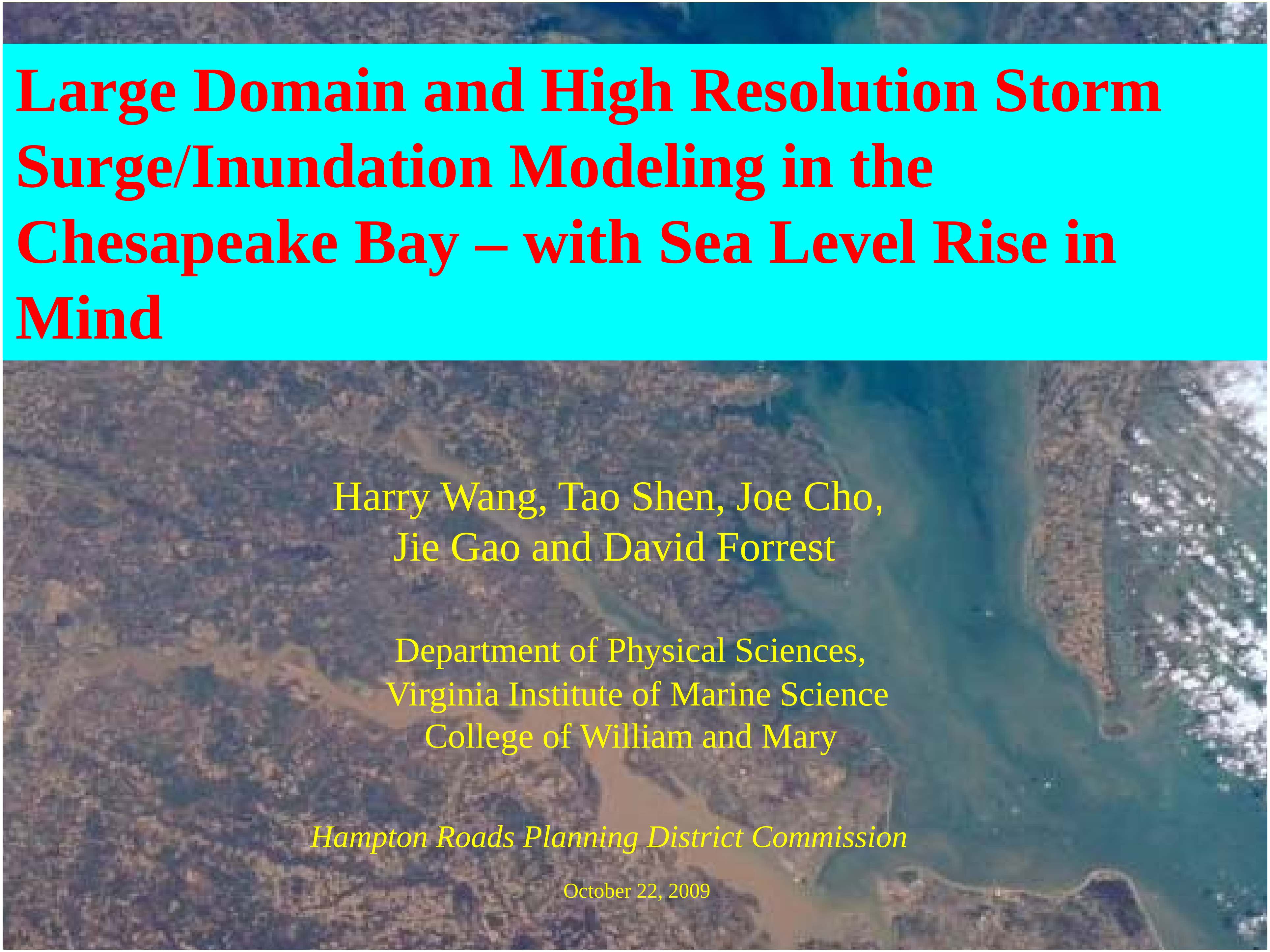
Large Domain and High Resolution Storm Surge/Inundation Modeling in the Chesapeake Bay – with Sea Level Rise in Mind

Harry Wang, Tao Shen, Joe Cho,
Jie Gao and David Forrest

Department of Physical Sciences,
Virginia Institute of Marine Science
College of William and Mary

Hampton Roads Planning District Commission

October 22, 2009



Natural Hazards (2006)
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Vulnerability of Hampton Roads, Virginia to Storm-Surge Flooding and Sea-Level Rise

LISA R. KLEINOSKY, BRENT YARNAL* and ANN FISHER
Center for Integrated Regional Assessment, The Pennsylvania State University, University Park, PA, 16802, USA

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Abstract. Sea-level rise will increase the area covered by hurricane storm surges in coastal zones. This research assesses how patterns of vulnerability to storm-surge flooding could change in Hampton Roads, Virginia as a result of sea-level rise. Physical exposure to storm-surge flooding is mapped for all categories of hurricane, both for present sea level and for future sea-level rise. The locations of vulnerable sub-populations are determined through an analysis and mapping of socioeconomic characteristics commonly associated with vulnerability to environmental hazards and are compared to the flood-risk exposure zones. Scenarios are also developed that address uncertainties regarding future population growth and distribution. The results show that hurricane storm surge presents a significant hazard to Hampton Roads today, especially to the most vulnerable inhabitants of the region. In addition, future sea-level rise, population growth, and poorly planned development will increase the risk of storm-surge flooding, especially for vulnerable people, thus suggesting that planning should steer development away from low-lying coastal and near-coastal zones.

Key words: storm-surge flooding, hurricanes, sea-level rise, climate change, coastal hazards, coastal development, vulnerability

1. Introduction

Global sea-level rise is a major impact of human-induced climate change. The Intergovernmental Panel on Climate Change (IPCC) projects a global sea-level rise of 48 cm over the next century, with an uncertainty range of 9–88 cm, resulting from thermal expansion of the oceans and glacial melt (Church and Gregory, 2001). Sea-level rise will be worse in regions experiencing subsidence. For example, Najjar *et al.* (2000) estimated that the coastline of the United States Mid-Atlantic region is sinking at the rate of about 2 mm per year due to crustal warping (Walker and Coleman, 1987), sediment compaction (Psuty, 1992; Nicholls and Leatherman, 1996), and groundwater withdrawal (Leatherman *et al.*, 1995). Because shorelines with

* Author for correspondence: Phone: +1-814-863-4894; Fax: +1-814-863-7943; E-mail: alibar@eesi.psu.edu

A NUMERICAL MODELING STUDY ON BAROTROPIC AND BAROCLINIC RESPONSES OF THE CHESAPEAKE BAY TO HURRICANE EVENTS

A Dissertation

Presented to

The Faculty of the School of Marine Science

The College of William and Mary in Virginia

In Partial Fulfillment

Of the Requirements for the Degree of

Doctor of Philosophy

by

Kyoung-Ho Cho

2009

Development of a Storm Surge Model Using a High-Resolution Unstructured Grid over a Large Domain

A Thesis

Presented to

The Faculty of the School of Marine Science

The College of William and Mary in Virginia

In Partial Fulfillment

Of the Requirements for the Degree of

Master of Science

by Tao Shen

2009

Outline

- Hampton Road sea level rise estimates and potential impact
- A reliable tools: A class of unstructured grid hydrodynamic models (using semi-implicit, Eulerian-Lagrangian schemes that are efficient, robust, and reliable).
- Coupled with atmospheric forecast model for ensemble forecasting
- The inundation simulation in the greater Hampton Road and sea level rise scenario

VIMS

Relative Sea Level Rise Along the East Coast of North America

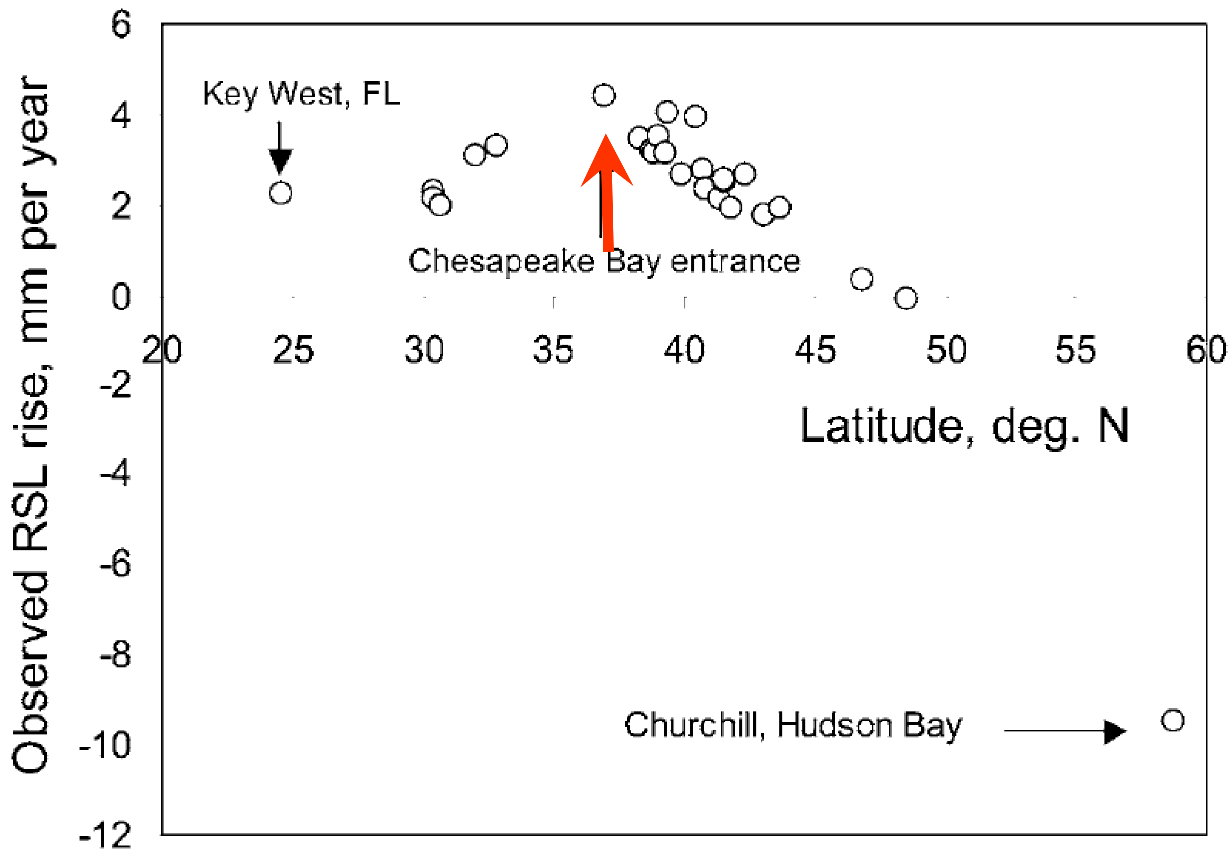


Figure 2. Relative sea level rise rates from Hudson Bay, Canada to Key West, Florida.

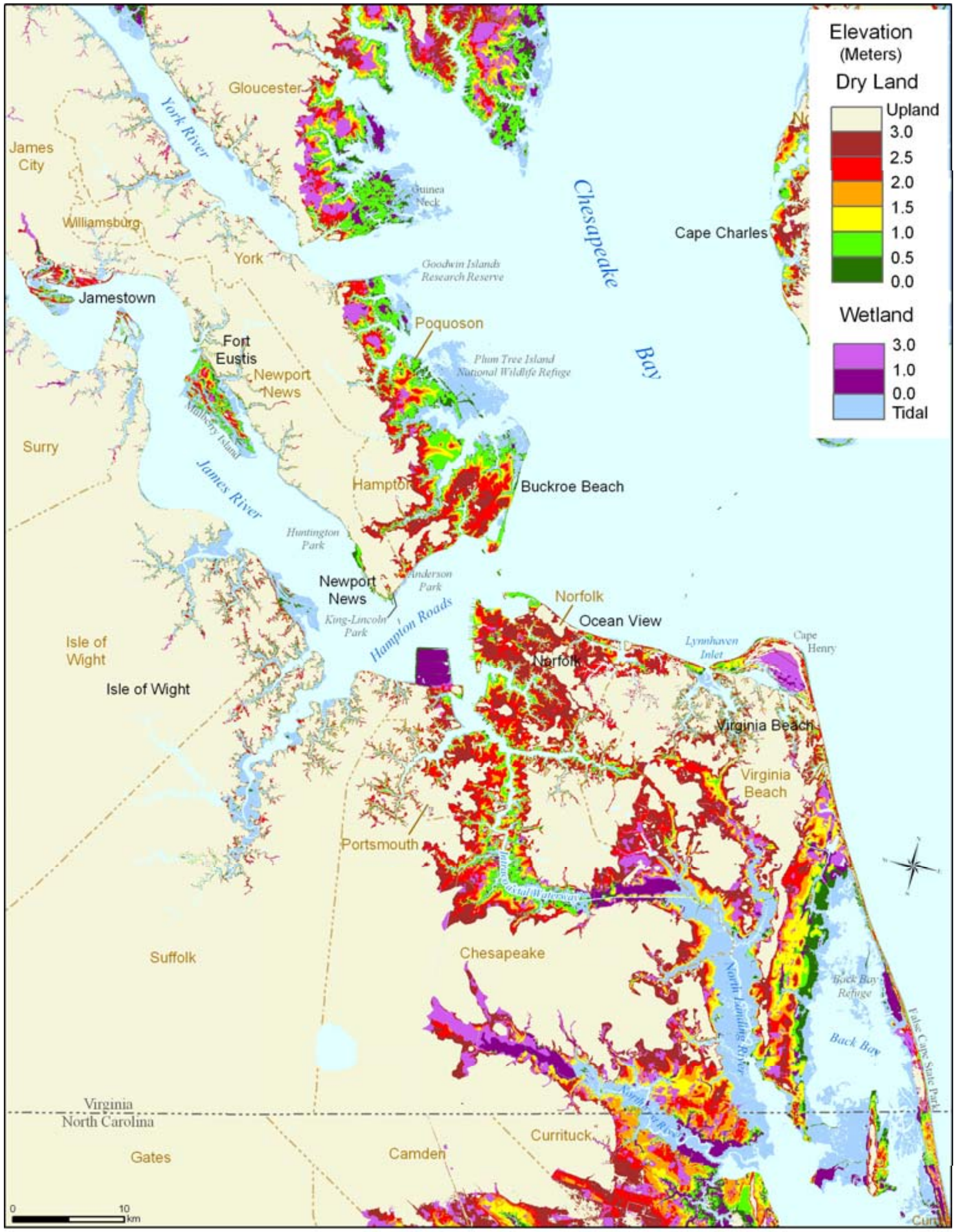
From Zhang et al. (2004) Climatic Change 64: 41–58.

Hampton Roads Inundation Estimates Under Different Sea Level Rise Scenarios

→Extent of flooding is a function of:
- *height of water*
- *land elevation*
- *land relief*

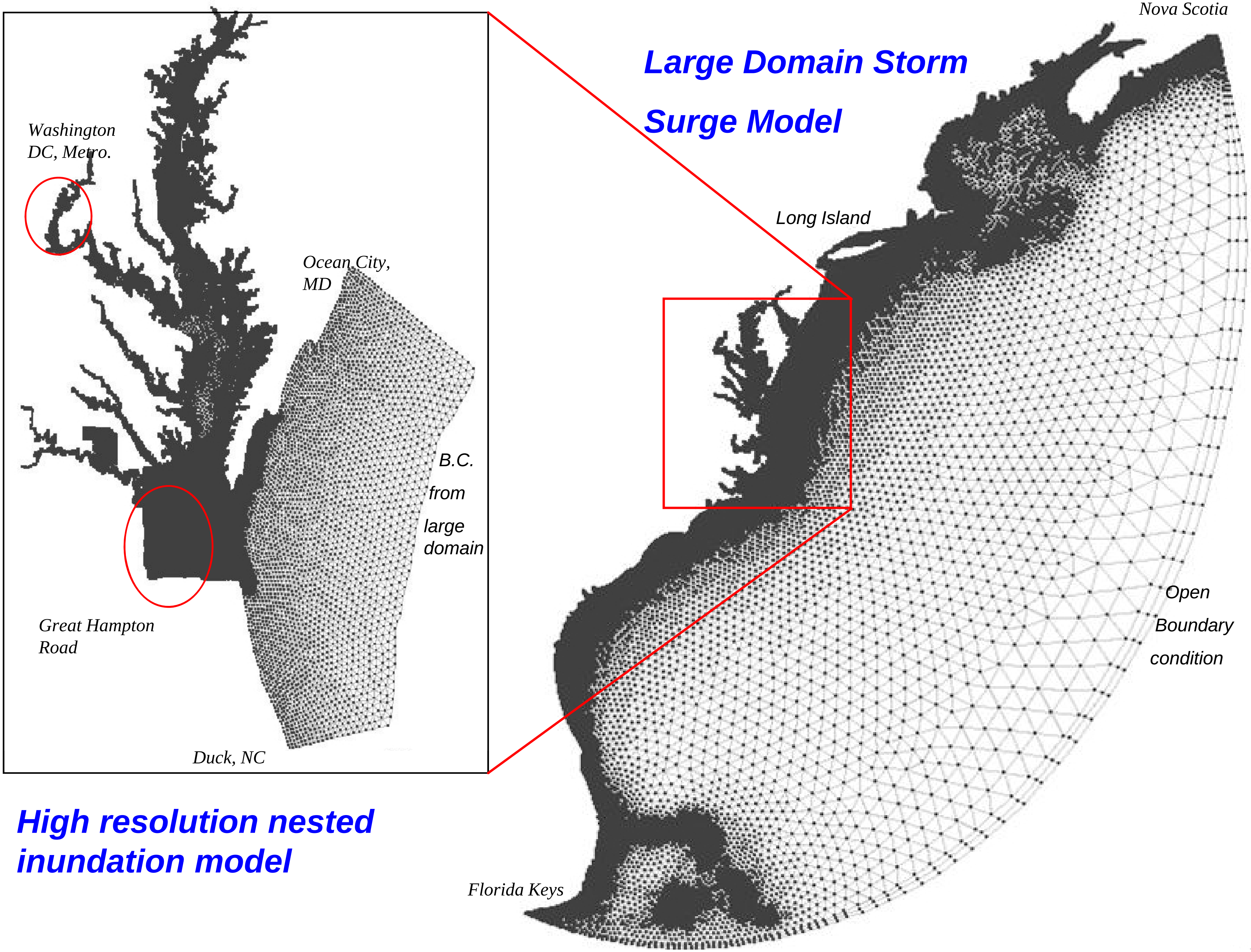
→With increasing sea level, additional flooding from storm surge effects will be greater than previously
- smaller storms will have equivalent destruction potential as larger storms pre-SLR

→Important implications for both human populations as well as living resources and coastal environments

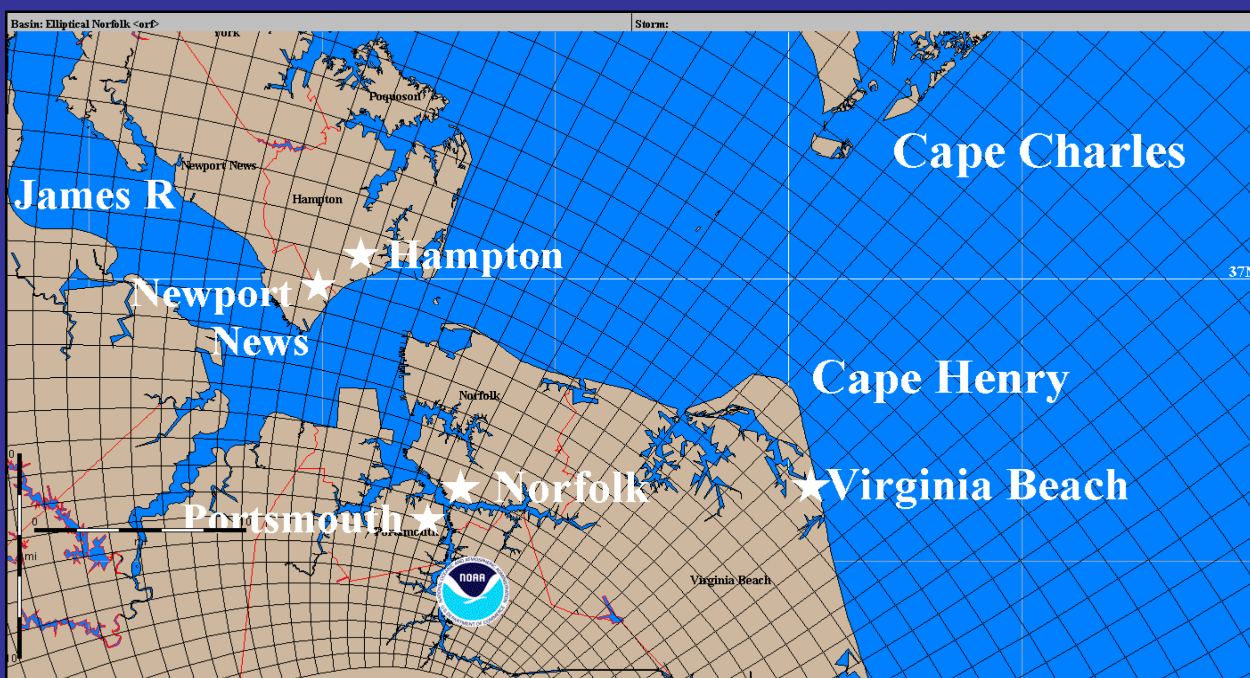


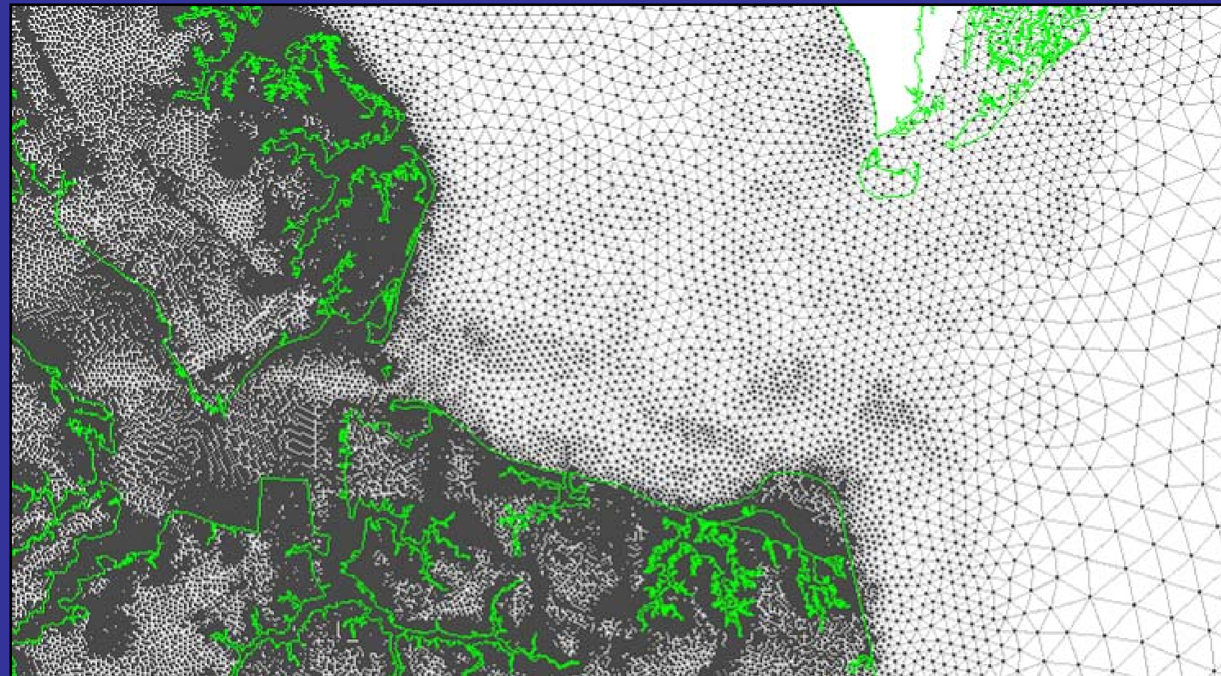
Elevations of Land Close to Sea Level
Elevations are above spring high water, which is the average high tide during new and full moons, and approximately the inland boundary of tidal wetlands. This map is a general graphical representation of elevations in the area depicted, not designed to estimate the precise elevations at specific locations. Actual elevations at specific locations may be 75 cm above or below the elevation shown.
Source: J.G. Titus and J Wang. 2008. "Maps of Lands Close to Sea Level along the Mid-Atlantic Coast". US Environmental Protection Agency.

From Titus and Wang (2008) EPA.


Large Domain Storm
Surge Model
Nova Scotia
Long Island
Washington
DC, Metro.
Ocean City,
MD
B.C.
from
large
domain
Great Hampton
Road
Duck, NC
Open
Boundary
condition
Florida Keys
High resolution nested
inundation model

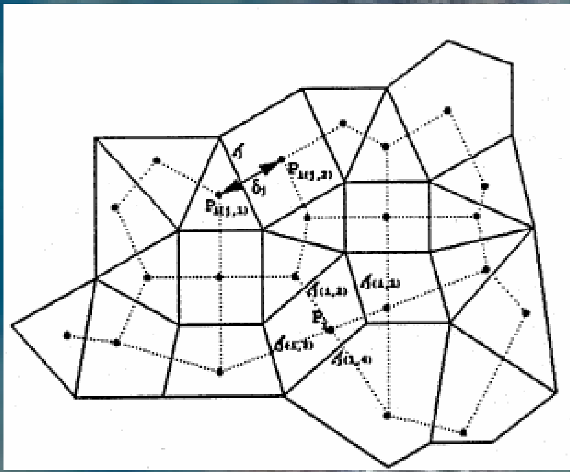
SLOSH Model Grid





VIMS Model Grid

A Class of Unstructured Grid Model using Semi-implicit, Eulerian-Lagragian Schemes



ELCIRC (Eulerian Lagrangian Circulation)

SELFE (Semi-Implicit Eulerian Lagrangian, Finite Element)

UnTRIM (Unstructured grid, Tidal Residual Intertidal Mudflat) models

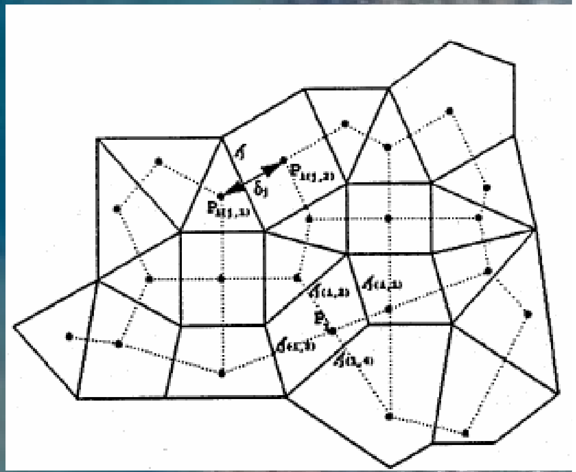
- **Unstructured mesh (w or w/o orthogonal) no coordinate transformations in x-, y-, or z-directions**
- **Stable and robust semi-implicit, finite-difference/ finite-volume/ finite element methods**

*Contrast with explicit scheme model

- **Efficient computational algorithms (semi-Lagrangian advection scheme); time step: 5 minute, used for 30 m resolution grid**

*Semi-implicitness circumvents CFL (most severe)
ELM bypasses Courant number condition for advection
Implicit transport scheme along the vertical bypasses Courant number condition

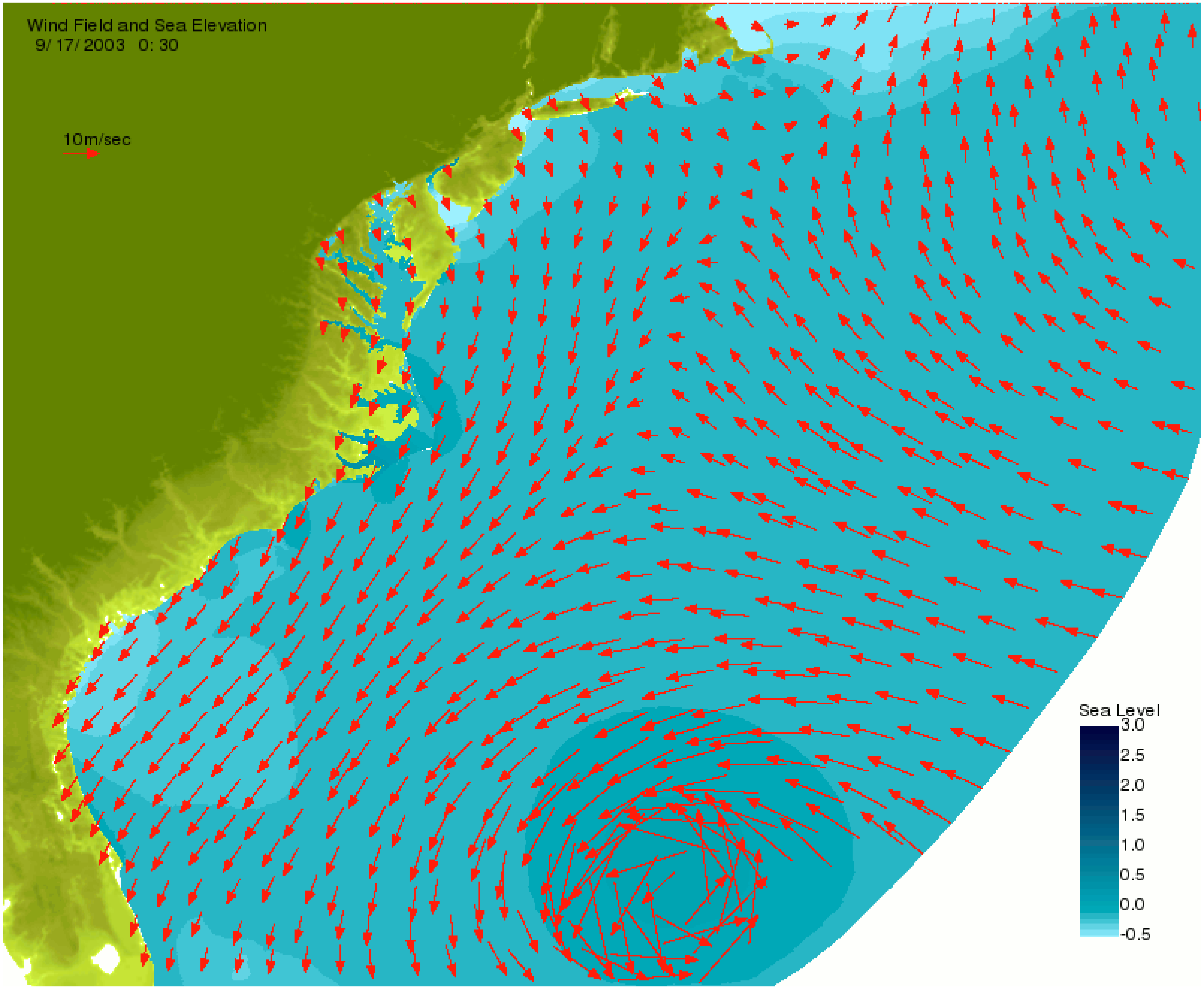
Explicit terms:
Baroclinicity → internal Courant number restriction
Horizontal viscosity/diffusivity → diffusion number condition

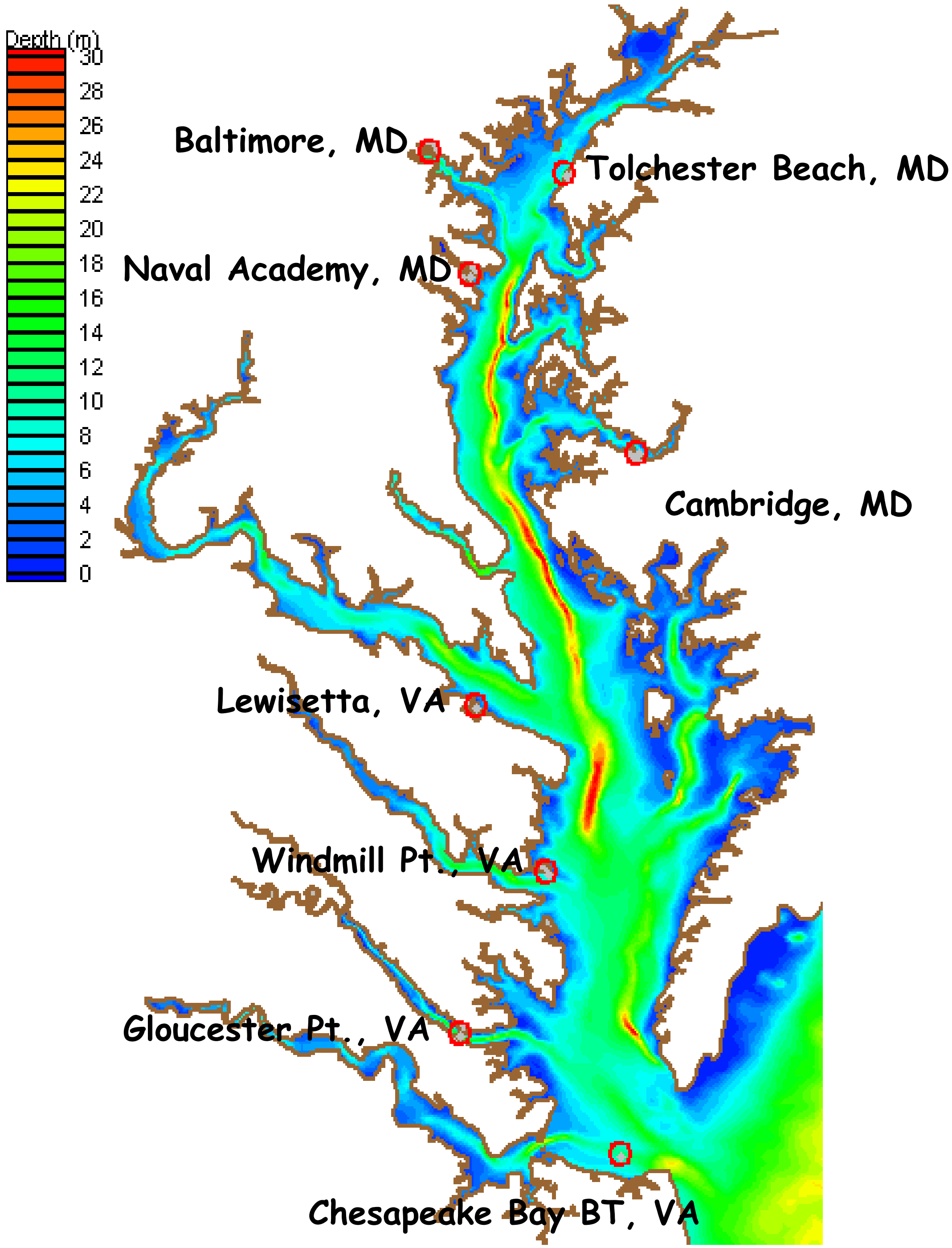


* The trade-off:
it needs matrix conversion

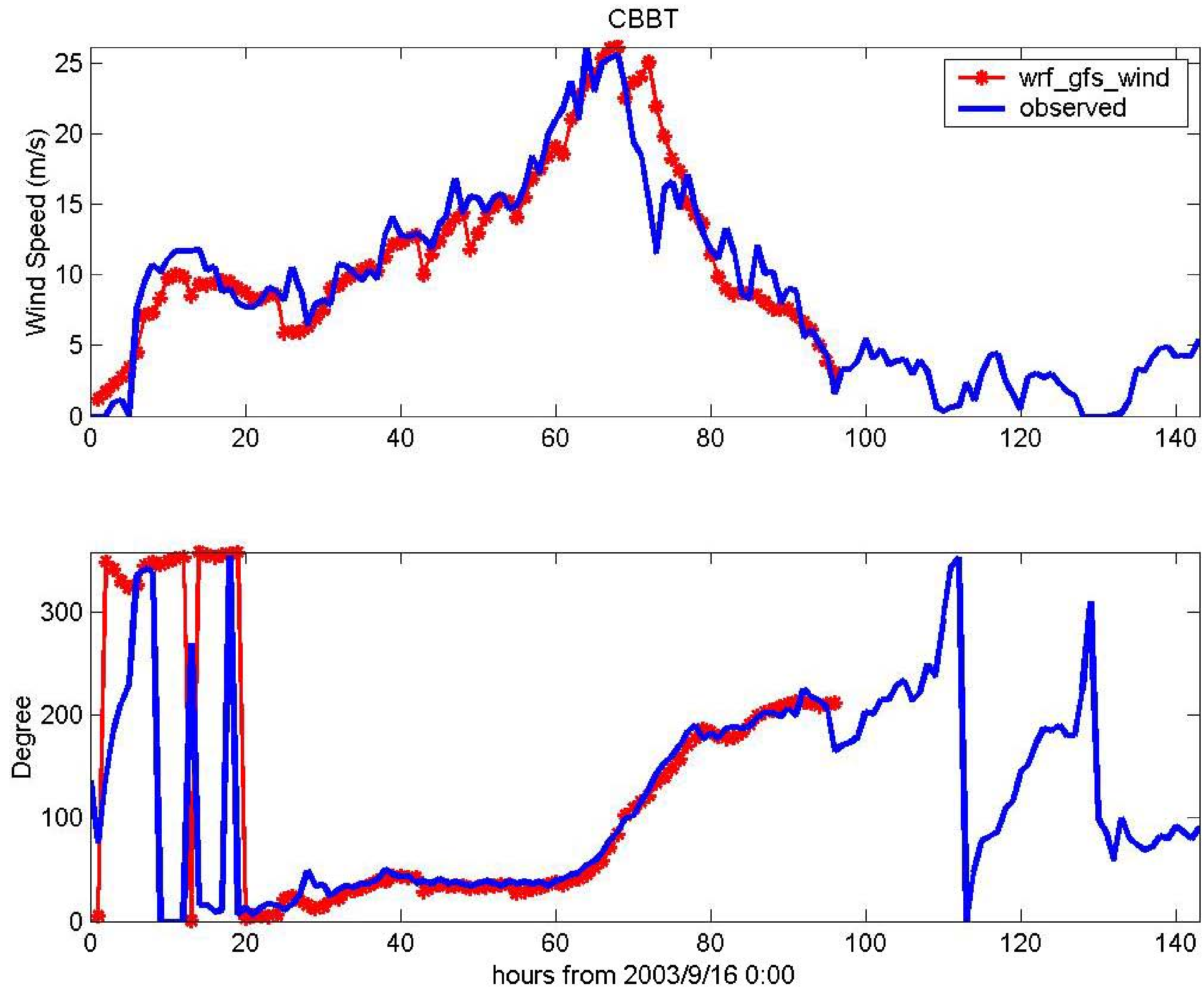
- **Capable of simulating flooding using implicit wetting-and-drying scheme**

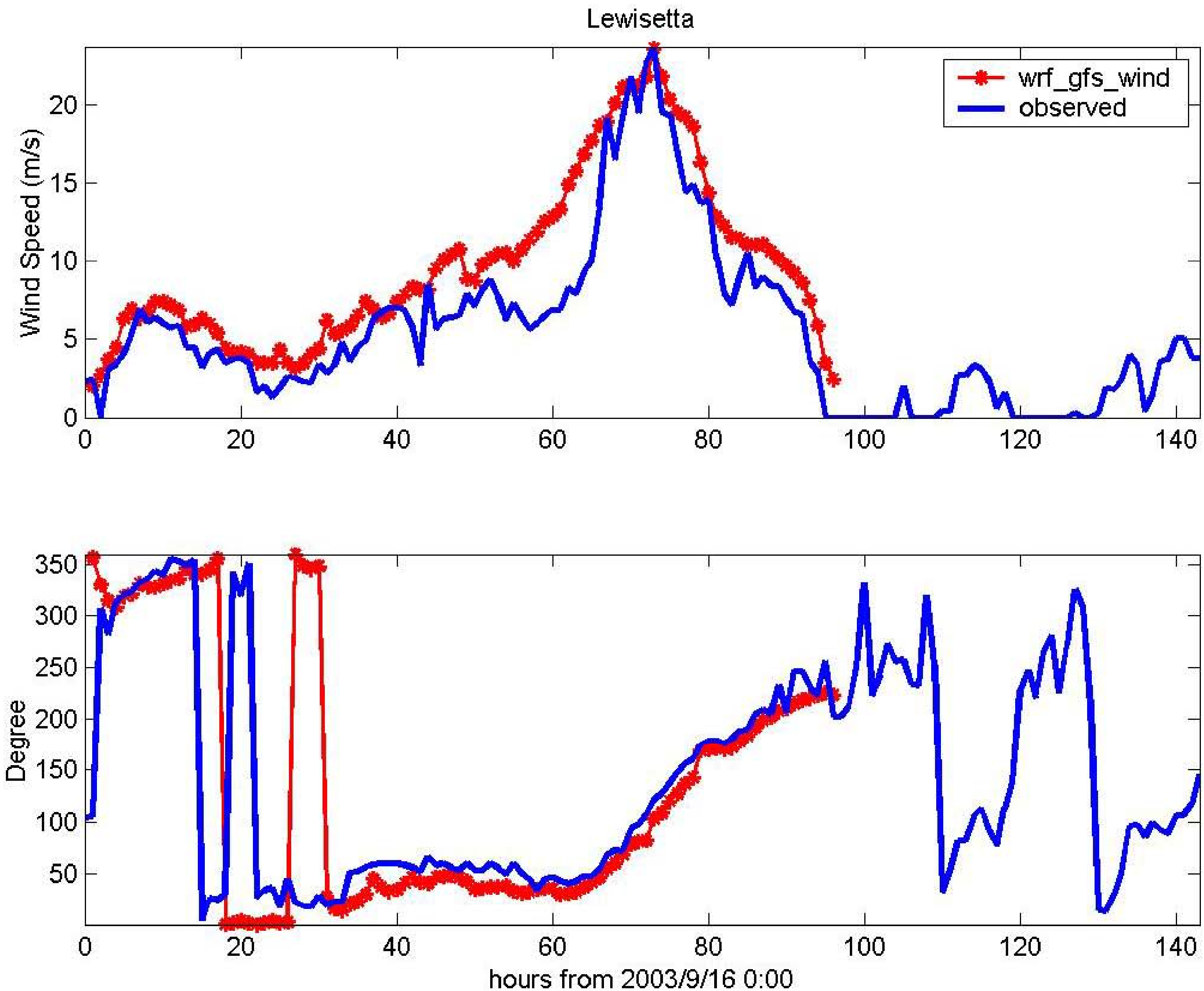
***E. g.** An advanced piecewise-linear iterative solver recently developed by Brugnano and Casulli, 2008 SIAM, J. Sci. Comp. Vol. 30, No. 1, pp463-472


Wind Field and Sea Elevation
9/ 17/ 2003 0: 30
10m/sec
Sea Level
3.0
2.5
2.0
1.5
1.0
0.5
0.0
-0.5

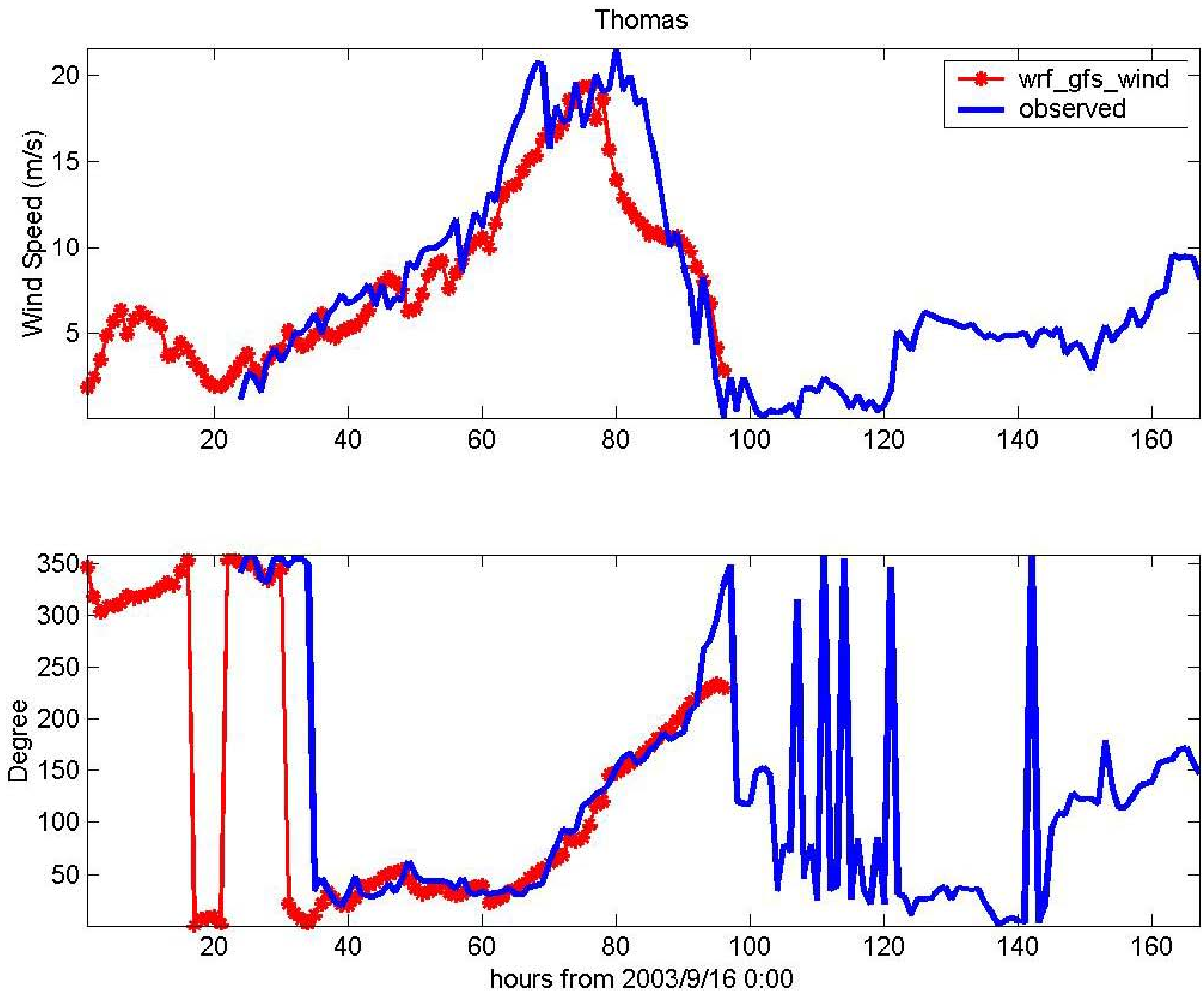


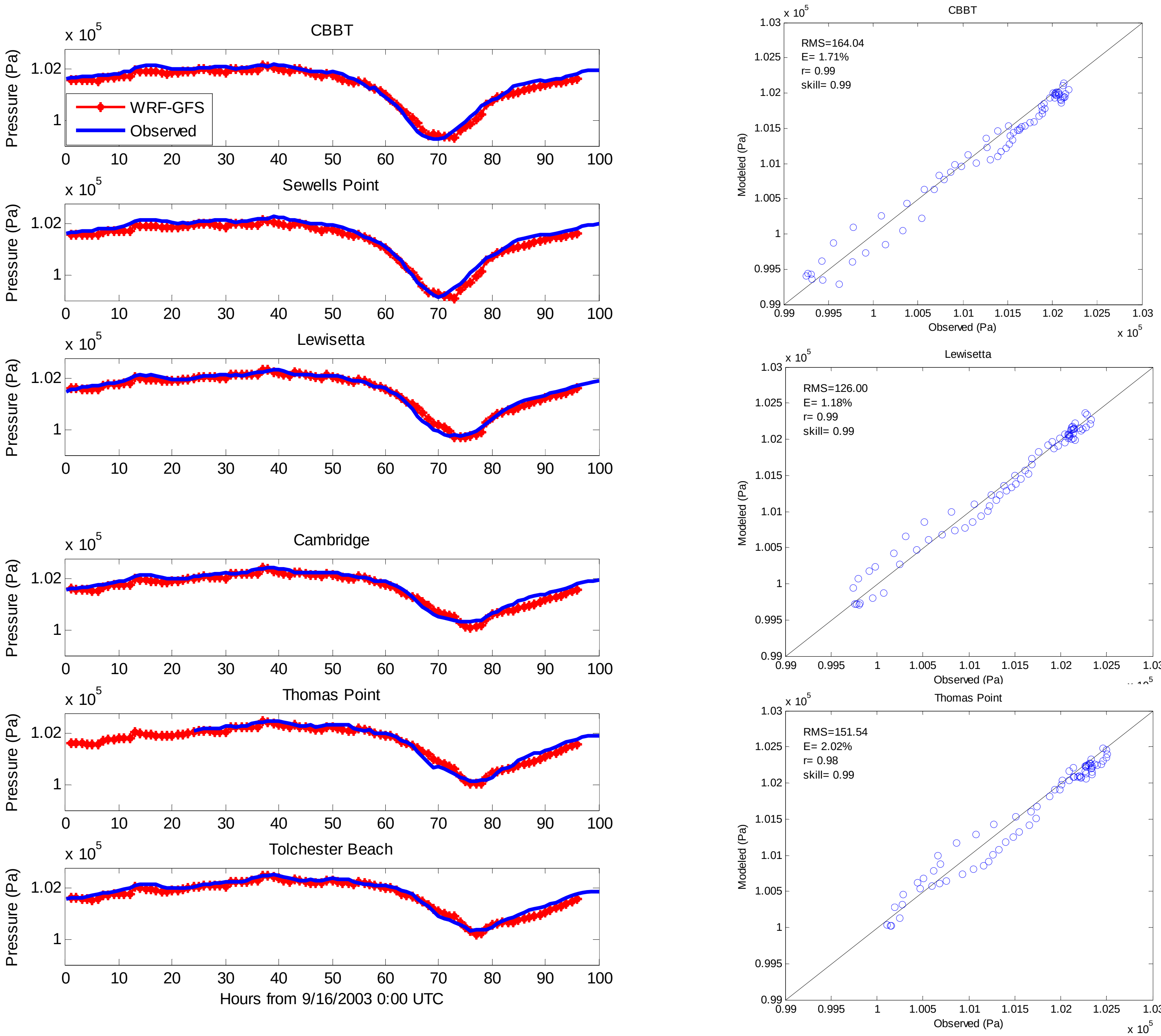
Station	Lon	Lat
Tolchester Beach	76° 14.7' W	39° 12.8' N
Baltimore	76° 34.7' W	39° 16.0' N
Naval Academy	76° 28.8' W	38° 59.0' N
Cambridge	76° 4.1' W	38° 34.4' N
Lewisetta	76° 27.9' W	37° 59.7' N
Windmill Point	76° 17.4' W	37° 36.9' N
Gloucester Point	76° 30.0' W	37° 14.8' N
Chesapeake Bay BT	76° 6.8' W	36° 58.0' N


CBBT
wrf_gfs_wind
observed
Wind Speed (m/s)
0
5
10
15
20
25
0
20
40
60
80
100
120
140
Degree
0
100
200
300
hours from 2003/9/16 0:00



Lewisetta
wrf_gfs_wind
observed
Wind Speed (m/s)
0
5
10
15
20
0
20
40
60
80
100
120
140
Degree
50
100
150
200
250
300
350
hours from 2003/9/16 0:00

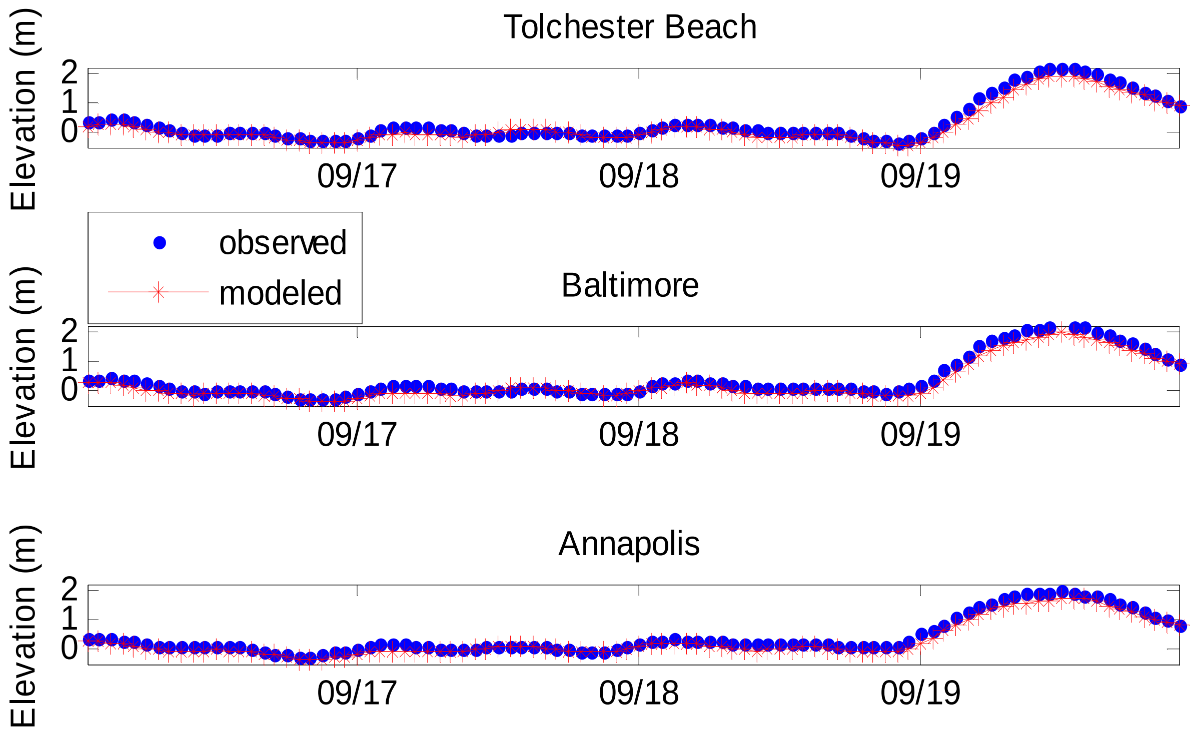

Thomas
wrf_gfs_wind
observed
Wind Speed (m/s)
20
15
10
5
20
40
60
80
100
120
140
160
Degree
350
300
250
200
150
100
50
hours from 2003/9/16 0:00

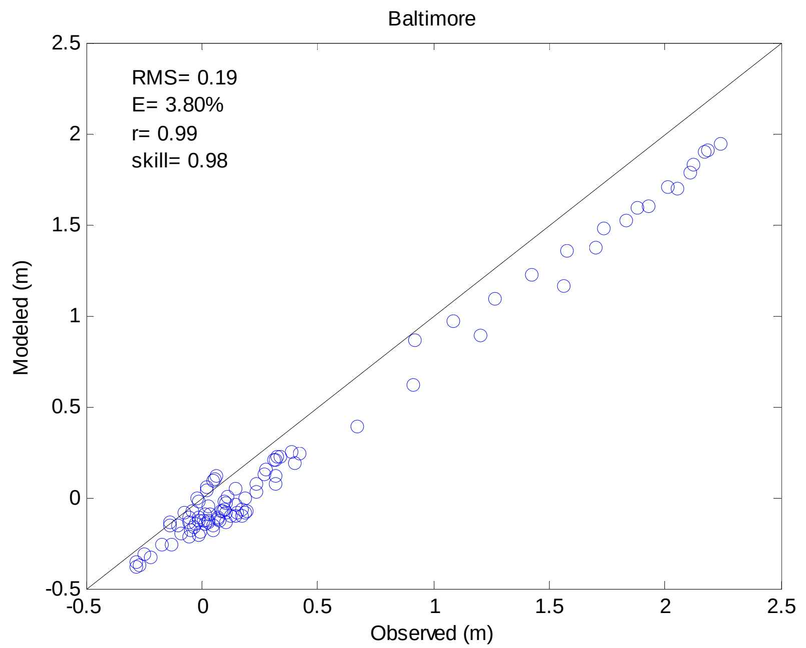


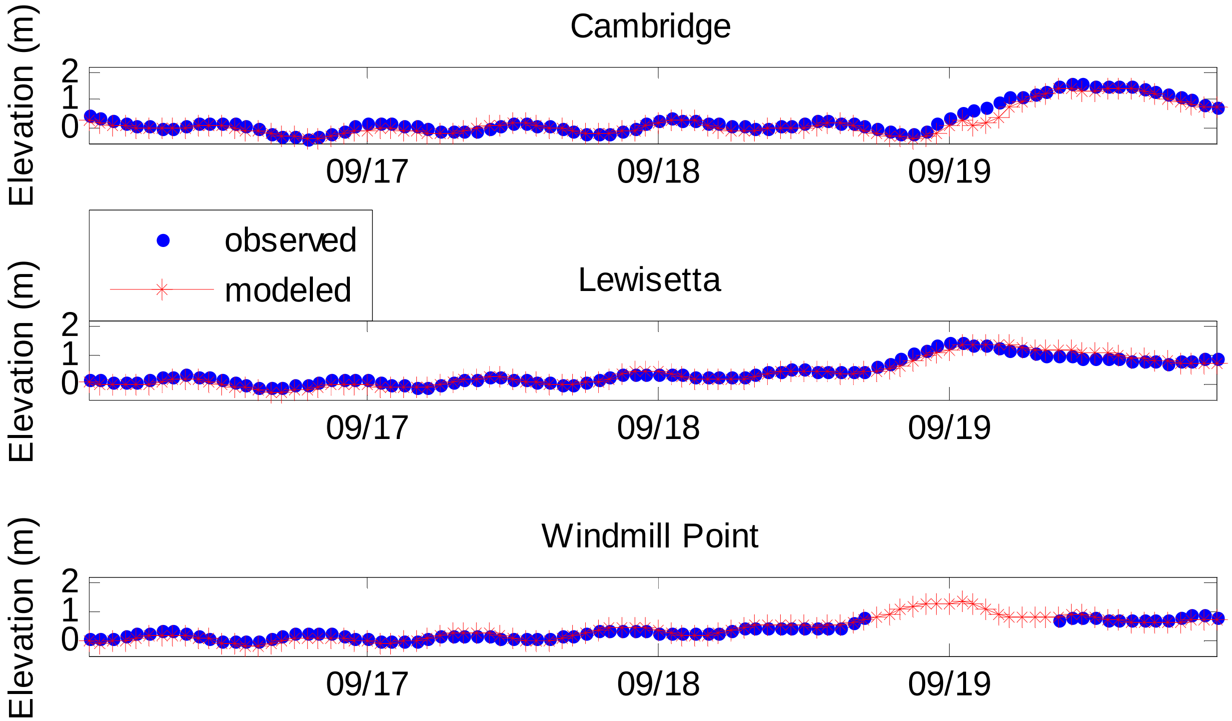
CBBT
Sewells Point
Lewisetta
Cambridge
Thomas Point
Tolchester Beach
Pressure (Pa)
x 10^5
WRF-GFS
Observed
Hours from 9/16/2003 0:00 UTC
RMS=164.04
E= 1.71%
r= 0.99
skill= 0.99
RMS=126.00
E= 1.18%
r= 0.99
skill= 0.99
RMS=151.54
E= 2.02%
r= 0.98
skill= 0.99
Modeled (Pa)
Observed (Pa)

ELCIRC model setup

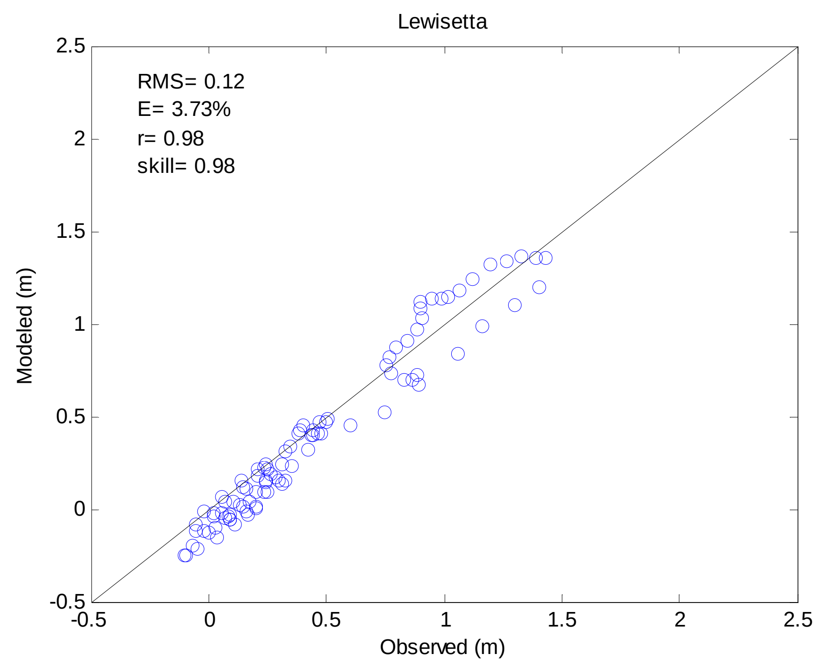
- 10-day Simulation: 9/12/03 0:00 to 9/22/03 0:00 EST
- Time step: 5 minutes
- Number of grid cell: 250,000
- The model was forced at its open boundary by 7 tidal constituents: M_2, S_2, N_2, O_1, K_1, Q_1, and K_2
- River Discharge from 8 major tributaries
- Using quasi-3D barotropic mode with semi-empirical eddy viscosity to better simulating Ekman dynamics.
- Vertical resolution: 5 m, 10 m,20 m, 50 m, and 100 m .. etc in the ocean.
- Benchmark: 10 days simulation in a single Linux processor takes 8 hour CPU


Tolchester Beach
Baltimore
Annapolis
Elevation (m)
2
1
0
09/17
09/18
09/19
observed
modeled

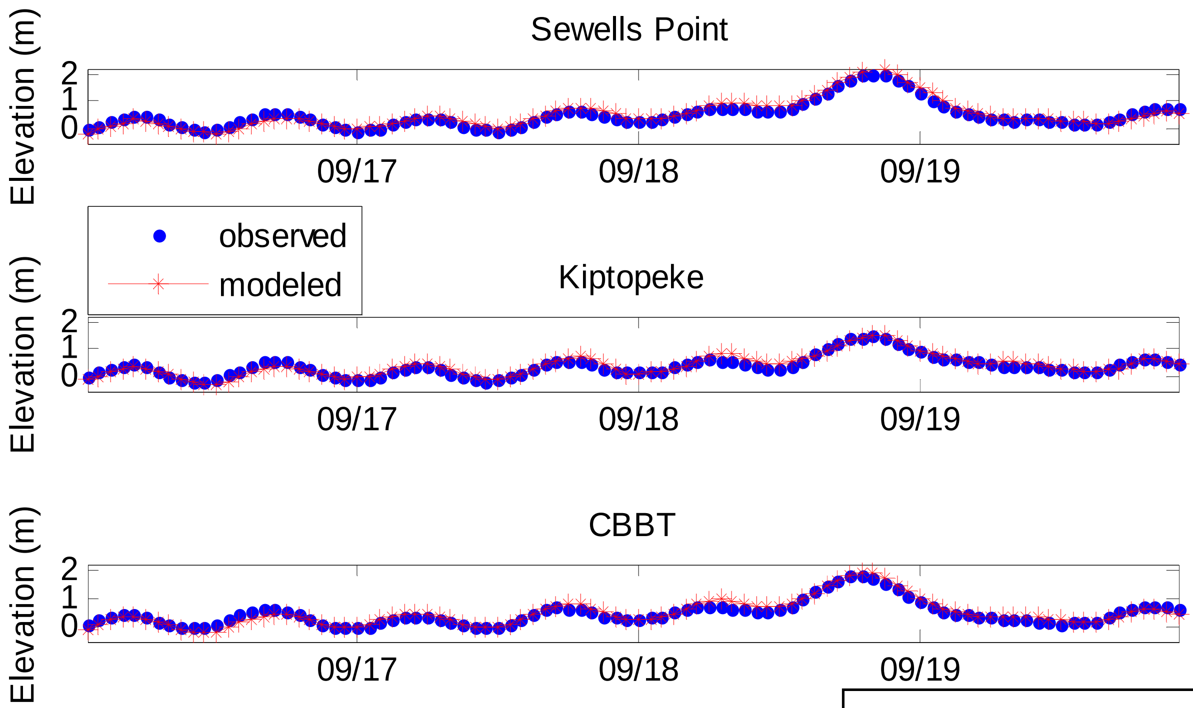

Baltimore
RMS= 0.19
E= 3.80%
r= 0.99
skill= 0.98
Modeled (m)
Observed (m)
-0.5
0
0.5
1
1.5
2
2.5

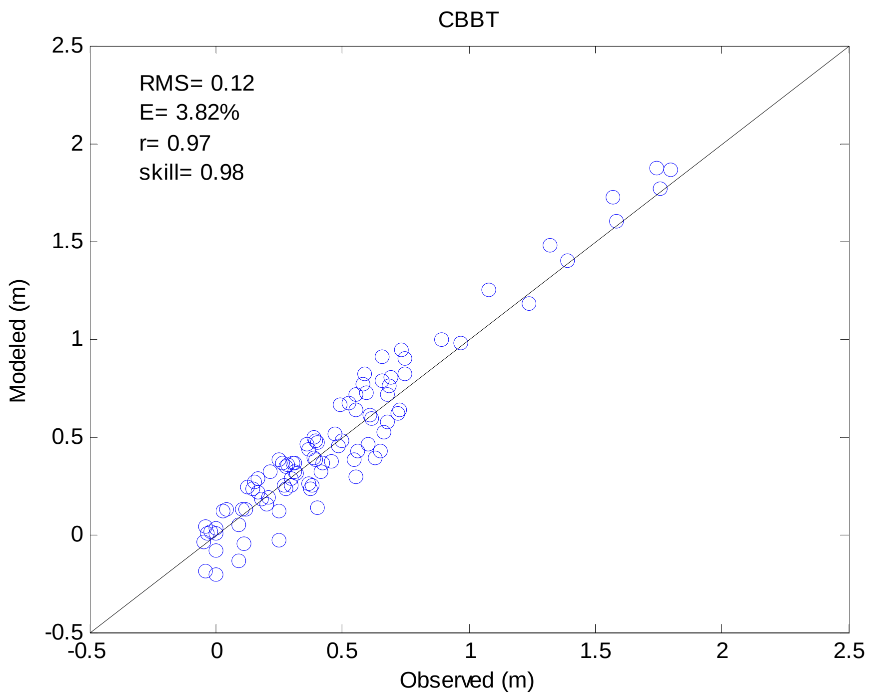


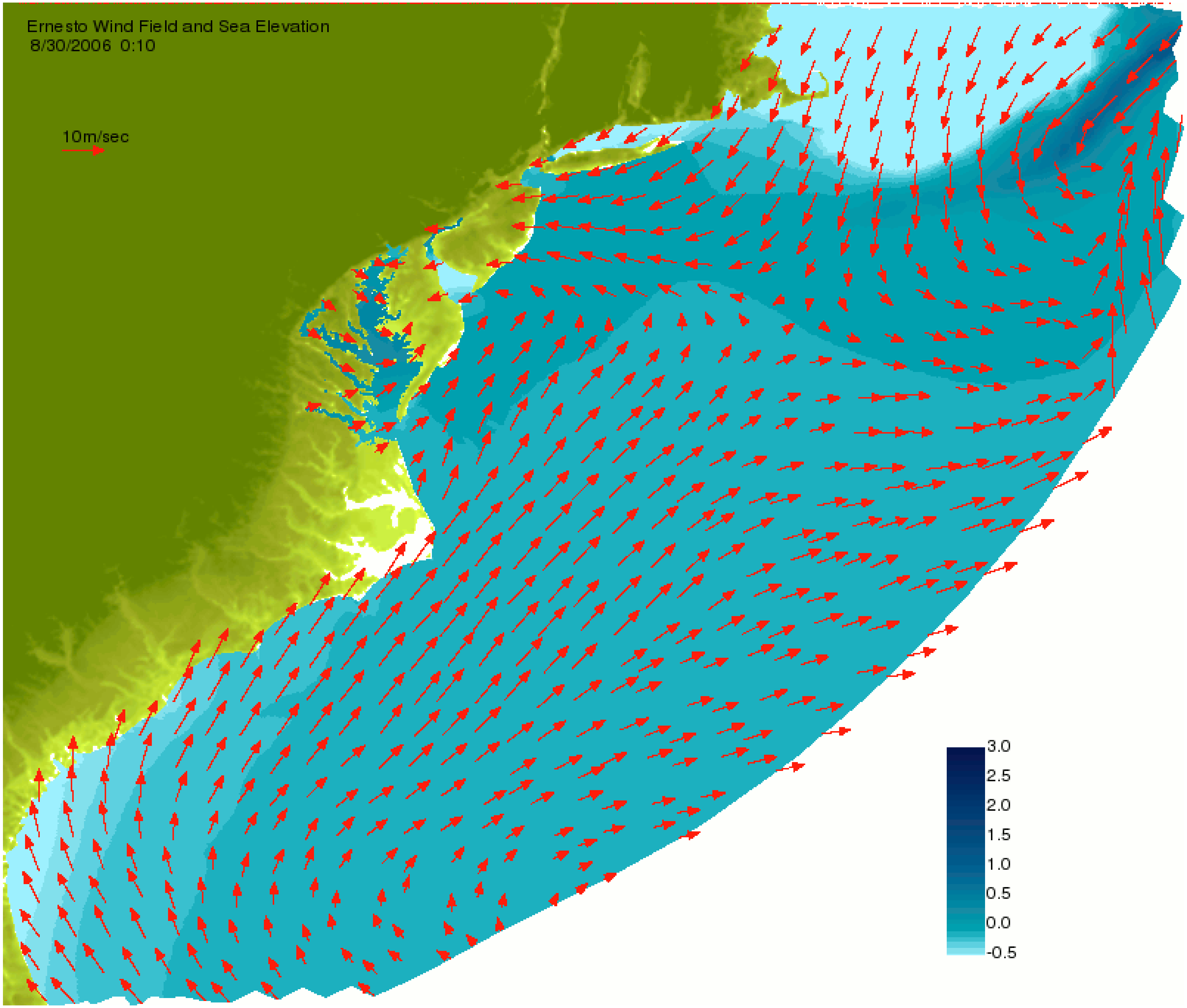
Cambridge
Lewisetta
Windmill Point
Elevation (m)
observed
modeled
09/17
09/18
09/19
0
1
2

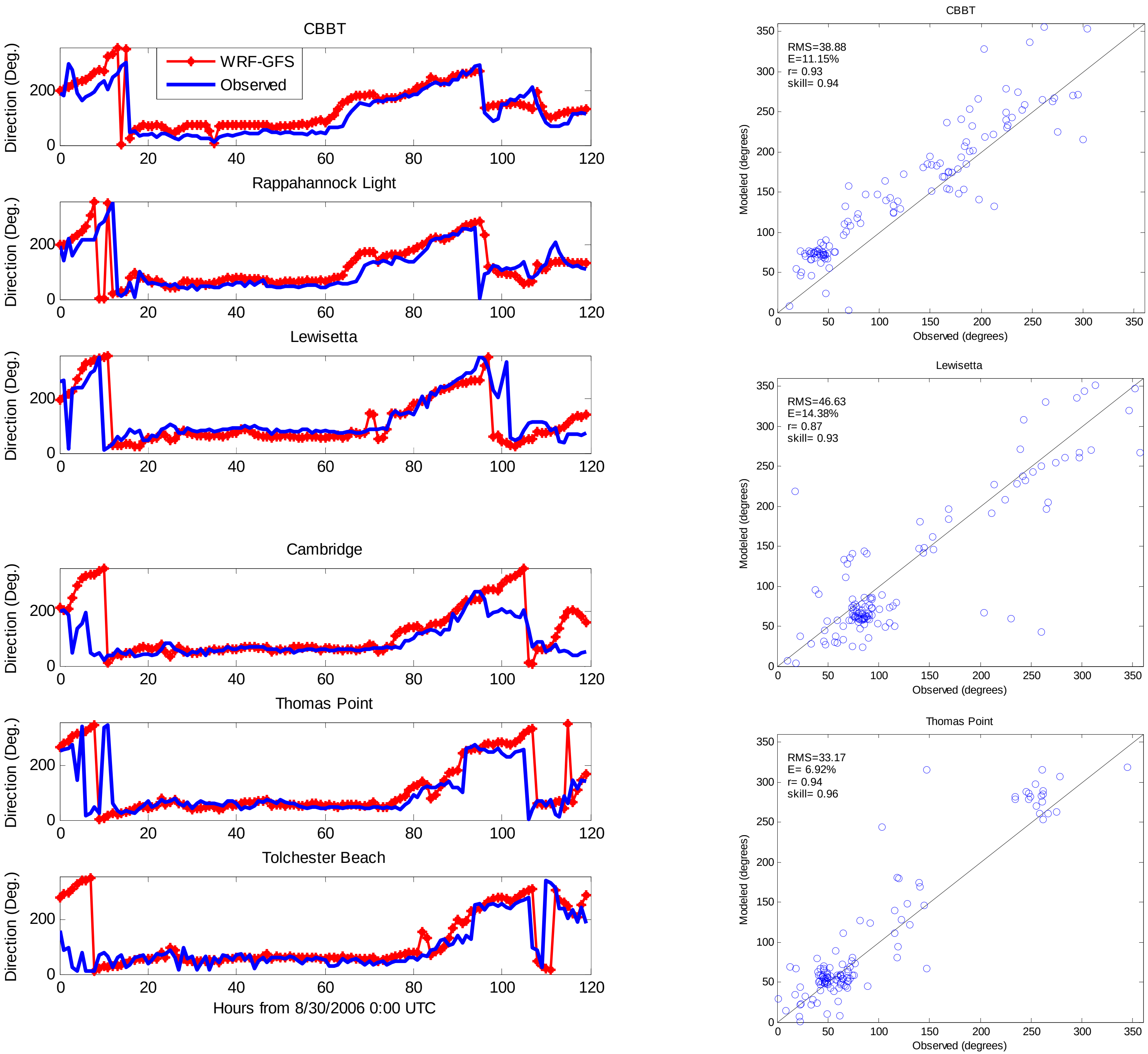


Lewisetta
RMS= 0.12
E= 3.73%
r= 0.98
skill= 0.98
Modeled (m)
Observed (m)
-0.5
0
0.5
1
1.5
2
2.5

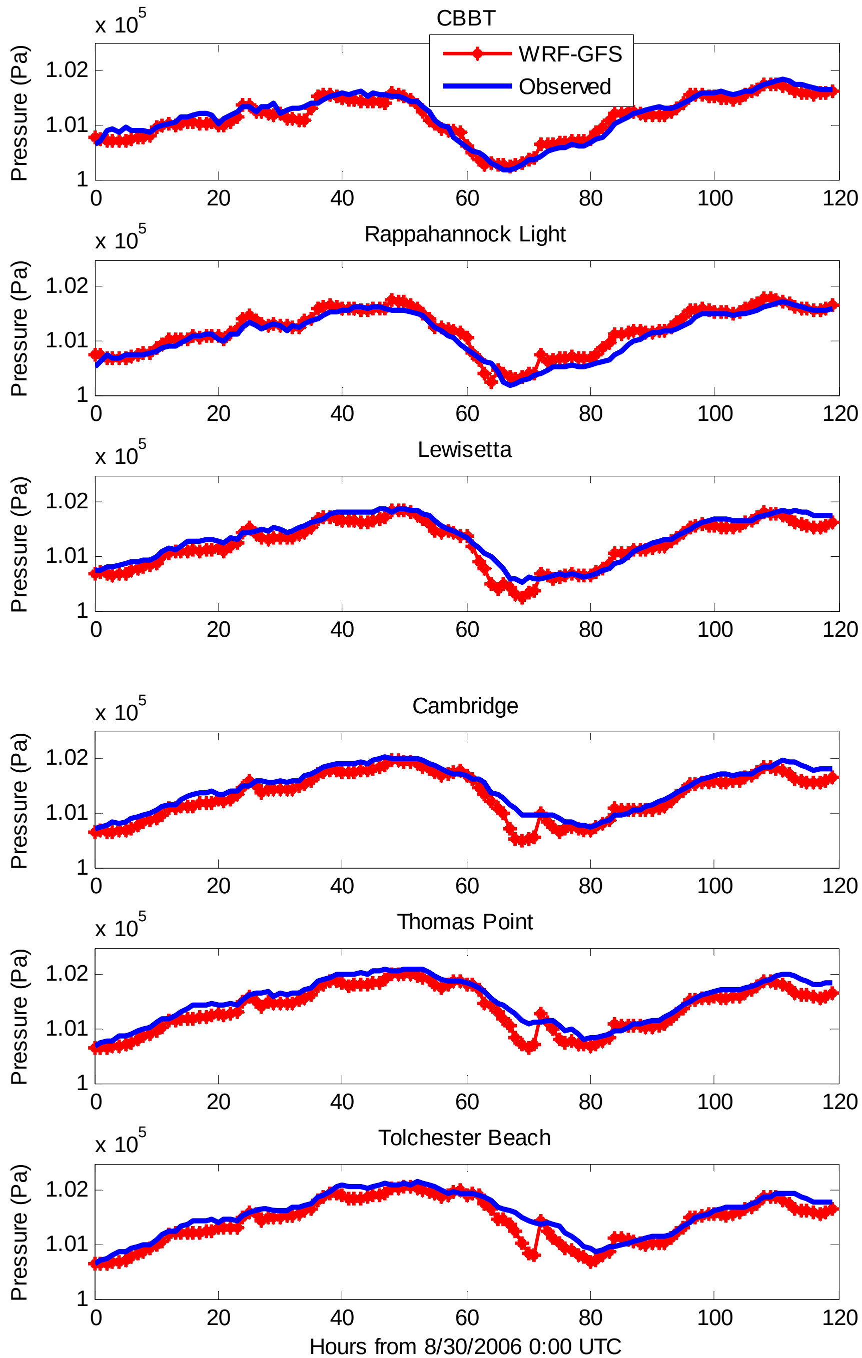

Sewells Point
Kiptopeke
CBBT
Elevation (m)
2
1
0
09/17
09/18
09/19
observed
modeled

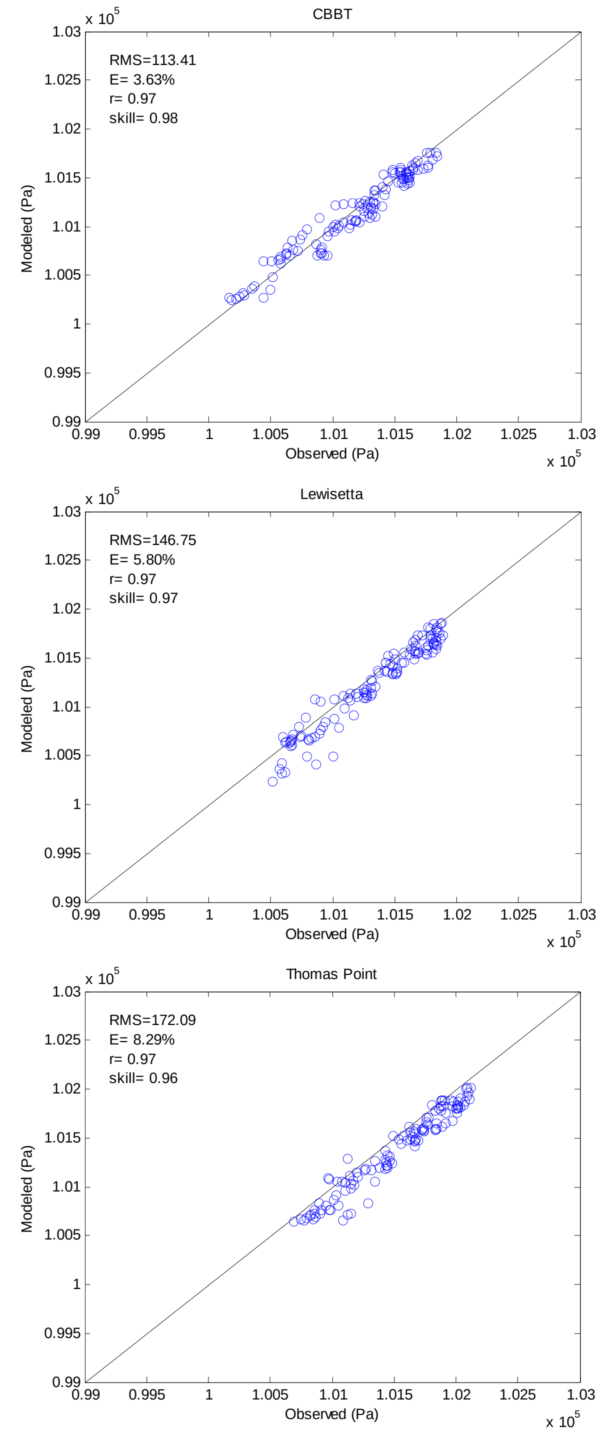

CBBT
RMS= 0.12
E= 3.82%
r= 0.97
skill= 0.98
Modeled (m)
Observed (m)
-0.5
0
0.5
1
1.5
2
2.5

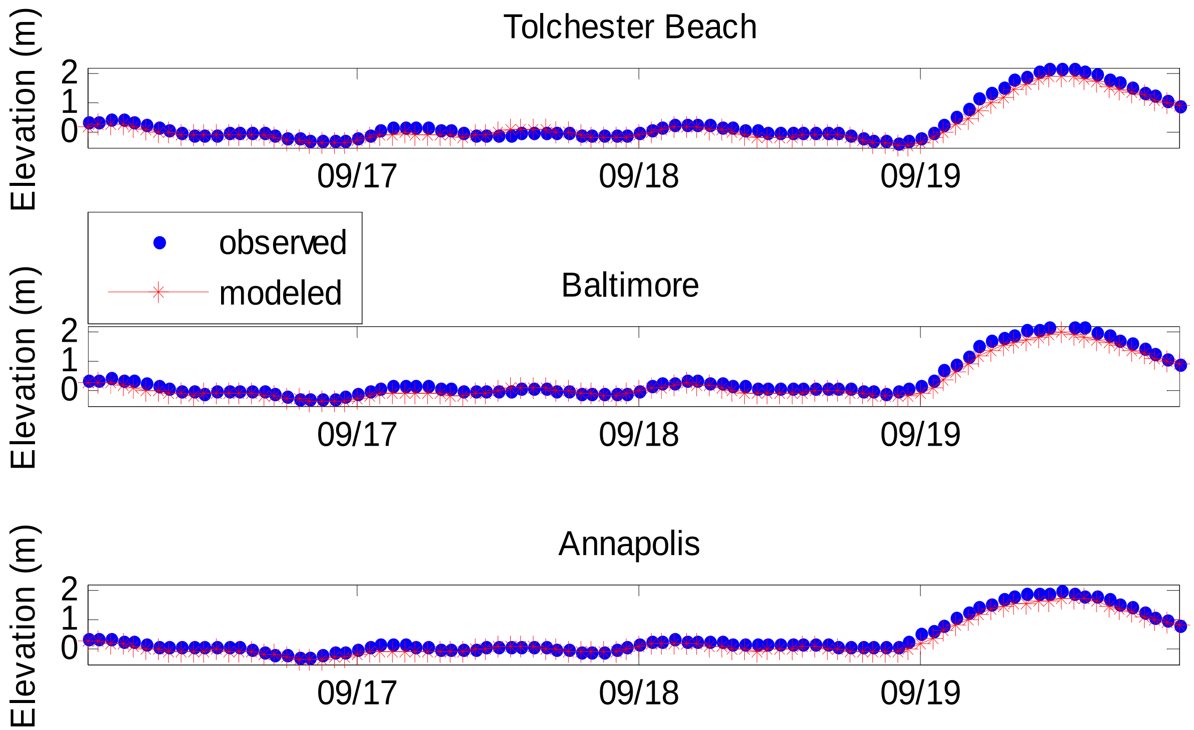

Ernesto Wind Field and Sea Elevation
8/30/2006 0:10
10m/sec
3.0
2.5
2.0
1.5
1.0
0.5
0.0
-0.5



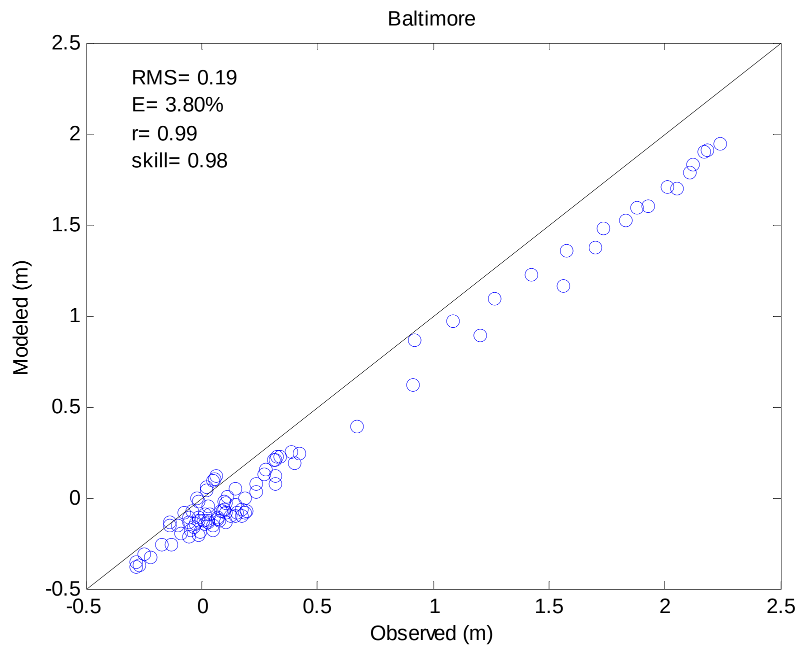
CBBT
WRF-GFS
Observed
Rappahannock Light
Lewisetta
Cambridge
Thomas Point
Tolchester Beach
Direction (Deg.)
Hours from 8/30/2006 0:00 UTC
CBBT
RMS=38.88
E=11.15%
r= 0.93
skill= 0.94
Lewisetta
RMS=46.63
E=14.38%
r= 0.87
skill= 0.93
Thomas Point
RMS=33.17
E= 6.92%
r= 0.94
skill= 0.96
Modeled (degrees)
Observed (degrees)


CBBT
WRF-GFS
Observed
Rappahannock Light
Lewisetta
Cambridge
Thomas Point
Tolchester Beach
Pressure (Pa)
x 10^5
Hours from 8/30/2006 0:00 UTC

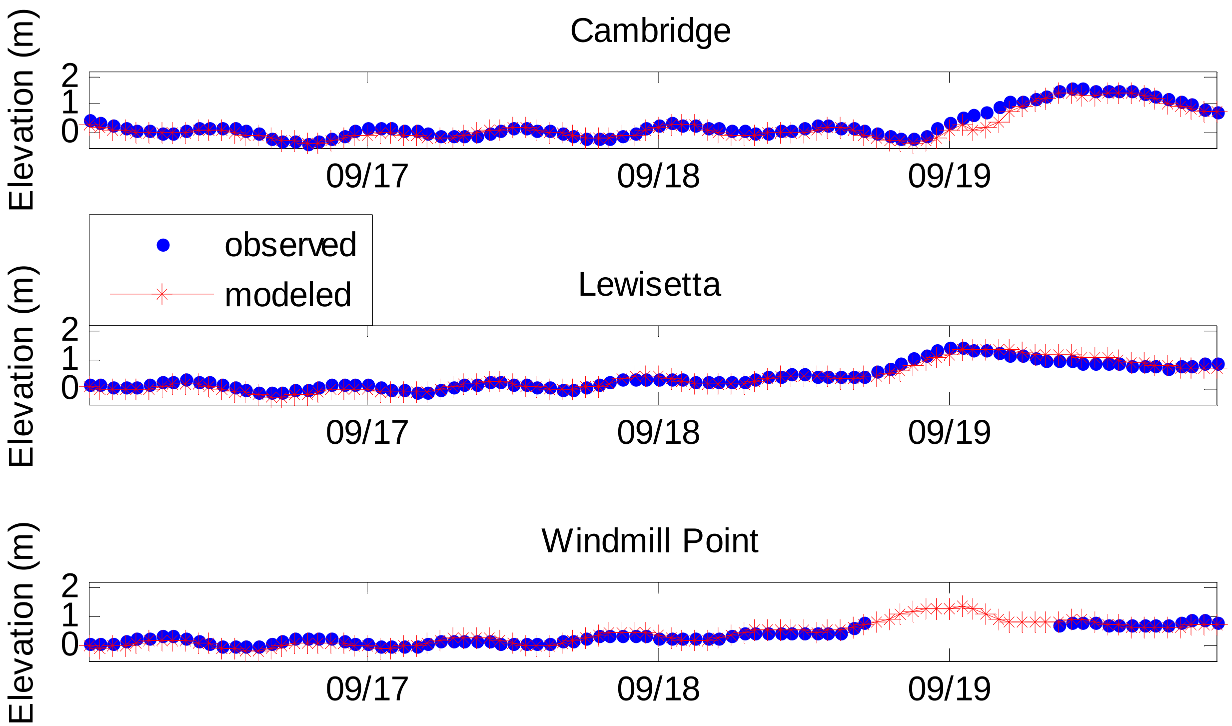

CBBT
RMS=113.41
E= 3.63%
r= 0.97
skill= 0.98
Lewisetta
RMS=146.75
E= 5.80%
r= 0.97
skill= 0.97
Thomas Point
RMS=172.09
E= 8.29%
r= 0.97
skill= 0.96
Modeled (Pa)
Observed (Pa)
x 10^5



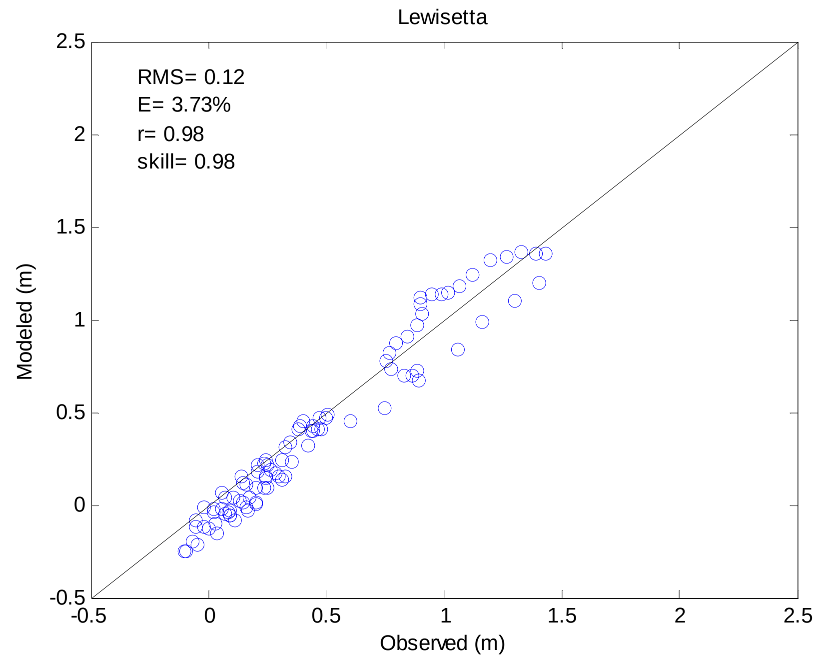
Tolchester Beach
Elevation (m)
2
1
0
09/17
09/18
09/19
observed
modeled
Baltimore
Elevation (m)
2
1
0
09/17
09/18
09/19
Annapolis
Elevation (m)
2
1
0
09/17
09/18
09/19



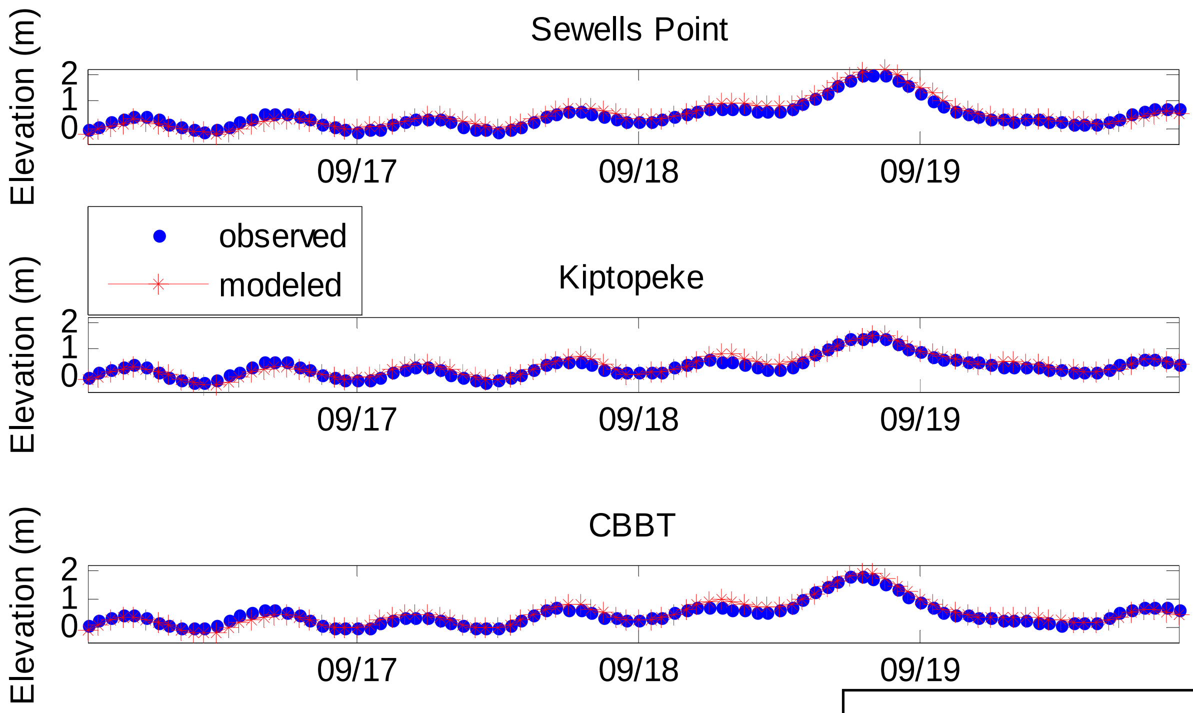
Baltimore
RMS= 0.19
E= 3.80%
r= 0.99
skill= 0.98
Modeled (m)
Observed (m)
2.5
2
1.5
1
0.5
0
-0.5
-0.5
0
0.5
1
1.5
2
2.5



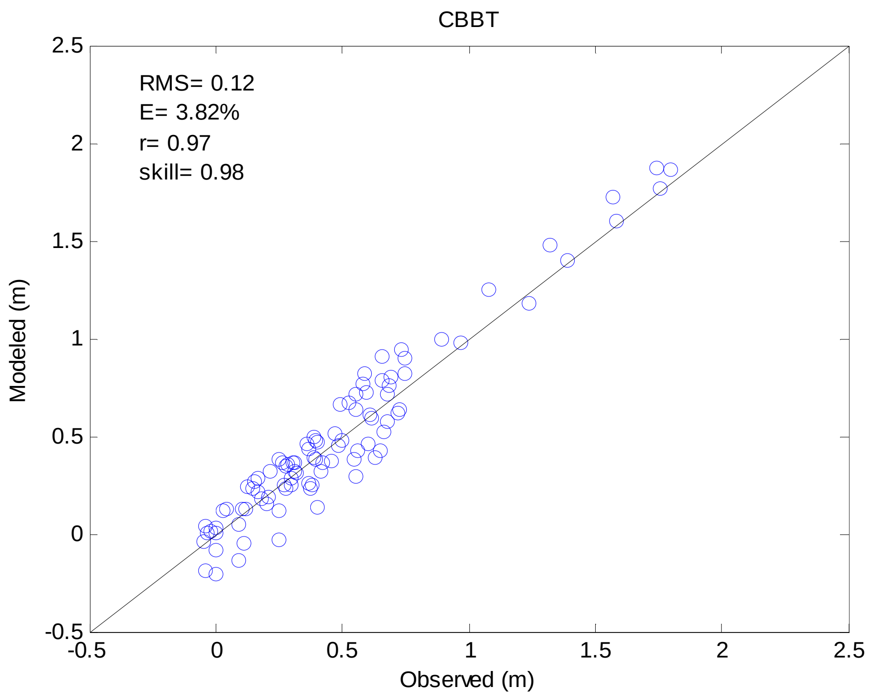
Cambridge
Lewisetta
Windmill Point
Elevation (m)
2
1
0
09/17
09/18
09/19
observed
modeled



Lewisetta
RMS= 0.12
E= 3.73%
r= 0.98
skill= 0.98
Modeled (m)
Observed (m)
-0.5
0
0.5
1
1.5
2
2.5

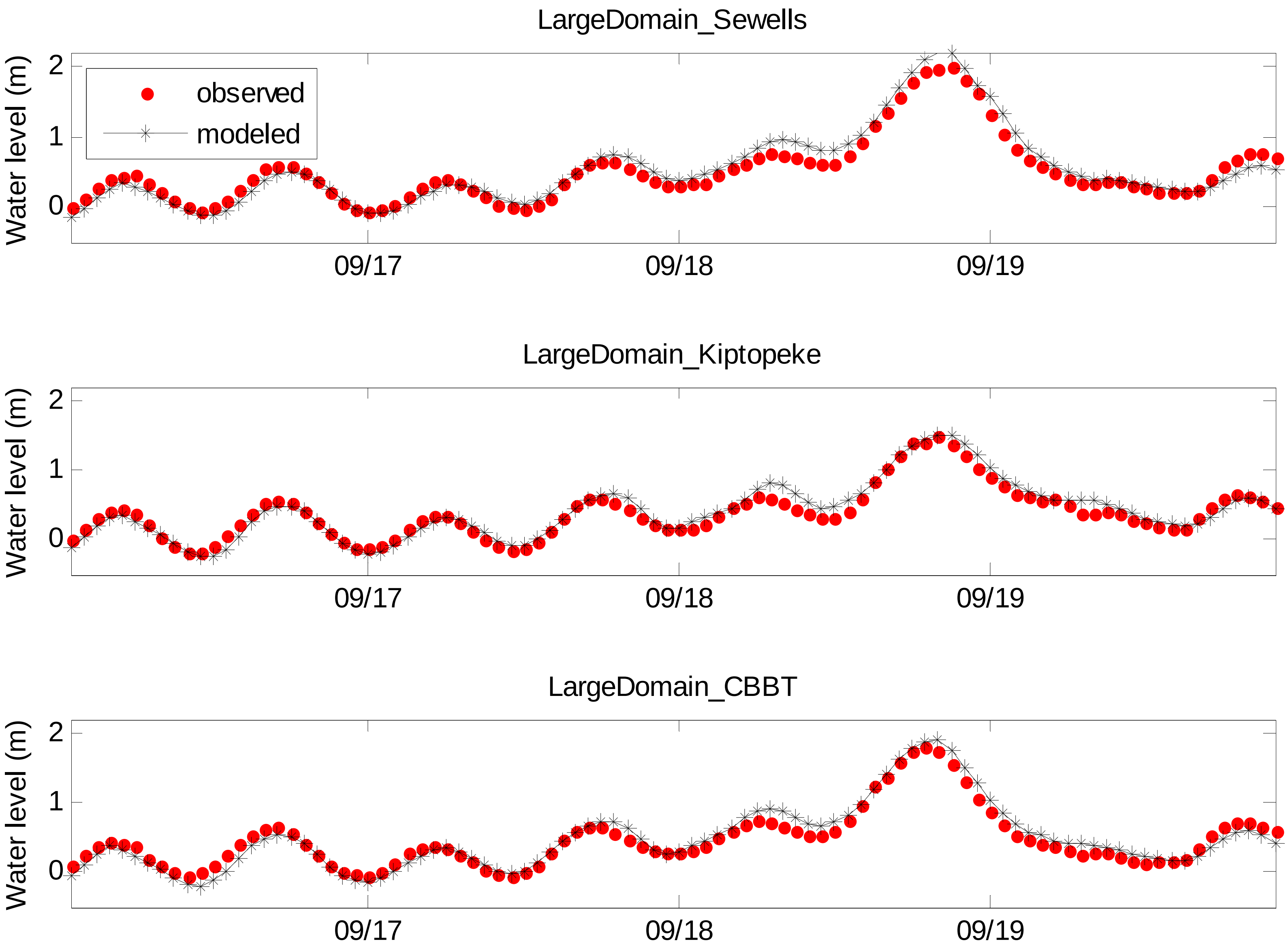


Sewells Point
Kiptopeke
CBBT
Elevation (m)
2
1
0
09/17
09/18
09/19
observed
modeled



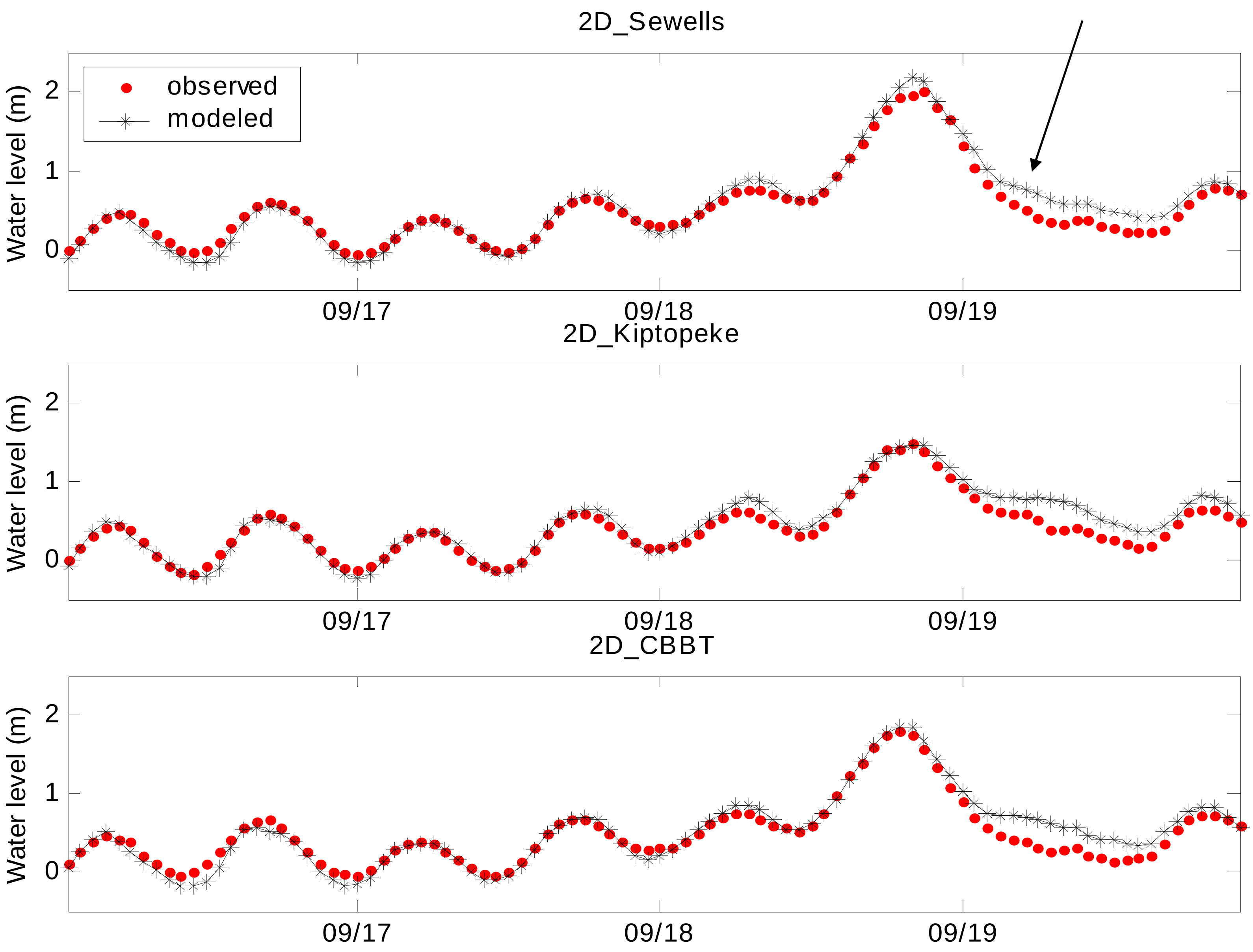
CBBT
RMS= 0.12
E= 3.82%
r= 0.97
skill= 0.98
Modeled (m)
Observed (m)
2.5
2
1.5
1
0.5
0
-0.5

Quasi-3D results



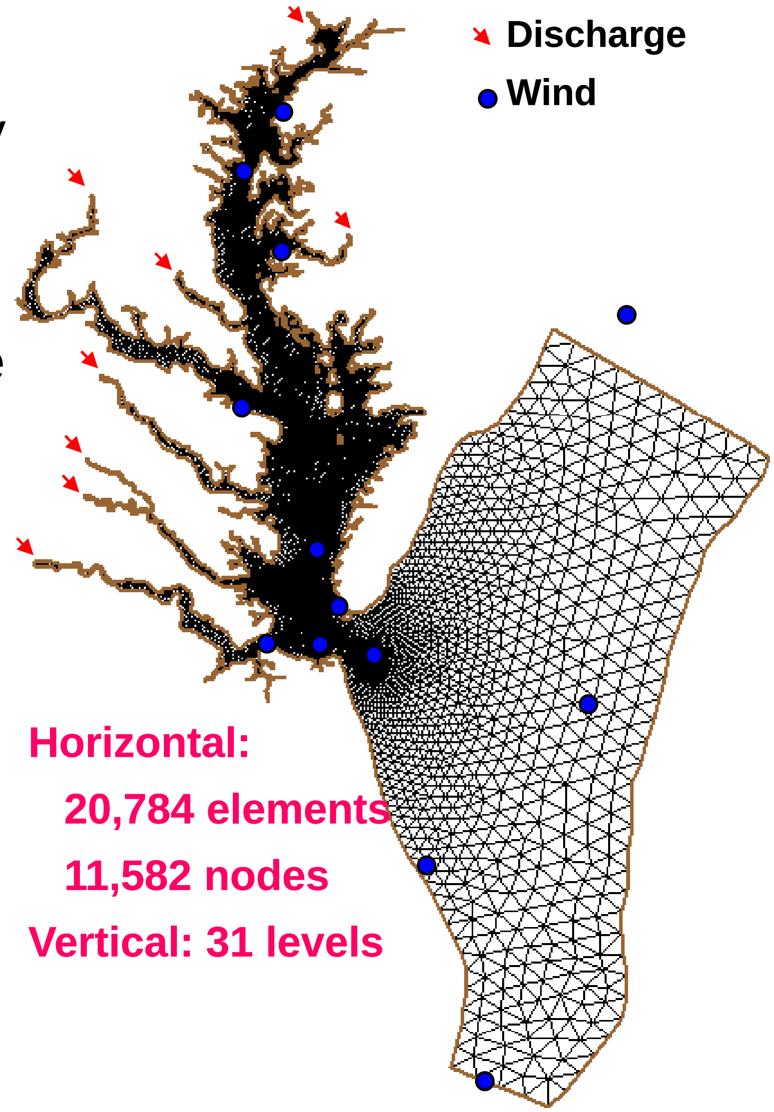
Vertical 2D Results

Ekman Transport was missing

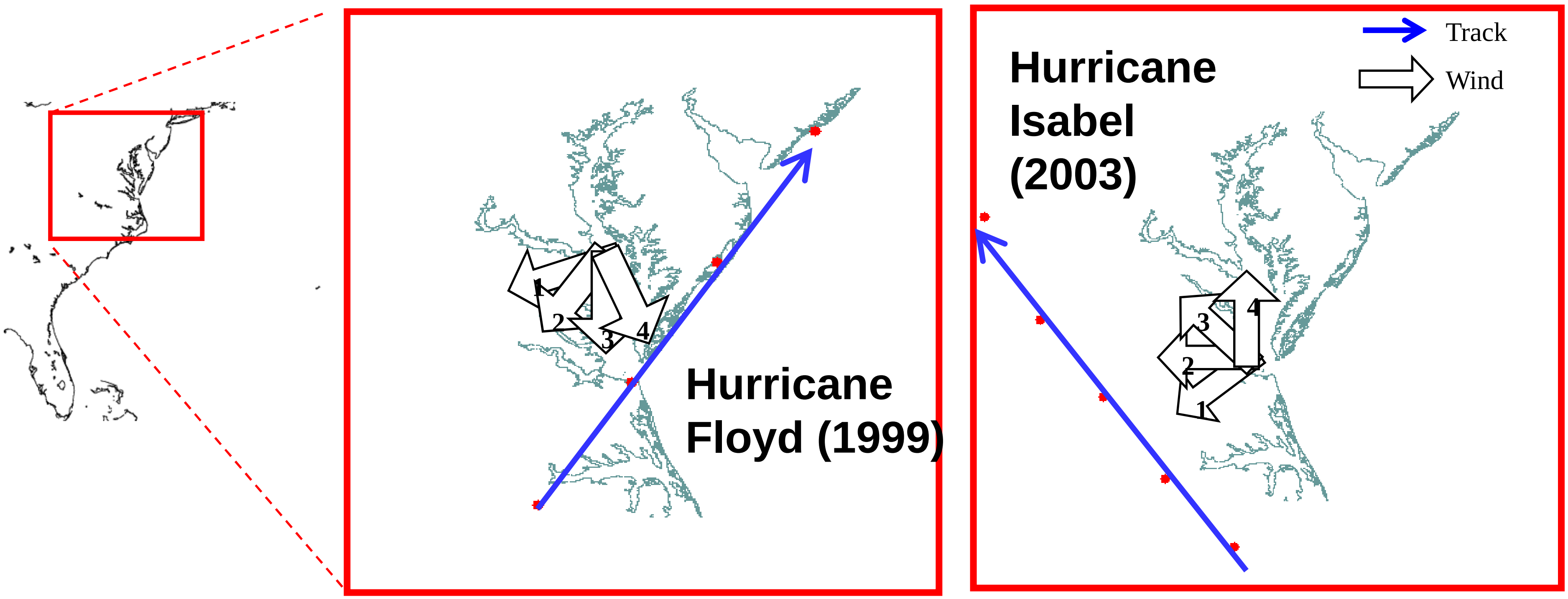


Model setup for baroclinic run

- Time step: Δt = 5 min
- The model is forced at its open boundary by 8 tidal constituents: M_2, S_2, N_2, O_1, K_1, Q_1, P_1, and K_2
- Winds: parametric model + inverse distance weighted method using NOAA hourly data at 13 stations
- Salinity Initial Condition: CBP data
- Salinity Boundary Condition: CORIOLIS dataset
- River Discharges: 8 rivers, USGS daily mean values
- K-ε scheme for turbulence closure

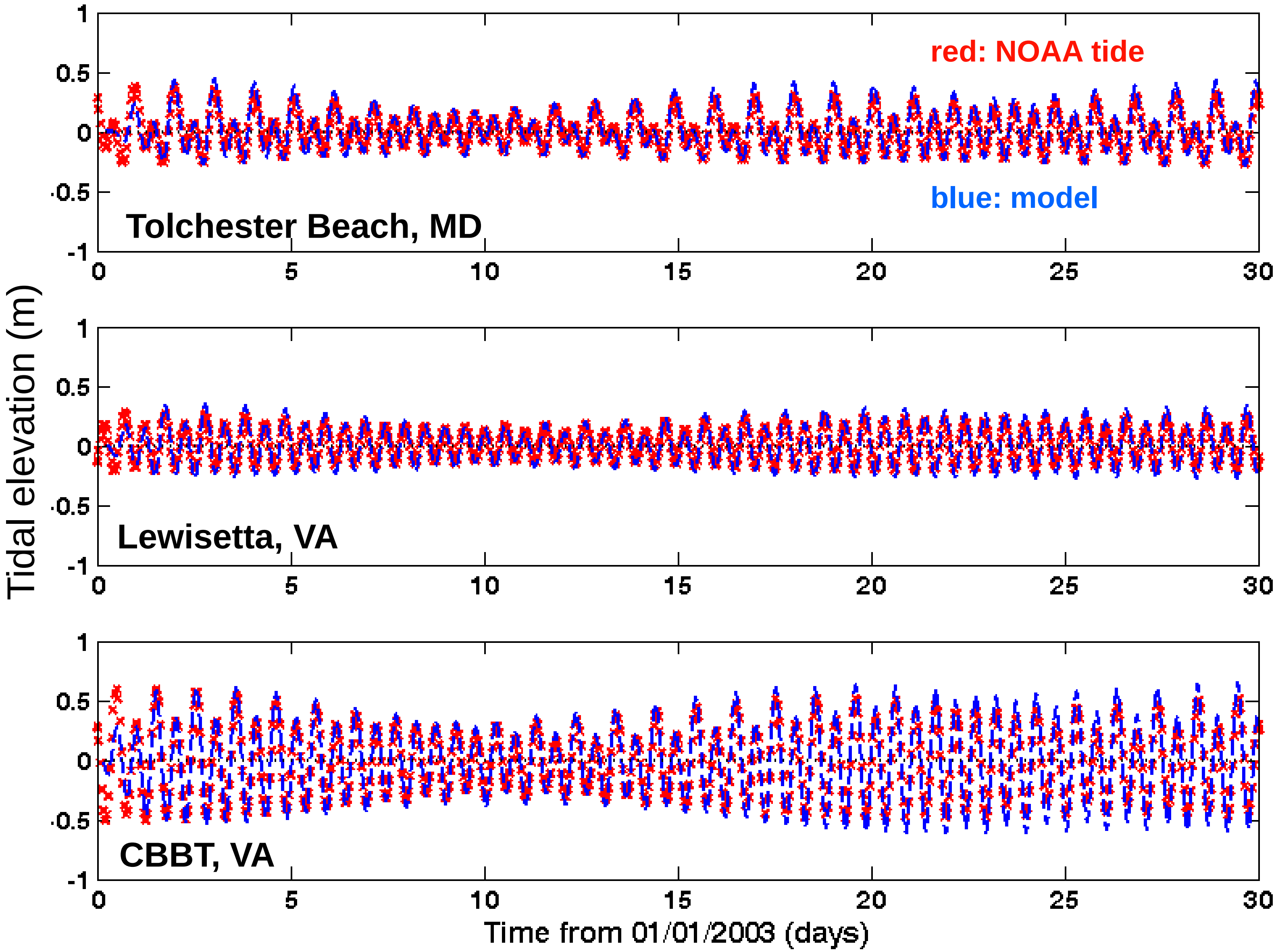


Hurricanes: Floyd vs. Isabel

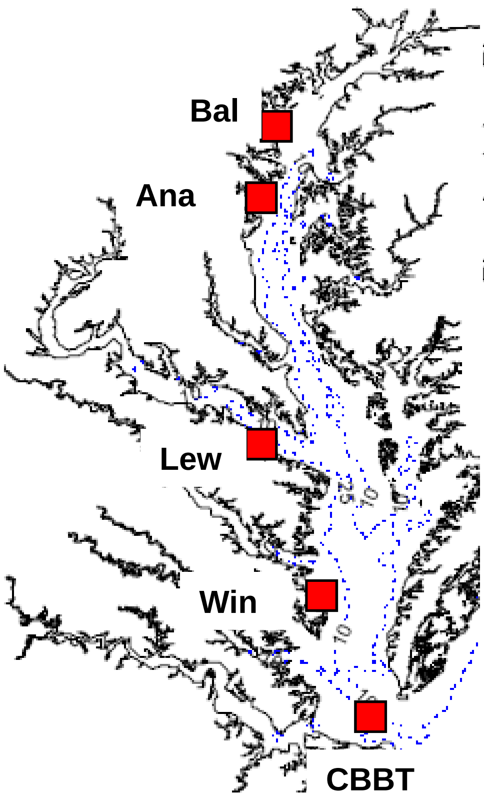


Name	Floyd	Isabel
Category at landfall	Category 2	Category 2
Total inflow of water into the Bay	291 billion gallons (Sept. 16-22, 1999; USGS)	1,190 billion gallons (Sept. 19-25, 2003; USGS)
Total rainfall	10–15 inches (Max 19.06 inches, NC)	1–2 inches (Max 20.20 inches, VA)

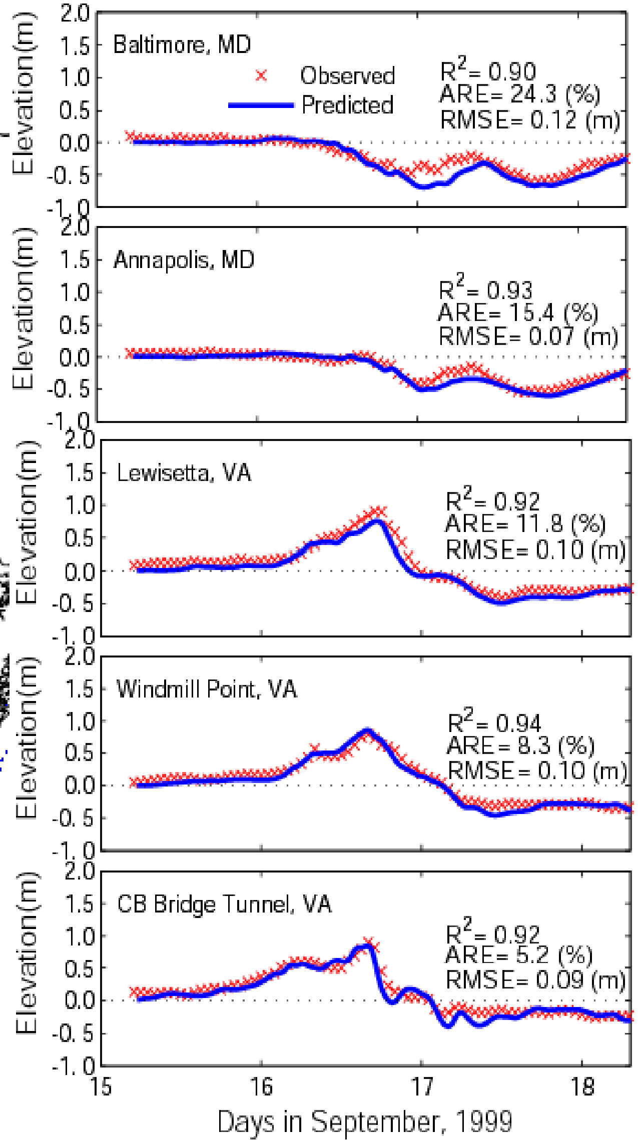
Tide comparison



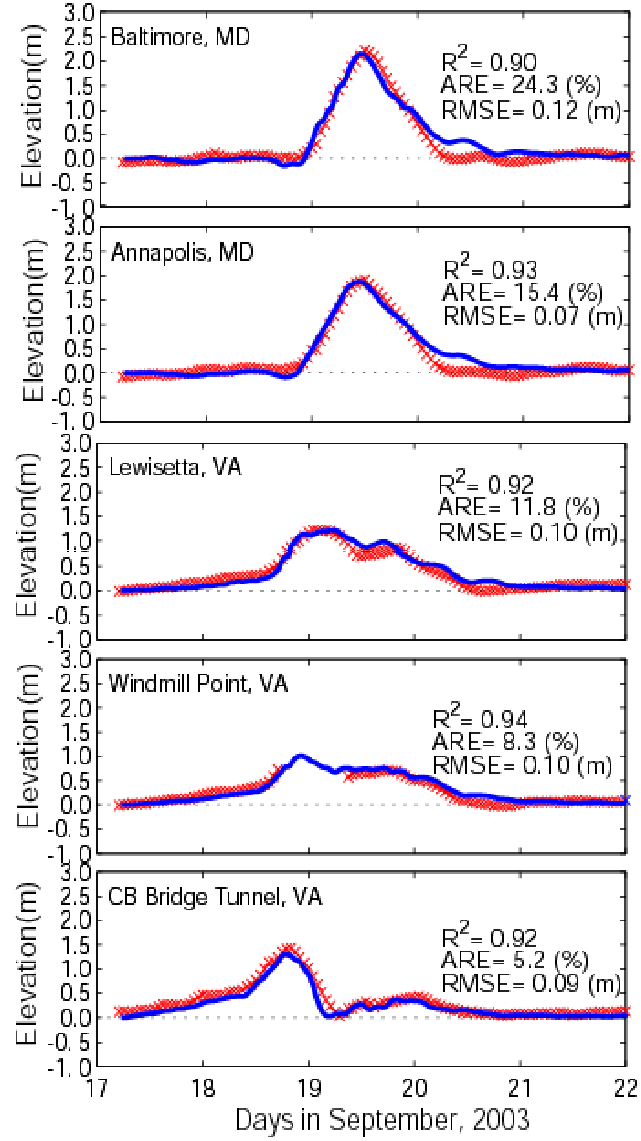
Storm surge comparison



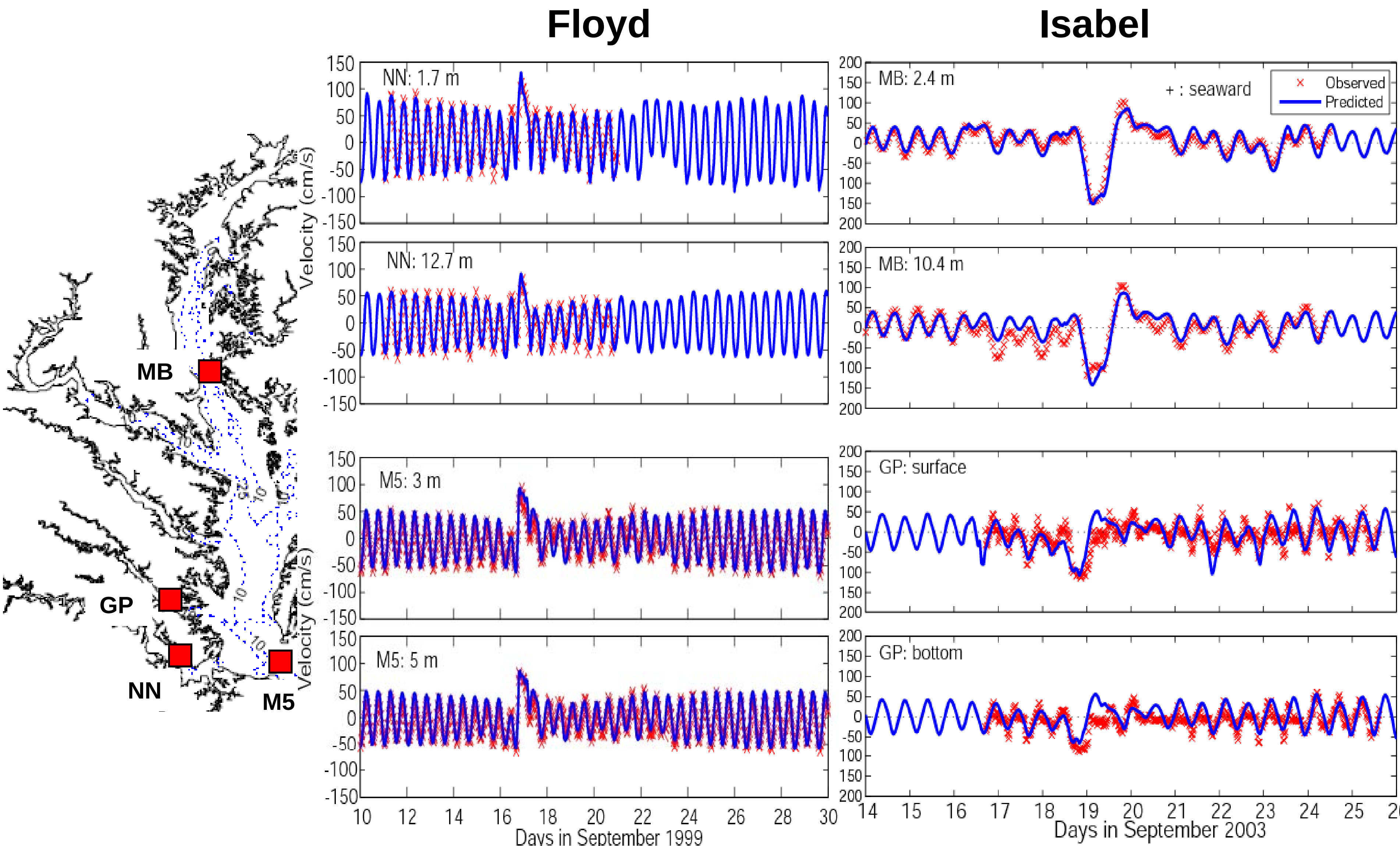
Floyd



Isabel

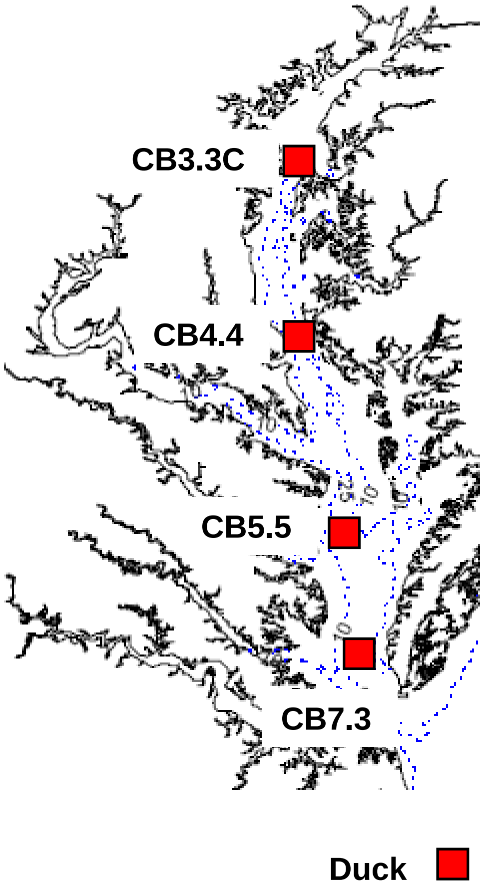


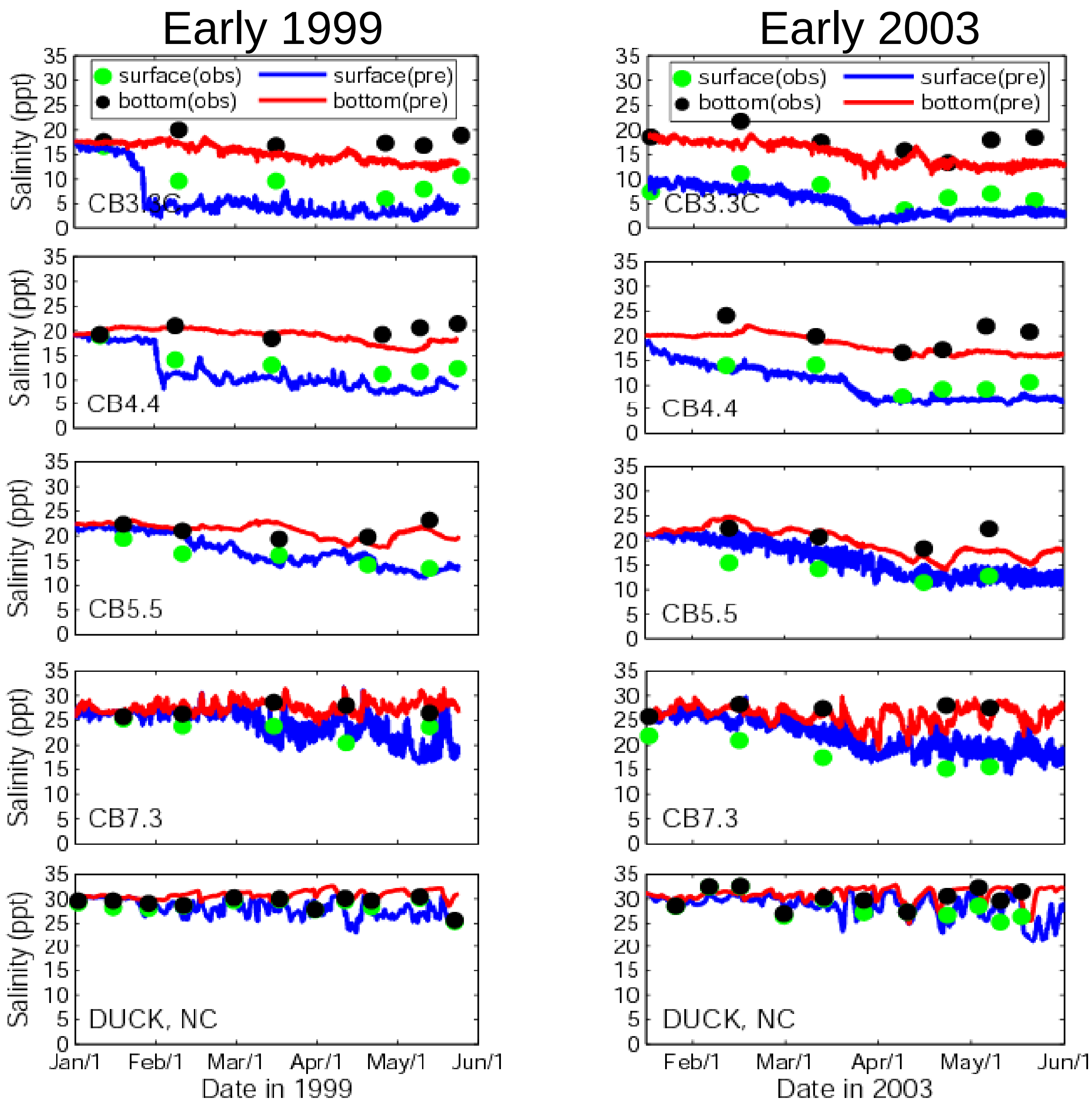
Axial velocity comparison (SELFE)



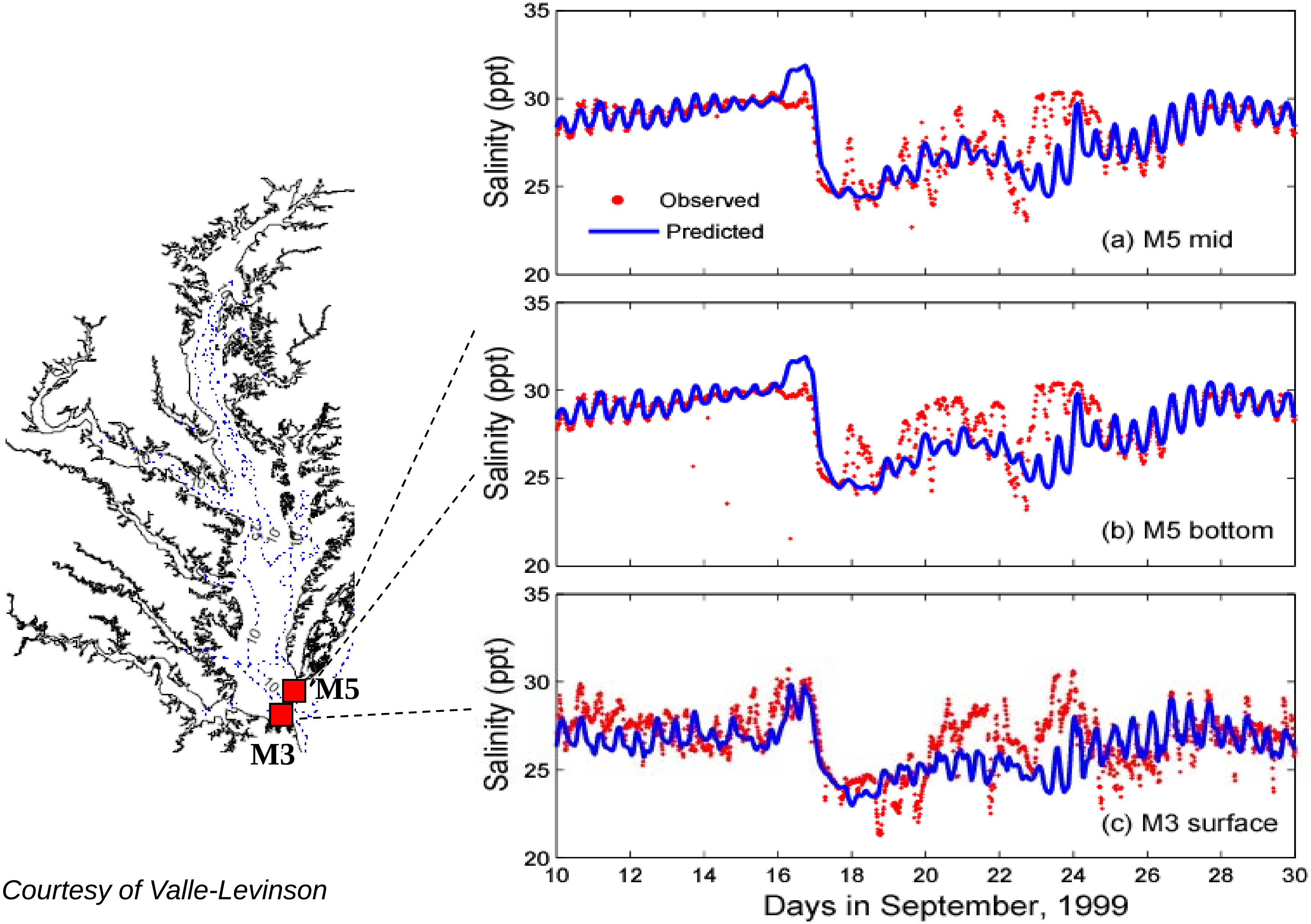
*** Courtesy of Valle-Levinson and NOAA*

Salinity comparison (SELFE)



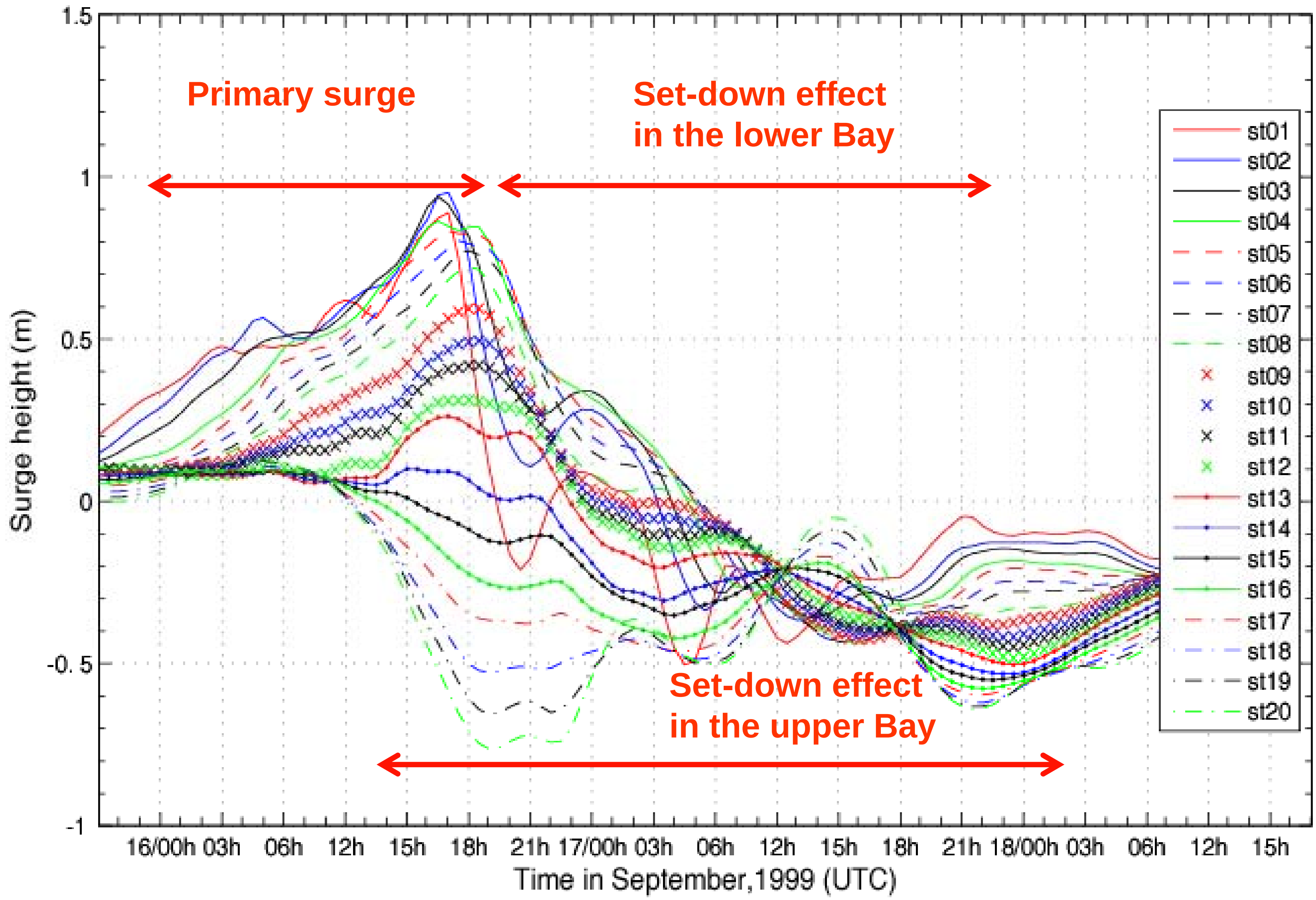


Salinity - Floyd (SELFE)



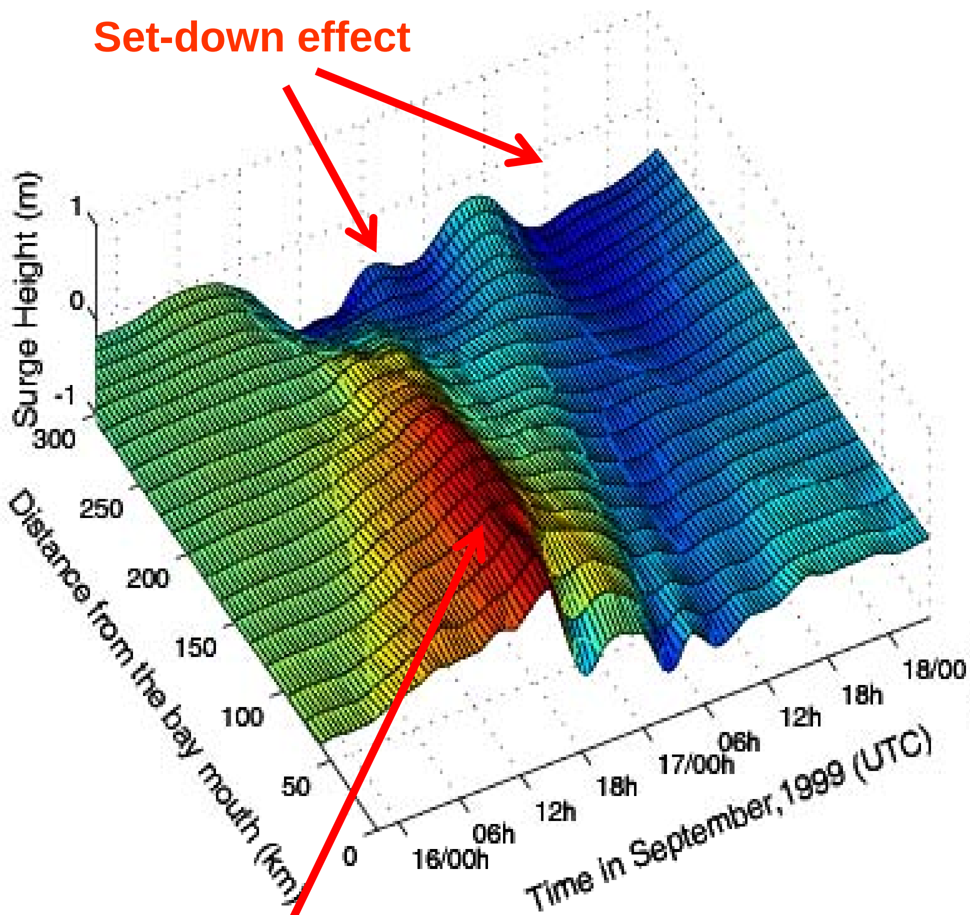
*** Courtesy of Valle-Levinson*

Storm surge time series - Floyd



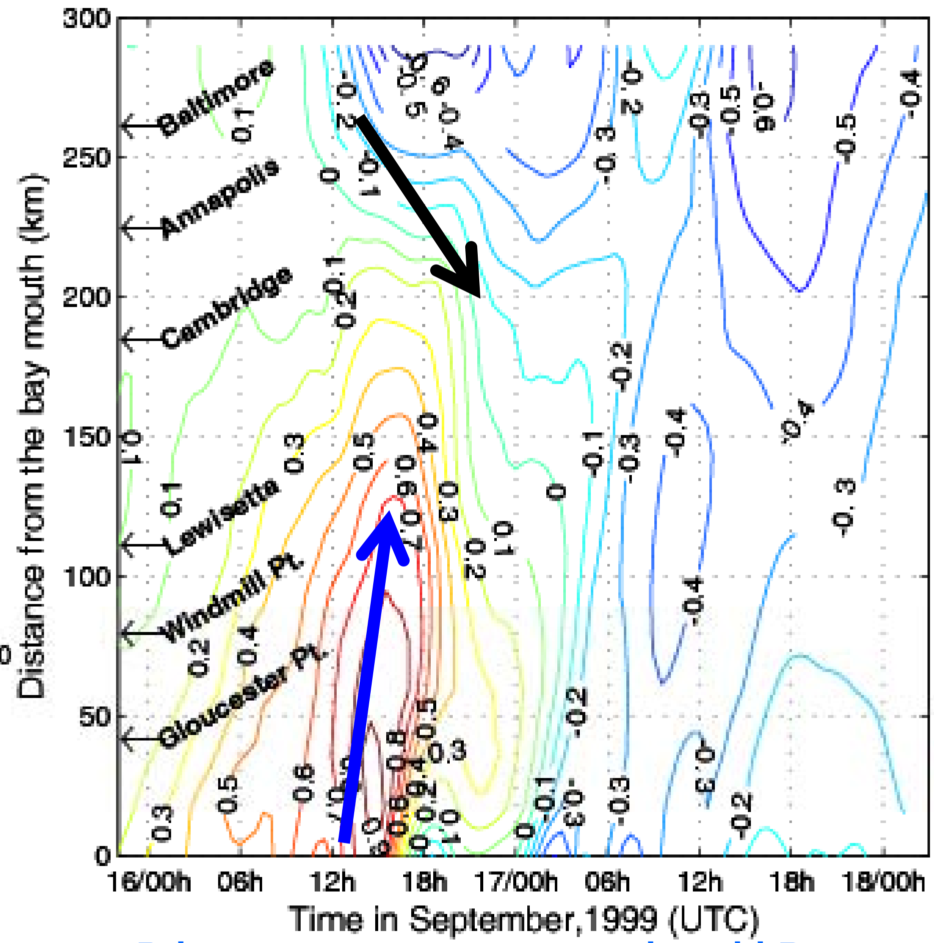
Storm surge plot in time-space domain - Floyd

Set-down effect



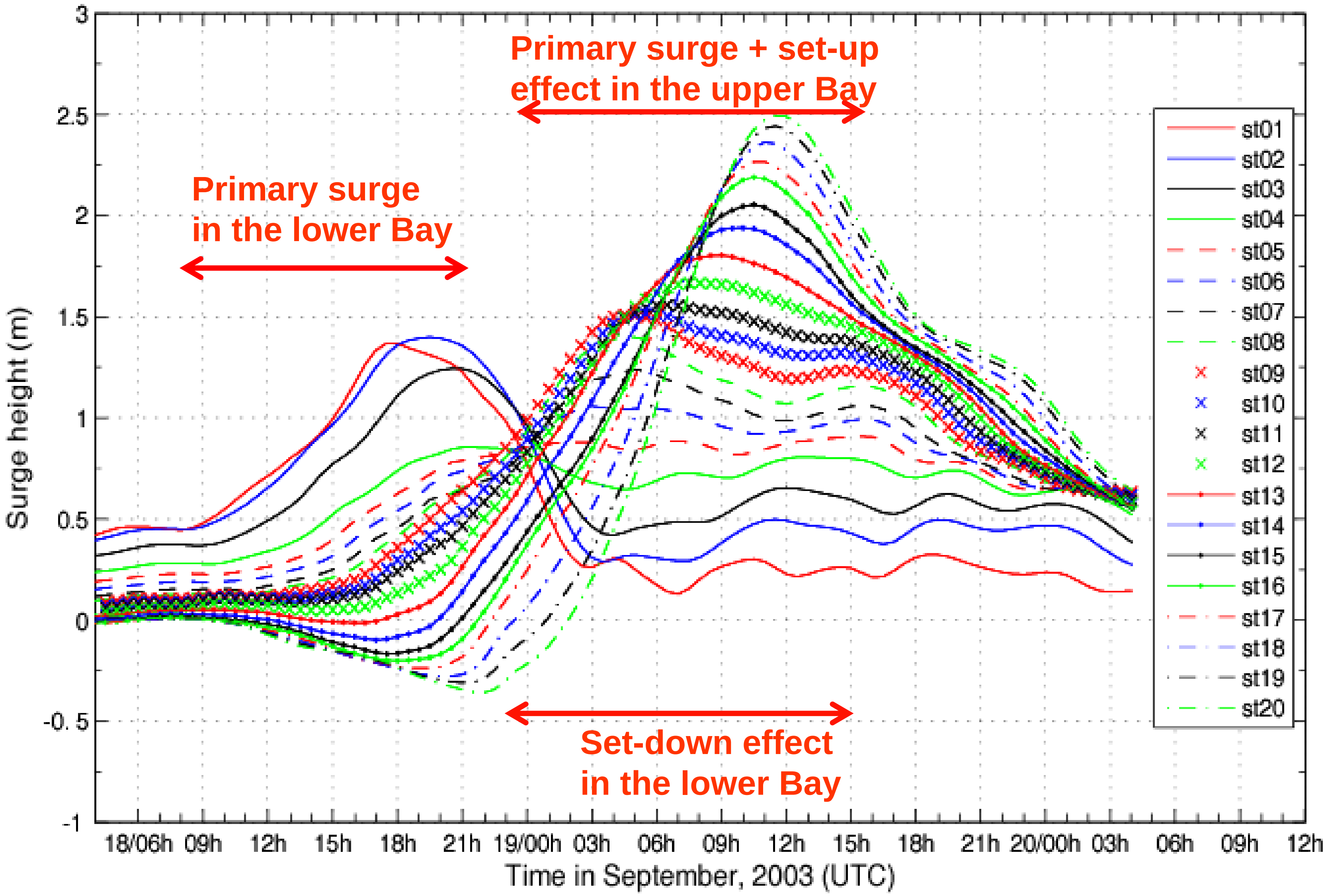
Primary surge + set-up effect

Negative surge phase appears to propagate to the mid-Bay



Primary surge propagate to the mid-Bay

Storm surge time series - Isabel



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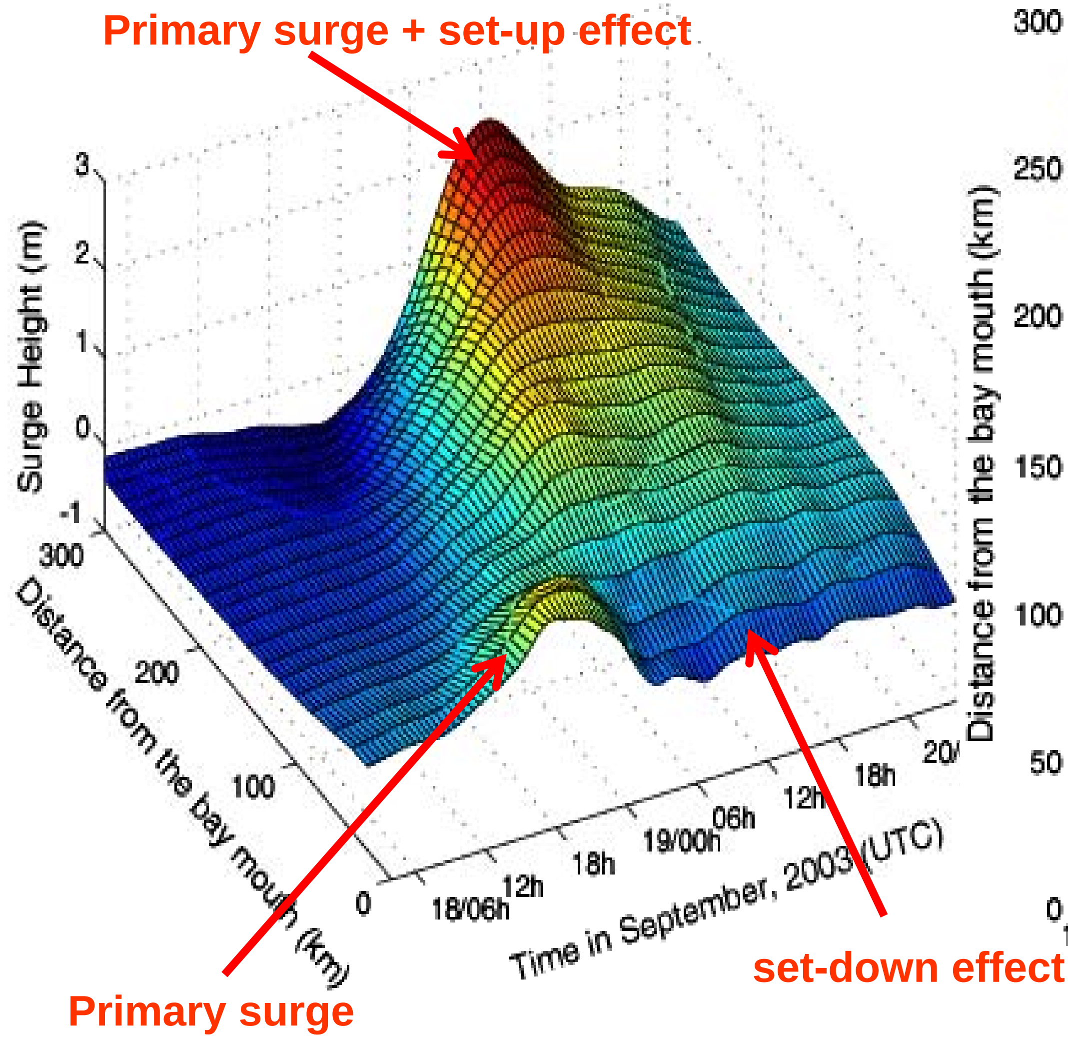
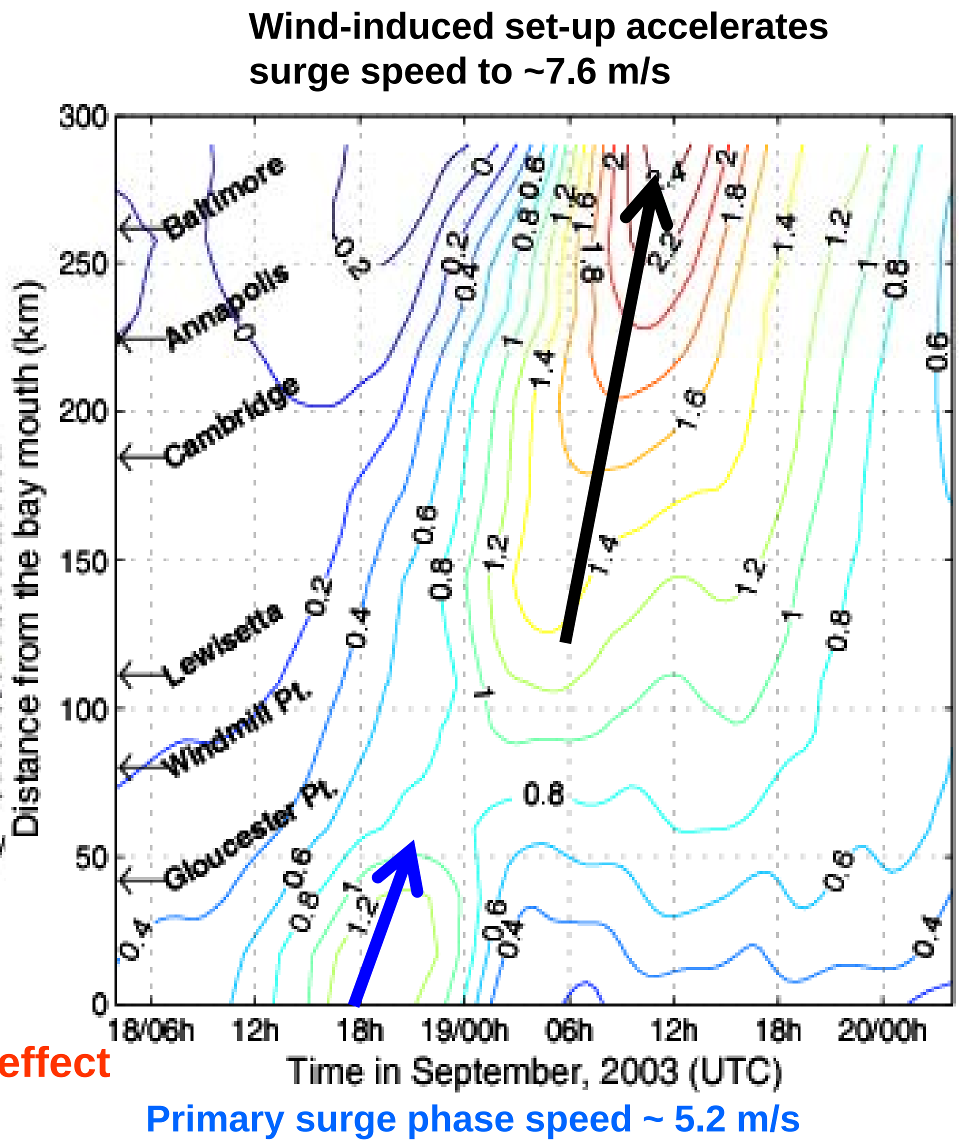
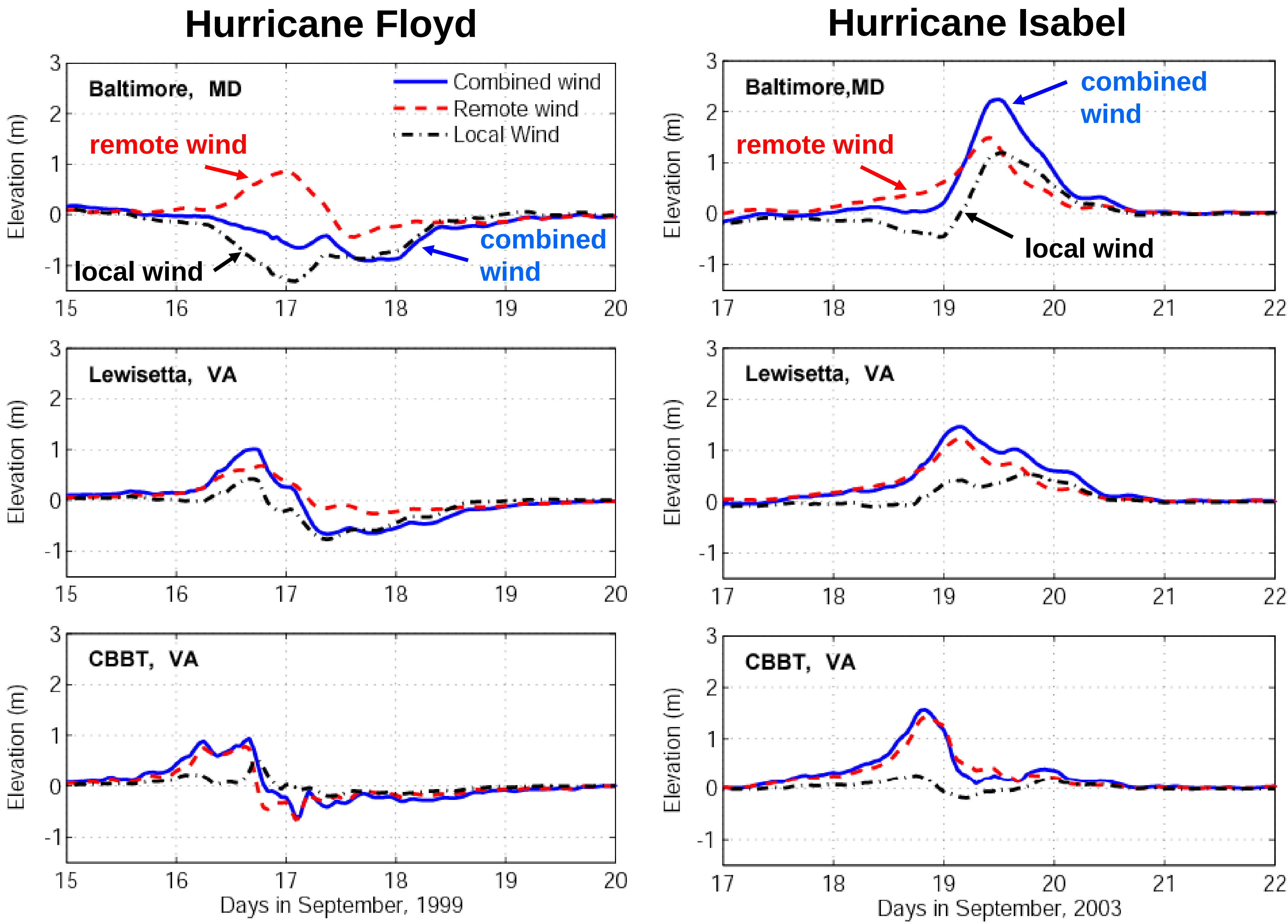
Surge plot in time-space domain - Isabel

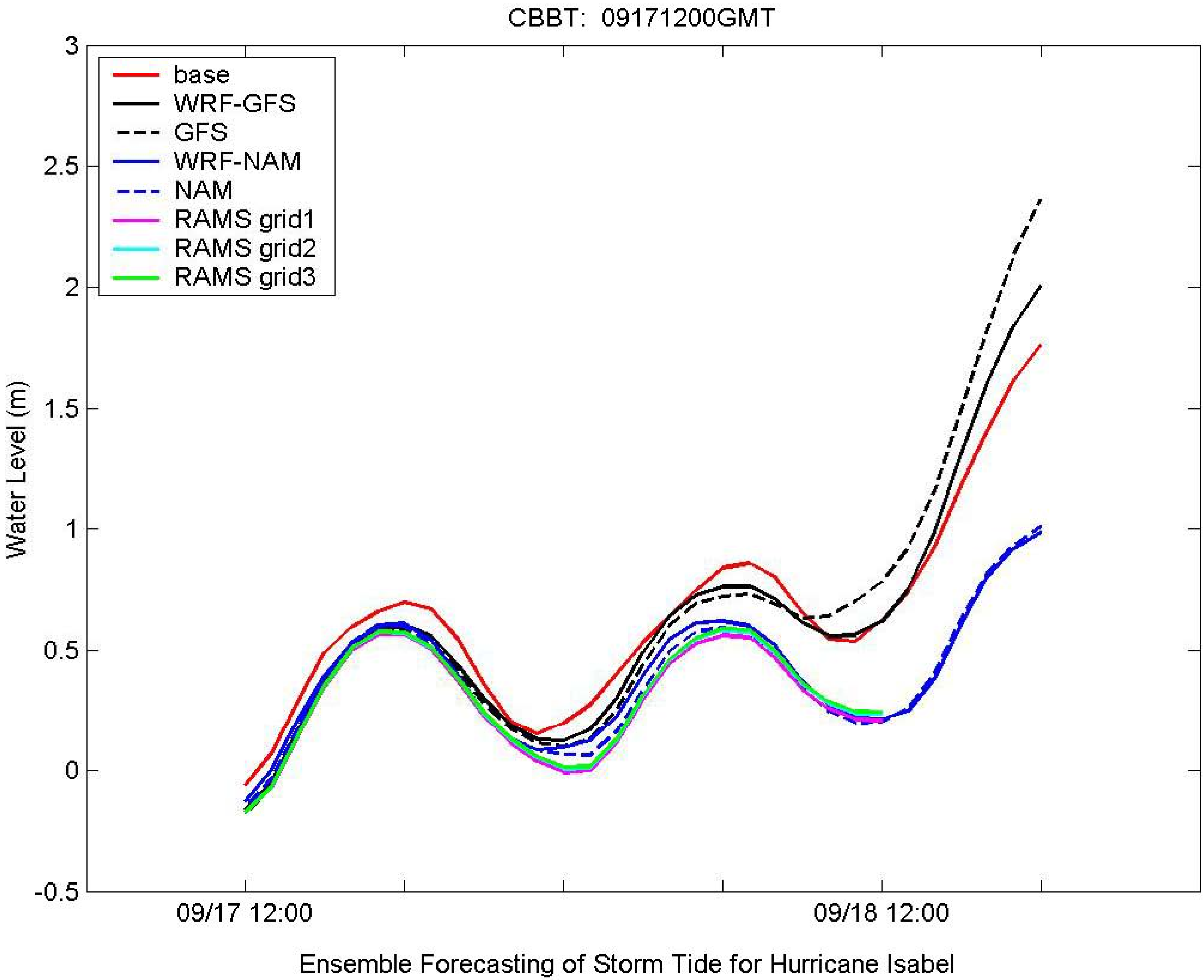


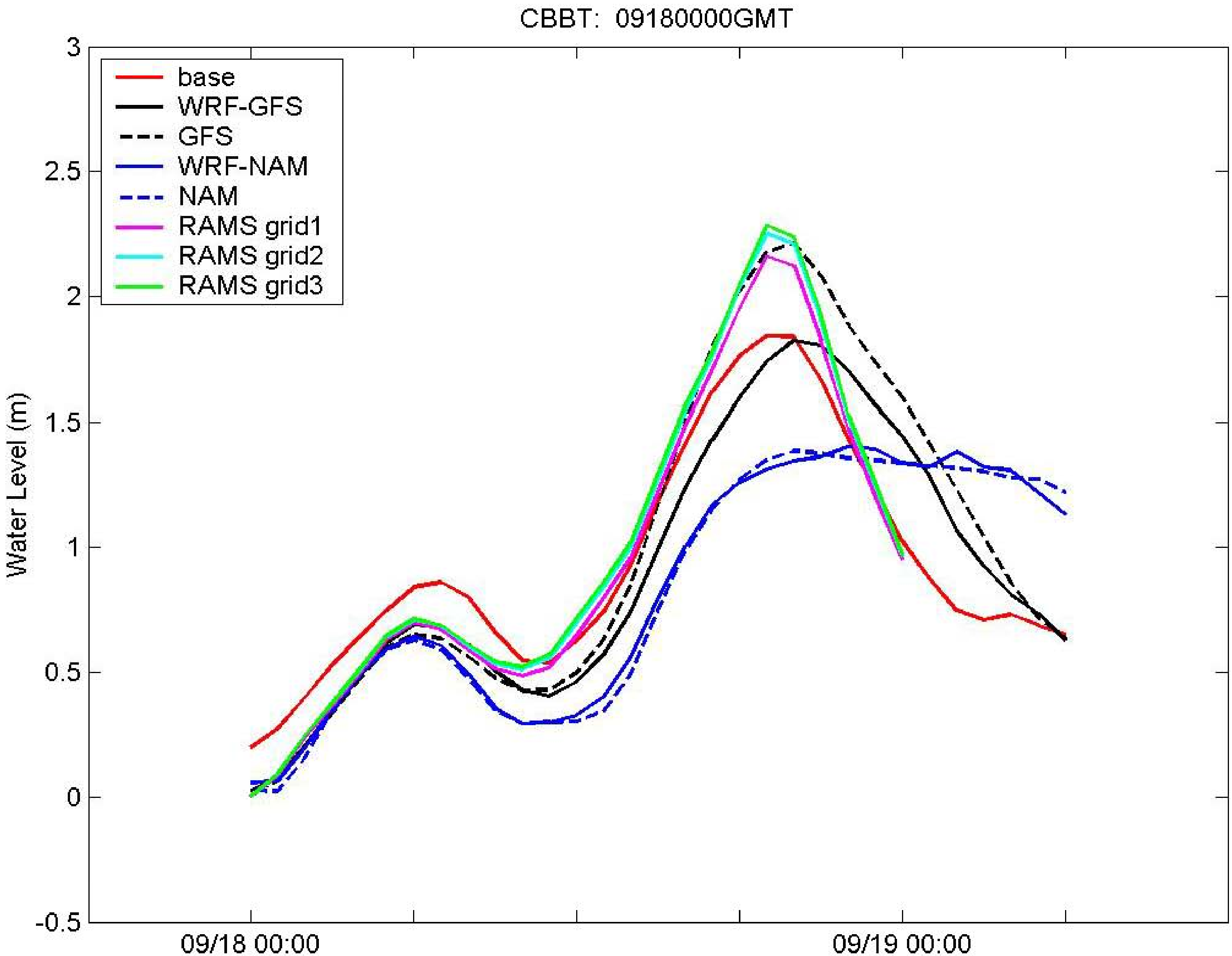


Effects of local wind versus remote wind

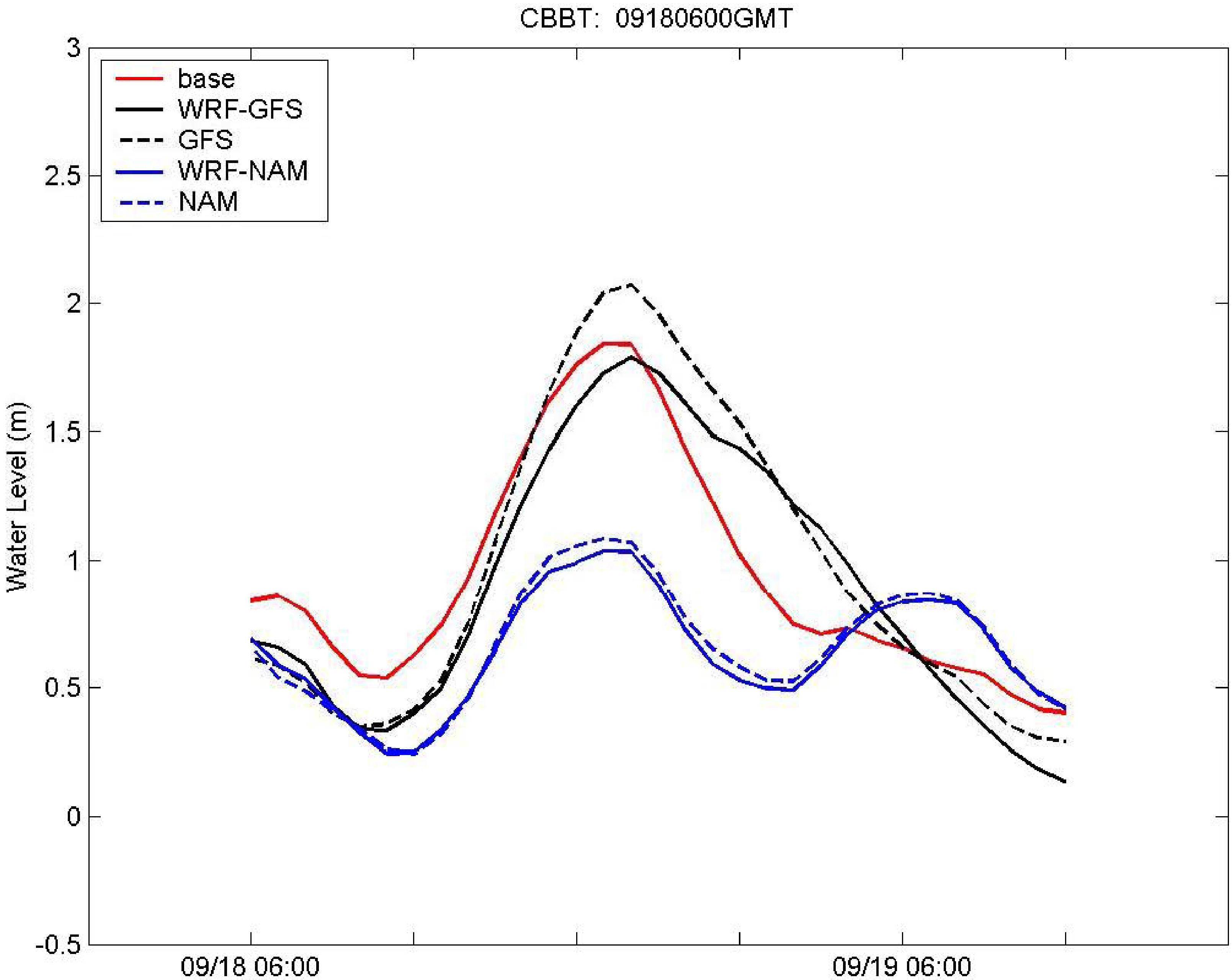


1. Ensemble simulation
2. Recent Northeaster event


CBBT: 09171200GMT
base
WRF-GFS
GFS
WRF-NAM
NAM
RAMS grid1
RAMS grid2
RAMS grid3
Water Level (m)
3
2.5
2
1.5
1
0.5
0
-0.5
09/17 12:00
09/18 12:00
Ensemble Forecasting of Storm Tide for Hurricane Isabel



Ensemble Forecasting of Storm Tide for Hurricane Isabel

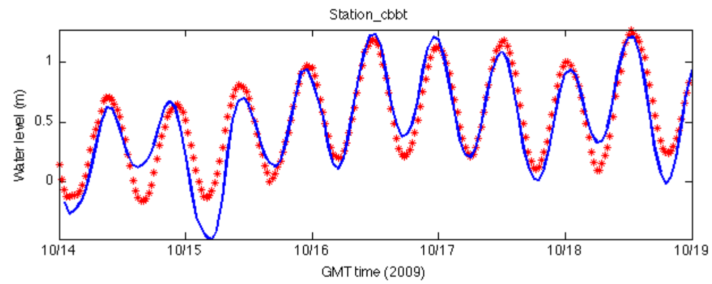


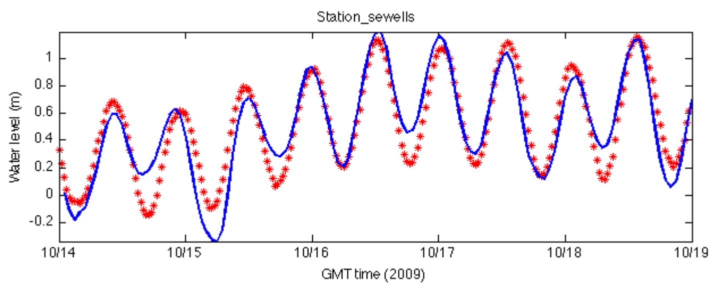
Ensemble Forecasting of Storm Tide for Hurricane Isabel

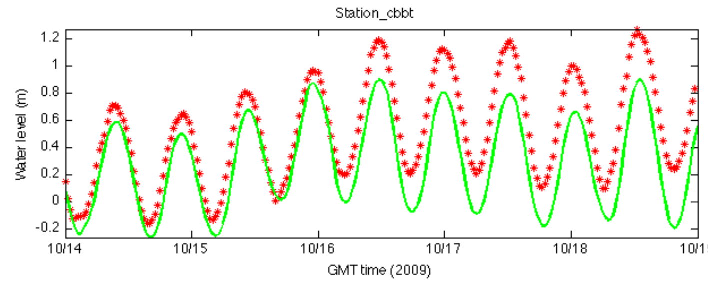
Northeaster October 14-18, 2009

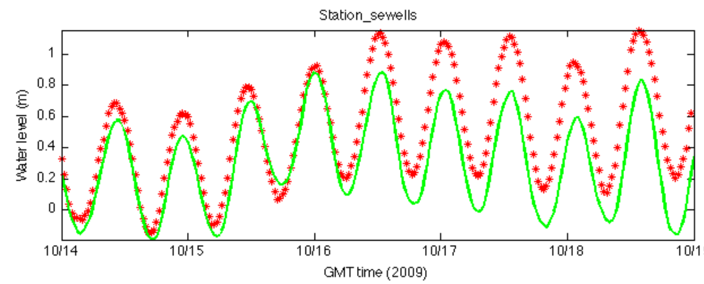
With large domain

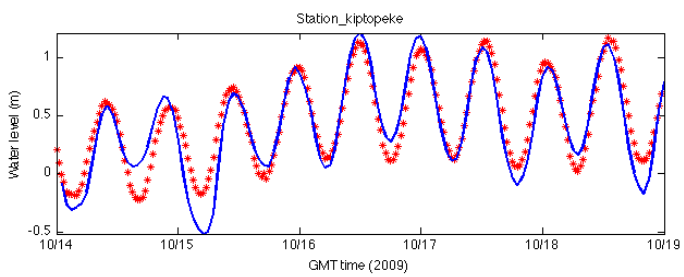
Without Large domain

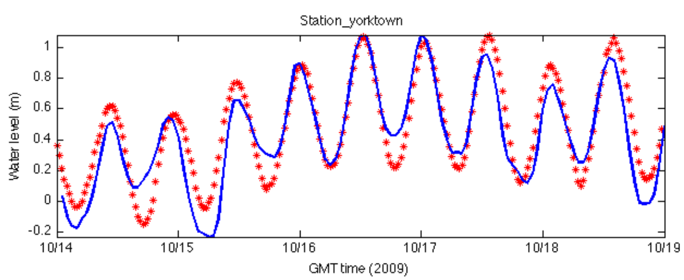


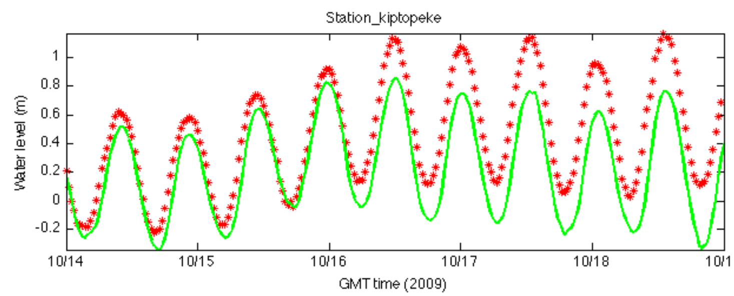


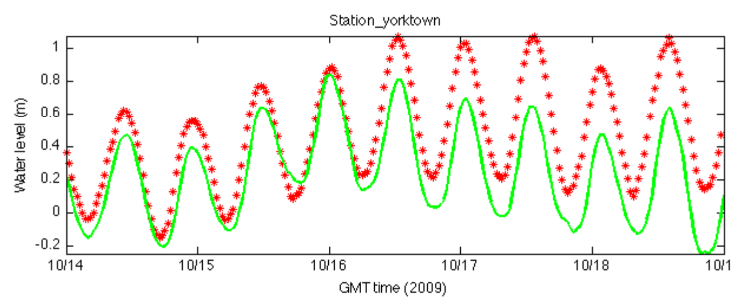


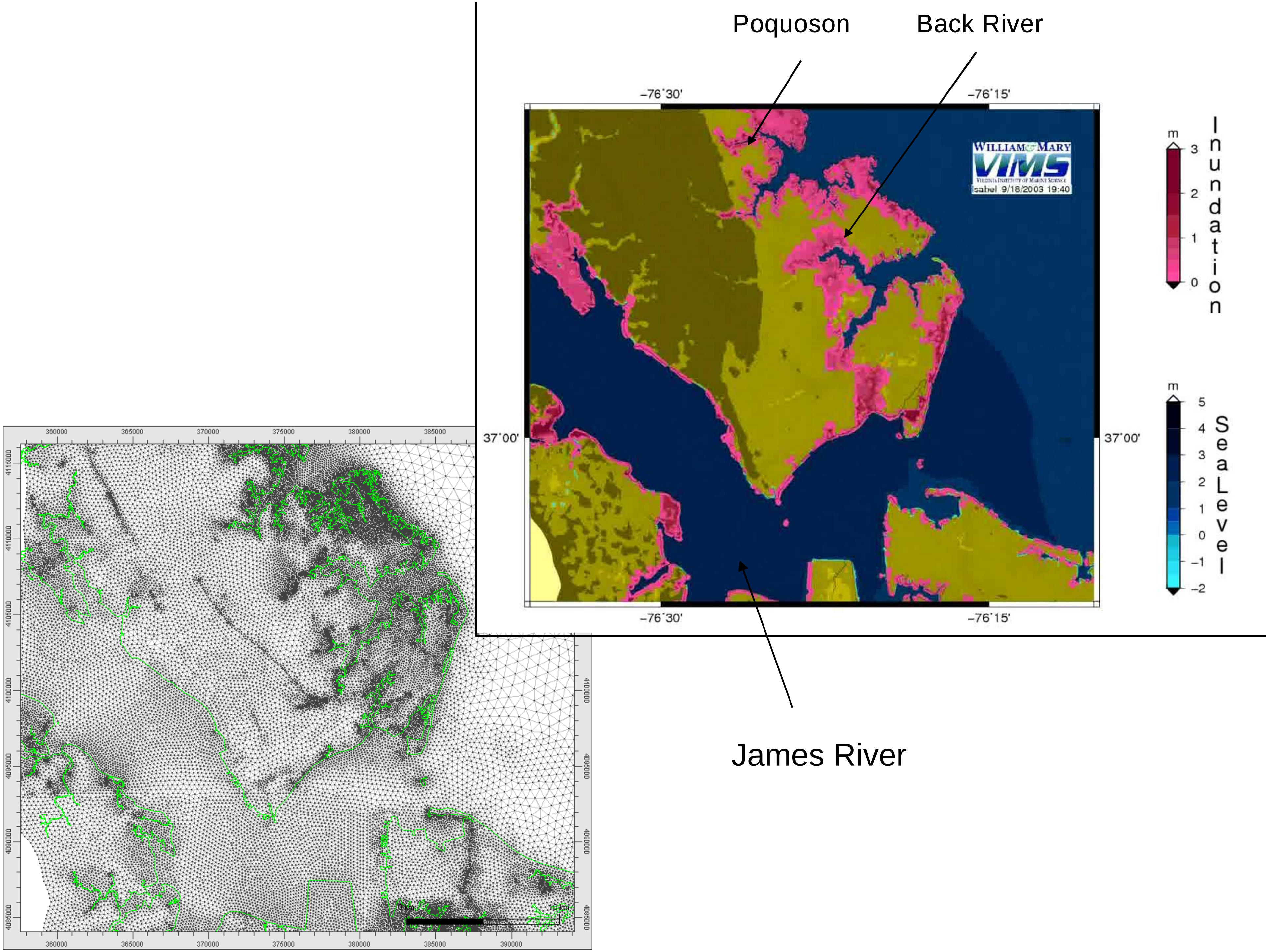











Poquoson
Back River
James River
-76°30'
-76°15'
37°00'
Isabel 9/18/2003 19:40
m
Inundation
m
Sea Level

Summary:

1. A prototype large domain and high resolution storm surge/inundation model system has been developed succefully for the Chesapeake Bay.

2. Hydrodynamic models employed are a class of unstructured grid model using semi-implicit, Eulerian-Lagragian schemes which are efficient, robust, and relatively stable. The computer resource required are moderate.

Summary (cont'):

3. The hydrodynamic model is coupled with large scale atmospheric models. The storm surge responses are tightly coupled with the wind field from the atmospheric model. Ensemble approach is used to reduce uncertainty.

4. The implementation of inundation simulation and sea level rise scenario will be followed by presentation from Noblis an Northrop Grumman. The results in Upper Potomac River and Hampton Road show promising results.

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