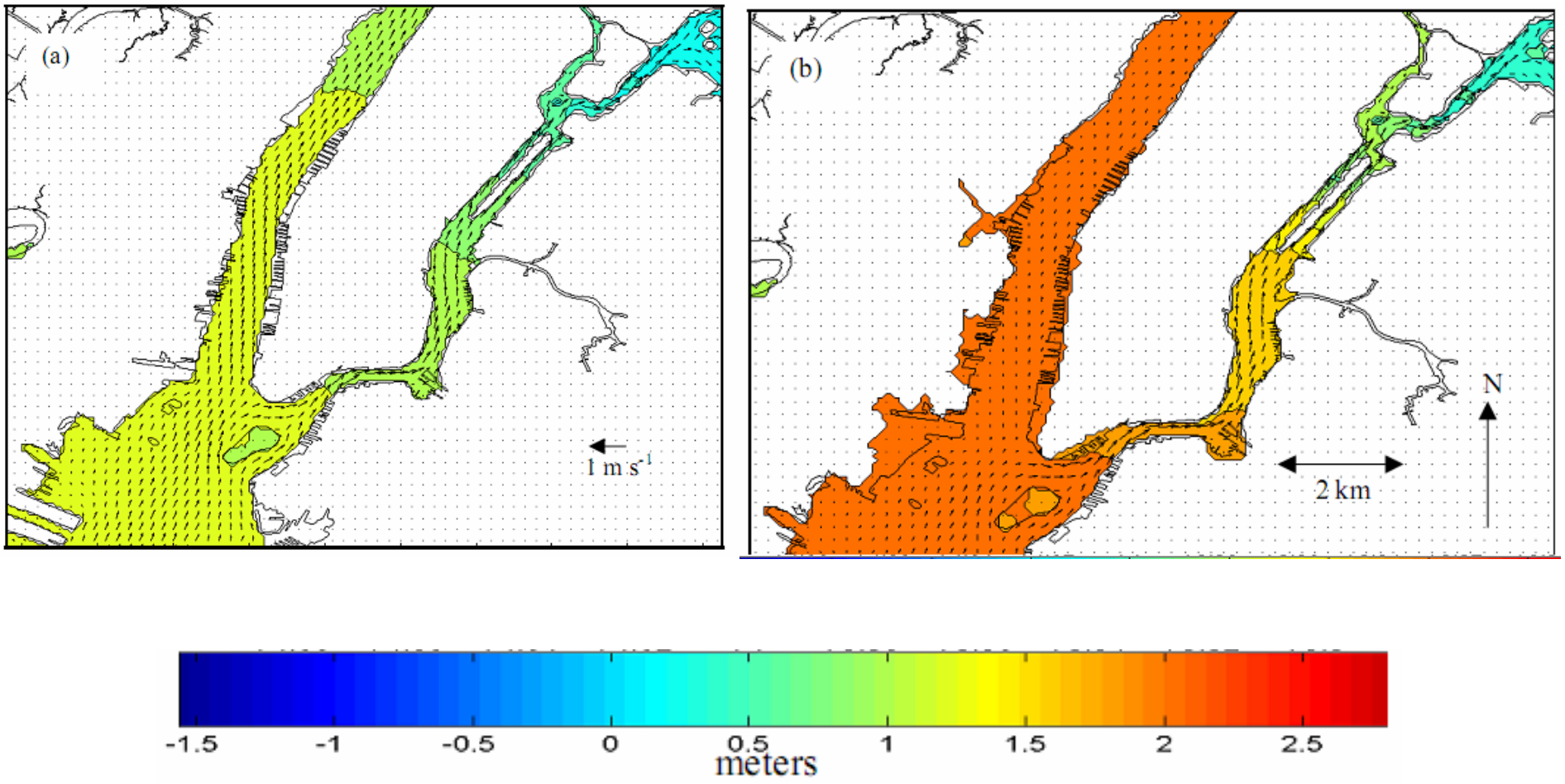
Dec 1992 storm. Surface 12-km MM5 winds (vectors in m s $^{-1}$) and water height relative to sea-level (shaded in meters) for
(a) 0400 UTC,
(b) 1300 UTC, and
(c) 1700 UTC 11 Dec.



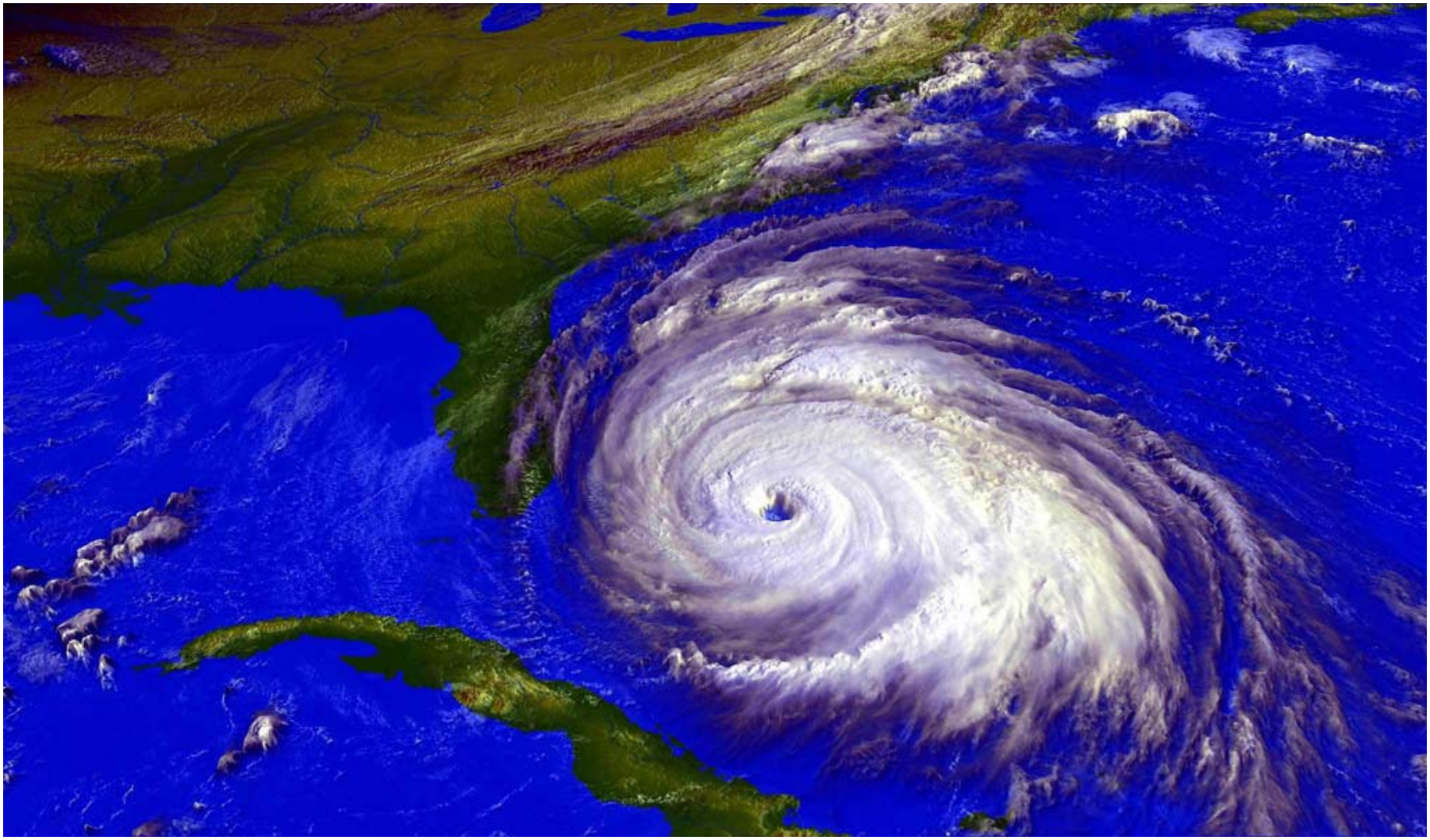
Dec 1992 storm.

Time series of water level above MSL for (a) Battery, NY, (b) Sandy Hook, NJ (SDH), and (c) Bridgeport, CT (BDR)

for the model (red), observed (blue), and astronomical tide (black).



Dec 1992 storm. New York City spatial storm surge evolution at (a) 1200 and (b) 1300 UTC 11 Dec 1992, showing ADCIRC current vectors and water elevation (color shaded in meters) above MSL.



Hurricane Floyd: 14 September 1999

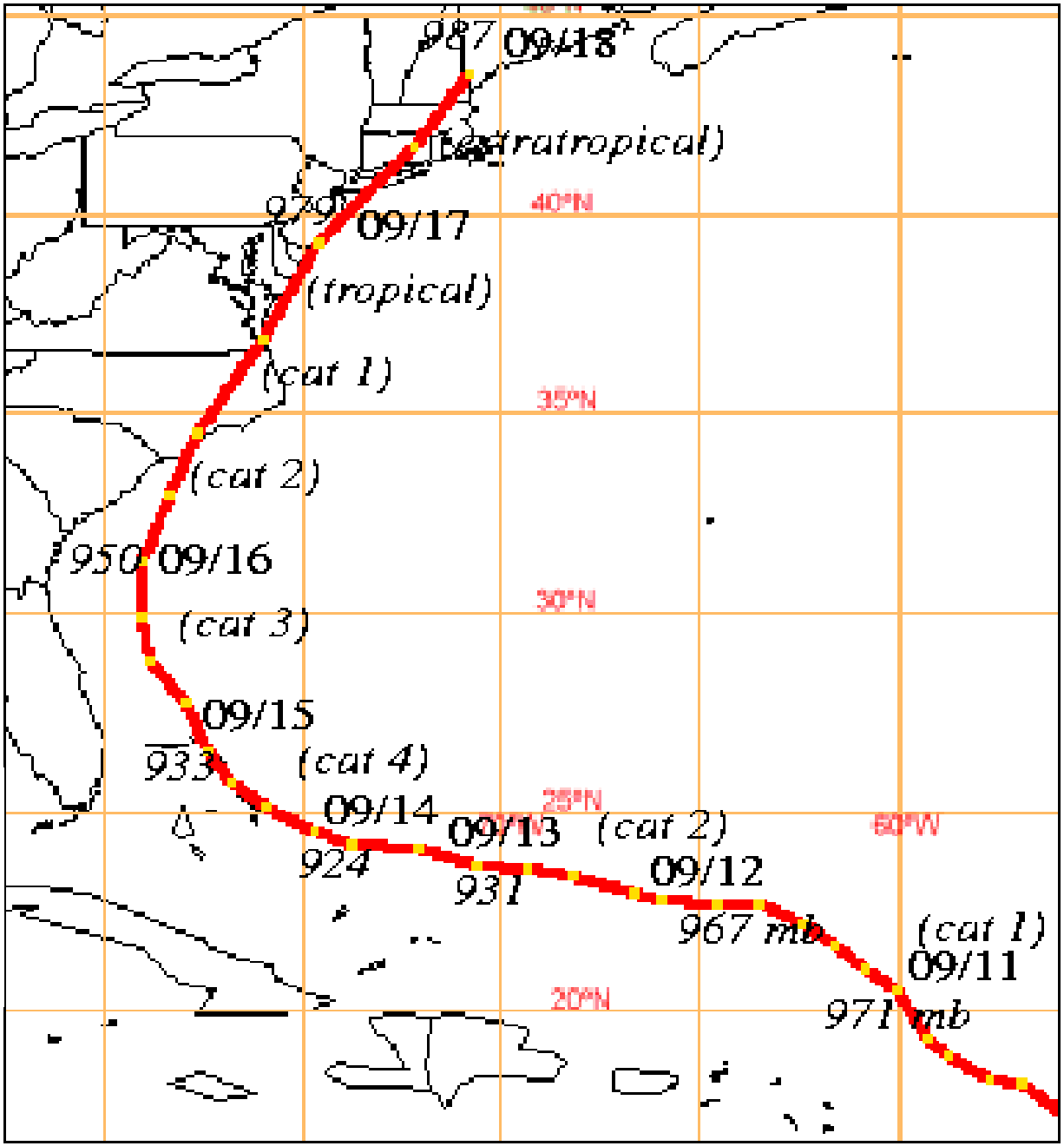
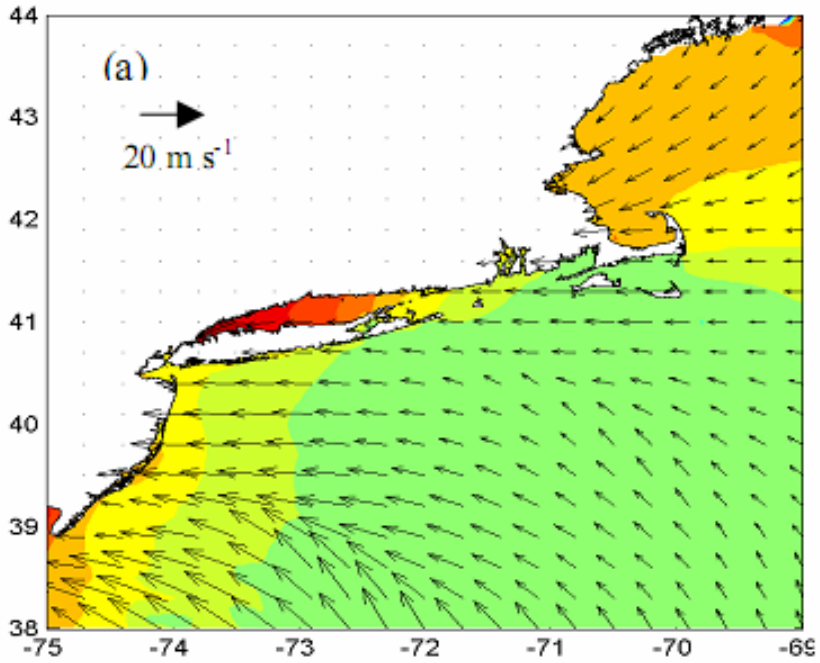
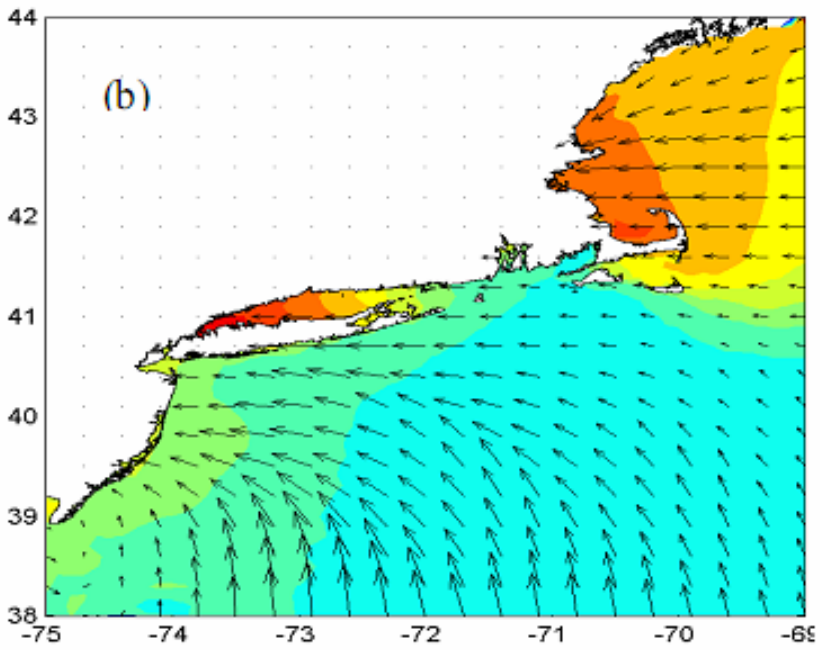
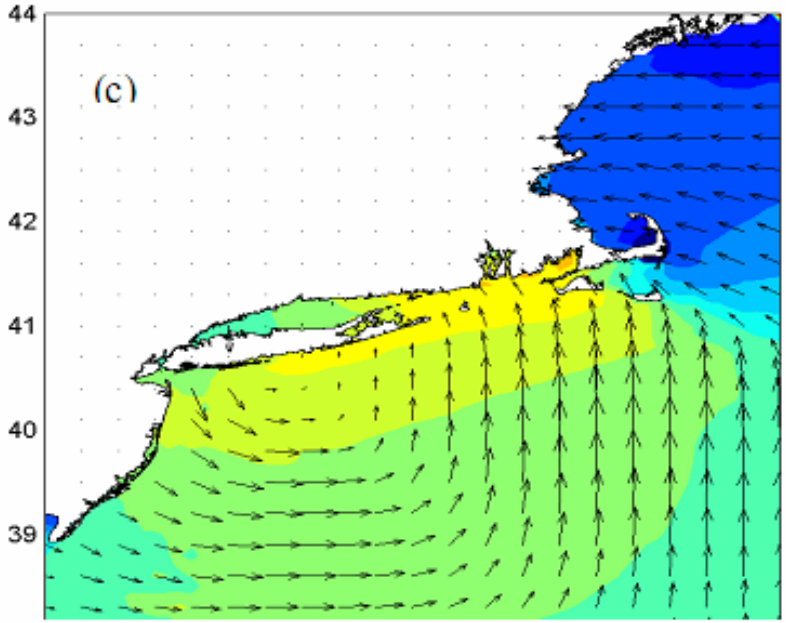


Fig 13: Hurricane Floyd track and pressures (09-11-99 to 09-18-99)

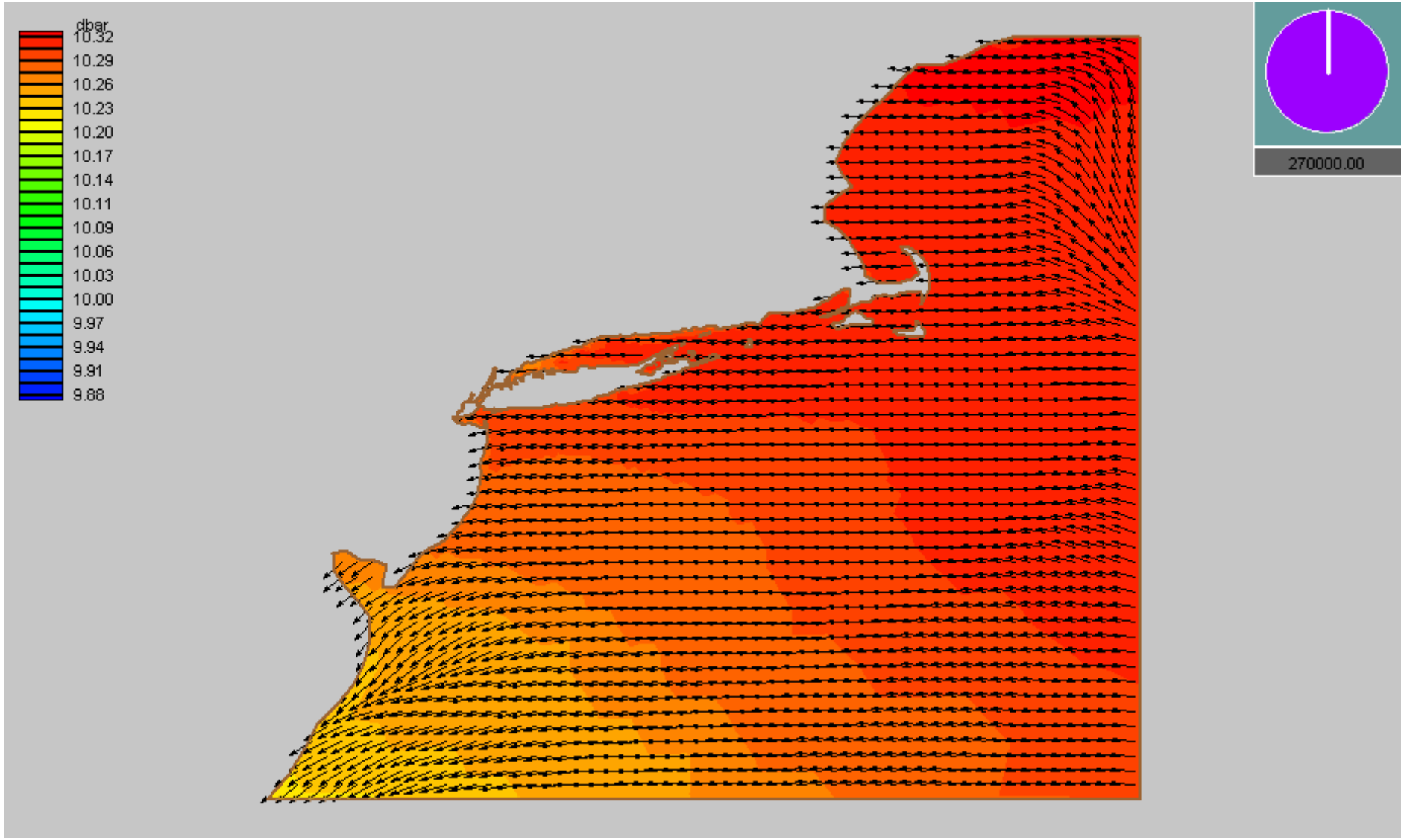






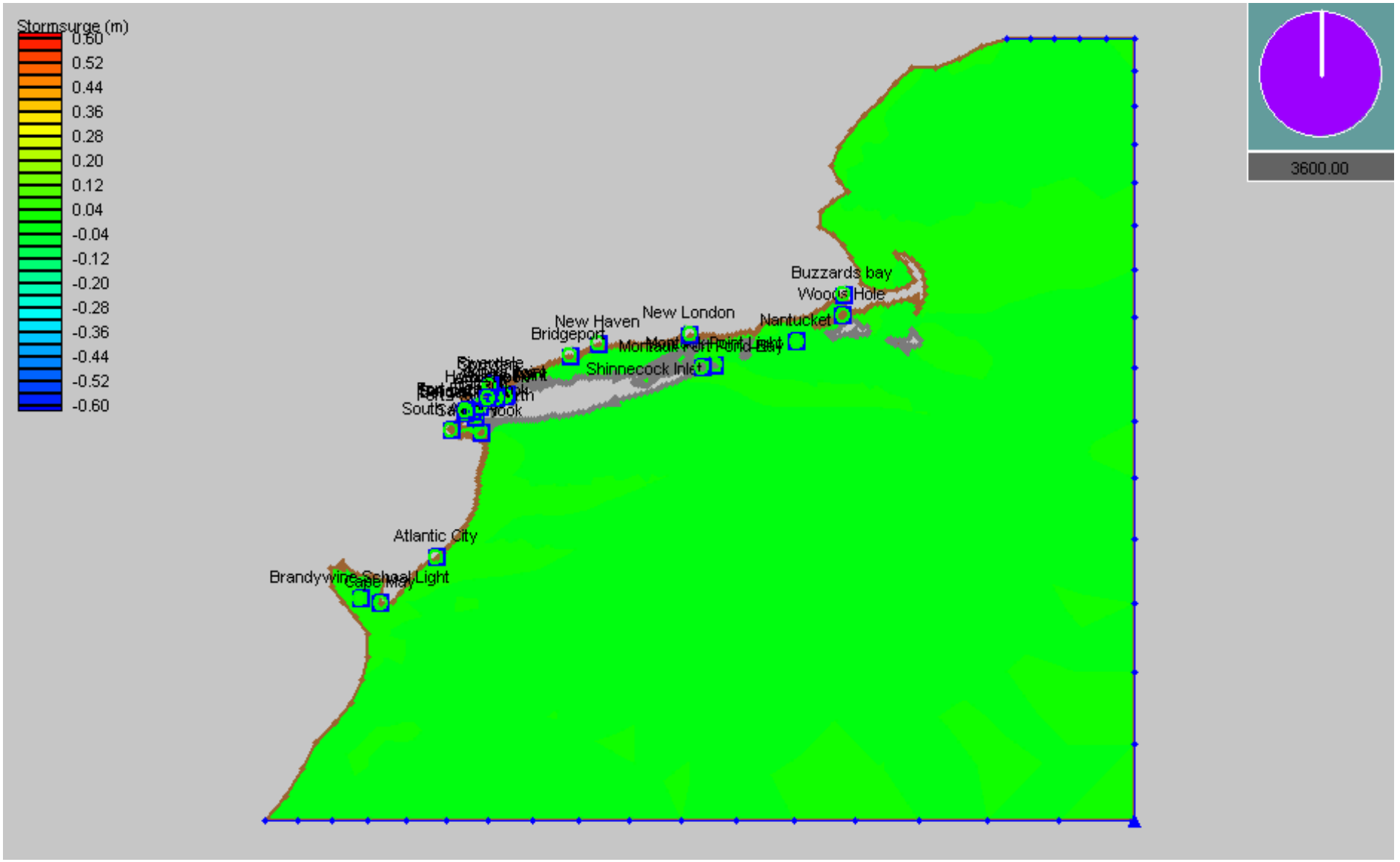
Extra-tropical storm Floyd

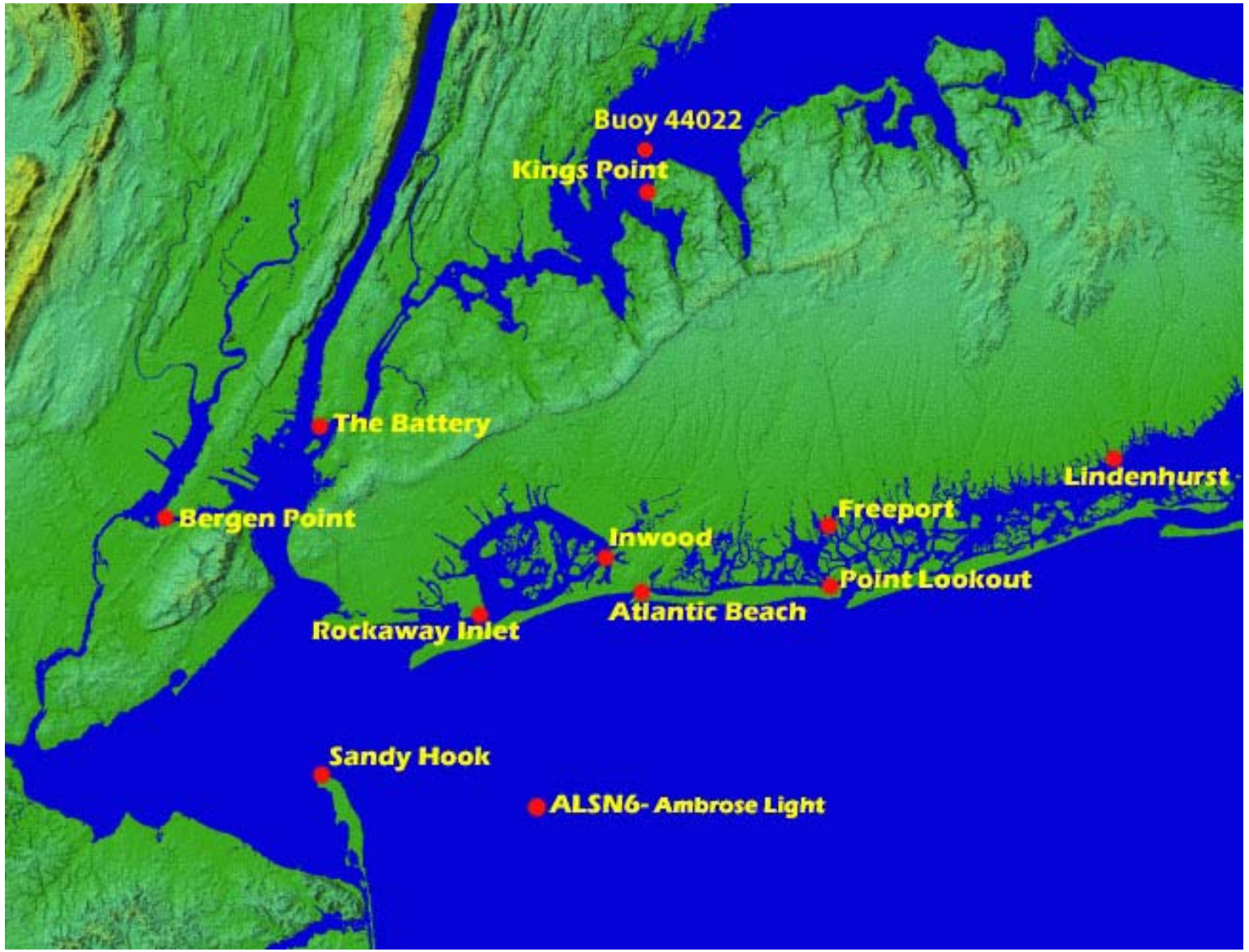
12-km MM5 surface winds and water height above MSL (shaded in meters) for (a) 1800 UTC 16 Sept, (b) 2100 UTC, 16 Sept and (c) 0300 UTC 17 Sept 1999.

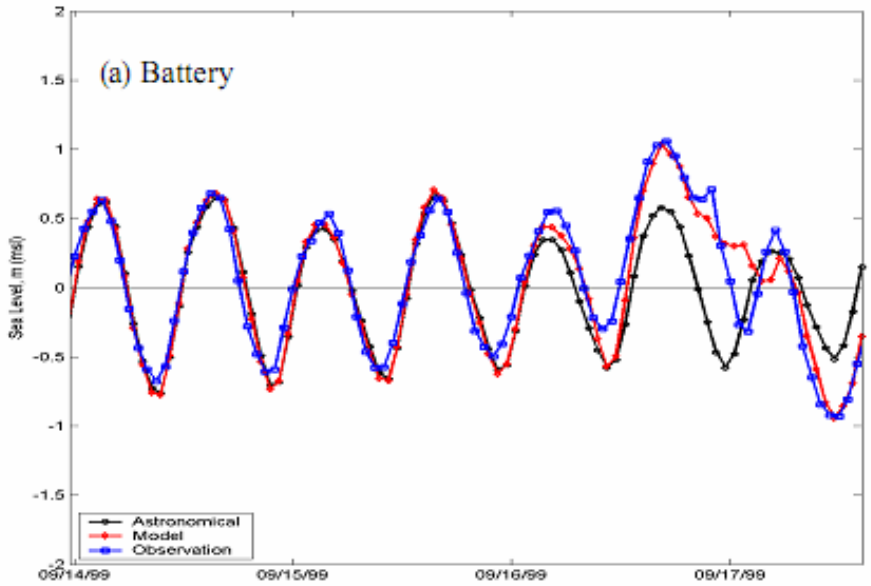


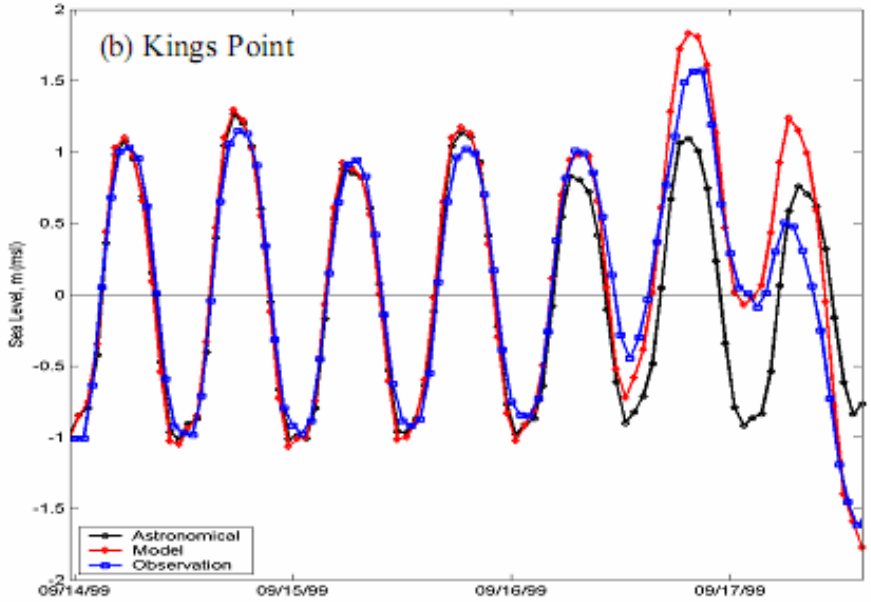
Modeled winds and surface atmospheric pressure during Hurricane Floyd

Storm surge (m) during Hurricane Floyd 16-19 Sept 1999




Buoy 44022
Kings Point
The Battery
Bergen Point
Lindenhurst
Freeport
Inwood
Point Lookout
Atlantic Beach
Rockaway Inlet
Sandy Hook
ALSN6- Ambrose Light





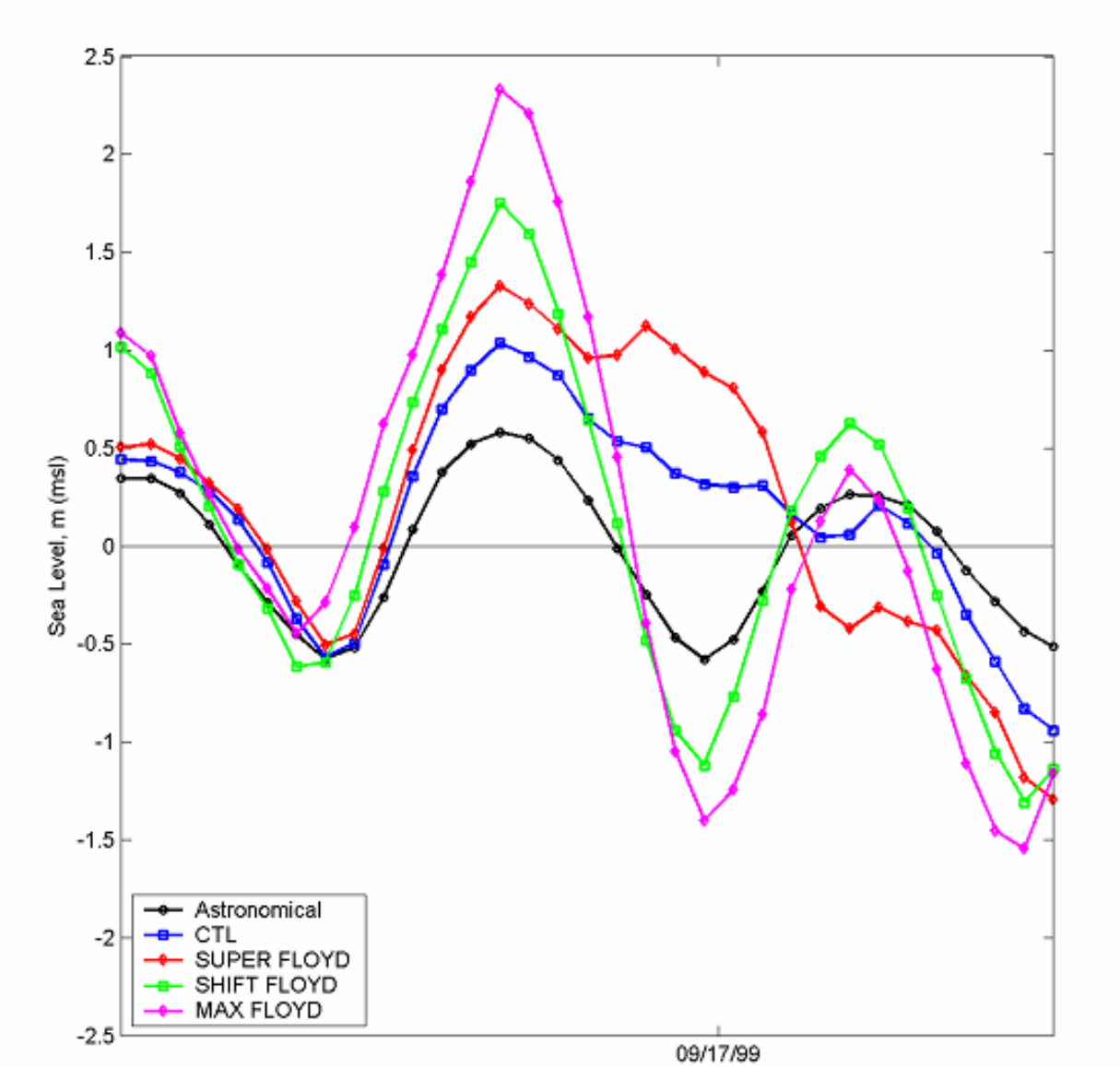
Extra-tropical storm Floyd.

Time series of water height versus time (hour) for

(a) Battery and

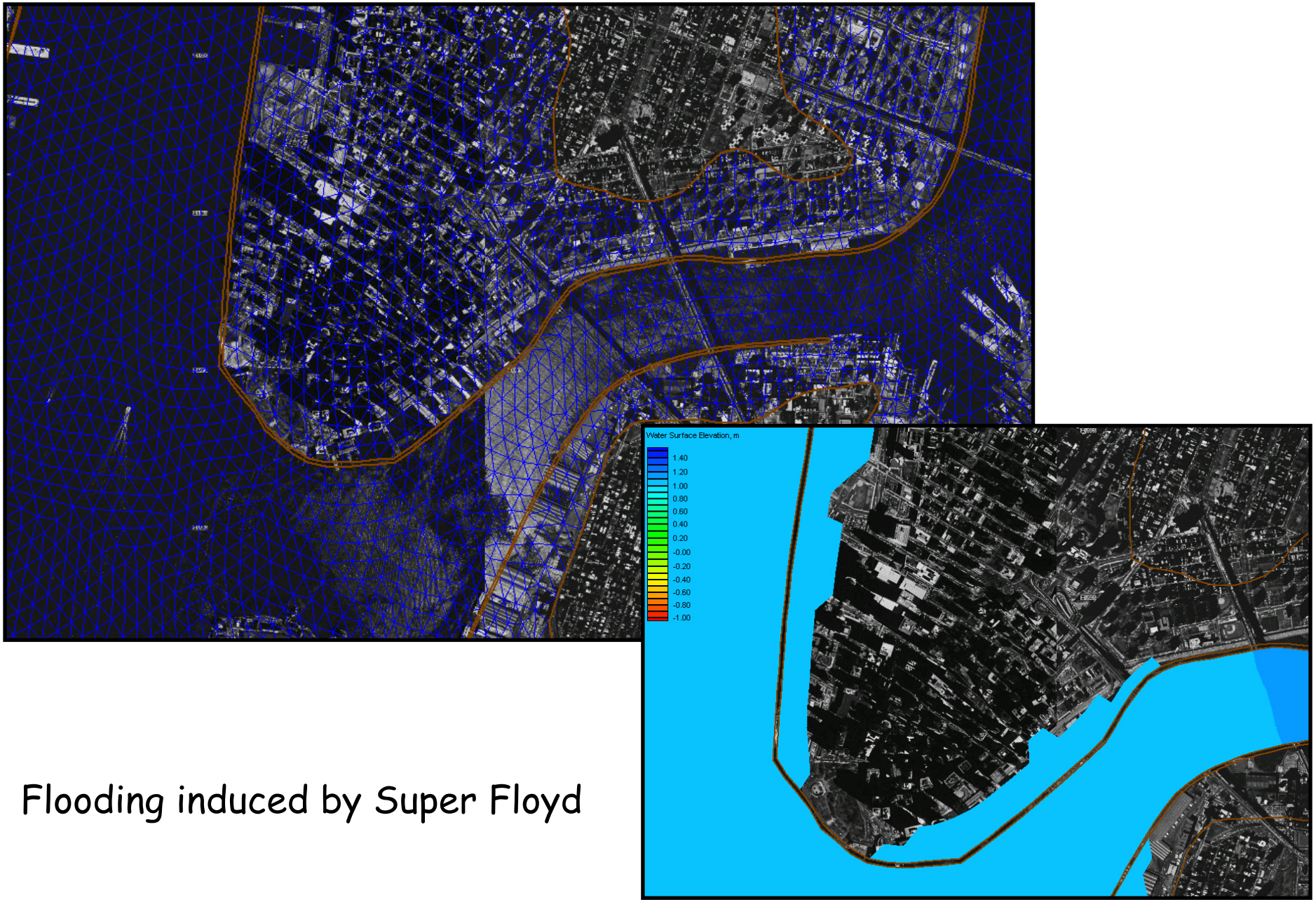
(b) Kings Point

for the model predicted (red), observed (blue), and astronomical tides (black).

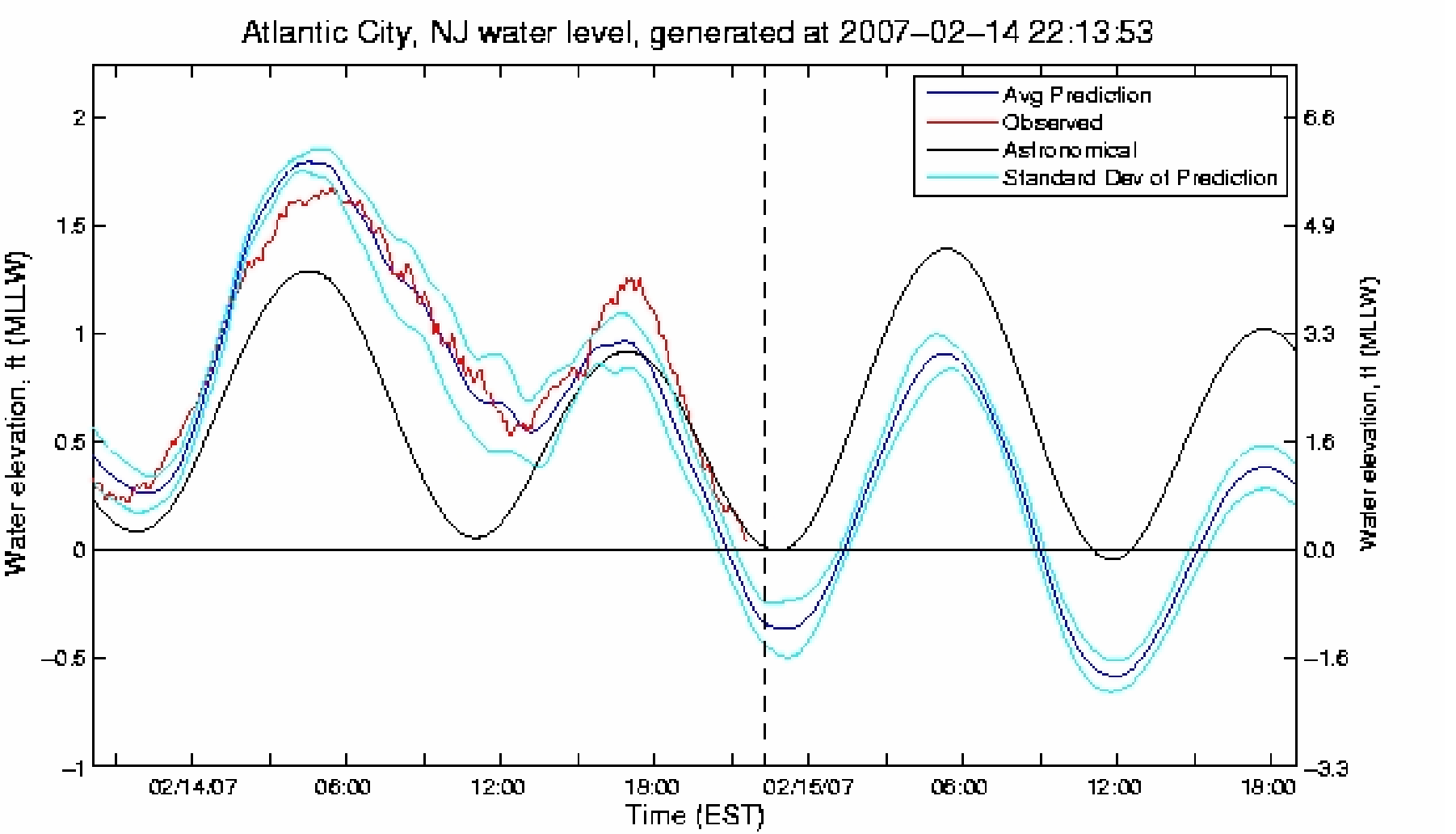


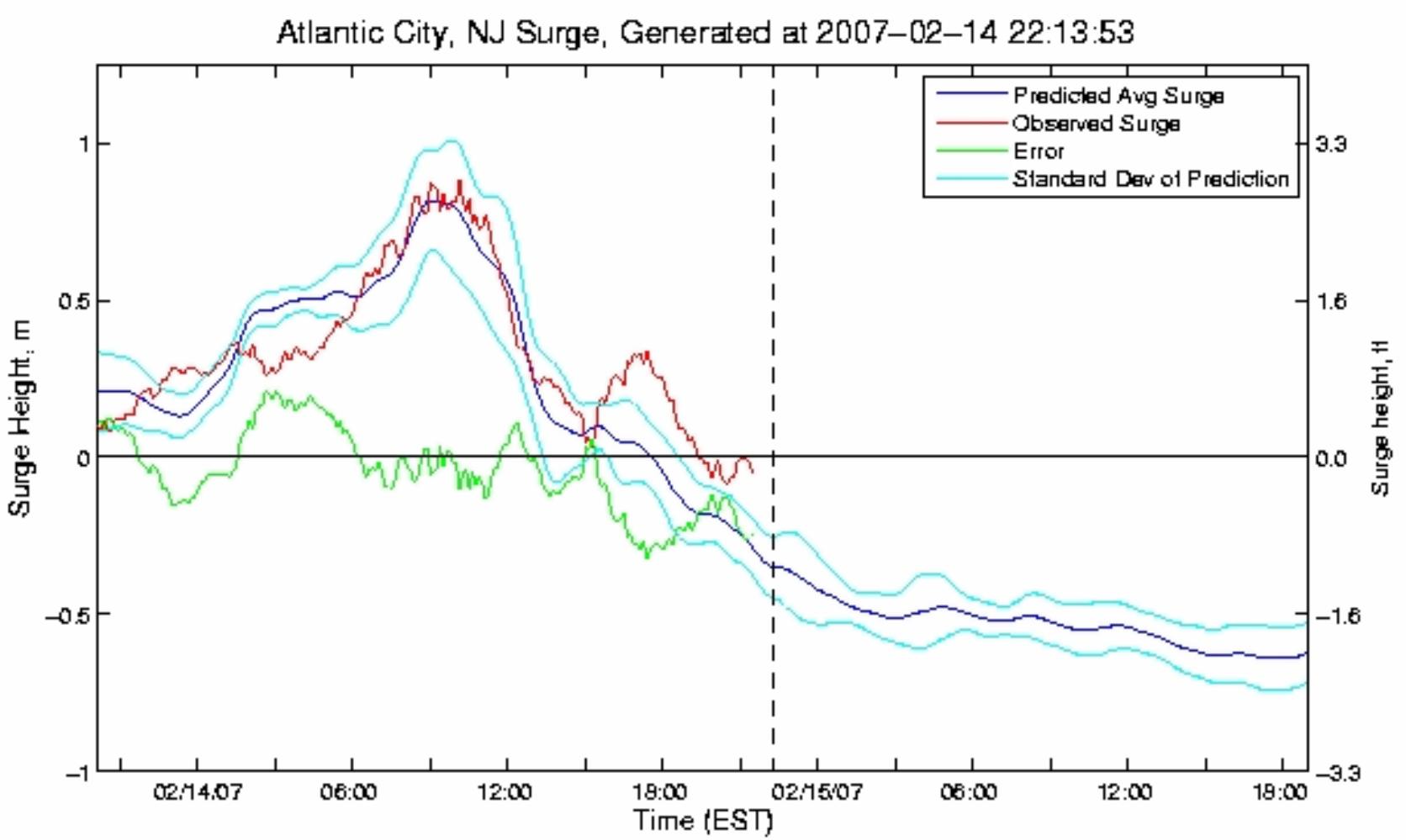
Time series of water height (in meters) at the Battery for the CTL, SUPERFLOYD, SHIFTFLOYD, and MAXFLOYD simulations as well as the astronomical tides. The time series starts at 0300 UTC 16 September, with each run labeled in the inset box.

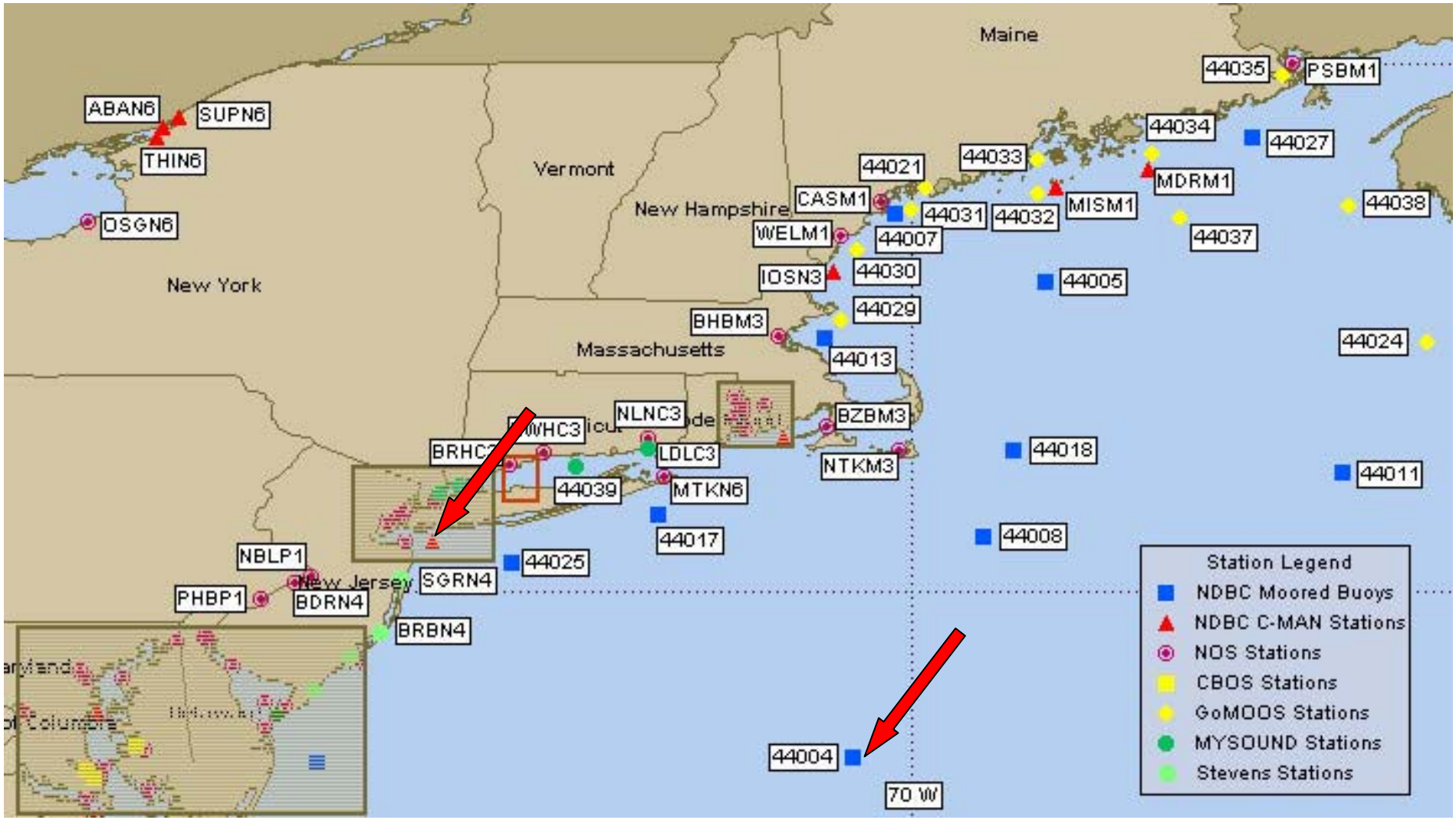
Lower Manhattan is gridded up to the 8 m contour.

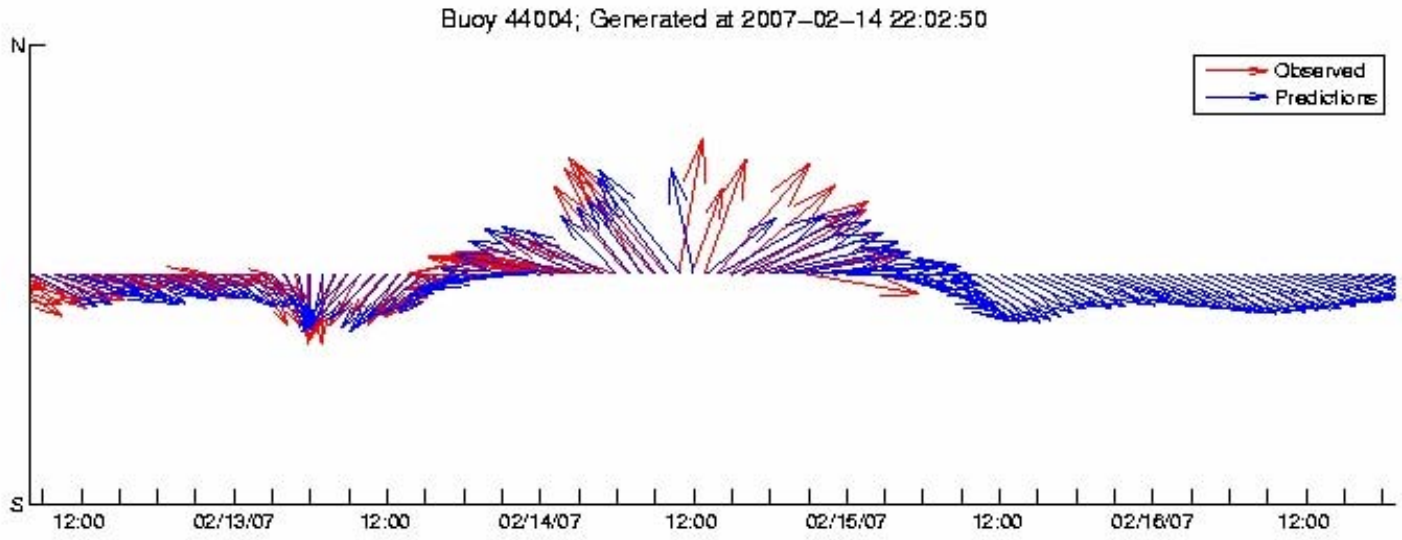


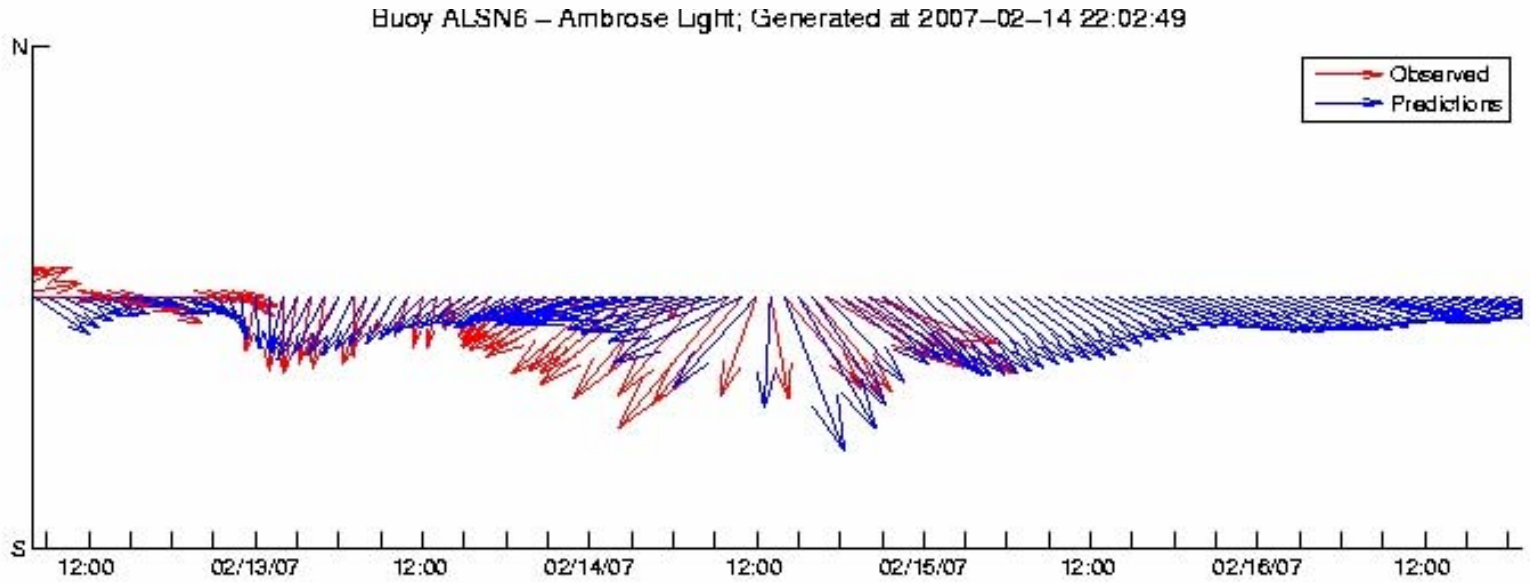
Flooding induced by Super Floyd

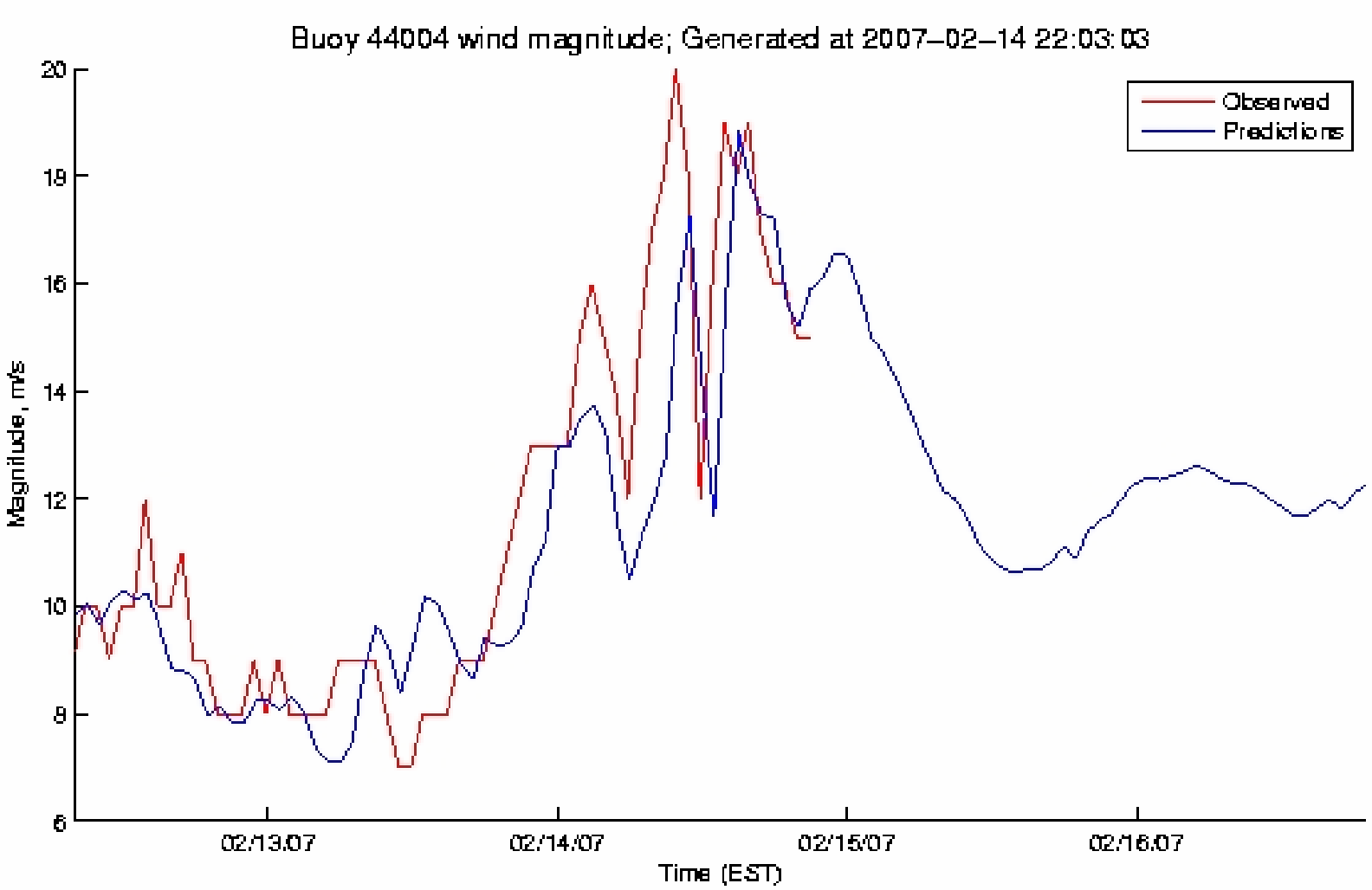

Atlantic City, NJ water level, generated at 2007–02–14 22:13:53
Avg Prediction
Observed
Astronomical
Standard Dev of Prediction
Water elevation, ft (MLLW)
Water elevation, ft (MLLW)
2
1.5
1
0.5
0
–0.5
–1
6.6
4.9
3.3
1.6
0.0
–1.6
–3.3
02/14/07
06:00
12:00
18:00
02/15/07
06:00
12:00
18:00
Time (EST)

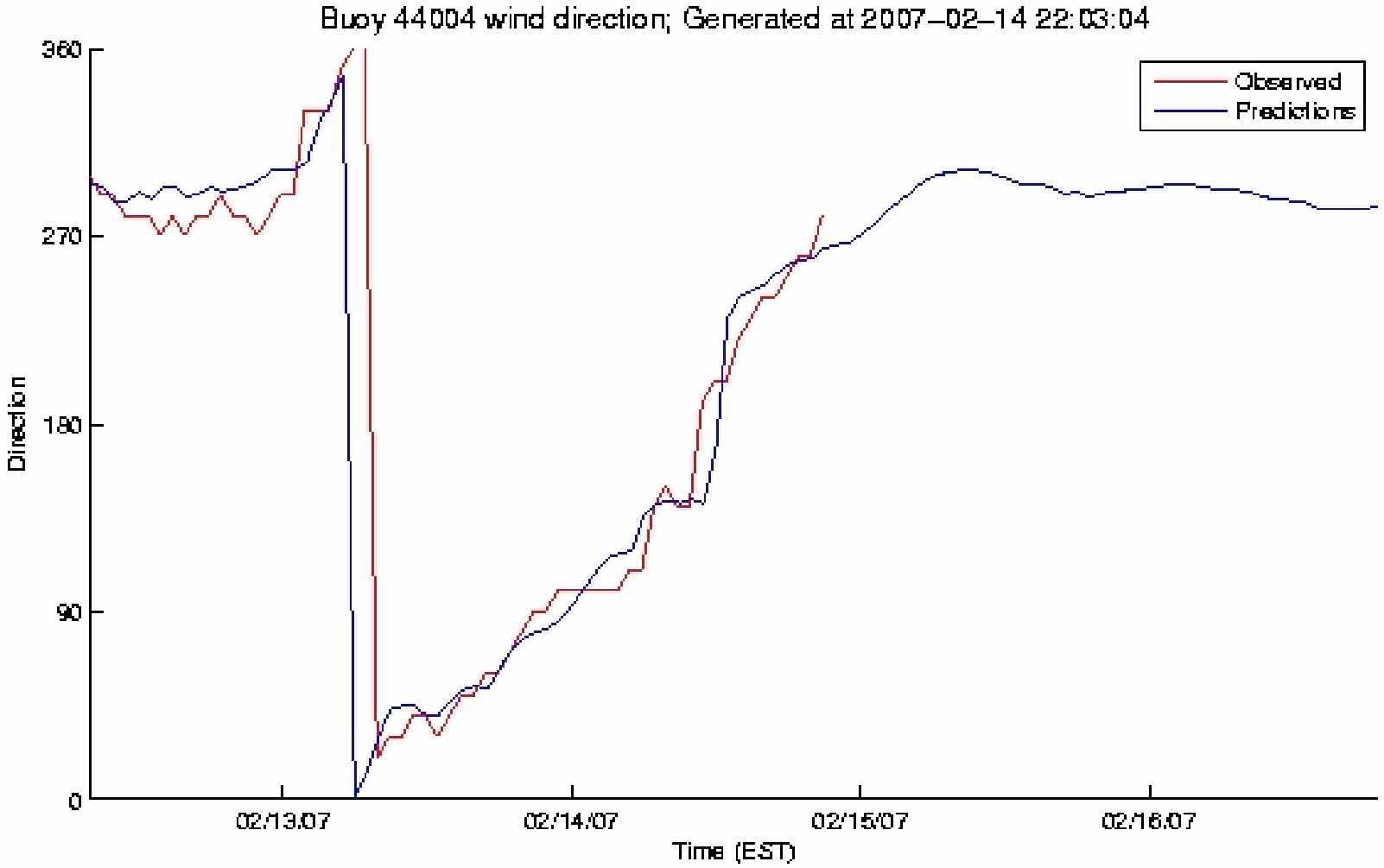

Atlantic City, NJ Surge, Generated at 2007–02–14 22:13:53
Predicted Avg Surge
Observed Surge
Error
Standard Dev of Prediction
Surge Height, m
Surge height, ft
1
0.5
0
−0.5
−1
3.3
1.6
0.0
−1.6
−3.3
02/14/07
06:00
12:00
18:00
02/15/07
06:00
12:00
18:00
Time (EST)

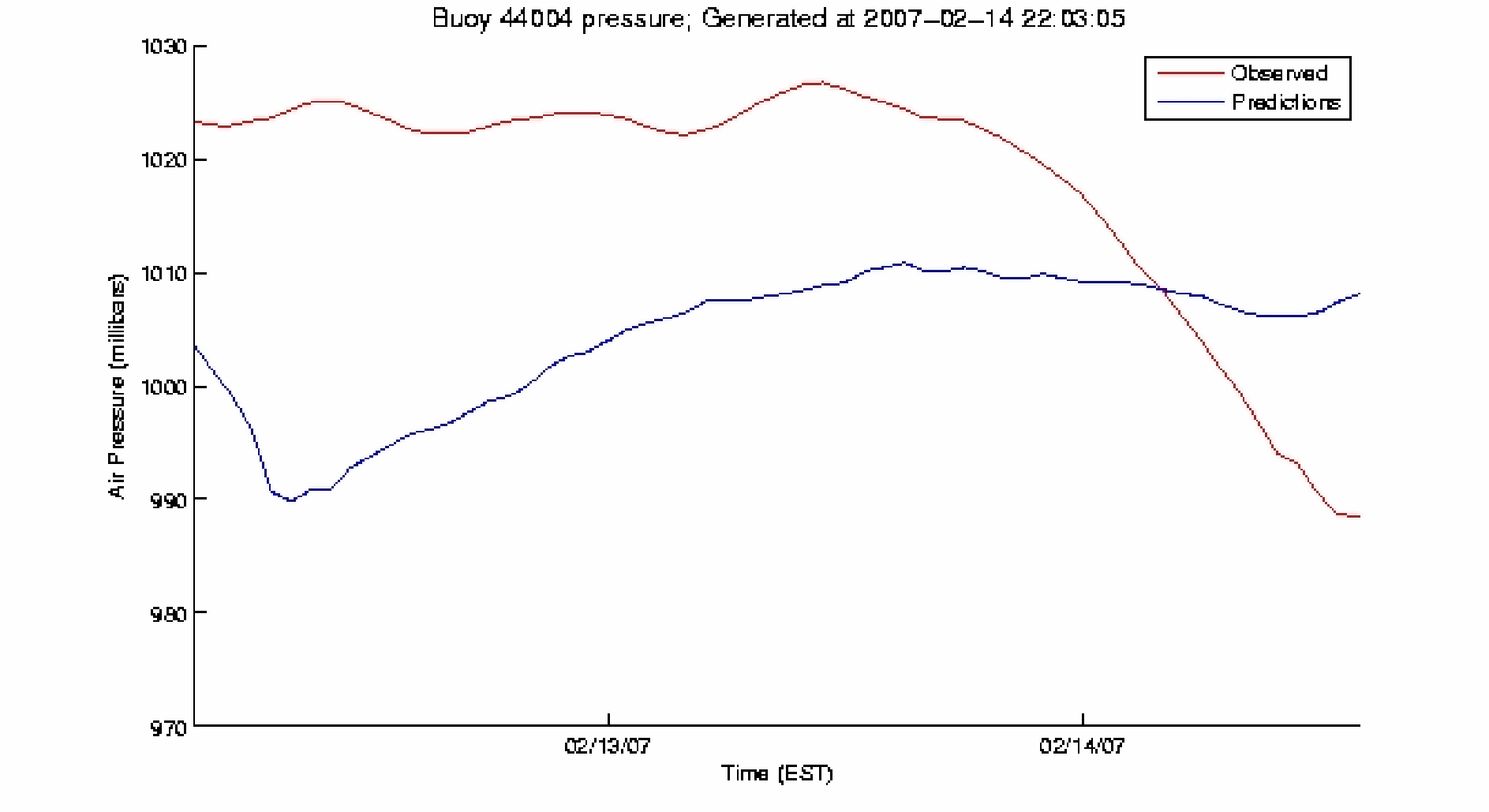

Maine
Vermont
New Hampshire
New York
Massachusetts
New Jersey
ABAN6
SUPN6
THIN6
OSGN6
44035
PSBM1
44034
44027
44033
44021
MDRM1
CASM1
MISM1
44038
44031
44032
WELM1
44007
44037
IOSN3
44030
44005
44029
BHBM3
44024
44013
NLNC3
BZBM3
LDLC3
NTKM3
44018
44039
MTKN6
44011
44017
44008
NBLP1
44025
SGRN4
PHBP1
BDRN4
BRBN4
44004
70 W
Station Legend
NDBC Moored Buoys
NDBC C-MAN Stations
NOS Stations
CBOS Stations
GoMOOS Stations
MYSOUND Stations
Stevens Stations


Buoy 44004; Generated at 2007-02-14 22:02:50
N
S
Observed
Predictions
12:00
02/13/07
12:00
02/14/07
12:00
02/15/07
12:00
02/16/07
12:00

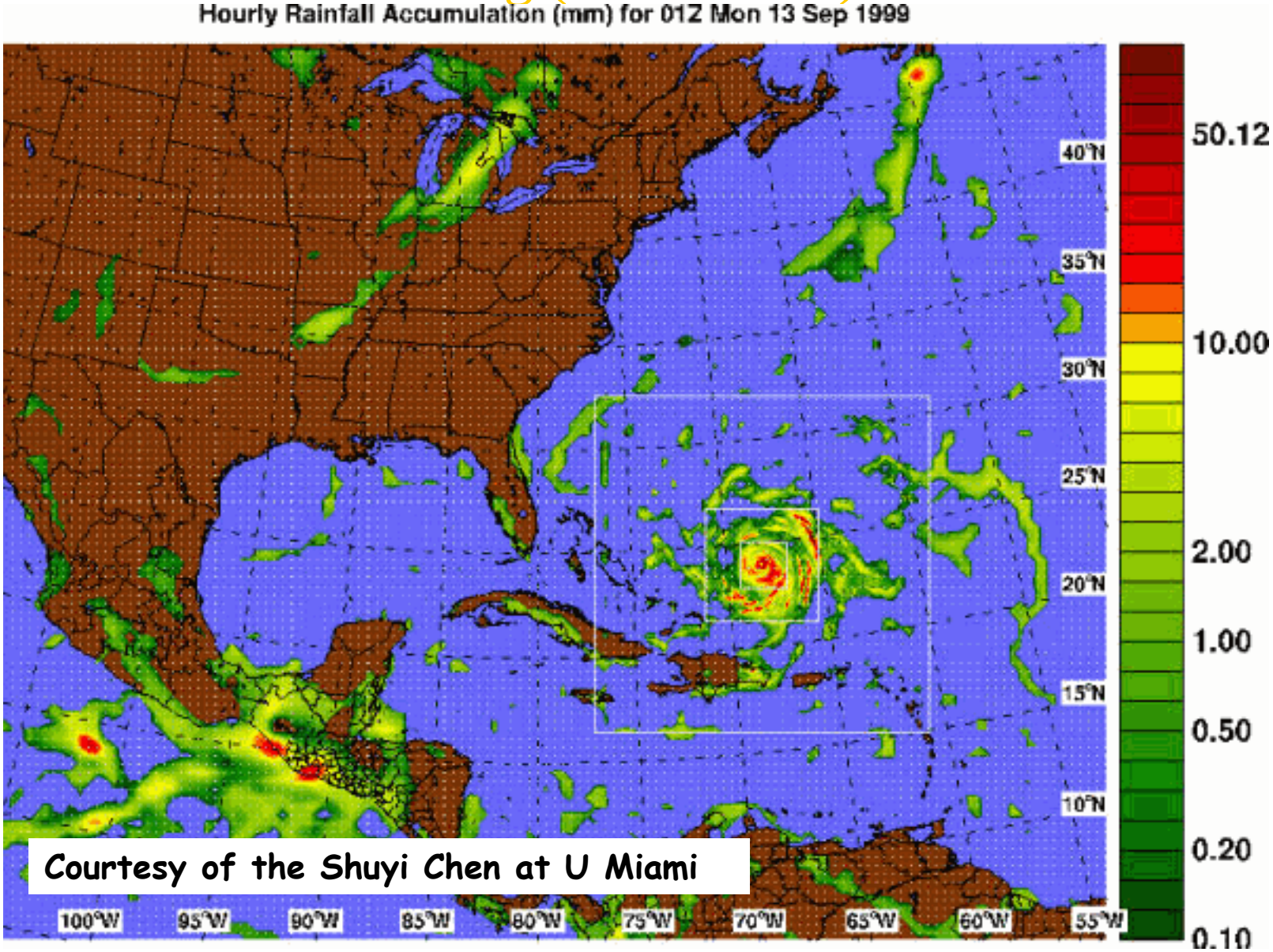

Buoy ALSN6 – Ambrose Light; Generated at 2007-02-14 22:02:49
N
S
Observed
Predictions
12:00
02/13/07
12:00
02/14/07
12:00
02/15/07
12:00
02/16/07
12:00


Buoy 44004 wind magnitude; Generated at 2007–02–14 22:03:03
Observed
Predictions
Magnitude, m/s
20
18
16
14
12
10
8
6
02/13/07
02/14/07
02/15/07
02/16/07
Time (EST)

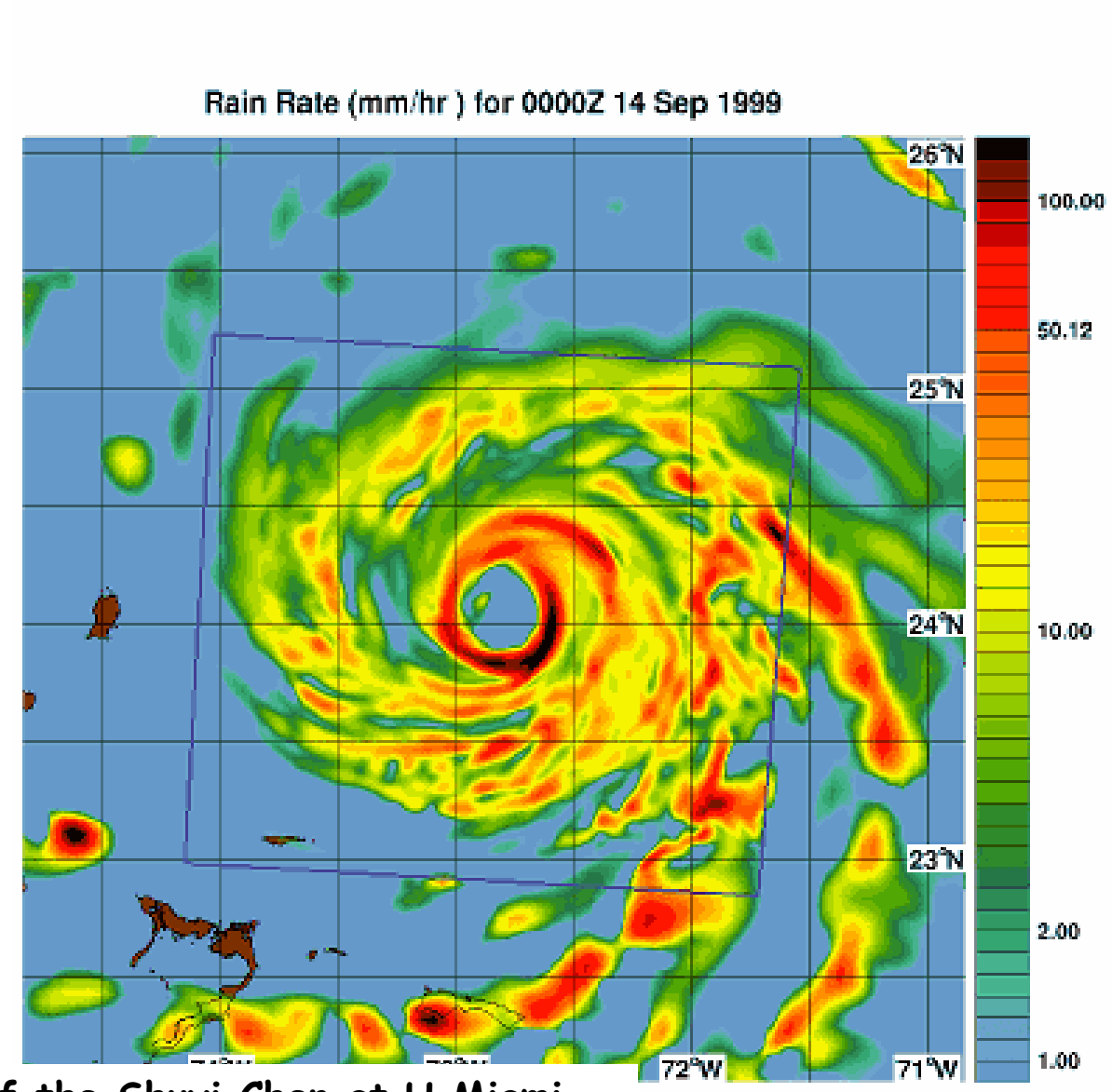

Buoy 44004 wind direction; Generated at 2007–02–14 22:03:04
Observed
Predictions
360
270
180
90
0
Direction
02/13/07
02/14/07
02/15/07
02/16/07
Time (EST)


Buoy 44004 pressure; Generated at 2007–02–14 22:03:05
Observed
Predictions
1030
1020
1010
1000
990
980
970
Air Pressure (millibars)
02/13/07
02/14/07
Time (EST)

Vortex-following (double nest) MM5 Run

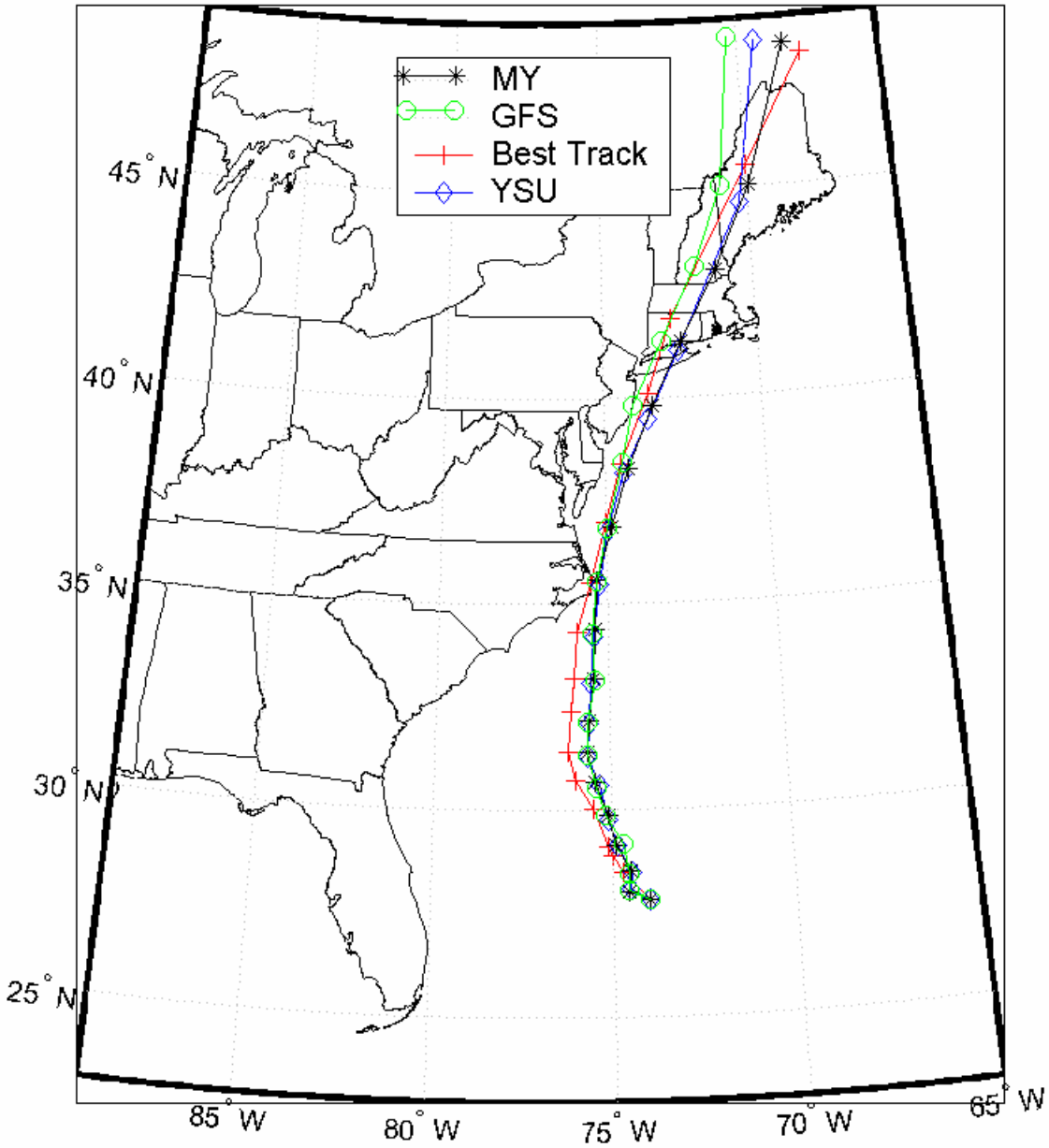


Floyd animation of 4-km moveable nest



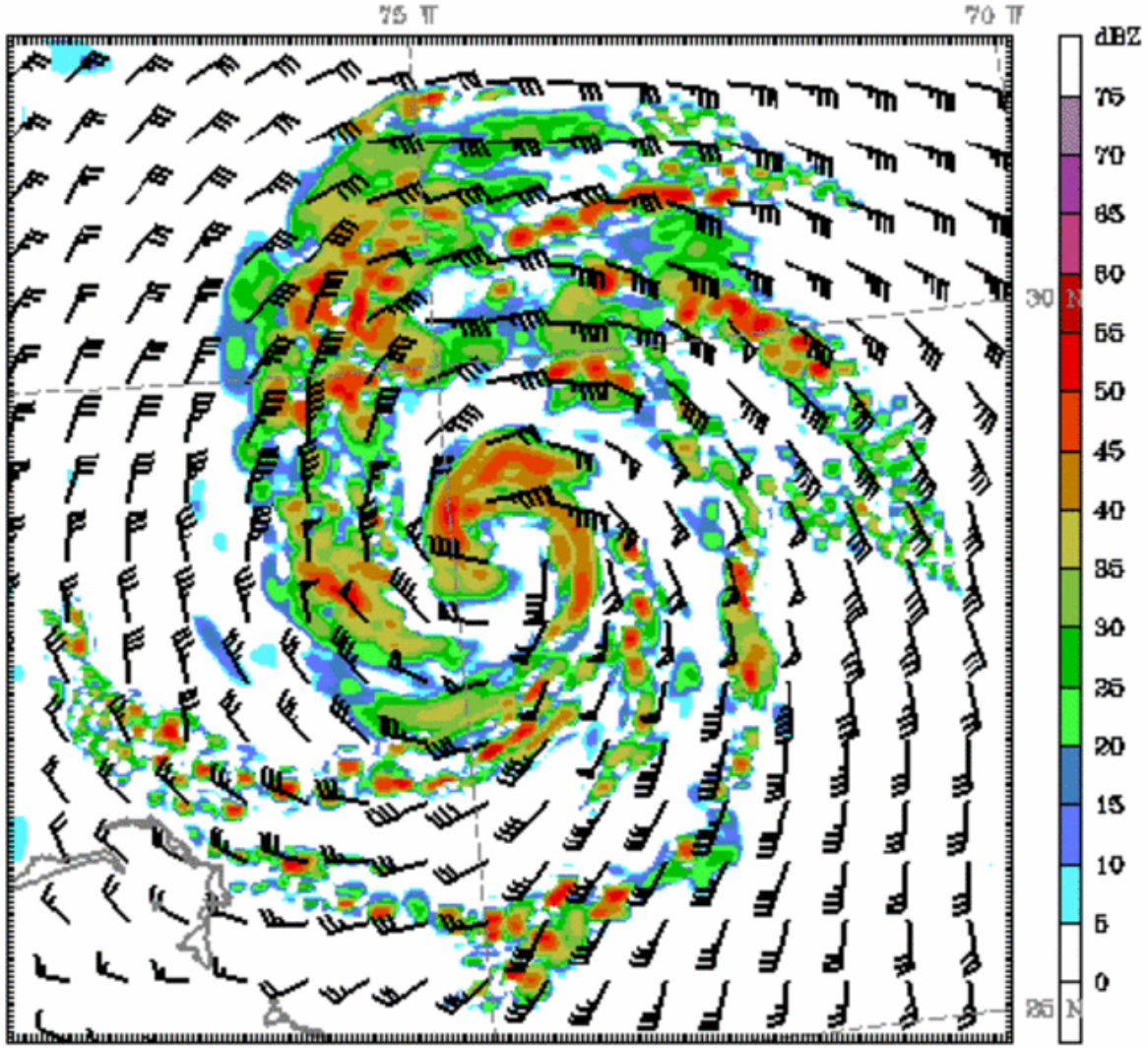
Courtesy of the Shuyi Chen at U Miami

Hurricane Gloria 00z Sept. 26th - 06z 28th, 1985



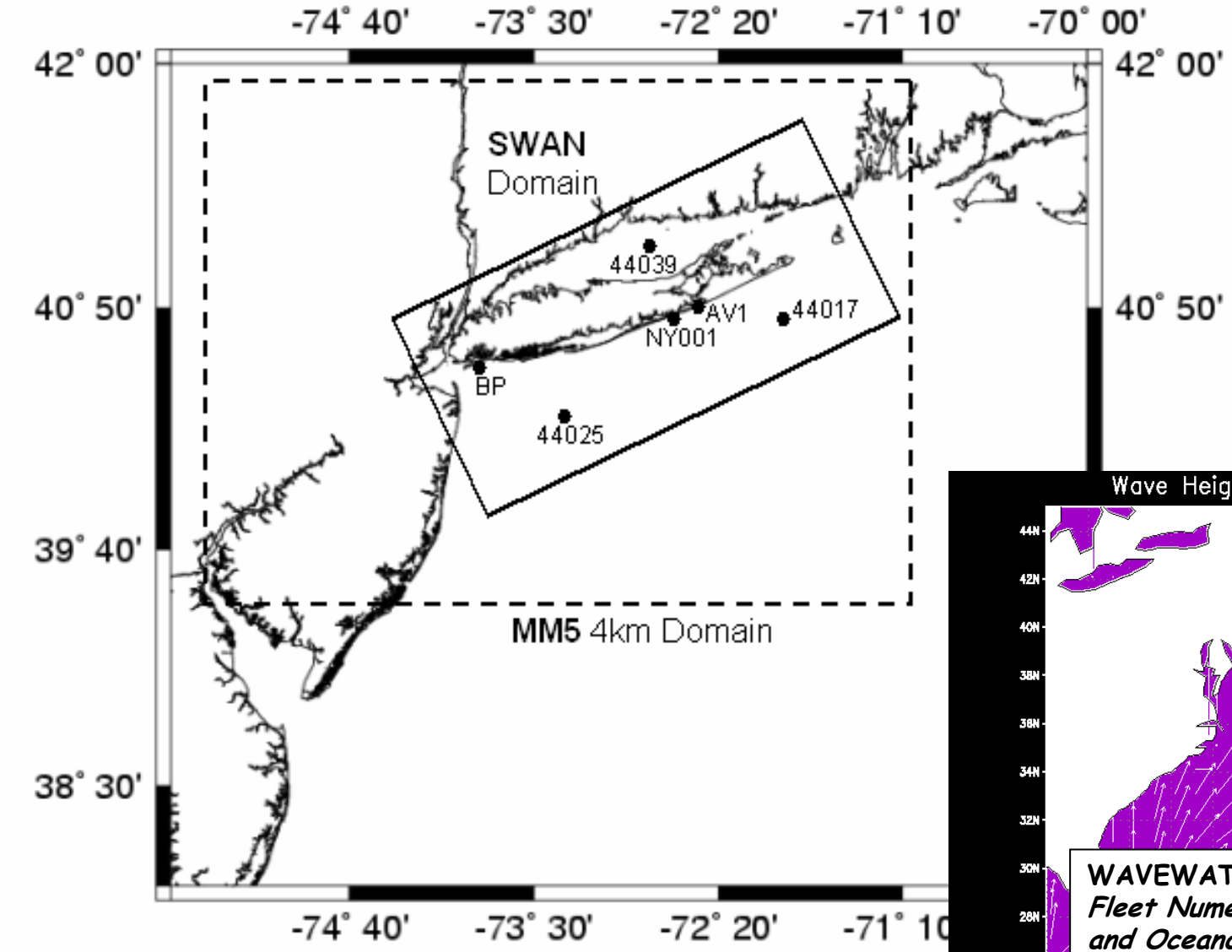
09 1985 NARR WRF Gloria
Fcst: 7 h
Reflectivity
Wind at lowest level(full barb = 10kts)

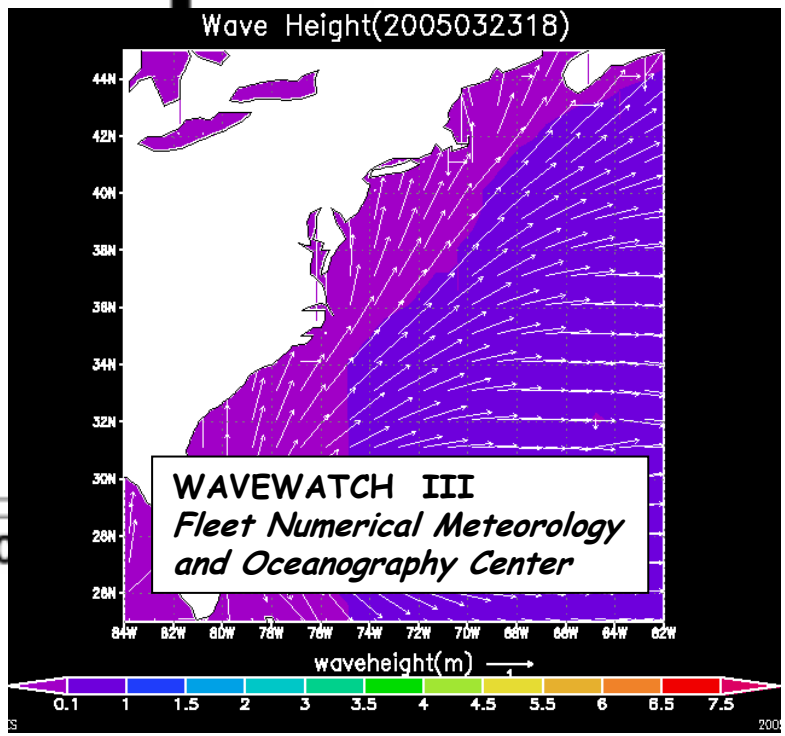
Init: 00 UTC Thu 26 Sep 85
Valid: 07 UTC Thu 26 Sep 85 (03 EDT Thu 26 Sep 85)
at k-index = 32

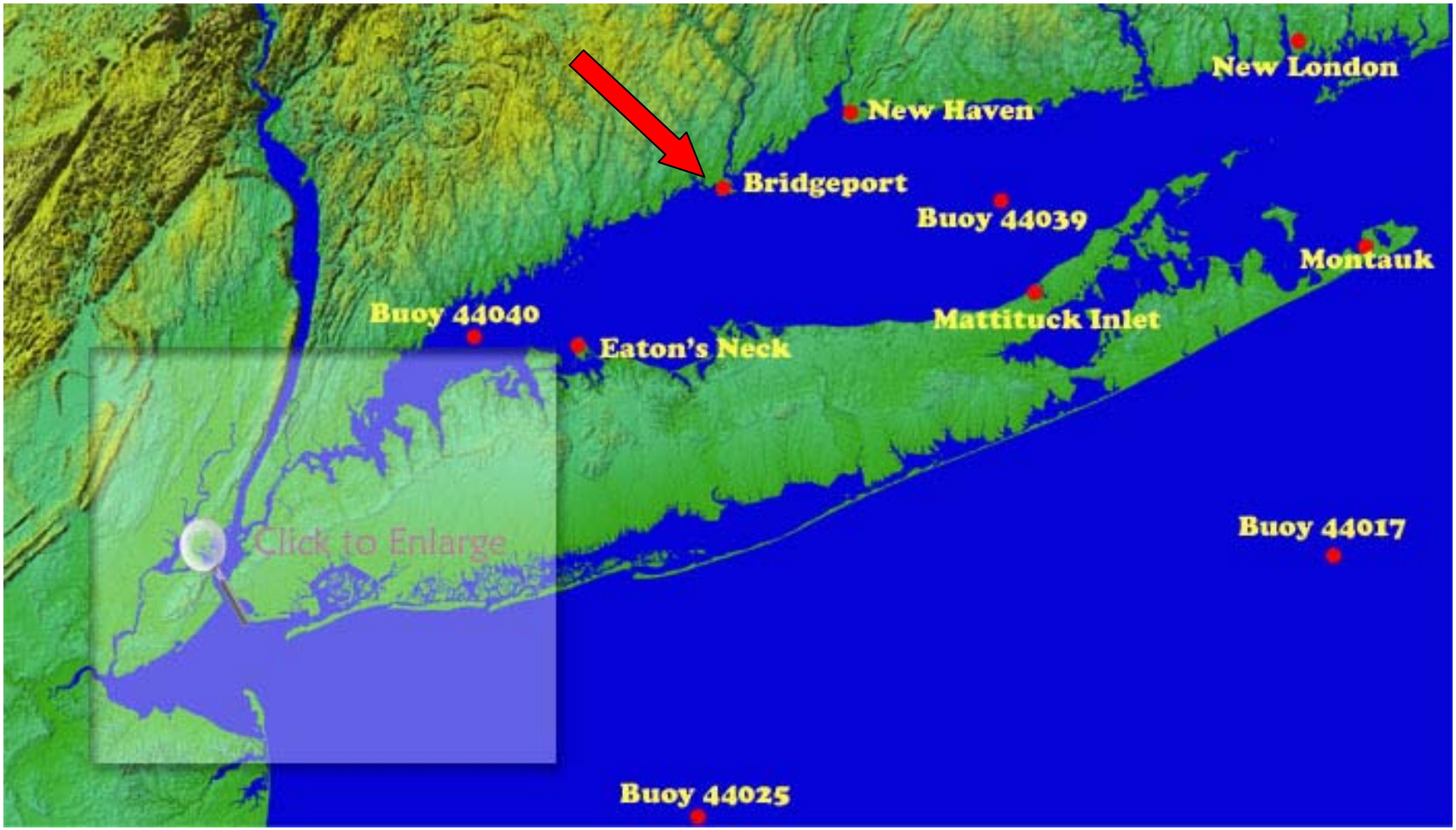


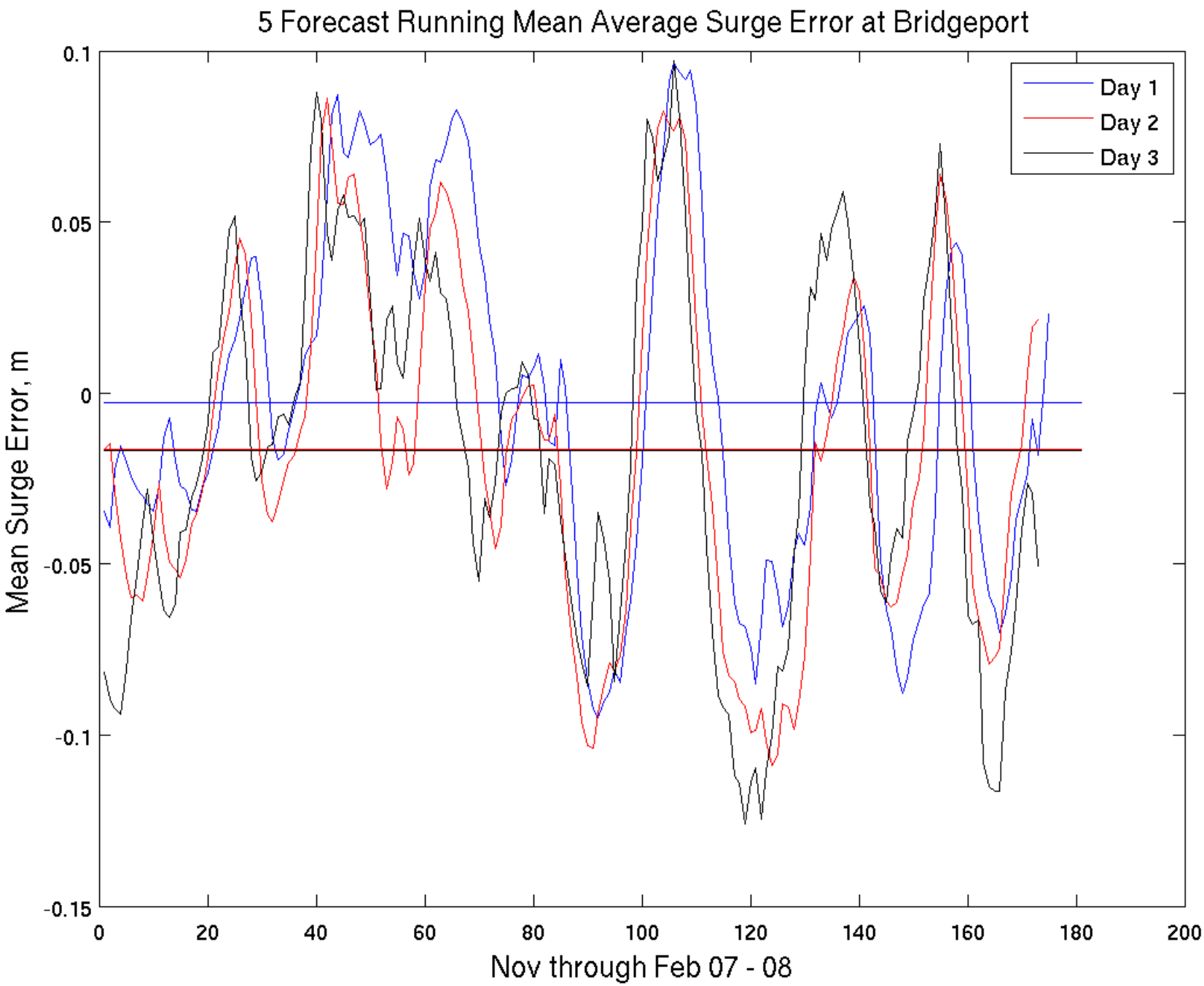
Model Info: V2.2 M No Cu YSU PBL Lin et al Ther-Diff 4.0 km, 32 levels, 10 sec

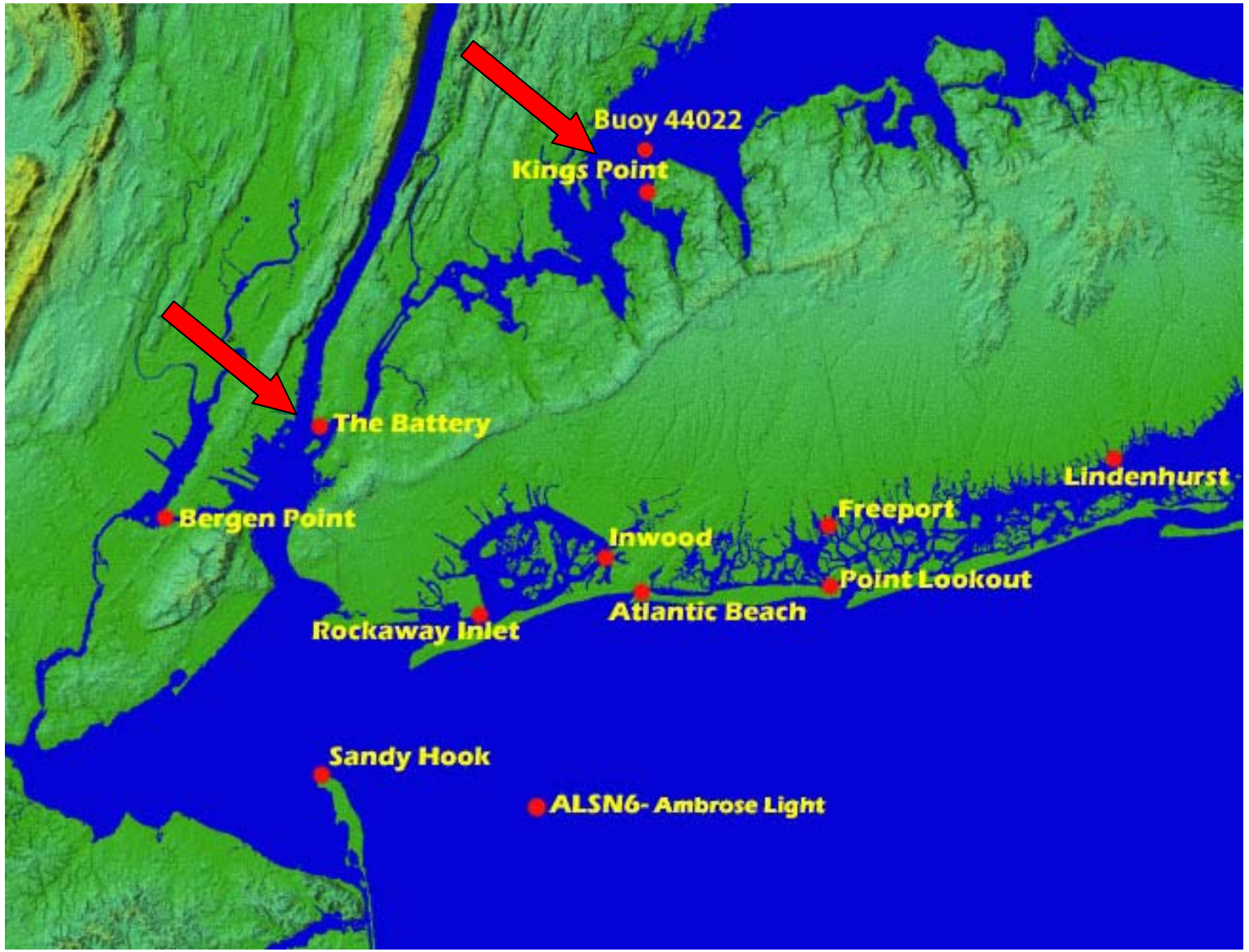
South Shore of L.I.

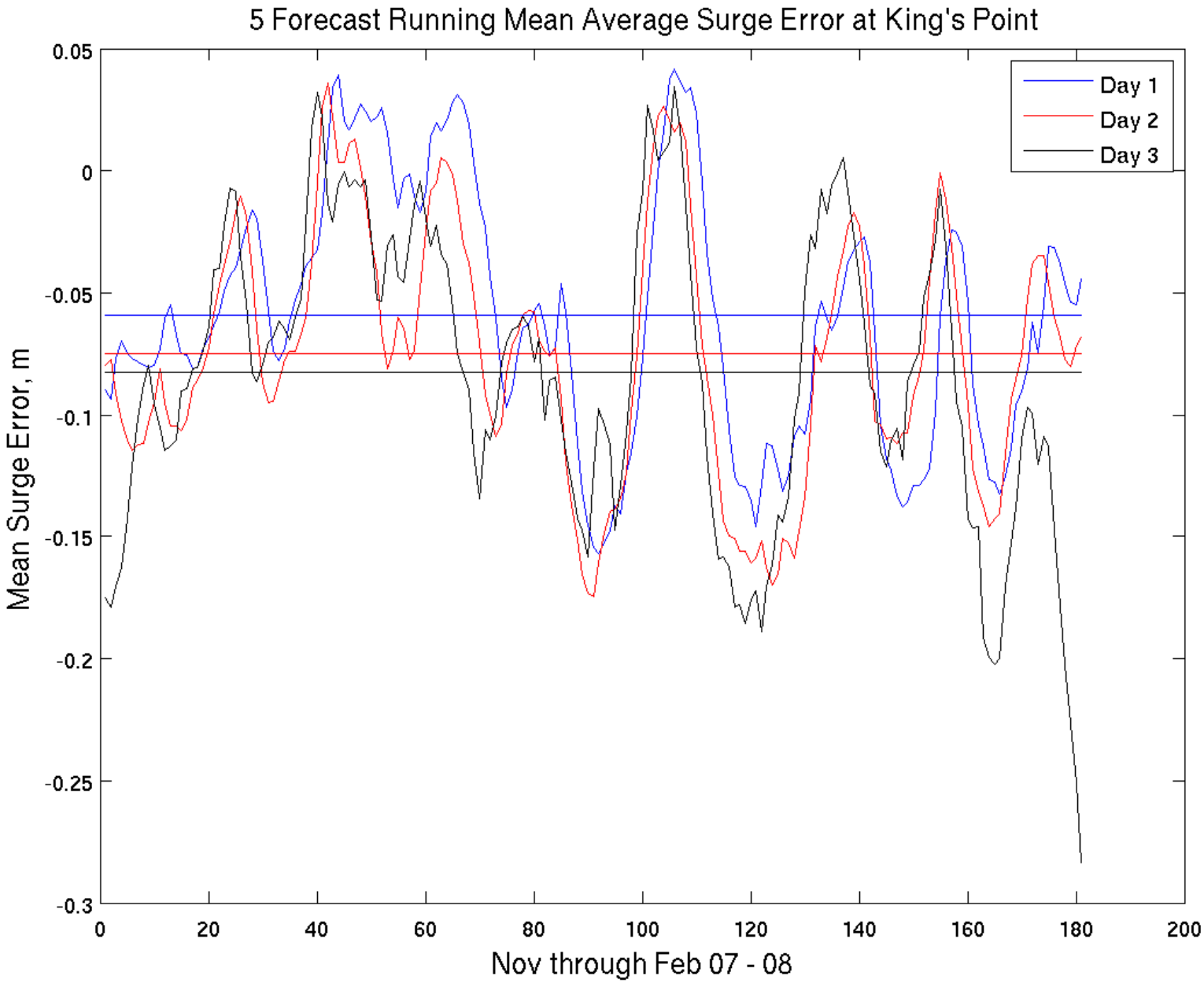


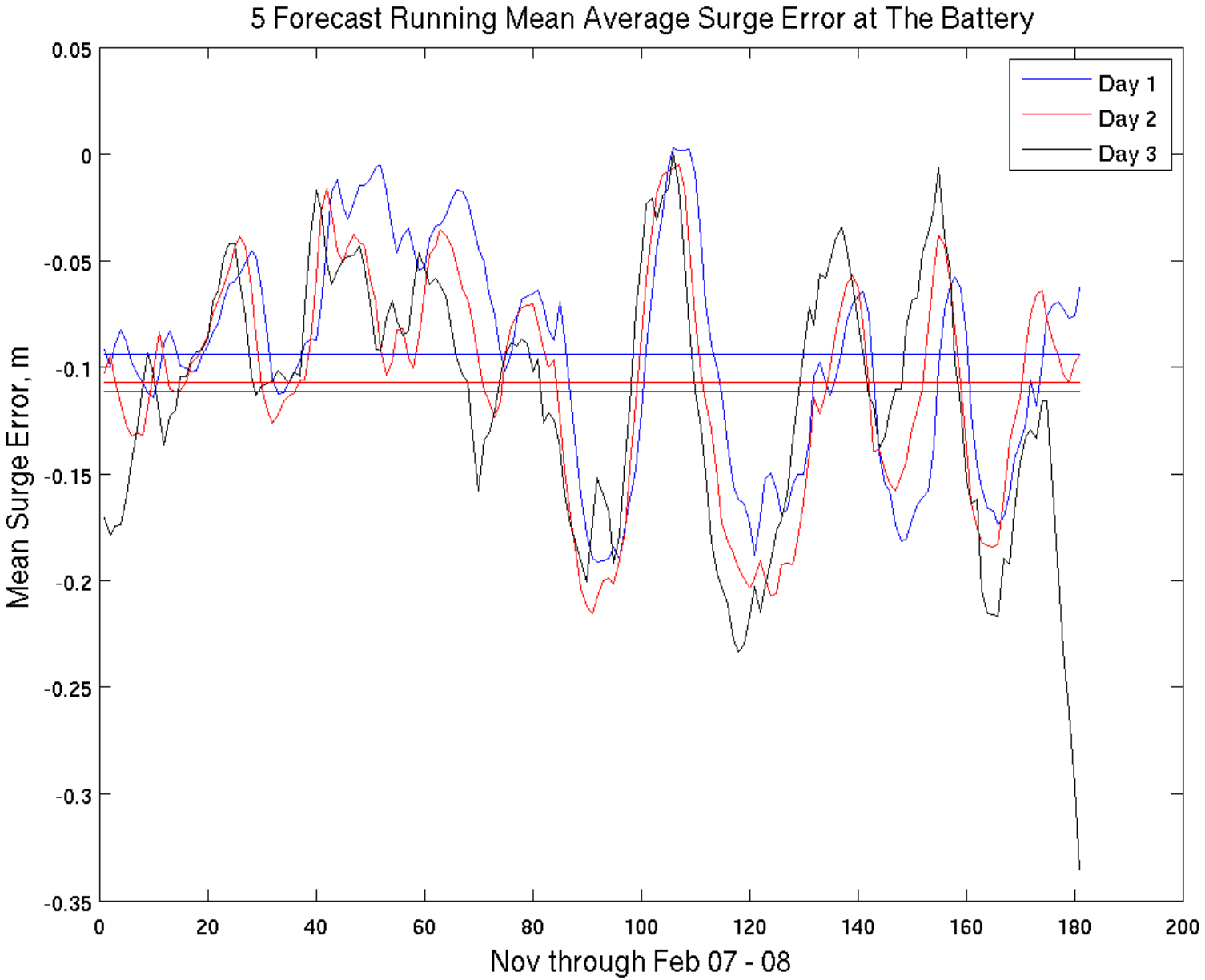


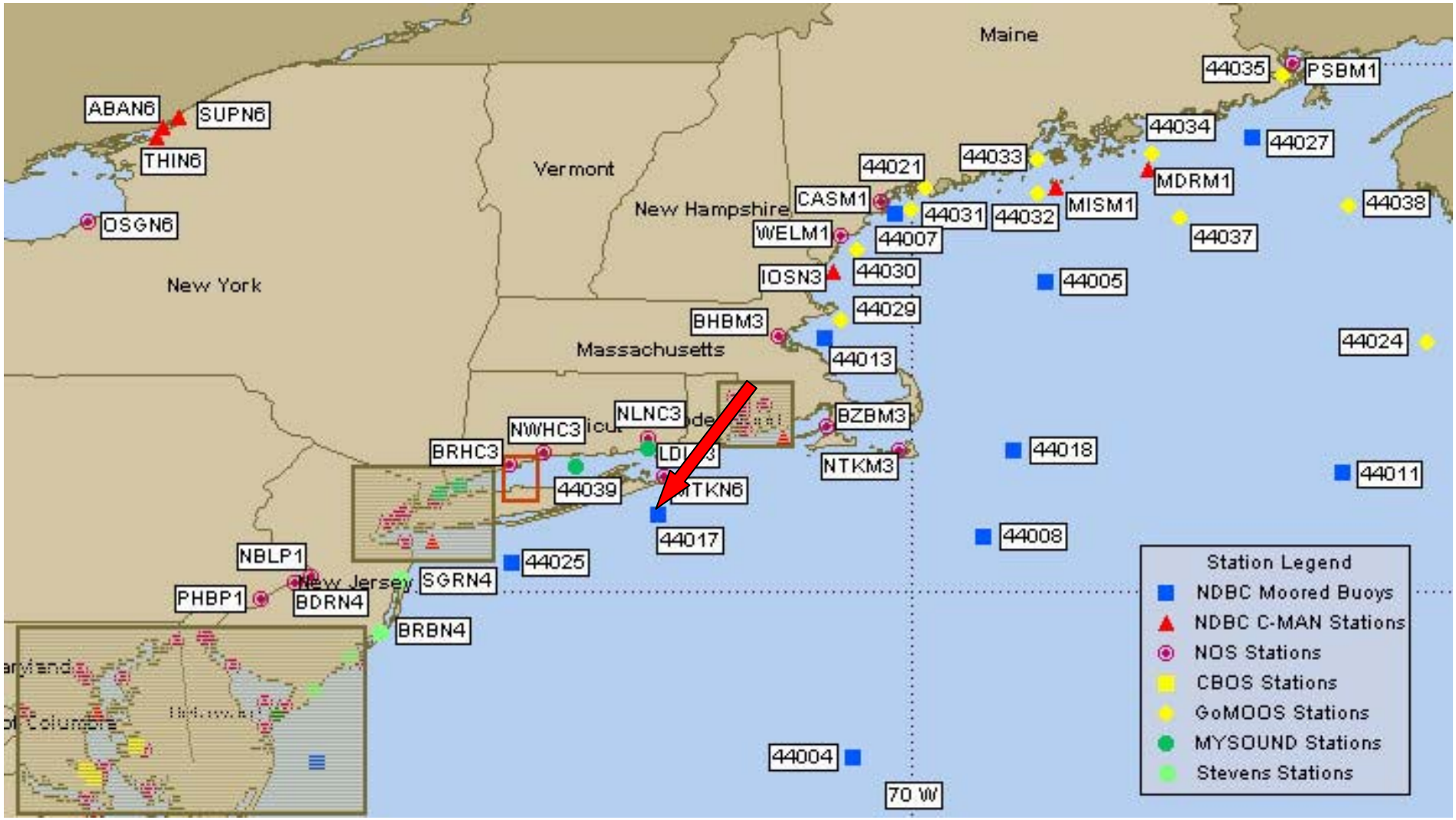

New London
New Haven
Bridgeport
Buoy 44039
Montauk
Buoy 44040
Mattituck Inlet
Eaton's Neck
Click to Enlarge
Buoy 44017
Buoy 44025

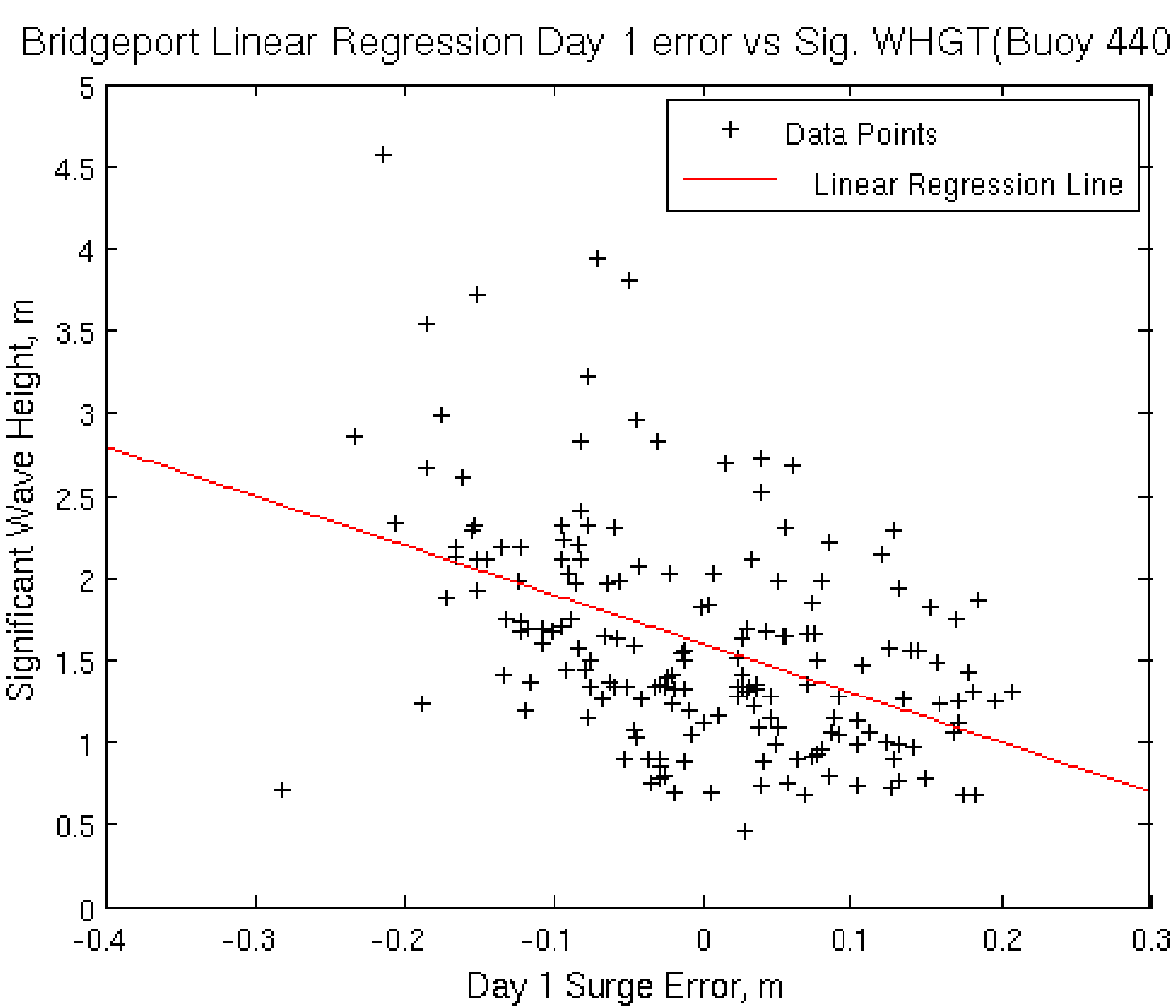

5 Forecast Running Mean Average Surge Error at Bridgeport
Mean Surge Error, m
0.1
0.05
0
-0.05
-0.1
-0.15
0
20
40
60
80
100
120
140
160
180
200
Nov through Feb 07 - 08
Day 1
Day 2
Day 3

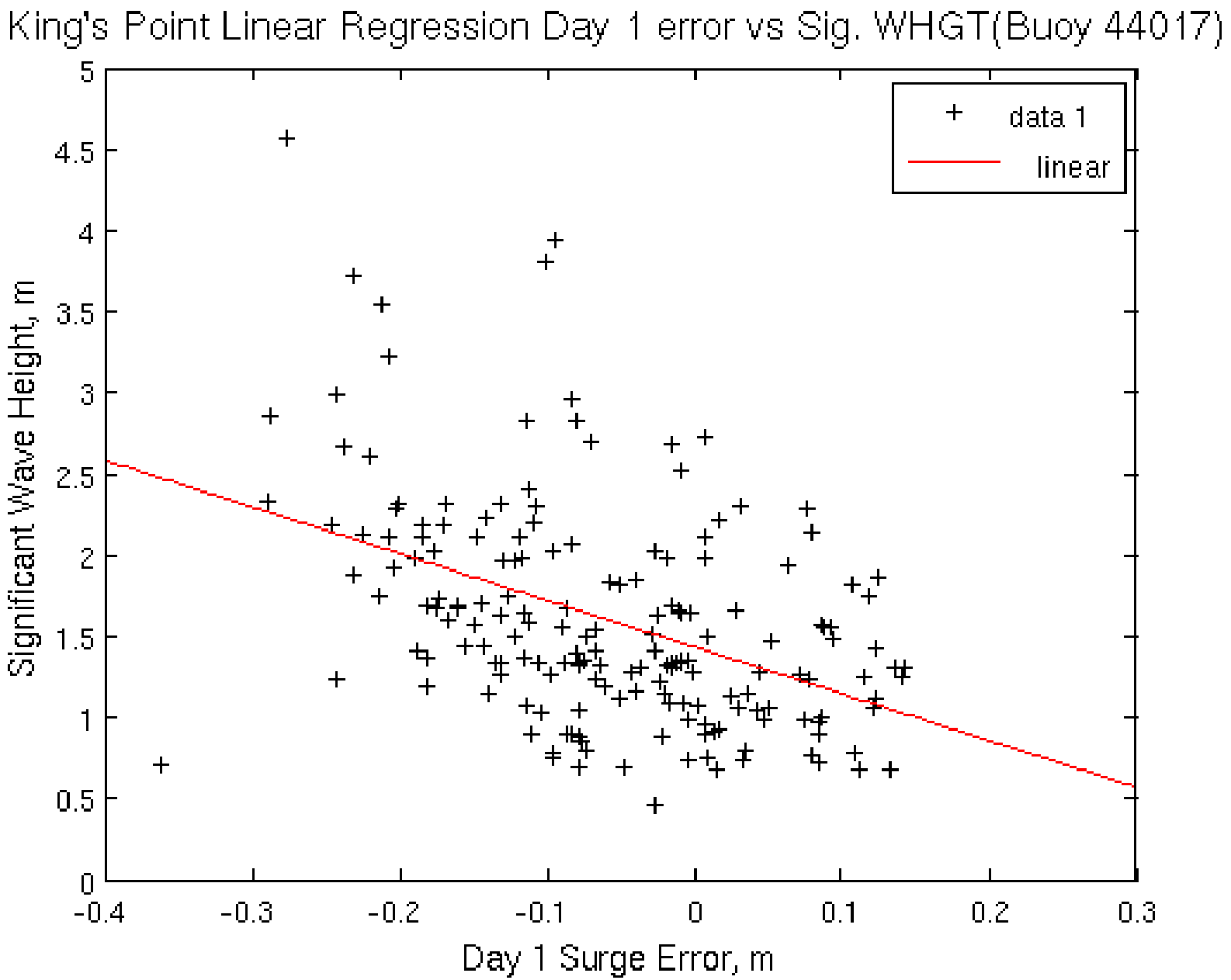

Buoy 44022
Kings Point
The Battery
Bergen Point
Lindenhurst
Freeport
Inwood
Point Lookout
Atlantic Beach
Rockaway Inlet
Sandy Hook
ALSN6- Ambrose Light

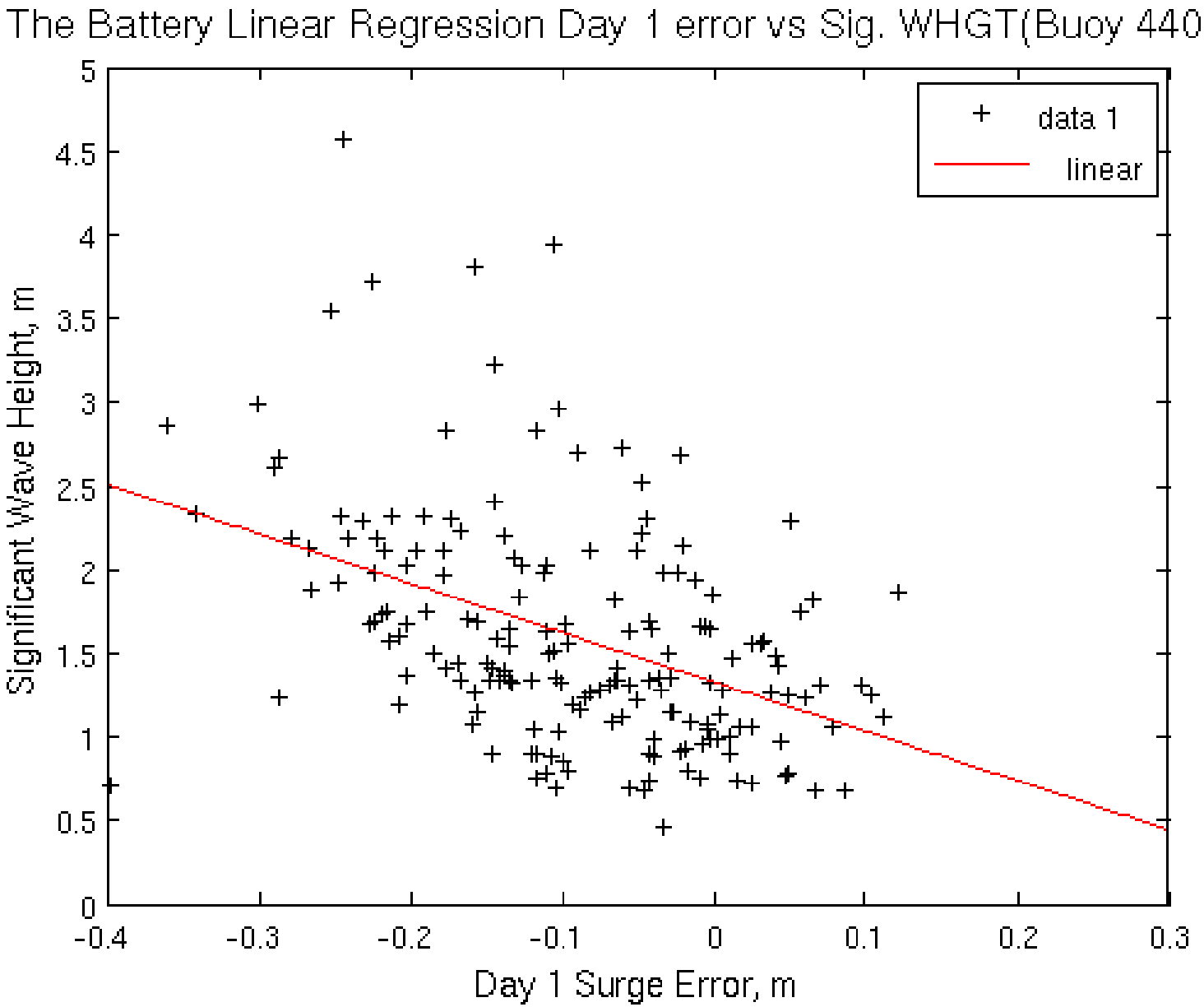

5 Forecast Running Mean Average Surge Error at King's Point
Mean Surge Error, m
Nov through Feb 07 - 08
Day 1
Day 2
Day 3
0.05
0
-0.05
-0.1
-0.15
-0.2
-0.25
-0.3
0
20
40
60
80
100
120
140
160
180
200


5 Forecast Running Mean Average Surge Error at The Battery
Mean Surge Error, m
Nov through Feb 07 - 08
Day 1
Day 2
Day 3
0.05
0
-0.05
-0.1
-0.15
-0.2
-0.25
-0.3
-0.35
0
20
40
60
80
100
120
140
160
180
200


Maine
Vermont
New Hampshire
New York
Massachusetts
New Jersey
ABAN6
SUPN6
THIN6
OSGN6
CASM1
WELM1
IOSN3
BHBM3
NLNC3
NWHC3
BRHC3
LDIC3
MTKN6
NBLP1
PHBP1
BDRN4
SGRN4
BRBN4
44035
PSBM1
44034
44027
44033
MDRM1
44021
44031
44032
MISM1
44038
44037
44007
44030
44005
44029
44024
44013
BZBM3
NTKM3
44018
44011
44039
44017
44025
44008
44004
70 W
Station Legend
NDBC Moored Buoys
NDBC C-MAN Stations
NOS Stations
CBOS Stations
GoMOOS Stations
MYSOUND Stations
Stevens Stations


Bridgeport Linear Regression Day 1 error vs Sig. WHGT(Buoy 44017)
Data Points
Linear Regression Line
Significant Wave Height, m
Day 1 Surge Error, m
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
-0.4
-0.3
-0.2
-0.1
0
0.1
0.2
0.3


King's Point Linear Regression Day 1 error vs Sig. WHGT(Buoy 44017)
data 1
linear
Significant Wave Height, m
Day 1 Surge Error, m
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
-0.4
-0.3
-0.2
-0.1
0
0.1
0.2
0.3


The Battery Linear Regression Day 1 error vs Sig. WHGT(Buoy 44017)
data 1
linear
Significant Wave Height, m
Day 1 Surge Error, m
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
-0.4
-0.3
-0.2
-0.1
0
0.1
0.2
0.3

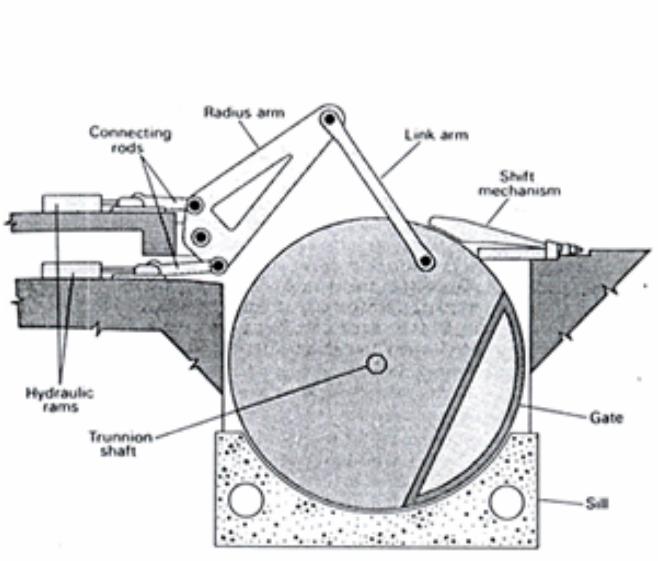
Storm Surge Barriers to Protect NYC?

- Why?
- Where located?
- How high?
- What design?
- Operating conditions?
- Environmental effects?
- When?

http://www.pbs.org/wgbh/nova/orleans/proo-nf.html

One new idea for New Orleans was already in development before Katrina. Construction has begun on a $36M sophisticated hurricane floodgate that would close across the Harvey Canal in the event of a storm surge.

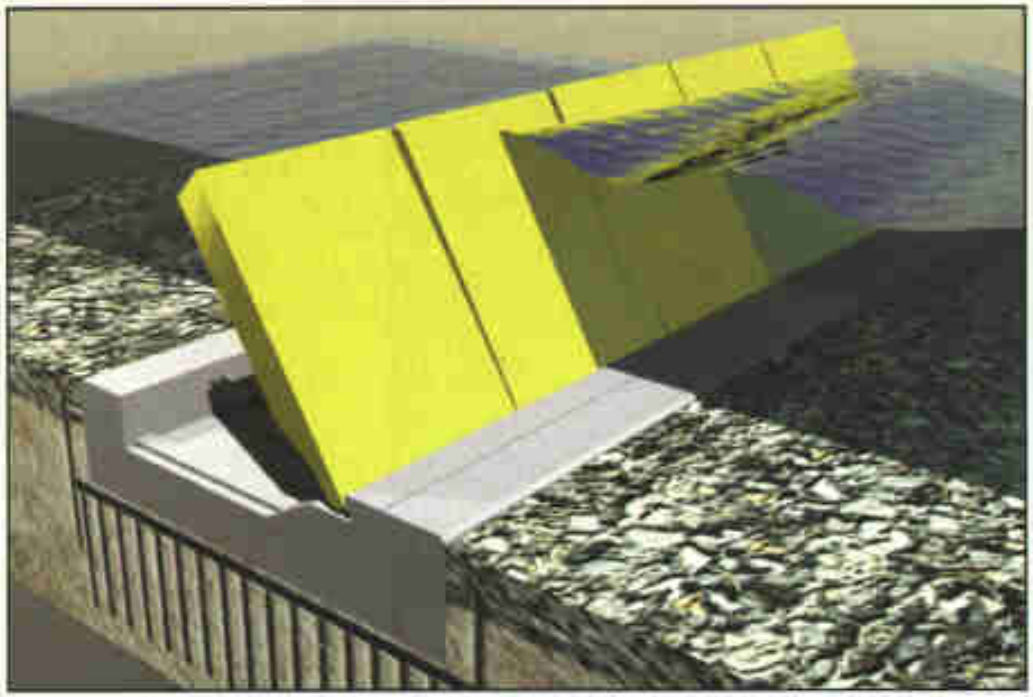
Thames River Tidal Barrier, England, 1982



The Thames barrier has been used over 200 times since it was opened in 1982.

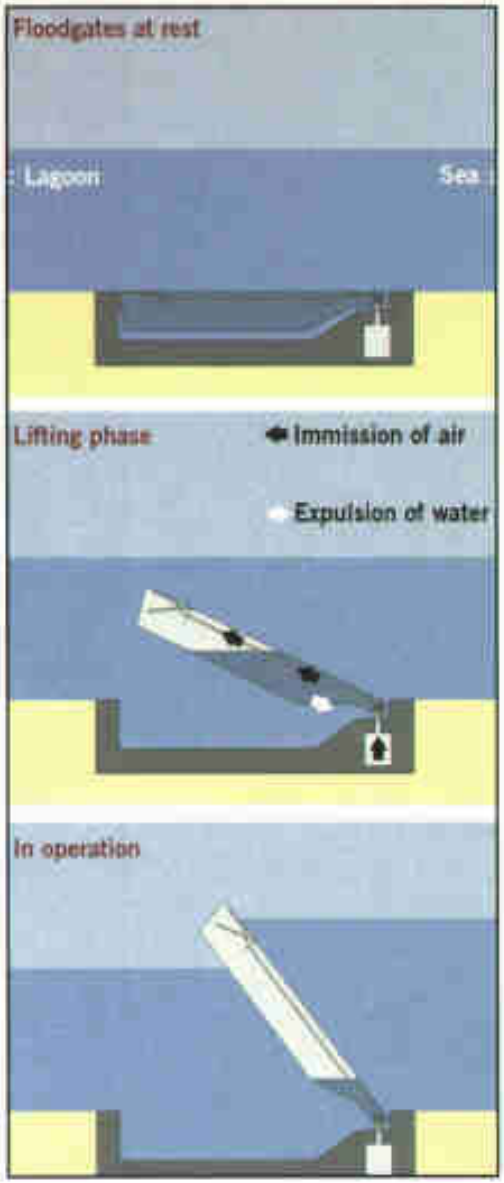
Eastern Scheldt, Netherlands, 1986

New Waterway, the Netherlands, 1997



THE GATES *fill with water under normal tidal conditions and rest on the inlet canal bed. When tides reach 100 cm, the gates will be filled with compressed air and rise to isolate the lagoon from the sea.*

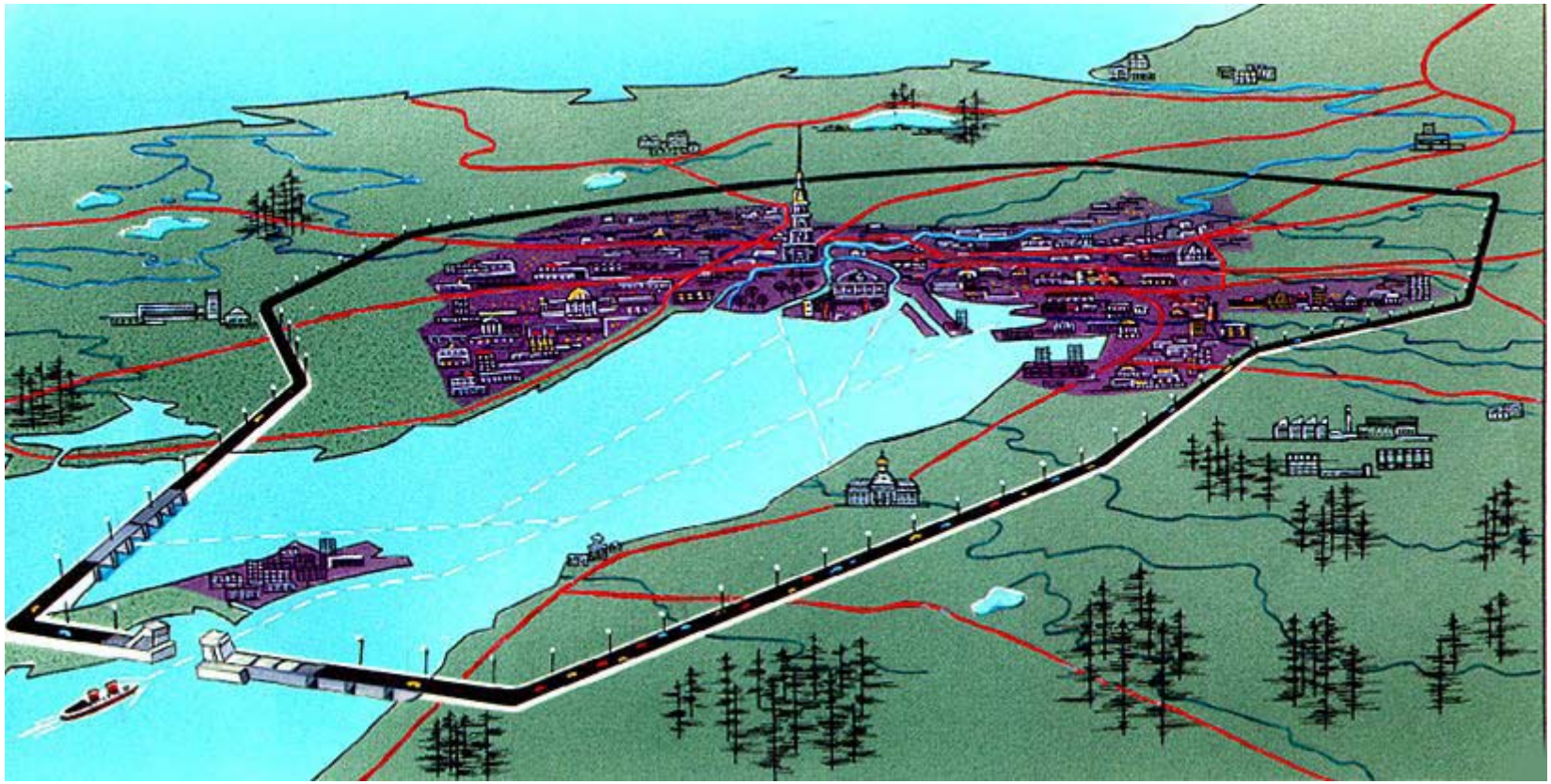
Venice Lagoon
2010



10

St. Petersburg, Russia's battles with flooding have been immortalized for centuries in Russian art and in literature. The city was built atop a swamp fed by the Neva River and the Gulf of Finland. Each fall and winter, strong winds and ice block the flow of the Neva into the Gulf, causing the river level to rise and, at least once a year, spill excess water into the city. The two largest floods in 1824 and 1924 left considerable death and destruction in their wake.

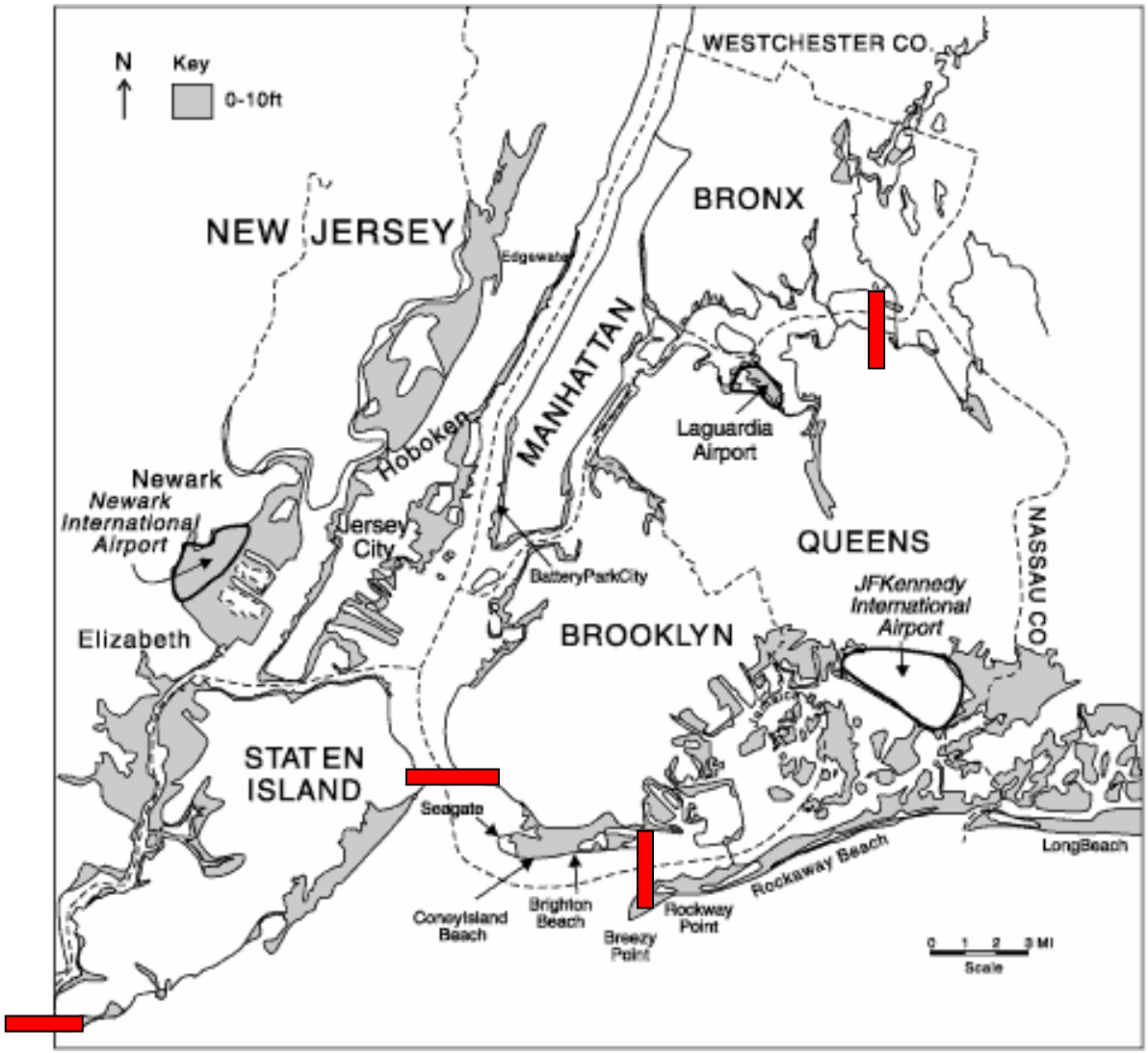
www.pbs.org/wgbh/nova/orleans/proo-nf.html



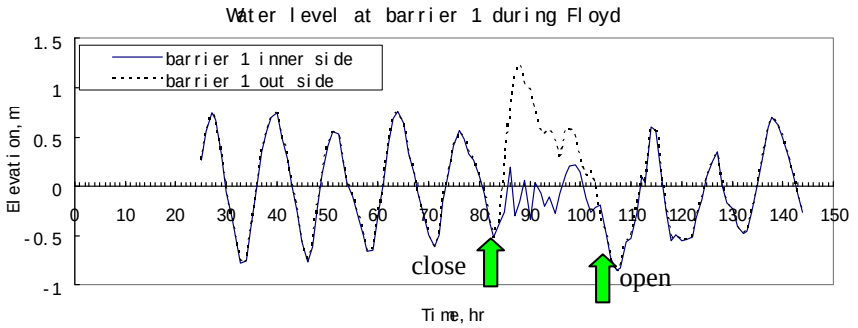
http://www.oceansatlas.org/unatlas/-ATLAS-/IMAGES/HIGH/i241-1.jpg

Water exchange gates

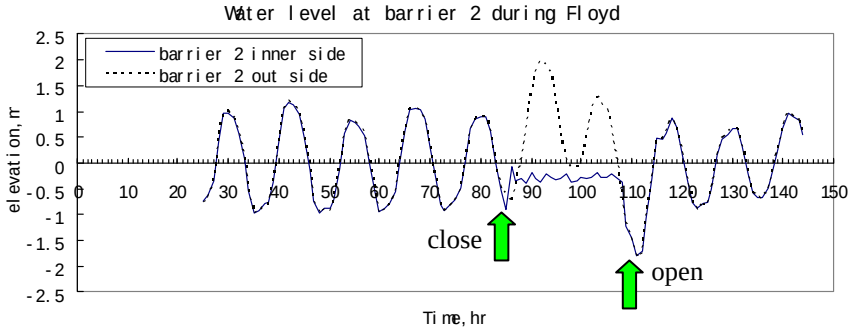
Proposed Barrier Locations



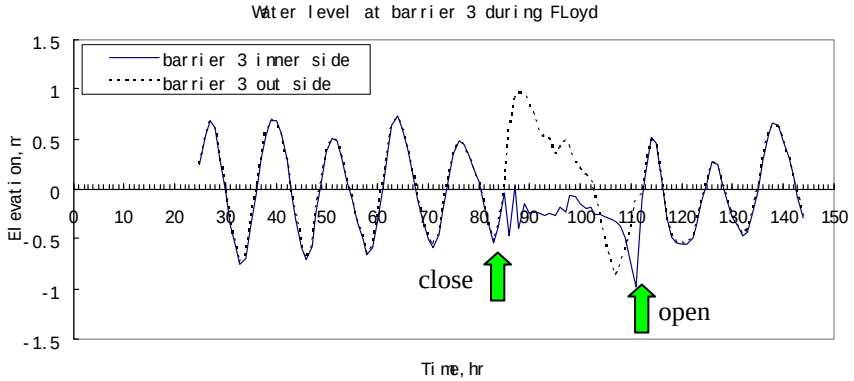
The 100-year flood at present mean sea level (from Gornitz, 2001)



Perth Amboy

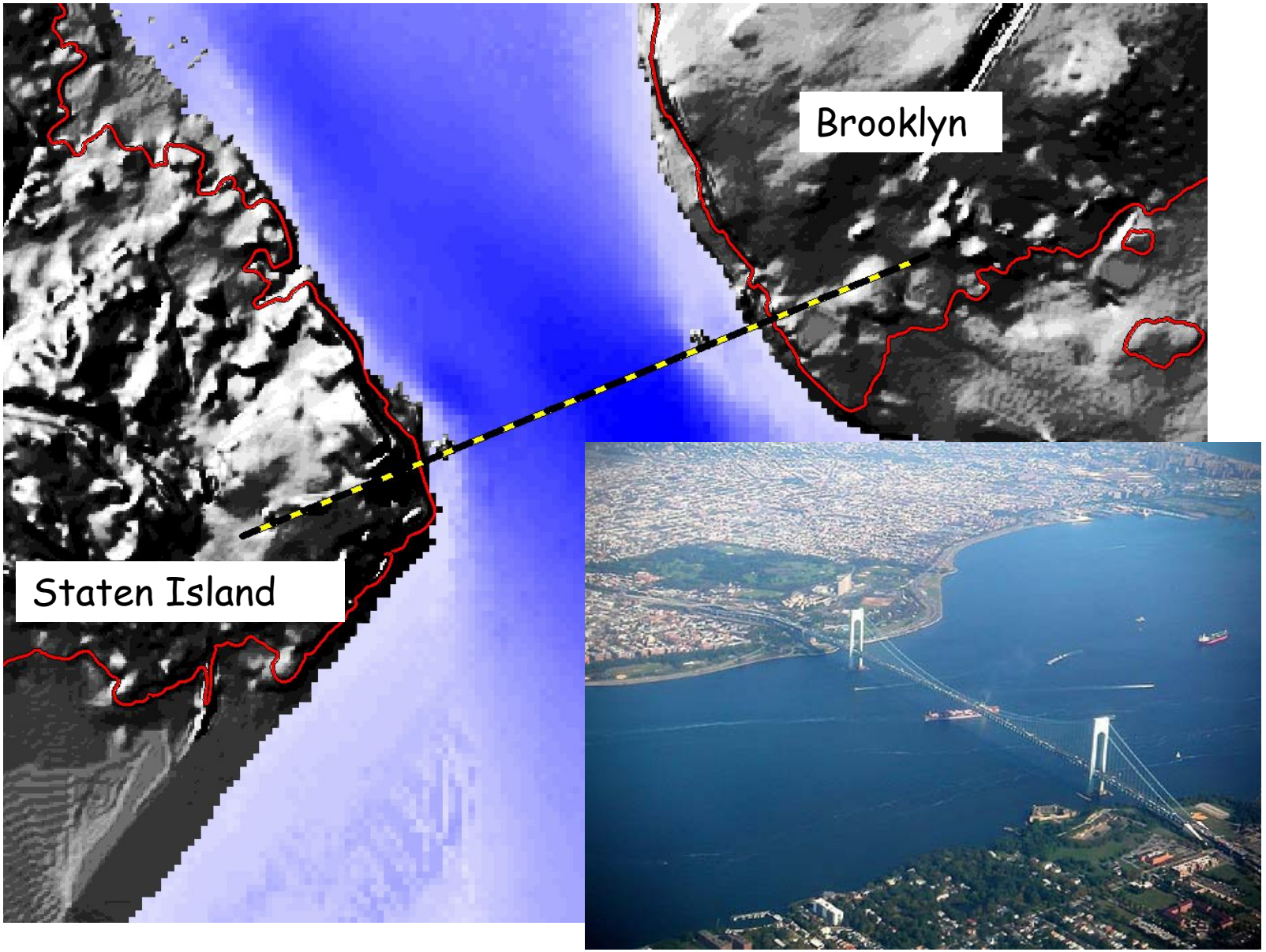


Upper East River

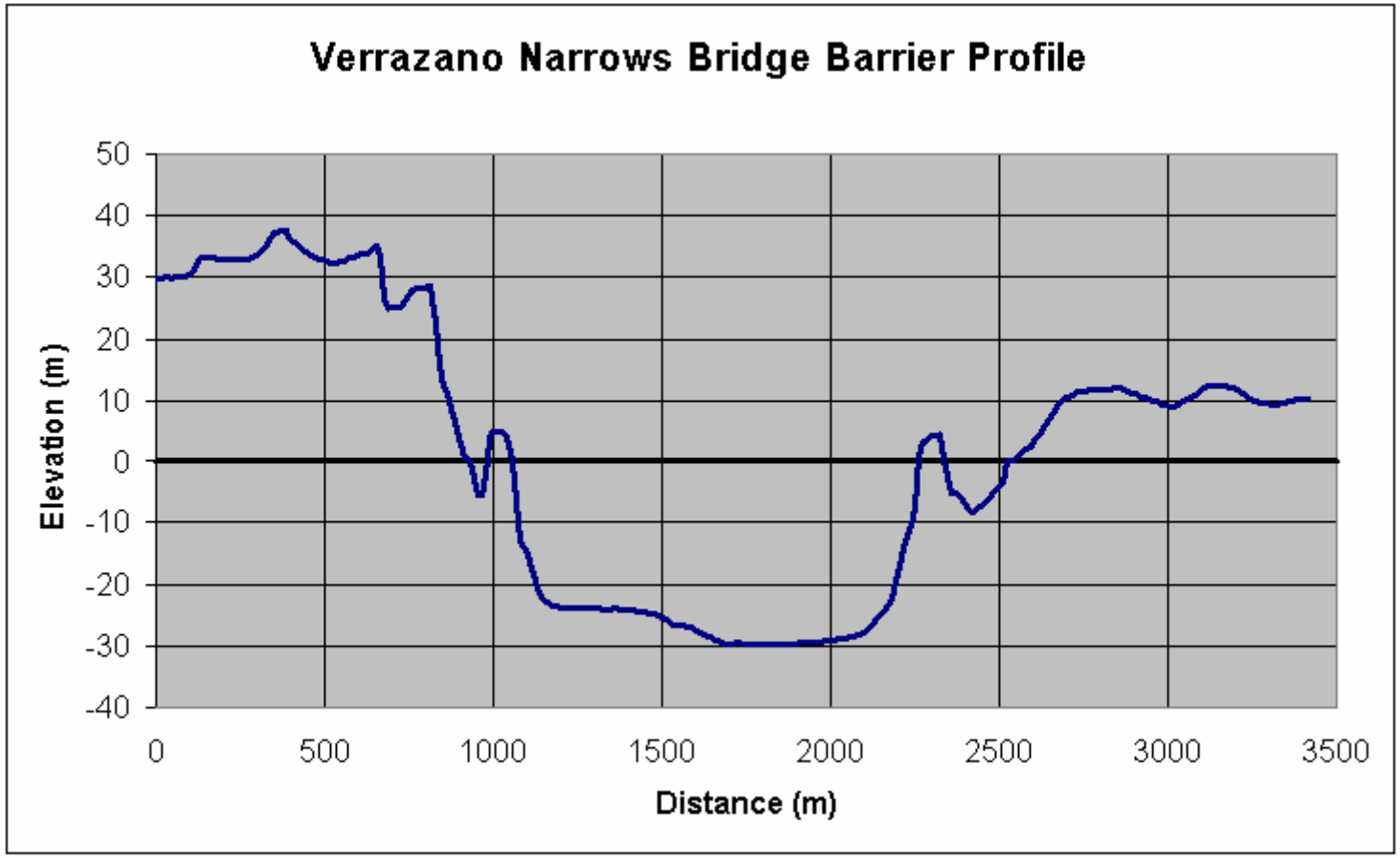


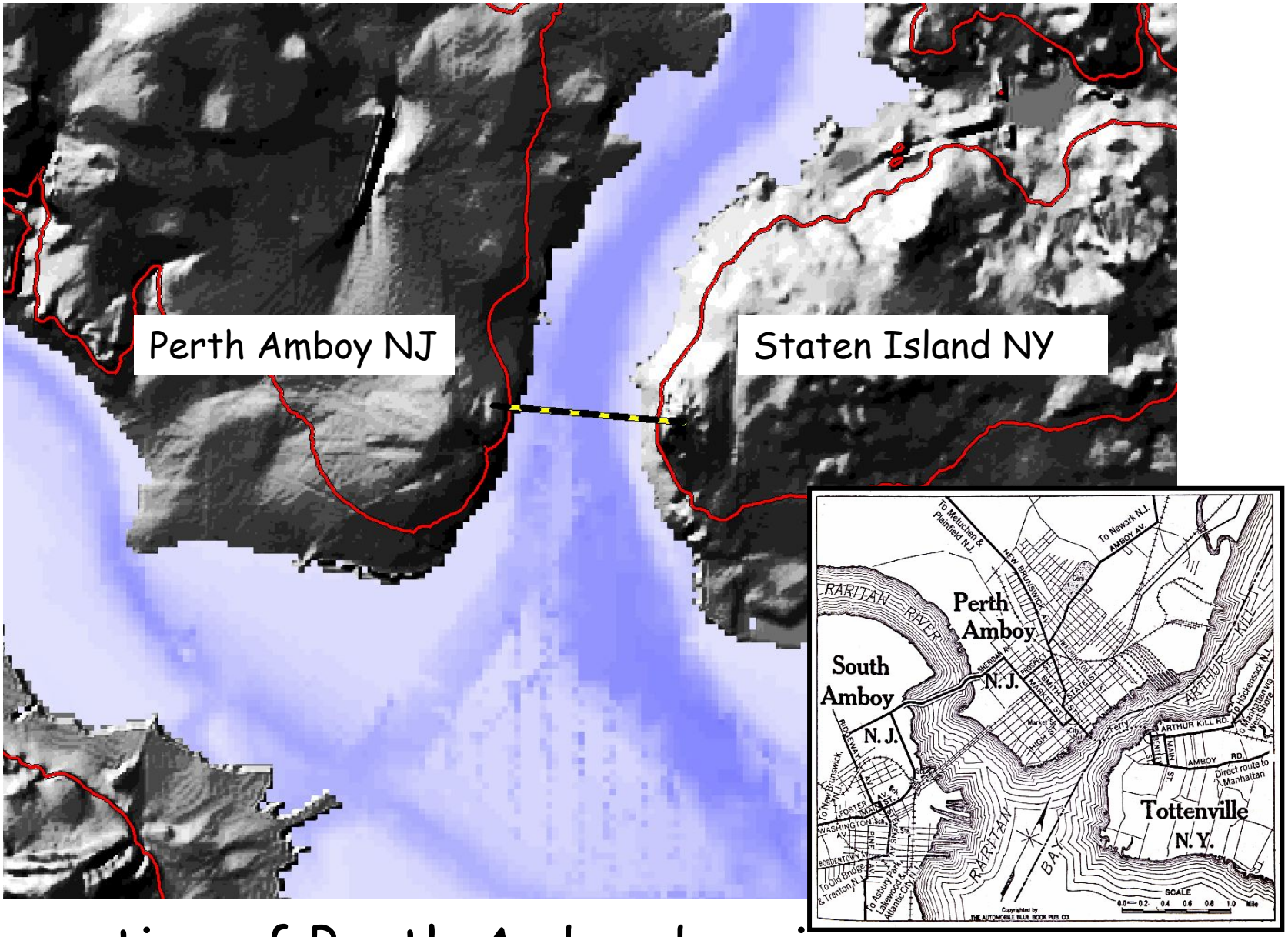
The Narrows

Fig. 22. Water levels with/without barriers for Floyd simulations.

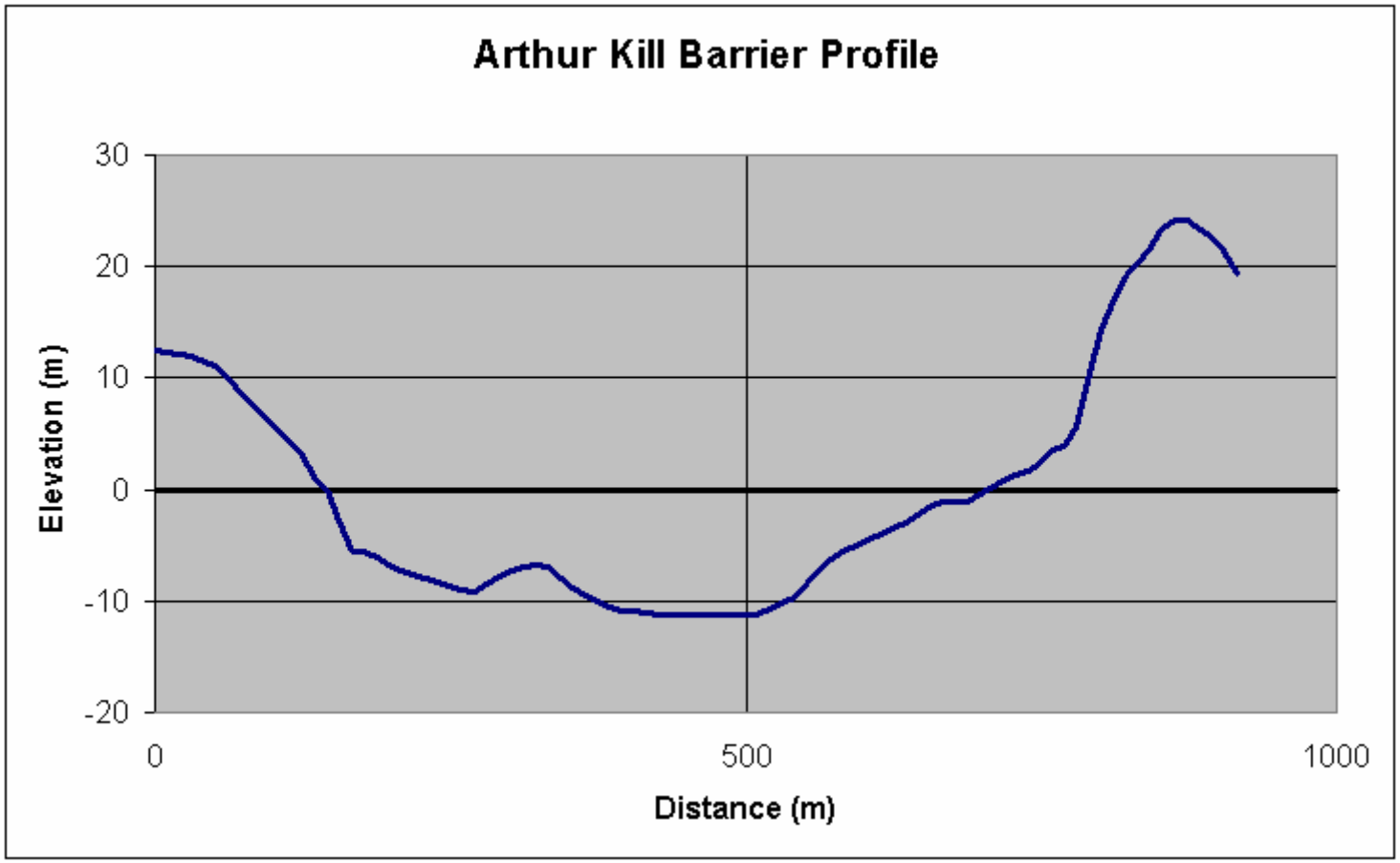


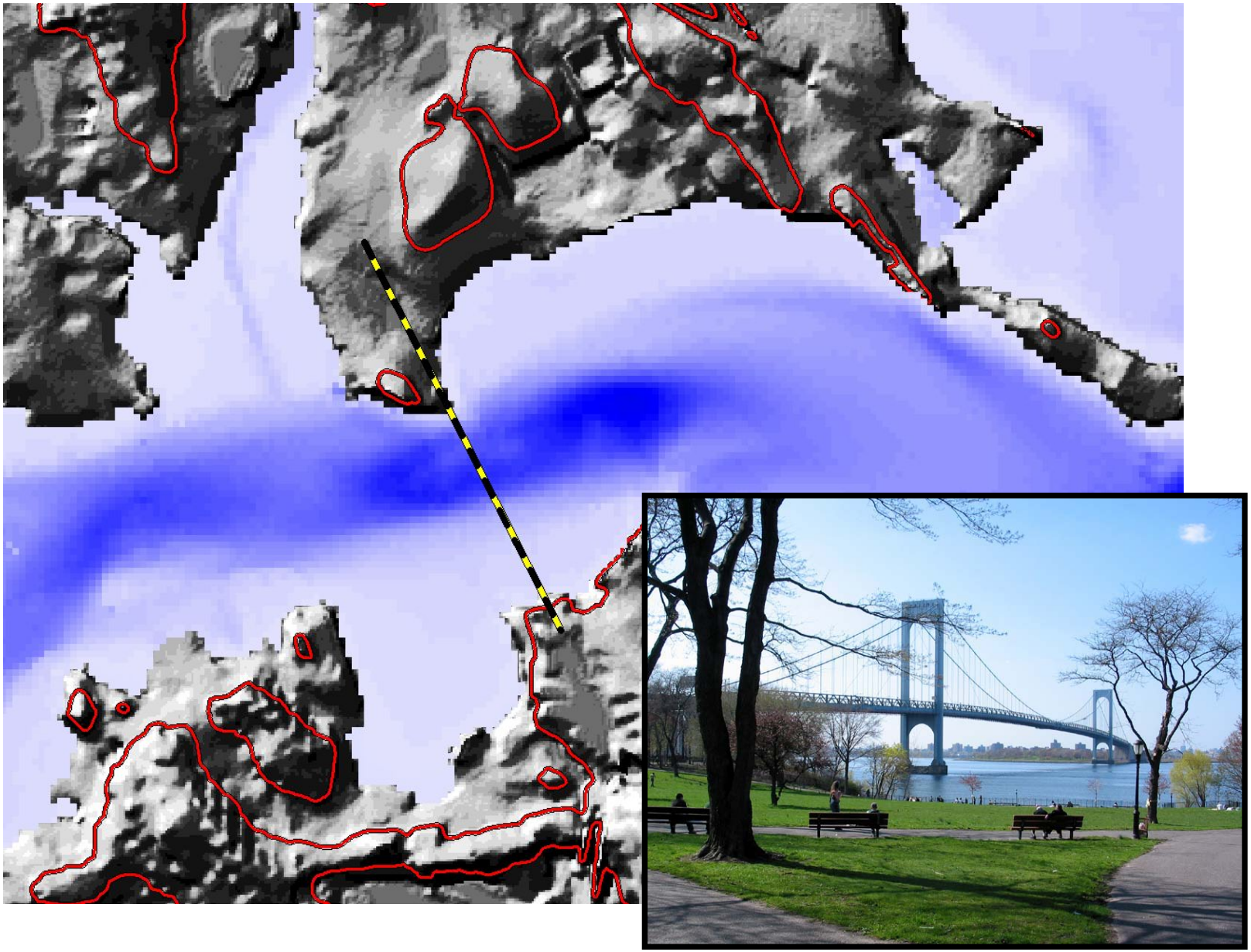
Location of Verrazano Narrows barrier


Verrazano Narrows Bridge Barrier Profile
Elevation (m)
50
40
30
20
10
0
-10
-20
-30
-40
0
500
1000
1500
2000
2500
3000
3500
Distance (m)

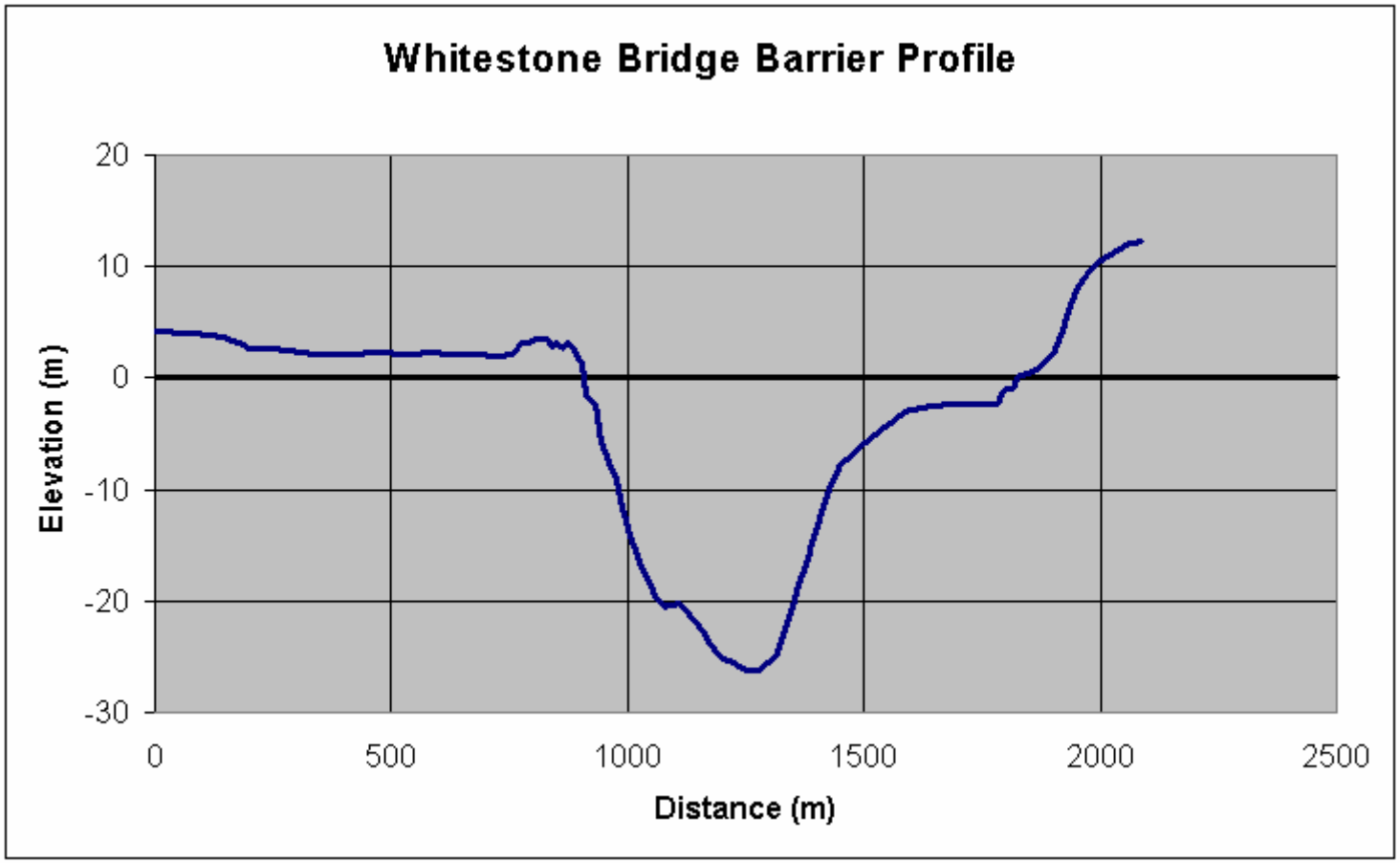


Location of Perth Amboy barrier


Arthur Kill Barrier Profile
30
20
10
0
-10
-20
Elevation (m)
0
500
1000
Distance (m)



Location of Upper East River barrier


Whitestone Bridge Barrier Profile
20
10
0
-10
-20
-30
Elevation (m)
0
500
1000
1500
2000
2500
Distance (m)

Design Criteria - Structural

- Suitable geology
- Alternative barrier configurations
  - fail-safe/slow-die
- Static load on piers (multiple cases)
  - height of barrier
  - relative water elevation inside and outside
- Alternative gate configurations
- Dynamic loads on gates when partly open
- Adjacent infrastructure considerations
- Power requirements

Design Criteria - Environmental

- Effect on harbor flushing
- Effect on water quality
- Effect on sedimentation patterns
- Effect of altered water level on wetlands
- Effect on fish migration

When? Delays between catastrophic events and barrier construction.

Barrier	Flood	Completed	Delay (yr)
New England	1938	1966, 1968	23-27
Thames River	1953	1982	29
Holland 1953		1958, 1986, 1997	1 - 36
Venice	1966	(2011)	44

Comparative Barrier Costs

Barrier	Dates	Cost	Exchange rate then	$ Cost then	Cost index *	2006 cost
Eastern Scheldt	1979-1986	3 billion guilders	3.32 guilders/ $	$900 million	299/159	**$1.7 billion**
Thames River	1973-1984	600 million £	$1.328/£	$800 million	299/153	**$1.6 billion**
East River	1993	$1 billion	---	$1 billion	299/190	**$1.6 billion**
TOTAL						**$5 billion**

*U.S. Bureau of Reclamation Construction Cost Trends Composite Trend

Development Delays

Barrier	Flood	Delay (years)	Start	Construction time (years)	Completion
Providence	1938	23	1961	5	1966
New Bedford	1938	24	1962	4	1966
Stamford	1938	27	1965	4	1969
Hollandse Ijessel	1953	1	1954	4	1958
Eastern Scheldt	1953	14-26	1967-1979	7	1986
Maeslant	1953	36	1989	8	1997
Venice	1966	37	2003	8	(2011)

So……

Q. When do you plan for a flood?

A. Too late?

So Start planning **NOW**!

Conclusions

- Storms are likely to increase in severity and frequency with climate change.
- Sea level will rise slowly but steadily accelerate.
- Storm surge barriers provide a feasible method of protecting the metropolitan infrastructure against storm damage for the next 100-200 years.
- Serious social, political and economic questions arise about whom and what are protected inside barriers *vs.* whom and what are shut out. Protection of Long Island will be extremely costly and probably ineffective.
- Professional community needs to begin studies and urge government agencies to start developing engineering plans and designing environmental studies around storm surge barriers to protect Metropolitan New York.

Acknowledgements

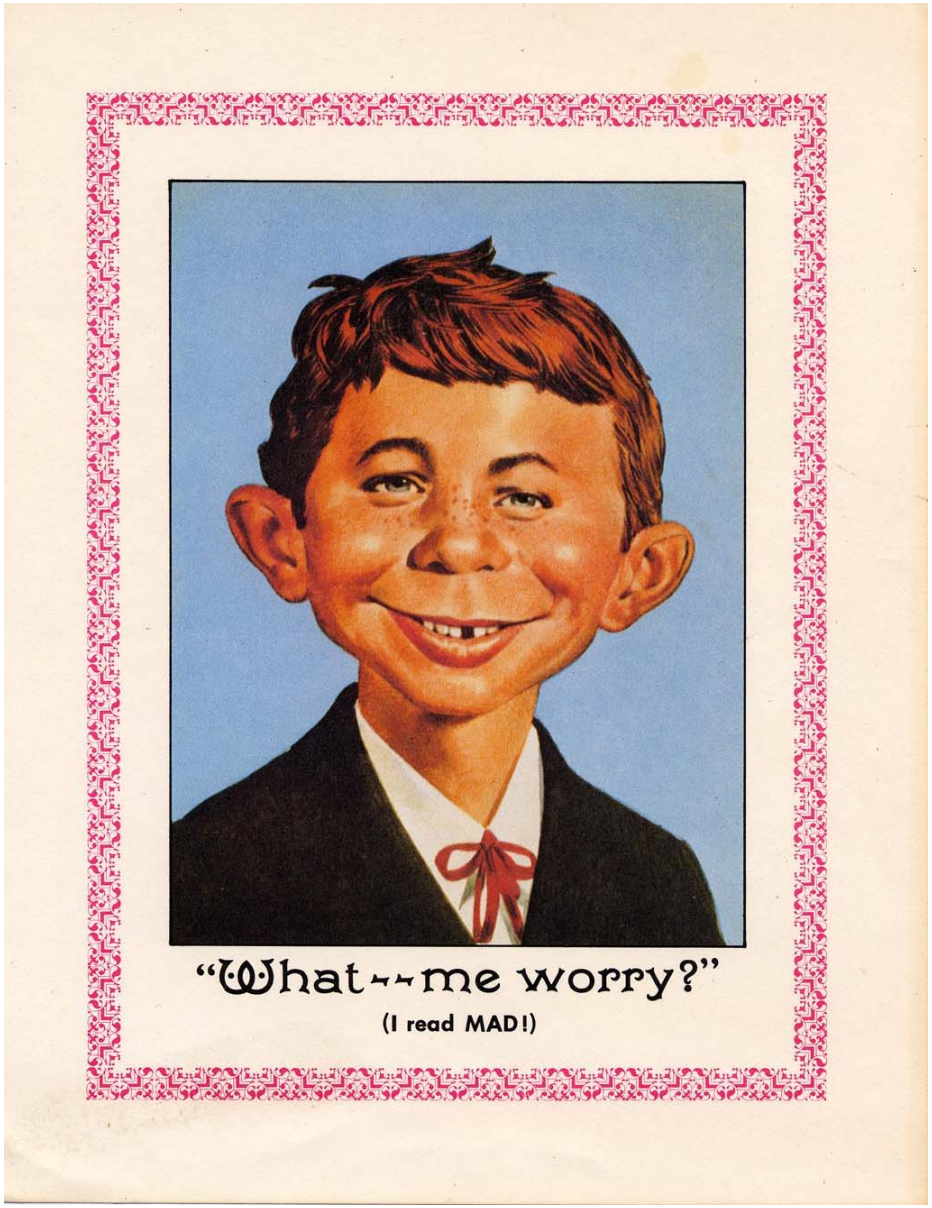
New York City Department of Environmental Protection

HydroQual, Inc.

New York Sea Grant

Eppley Foundation

Marine Sciences Research Center



Thank you!

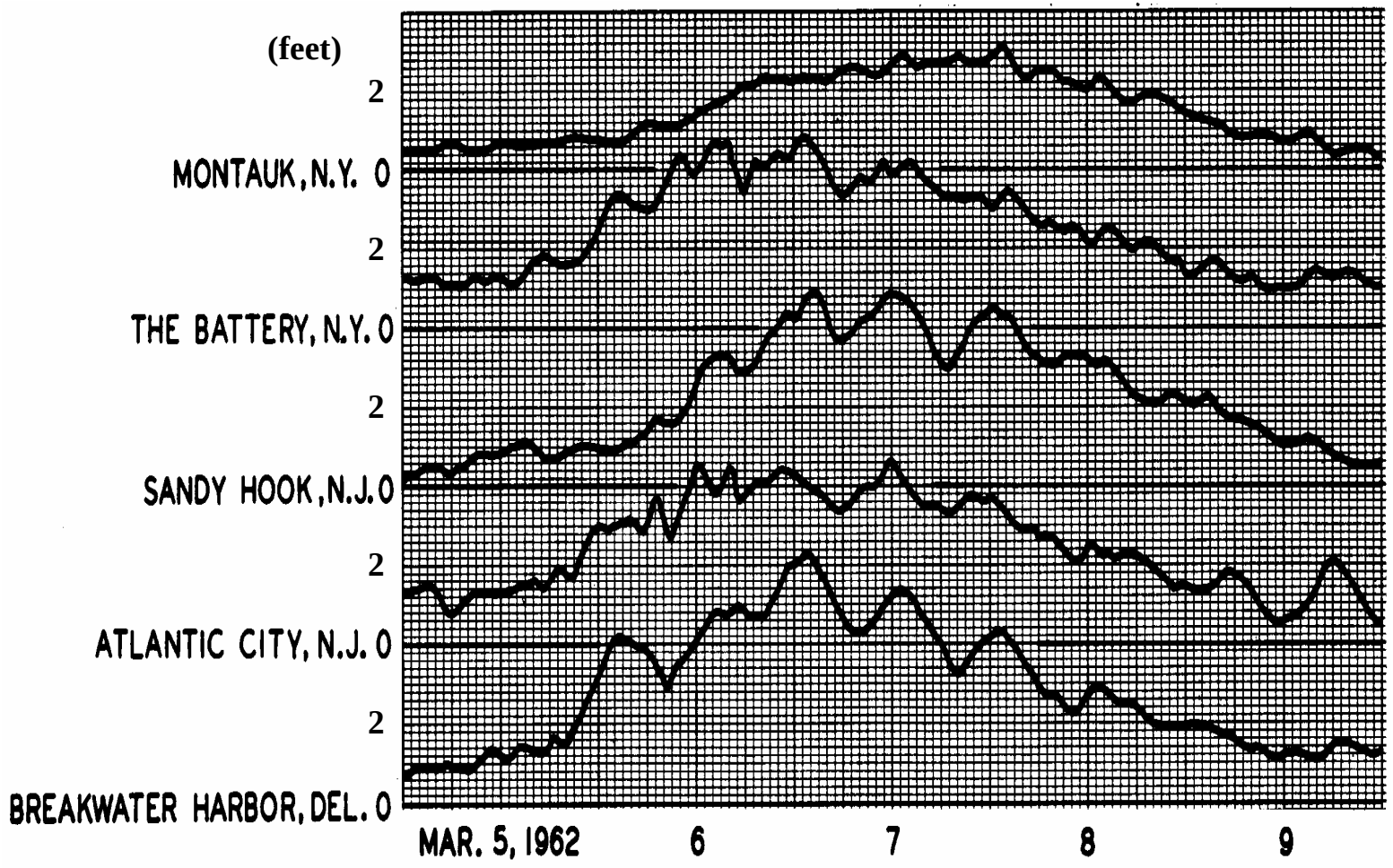
Towards a Predictive Storm Surge Modeling System for the Northeastern Seaboard, USA

Malcolm J. Bowman, Frank S. Buonaiuto, Brian A. Colle, Robert E. Wilson, Robert E. Hunter and Tom Diliberto

Storm Surge Research Group
School of Marine and Atmospheric Sciences
State University of New York at Stony Brook
Stony Brook, NY

Presented at the International Workshop for Numerical Ocean Modeling and Prediction
Taipei, Taiwan, April 23-25, 2008

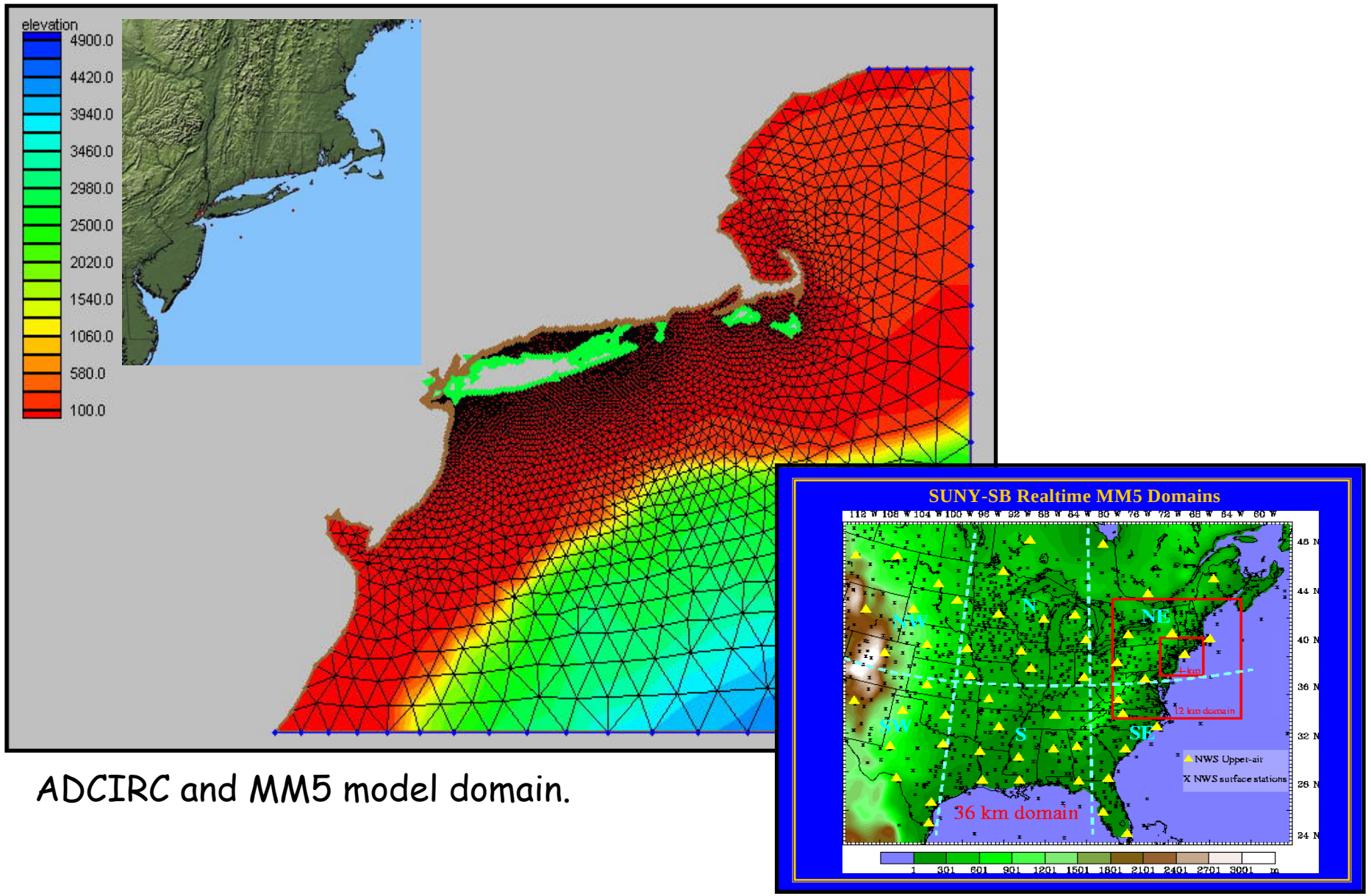
Nor’easter Storm Surge



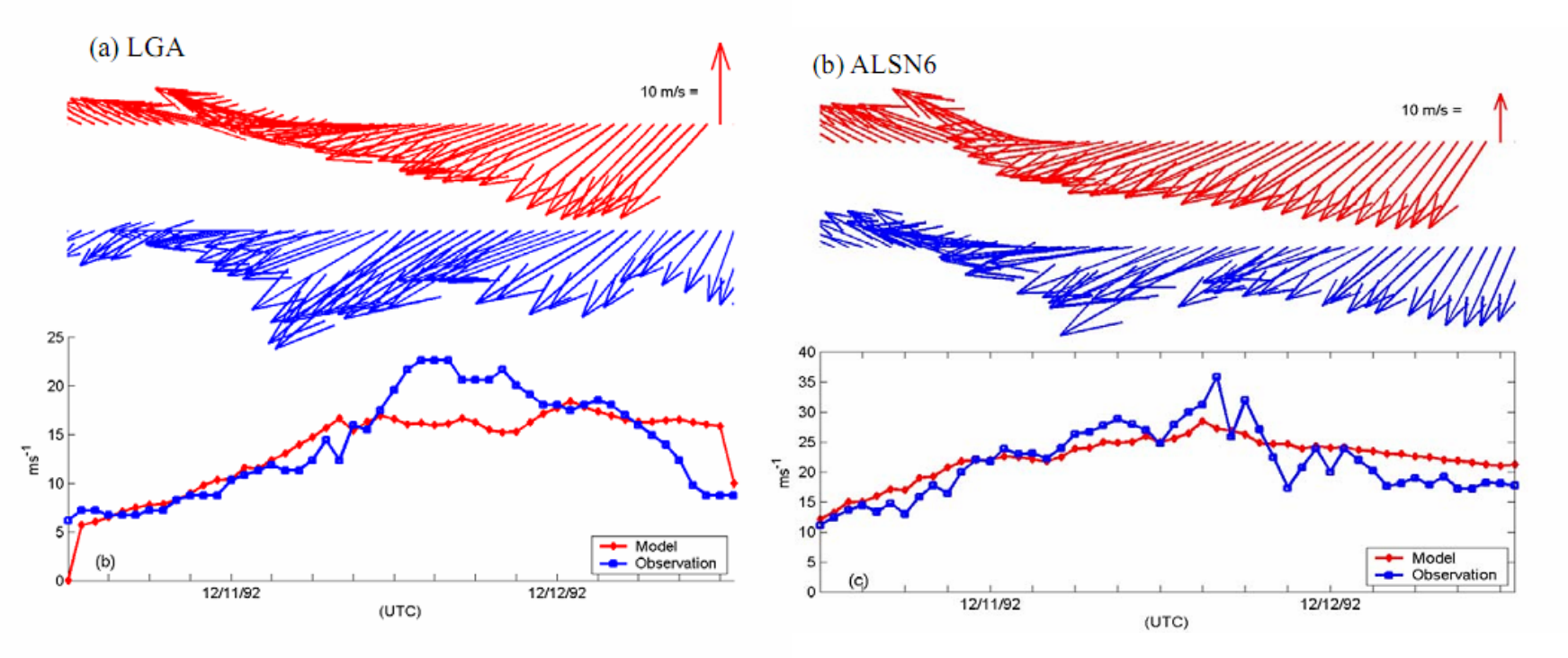
5-8 March 1962 storm

Source: N.A. Pore and C.S Barrientos, Storm Surge, 1976.

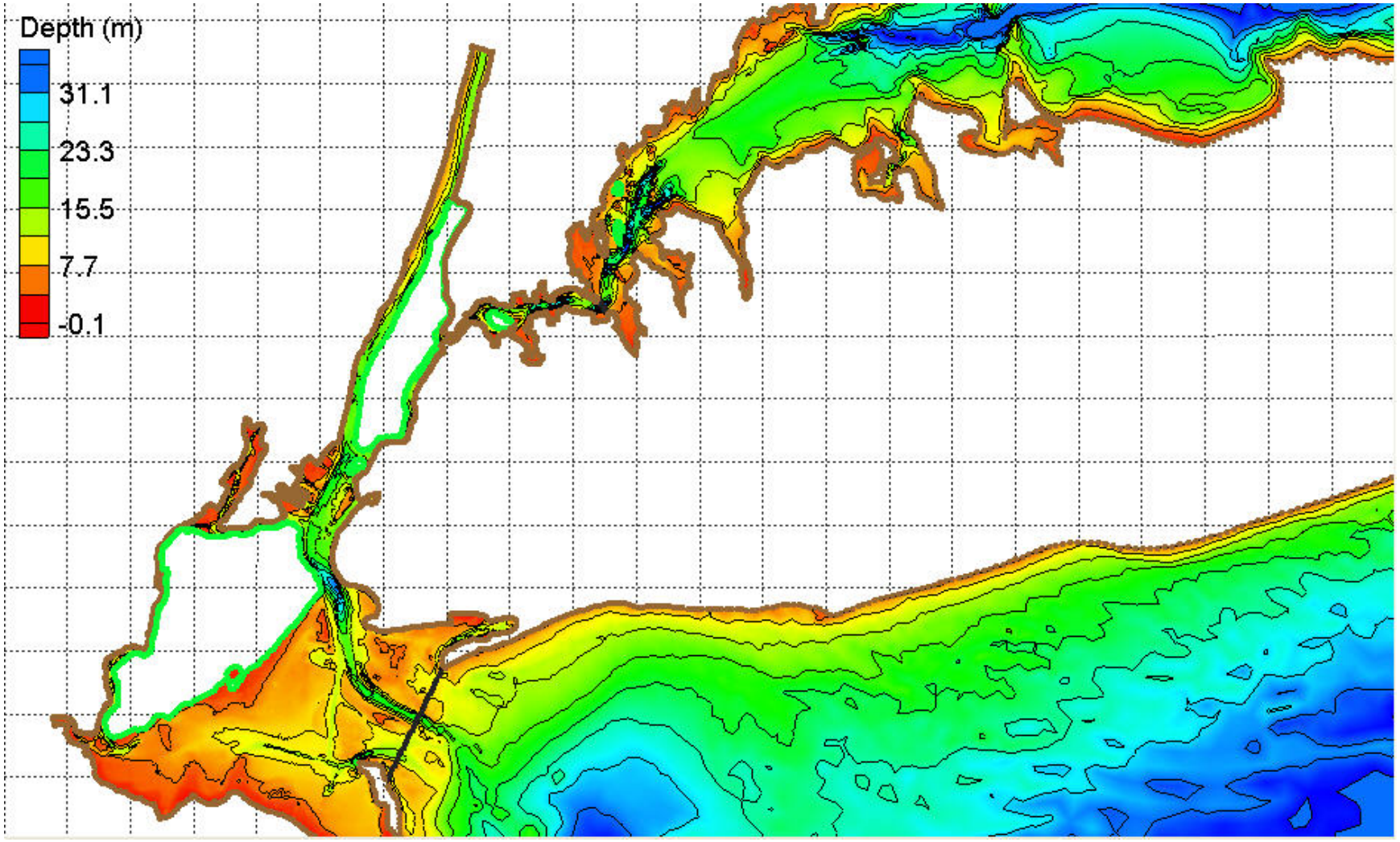
Overview of Modeling System



ADCIRC and MM5 model domain.



Dec 1992 storm. Meteorological wind time series for (a) LGA and (b) ALSN6 showing wind speed (m s^{-1}) for the observed (red) and 12-km MM5 (blue) and wind vectors.



Model bathymetry for a segment of the ADCIRC/FVCOM grid

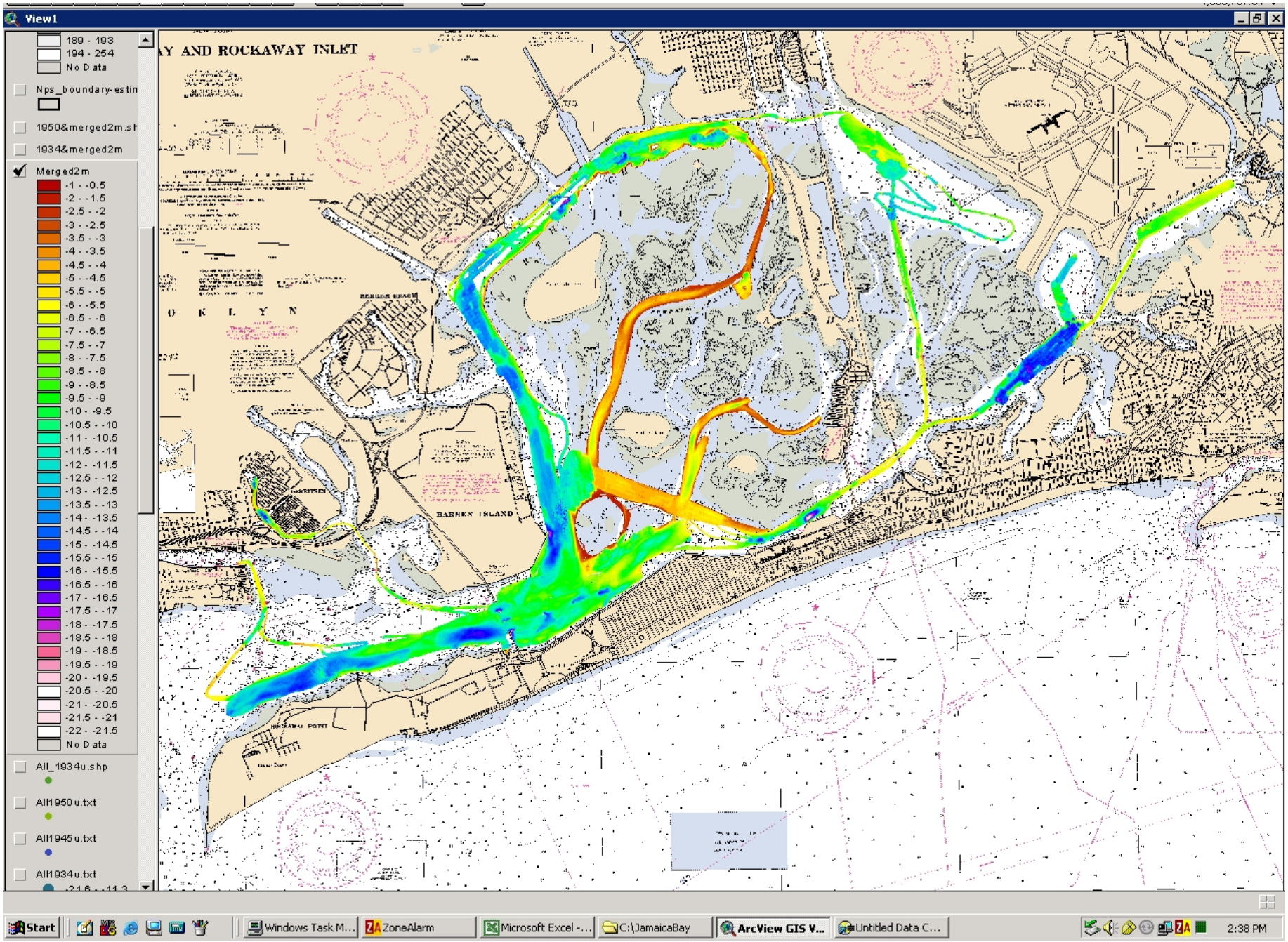
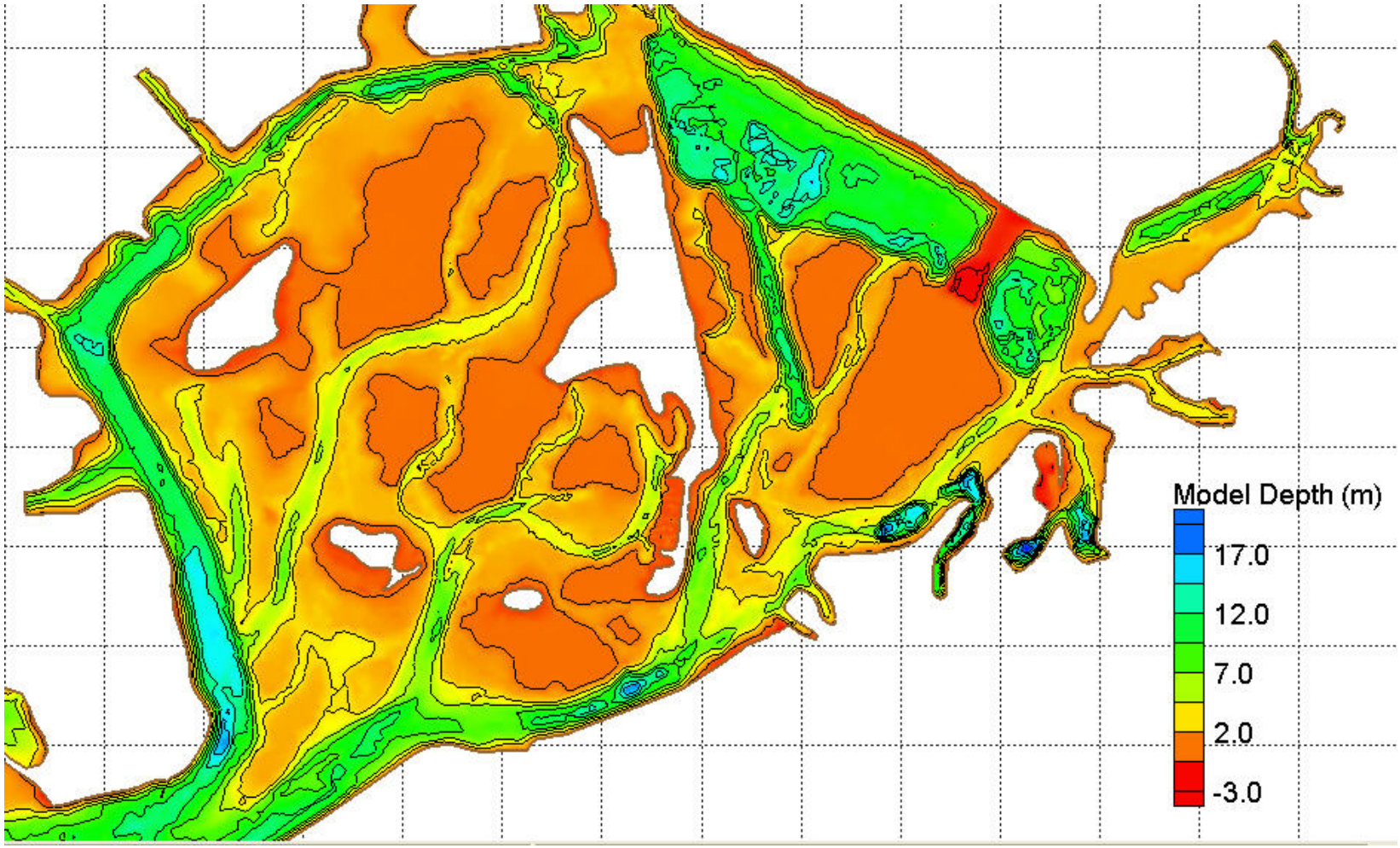
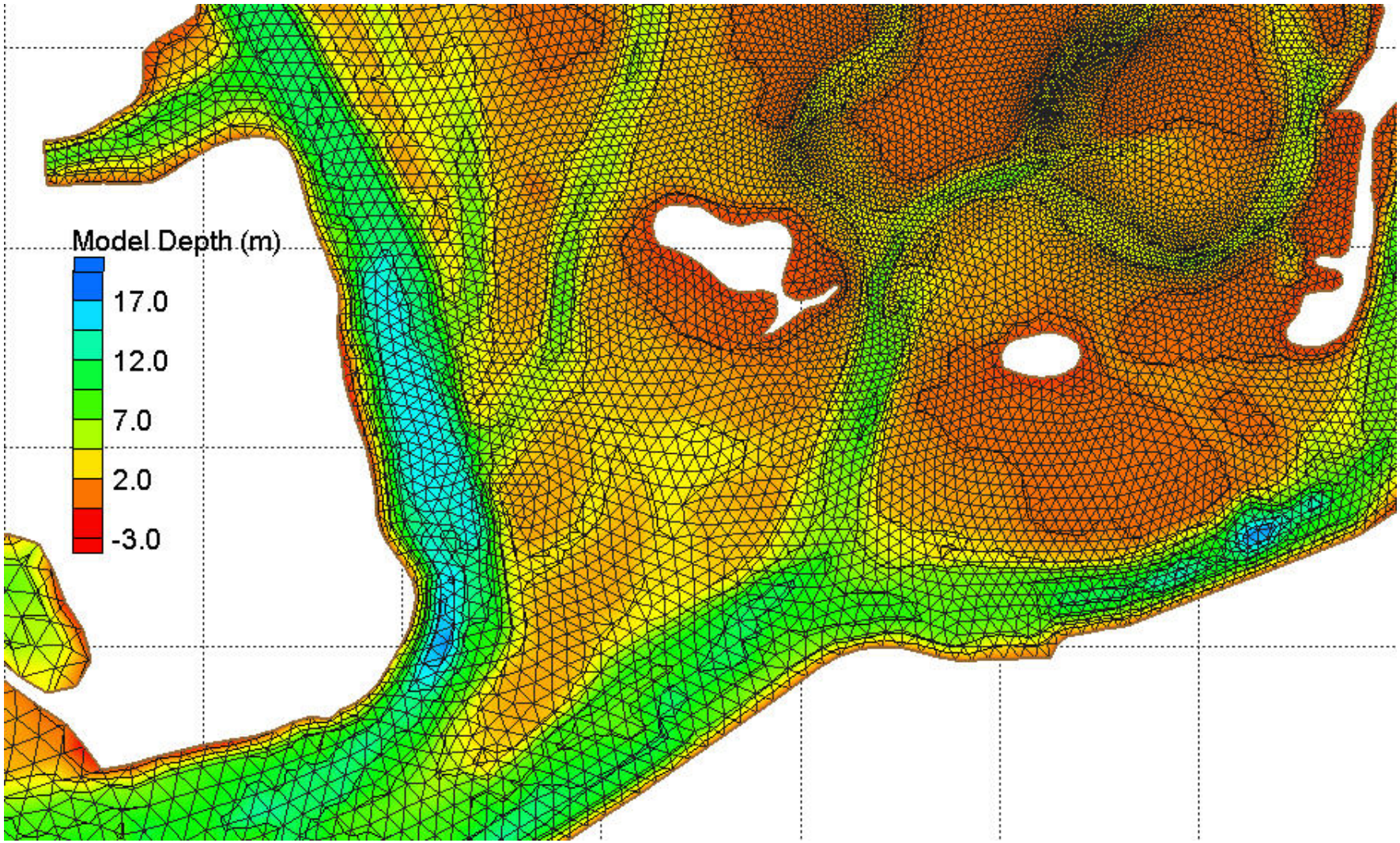


Figure 2. MSRC multi-beam data for 2000 and 2003.



Example of model domain and bathymetry for Jamaica Bay using SMS version 8.1

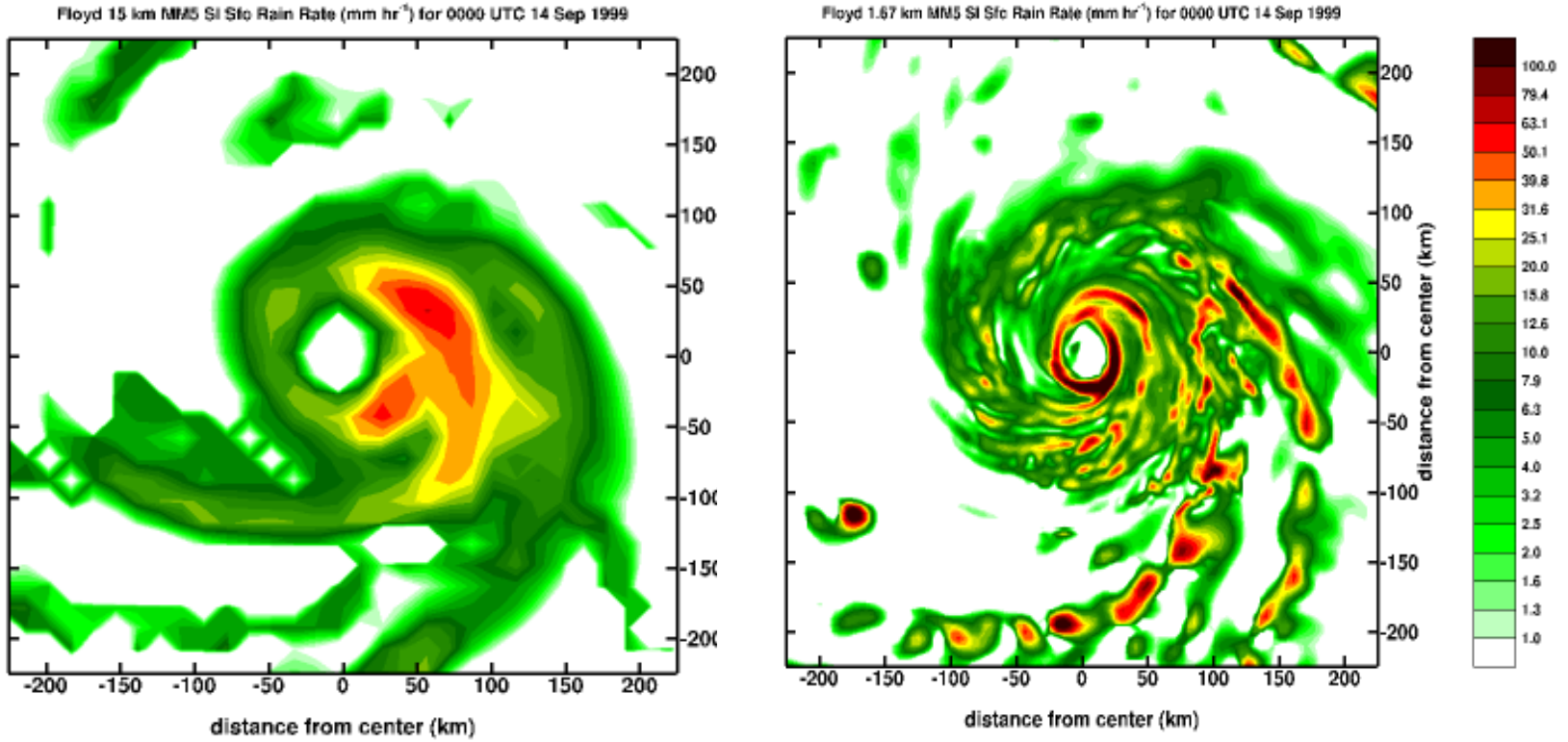


Insight into the resolution available to ADCIRC and FVCOM (Jamaica Bay).

OTHER FORECAST DIFFICULTIES FOR TROPICAL SYSTEMS: Impact of Horizontal Resolution

15-km grid spacing

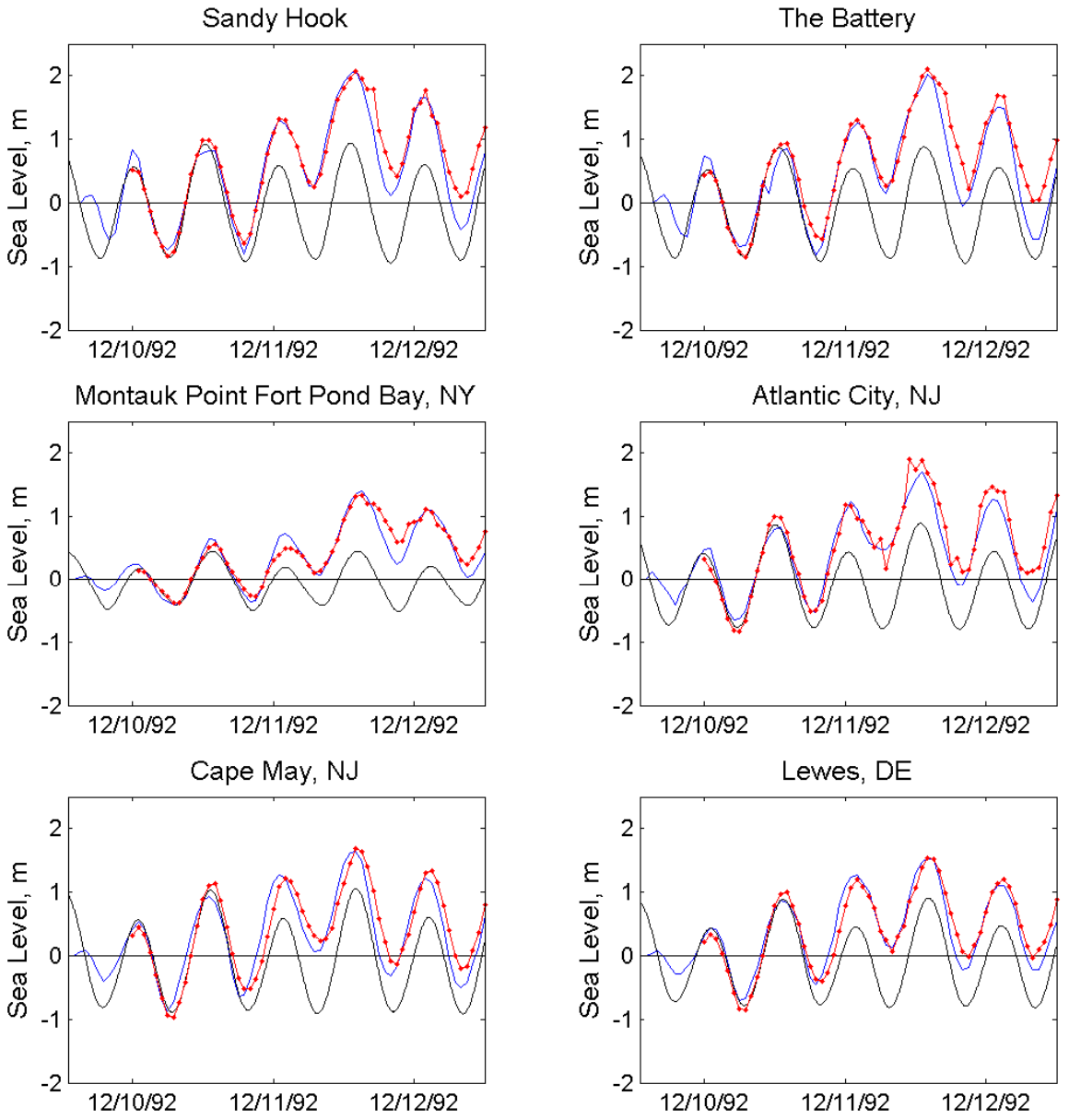
1.67-km grid spacing

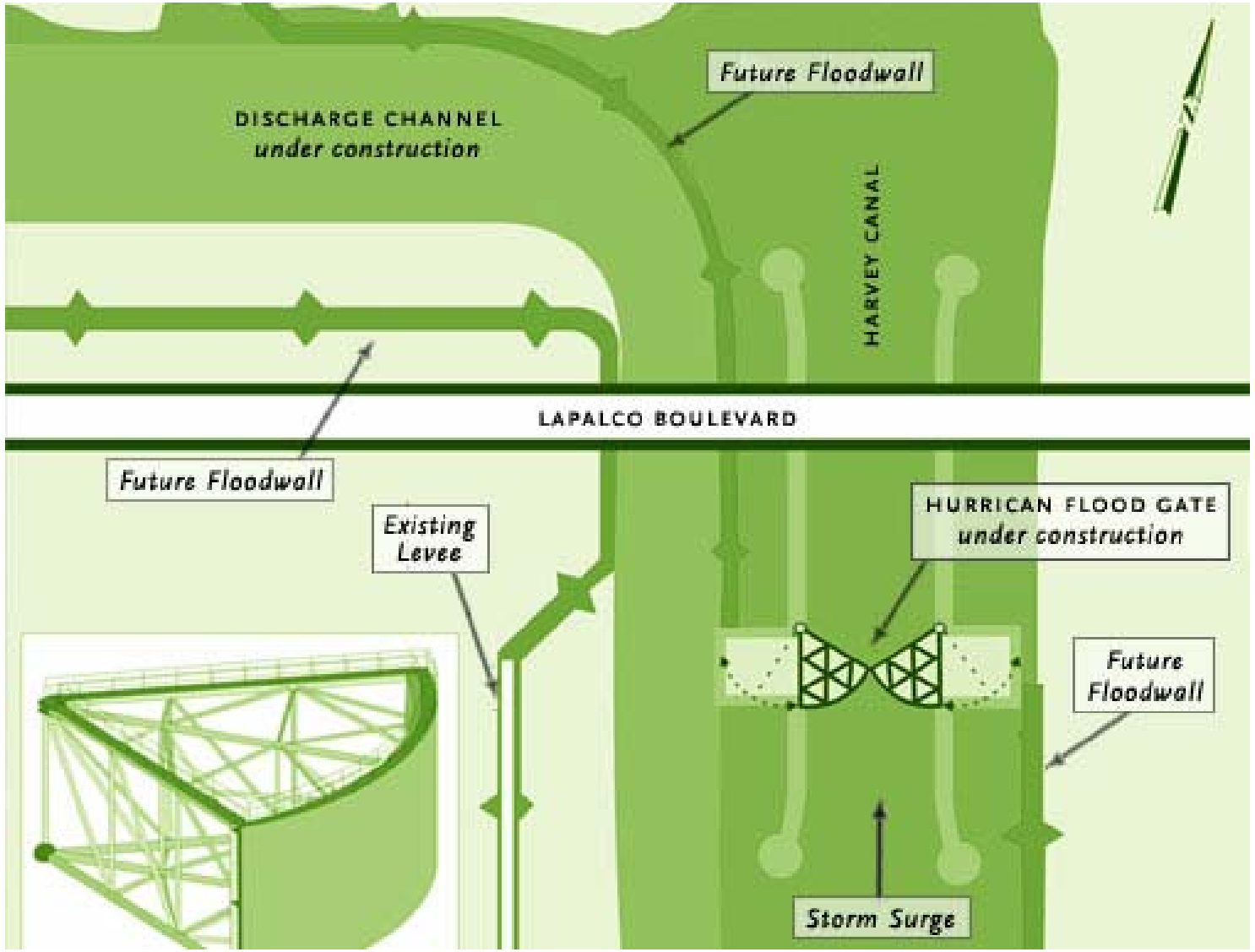


Black = Ast. Tide

Blue = Model Hindcast

Red = NOAA Obs.

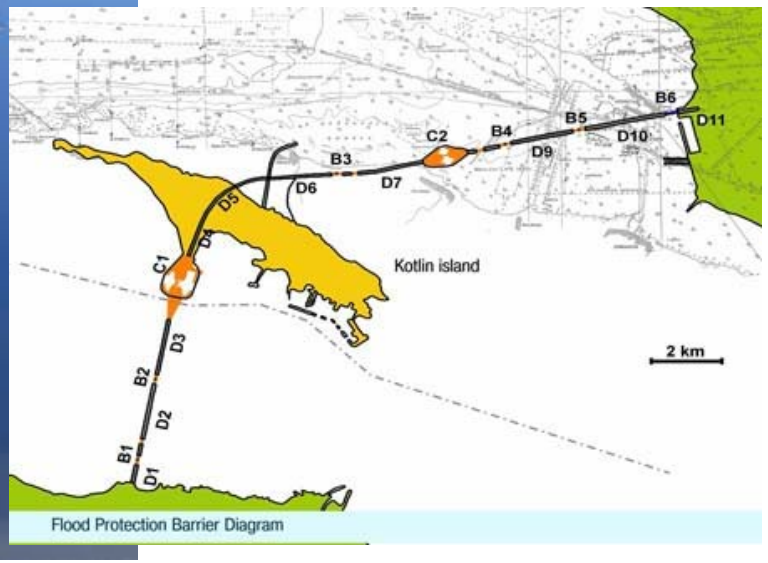




http://www.pbs.org/wgbh/nova/orleans/proo-nf.html

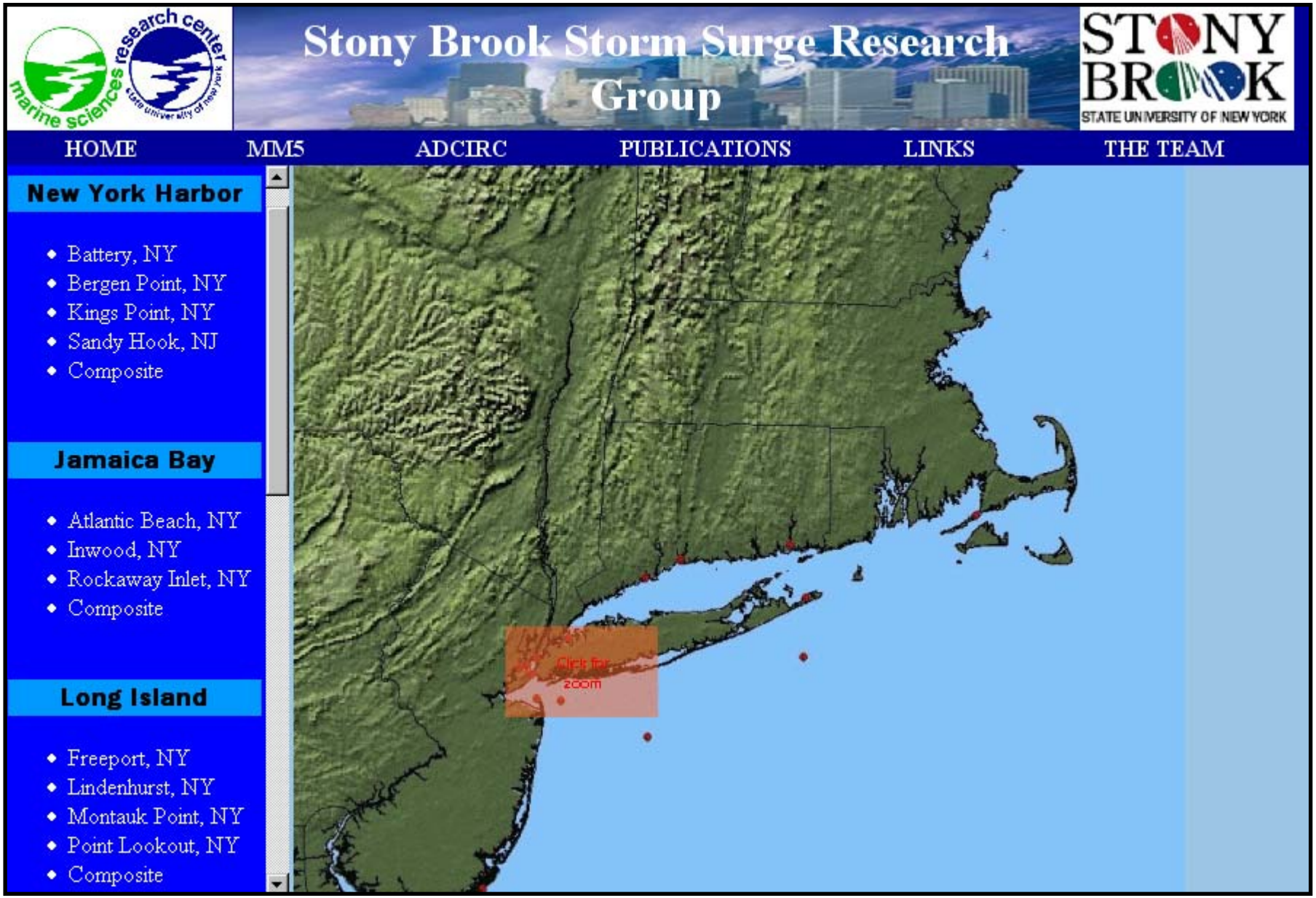
Map of St Petersburg and the location of the Flood Protection Barrier (FPB) in Neva Bay. The FPB is 25 km long, across the island of Kotlin. To the east is the Gulf of Finland, to the east is Neva Bay. The Neva River flows through St Petersburg into Neva Bay.

www.wldelft.nl/proj/pdf/3uk00167.scherm.pdf



In 1980, the Soviet government began to erect a pair of massive storm surge barriers. With the project nearly 65 percent complete, financial problems and environmental concerns brought it to halt less than 10 years later.

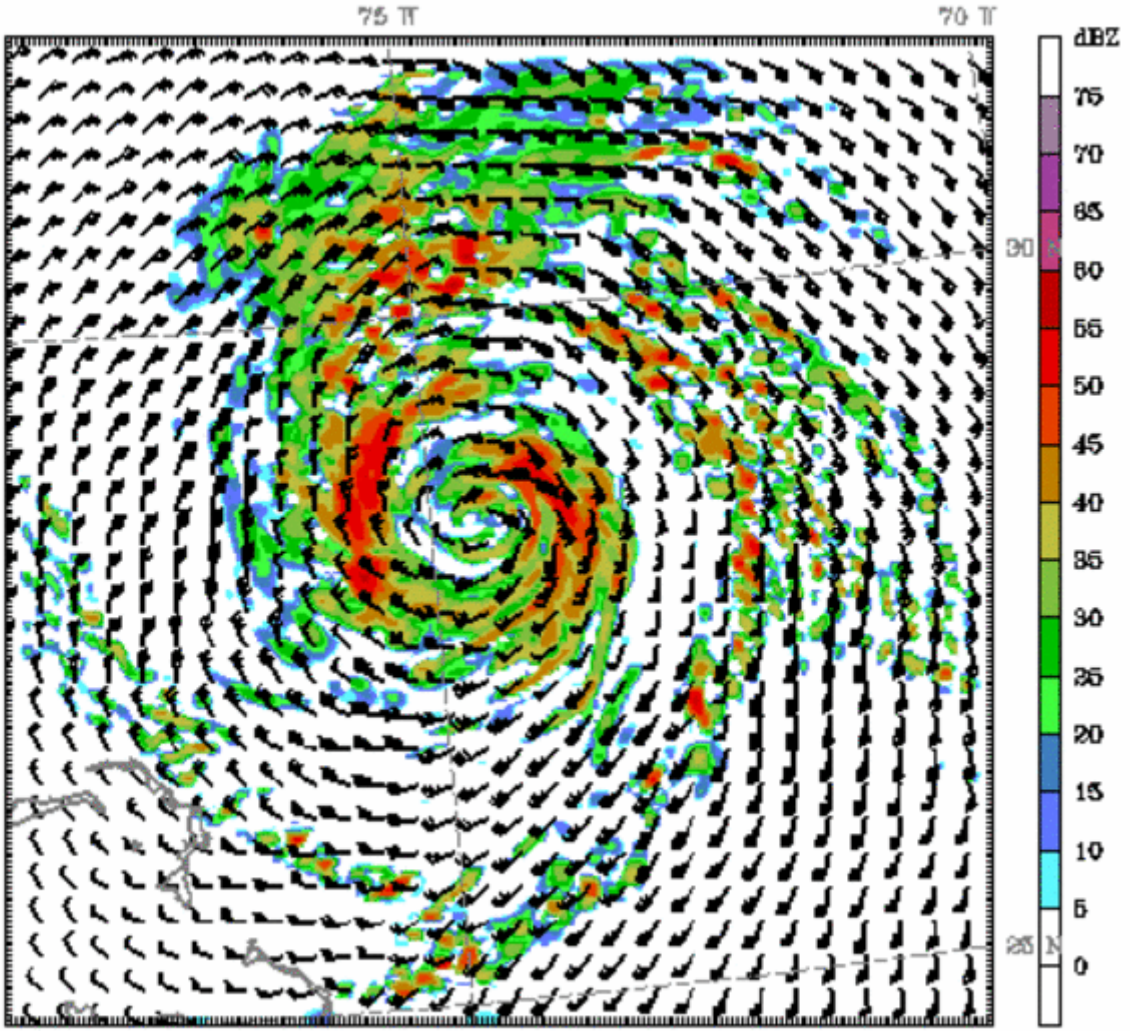
In 2003, with new foreign funding and a plan to keep the river healthy, the project was revived. Construction is now under way to finish the barriers with a $245M loan from the European Bank.



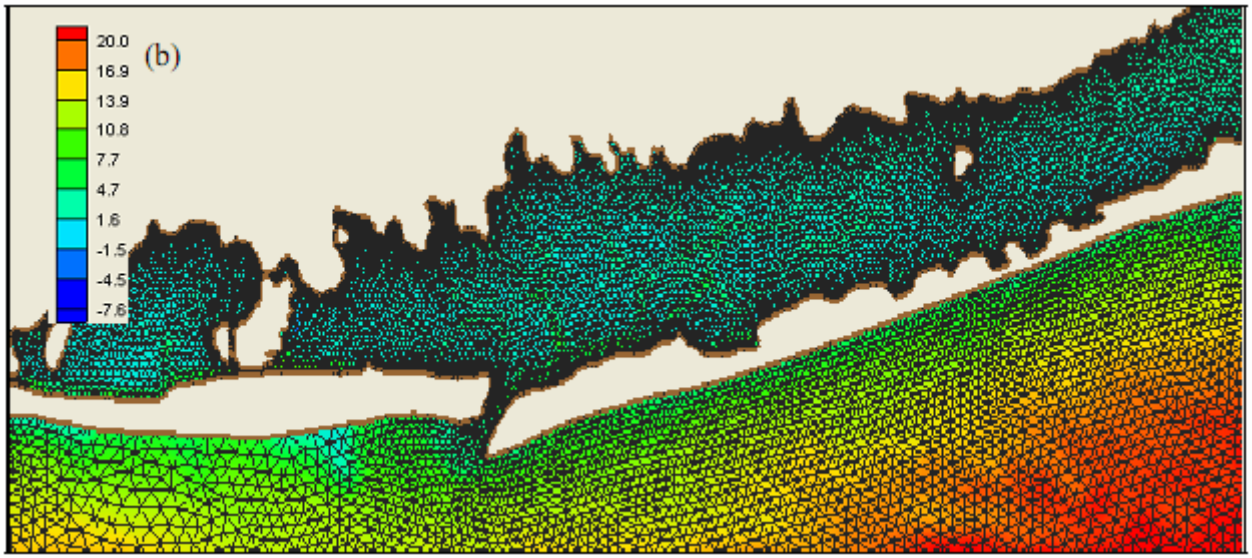
http://stormy.msrc.sunysb.edu/

09 1985 NARR WRF Gloria
Fcst: 6 h
Reflectivity
Wind at 30m(full barb = 10knots)

Init: 00 UTC Thu 26 Sep 85
Valid: 06 UTC Thu 26 Sep 85 (02 EDT Thu 26 Sep 85)
at k-index = 32



Model Info: V2.2 M No Cu Lin et al Ther-Diff 4.0 km, 32 levels, 10 sec



(b) A portion of the ADCIRC domain for the blue box in (a) along the south shore of Long Island.