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

**Tidal Flooding Is Rising with the Sea**

The frequency of high-tide flooding has doubled over the past 30 years along U.S. coasts, driven by rising sea levels. This chart shows the average number of days per year across tide gauges tracked by NOAA.

**U.S. HIGH-TIDE FLOODING AND COASTAL SEA LEVEL 1920-2017**

SOURCE: NOAA

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

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)
**METHOD**

- \( \nabla B \) calculated from the density \( \rho \) on the HYCOM-GOFS 3.1 grid and interpolated to 2D ADCIRC model

- GOFS 3.1 outputs (\( T \) and \( S \)) converted to \( \rho \)

- Internal tide wave drag parameterization uses buoyancy frequencies computed from GOFS 3.1

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

- **Baroclinic pressure gradient (BPG):**

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

- **Momentum Dispersion due to non-uniform velocity structure**

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

APPLICATION TO PUERTO RICO AND US VIRGIN ISLANDS (PRVI)

- 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

PRVI high-resolution region

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

- Maguayes Island, PR - ID: 9759110
- Yabucoa Harbor, PR - ID: 9754228
- Mona Island, PR - ID: 975
- Vieques Island, PR - ID: 9752695
- Isabel Segunda, Vieques Island, PR - ID: 9752619
- Mayaguez, PR - ID: 9759394
- Culebra, PR - ID: 9752235
- Lameshur Bay, St John, VI - ID: 9751381
- Charlotte Amalie, VI - ID: 9751639
- Fajardo, PR - ID: 9753216
- San Juan Bay, PR - ID: 9755371
- Arecibo, PR - ID: 9757809

- RMSE [m]
- Skill

Observed
2DDI-BT
2DDI-BC
Estimated Resonant Period

Station ID
Station ID
Station ID
HURRICANES IRMA AND MARIA

Surge (non-tidal residual)

San Juan Bay, PR - ID: 9755371

Effect of TC cooling of ocean surface
GLOBAL TIDE AND SURGE MODELING WITH OCEAN-CIRCULATION COUPLING

~10 m

~1000 km

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

Forcing with CFSv2 winds and GOFS 3.1 HYCOM Model

The Boundary is Antarctica
SEA SURFACE HEIGHT VARIABILITY (NO TIDES)

Ocean-circulation coupled ADCIRC

HYCOM GOFS 3.1
(No inverted barometer)

\[ C_d = 0.12e^{-9.4x} \]
\[ x = \text{MLD}/H \]

MLD: mixed-layer depth
H: water depth
MEAN TOTAL KINETIC ENERGY (NO TIDES)

Ocean-circulation coupled ADCIRC

No Momentum Dispersion coefficient

\[ \sum KE = 18.6 \text{ EJ} \]

Momentum Dispersion \( C_d \) coefficient

\[ \sum KE = 5.6 \text{ EJ} \]

\[ \sum KE = 7.5 \text{ EJ} \]

HYCOM GOFS 3.1
SUMMARY

- Ocean baroclinic coupled coastal ocean models can be a useful tool for taking into account the effects of seasonal fluctuations, local baroclinic effects, and the effects of climate change on the coastal zone.

- 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.