COUPLING 3D OCEAN BAROCLINICITY INTO 2D DEPTH-INTEGRATED COASTAL OCEAN MODELS

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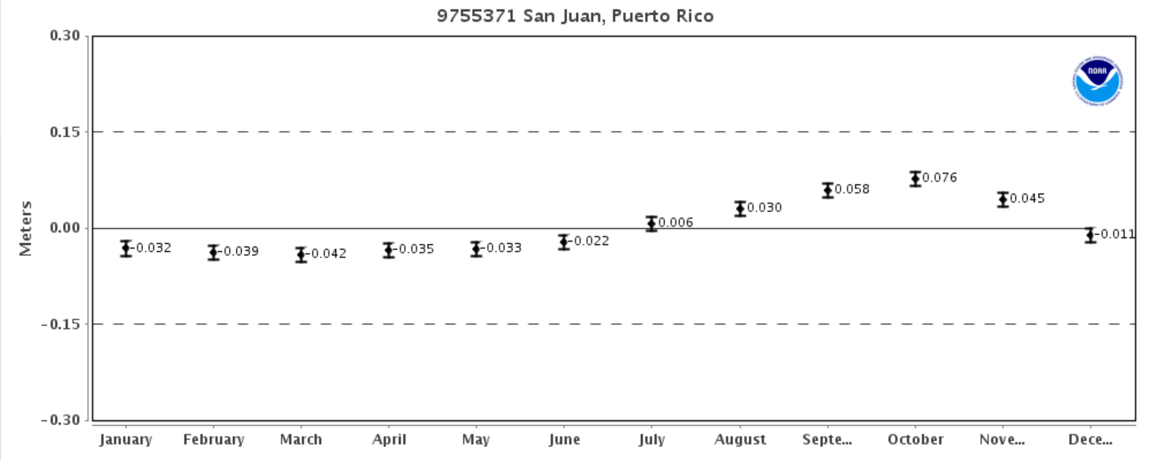
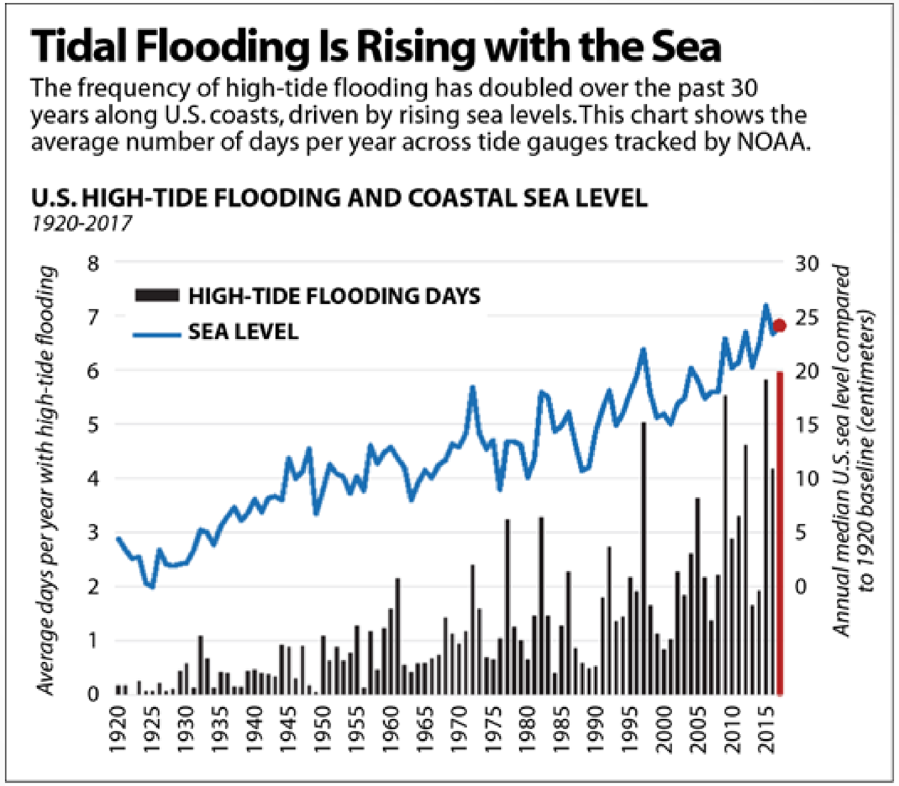
MOTIVATION

- For a certain storm, flooding risks for coastal cities change based on long term, seasonal, and other (e.g. climate induced) variabilities in water levels
  - Long term warming of the ocean and melting of glaciers
  - Seasonal warming and cooling

Average Seasonal Cycle
9755371 San Juan, Puerto Rico



  - Changes in ocean current systems
  - Changes to freshwater runoff
  - Interaction of winds and nearshore stratification



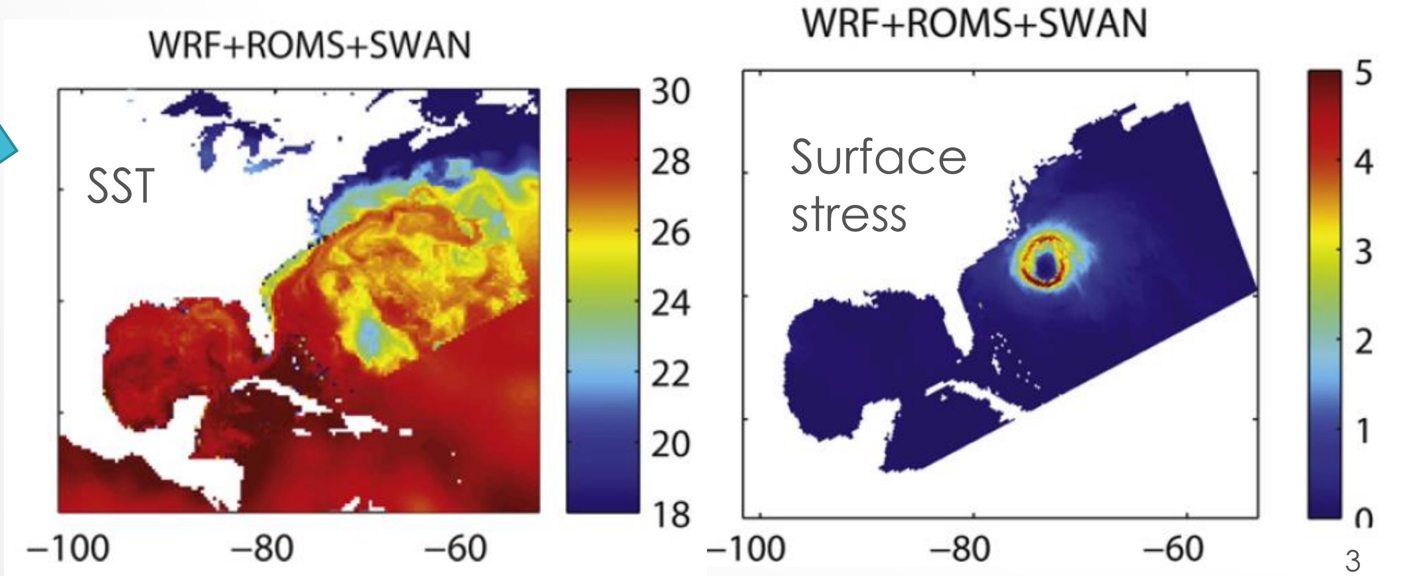
SOURCE: NOAA InsideClimate News

Density driven

PROBLEM

- ❑ Tide + Surge analysis is often conducted using 2D barotropic model
  - ➢ Model does not take into account vertical density structure
- ❑ 3D models are being used more for surge analysis but..
  - ➢ 3D model is more sensitive and adds a greater degree of freedom compared to 2D
  - ➢ Horizontal resolution, temporal resolution, and domain size typically sacrificed

3D baroclinic ROMS coupled system
during Hurricane Isabel

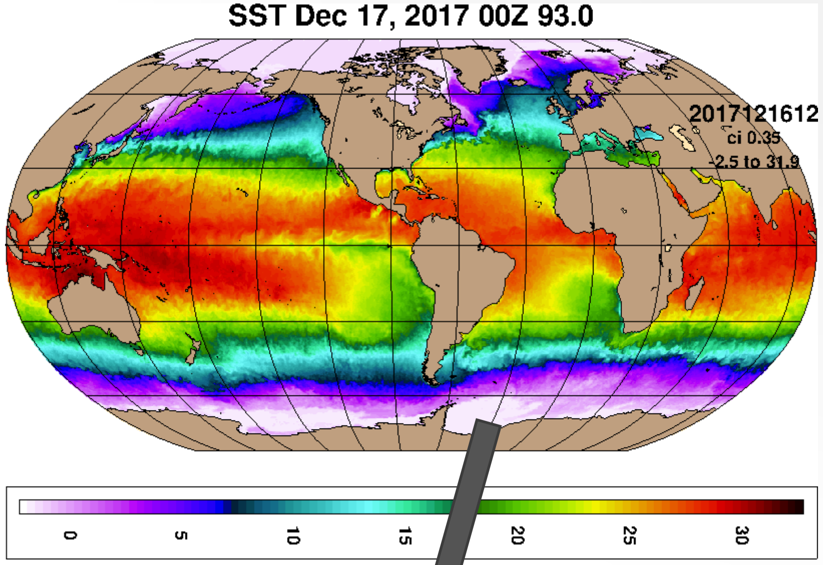


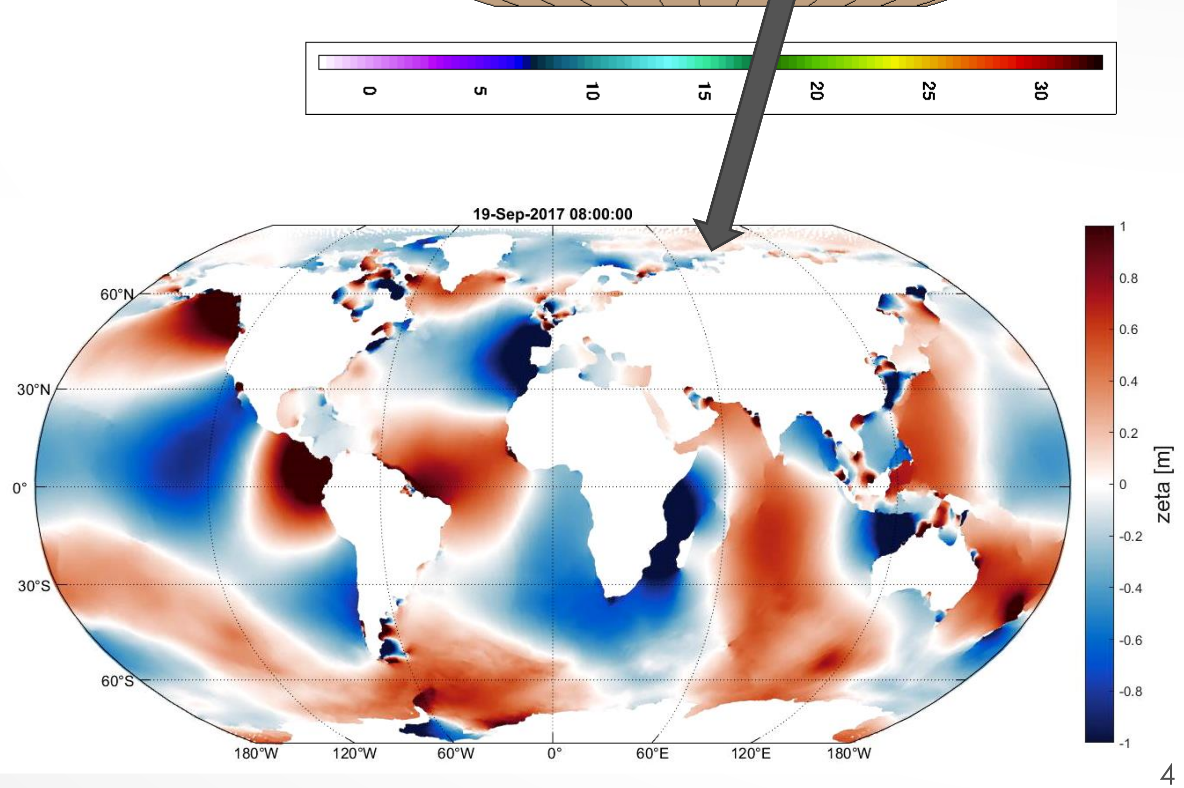
J.C., Armstrong, B., He, R., Zambon, J.B., 2010. Development of a Coupled Ocean-Atmosphere-Wave-Sediment Transport (COAWST) Modeling System. Ocean Model. 35, 230–244. doi:10.1016/j.ocemod.2010.07.0100

MY SOLUTION

- Feed a 2D barotropic model (ADCIRC here) internal density information from an operational and freely available 3D baroclinic ocean model (HYCOM)
- Preserve the high horizontal and temporal resolution, and numerical stability associated with 2D barotropic models that makes them so useful
- Accounts for the effects of 3D ocean baroclinicity on coastal water levels
- Leverages on the quality of existing widely validated and used ocean circulation models (e.g. HYCOM)

HYCOM - GOFS 3.1





METHOD

- ∇B calculated from the density ρ on the HYCOM-GOFS 3.1 grid and interpolated to 2D ADCIRC model
- GOFS 3.1 outputs (T and S) converted to ρ
- Internal tide wave drag parameterization uses buoyancy frequencies computed from GOFS 3.1

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

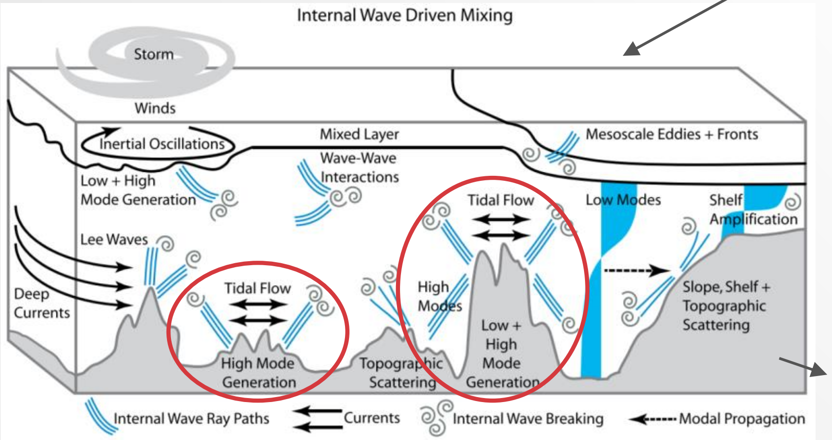
Internal tide wave drag

- 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 due to non-uniform velocity structure

- Need to parameterize, e.g. through additional bottom friction and horizontal mixing



MacKinnon, J.A., et al., 2017: Climate Process Team on Internal Wave–Driven Ocean Mixing. Bull. Amer. Meteor. Soc., 98, 2429 2454, https://doi.org/10.1175/BAMS-D-16-0030.

(see e.g., Pringle, W.J., et al., 2018. Finite-Element Barotropic Model for the Indian and Western Pacific Oceans: Tidal Model-Data Comparisons and Sensitivities. Ocean Model. 129, 13–38. doi:10.1016/j.ocemod.2018.07.003

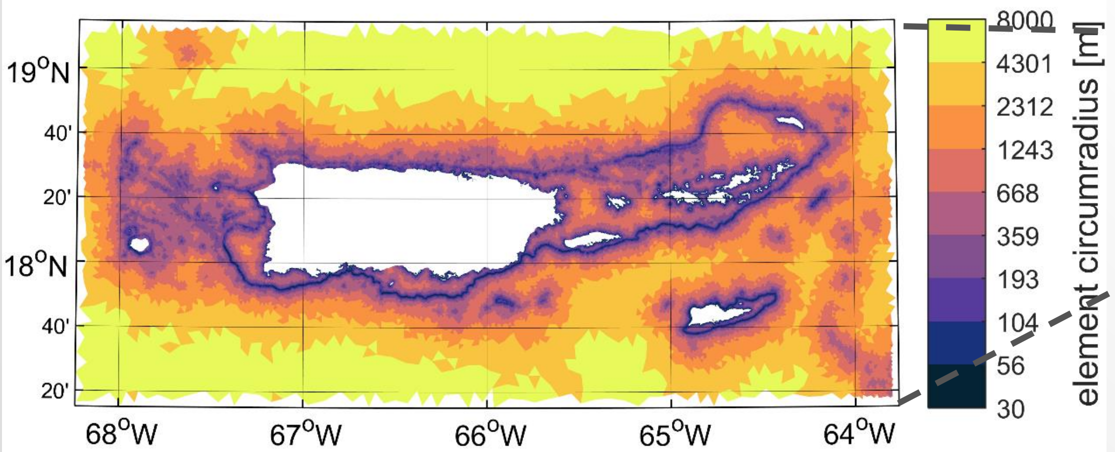
APPLICATION TO PUERTO RICO AND US VIRGIN ISLANDS (PRVI)

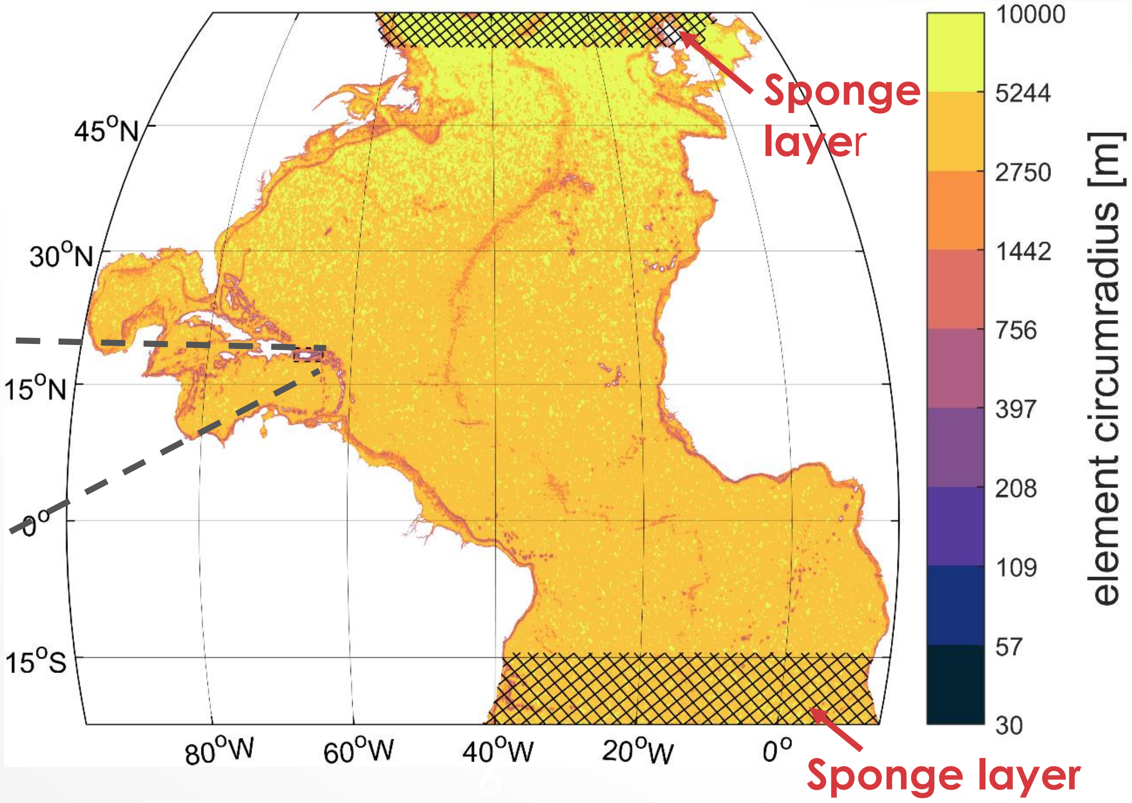
U.S. IOOS - NOAA Coastal and Ocean Modeling Testbed Project

- Maximum resolution ~8 km in ocean (same as HYCOM GOFS 3.1)
- ~30m resolution around PRVI coast and shelf breaks
- Force with CFSv2 atmospheric data

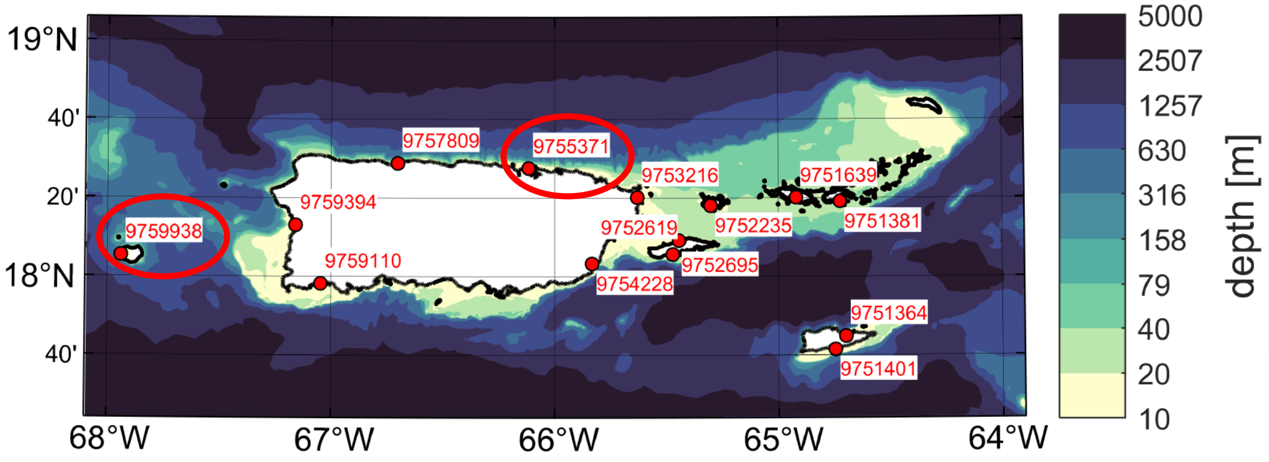
North Atlantic Ocean Domain
~1.5 million nodes (HYCOM has ~30 million wet nodes in same region)

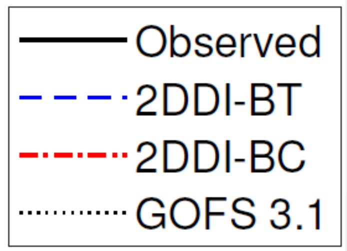
PRVI high-resolution region



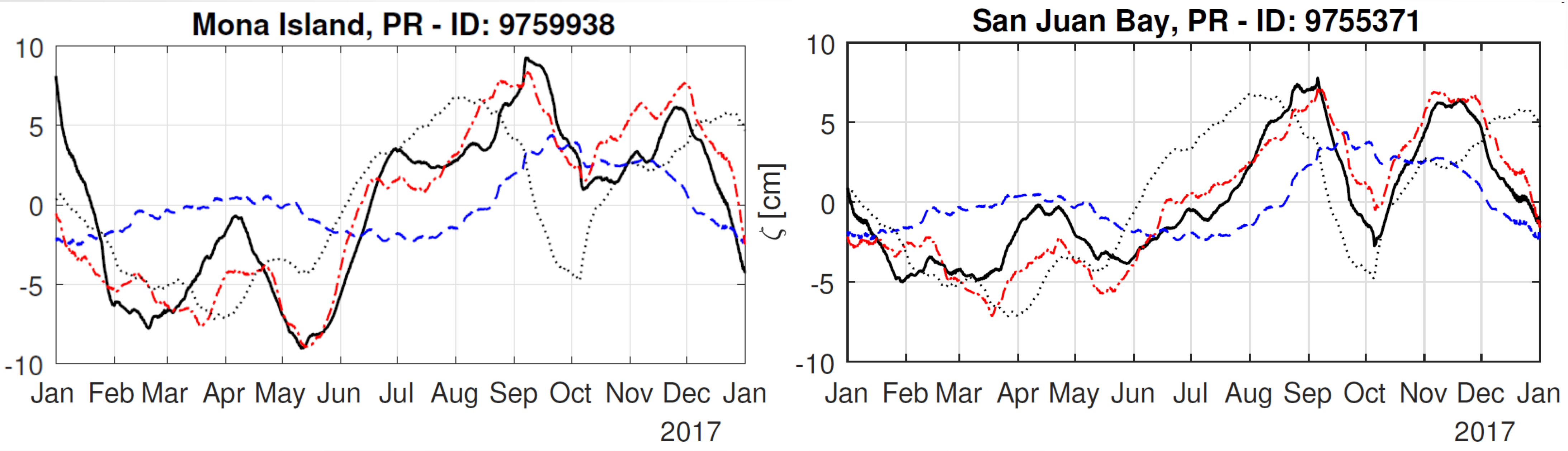


RESULTS FROM PUERTO RICO IN 2017

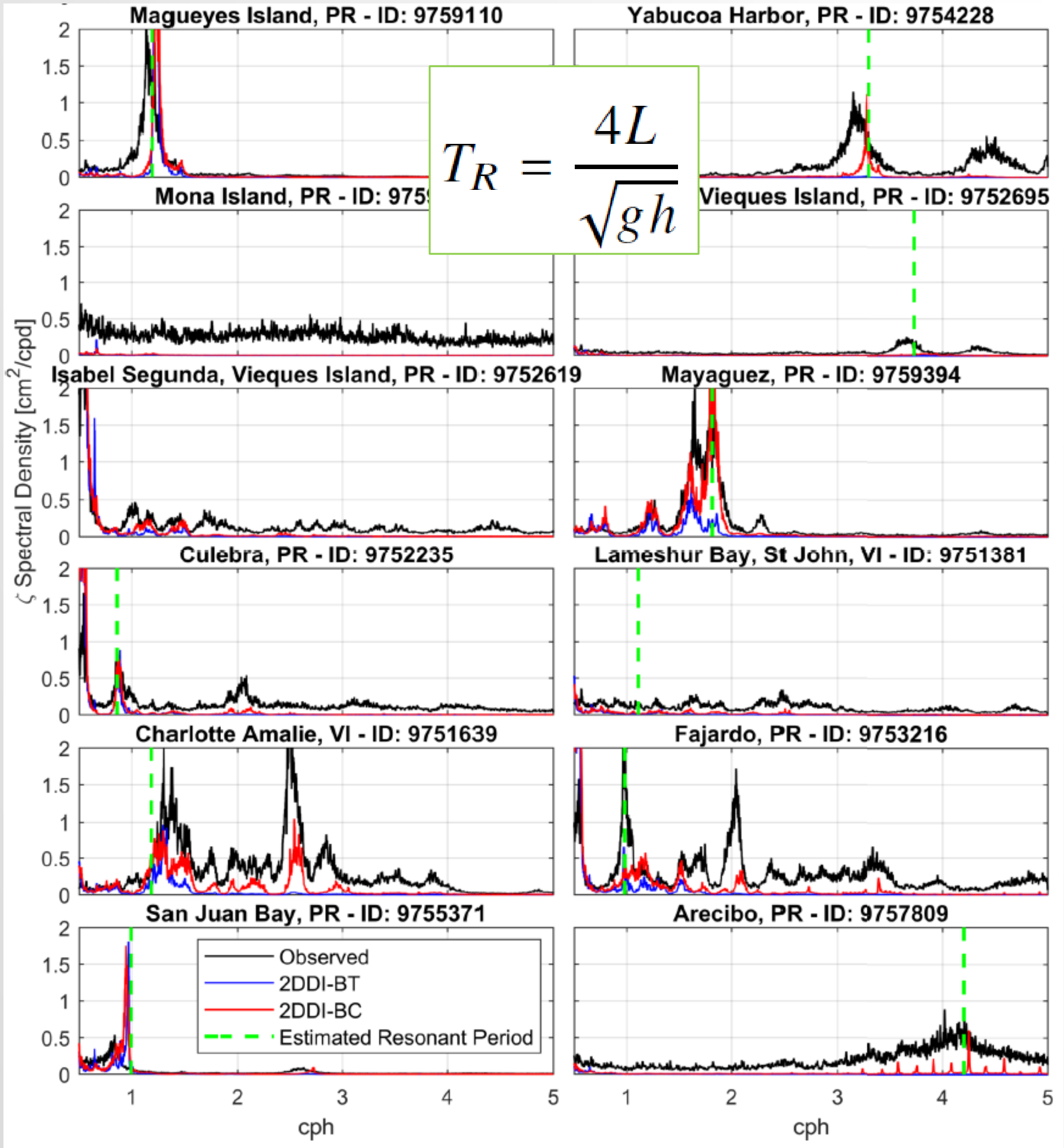




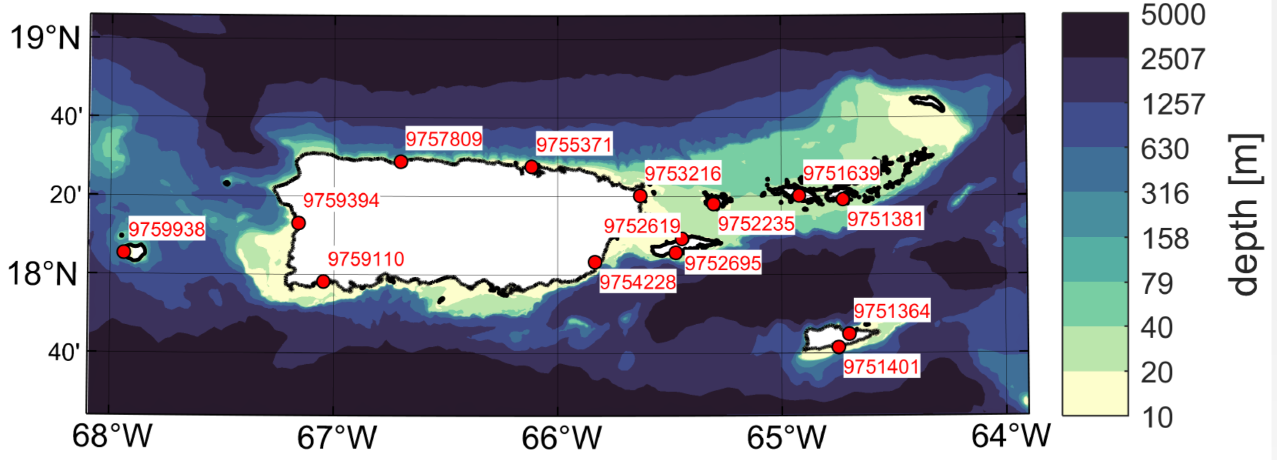
30-day moving average



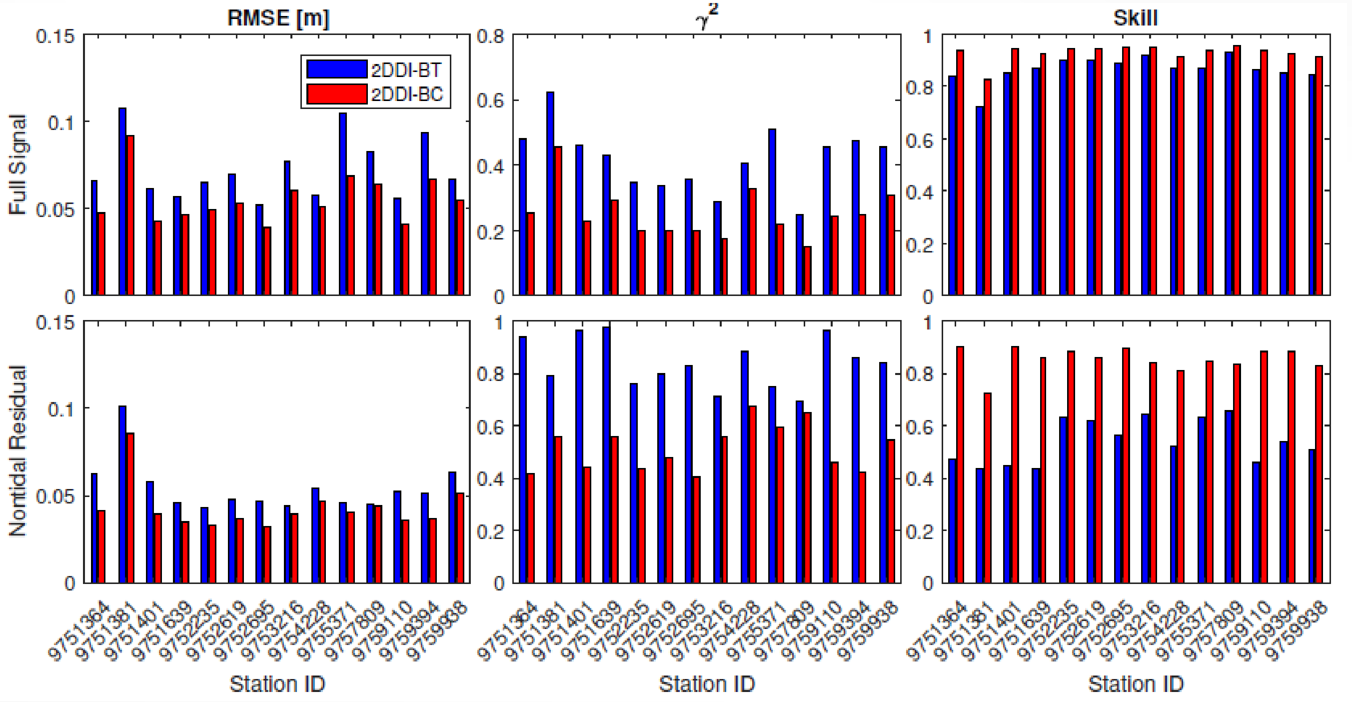
HIGH-FREQUENCY SPECTRAL DENSITIES



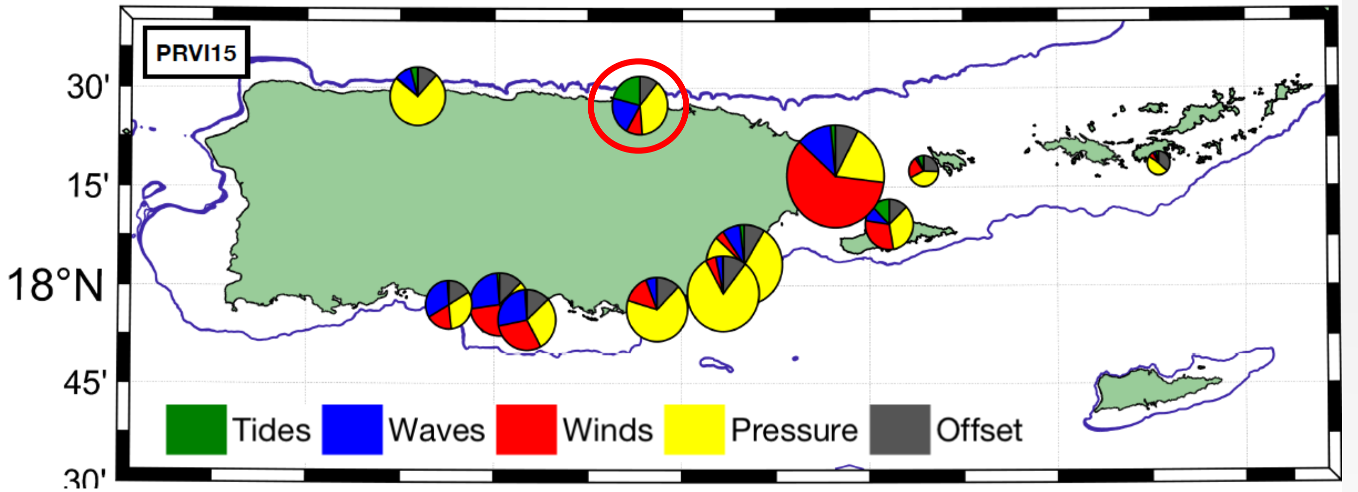
$$T_R = \frac{4L}{\sqrt{gh}}$$



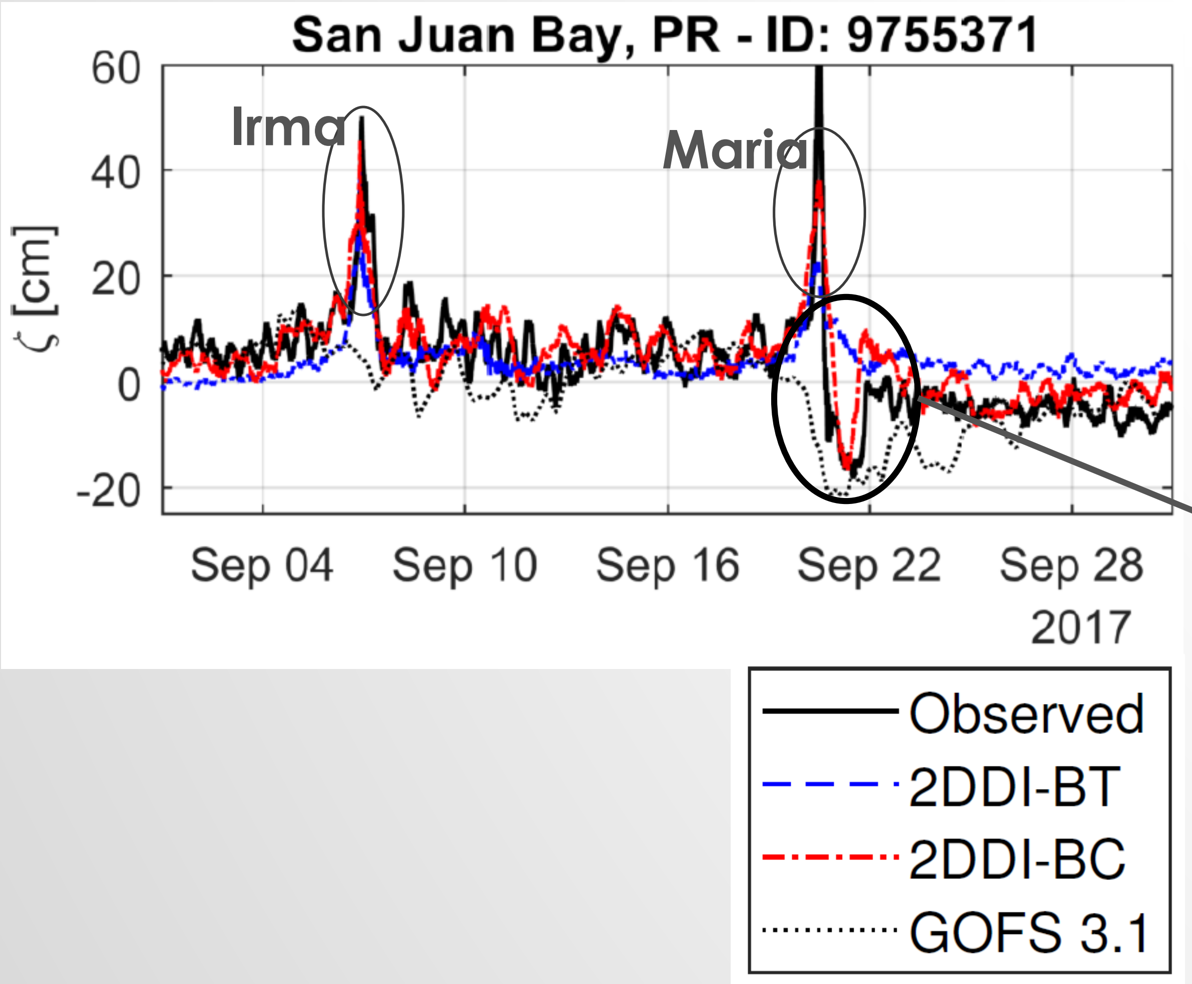
Yearly Errors/Skill Level



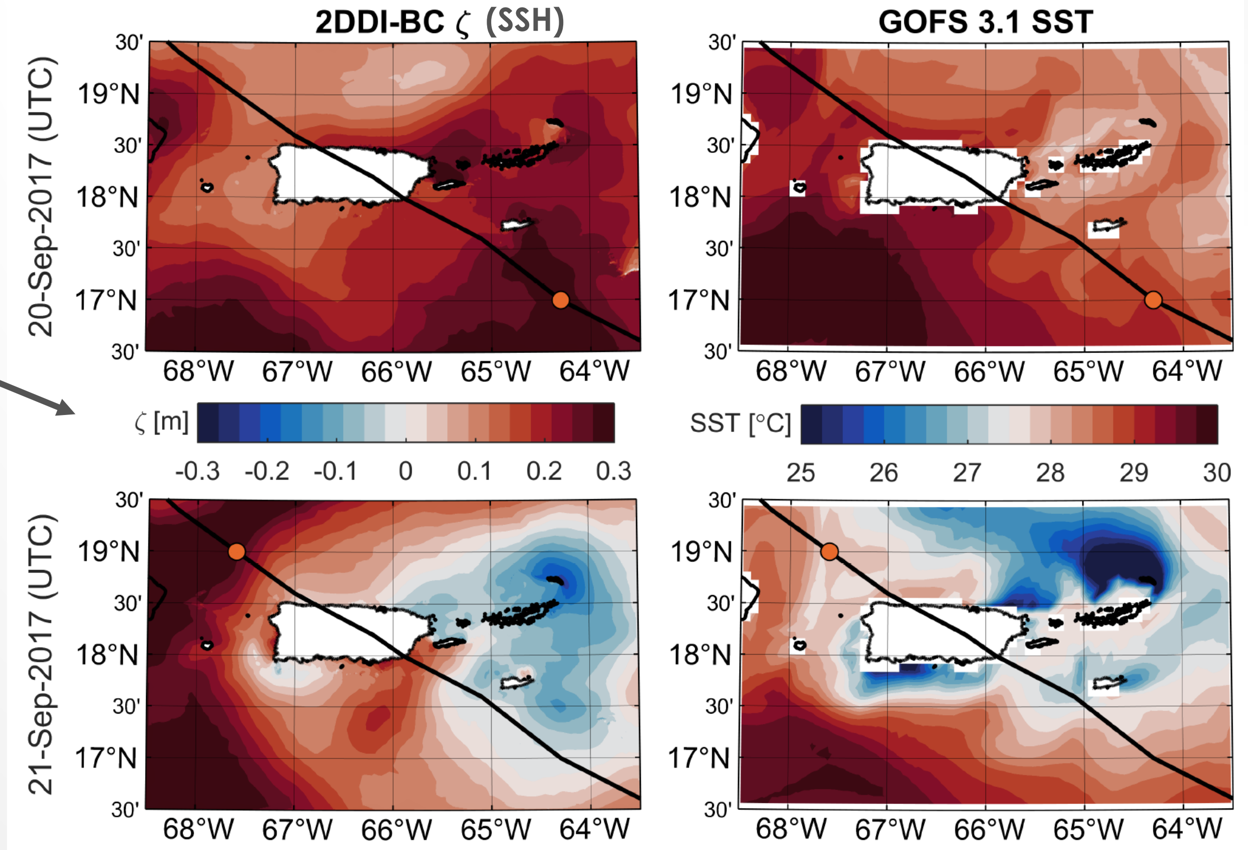
HURRICANES IRMA AND MARIA



Surge (non-tidal residual)

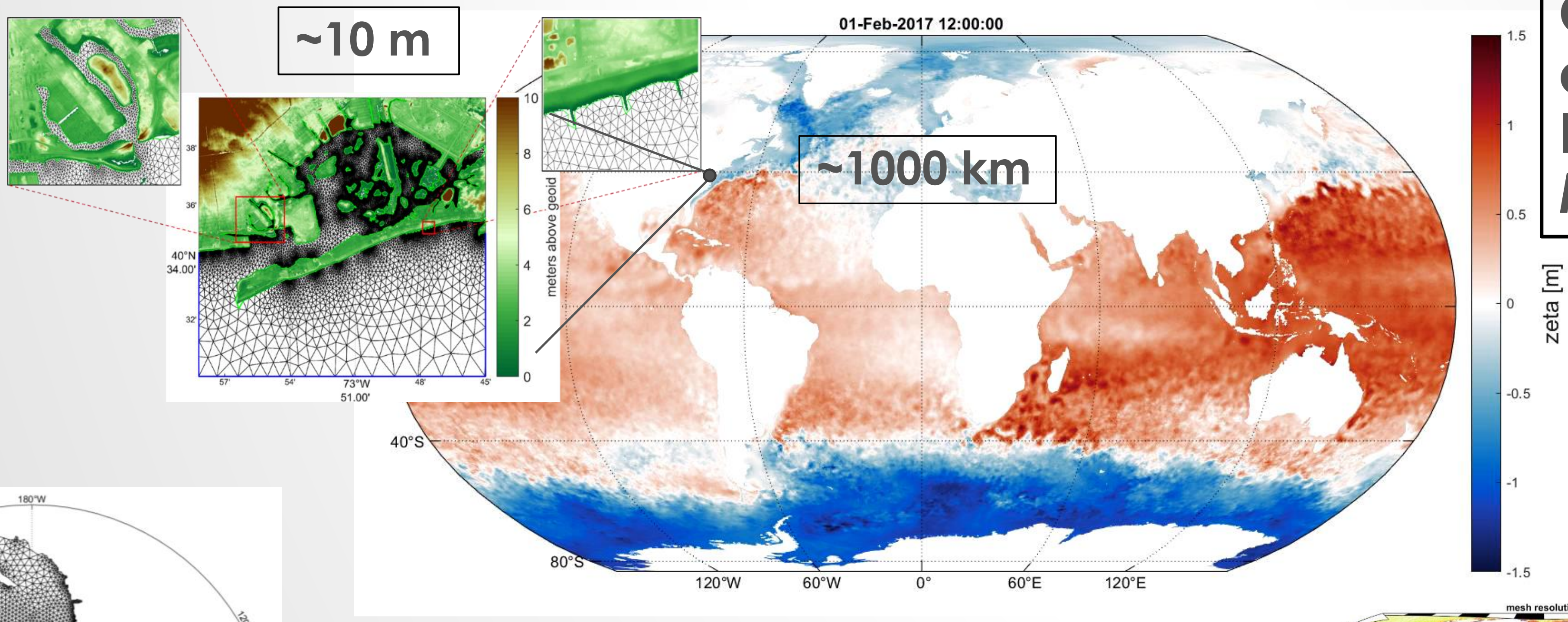


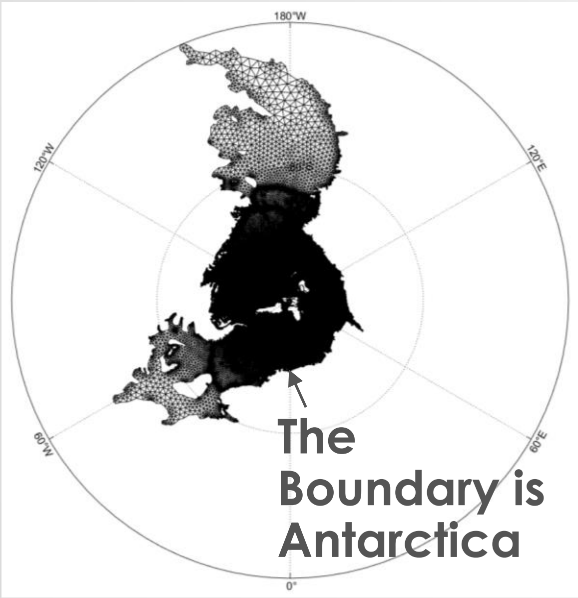
Effect of TC cooling of ocean surface



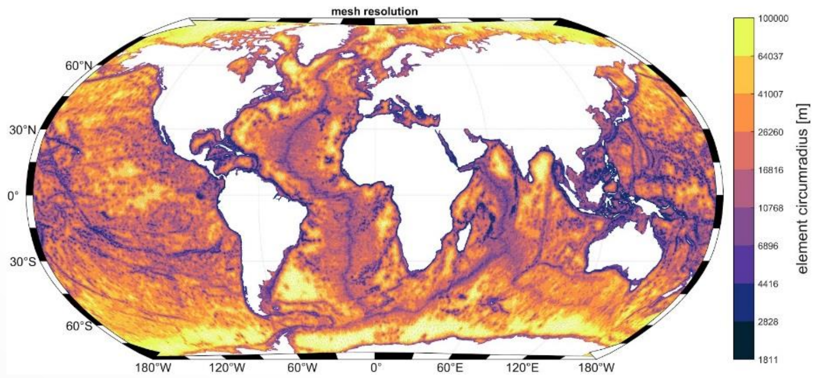
GLOBAL TIDE AND SURGE MODELING WITH OCEAN-CIRCULATION COUPLING

Forcing with CFSv2 winds and GOFS 3.1 HYCOM Model





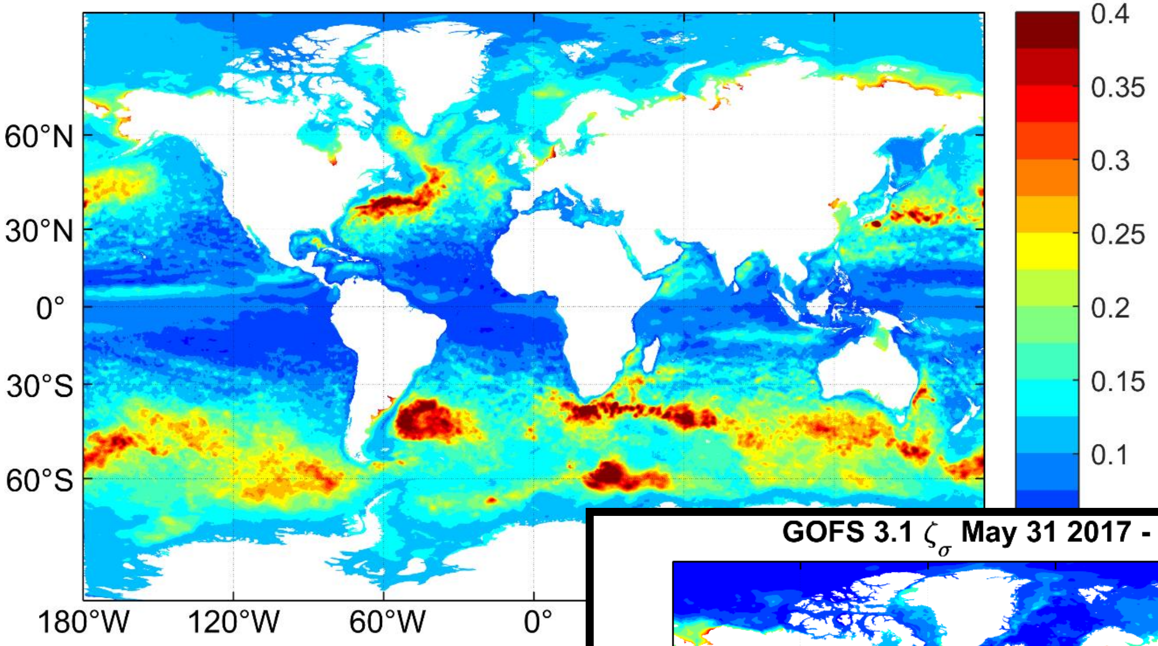
Global Meshing achieved through Stereographic projection:
Wraps around globe and is conformal
Implemented in **OceanMesh2D**:
https://github.com/CHLNDDEV/OceanMesh2D/tree/Projection



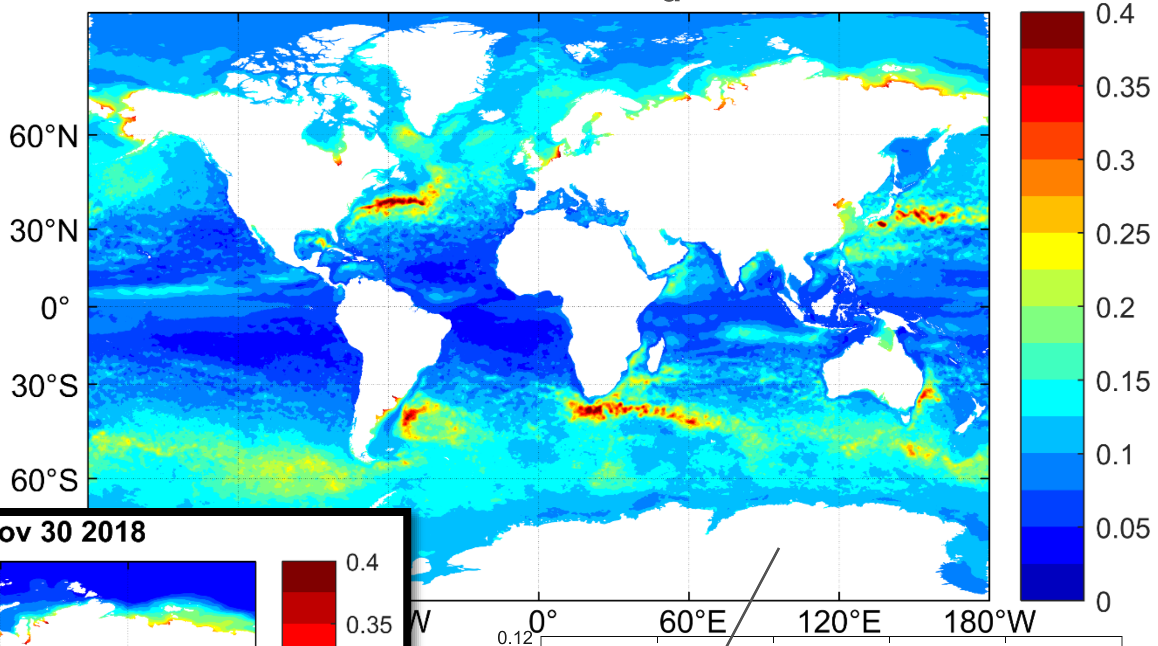
SEA SURFACE HEIGHT VARIABILITY (NO TIDES)

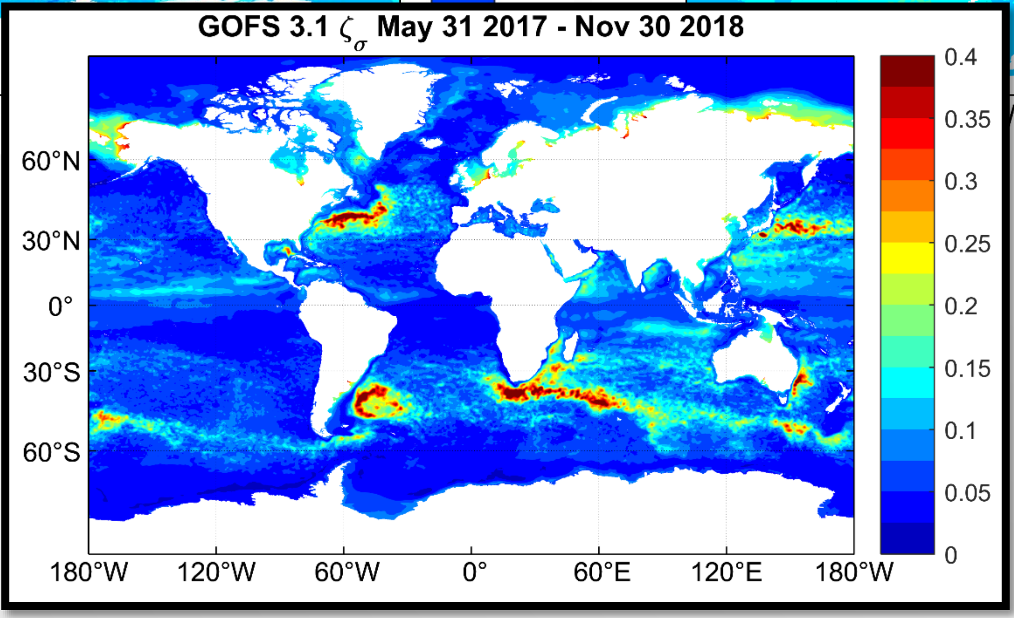
Ocean-circulation coupled ADCIRC

No Momentum Dispersion coefficient



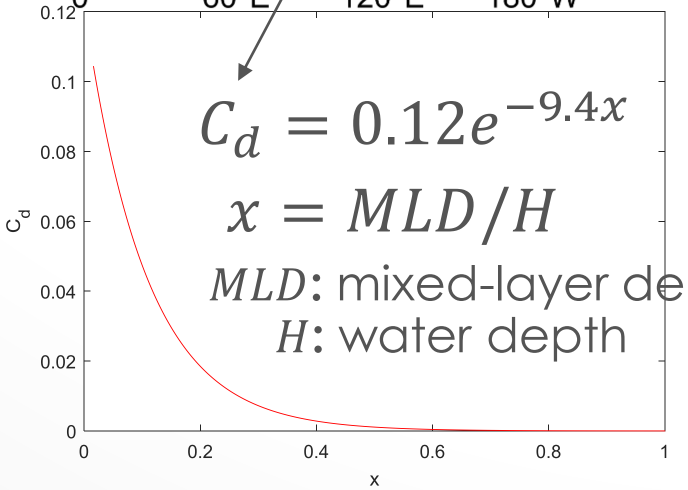
Momentum Dispersion C_d coefficient





HYCOM GOFS 3.1

(No inverted barometer)



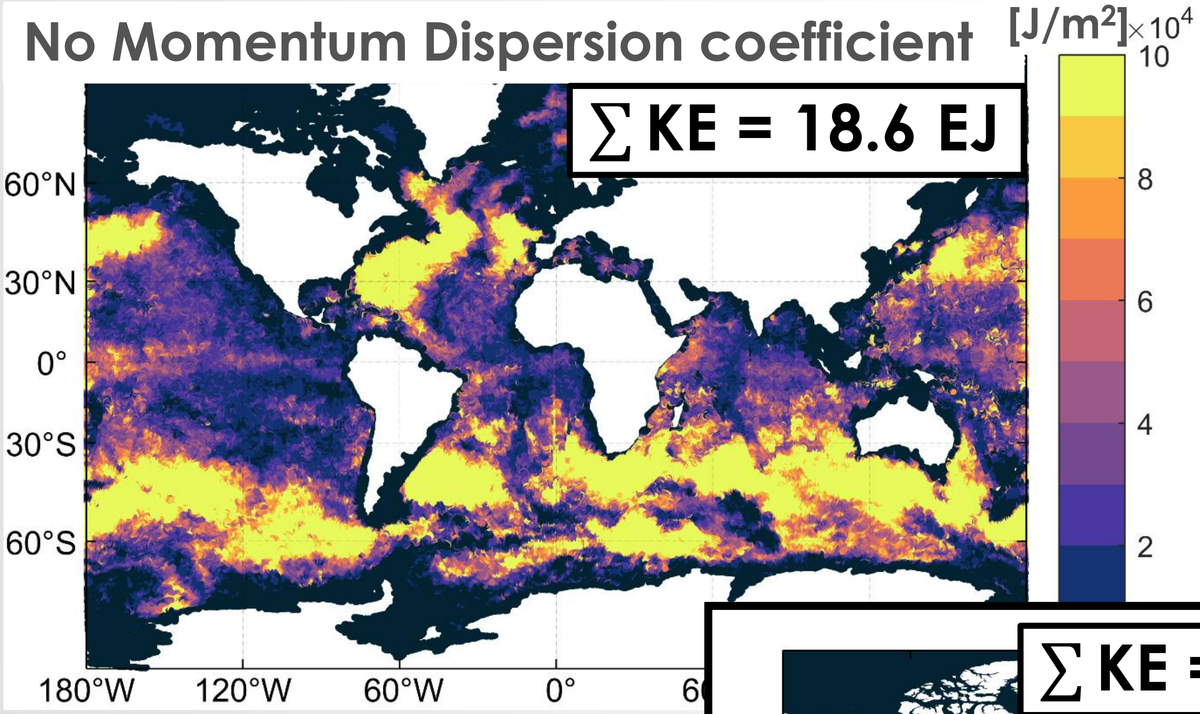
$$C_d = 0.12e^{-9.4x}$$

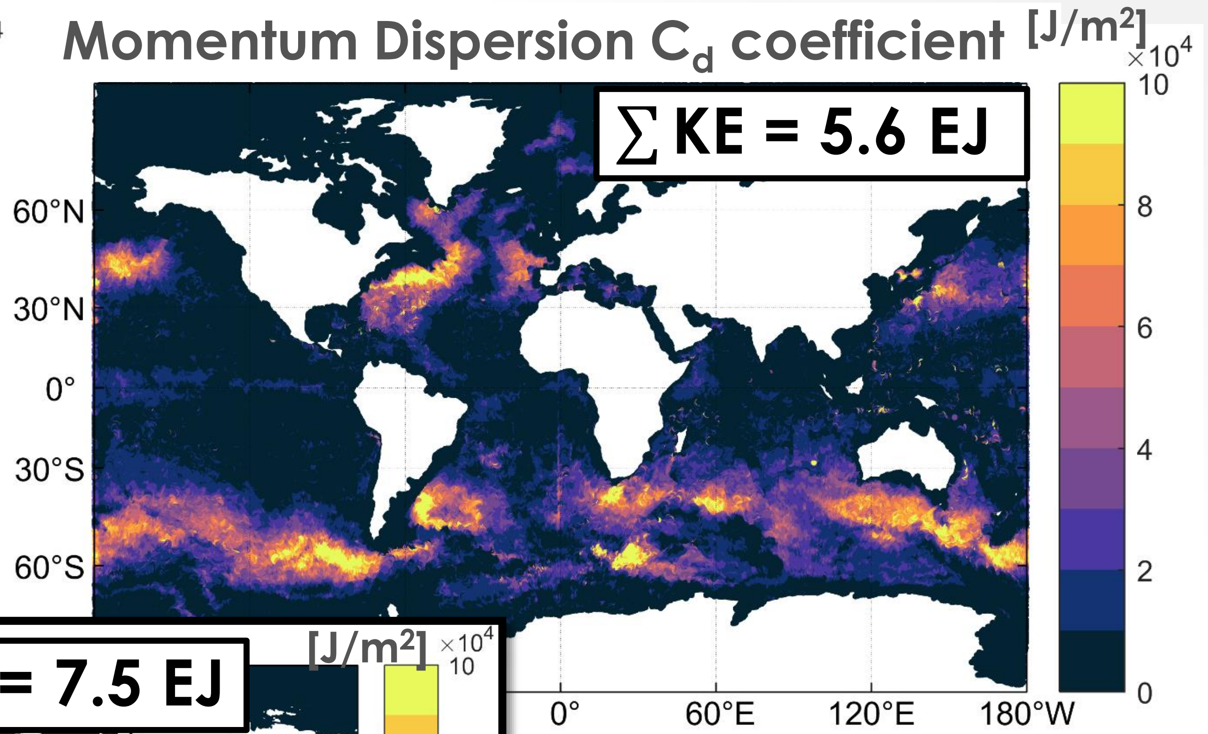
$$x = MLD/H$$

MLD: mixed-layer depth
H: water depth

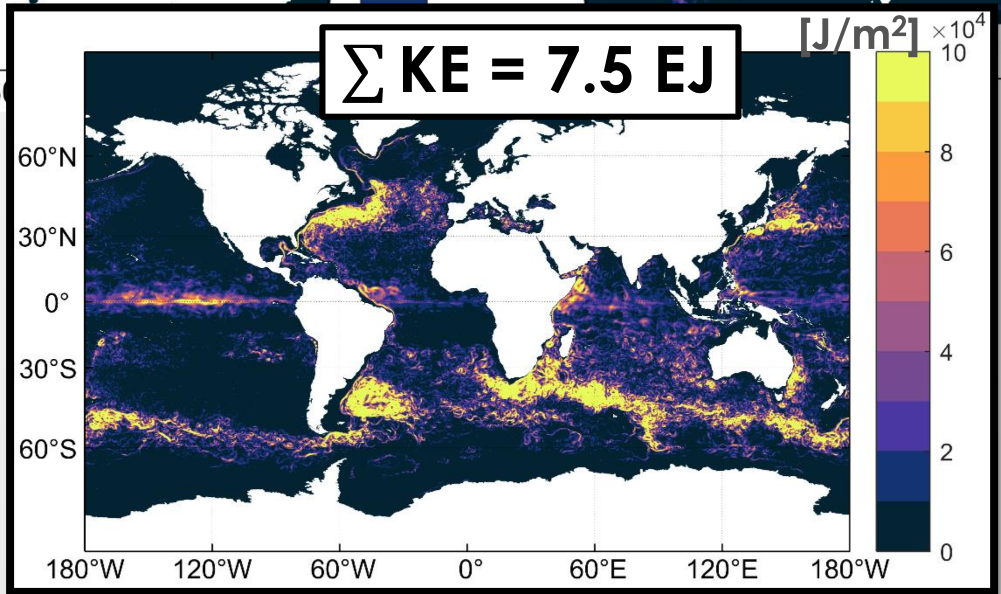
MEAN TOTAL KINETIC ENERGY (NO TIDES)

Ocean-circulation coupled ADCIRC





HYCOM GOFS 3.1



SUMMARY

- Ocean baroclinic coupled coastal ocean models can be useful tool for taking into account the effects of seasonal fluctuations, local baroclinic effects, and the **effects of climate change on the <u>coastal zone</u>**
- Demonstrated improvements to capturing coastal water level signal including seasonal variability and TC ocean cooling effects around PRVI
- Currently developing **Global Tide and Surge** model that efficiently predicts global coastal flooding taking into account density stratification