Force Globally, Flood Locally: Advances in High-Resolution Global Coastal Flood Modelling

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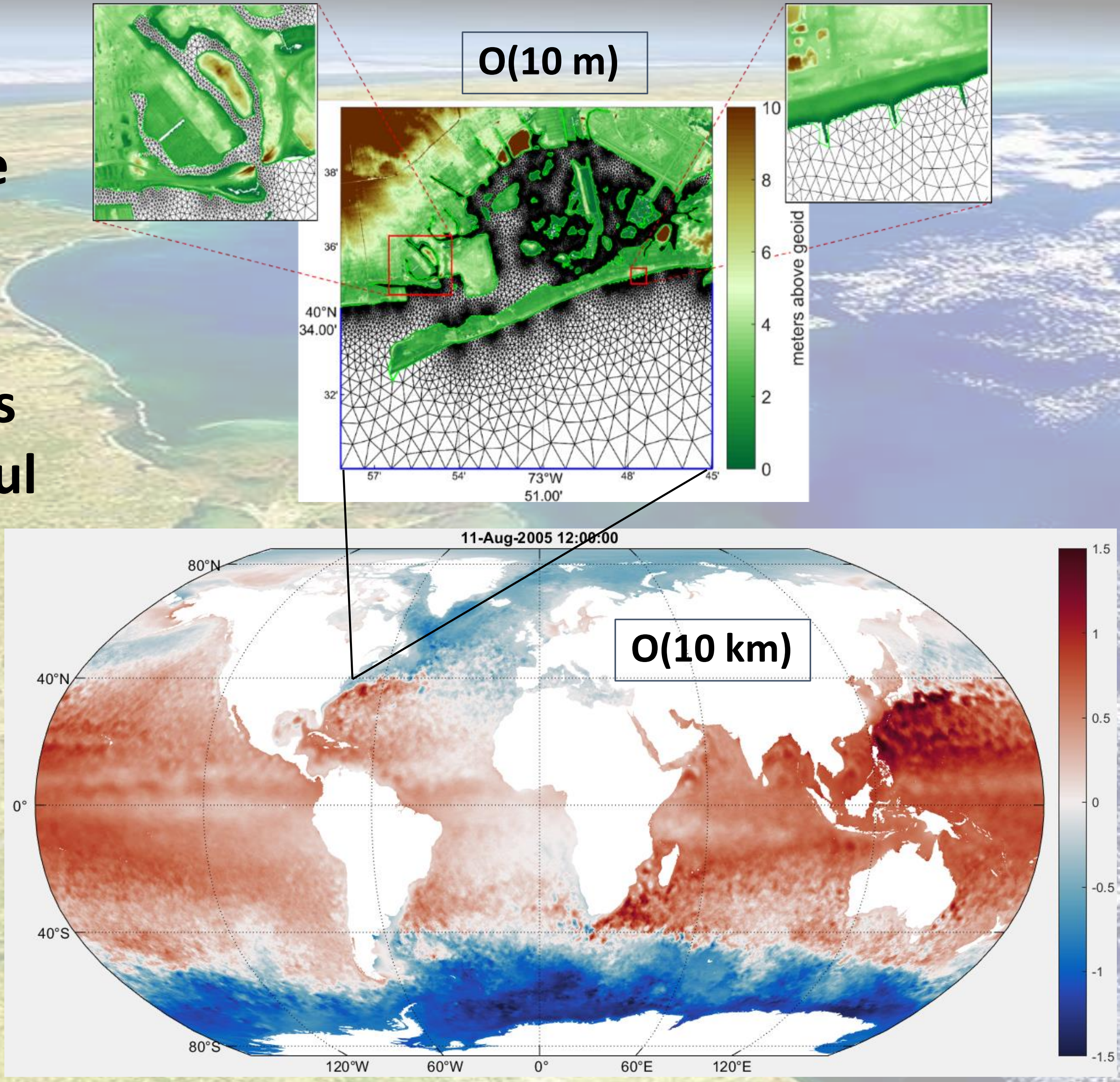
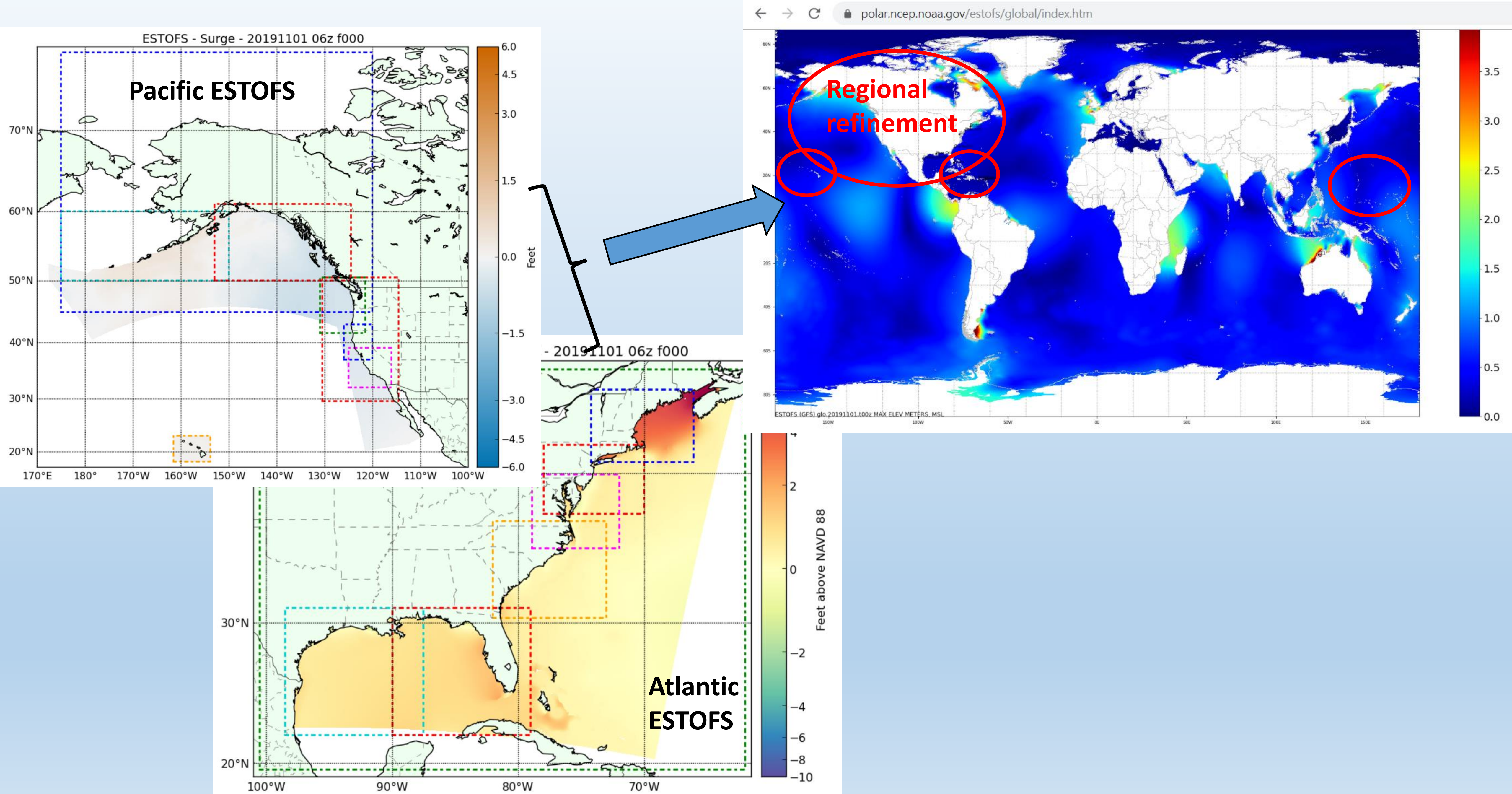
Philosophy

- Modeling large-scale tides, surge (and other effects on SSH) on a global mesh
- Use unstructured mesh elements to seamlessly downscale to useful local scale resolution, O(10 m)
- <u>Benefits:</u>
  - No open boundaries / nesting
  - Capture all events at all times
  - Account for all spatial modes
  - Everything coupled at physics level



NOAA

Global ESTOFS



My Own - GLOCOFFS

wpringle.github.io/GLOCOFFS/

GLObal Coastal Ocean Flood Forecasting System

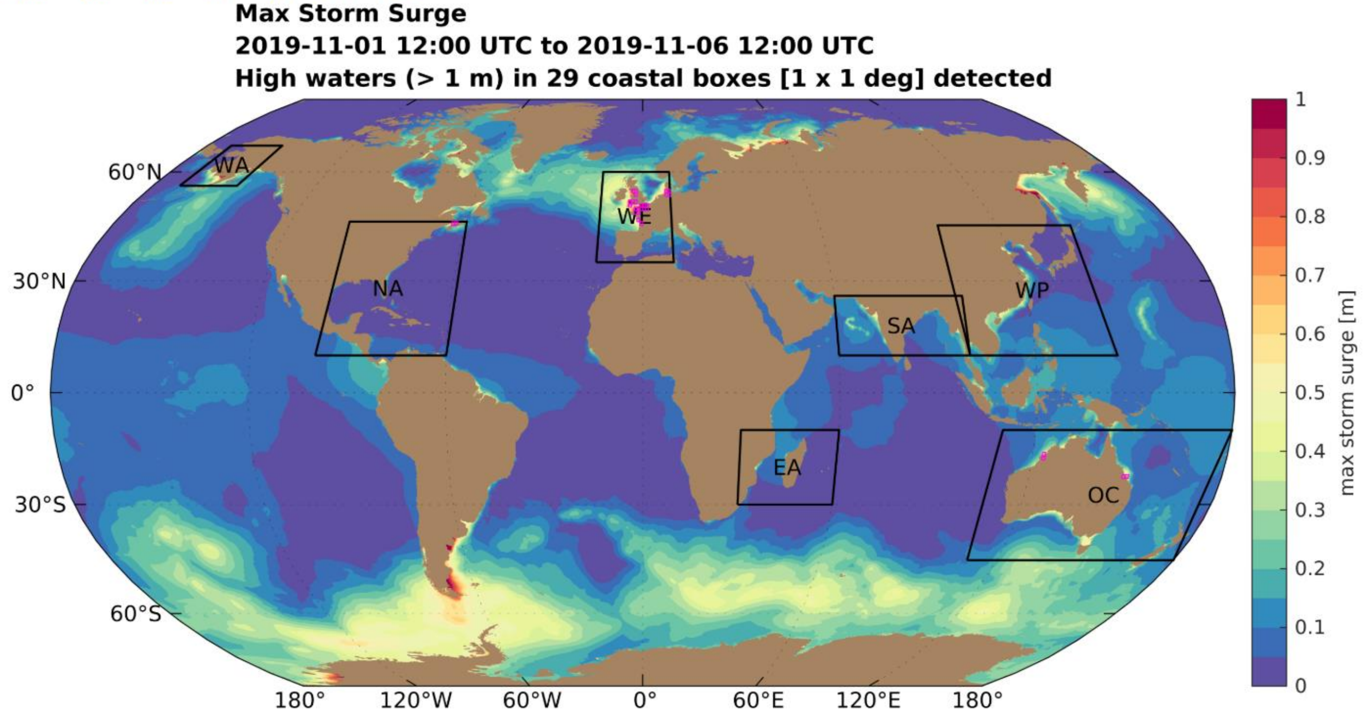
An ADCIRC-based global storm tide modeling system providing real-time predictions for coastal flooding

View on GitHub

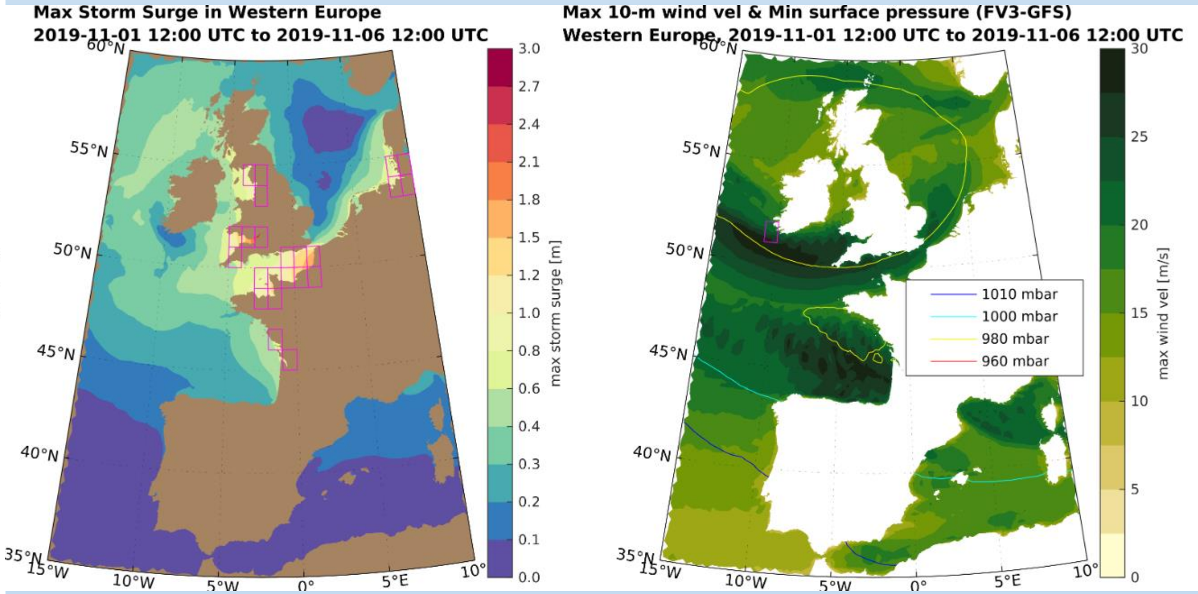
Hydrodynamic: Maximum Surge (meteorological driven component above tides)

Click to see closeup of maximum surge and maximum winds/minimum pressure in individual regions

WA · NA · WE · EA · SA · WP · OC



Western Europe



Advances we have been working on – briefly show today

1. **Extend a commonly used finite-element (FEM) coastal storm surge model (ADCIRC) to accurately and quickly simulate the whole Earth**

2. **Introduce seamless refinement at the coast and on-land where/when required to dynamically simulate flooding**
   - FEM is useful here because even meshes with fast size transitions and skewed elements will simulate adequately

3. **Account for low-frequency modes (e.g., ocean currents) that impact sea levels**

1. Improving shallow water wave equations for global simulations

<u>Generalized Wave Continuity Model (ADCIRC)</u>

- Reformulates SWEs into the generalized wave continuity equation (GWCE) – a 2nd order PDE to remove oscillations by FEM
- So far has been used to model local and regional domains
- Some modifications required to extend ADCIRC to correctly solve the SWE on the sphere (Global model)

Shallow water equations in spherical coordinates

$$\frac{\partial \zeta}{\partial t} = -\frac{1}{R\cos\phi}\left[\frac{\partial(UH)}{\partial\lambda} + \frac{\partial(VH\cos\phi)}{\partial\phi}\right] \qquad (1)$$

$$\begin{aligned}\frac{\partial U}{\partial t} = &-\frac{U}{R\cos\phi}\frac{\partial U}{\partial\lambda} - \frac{V}{R}\frac{\partial U}{\partial\phi} - (\mathcal{C}_{\lambda\phi} - f')V - \frac{1}{R\cos\phi}\frac{\partial\Psi}{\partial\lambda} + \tau_w U_w - (\tau_b + \mathcal{C}_{\lambda\lambda})U \\ &+ \frac{\nu_t}{R}\left[\frac{1}{\cos\phi}\frac{\partial\tau_{\lambda\lambda}}{\partial\lambda} + \frac{\partial\tau_{\lambda\phi}}{\partial\phi} - \tan\phi(\tau_{\lambda\phi} + \tau_{\phi\lambda})\right]\end{aligned} \qquad (2)$$

$$\begin{aligned}\frac{\partial V}{\partial t} = &-\frac{U}{R\cos\phi}\frac{\partial V}{\partial\lambda} - \frac{V}{R}\frac{\partial V}{\partial\phi} - (\mathcal{C}_{\phi\lambda} + f')U - \frac{1}{R}\frac{\partial\Psi}{\partial\phi} + \tau_w V_w - (\tau_b + \mathcal{C}_{\phi\phi})V \\ &+ \frac{\nu_t}{R}\left[\frac{\partial\tau_{\phi\phi}}{\partial\phi} + \frac{1}{\cos\phi}\frac{\partial\tau_{\phi\lambda}}{\partial\lambda} + \tan\phi(\tau_{\lambda\lambda} - \tau_{\phi\phi})\right]\end{aligned} \qquad (3)$$

$\Psi = \frac{p_s}{\rho_0} + g(\zeta - \eta)$: water column pressure anomaly

$f' = 2\Omega\sin\phi + \frac{\tan\phi}{R}U$: Coriolis + component of advection expanded in spherical coordinates

$\tau_w = C_D\frac{\rho_s\sqrt{U_w^2 + V_w^2}}{\rho_0 H}$: quadratic surface stress due to winds

$\tau_b = C_f\frac{\sqrt{U^2 + V^2}}{H}$: quadratic bed stress due to friction

$\mathcal{C} = \begin{pmatrix}\mathcal{C}_{\lambda\lambda} & \mathcal{C}_{\lambda\phi} \\ \mathcal{C}_{\phi\lambda} & \mathcal{C}_{\phi\phi}\end{pmatrix}$: internal tide wave drag tensor

$$\begin{aligned}\tau &= \begin{pmatrix}\tau_{\lambda\lambda} & \tau_{\lambda\phi} \\ \tau_{\phi\lambda} & \tau_{\phi\phi}\end{pmatrix} \quad : \text{lateral stress tensor} \\ &= \begin{pmatrix}\frac{1}{R\cos\phi}\frac{\partial U}{\partial\lambda} & \frac{1}{R\cos\phi}\frac{\partial V}{\partial\lambda} \text{ or } \frac{1}{R}\frac{\partial U}{\partial\phi} + \frac{1}{R\cos\phi}\frac{\partial V}{\partial\lambda} \\ \frac{1}{R}\frac{\partial U}{\partial\phi} \text{ or } \frac{1}{R}\frac{\partial U}{\partial\phi} + \frac{1}{R\cos\phi}\frac{\partial V}{\partial\lambda} & \frac{1}{R}\frac{\partial V}{\partial\phi}\end{pmatrix}\end{aligned}$$

Current ADCIRC model equations

- tan(ϕ) terms ignored…

$$\frac{1}{R\cos\phi}\frac{\partial(VH\cos\phi)}{\partial\phi} = \frac{1}{R}\frac{\partial(VH)}{\partial\phi} - \frac{\tan\phi}{R}VH$$

0

$$\frac{\partial\zeta}{\partial t} = -\frac{1}{R\cos\phi}\left[\frac{\partial(UH)}{\partial\lambda} + \frac{\partial(VH\cos\phi)}{\partial\phi}\right] \quad (1)$$

$$\frac{\partial U}{\partial t} = -\frac{U}{R\cos\phi}\frac{\partial U}{\partial\lambda} - \frac{V}{R}\frac{\partial U}{\partial\phi} - (\mathcal{C}_{\lambda\phi} - f')V - \frac{1}{R\cos\phi}\frac{\partial\Psi}{\partial\lambda} + \tau_w U_w - (\tau_b + \mathcal{C}_{\lambda\lambda})U$$
$$+ \frac{\nu_t}{R}\left[\frac{1}{\cos\phi}\frac{\partial\tau_{\lambda\lambda}}{\partial\lambda} + \frac{\partial\tau_{\lambda\phi}}{\partial\phi} - \tan\phi(\tau_{\lambda\phi} + \tau_{\phi\lambda})\right] \quad (2)$$

0

$$\frac{\partial V}{\partial t} = -\frac{U}{R\cos\phi}\frac{\partial V}{\partial\lambda} - \frac{V}{R}\frac{\partial V}{\partial\phi} - (\mathcal{C}_{\phi\lambda} + f')U - \frac{1}{R}\frac{\partial\Psi}{\partial\phi} + \tau_w V_w - (\tau_b + \mathcal{C}_{\phi\phi})V$$
$$+ \frac{\nu_t}{R}\left[\frac{\partial\tau_{\phi\phi}}{\partial\phi} + \frac{1}{\cos\phi}\frac{\partial\tau_{\phi\lambda}}{\partial\lambda} + \tan\phi(\tau_{\lambda\lambda} - \tau_{\phi\phi})\right] \quad (3)$$

0

$$f' = 2\Omega\sin\phi + \frac{\tan\phi}{R}U$$

0

Proposed solution

- Use an arbitrary cylindrical projection to map (λ,ϕ) onto (*x*,*y*): (Select desired *p* = 0, 1, 2)

$$x = R(\lambda - \lambda_0)\cos\phi_0$$

(λ_0,ϕ_0) is arbitrary origin

$$y = \begin{cases} R\sin\phi\sec\phi_0 & \text{if } p = 0: \text{ Equal-area} \\ R\phi & \text{if } p = 1: \text{ Equidistant (CPP)} \\ R\ln(\tan\phi + \sec\phi)\cos\phi_0 & \text{if } p = 2: \text{ Conformal (Mercator)} \end{cases}$$

- Multiply continuity by *cos^p(ϕ)* [= 1 when *p* = 0]:

$$\frac{\partial\zeta}{\partial t} = -\frac{1}{R\cos\phi}\left[\frac{\partial(UH)}{\partial\lambda} + \frac{\partial(VH\cos\phi)}{\partial\phi}\right]$$

$$\frac{\partial(\zeta\cos^p\phi)}{\partial t} = -L_x\frac{\partial(UH)}{\partial x} - L_y\frac{\partial(VH\cos\phi)}{\partial y}$$

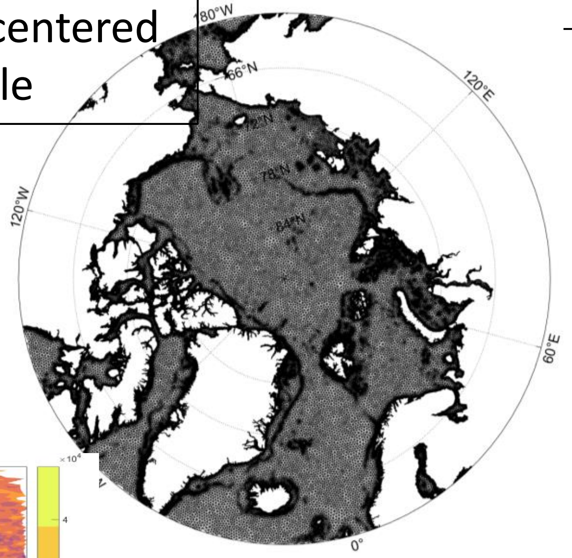
$$L_x = \cos\phi_0(\cos\phi)^{p-1}, \qquad L_y = (\cos\phi_0)^{p-1},$$

this is just a constant

Testing on a global mesh

Note:
We have been able to use around **2 min time step** on this mesh. Equivalent to CFL of 13.
5-day forecast on 48 CPUs takes 10 minutes

Stereographic projection centered at North Pole

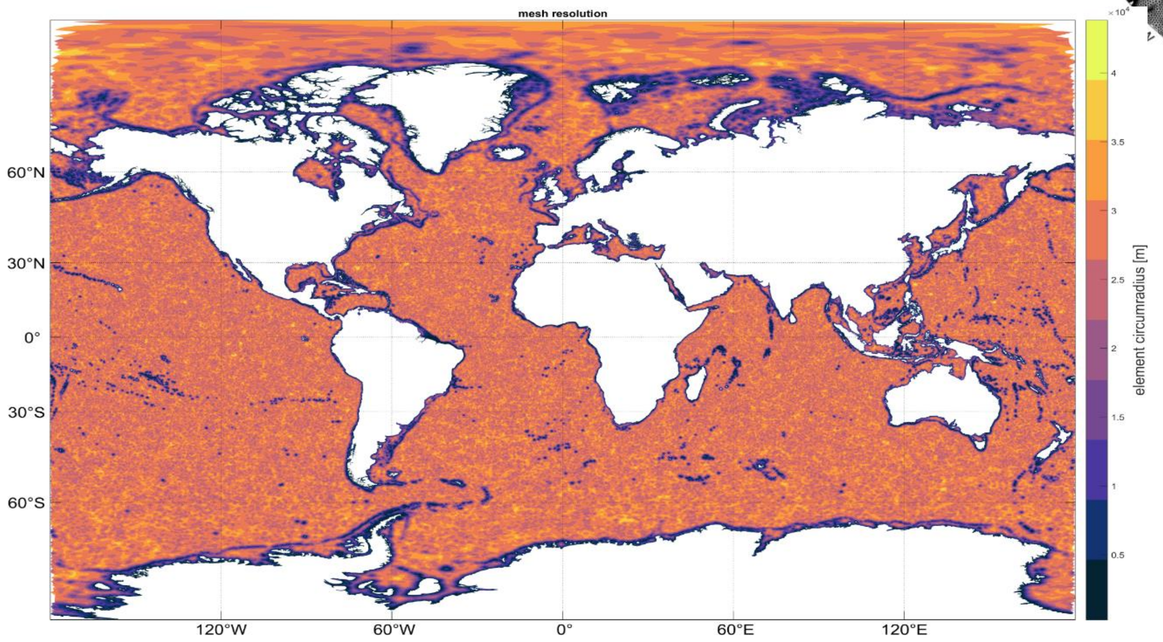


Roberts, K.J., Pringle, W.J., Westerink, J.J., 2019. OceanMesh2D 1.0: MATLAB-based software for two-dimensional unstructured mesh generation in coastal ocean modeling. Geosci. Model Dev, 12, 1847-1868. doi:10.5194/gmd-12-1847-2019

Made using OceanMesh2D

https://github.com/CHLNDDEV/OceanMesh2D/

Nominal element sizes range ~2 km to 25 km



Branch: dev ▾ OceanMesh2D / Example_7_Global.m

WPringle Update Example_7_Global.m

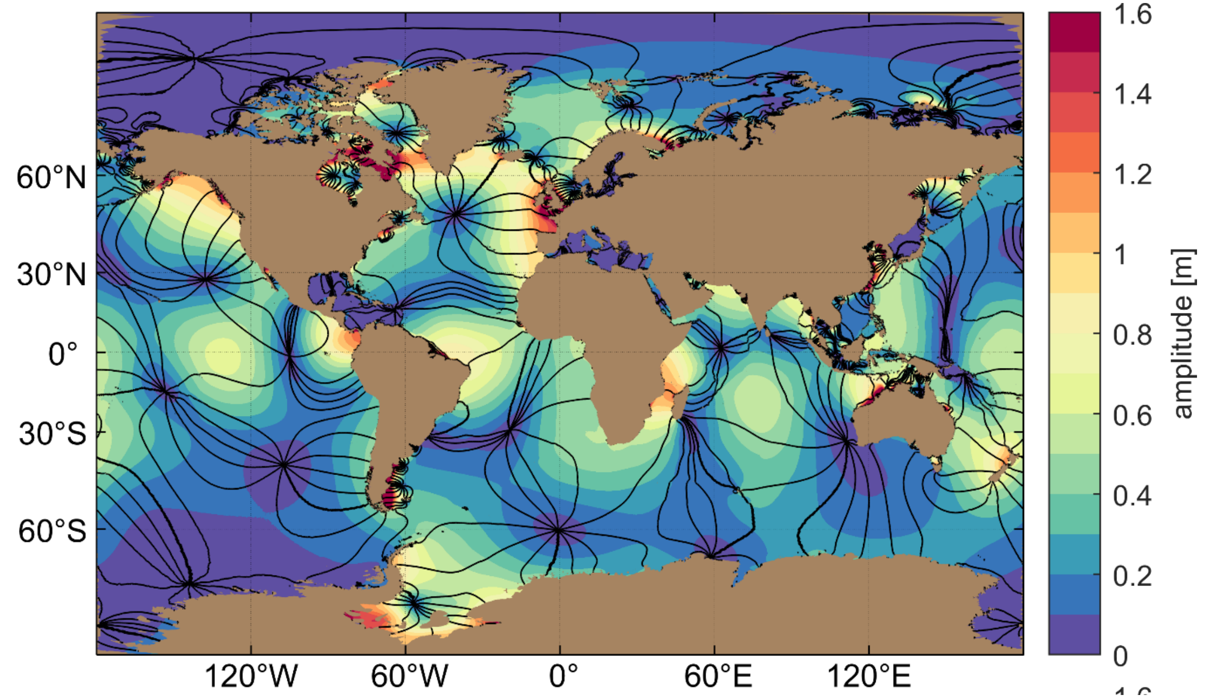
1 contributor

44 lines (37 sloc) 1.65 KB

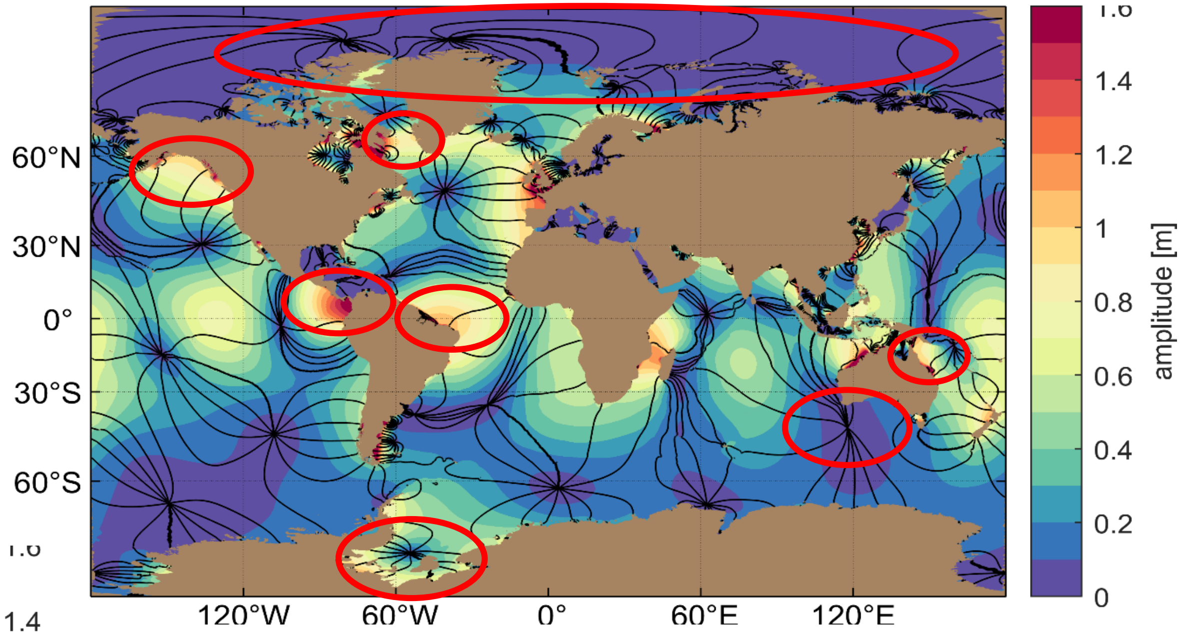
```
% Example_7_Global: Make a global mesh
clearvars; clc;
addpath(genpath('utilities/'));
addpath(genpath('datasets/'));
addpath(genpath('m_map/'));

%% STEP 1: set mesh extents and set parameters for mesh.
%% The globe
bbox      = [-180 180; -88  90]; % lon min lon max; lat min lat max
min_el    = 4e3;                  % minimum resolution in meters.
max_el    = 20e3;                     % maximum resolution in meters.
wl        = 30;                  % 30 elements resolve M2 wavelength.
dt        = 0;                   % Only reduces res away from coast
grade     = 0.25;                % mesh grade in decimal percent.
R         = 3;                        % Number of elements to resolve feature.
slp       = 10;                  % slope of 10

outname = 'Global_4km_20km';
```

M2 tides

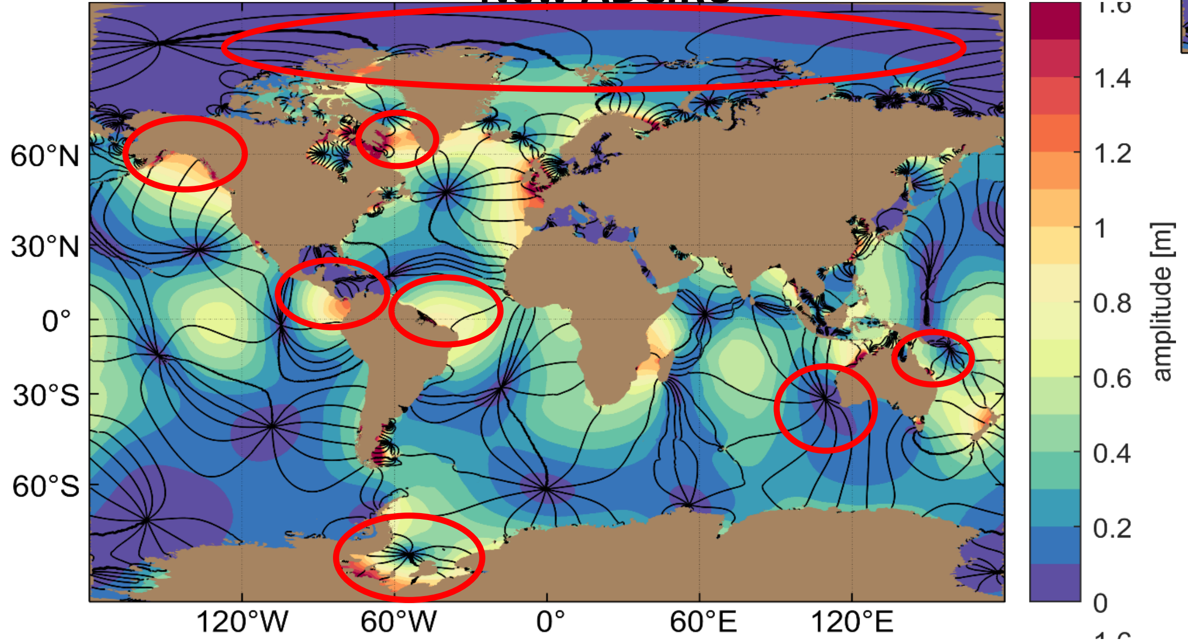
TPXO9-Atlas



Old ADCIRC



New ADCIRC



M2 tide RMSE

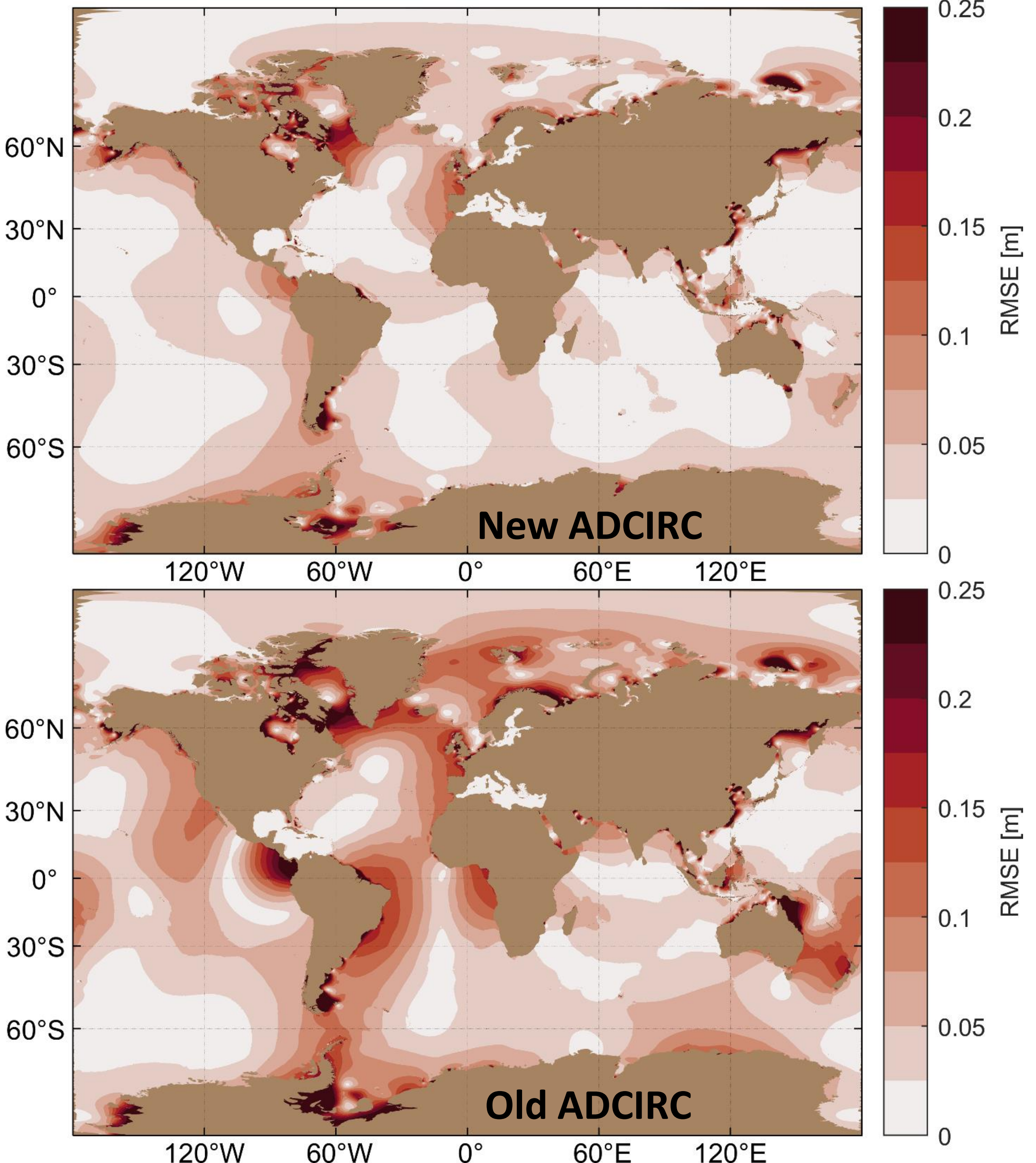
- RMSE in deep ocean almost half old ADCIRC version
- All projections give same solution
- RMSE also decreased from previous non-assimilated models in Stammer et al., (2014)

Area-averaged global RMSE

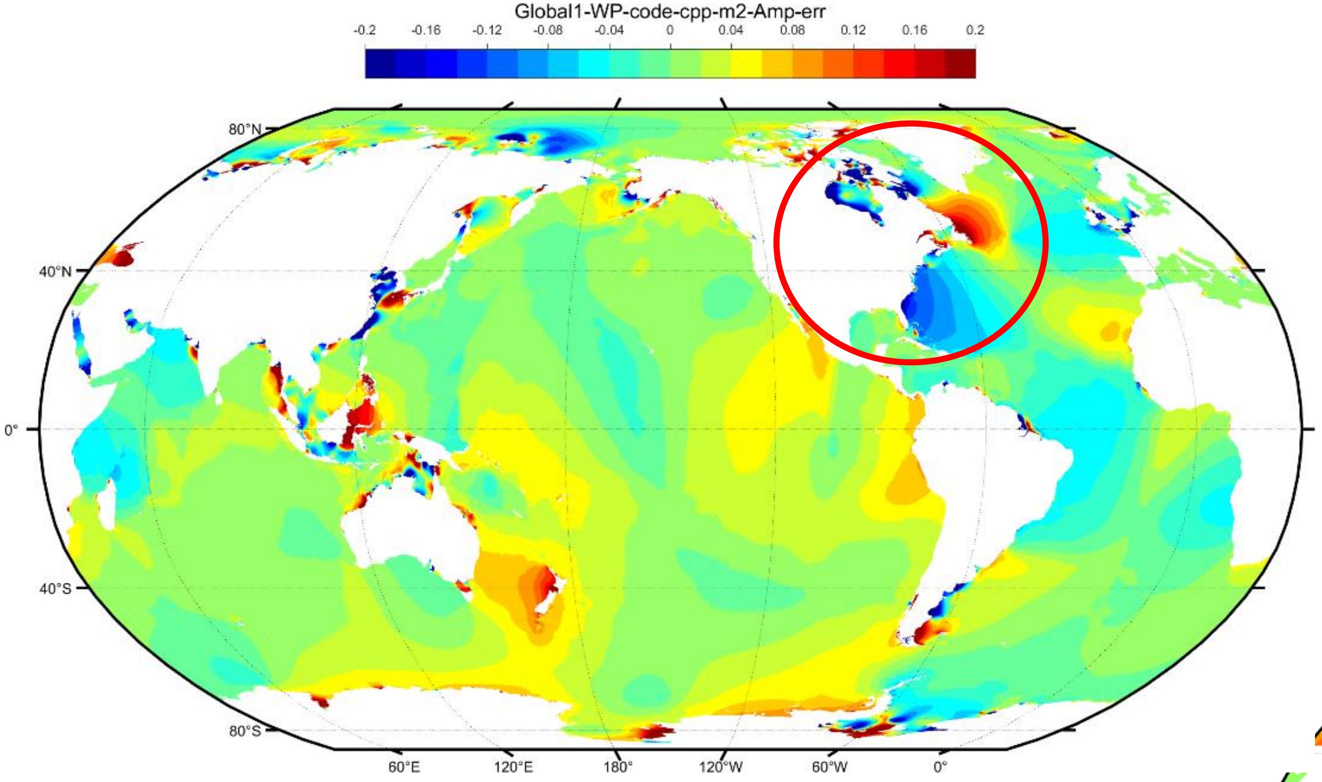
ADCIRC version	p	$\overline{\text{RMSE}}$ [cm] Deep water	$\overline{\text{RMSE}}$ [cm] Shallow water
Standard	1	6.2	16.7
Present	0	3.2	13.7
Present	1	3.2	13.7
Present	2	3.2	13.7
Stammer et al. (2014)*	-	5.25-7.76	18.6-27.9

*: $\overline{\text{RMSE}}$ is computed against TPXO8-Atlas rather than TPXO9-Atlas.

1 km cutoff



Comparisons of M2 amp difference to TPXO9-Atlas for different bathymetry



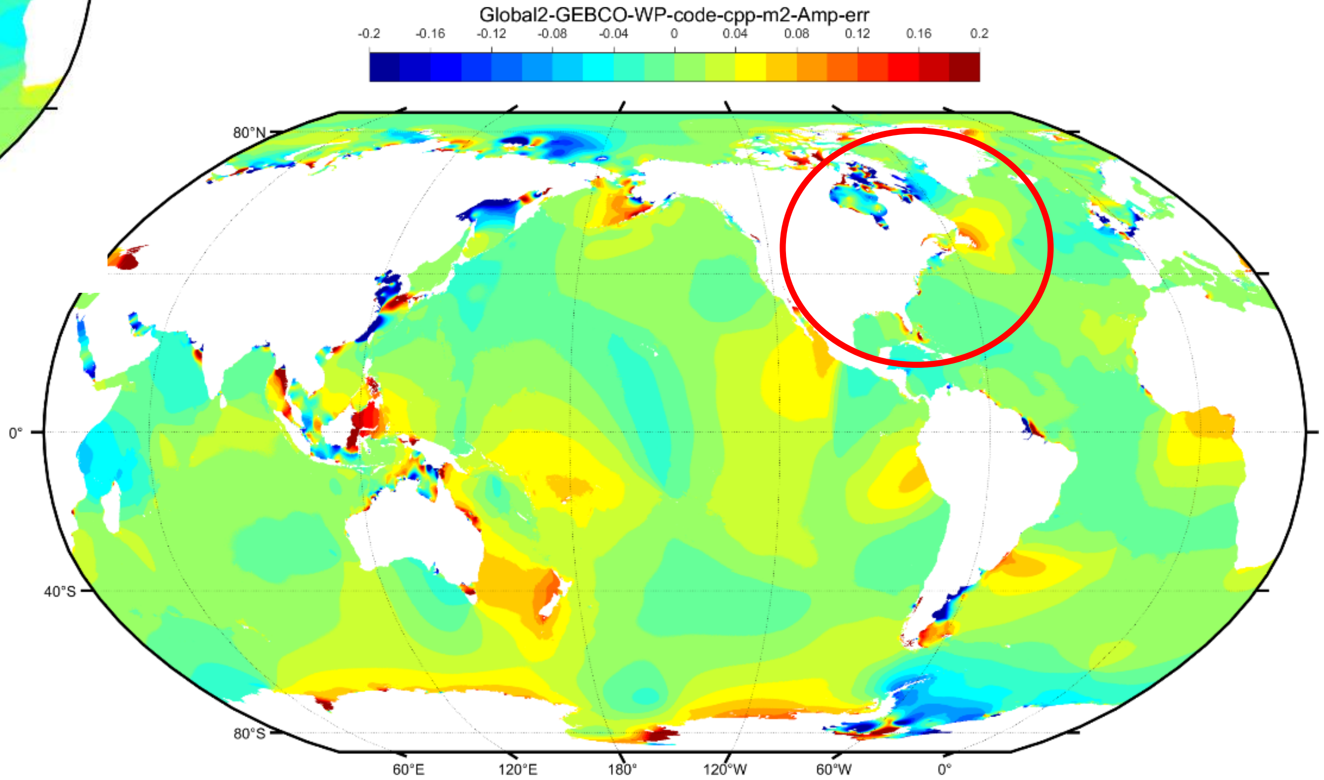
Old GEBCO

Both use depths under ice shelves in Antarctica from
Schaffer, J et. al. (2016). A global, high-resolution data set of ice sheet topography, cavity geometry, and ocean bathymetry. Earth Syst. Sci. Data, 8, 543–557. doi:10.5194/essd-8-543-2016
(merged into the old GEBCO)

GEBCO Seabed 2030 Project is already helping

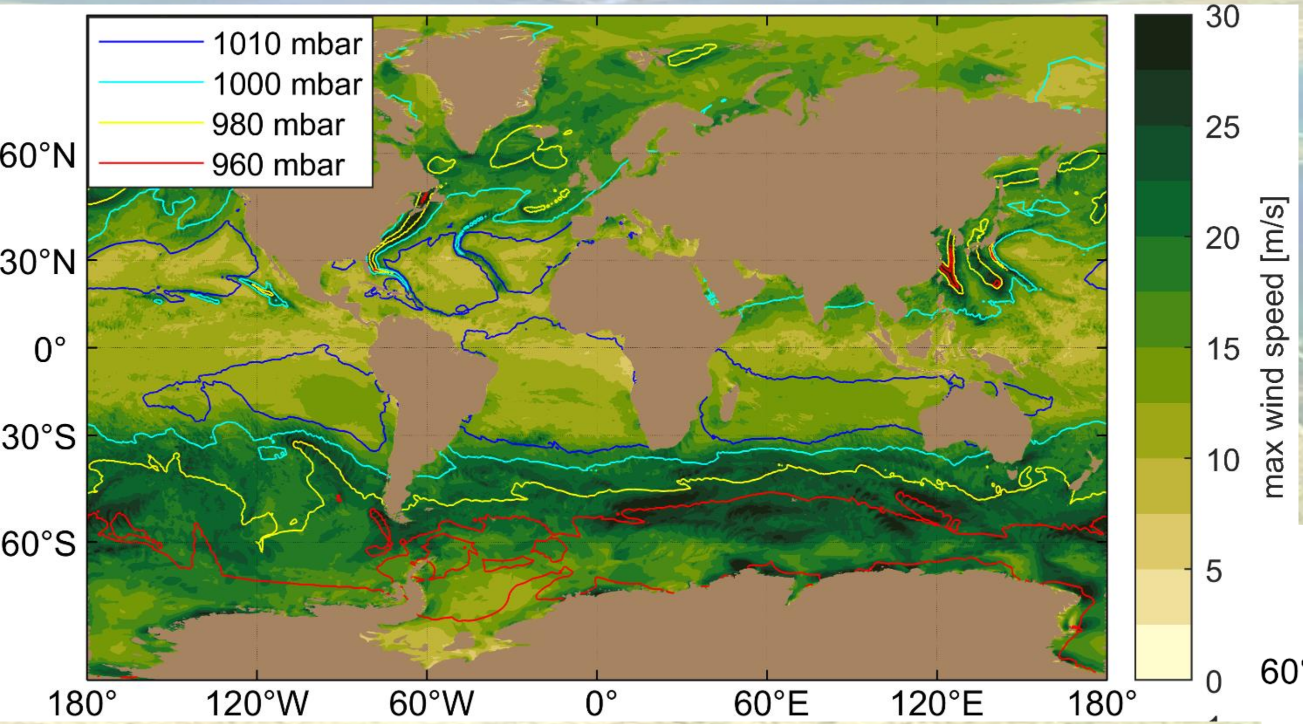
100-m DEMS from DeepReef Explorer for Northwest Aus and Coral Sea (https://www.deepreef.org/bathymetry/) & Canadian Hydrographic Service NONNA-100 https://open.canada.ca/data/en/dataset/d3881c4c-650d-4070-bf9b-1e00aabf0a1d

New GEBCO 2019 + 100-m DEMS



Simulating Tide and Surge: Aug 2 – Sep 10, 2019

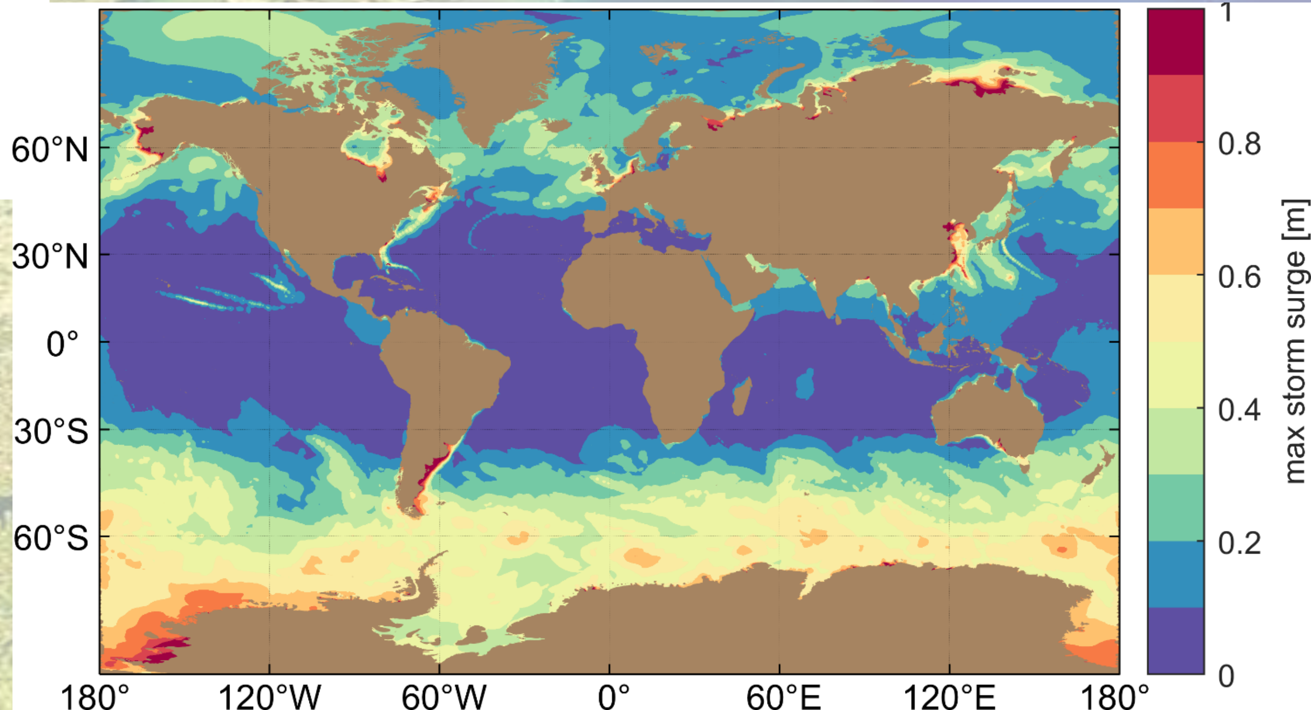
Maximum wind speeds/minimum surface pressure at sea level



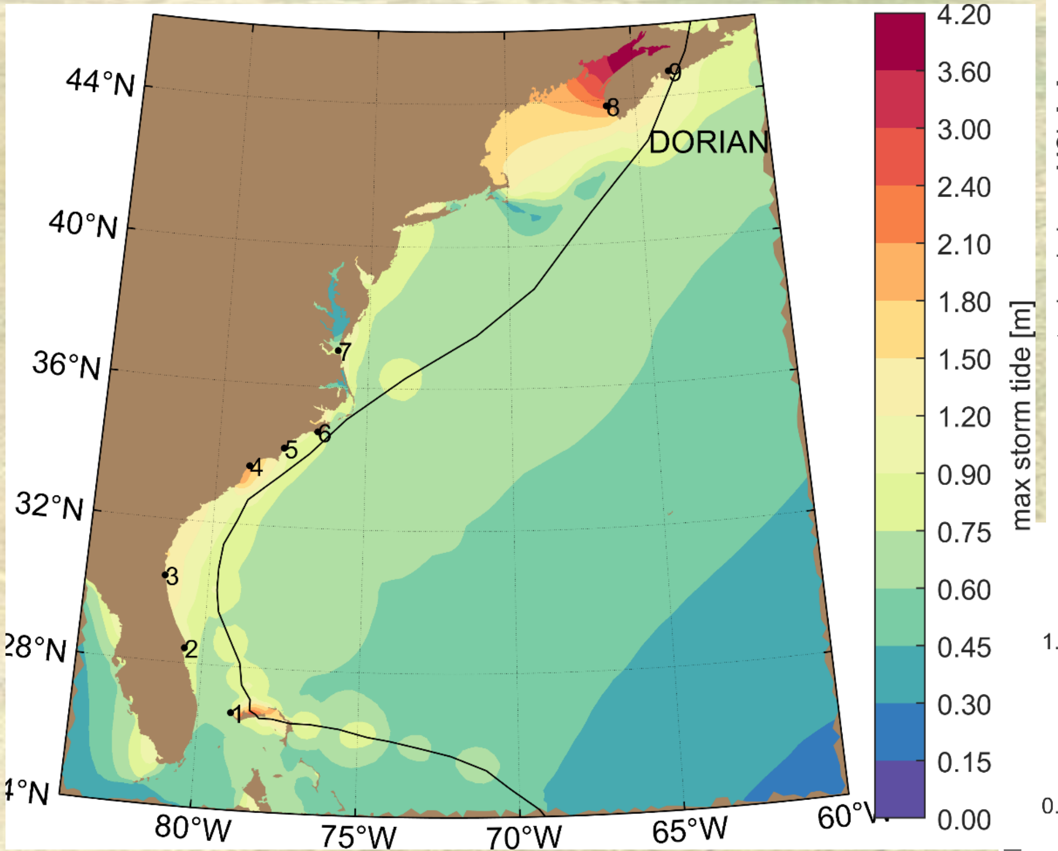
~10 min wall-clock time on 240 CPUs

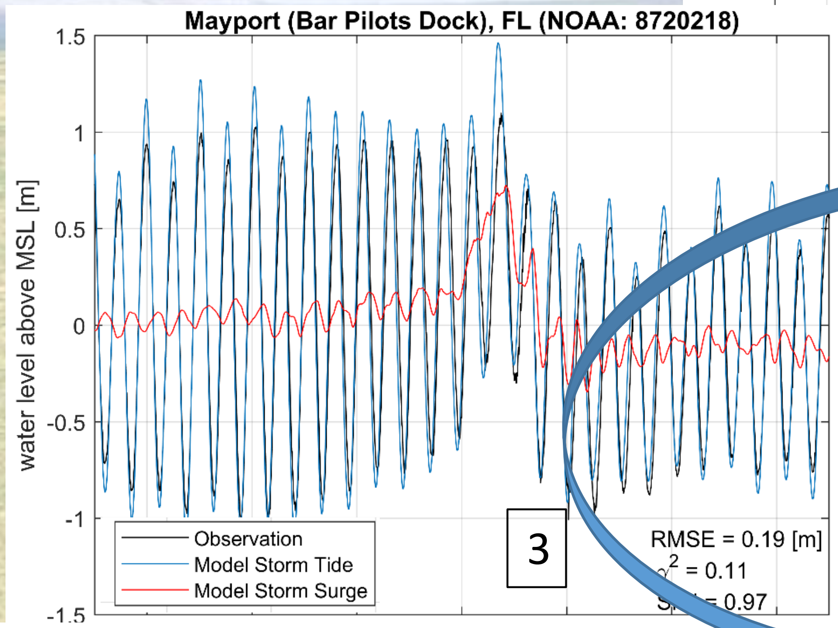
GFS 0.25 deg atmos forcing

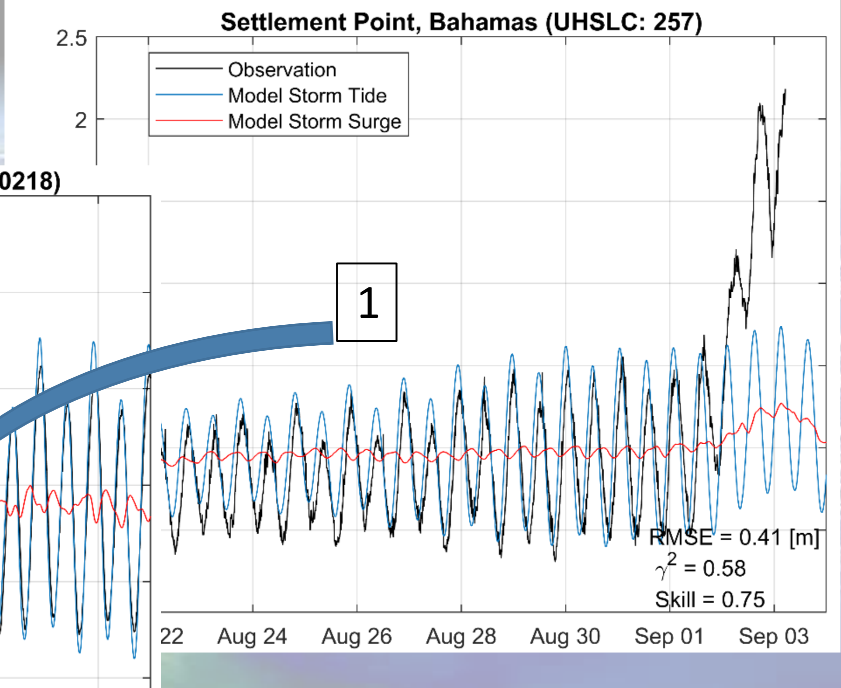
Maximum storm surge (no tides)

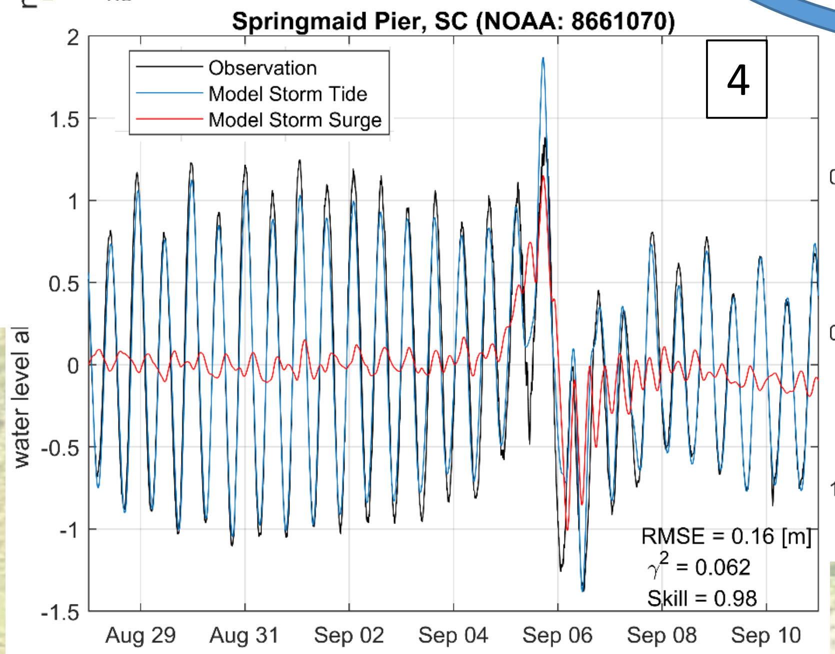


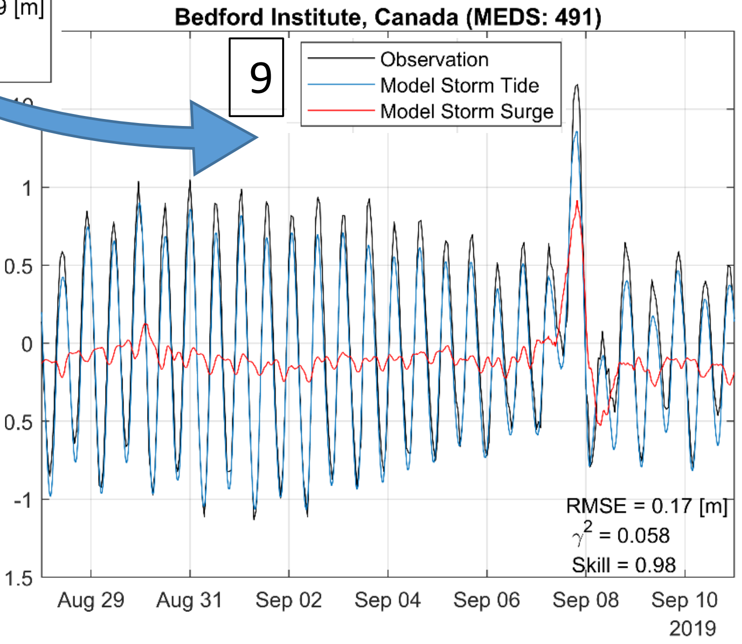
Maximum Storm Tide: Aug 2 – Sep 10, 2019





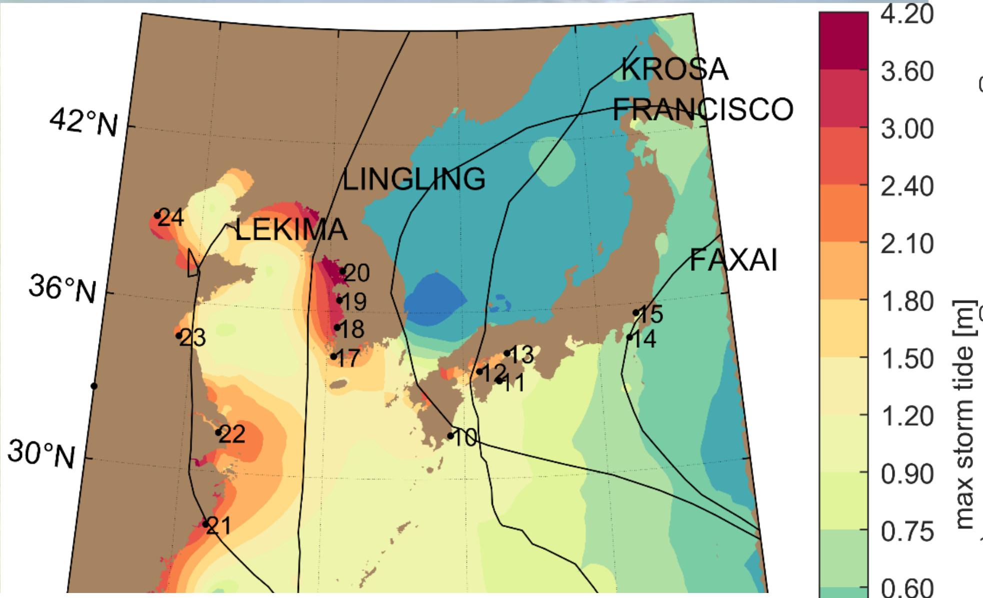


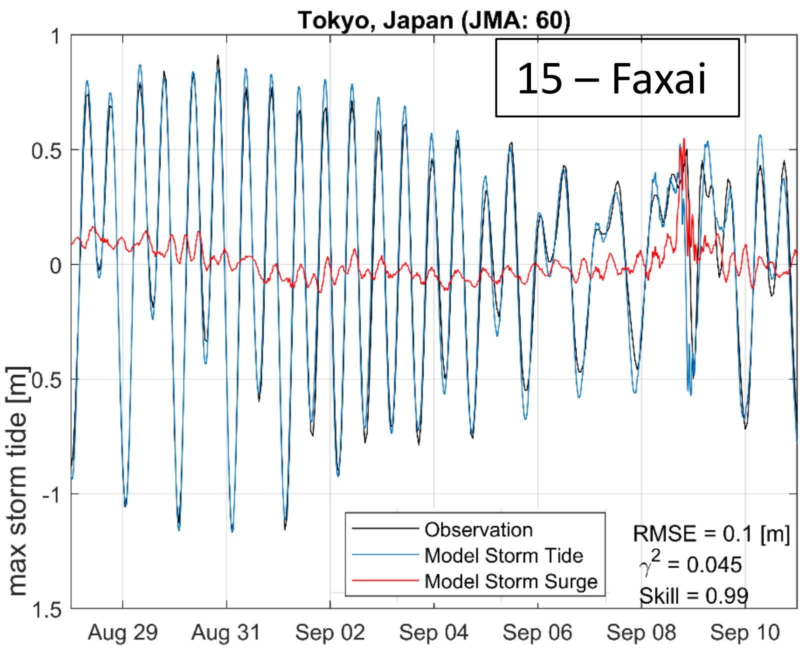


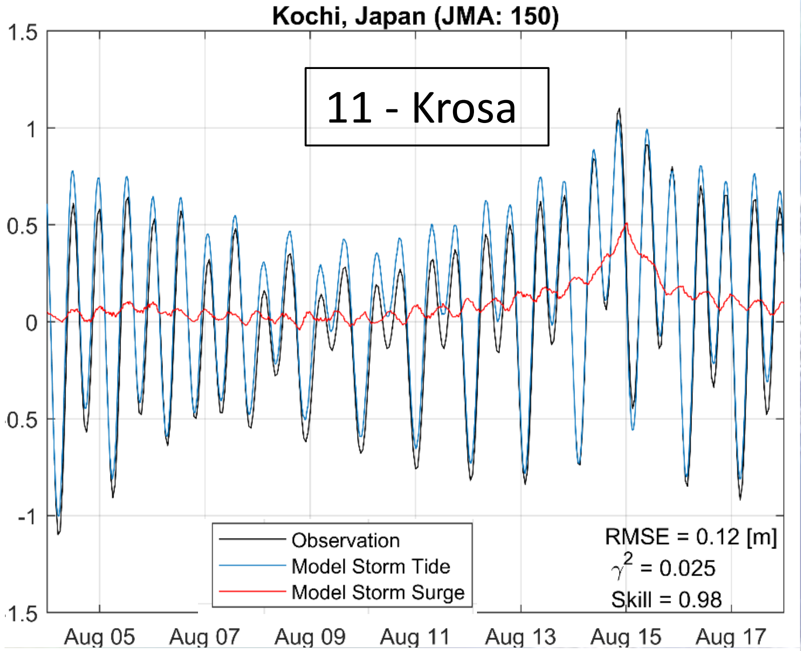


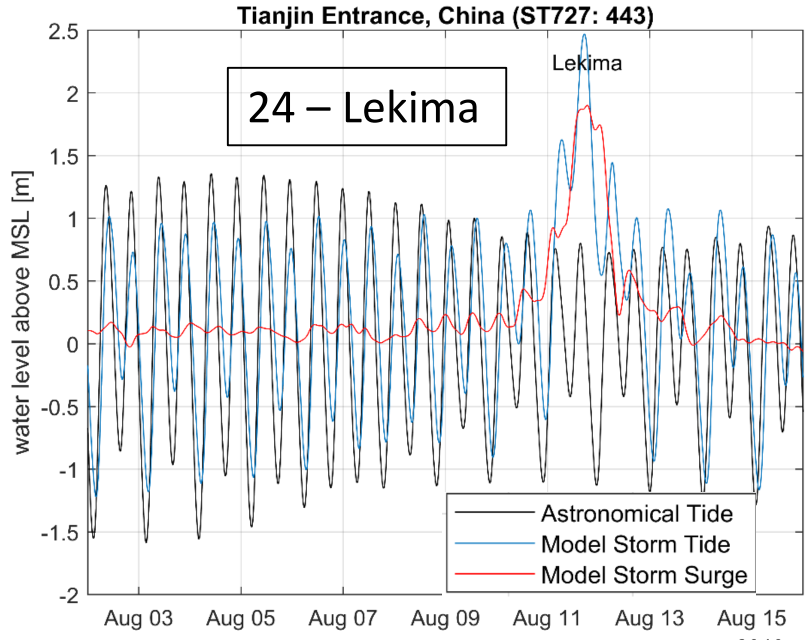
Maximum Storm Tide: Aug 2 – Sep 10, 2019

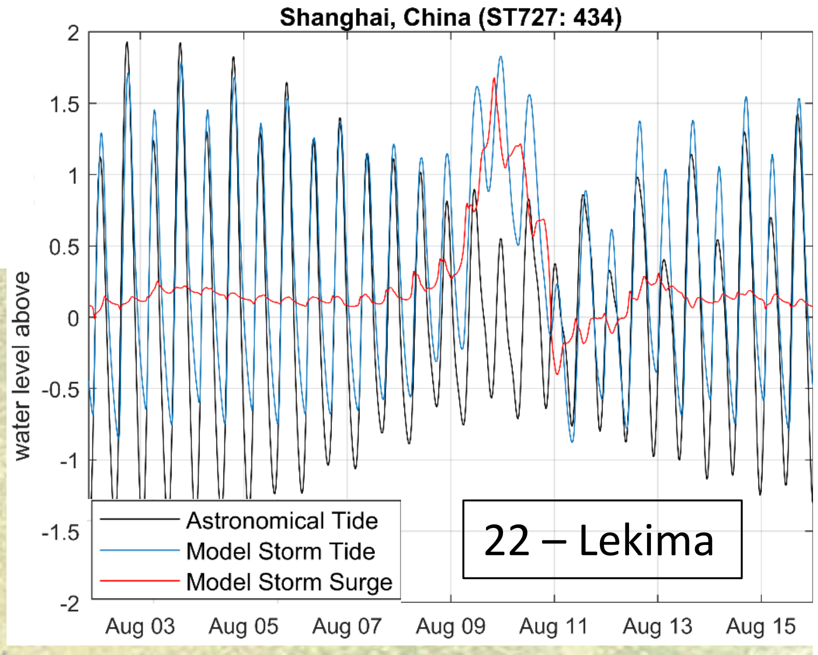
Western North Pacific

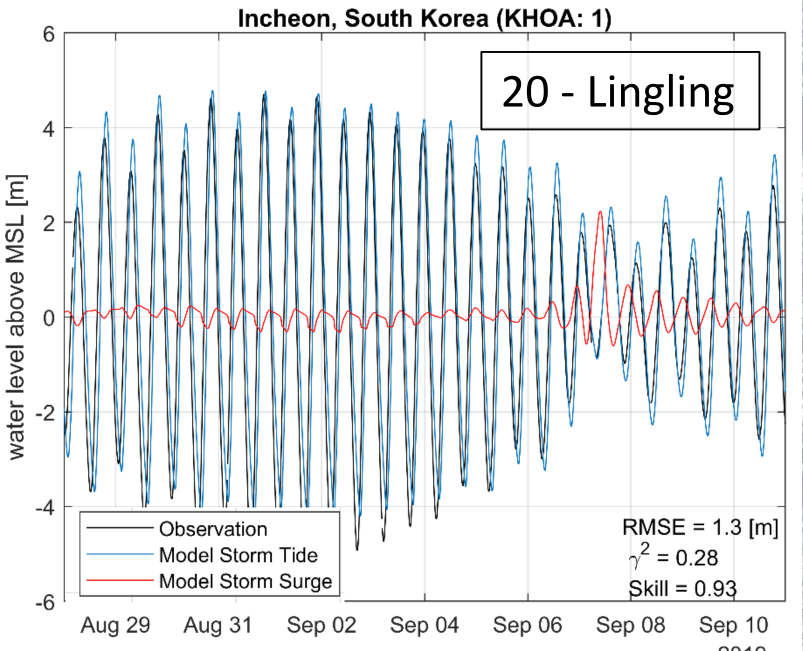








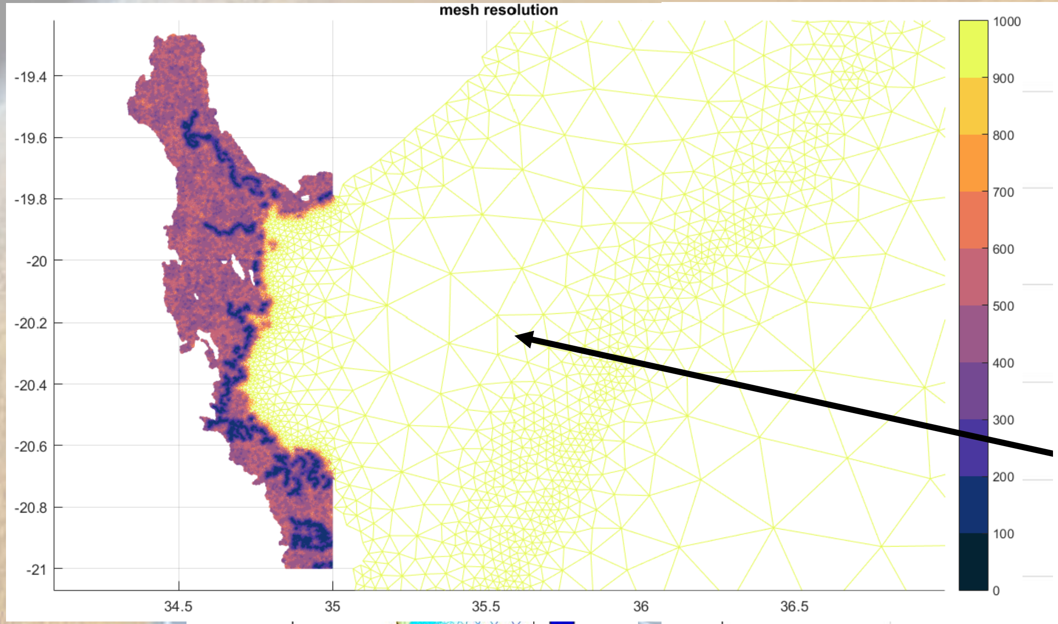


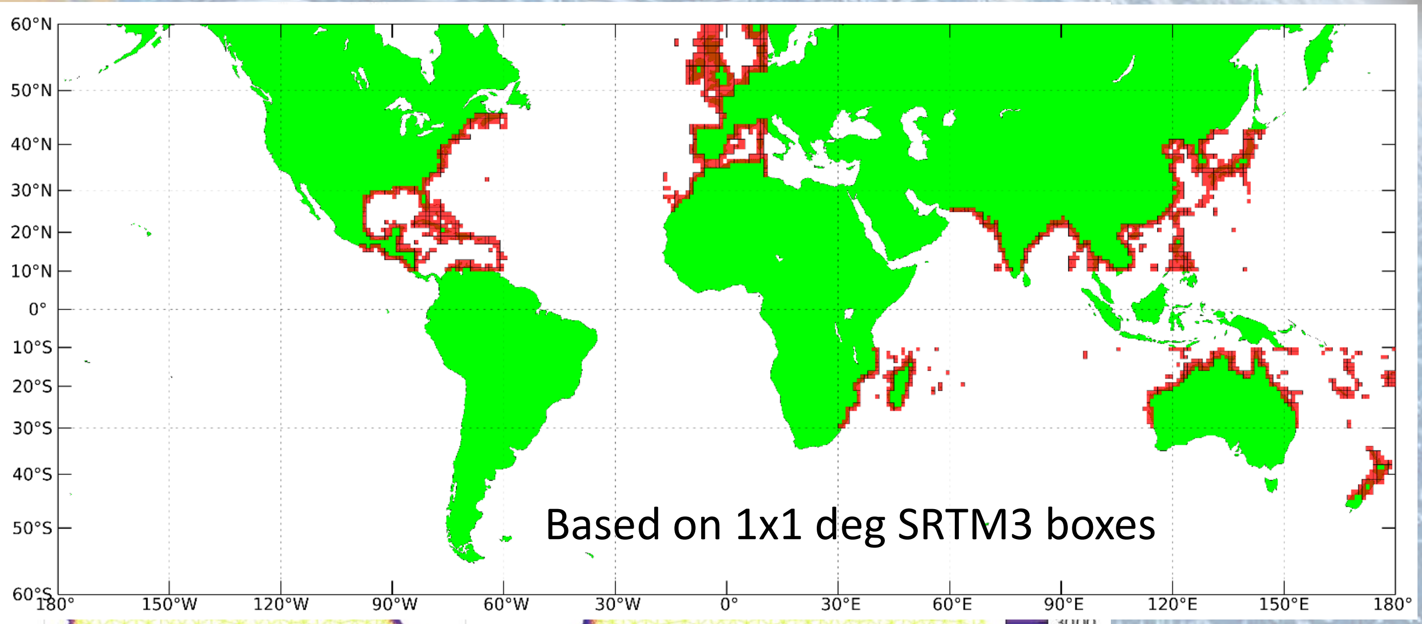


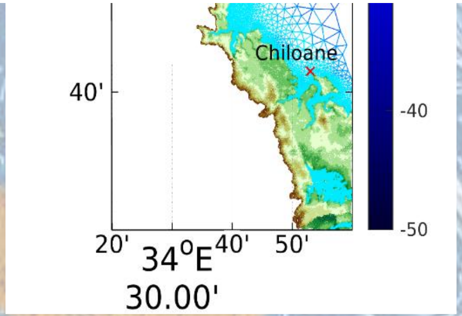
2. Seamless local refinement at the coast for coastal flooding simulation

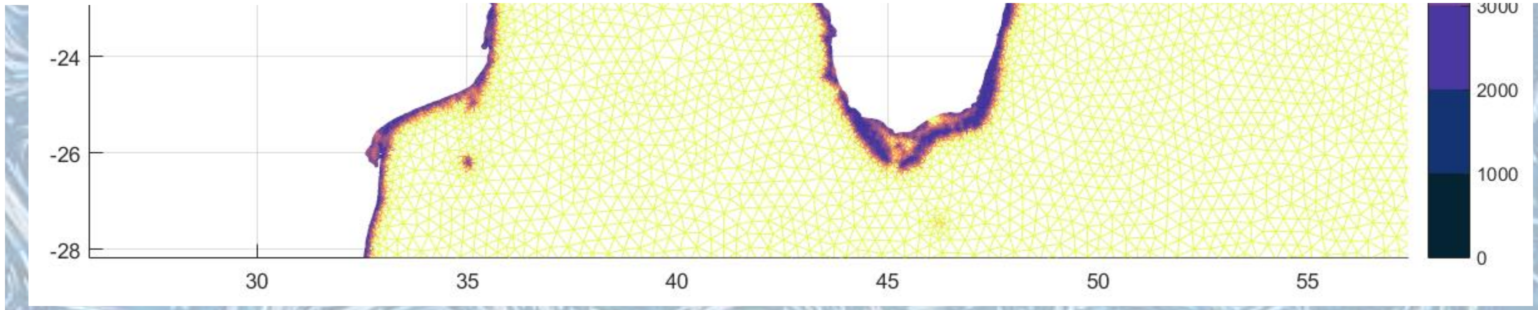
Prepare mesh using OceanMesh2D Mesh Arithmetic

Beira, Mozambique



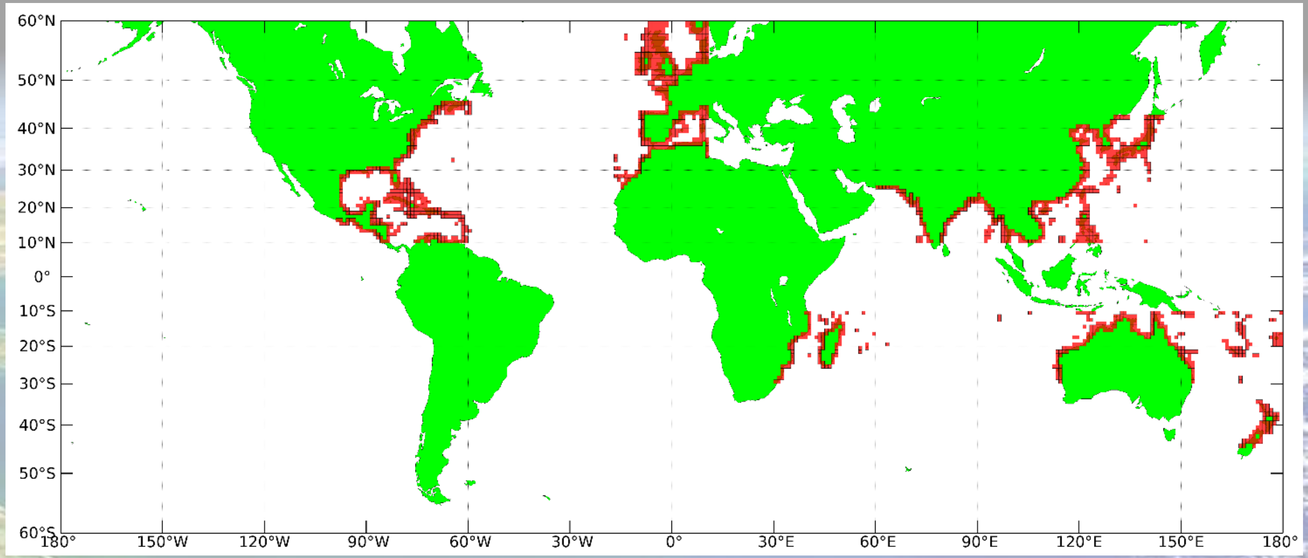


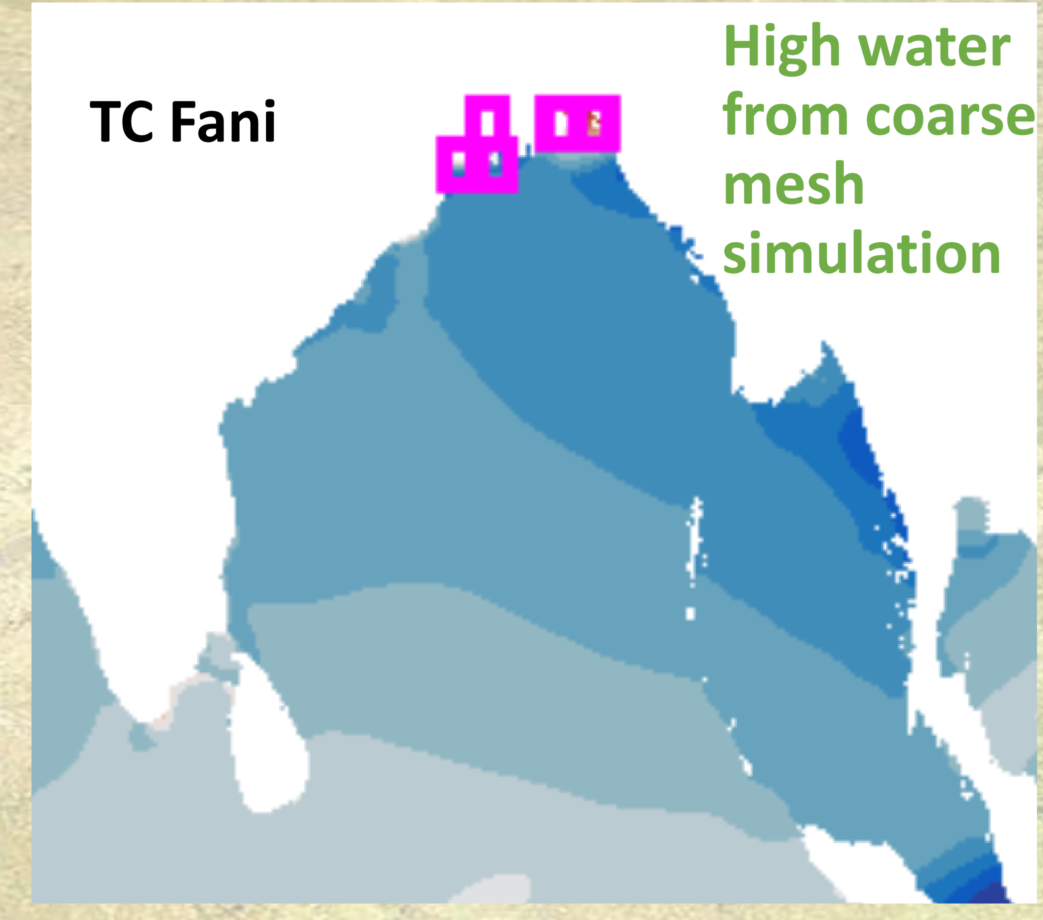


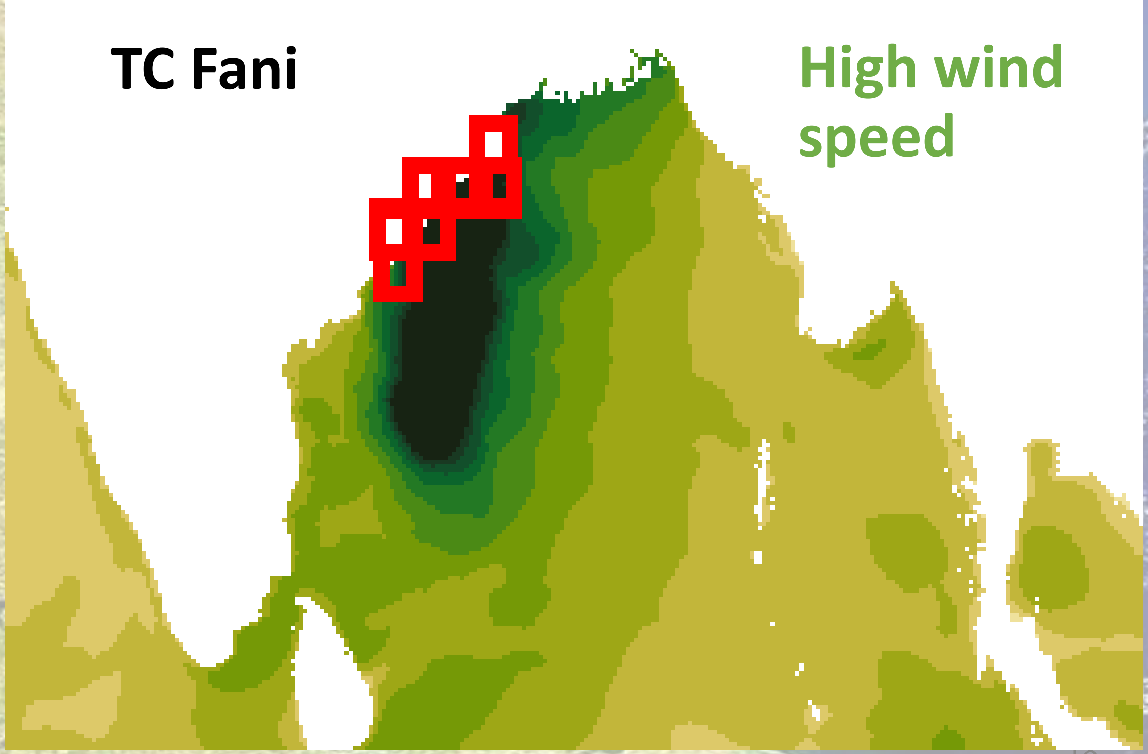


non-commutative (order matters, first mesh is given priority)

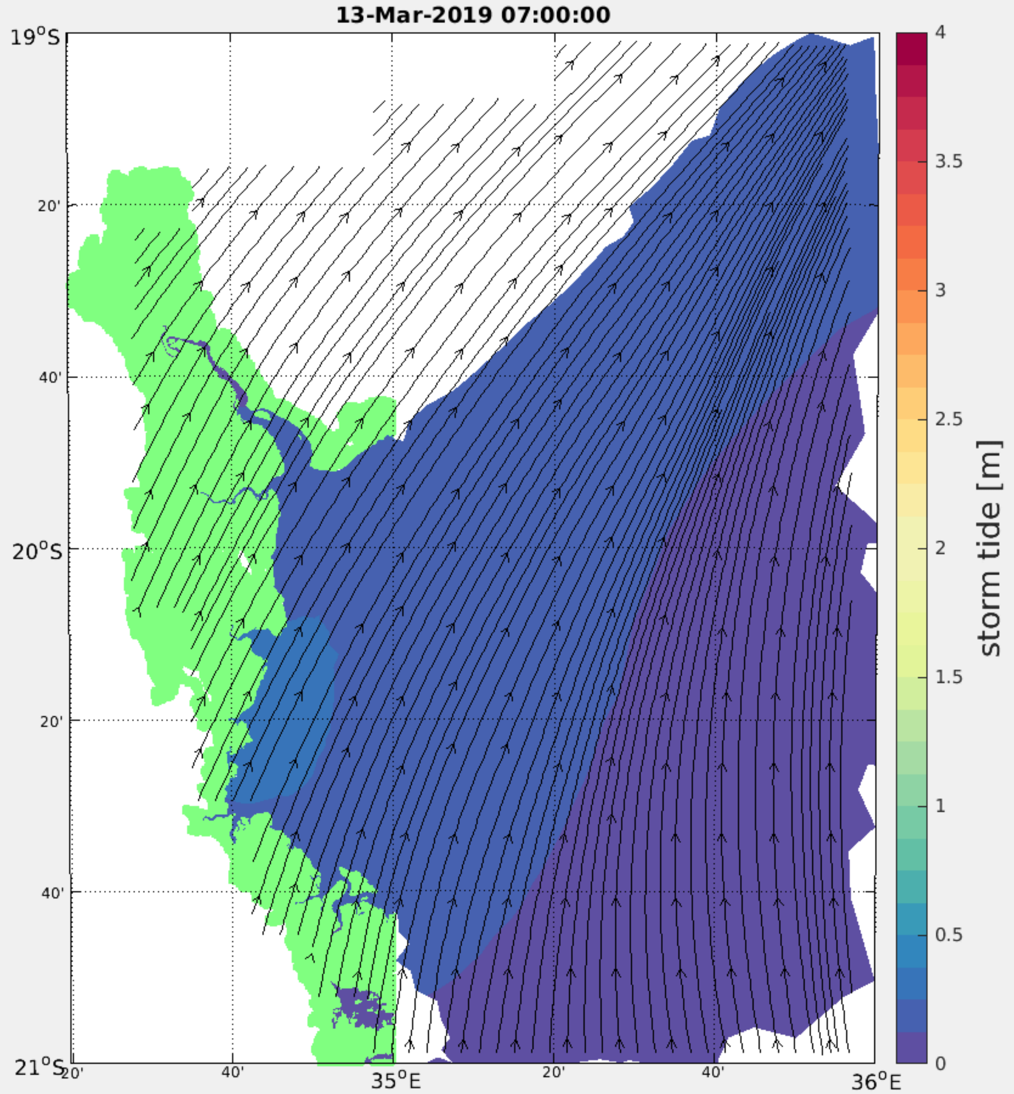
Forecast mode: Pre-compute locally refined meshes and select which to "plus in"

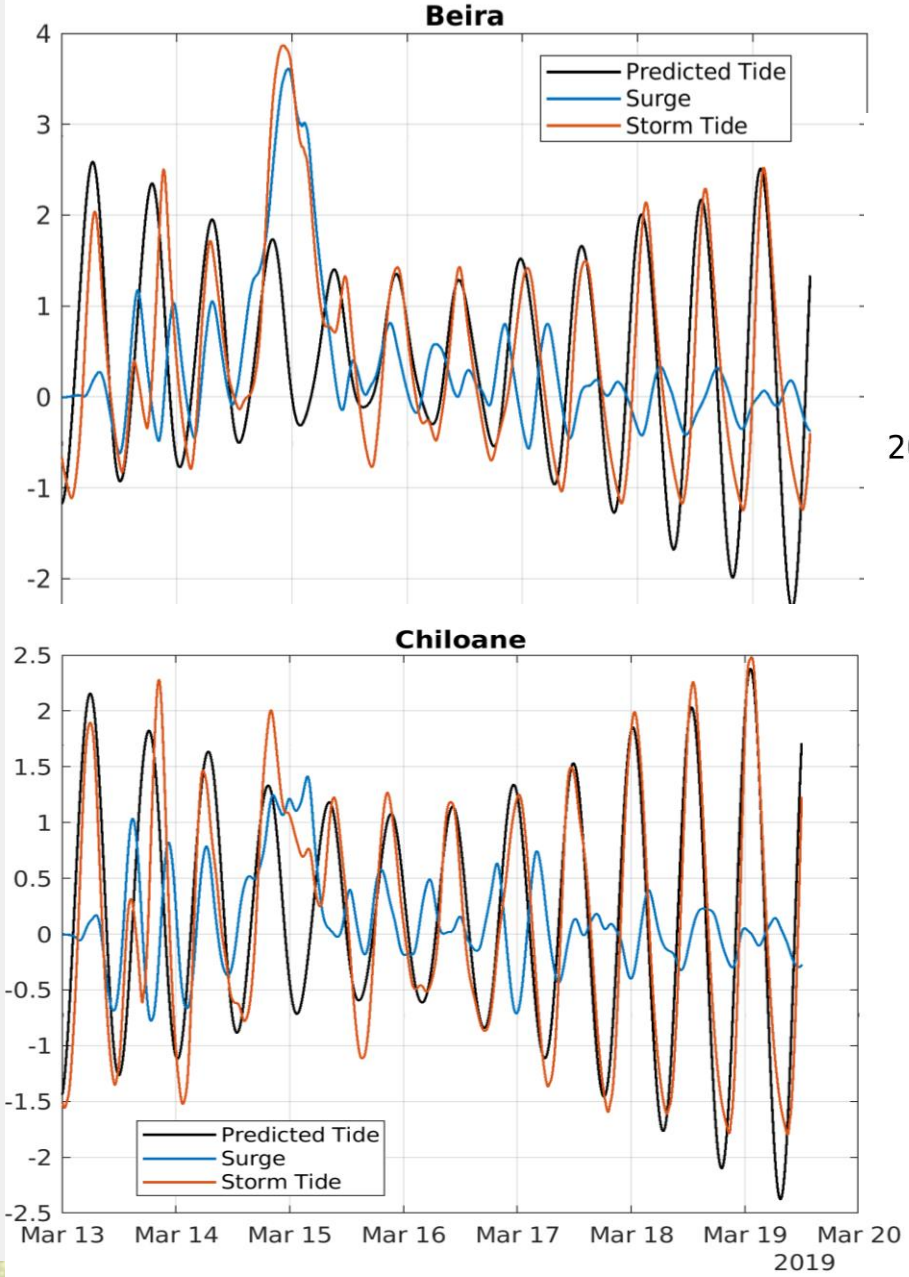


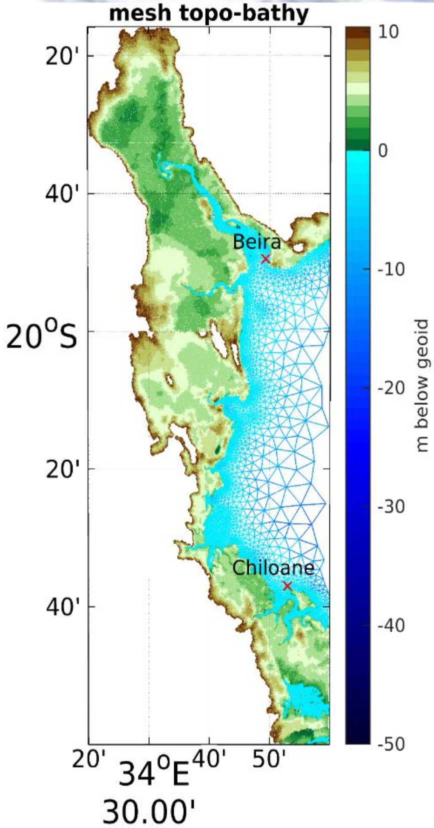


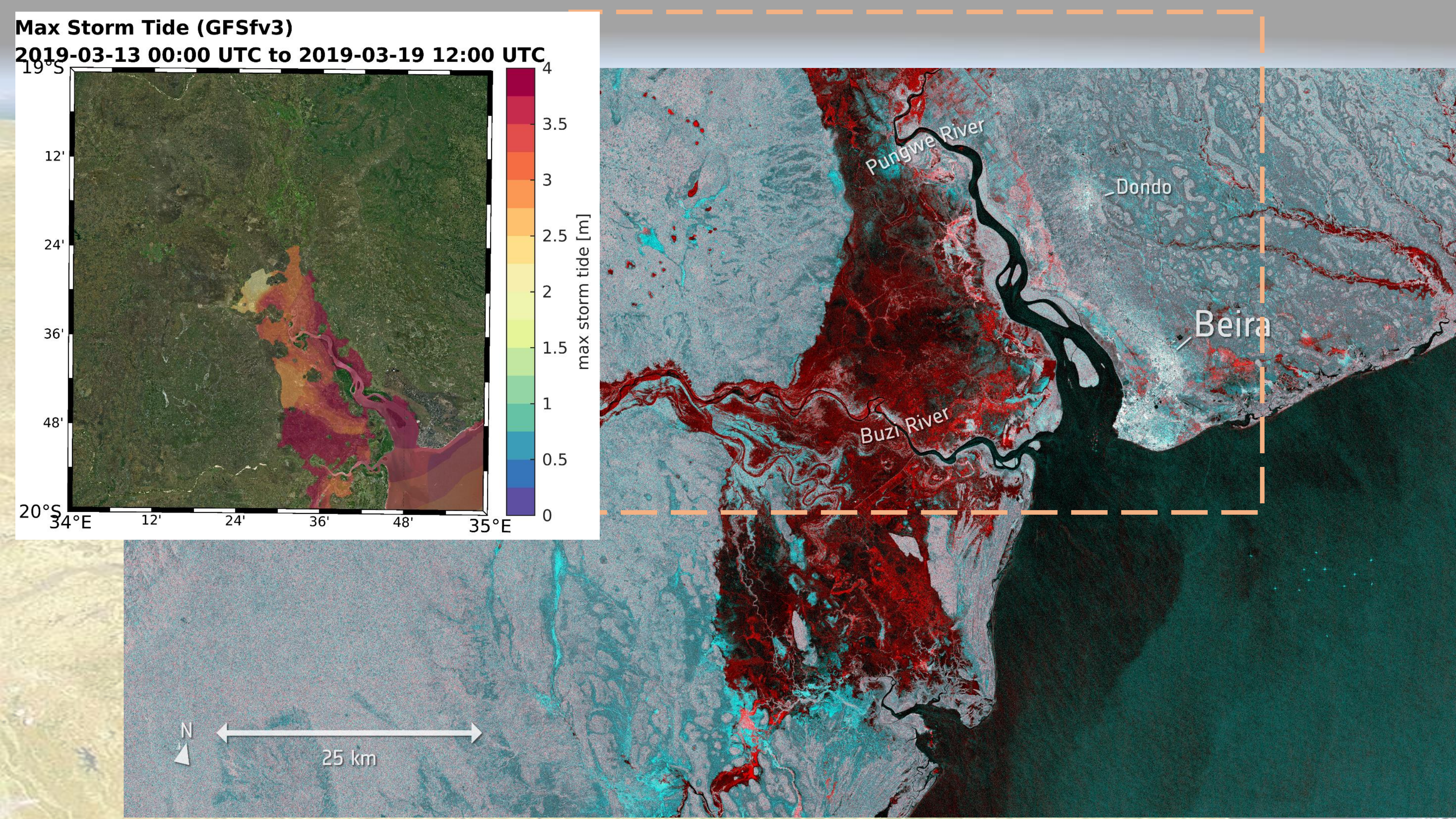


Tropical Cyclone Idai – Mid-March 2019









Max Storm Tide (GFSfv3)
2019-03-13 00:00 UTC to 2019-03-19 12:00 UTC
19°S
12'
24'
36'
48'
20°S
34°E
12'
24'
36'
48'
35°E
4
3.5
3
2.5
2
1.5
1
0.5
0
max storm tide [m]
Pungwe River
Dondo
Beira
Buzi River
N
25 km

3. Including effects of low frequency modes on SSH by coupling to density structure of ocean

- **Can be used to ensure sea level in storm surge models are referenced to the geoid**

  Slobbe, D. C., Verlaan, M., Klees, R., & Gerritsen, H. (2013). Obtaining instantaneous water levels relative to a geoid with a 2D storm surge model. *Continental Shelf Research*, *52*, 172–189. https://doi.org/10.1016/j.csr.2012.10.002

- **We have shown spectral energy of elevations is increased to better match observed time series**

  Pringle, W.J., et al., (2019). Baroclinic Coupling Improves Depth-Integrated Modeling of Coastal Sea Level Variations around Puerto Rico and the U.S. Virgin Islands. JGR Oceans, 124 (3), 2196-2217. doi:10.1029/2018JC014682

  - Follows seasonal variations in sea levels
  - Captures local set-down in sea levels due to hurricane cold wakes
  - Overall model skill is increased

    Also see: Kodaira, T., Thompson, K. R., & Bernier, N. B. (2016). The effect of density stratification on the prediction of global storm surges. *Ocean Dynamics*, *66*(12), 1733–1743. https://doi.org/10.1007/s10236-016-1003-6

- **Other possibilities**

  e.g., *downscaling* climate-ocean models to get long-term variation in coastal elevations

2D-Momentum equations

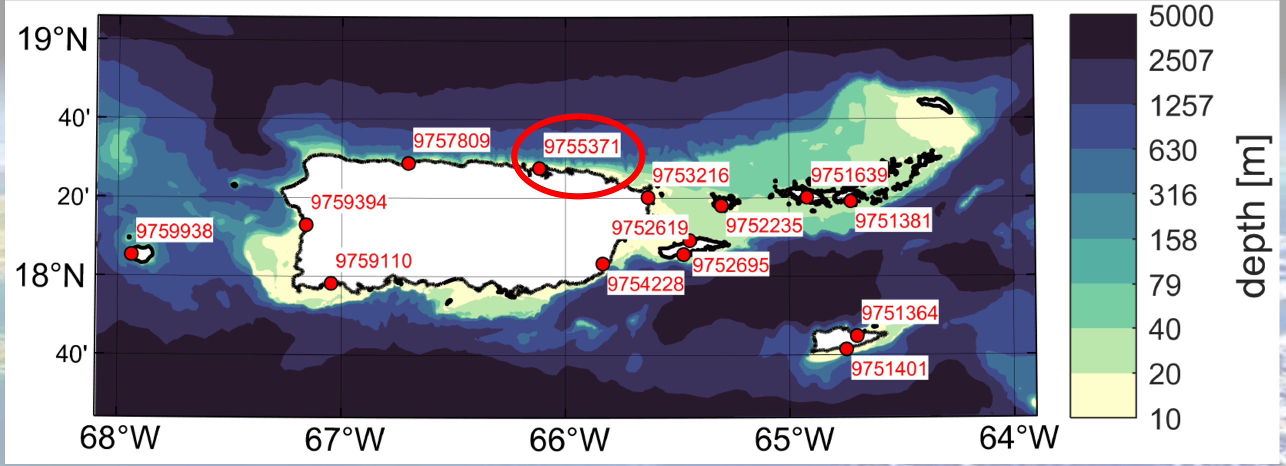
$$\frac{\partial \mathbf{U}}{\partial t} + \mathbf{U}\cdot\nabla\mathbf{U} + f\mathbf{k}\times\mathbf{U} = -\nabla\left[\frac{p_s}{\rho_0} + g(\zeta - \zeta_{EQ} - \zeta_{SAL})\right] + \frac{\nabla M}{H} - \frac{\nabla D}{H} - \frac{\nabla B}{H} + \frac{\boldsymbol{\tau}_s - \boldsymbol{\tau}_b}{\rho_0 H} - C - \sigma(\mathbf{x})(\mathbf{U} - \mathbf{U}_c),$$

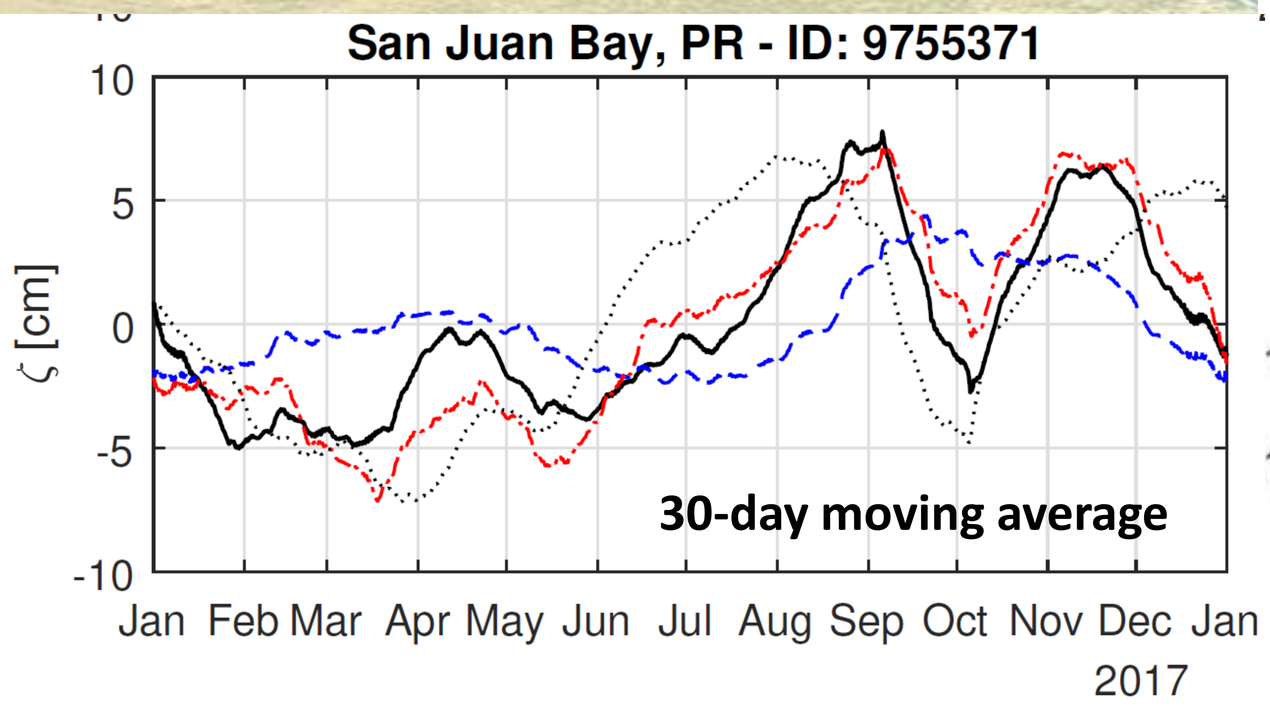
Baroclinic pressure gradient

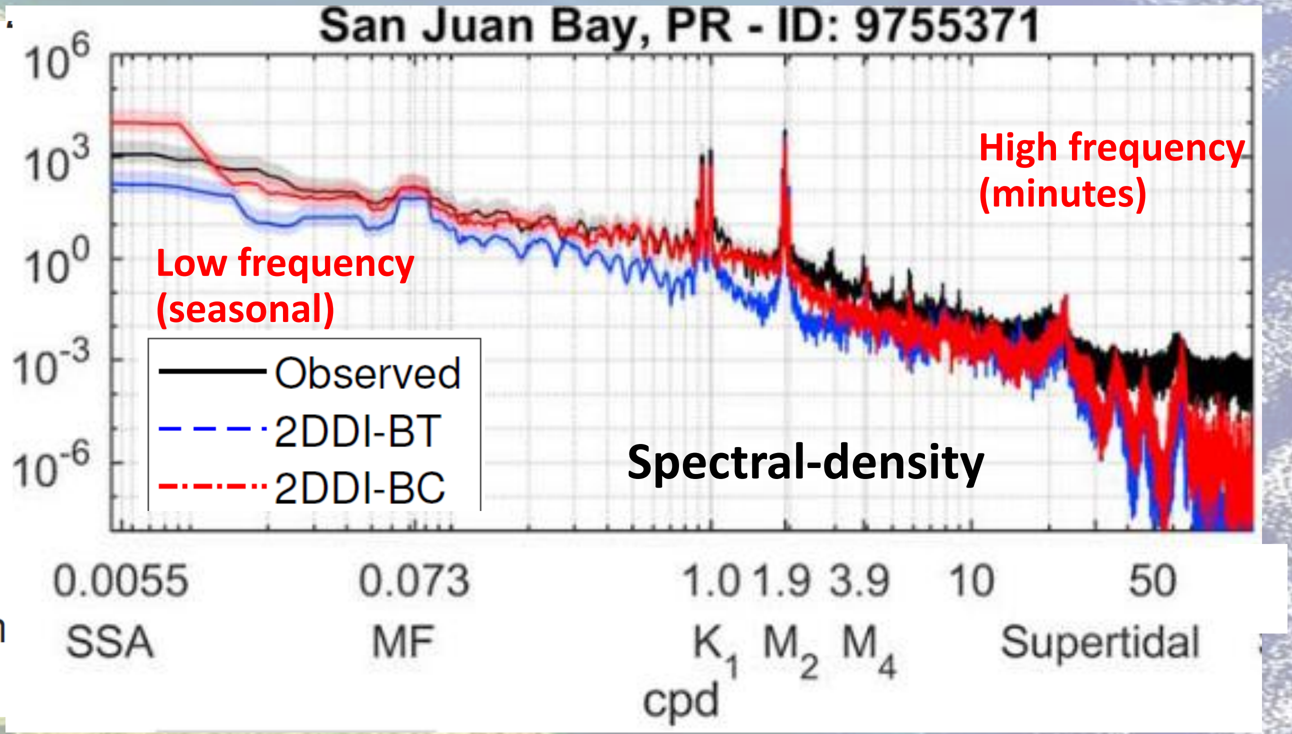
$$\nabla B = \int_{-h}^{\zeta}\left(g\nabla\left[\int_{z}^{\zeta}\frac{\rho - \rho_0}{\rho_0}\,dz\right]\right)dz,$$

Obtain ρ from an ocean circulation model

Matching seasonal variations in SSH and increasing spectral energy

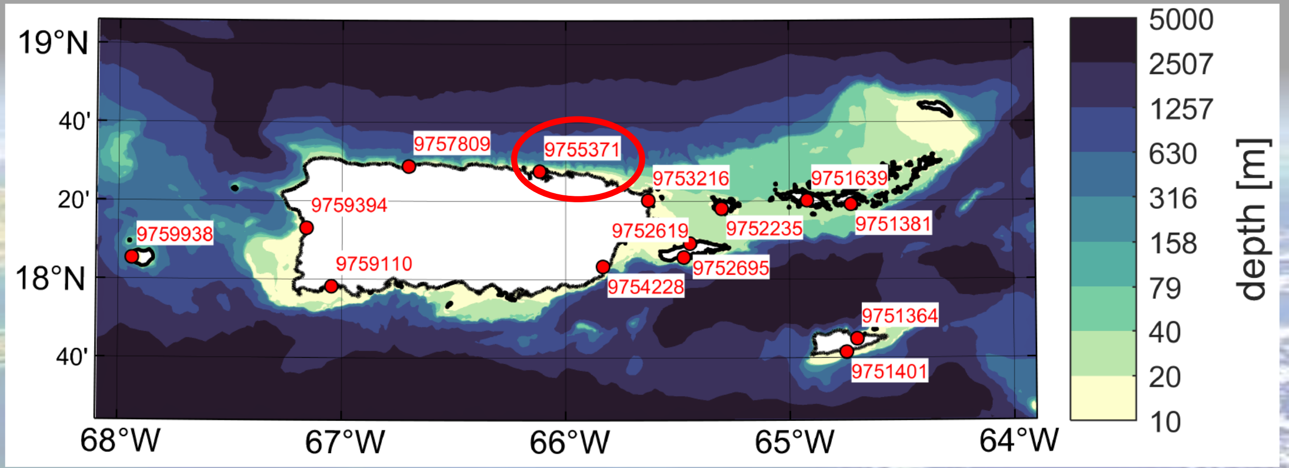




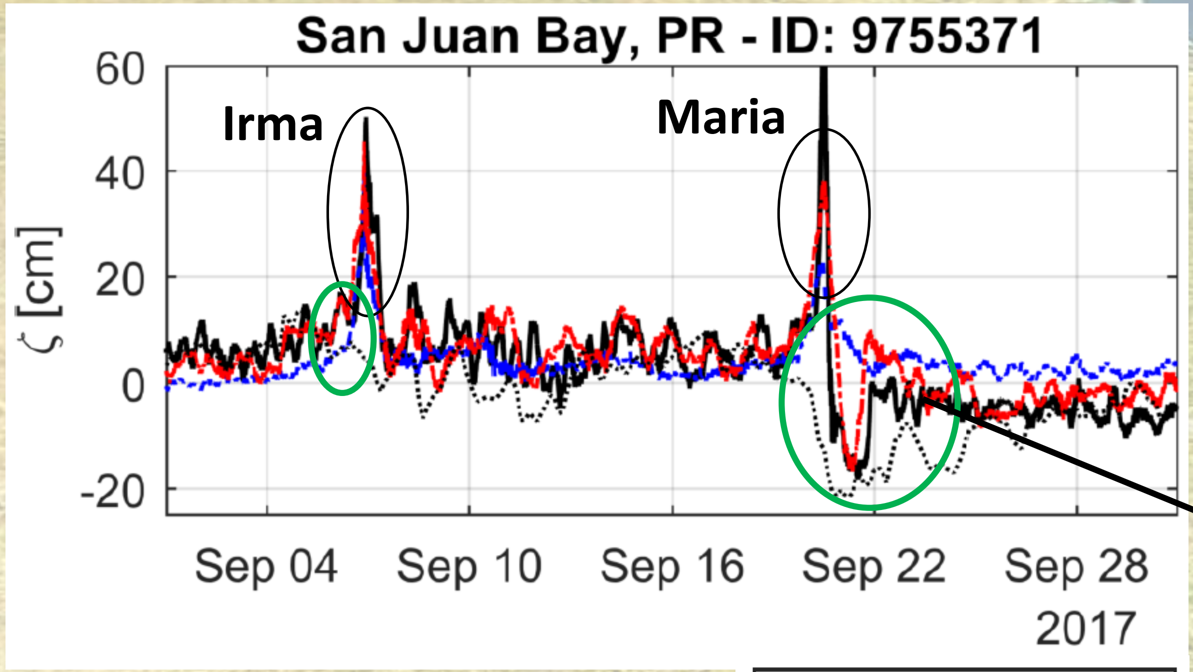


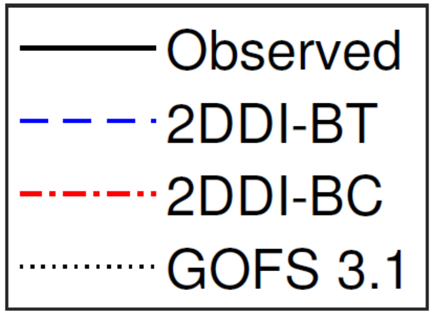
Pringle, W.J., et al., 2019. Baroclinic Coupling Improves Depth-Integrated Modeling of Coastal Sea Level Variations around Puerto Rico and the U.S. Virgin Islands. JGR Oceans, 124 (3), 2196-2217. doi:10.1029/2018JC014682

Better match during Hurricanes Irma and Maria

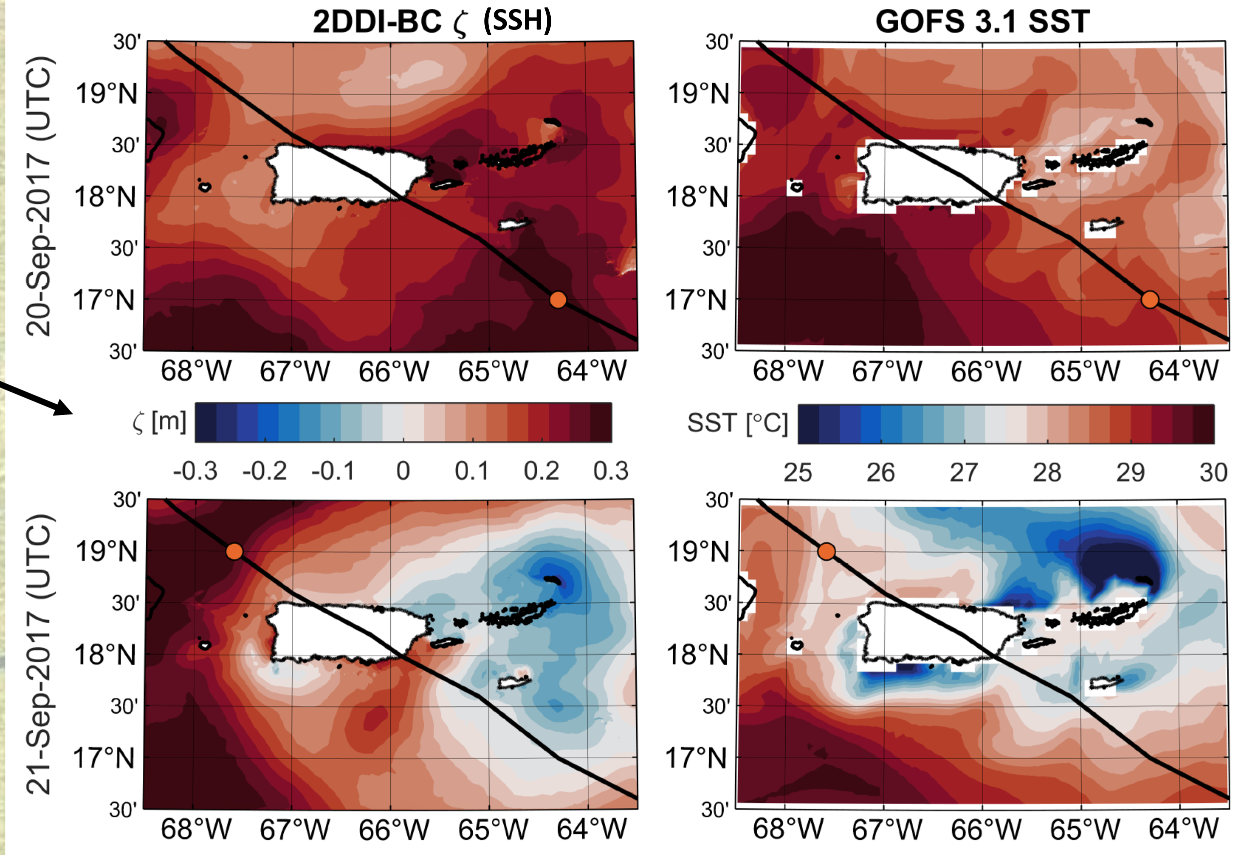


Surge (non-tidal residual)





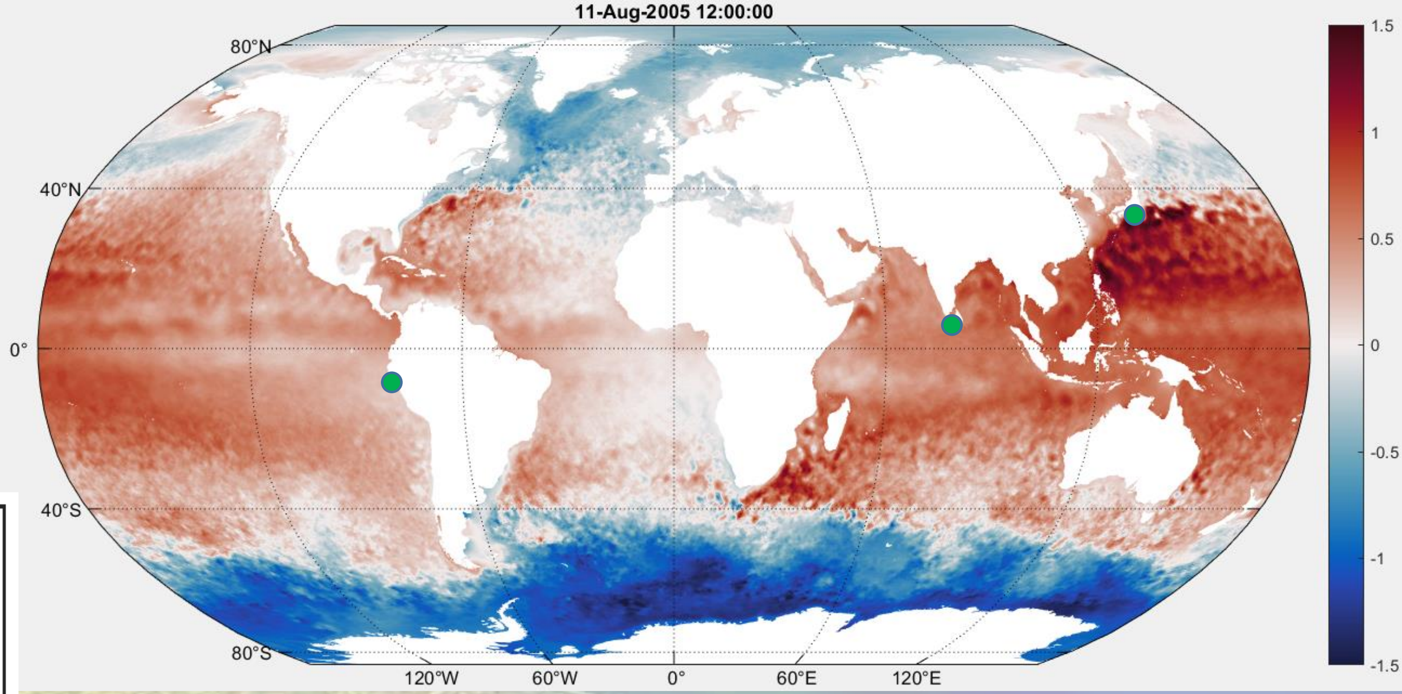
Effect of TC cooling ocean surface (cold wake)

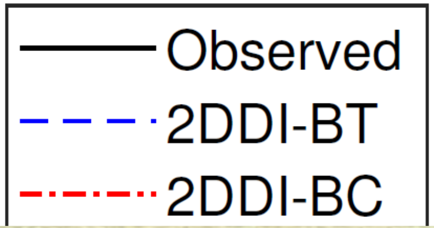


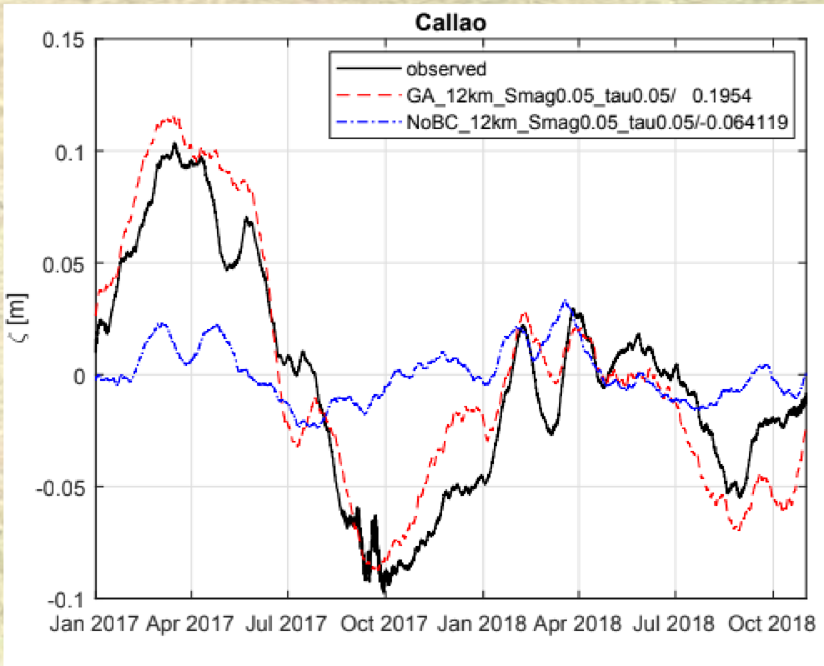
Pringle, W.J., et al., 2019. Baroclinic Coupling Improves Depth-Integrated Modeling of Coastal Sea Level Variations around Puerto Rico and the U.S. Virgin Islands. JGR Oceans, 124 (3), 2196-2217. doi:10.1029/2018JC014682

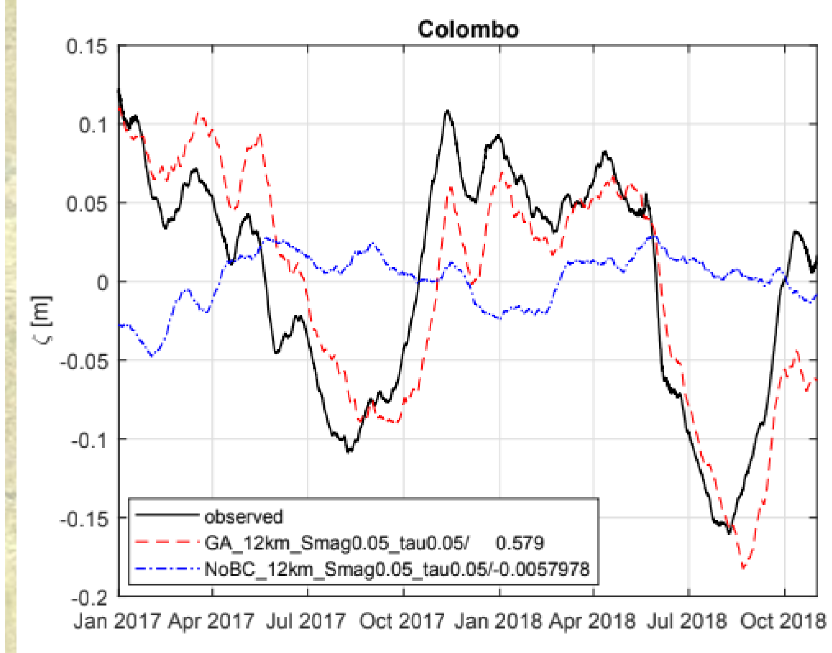
Some time series for preliminary global model

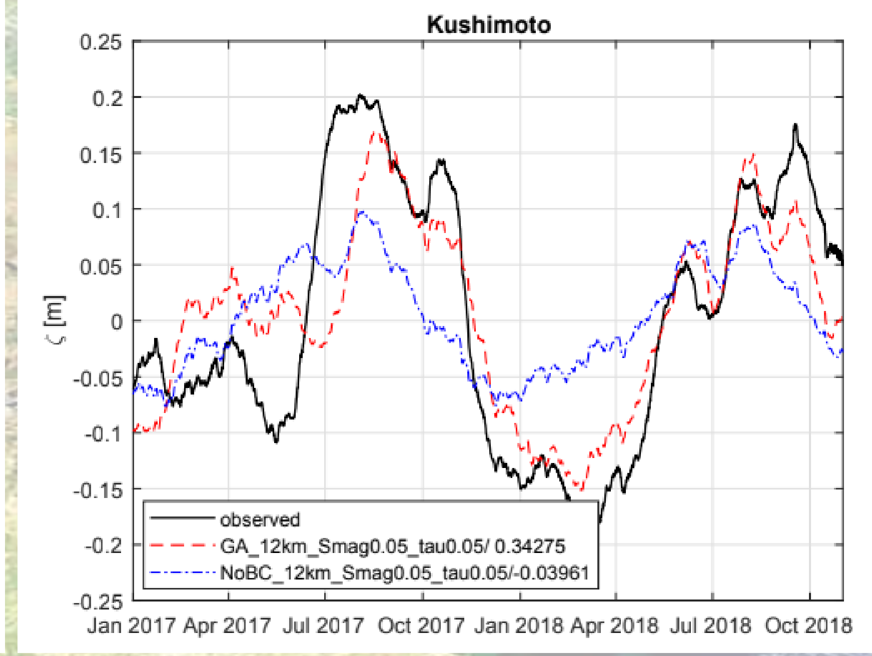
30-day moving average











Further advances/things we want to do

1. Execute and deploy the automatic local refinement for forecast model
   - Investigating local refinement indicators
   - Investigating sub-grid parameterizations to avoid excessive refinement

2. Further improve parameterizations of internal tide dissipation, bottom friction, ice-sea dissipation
   - May be a good application for AI

3. Further investigate and improve on the global storm surge model coupling with ocean circulation models
   - Sensitivities to interpolation, resolution, and dissipation