Simulating Compound flooding events in a hurricane using SCHISM

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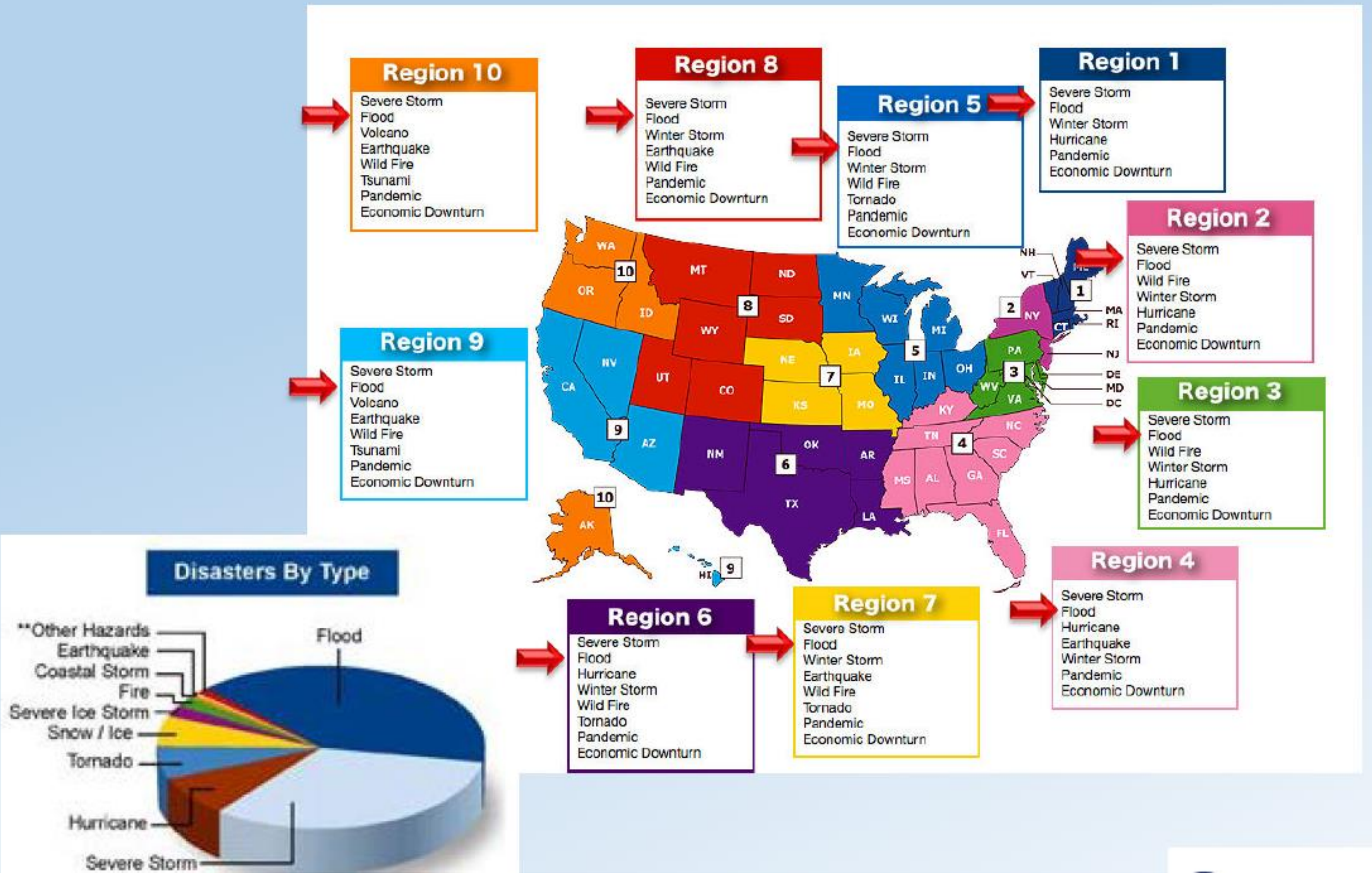
CCCoP webinar, July 10, 2019

Motivation



- Most flood hazard losses are from inland flooding (e.g. the recent Missouri flood)!
- Coastal zones often experience both river & storm induced flooding

c/o: Maryam Haji, TransRE

Overview

- Total Water Level Project
- Hurricane Irene (2011): observation of compound flooding
- SCHISM modeling system
- Storm surge, river flooding and compound surges
- Conclusions

Water Initiative

NOAA Water Initiative (TWL-projects, NOS/CSDL)

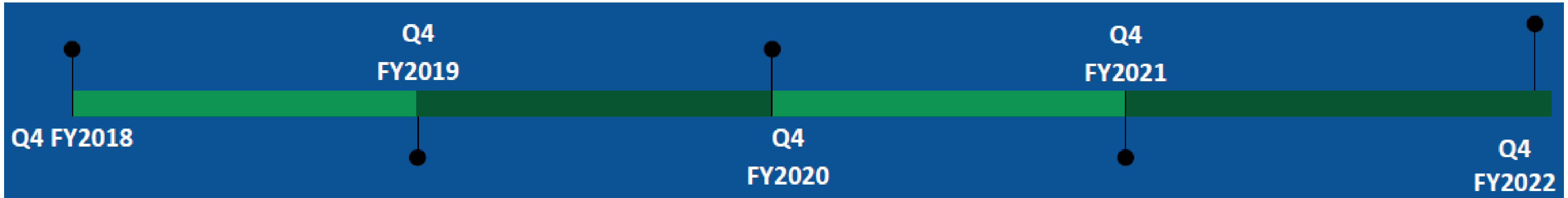
- University of Oklahoma: “Steps Towards Automating River Connections and Addressing Precipitation in ADCIRC”
- Notre Dame University: “Grid Development and Automated Grid Generation for River Connections”
- Virginia Institute of Marine Sciences: “Implementing SCHISM model to Improve Integrated Water Modeling Projects”

IOOS Coastal Ocean Modeling Testbed (COMT)

- University of North Carolina: “Coupling the National Water Model to the Coastal Ocean for Predicting Water Hazards”
- University of Massachusetts-Dartmouth: “Coupling the Northeast Coastal Ocean Forecast System (NECOFS) to NWM and the Water Balance Model”
- North Carolina State University: “Multi-Level River-Ocean Coupling using the Coupled Northwest Atlantic Prediction System”

Joint Technology Transfer Initiative (JTTI)

- Notre Dame University: “Advancing ADCIRC U.S. Atlantic and Gulf Coast Grids and Capabilities to Facilitate Coupling to the National Water Model in ESTOFS Operational Forecasting”



Q4 FY2018

Q4 FY2019

Q4 FY2020

Q4 FY2021

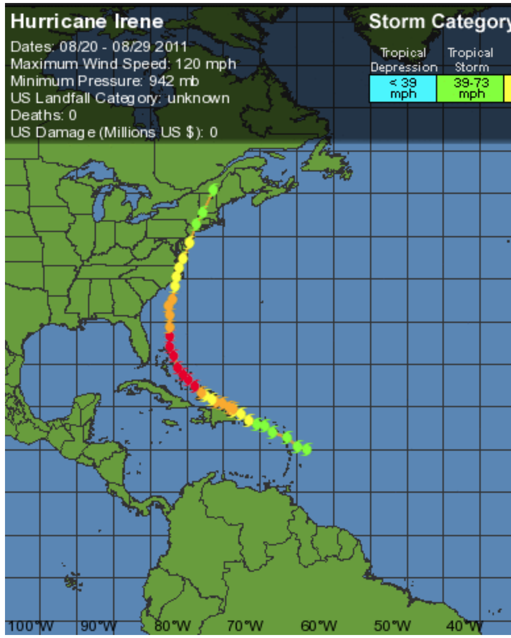
Q4 FY2022

c/o Saeed Moghimi

Hurricane Irene (2011)

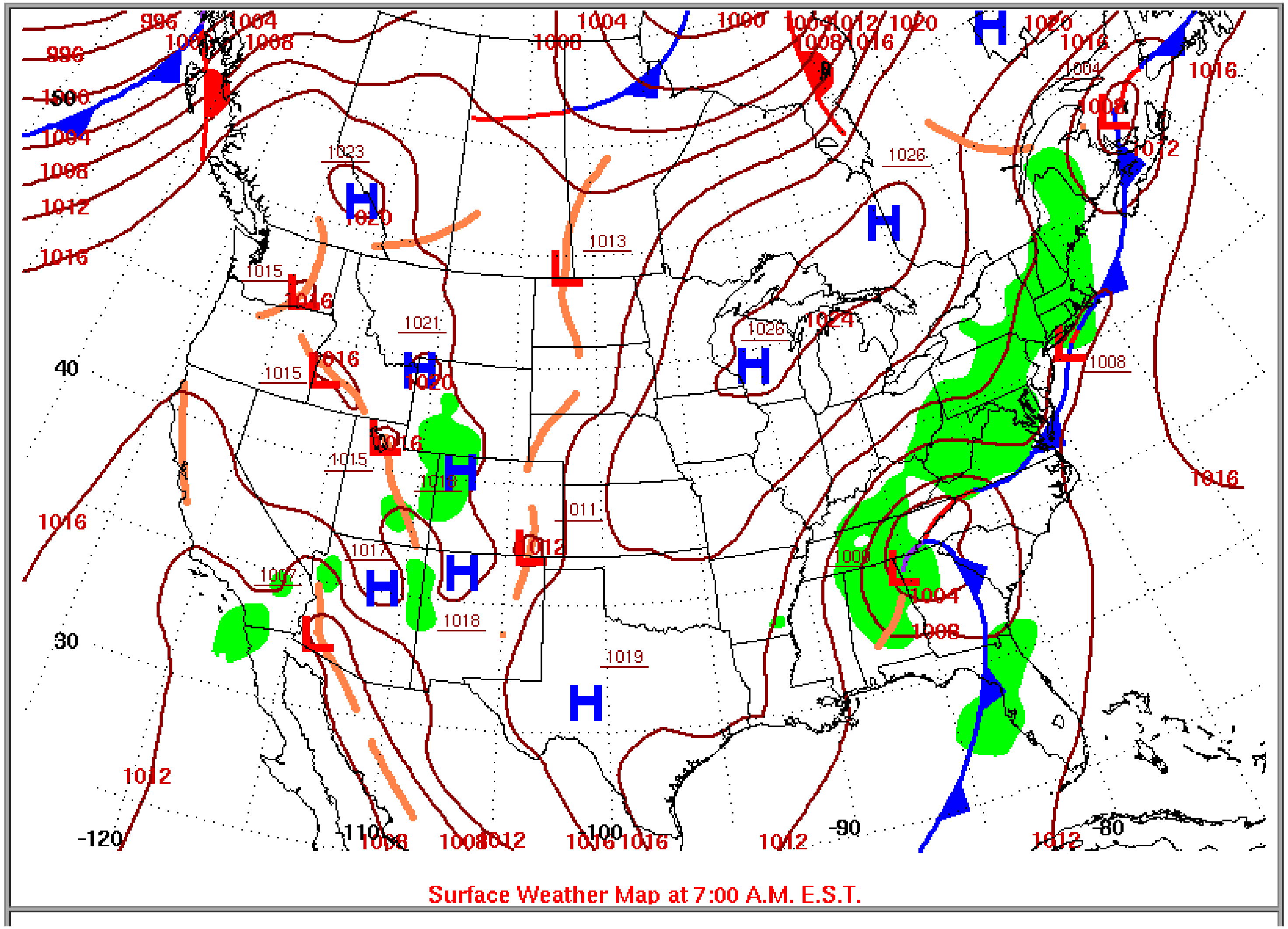
- A large and destructive tropical cyclone that affected much of the Caribbean and East Coast of the United States during late August 2011
- The ninth named storm, first hurricane, and first major hurricane of the 2011 Atlantic hurricane season, originated from a tropical wave east of the Lesser Antilles
- Made first landfall in St. Croix as a strong tropical storm on August 20, 2011
- Made a second landfall in Puerto Rico on August 21 and while crossing the island, Irene strengthened into a Category 1 hurricane
- Continued to slowly intensify offshore of Hispaniola and made fourth landfall in the Bahamas as a Category 3 hurricane

- The storm curved northward after passing east of Grand Bahama before making landfall on the Outer Banks of North Carolina on August 27, becoming the first hurricane to make landfall in the United States since Hurricane Ike in 2008
- The storm re-emerged into the Atlantic from southeastern Virginia and weakened to a tropical storm while making yet another landfall in the Little Egg Inlet in southeastern New Jersey on August 27
- A few hours later, Irene made its ninth and final landfall in Brooklyn, New York City
- On August 29, Irene transitioned into an extratropical cyclone hitting Vermont
- Irene caused widespread destruction (~$13.5 billion) and at least 49 deaths, making it one of the costliest hurricanes on record in the country.

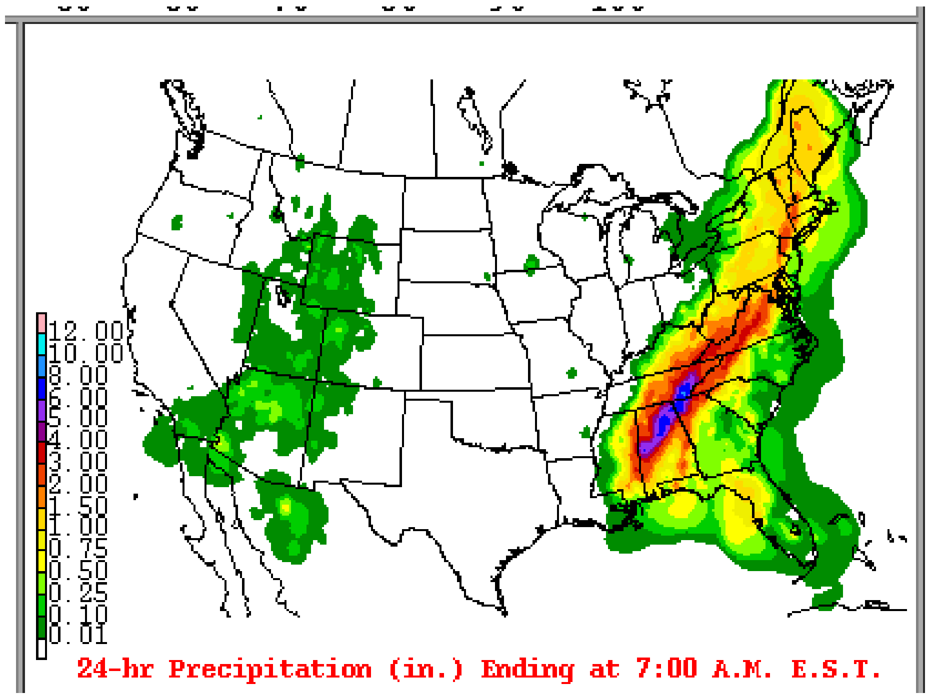


Weather map

TUESDAY SEPTEMBER 6, 2011



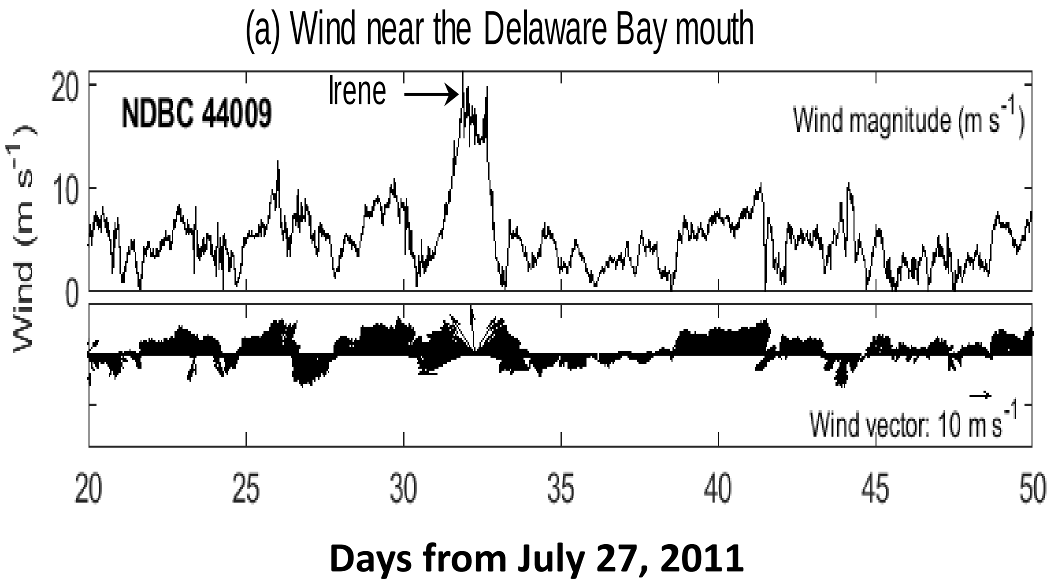
Surface Weather Map at 7:00 A.M. E.S.T.

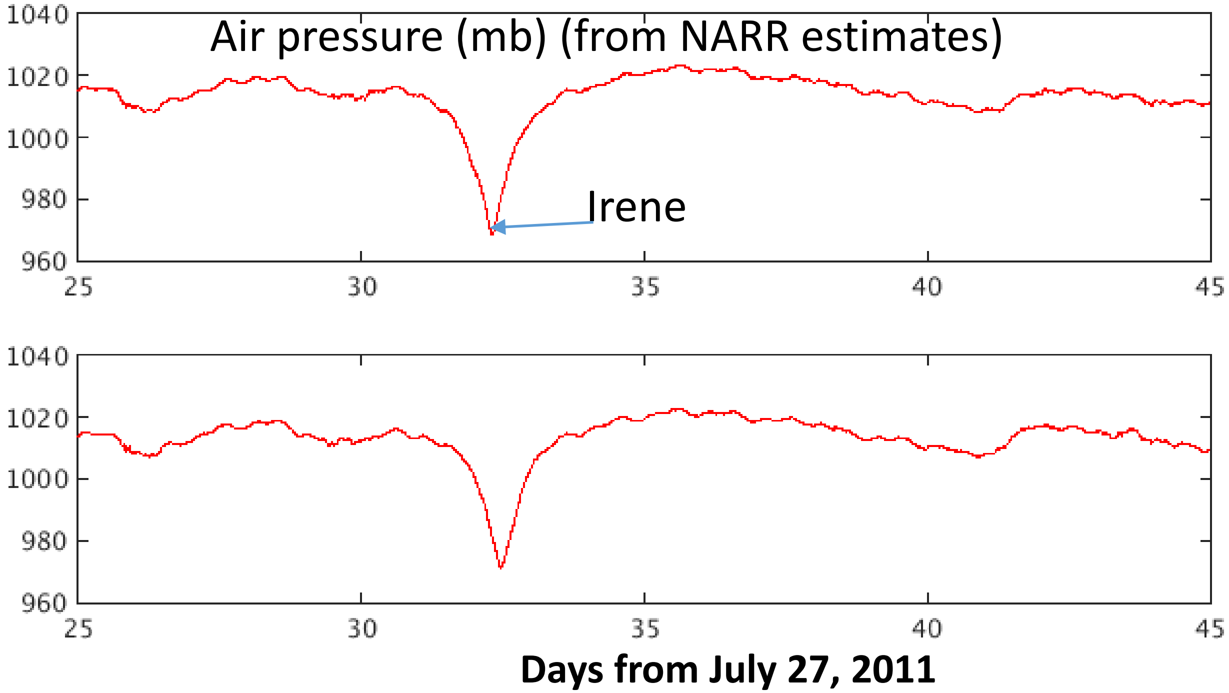


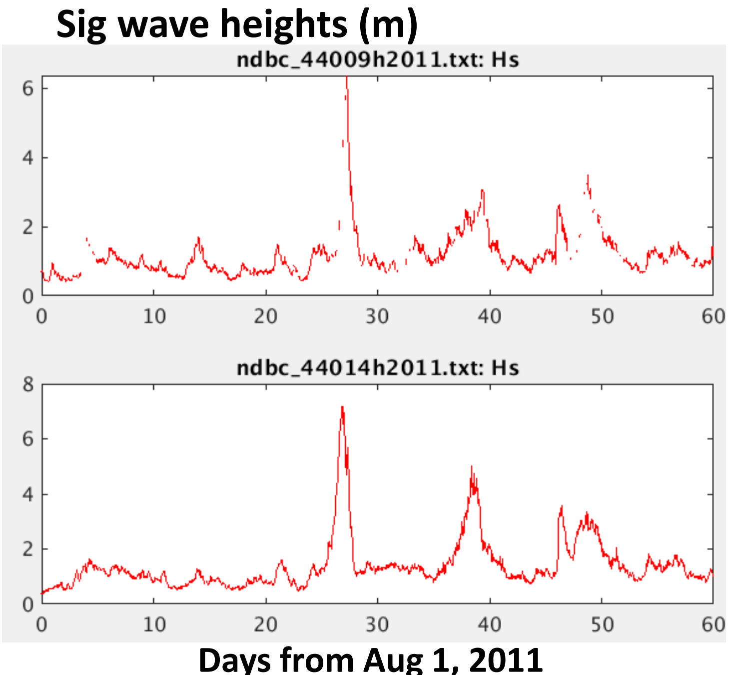
24-hr Precipitation (in.) Ending at 7:00 A.M. E.S.T.

Heavy precipitation persisted *after* Irene, setting stage for compound flooding

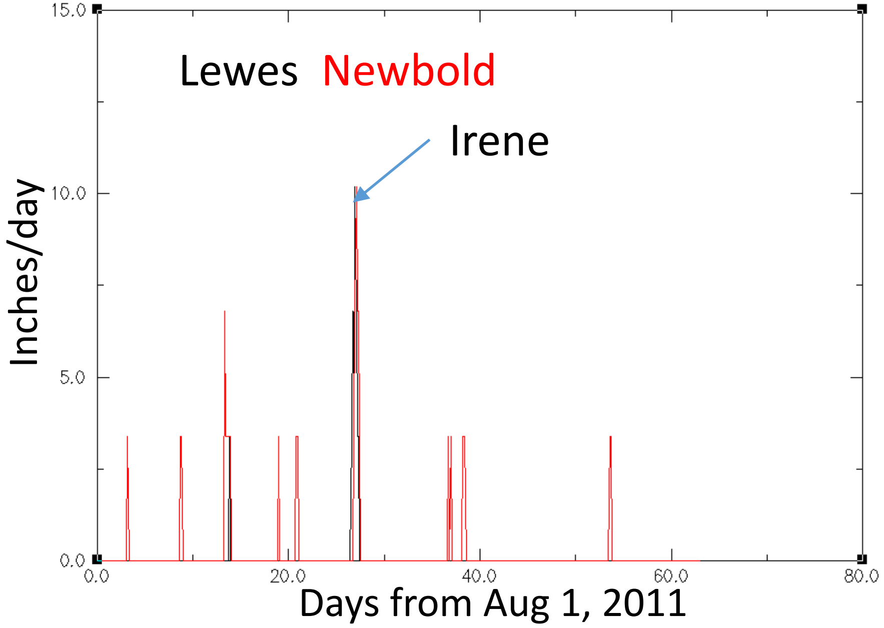
Hurricane Irene: precipitation & wind observation





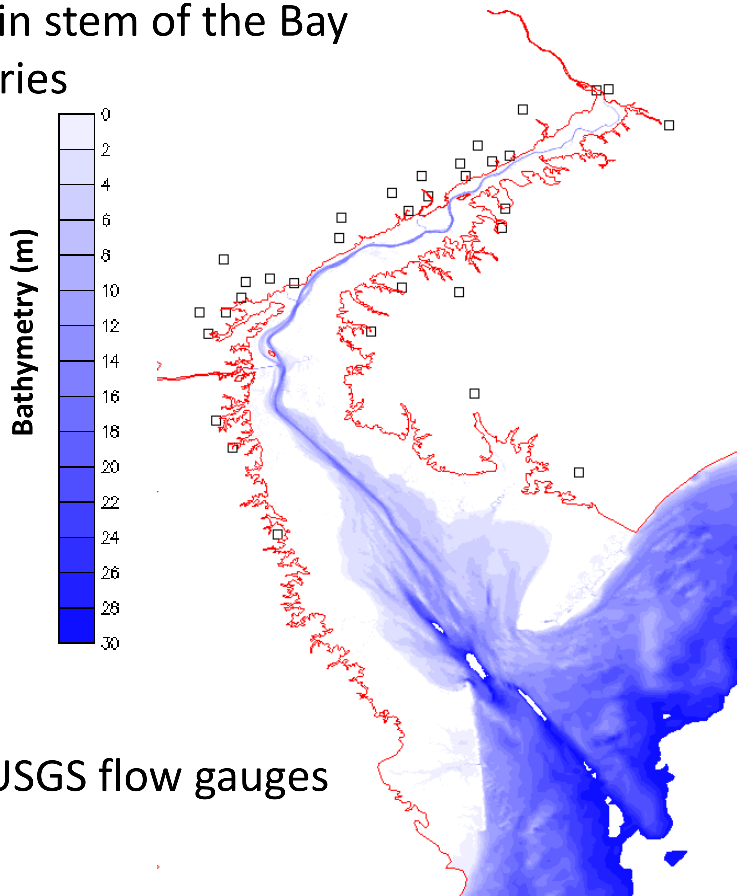


- Wind is strongest during Irene
- Heavy precipitation accompanied the hurricane. There are also a few smaller events before & after the hurricane

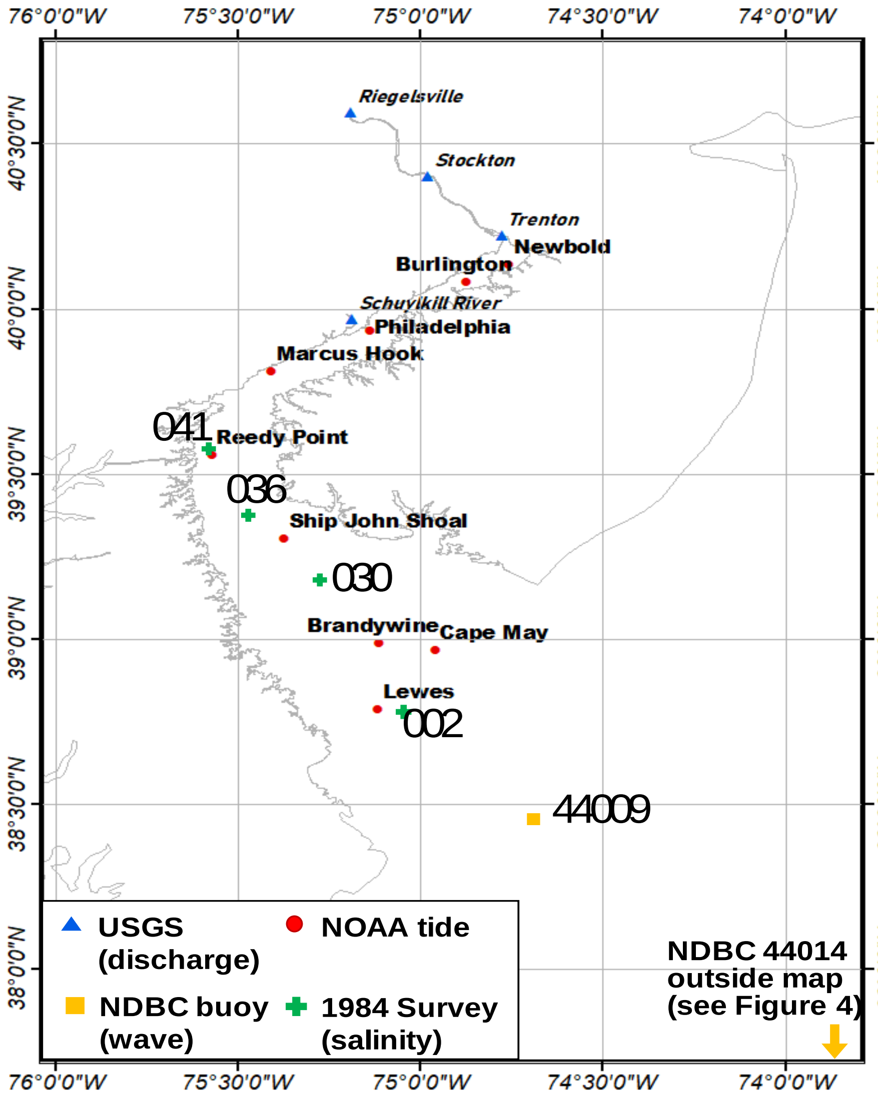


Observational datasets

- Many NOAA and USGS stations were operational during the hurricane
- Multiple state agencies also have estimates on inundation extent
- In addition we have also looked at weather station records for precipitation etc
- We will focus on Delaware Bay at stations below 10m NGVD29 and let NWM deal with stations on higher ground
    - NOAA gauges: along main stem of the Bay
    - USGS gauges: on tributaries
    - Satellite

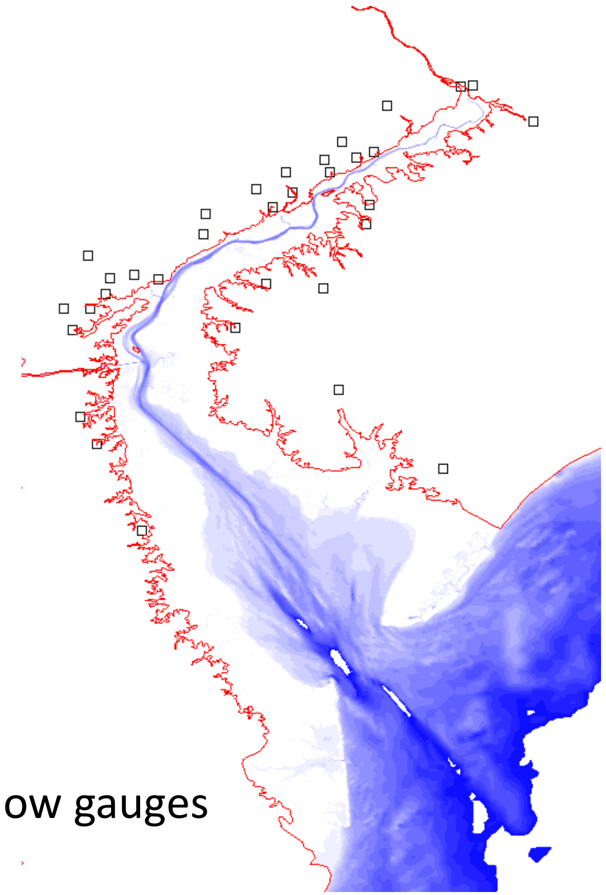


USGS flow gauges

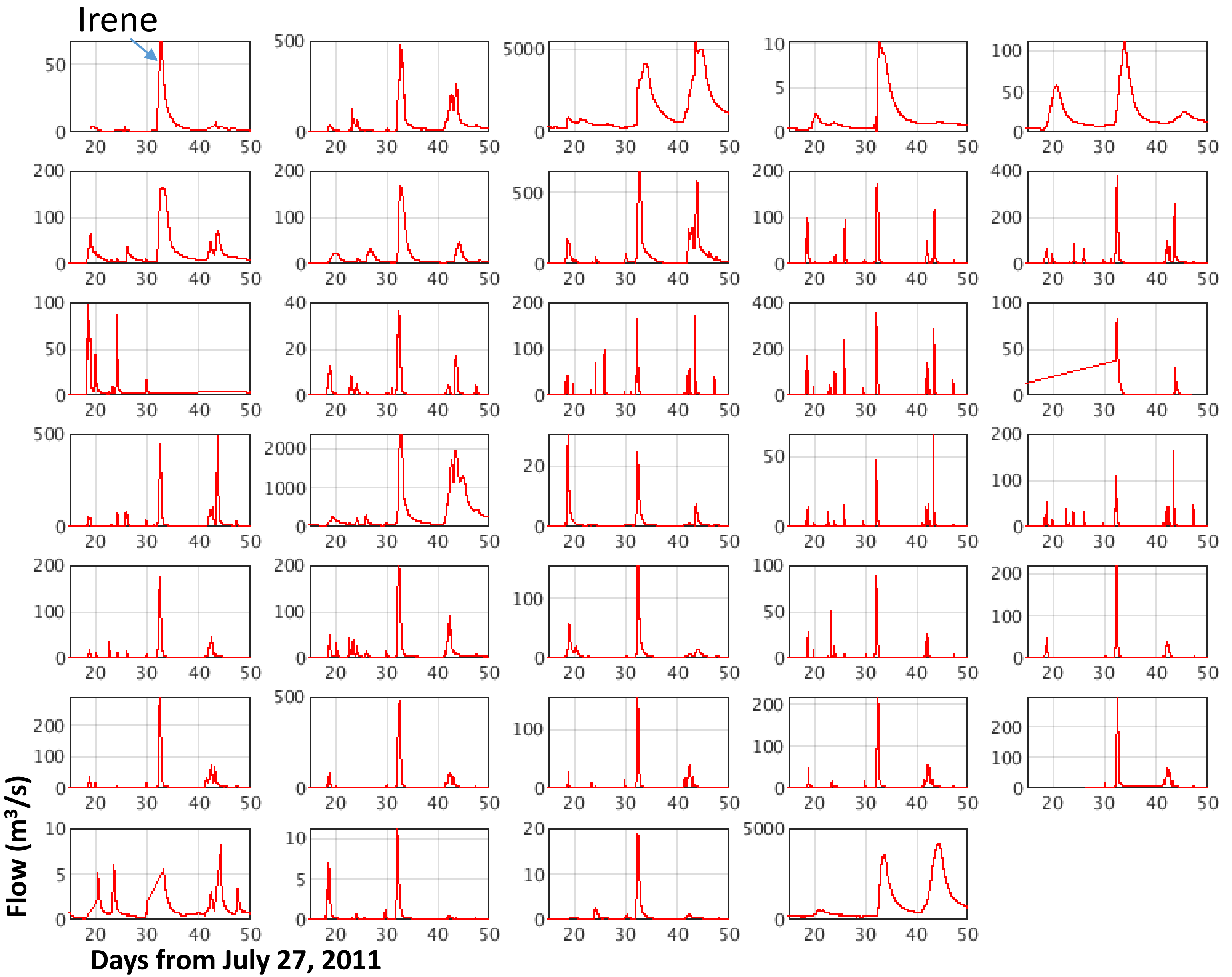


Hurricane Irene: observed flow (USGS)

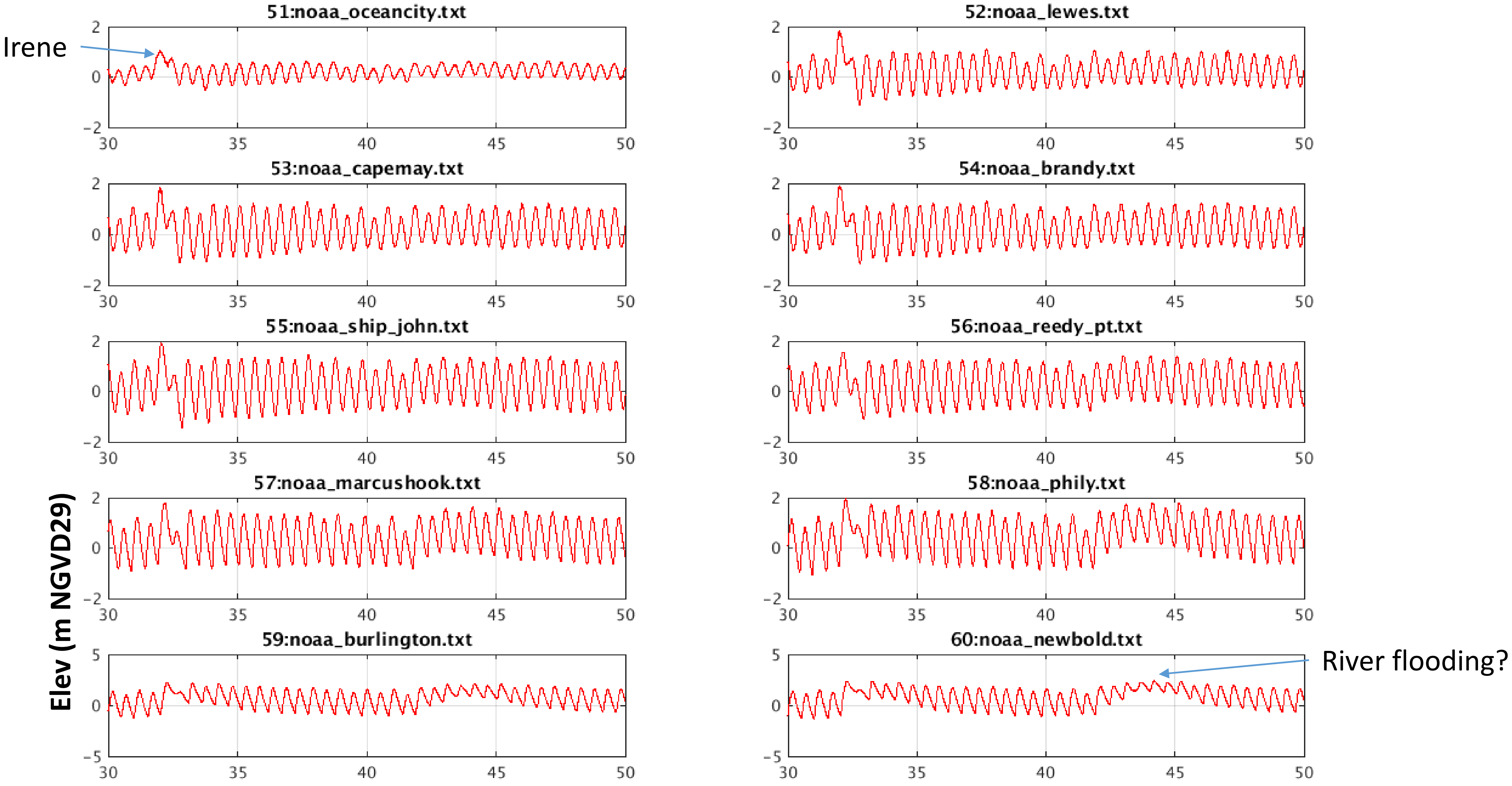
Flash floods in most rivers after Irene!



USGS flow gauges



Hurricane Irene: observed surface elevation (NOAA)



* Besides Irene, there is a 2nd surge a week later, due to river flooding

SCHISM: Semi-implicit Cross-scale Hydroscience Integrated System Model

SELFE/SCHISM

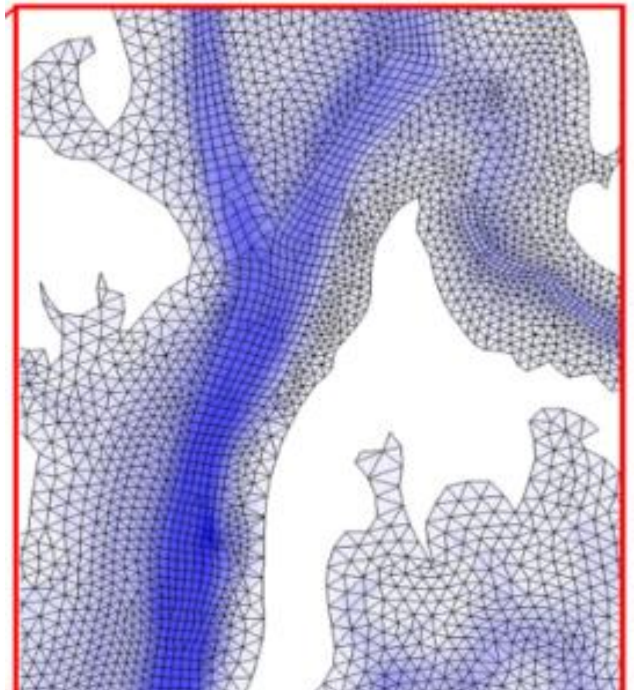
- From SELFE to SCHISM
  - A derivative product of SELFE v3.1, distributed with open-source Apache v2 license
  - Substantial differences now exist between the two models
  - Active community participation: ~70 developers/power users via svn
- Solves Navier-Stokes equations in hydrostatic form with Boussinesq approximation
- Galerkin finite-element and finite-volume approach: generic unstructured grids
- Semi-implicit time stepping: no mode splitting → large time step and no splitting errors
- Eulerian-Lagrangian method (ELM) for momentum advection → efficiency & robustness
- Major differences from SELFE v3.1

SCHISM

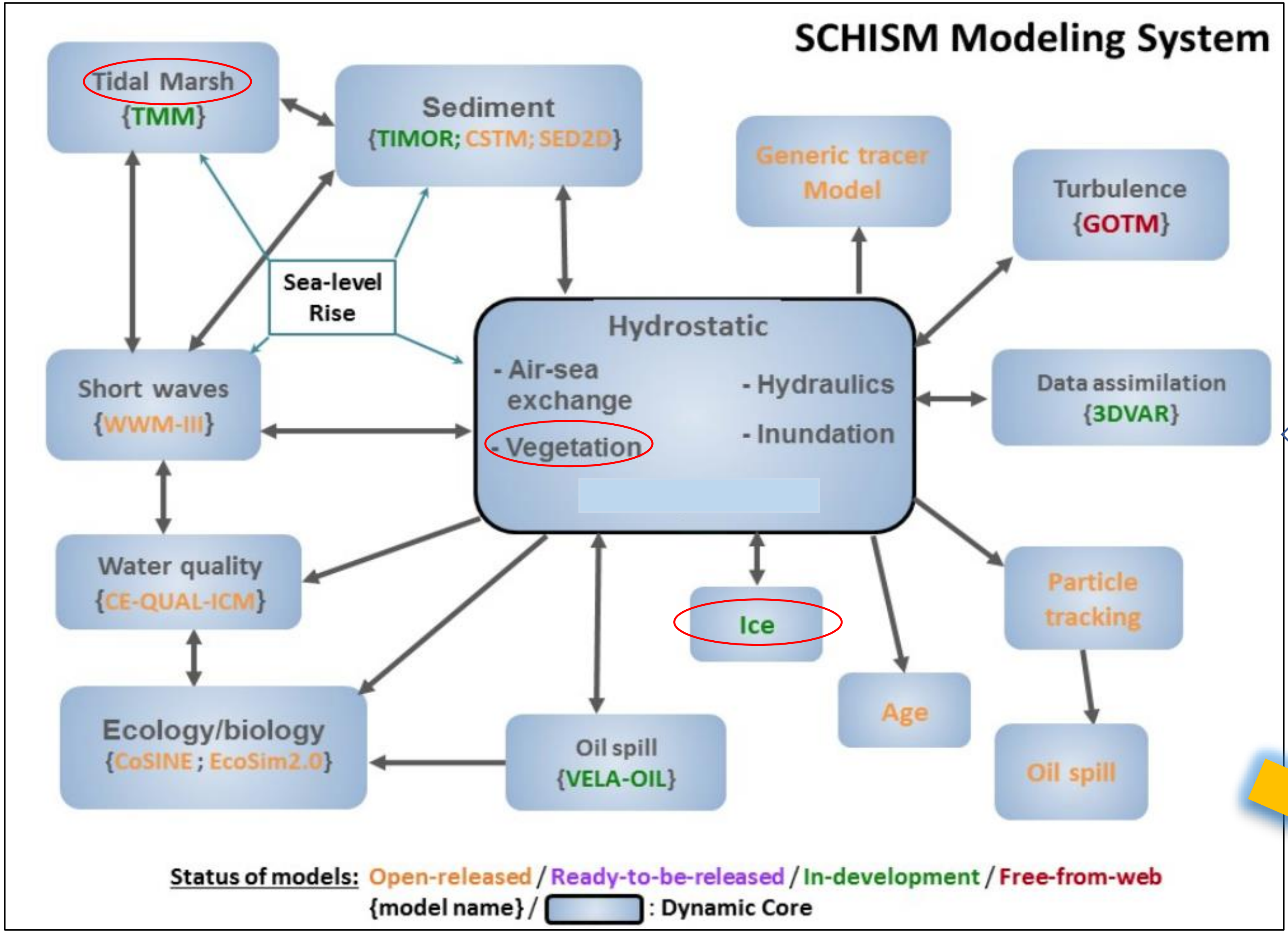
  - Apache license
  - Mixed grids (tri-quads)
  - LSC^2 vertical grid
  - Implicit TVD transport (TVD^2); WENO3; *all with monotonicity enforced*
  - Higher-order ELM with ELAD
  - Upwind biased momentum advection
  - Bi-harmonic viscosity

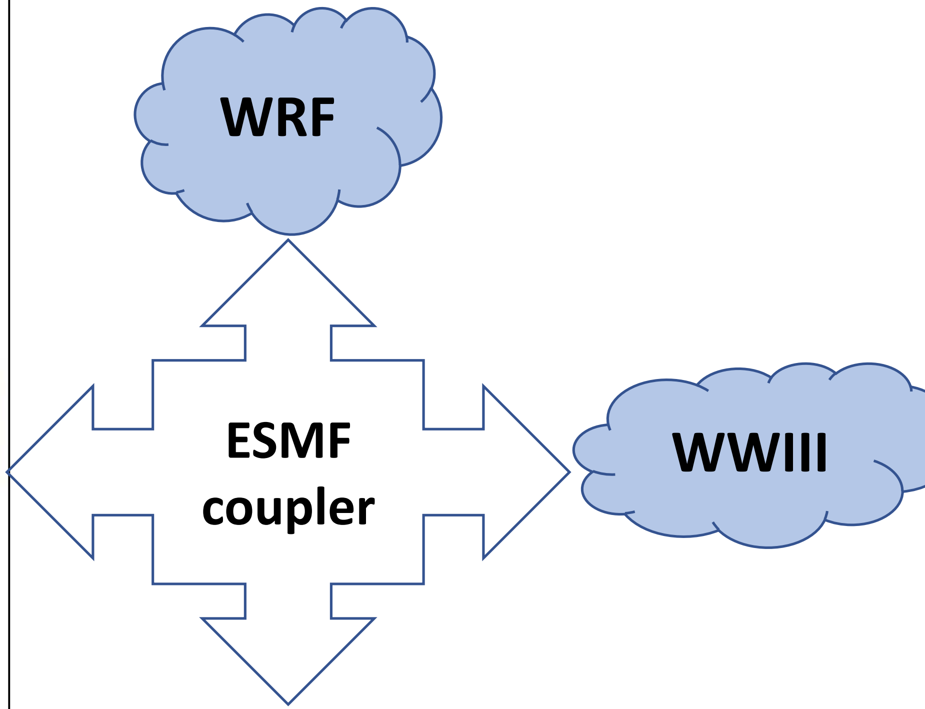
polymorphism

Eddying regime (Zhang et al. 2016)



visit schism.wiki




WRF

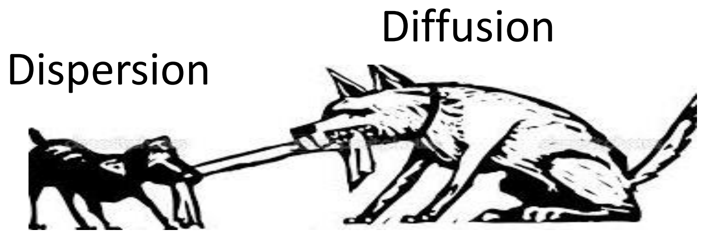
ESMF
coupler

WWIII

ELCIRC-sub (street-level inundation)

Challenges in UG cross-scale modeling

- Part of these challenges are due to poorly understood physics (e.g., scale differences =>different parameterizations)
- Scale-aware parameterization is an active research area, and is badly needed for UG models
- Different regimes pre
  - Estuarine regime is   dissipation might be acceptable?
  - Eddying regime is w   numerical dissipation *and* *dispersion* (to control
  - May be best to accommodate the eddying regime and keep the inherent numerical dissipation and dispersion low, and add dissipation when needed (via numerical scheme or explicit mixing)
  - Eddying and transitional regimes require smoothly transitioned grid in order to not distort eddying processes
  - Estuarine regime generally allows more liberal use of skew elements as there is sufficient amount of (physical) dissipation
  - The key is to strike a balance between numerical dispersion and dissipation



Eternal struggle between diffusion and dispersion

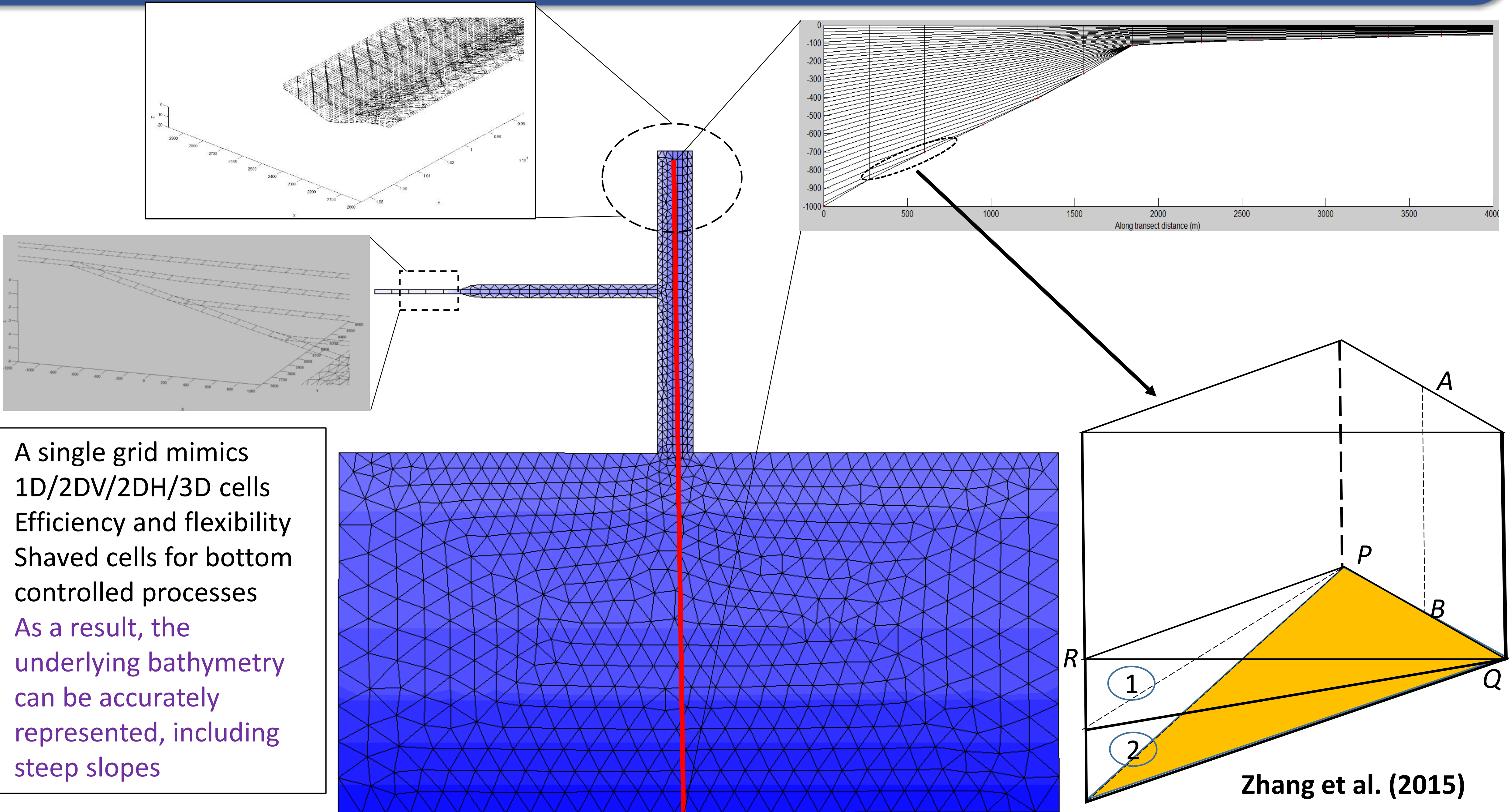
SCHISM’s unique capabilities

SCHISM offers the following technological advantages:

- Unsmoothed bathymetry
- Polymorphism
- Resolution on demand
- Seamless ‘creek-to-ocean’ capability

… the goal is to minimize grid nesting as much as possible

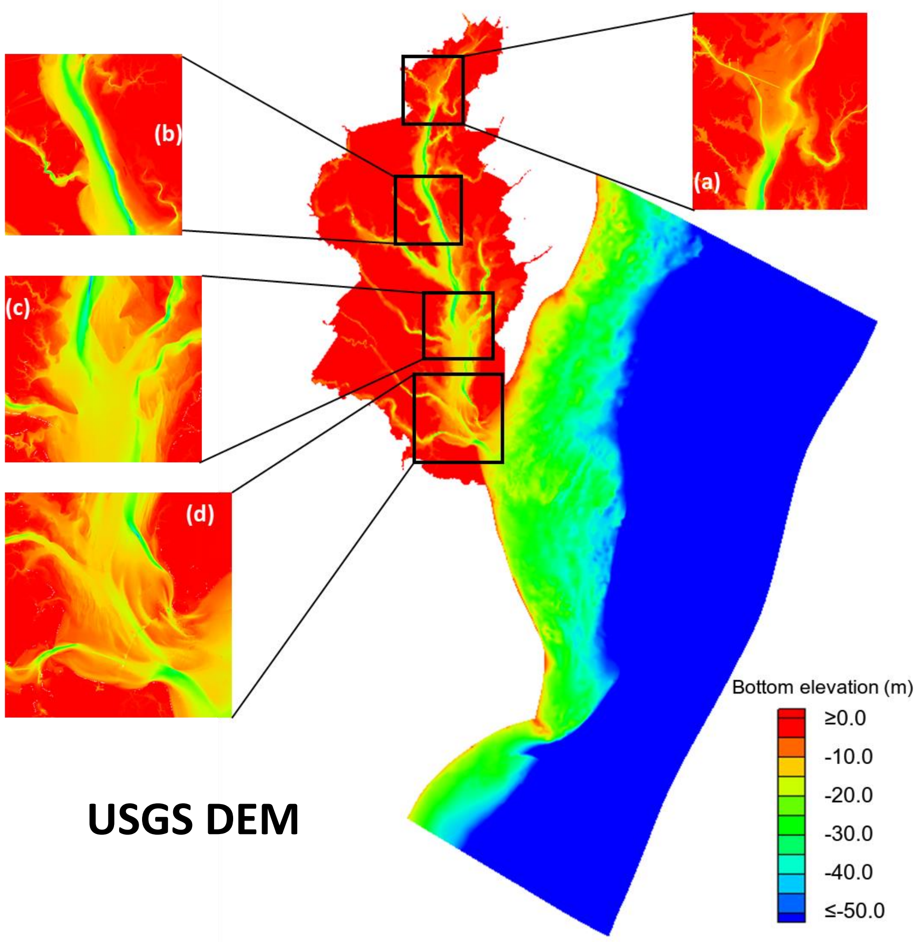
Polymorphism



Zhang et al. (2015)

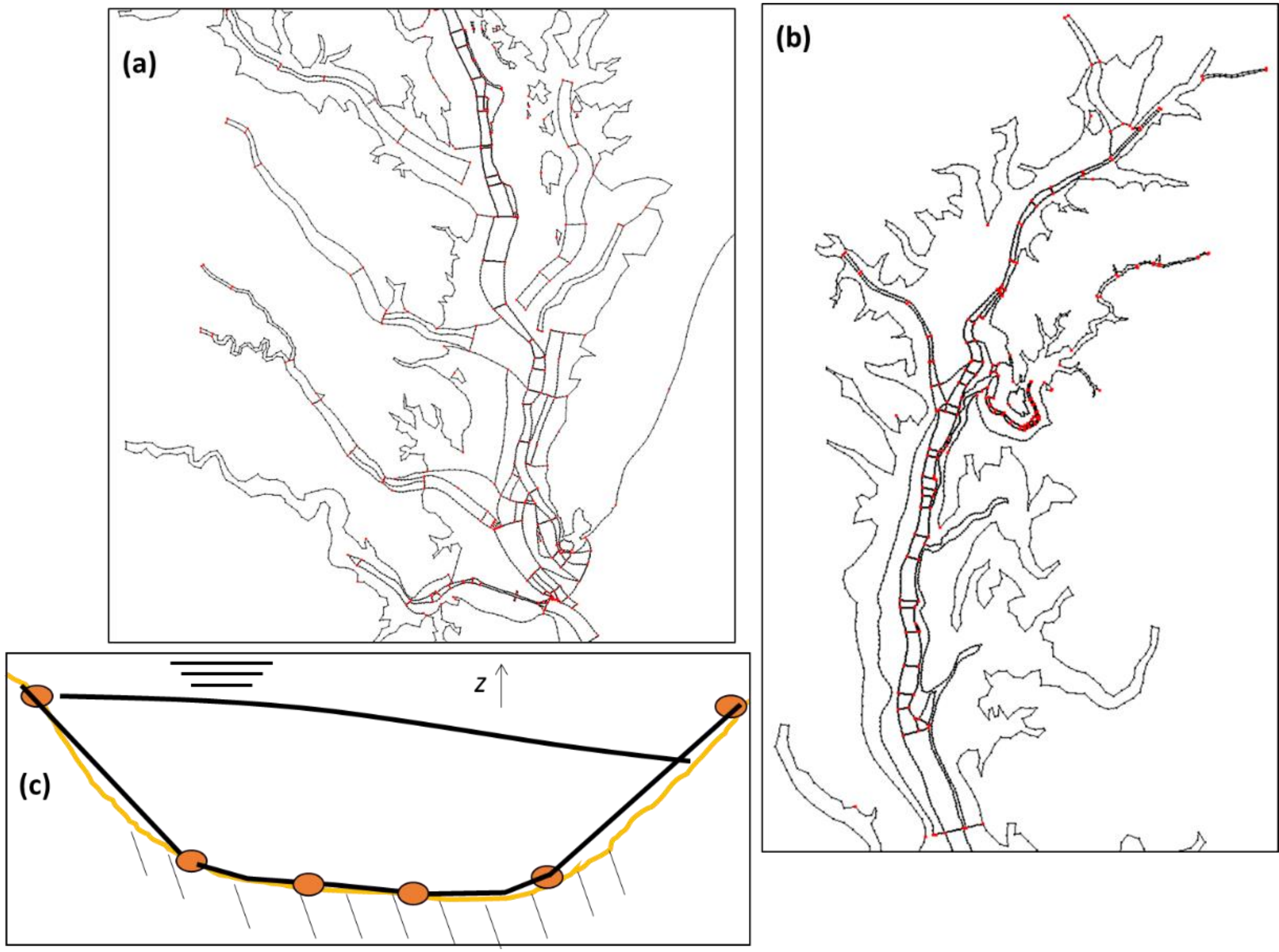
- A single grid mimics 1D/2DV/2DH/3D cells
- Efficiency and flexibility
- Shaved cells for bottom controlled processes
- As a result, the underlying bathymetry can be accurately represented, including steep slopes

Horizontal grid design



USGS DEM

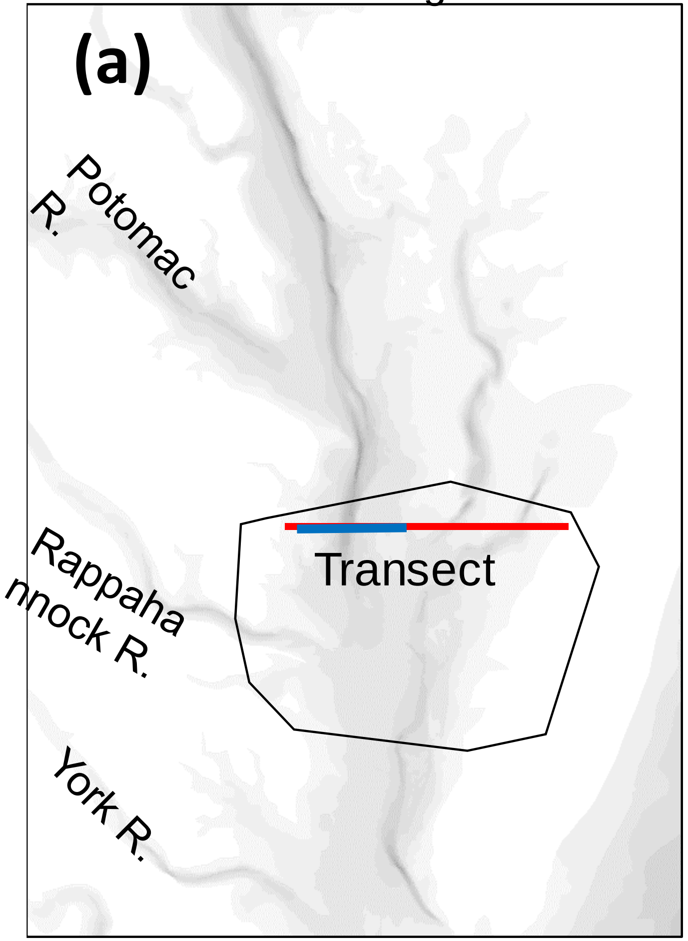
Complex channel systems. How to accurately represent them in the model?

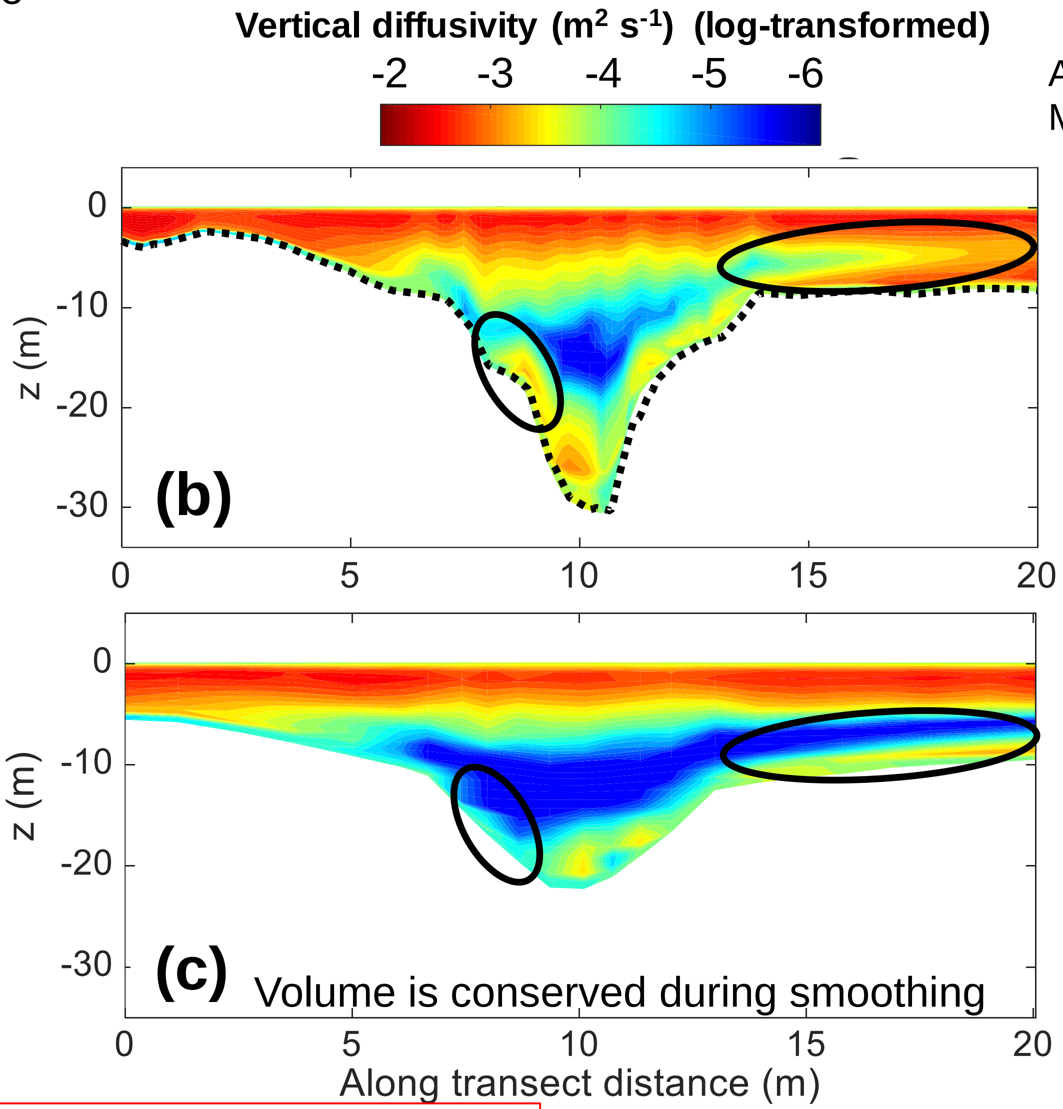


- Less numerics, more physics
- Key ‘choke points’ need to be adequately resolved
- Skew elements are almost unavoidable if we want to faithfully represent key features like channel
- Although a smooth transitioned grid is theoretically preferred, it’s often impractical (e.g. at steep slopes)
- On the other hand, mixing regimes should be different across those steep slopes (more later)

Bathymetry smoothing: why it is bad

Smoothing in a critical region where the center channel constricts and bends, with multi-channel configurations





Volume is conserved during smoothing

Averaged through May-Oct, 2012

Original bathymetry

Low mixing-zone (blue) confined in the main channel

Smoothed bathymetry

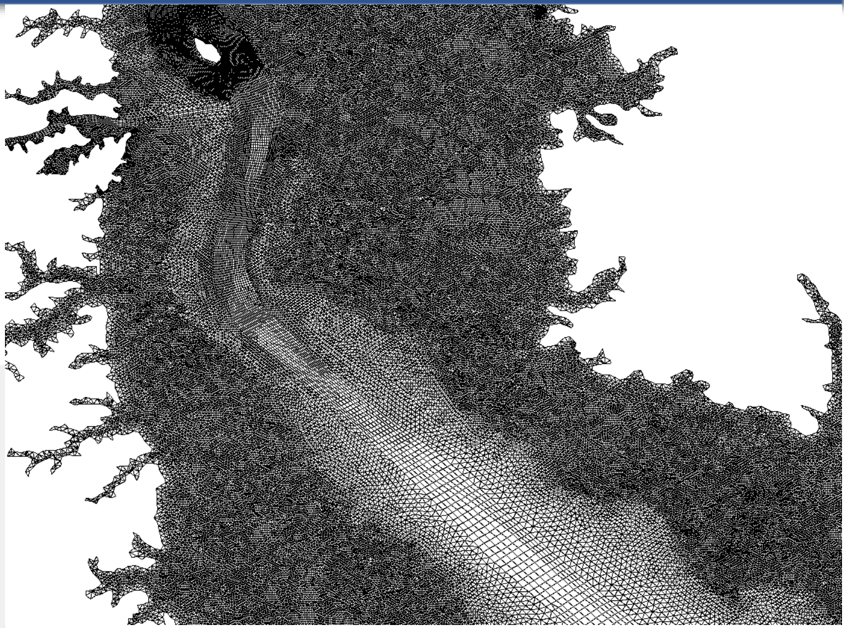
Low mixing-zone (blue) extending to the shoal

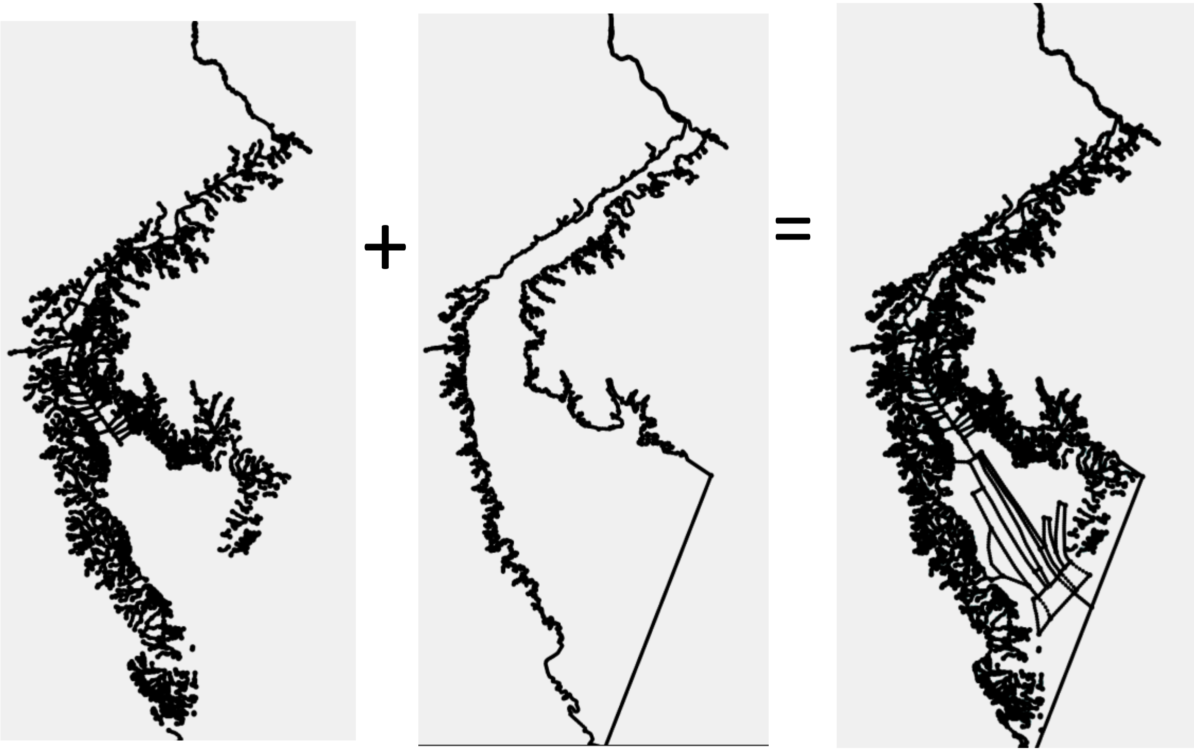
- Physical mixing is under-estimated; as a result, numerical dissipation can be masked
- Similar reduction of turbulence is observed near channel constrictions ('choke points')
- It's hard to recover the original mixing pattern by tuning the dissipation

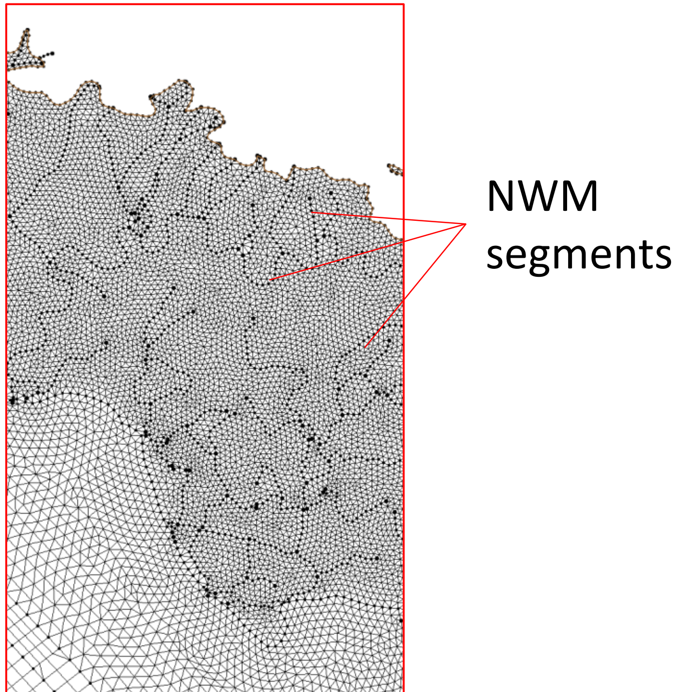
Ye et al. (2018)

Grid Generation for DE Bay

- Simply combine shapefiles and the grid boundary into a single map
- Add main shipping channel that is missing in NWM
- Use a large domain for storm surge
- Resolve Gulf Stream to get baroclinic response right during storms
- Seamless creek-to-ocean capability



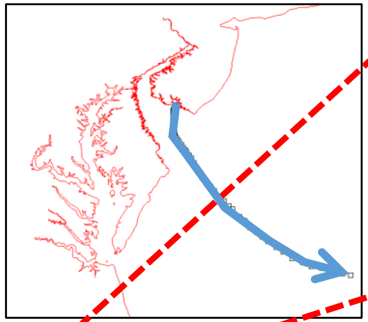




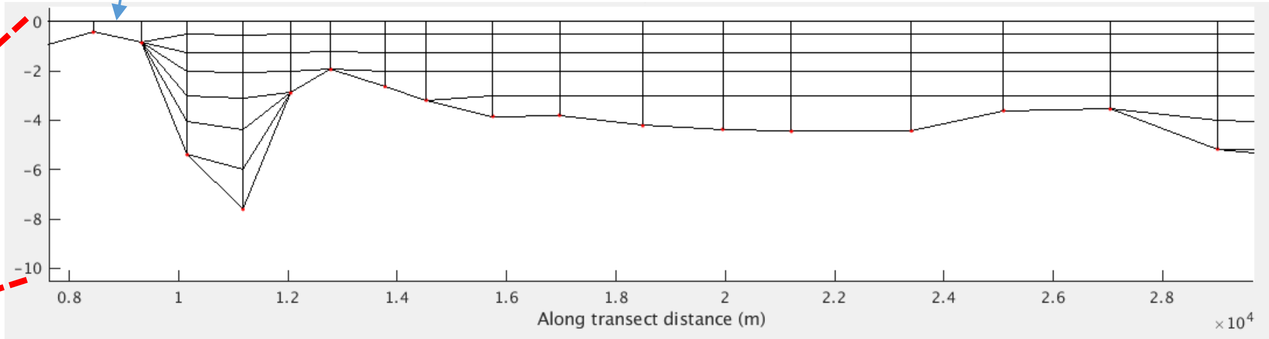
Baroclinic model setup

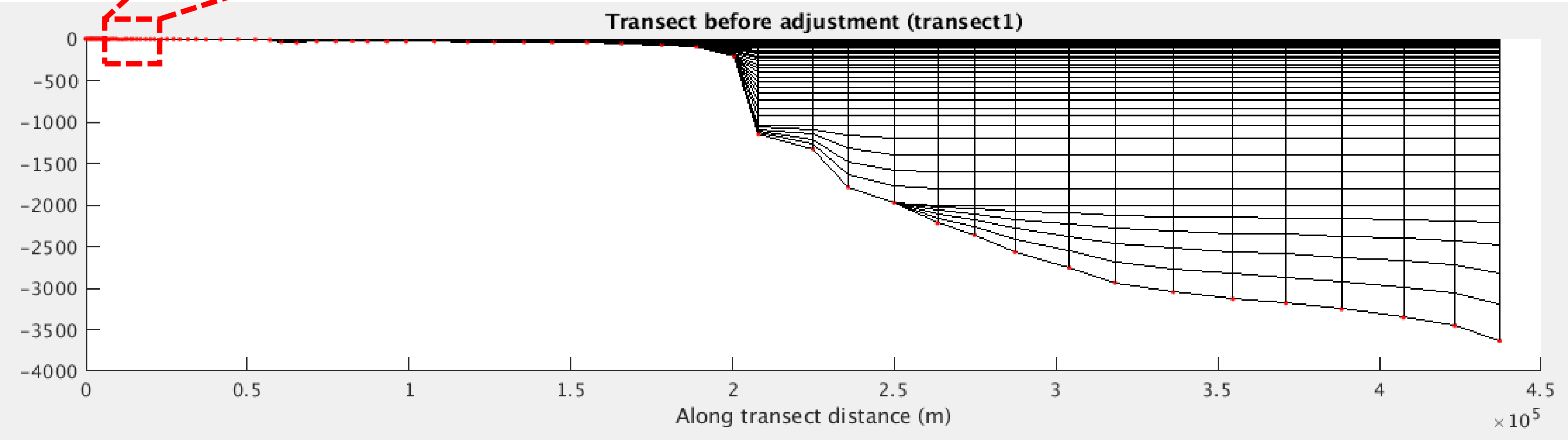
- Un-smoothed bathymetry
- USGS high-resolution DEM (NAVD88) (flat datum)
- Explicitly representing NWM segments in the horizontal grid: 759K nodes and 1,478K elements
- Grid resolution: 2~7 km in the ocean; 50-200 m in the main channel of DB; down to ~20m in small streams
- Terrain following vertical grid with varying number of layers (LSC^2): 19 levels on average: 1 vertical layer if depth is shallower than 0.5m (over 30% of the grid cells are 2D)
- Ocean boundary forced by HYCOM
- Hot start from HYCOM (with approximated salinity/temperature field inside the Delaware Bay)

- Atmospheric forcing from ECWMF (ERA)
- Simulation period: 2011-7-27 ~ 2011-9-10 (50 days)
- 3rd order transport scheme based on WENO
- Bottom roughness varies from 0.5 mm in ocean to 0.05 mm in upper Bay; 1mm in watershed
- Freshwater inflow inside Delaware Bay from NWM
- 80x RT on 1440 cores of Pleiades (NASA)



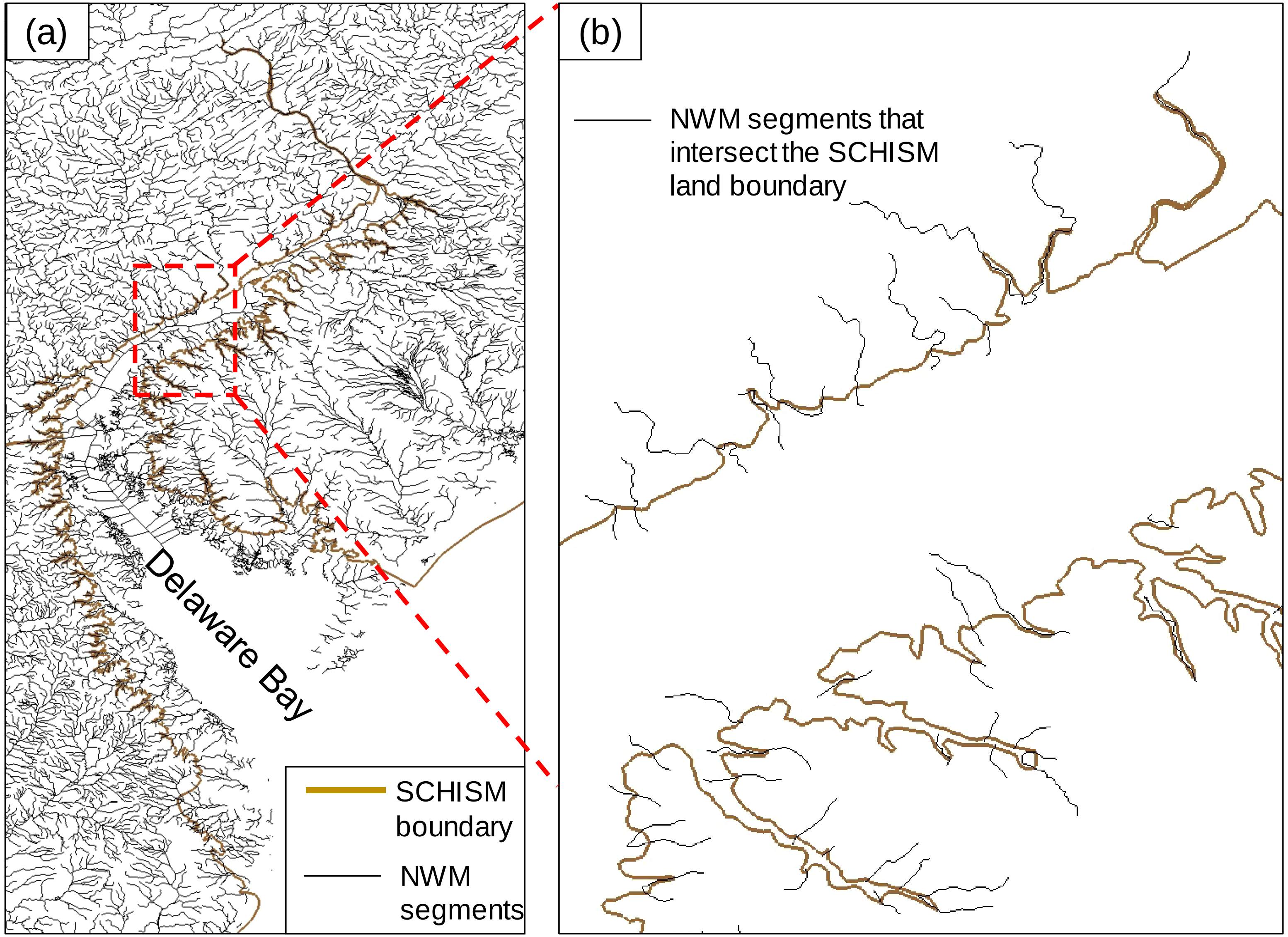
Higher ground is represented with 1 vertical layer (2D)





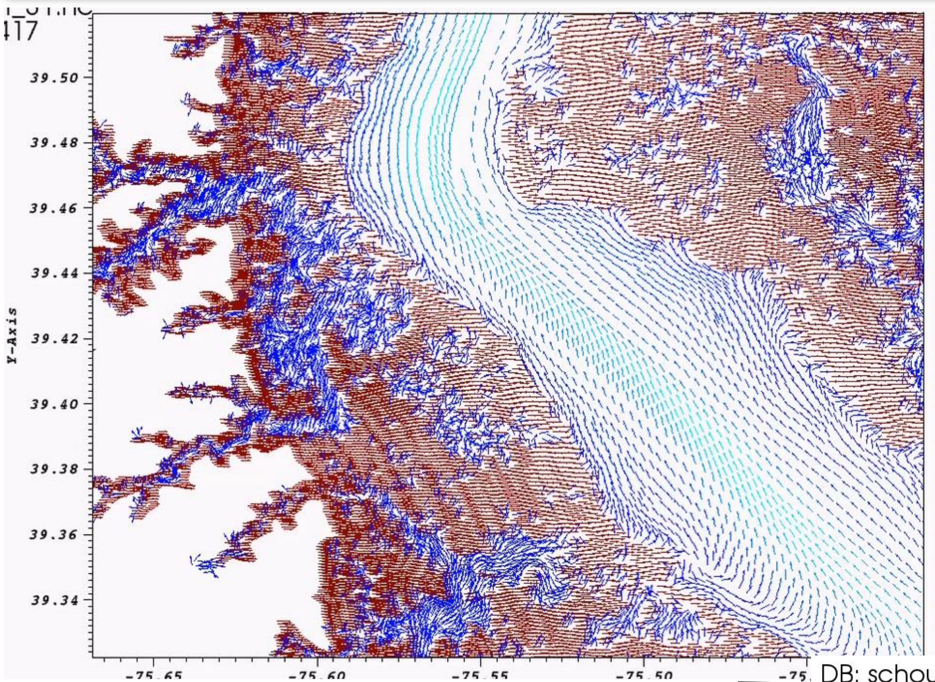
Coupling with NWM

All NWM (v1.2) segments
, from 00_TWL_Shared\01_data\01-NWM-4-isabel-irene-sandy-13sep2018\CoastalAct_NWM-data\shapefiles\nwm_channels_v12.shp

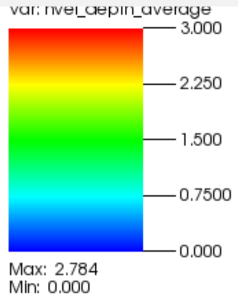


- All points on each segment are extracted from "nwm_channels_v12.shp" to determine the intersection points with SCHISM land boundary.
- NWM flows are directly imposed based on the streamflow of the intersecting segments
- Sources from NWM *inside* SCHISM domain can also be included in the same fashion
- This 1-way coupling strategy is straightforward

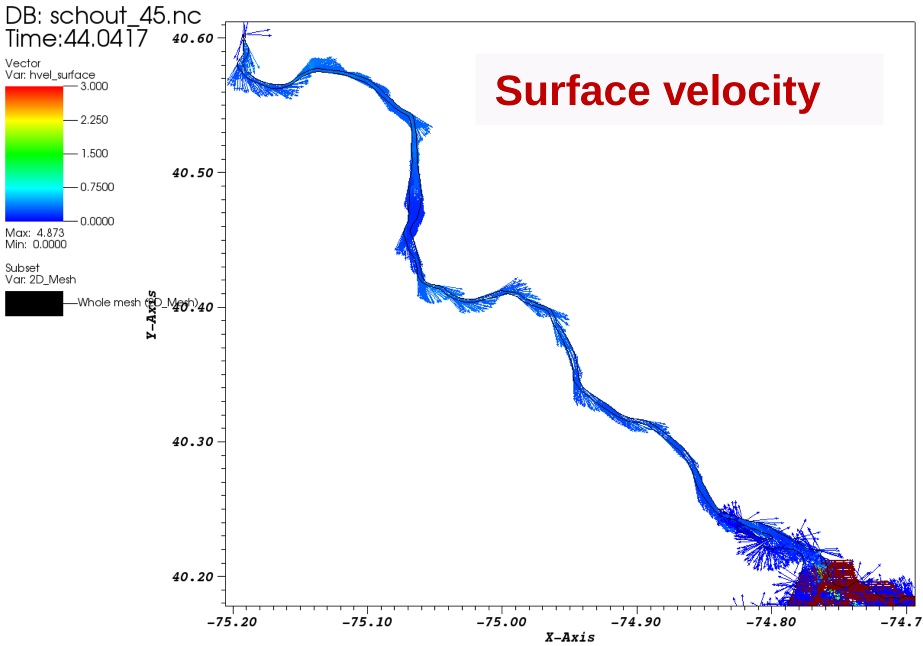
Results: overview



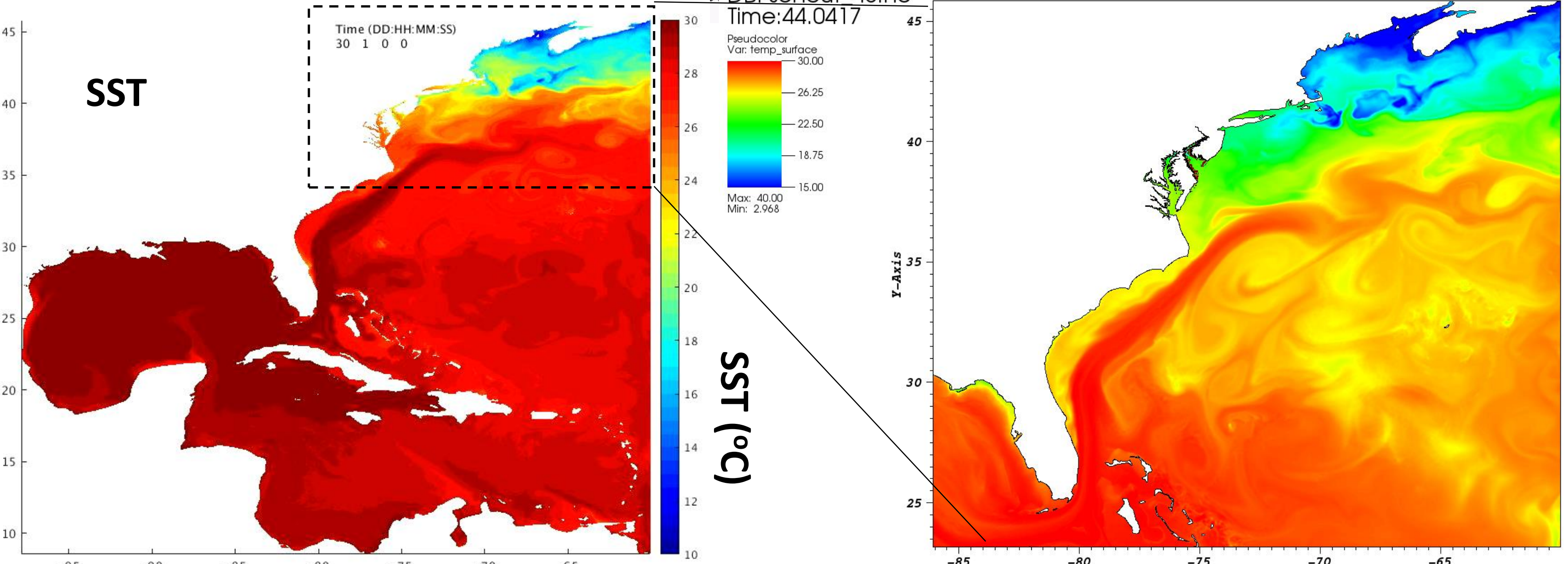
Depth-averaged velocity (m/s)

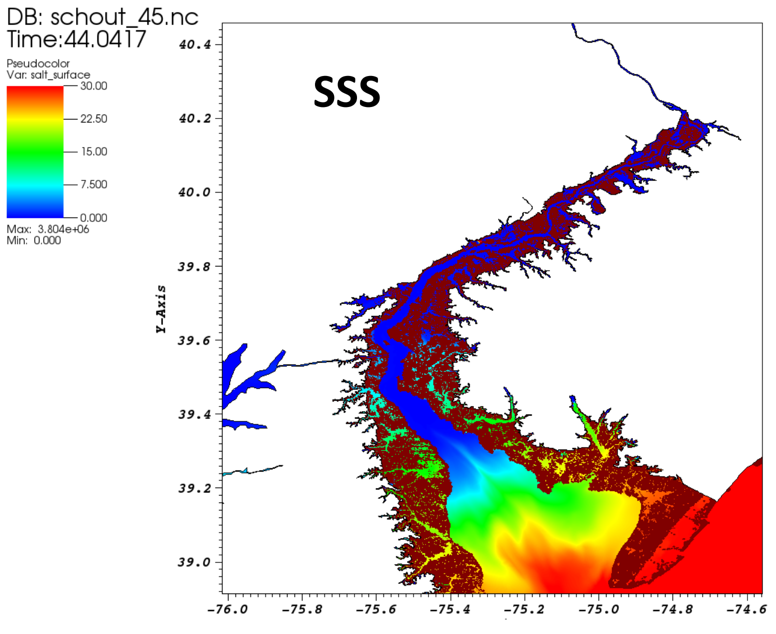


Brown color is dry land



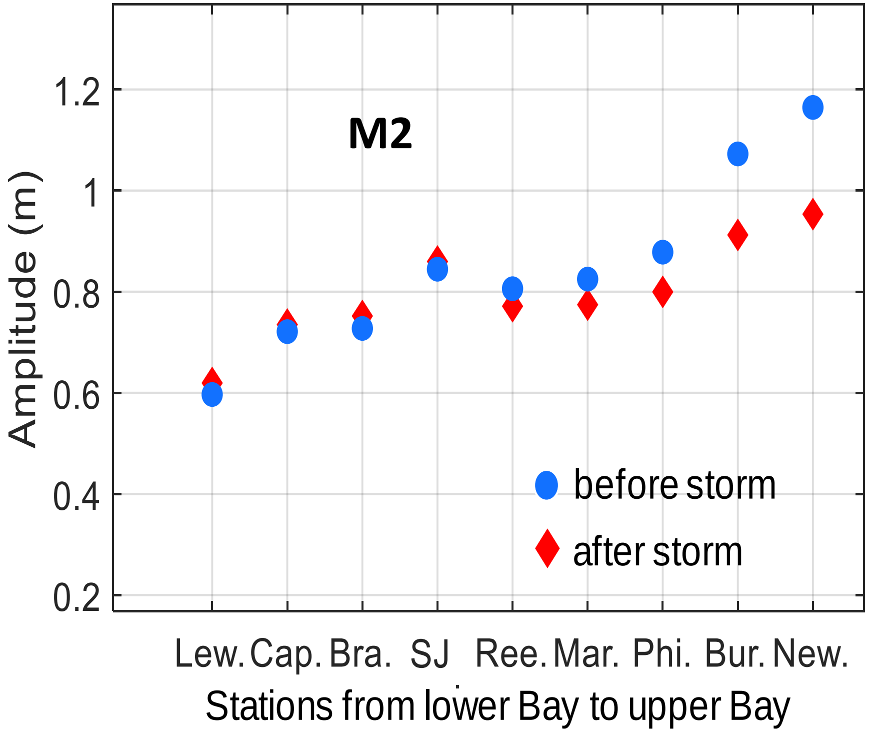
Surface velocity

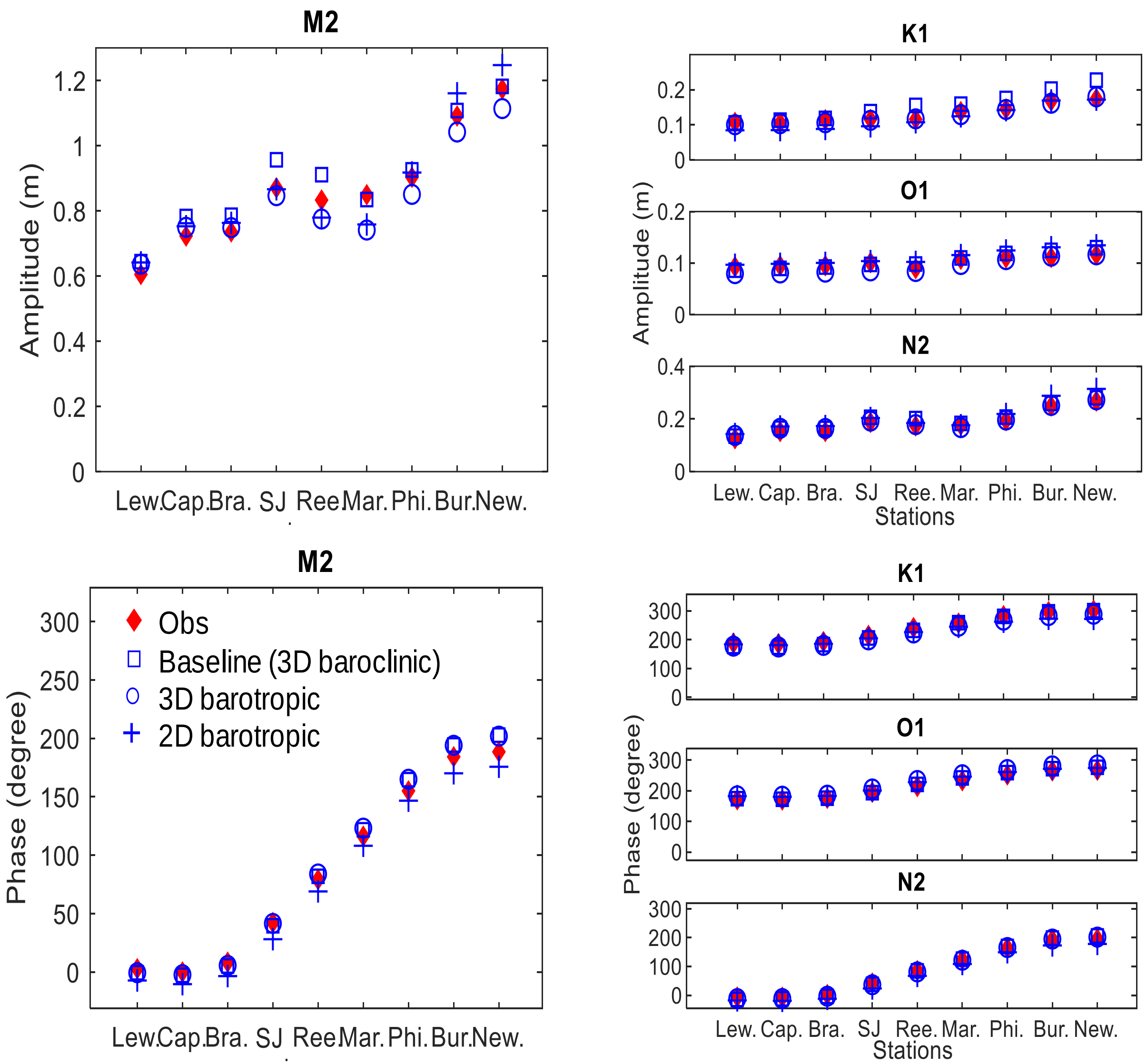




Harmonics

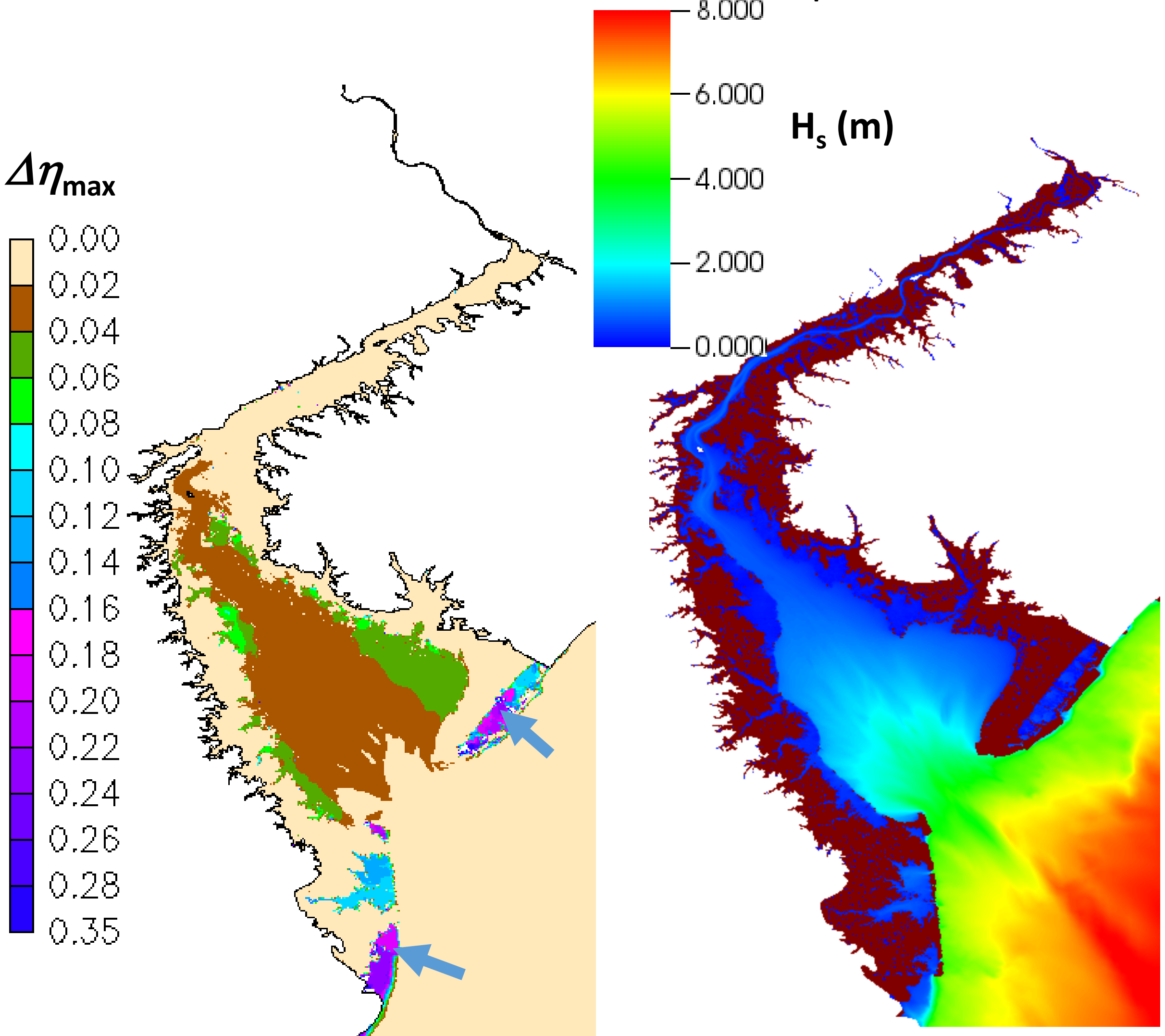
- Tidal ranges vary by a factor of 2 from mouth to upstream river
- The variation is driven by bottom friction and funneling effects as well as channel meandering
- Model generally captured the tidal propagation well
- The river stations have non-stationary tides

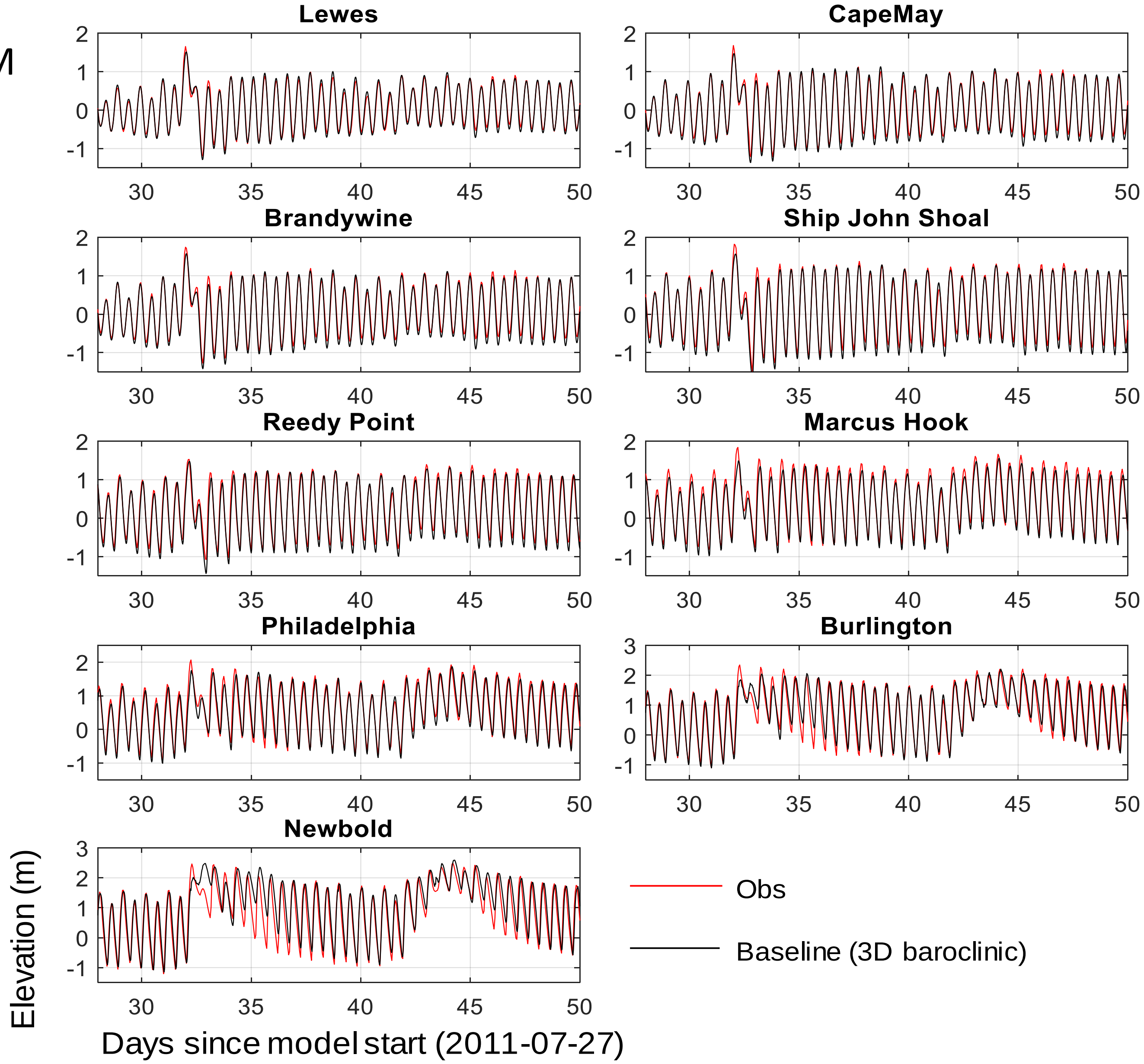




Total water elevation

- Elevations are generally well simulated
- Larger errors upstream possibly due to uncertainties in DEM and datum
- Wave effects are confined near steep slopes

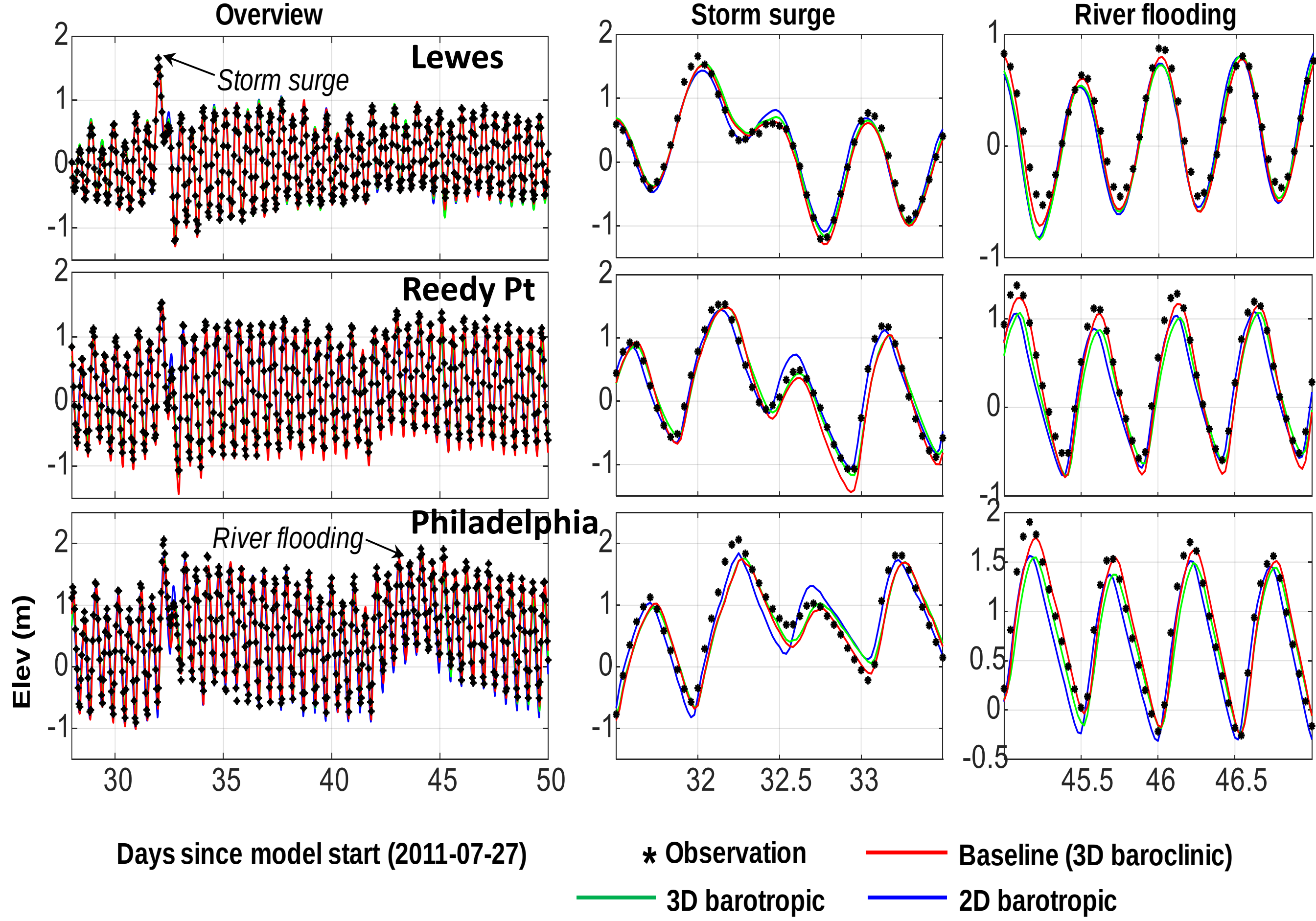


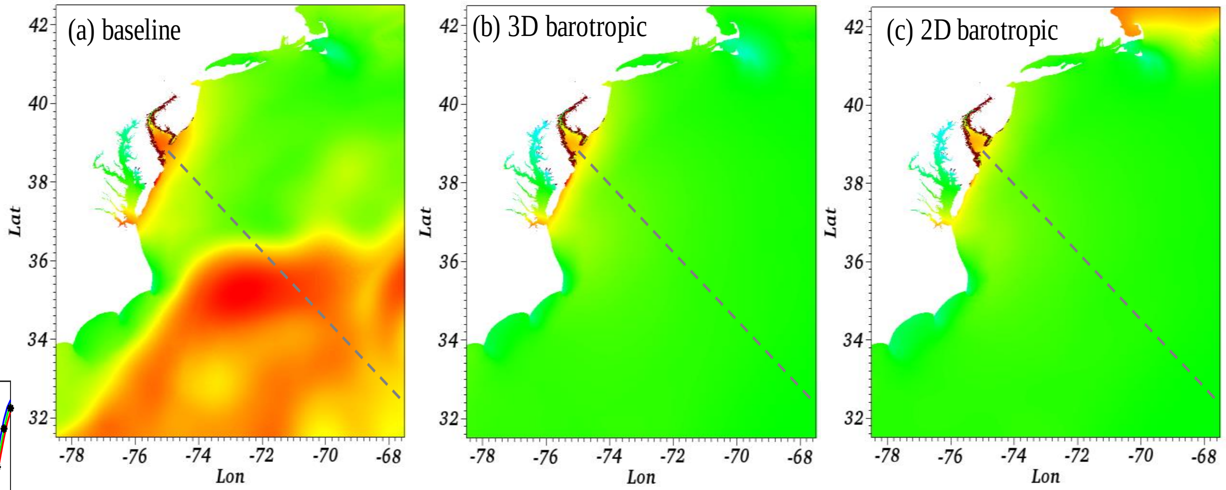


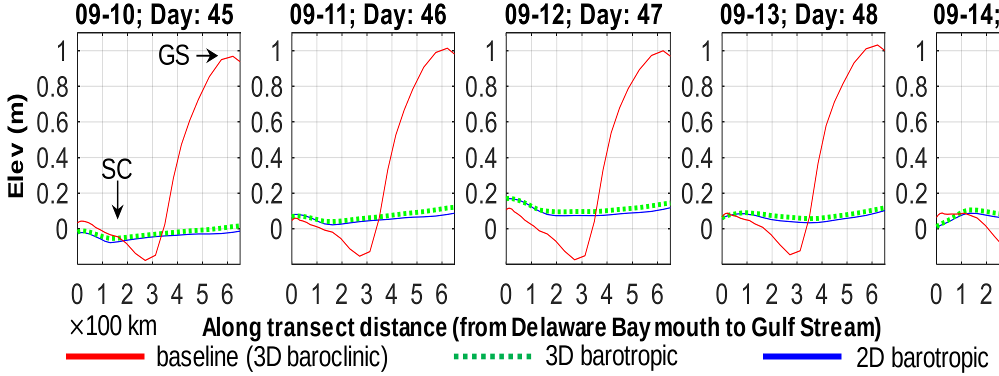
Importance of baroclinicity

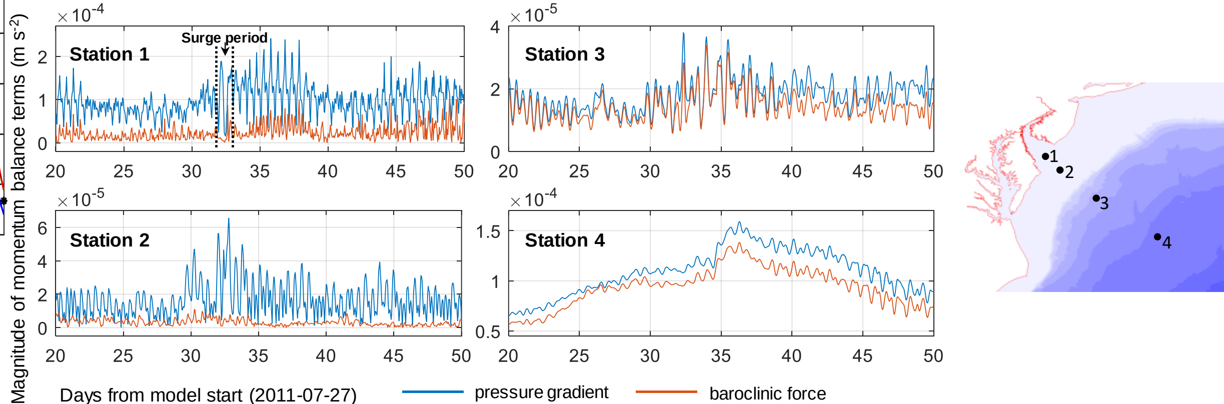
- The surface slope induced by the Gulf Stream prevents the surface from falling too low after the storm
- Baroclinic pressure gradient accounts for up to 67% of barotropic pressure gradient in the nearshore region

MAE: 0.13m for baroclinic; 0.15m for 2D





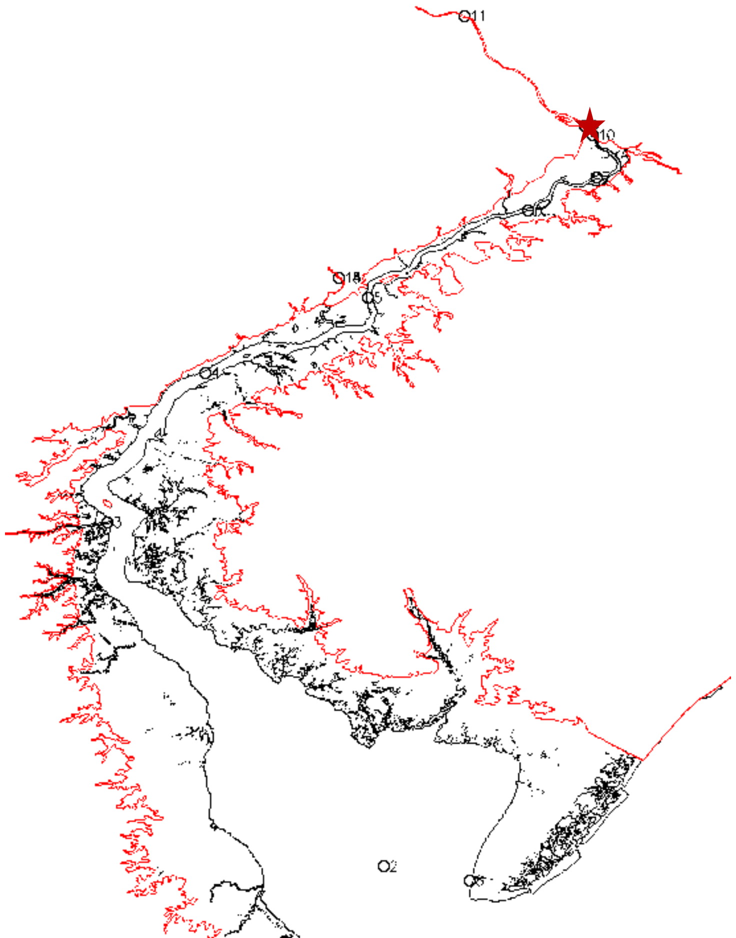


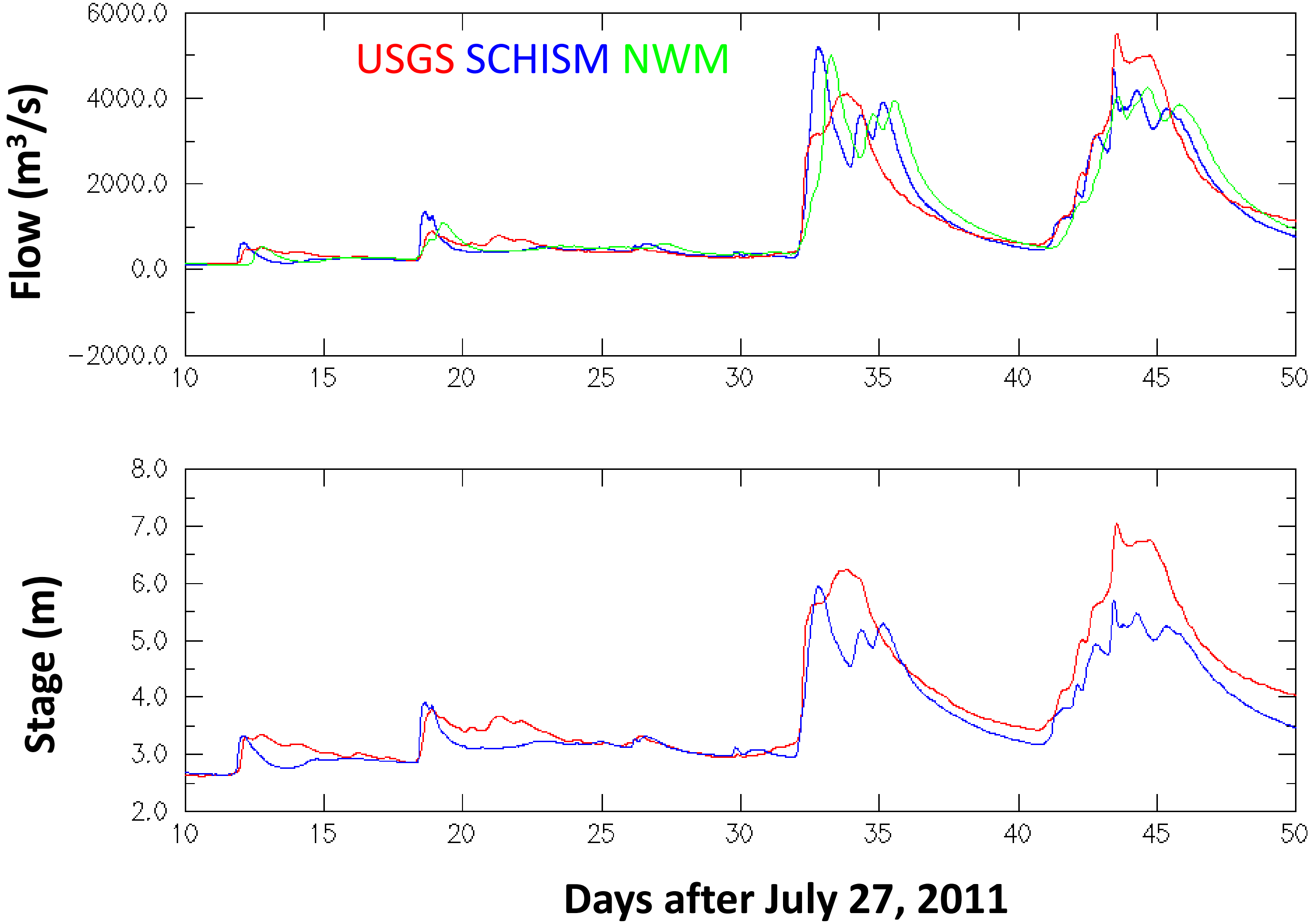


Trenton (USGS)

- River station with no tides
- SCHISM captured the surface elevation and surges well!
- SCHISM and NWM match well
- Both match the USGS gauged flow reasonably well, with some errors for peaks

- The observation indicated a higher 2nd surge

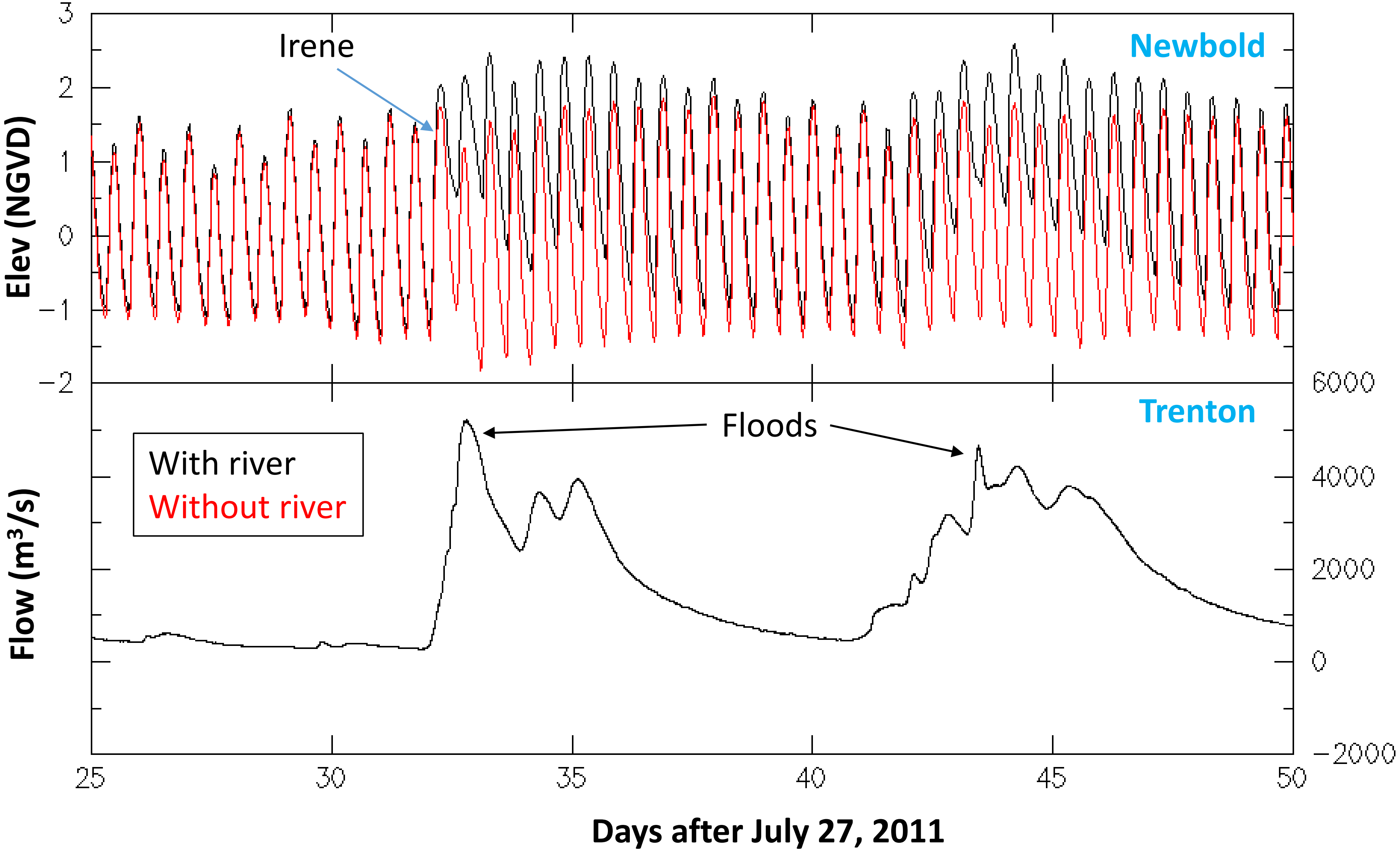




River influence

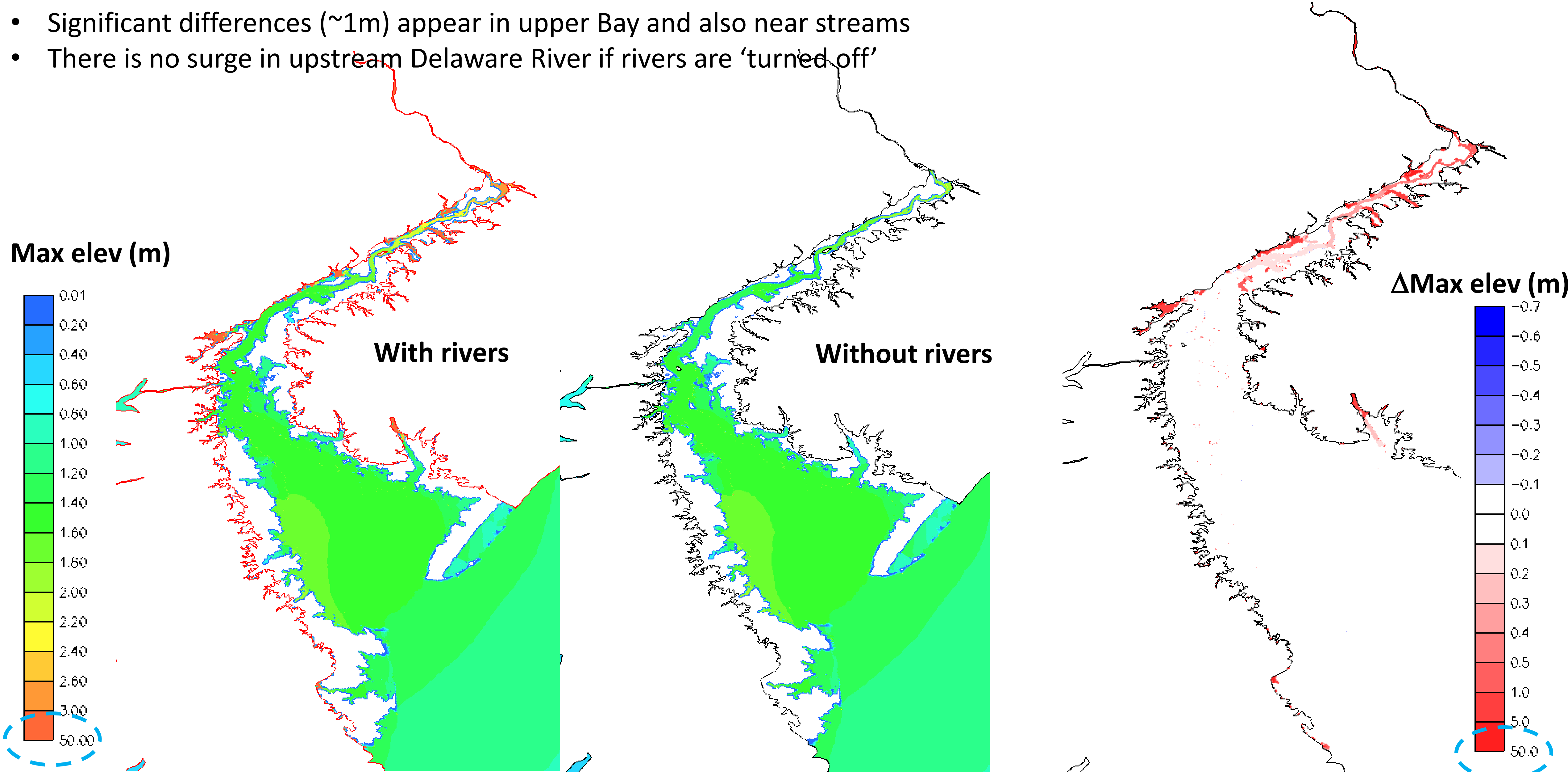
- Compound flooding effects are obvious at upstream stations

- The river influence takes off after the hurricane and lasts more than 2 weeks!



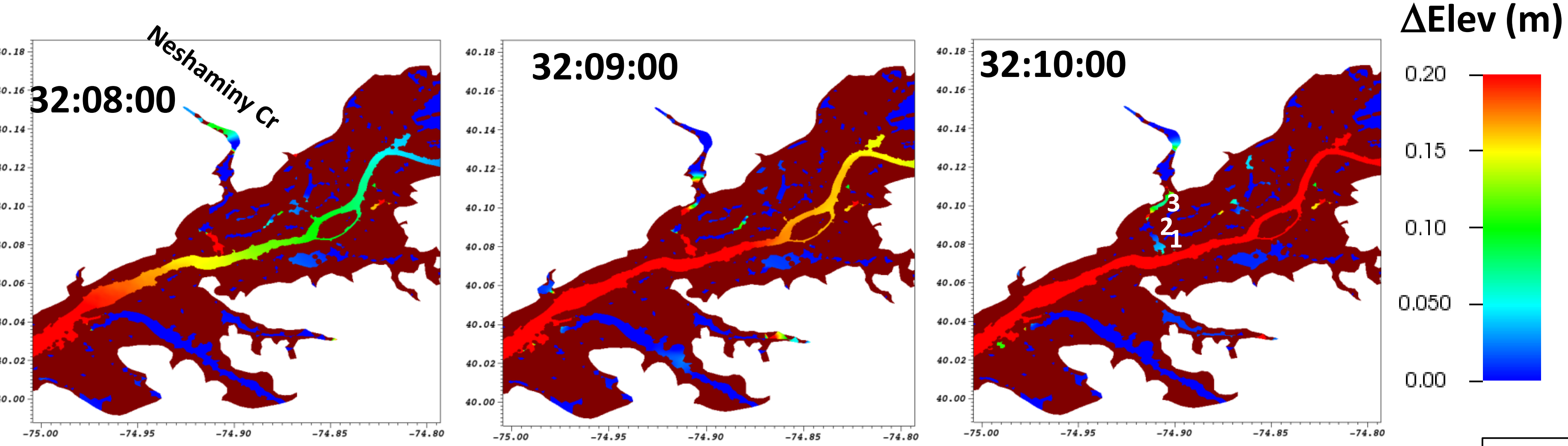
River influence

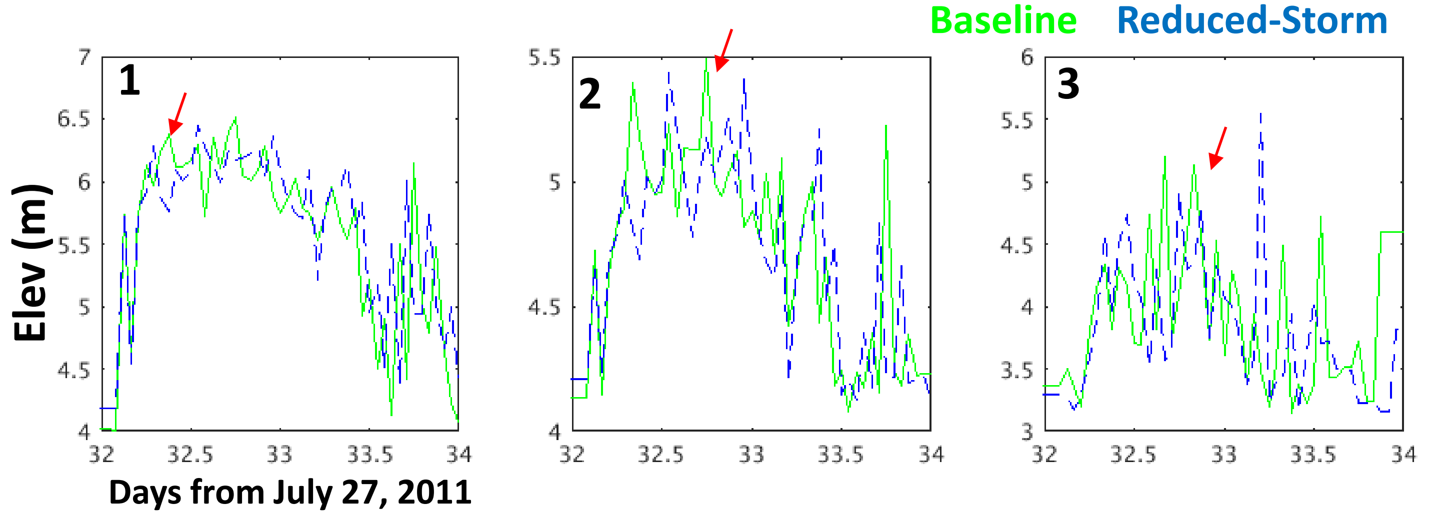
- Maximum elevations are similar with and without rivers at downstream locations
- Significant differences (~1m) appear in upper Bay and also near streams
- There is no surge in upstream Delaware River if rivers are ‘turned off’

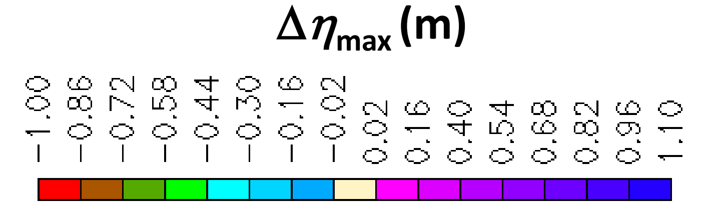


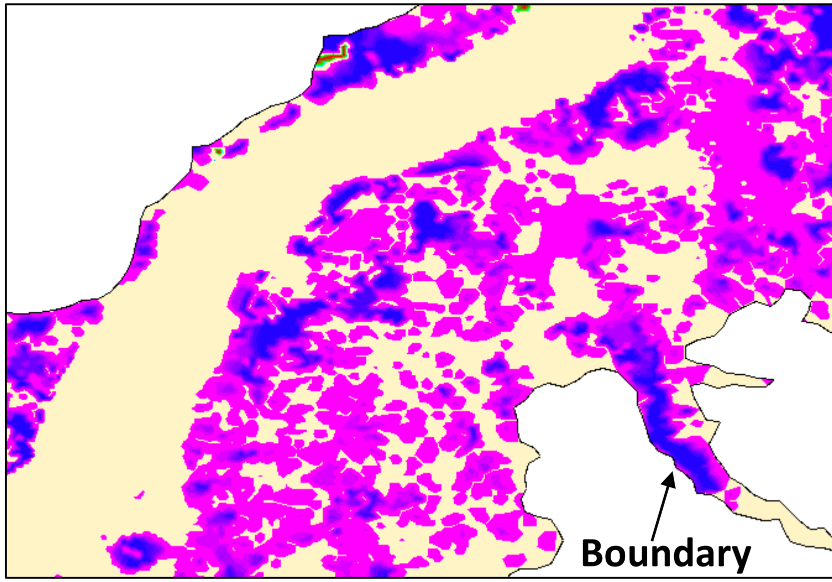
Backflow

- To find out if the coastal influence can reach the domain boundary, we artificially reduced the storm by capping the maximum wind velocity (u,v) at 10m/s, and compared the elevation from this run with baseline
- The backflow effect reached the boundary at several places: 2-way coupling with NWM?









Conclusions

- During Hurricane Irene (2011), both storm and river induced surges are important for DE Bay
- The first surge is mostly from ocean but at stations away from the coast, compound flooding from rivers is also important
- Second and later surges are mostly due to river flooding; this is especially obvious at upstream stations
- Inflow from National Water Model is reasonably accurate for predicting compound surges
- Baroclinic adjustment is significant after the storm surge due to Gulf Stream adjustment
- The direct precipitation is not important except for places influenced by flash floods
- Errors and uncertainties in DEM in upstream creeks are a major contributor to model errors
    - New technology like ground based Lidar can help!
- Backflow effect is significant in rivers and creeks and reached several locations on the domain boundary
- While it's possible to enlarge the SCHISM domain to cover more watershed, a two-way coupling with NWM is probably the better way to go

Thank you!