Advancing Global STOFS 2D^{+}: NOAA's *Fast* Integrated Multi-Scale Multi-Process Operational Water Level Model

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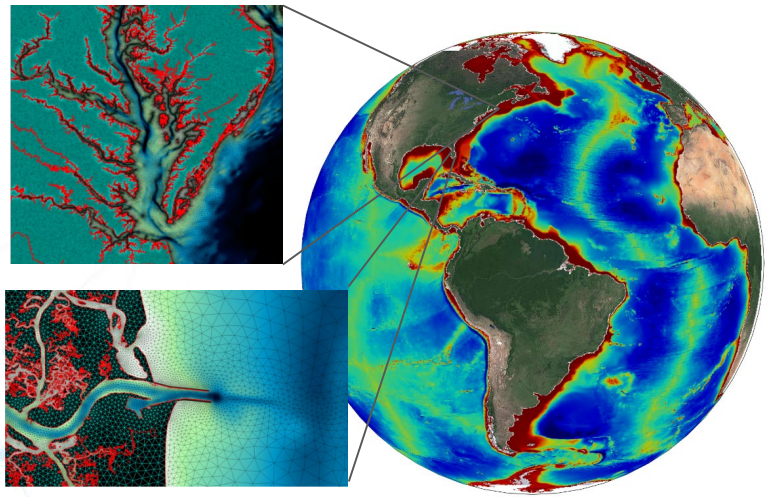
Global STOFS 2D: *v1.0 currently in operation*



- Global STOFS 2D operationally forced with tidal potential, internal tide dissipation, GFS-FV3 and CICE
- Runs at NCEP and Notre Dame

GFS-FV3 Global Atmospheric Model

ADCIRC **Circulation**

CICE Global Sea Ice Model

At NCEP https://polar.ncep.noaa.gov/estofs/glo.htm
At Notre Dame https://dylnwood.github.io/GESTOFS-develop/

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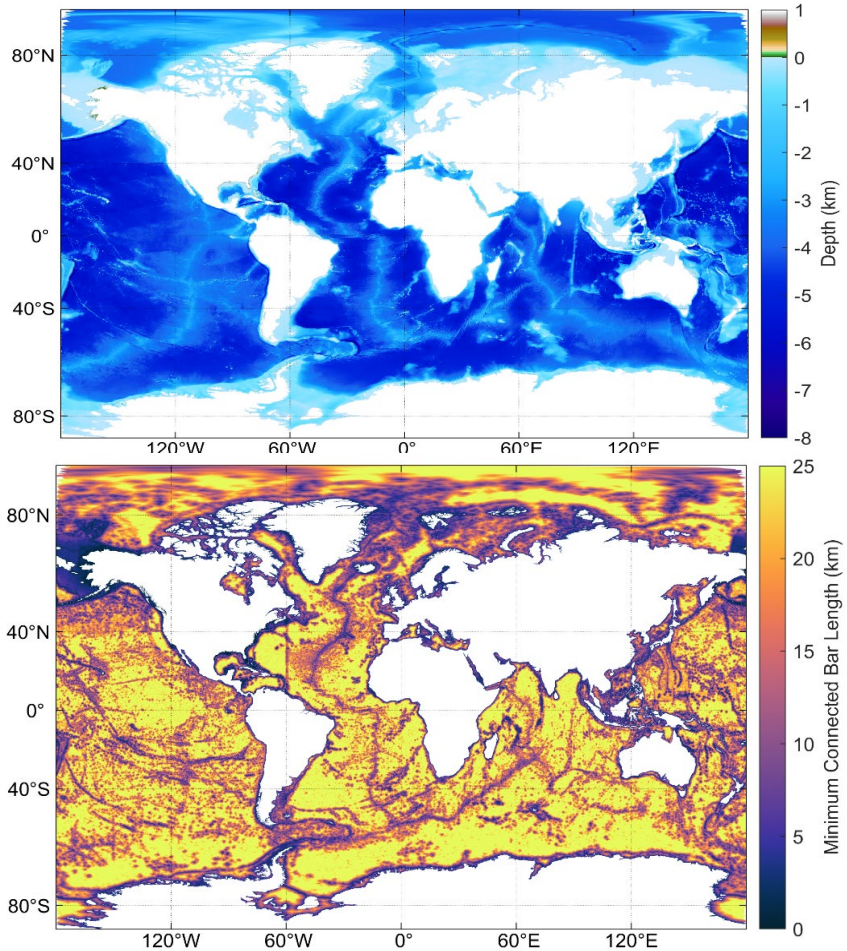
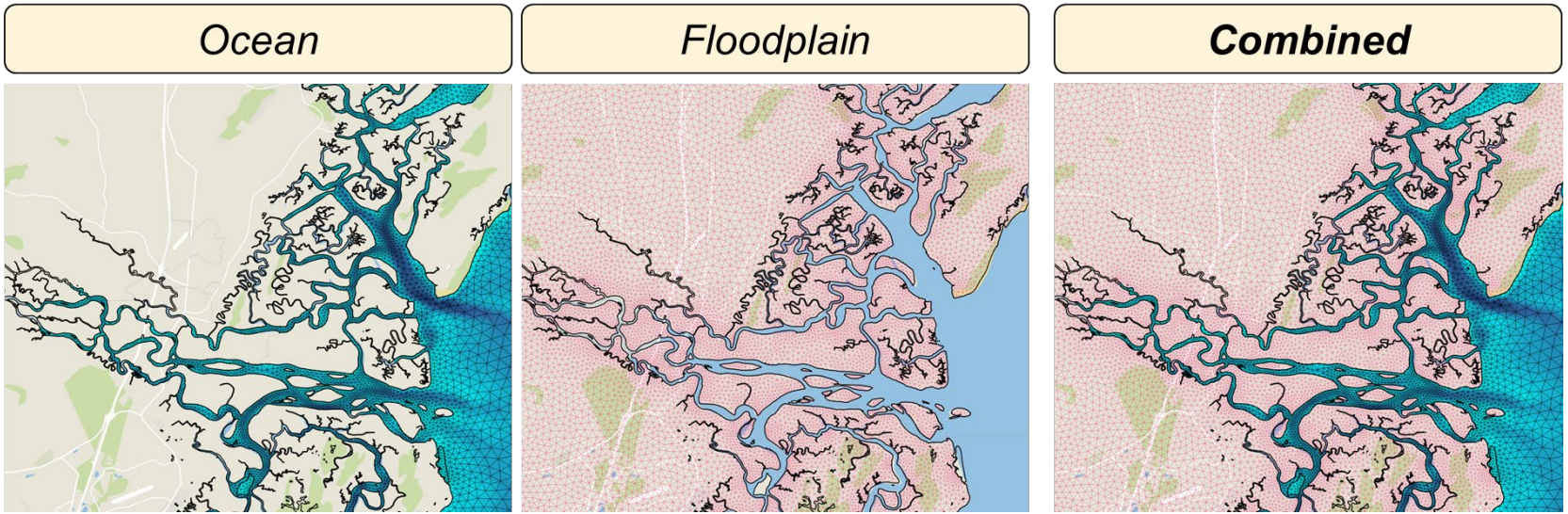


- Unstructured finite element mesh contains 13.6 million nodes and applies pole shifts to optimize accuracy at high latitudes
- Mesh resolution varies between 25 km across abyssal plains to 2.5 km across mid ocean ridges and shelf breaks to improve internal tide dissipation accuracy
- Resolution in **all** U.S. coastal waters and floodplains down to 80 – 120 meters.
- **Most *accurate* published global model with an M_2 tide deep water error of 1.95 cm**
- **U.S. East/Gulf of Mexico coast M_2 tide errors R^2 = 0.9848, average absolute error = 2.5 cm, and a normalized RMS error = 0.089**
- **Runs *fast* in 2.4 wall clock minutes per day of simulation on 2400 TACC Frontera cores**

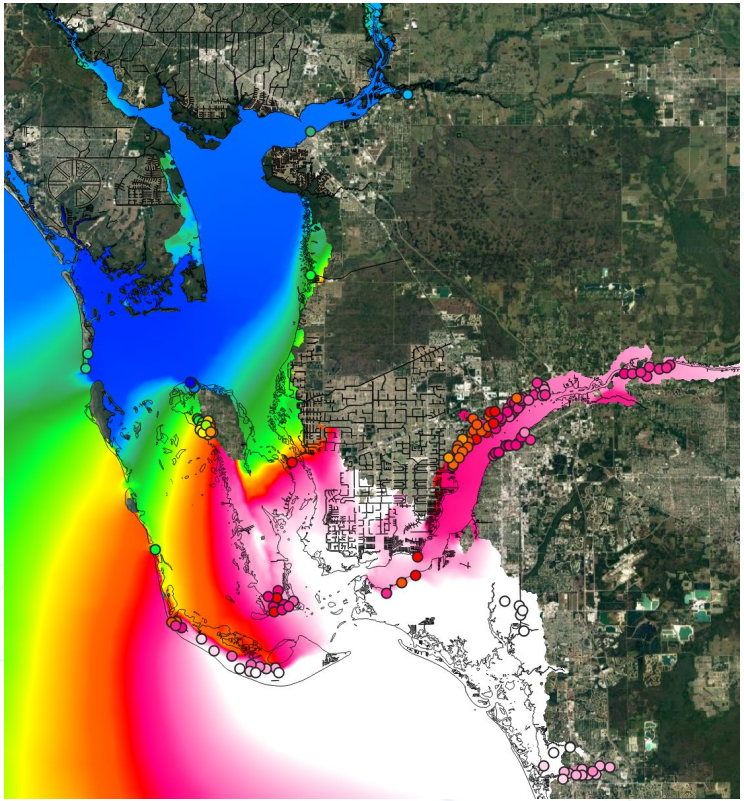
Global STOFS 2D: *v1.0 currently in operation*

- Mesh design efficiency is focused on resolving the inland arterial channel networks and wet/dry separation
- Aligning nodes along the water/floodplain interface and applying medial axis values allows for representing the smallest scale features in the model
  - Clear hydraulic connectivity of small channels
  - Incorporation of barrier islands and small islands

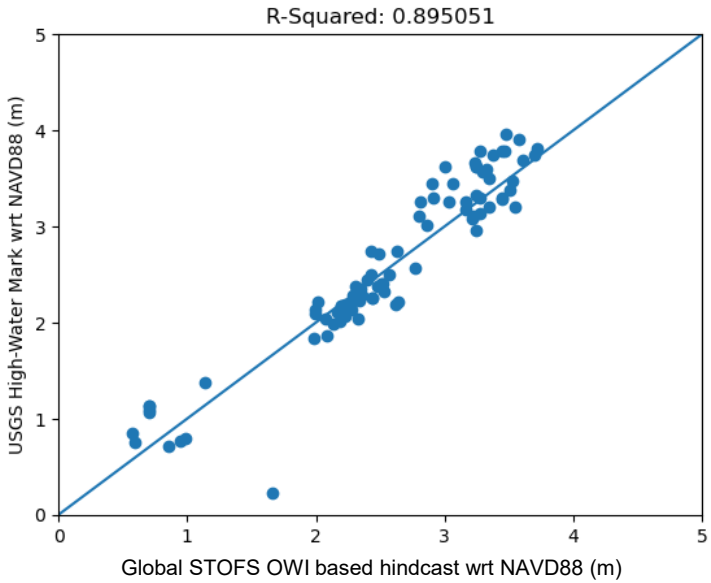


Global STOFS 2D: *v1.0 currently in operation*

Hurricane Ian (2022) hindcast driven by OWI re-analysis winds compared to USGS data



Contour lines: Global STOFS 2D event high water in NAVD88
Circles: USGS High Water Marks in NAVD88



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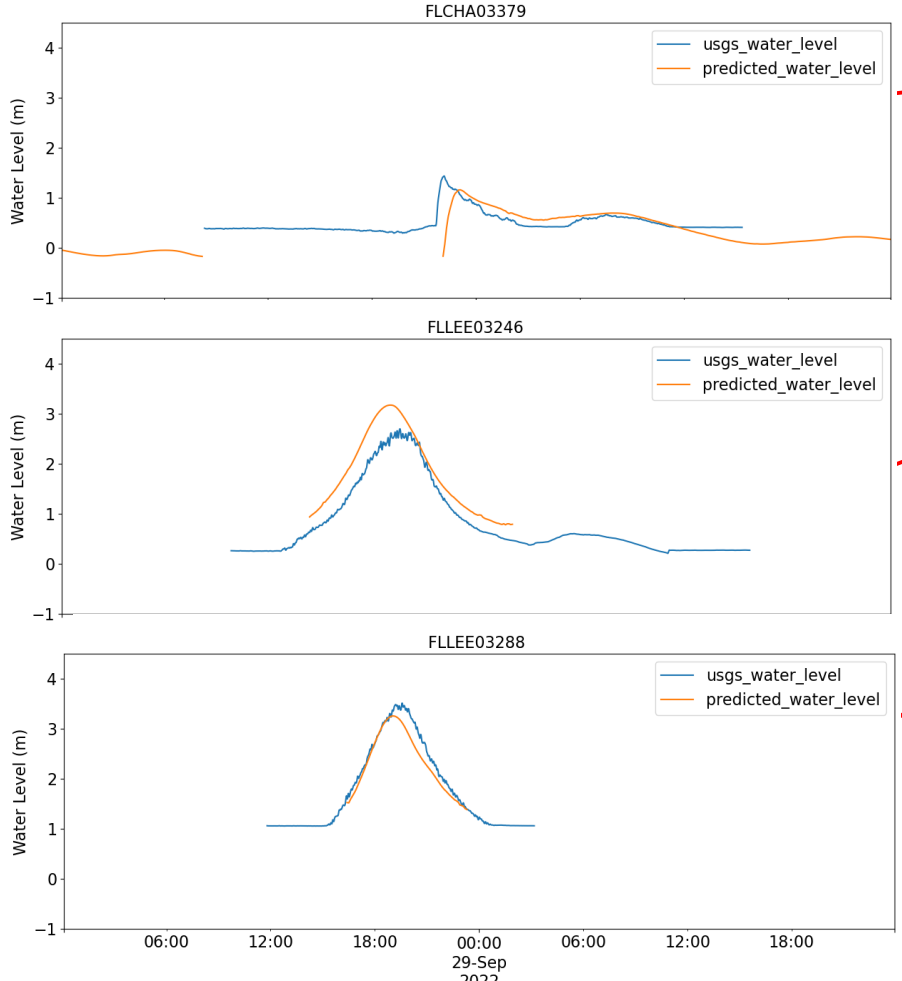
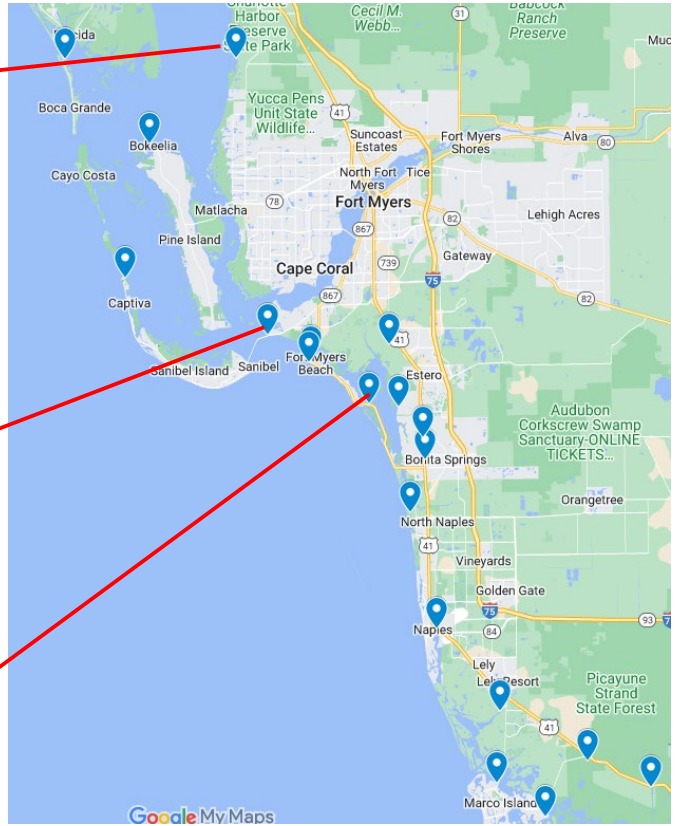
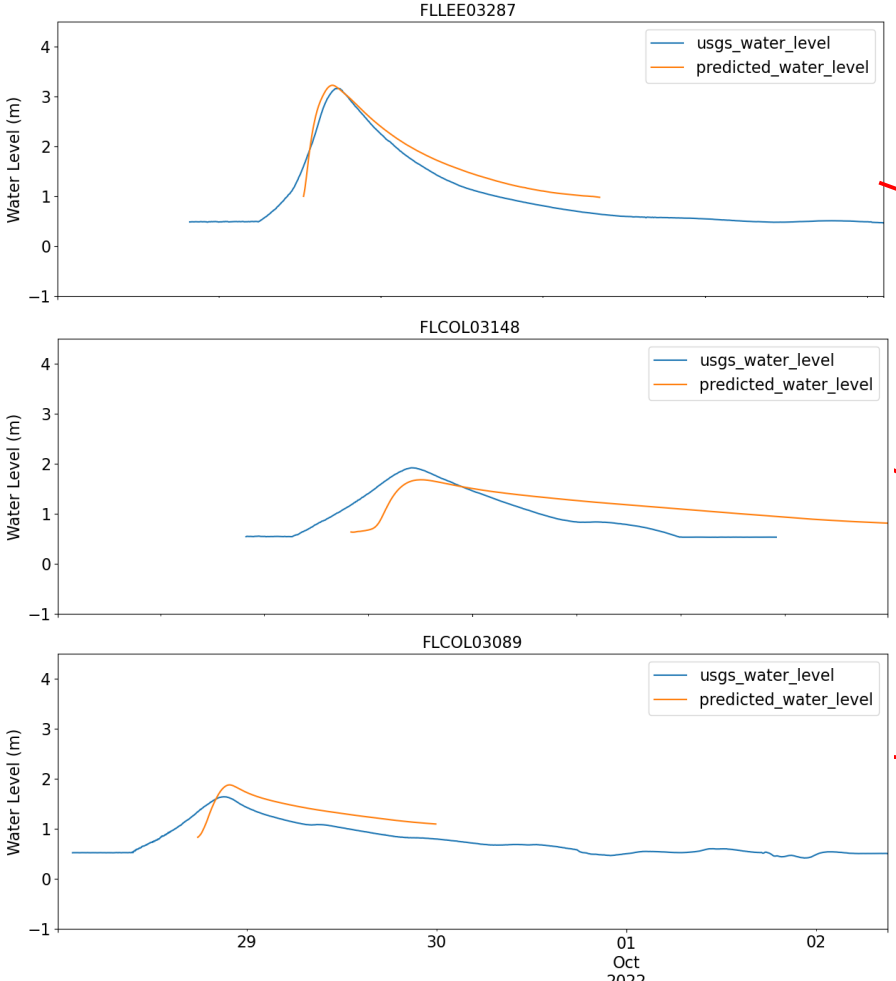
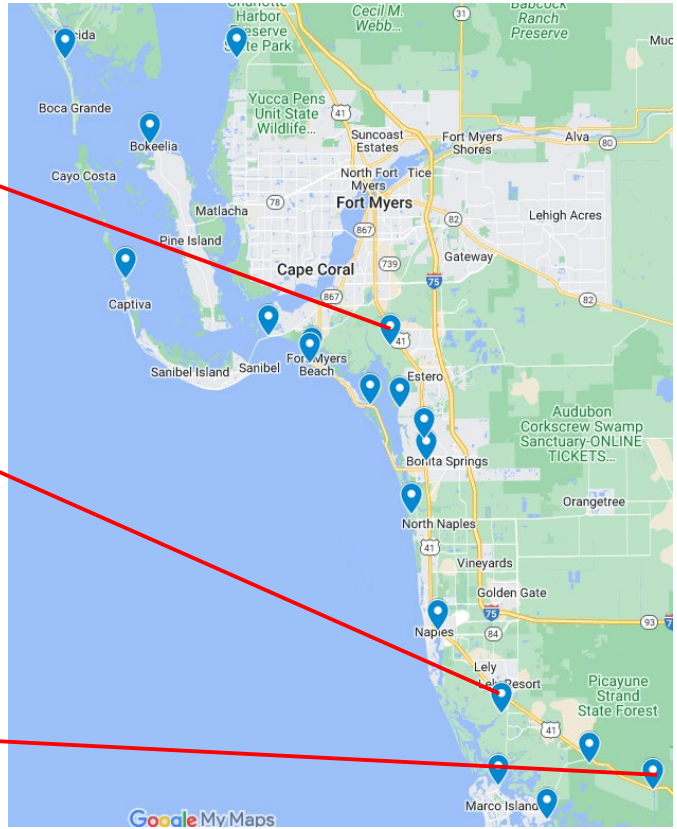
Global STOFS 2D: *Hurricane Ian hindcast*





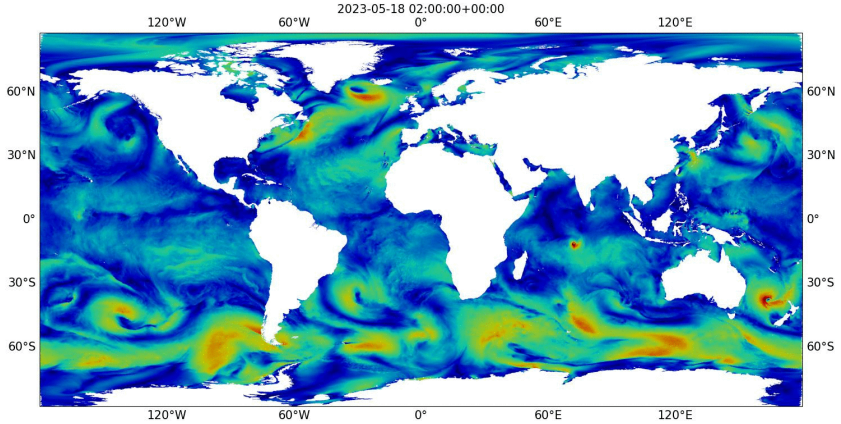
Global STOFS 2D: *Hurricane Ian hindcast*

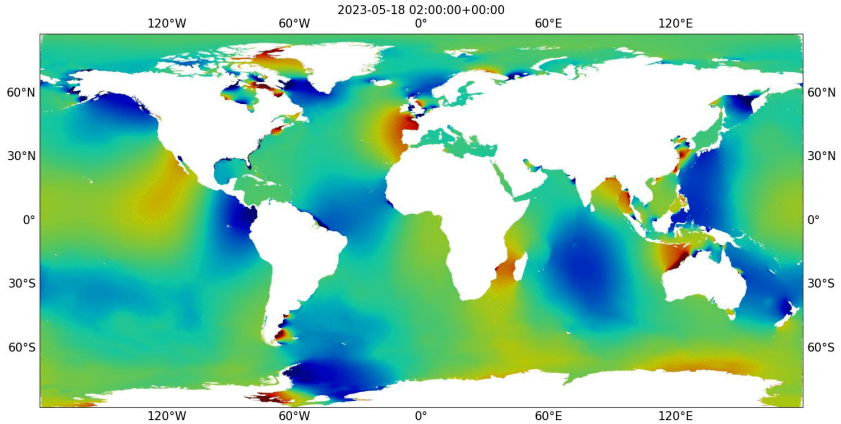


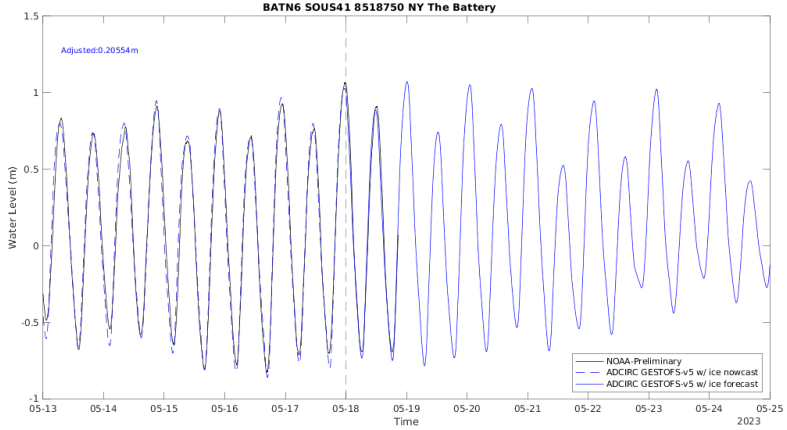


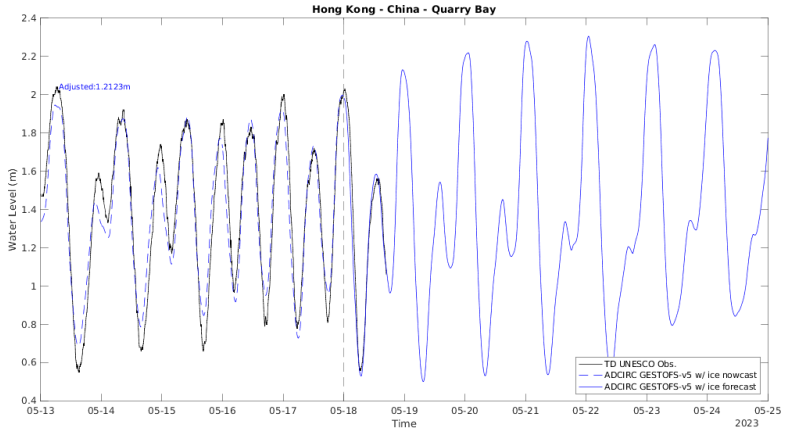
Global STOFS 2D: *v1.0 currently in operation*

Operational model forecasts run 4x per day at NOAA and 1x per day at ND



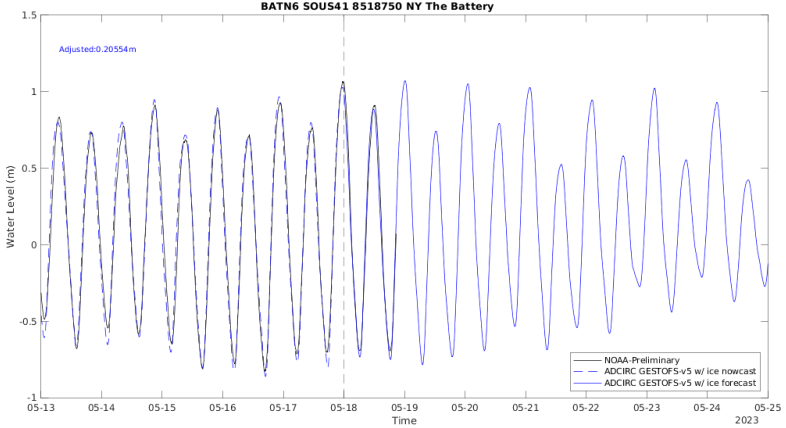


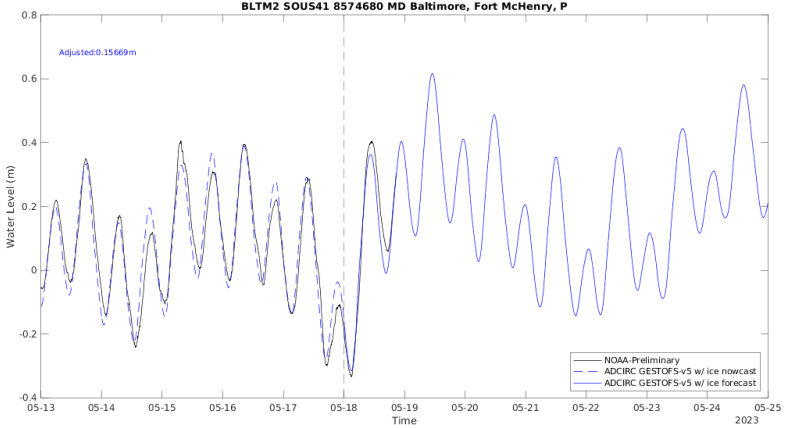


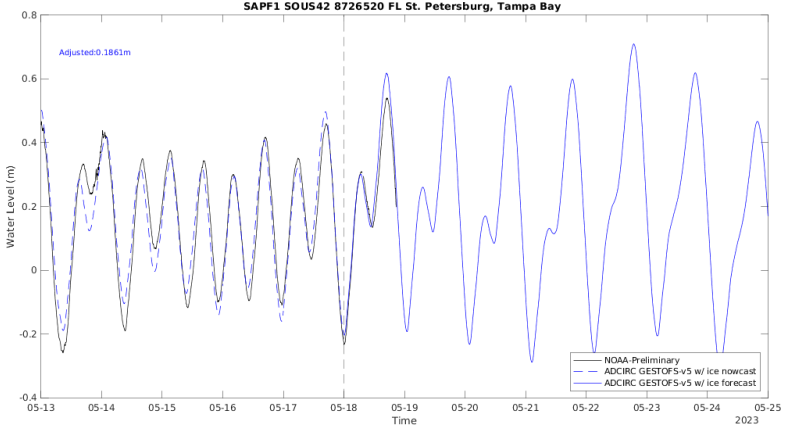


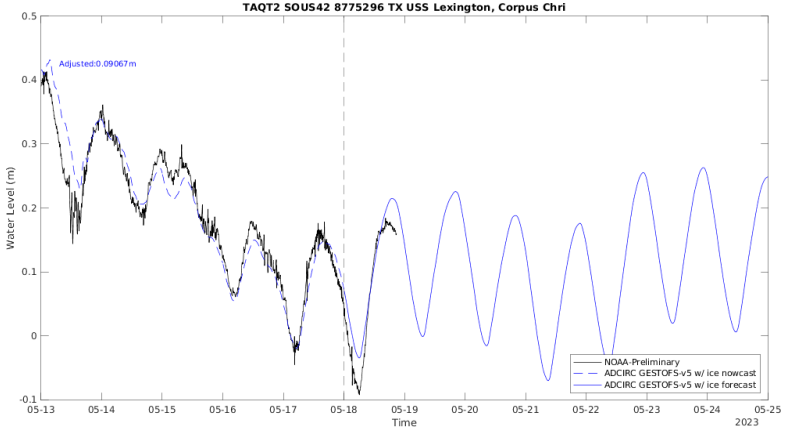
Global STOFS 2D: *v1.0 currently in operation*

Operational model forecasts with 5 day previous nowcast compared to NOS WL data









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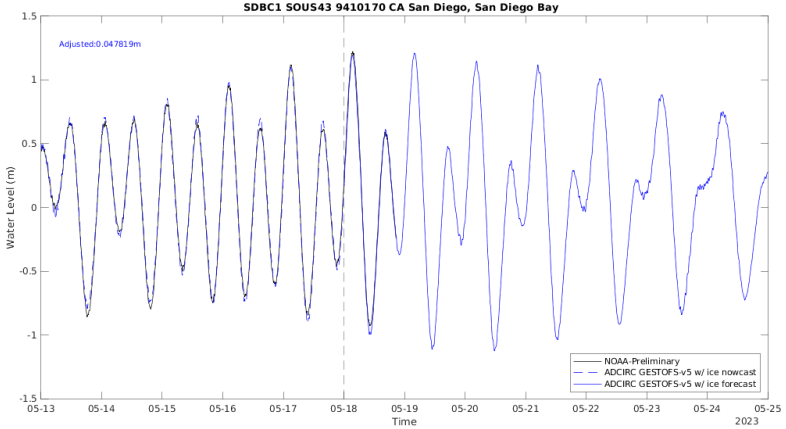

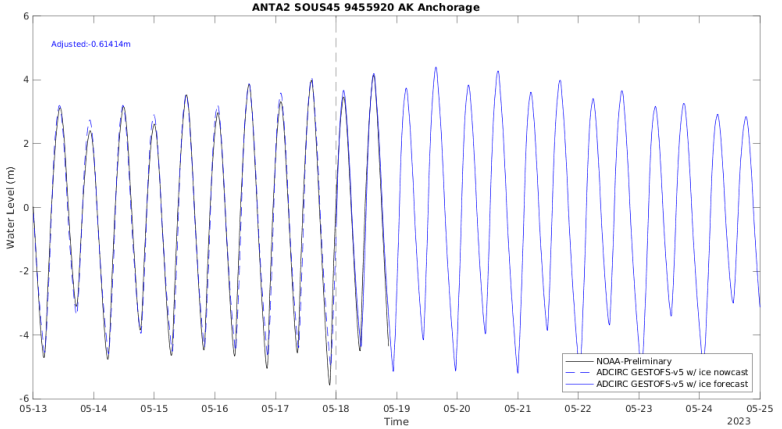

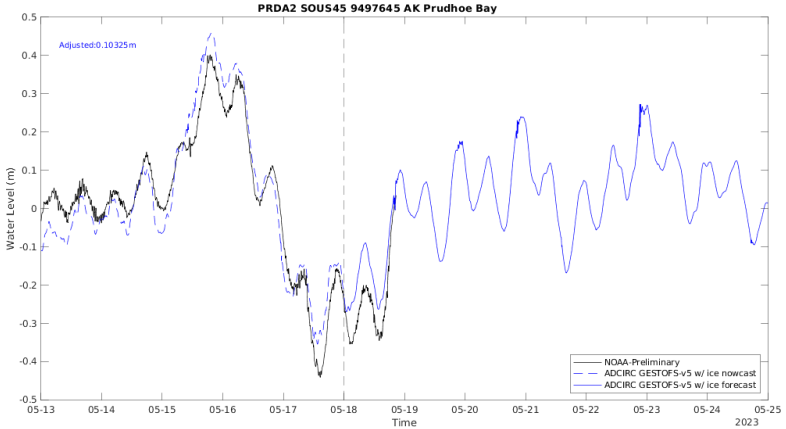

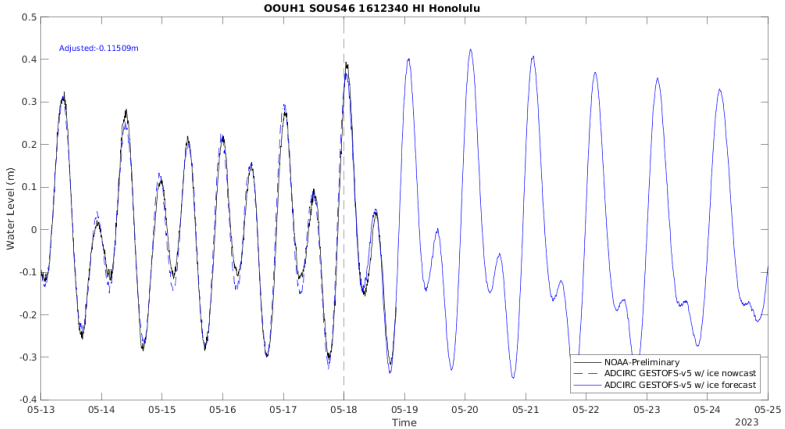

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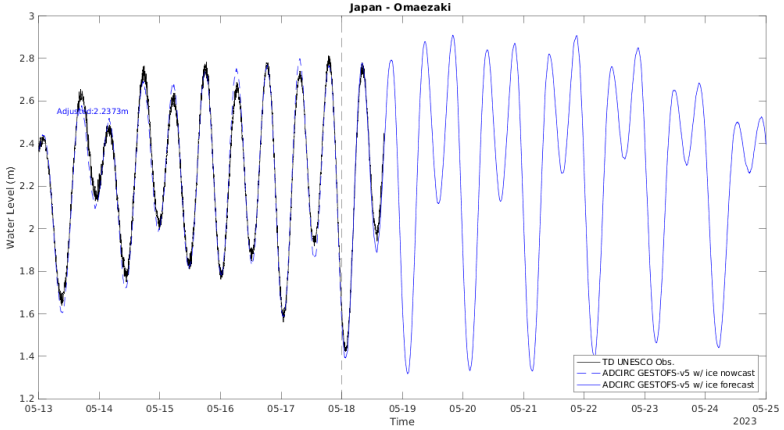
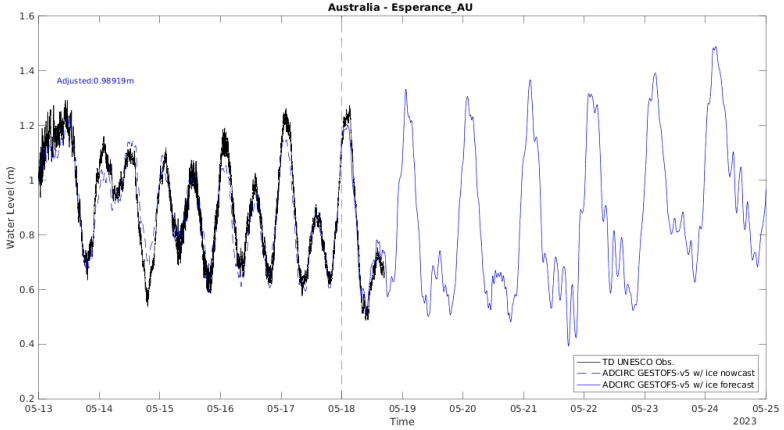
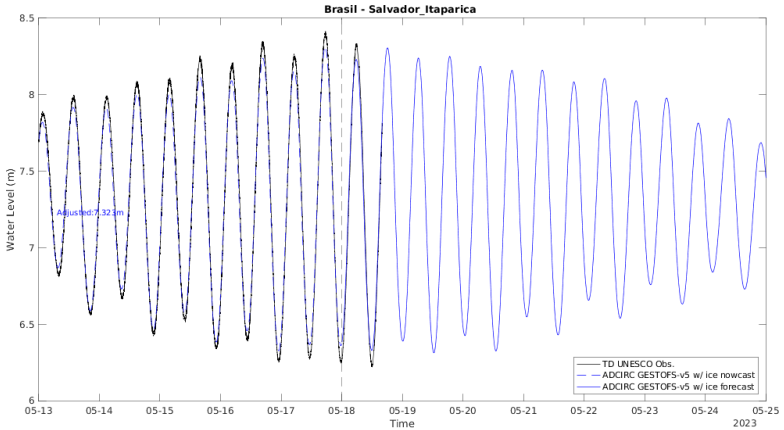
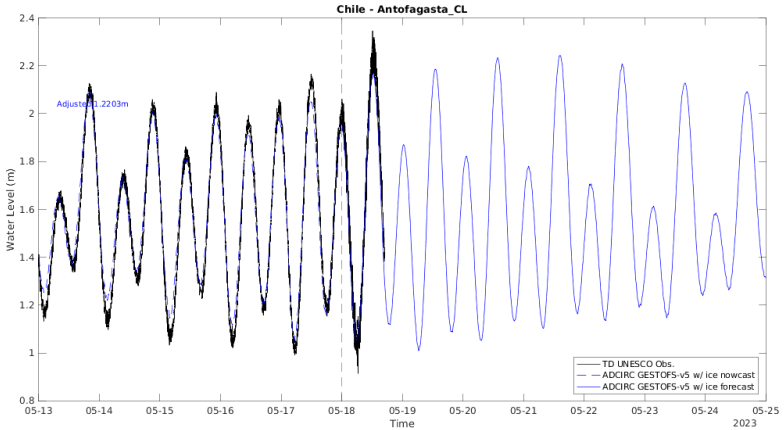
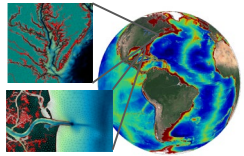








Global STOFS 2D$^+$: *Thermohaline engine transitioning to operations*



Coupling of *ADCIRC*, *GFS-FV3*, *and* *G-RTOFS /HYCOM using downscaling* over a unified domain on heterogeneous meshes/grids

$$\frac{\partial \boldsymbol{u}}{\partial t} + (\boldsymbol{u}\cdot\nabla)\boldsymbol{u} + f\mathbf{k}\times\boldsymbol{u} = -\nabla\left[\frac{p_s}{\rho_0} + g(\zeta - \zeta_{EQ} - \zeta_{SAL})\right] + \frac{\nabla M}{H} - \frac{\nabla D}{H} - \frac{\nabla B}{H} + \frac{\boldsymbol{\tau}_s}{\rho_0 H} - \frac{\boldsymbol{\tau}_b}{\rho_0 H} - \mathcal{F}_{IT}$$

- Baroclinic pressure gradient (BPG):

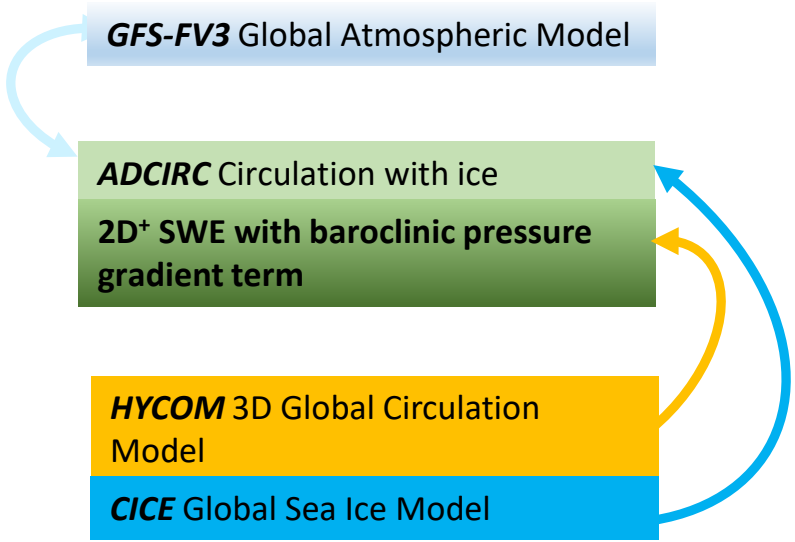
$$\nabla B = \int_{-h}^{\zeta}\left(g\nabla\left[\int_{z}^{\zeta}\frac{\rho-\rho_0}{\rho_0}\right]dz\right)dz$$

- Momentum Dispersion:

$$\nabla D = \nabla\int_{-h}^{0}[(\boldsymbol{v}-\boldsymbol{V})\cdot(\boldsymbol{v}-\boldsymbol{V})]\,dz$$

- Internal tide induced barotropic energy conversion:

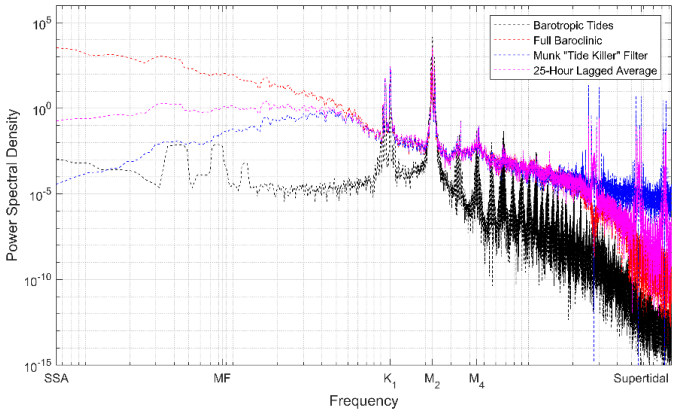
$$\mathcal{F}_{IT} = C_{IT}\frac{[(N_b^2-\omega^2)(\tilde{N}^2-\omega^2)]^{1/2}}{\omega}(\nabla h\cdot\boldsymbol{u})\nabla h$$



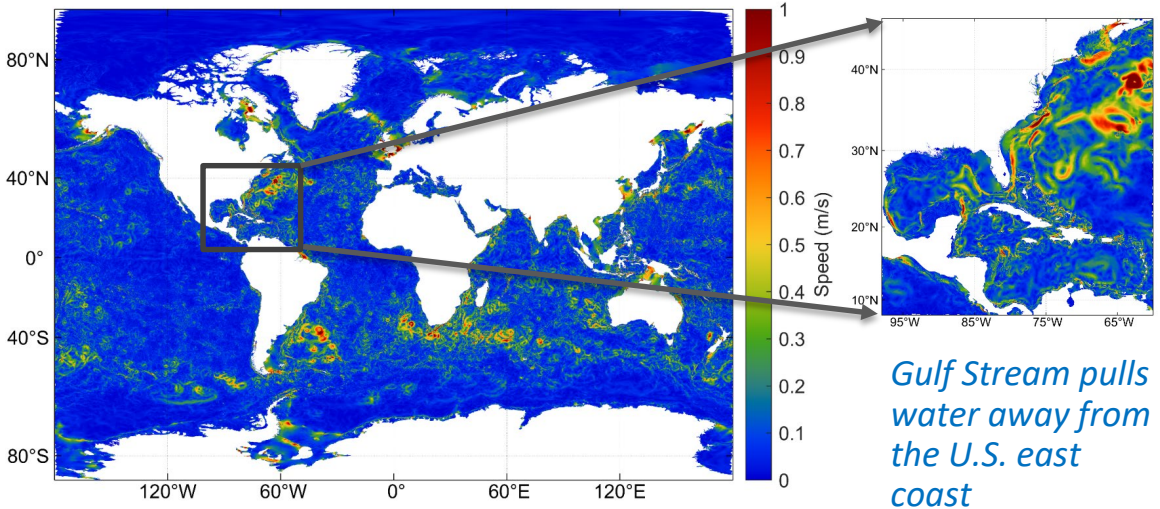
Global STOFS 2D⁺: *Thermohaline engine transitioning to operations*

Keys to successful implementation

- **Focused resolution on internal tide dissipation regions** (steep topo gradients coincident with high vertical density gradients)
- **Focused resolution on intense boundary layer dissipation areas** (99% of total global tidal boundary layer dissipation occurs over 4.3% of the ocean)
- **Highly specific banded filter applied to total velocity to extract only tidal frequencies**



It is critical to force the internal tide dissipation term only with tidal currents

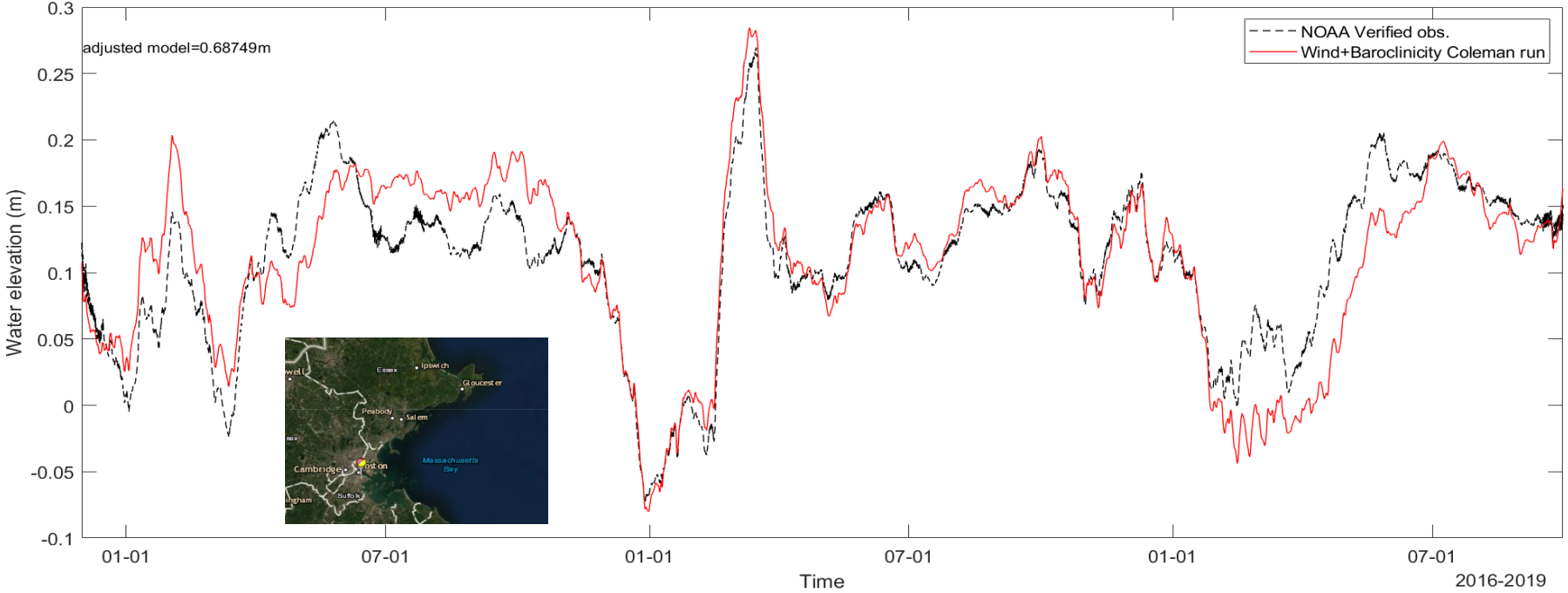


Currents in Global STOFS 2D⁺

Gulf Stream pulls water away from the U.S. east coast

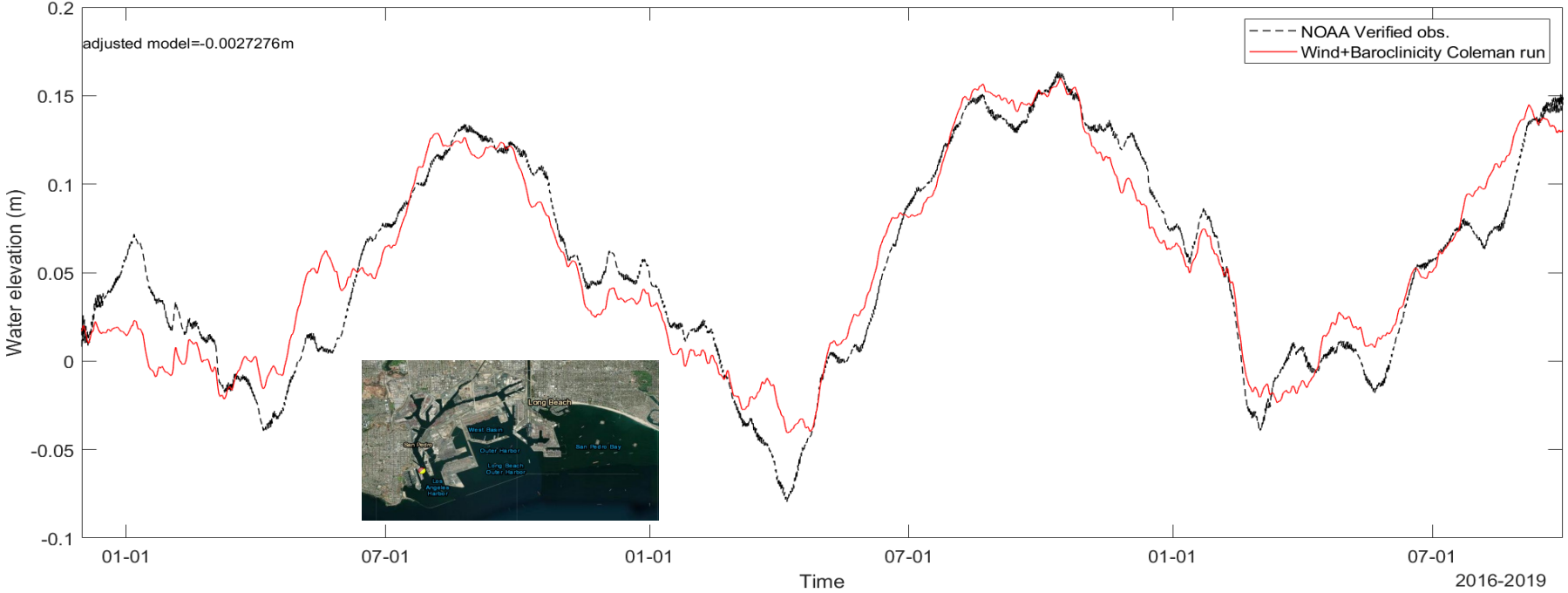
Global STOFS 2D+: *Thermohaline engine transitioning to operations*

30 day mean water levels compared at NOS Boston station



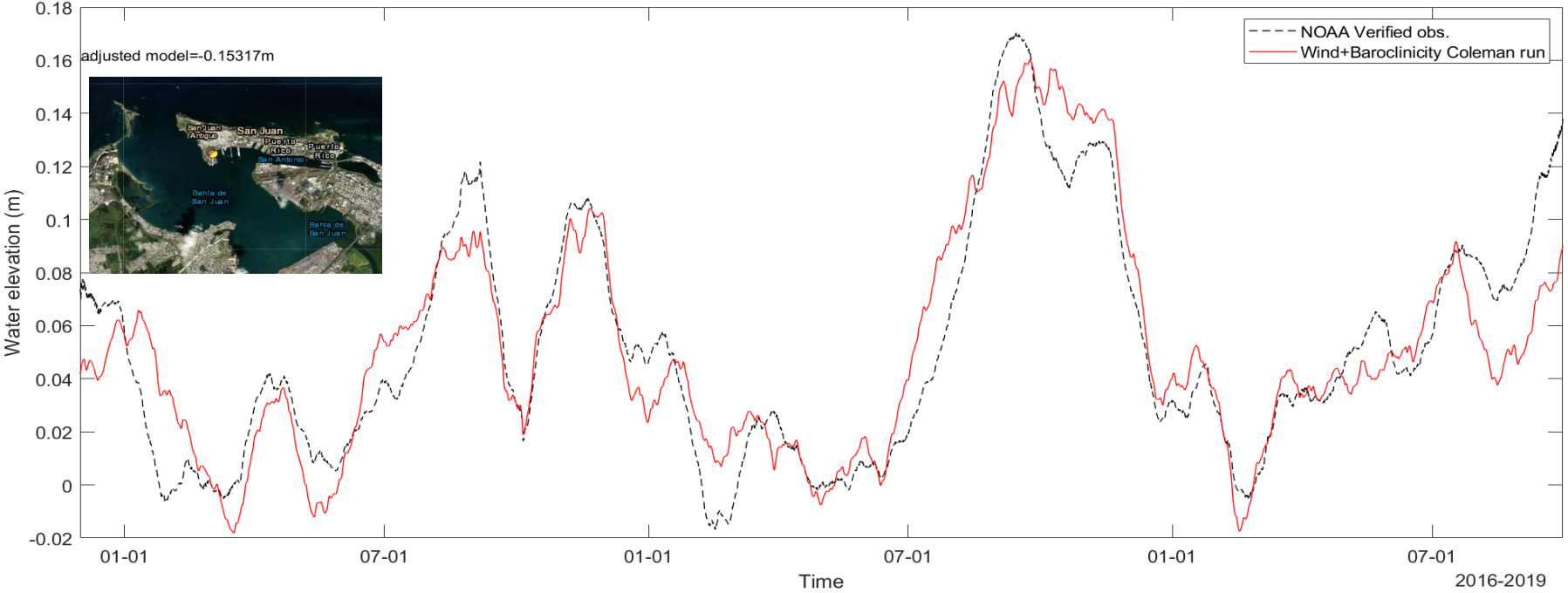
Global STOFS 2D+: *Thermohaline engine transitioning to operations*

30 day mean water levels compared at NOS Los Angeles station

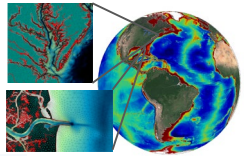


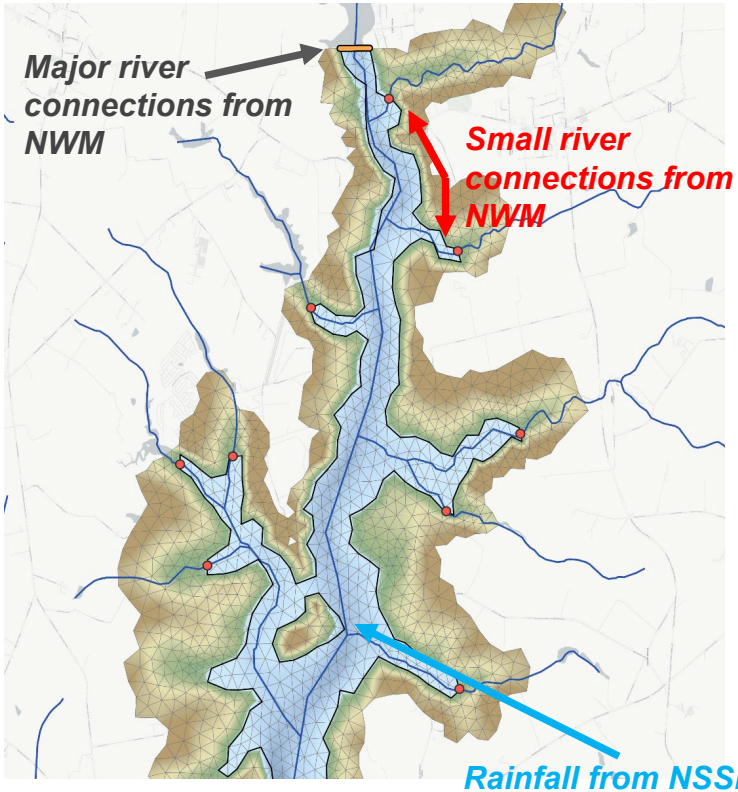
Global STOFS 2D+: *Thermohaline engine transitioning to operations*

30 day mean water levels compared at NOS San Juan PR station



Global STOFS 2D+ with NWM: *Thermohaline engine plus hydrology*





GFS-FV3 Global Atmospheric Model

ADCIRC Circulation

2D SWE with baroclinic pressure gradient term

HYCOM 3D Global Circulation Model

CICE Global Sea Ice Model

WRF Hydro National Water Model

Global STOFS 2D+ with NWM: *Hurricane Irene forced with NWM hydrology*

Original

OWI Winds and Atm. Pressure

Rivers

Original + River discharge

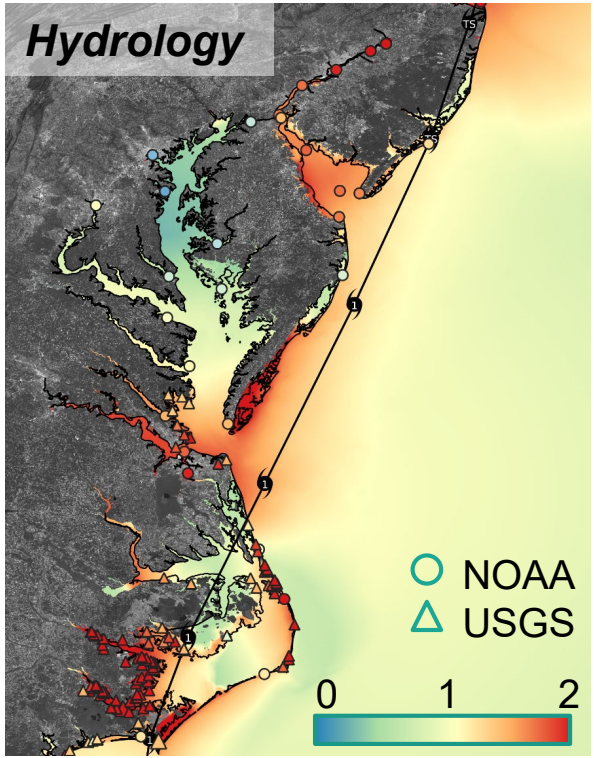
Precipitation

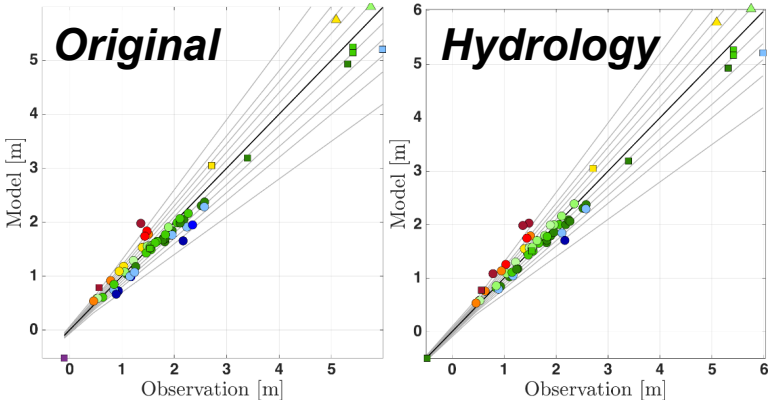
Original + Precipitation nearshore

Hydrology

Original + Rivers + Precipitation

HWMs [m above NAVD88]





	Original	Hydrology
R^2	0.9683	0.9699
$\overline{Err}$	-0.0475	0.0004
$\overline{\lvert Err \rvert}$	0.174	0.159
$nRMSE$	0.1026	0.0992

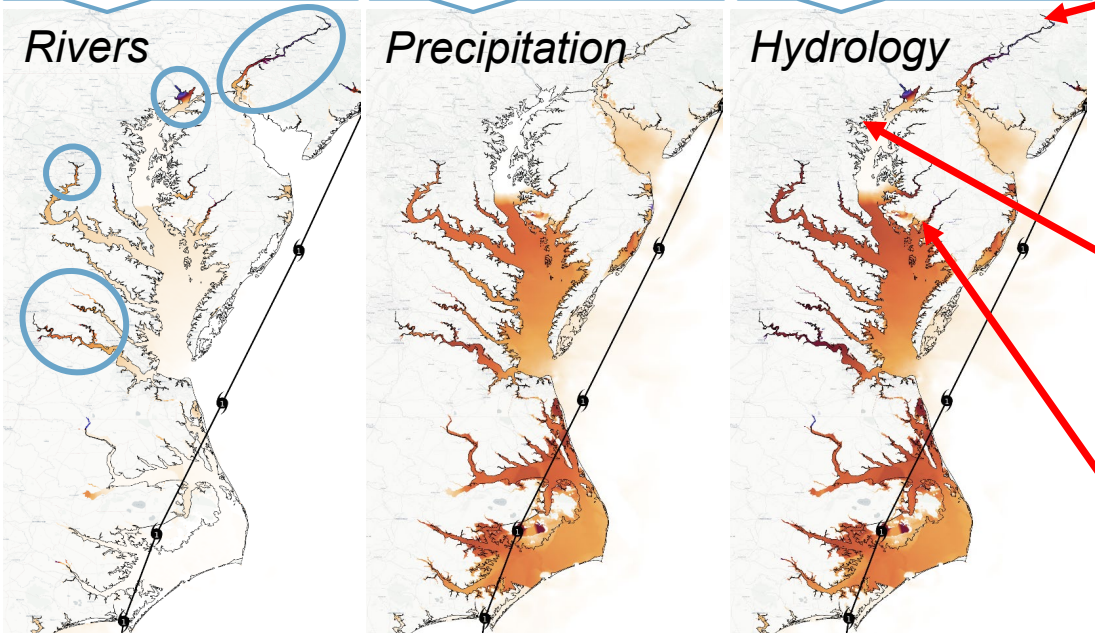
Global STOFS 2D+ with NWM: *Hurricane Irene forced with NWM hydrology*

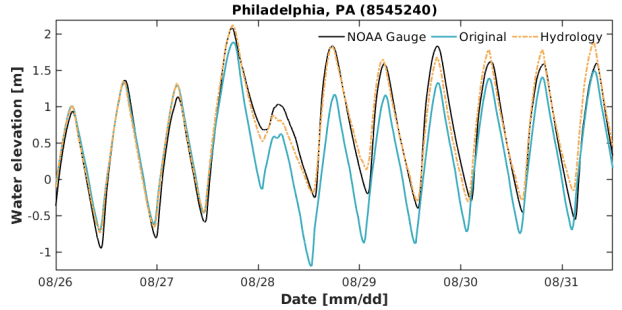
Effect on Max water surface elevation [m above NAVD88]

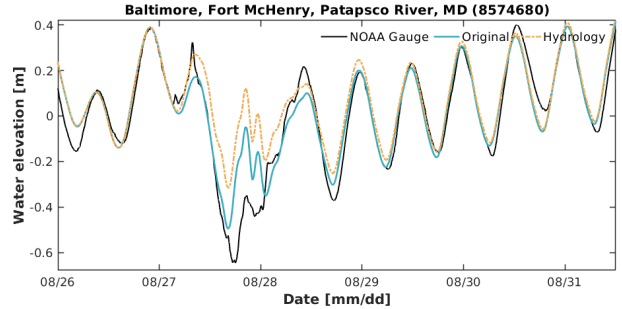
Large but localized effect of river discharge

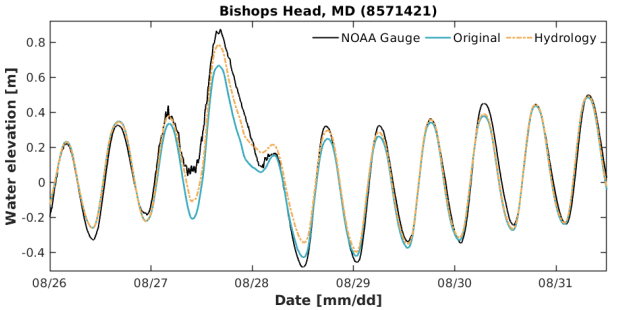
Smaller effect distributed across the bays

Linear coupled effect

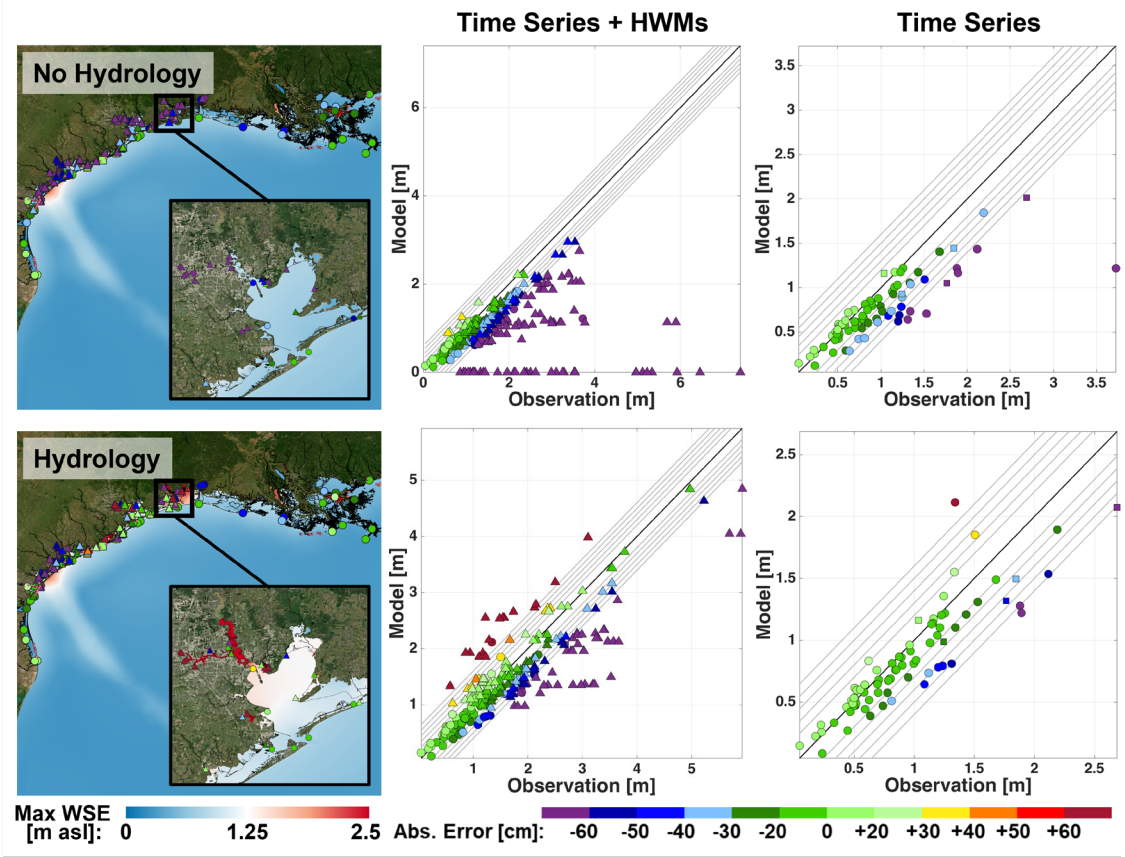








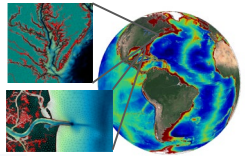
Global STOFS 2D+ with NWM: *Hurricane Harvey forced with NWM hydrology*



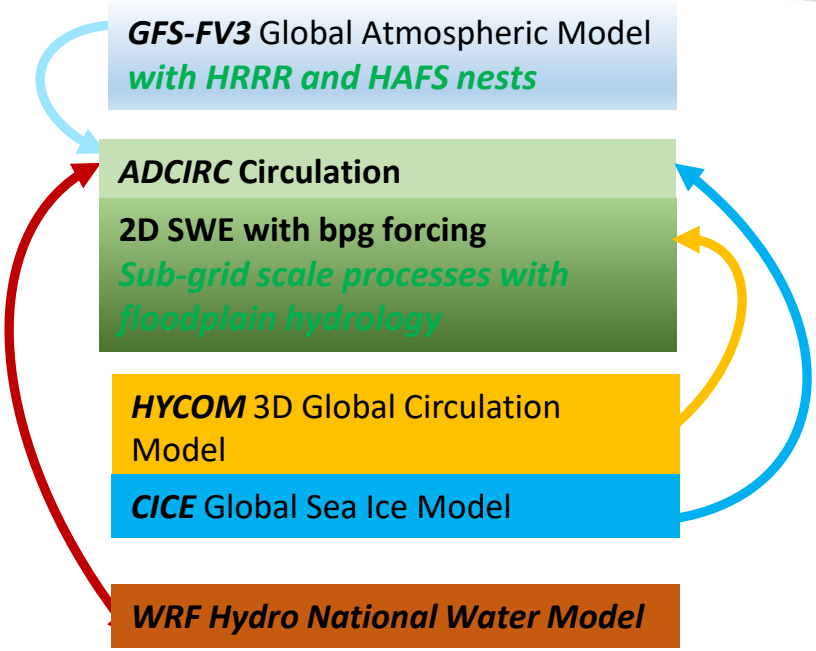
	TS+HWMs	Time Series
R^2	0.0462	0.7068
$\overline{Err}$	-0.8426	-0.2232
$\overline{\lvert Err \rvert}$	0.8632	0.2451
$nRMSE$	0.6769	0.3621

	TS+HWMs	Time Series
R^2	0.7189	0.8069
$\overline{Err}$	-0.1184	-0.1029
$\overline{\lvert Err \rvert}$	0.4070	0.1670
$nRMSE$	0.2835	0.2291

Global STOFS 2D+ with NWM*: Meteo nesting and sub-grid scale*



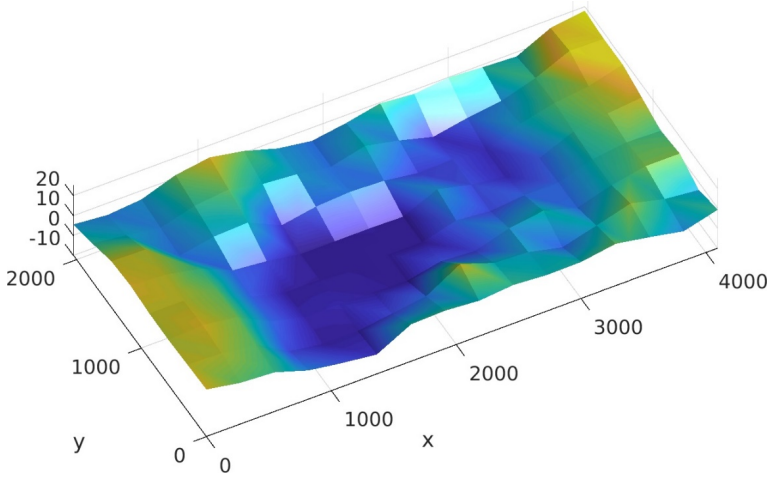
- Advancements under development
  - Refined forcing from nested meteorological models including HRRR and HAFS
  - Real time improvements in the hurricane core based on NHC advisories
  - Sub-grid scale averaging to incorporate unresolved processes

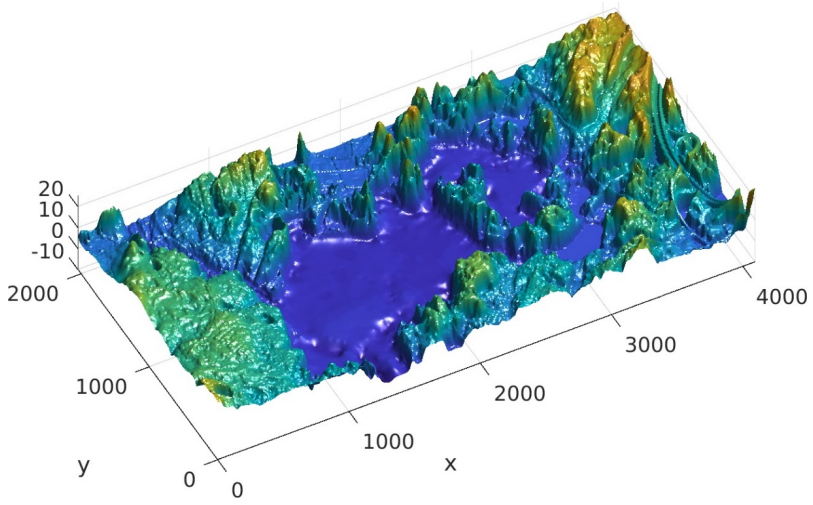


Global STOFS 2D+ with NWM: *Meteo nesting and sub-grid scale processes*

Subgrid scale implementation for features less than 80m to 120m

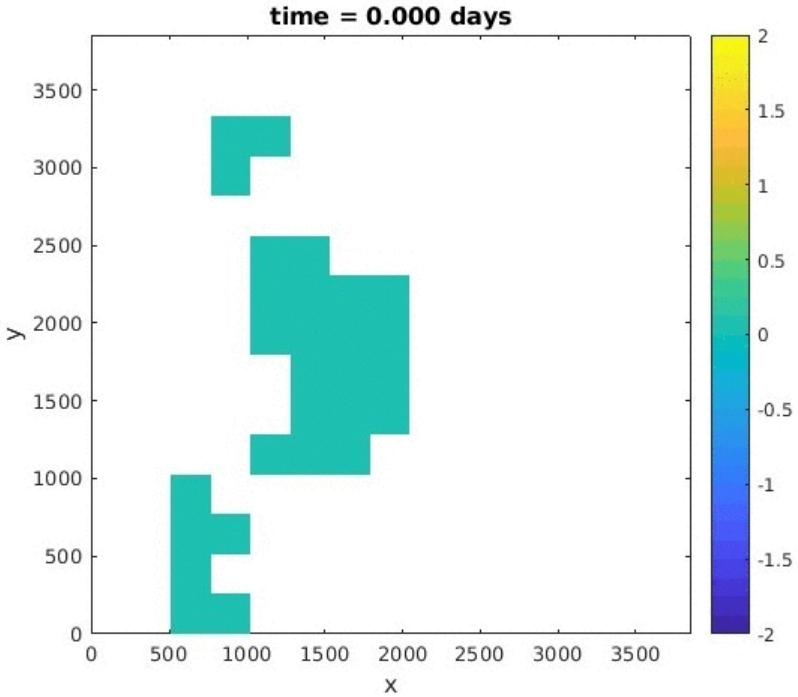
- Develop ideas from Casulli and others to include sub-grid scale features using averaging and porosity concepts
- Apply pre-computed lookup tables in order to establish porosity
- Implemented in ADCIRC/GWCE, our own FV/FD codes, and now DG p0/p0 and p0/p1 based floodplain elements



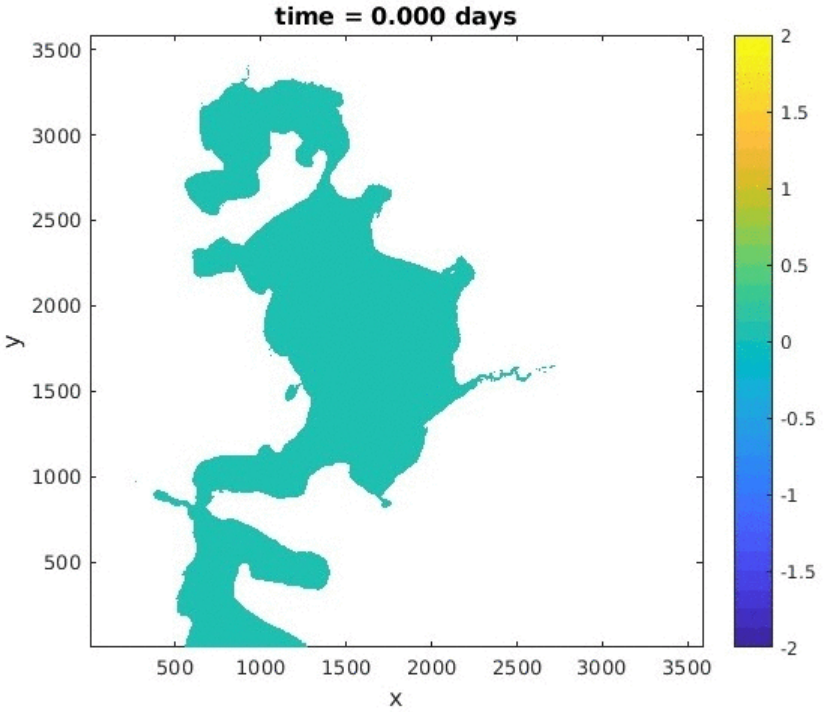


Global STOFS 2D+ with NWM*: Meteo nesting and sub-grid scale processes*

256m mesh

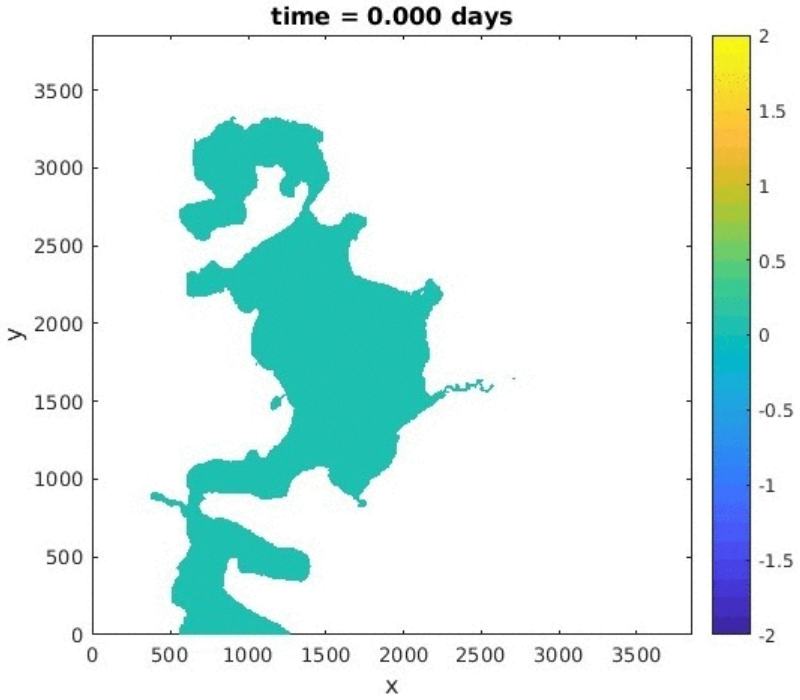


8m mesh

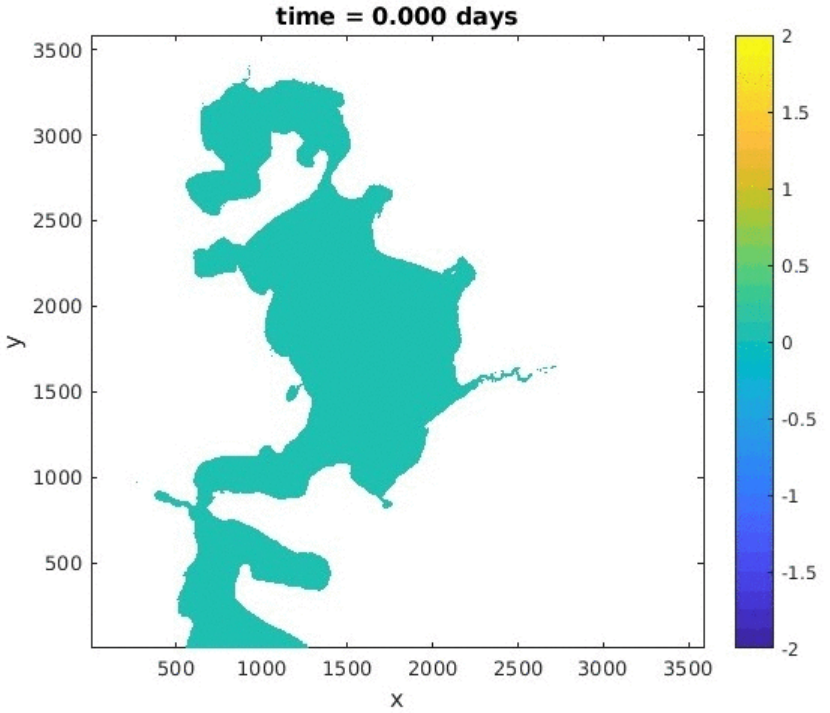


Global STOFS 2D+ with NWM*: Meteo nesting and sub-grid scale processes*

8m mesh



256m mesh with SGS



This model runs 10,000 times faster than the 8m model

Global