Bipartisan Infrastructure Law (BIL)-focused ocean initiatives

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Q3: How can GFDL research and modeling be further utilized to meet NOAA stakeholder needs and enhance research partnerships to ensure GFDL's success?

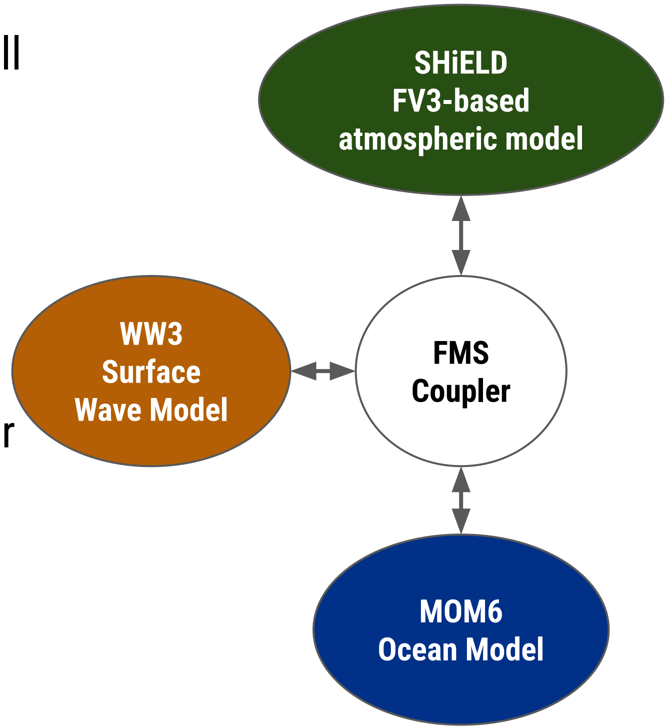
1. SHiELD-MOM6 High Resolution Coupled Model Project Overview

Mission

To improve representation of atmosphere-ocean processes at small scales (~1 km) that are parameterized in operational models.

Goals & Deliverables

- Open-source development of high-resolution regional SHiELD-MOM6-WW3 coupled model codebase w/ FMS.
- Real model case-study implementations with observation-based evaluation focusing on regions relevant for NOAA and its partners (e.g., mid-Atlantic US coast).
- Make scientific advances to understand km-scale air-sea interaction on coastal storms and flooding. Connect understanding w/ model improvements that support operational model applications (e.g., GFS, HAFS).



2. SHiELD-MOM6-WW3: Technical progress on implementation

- SHiELD code updated from simple coupler to full FMS coupler
  - Provide atmospheric fields from SHiELD to exchange grids that are used to compute air-sea fluxes
  - Replace SHiELD air-sea fluxes w/ FMS fluxes as bottom boundary conditions for flux routines
  - Incorporate surface radiation and precipitation fluxes consistent w/ FMS coupler
- SHiELD-MOM6 grids generated and used to complete proof-of-concept atmosphere-ocean runs in (i) idealized double-periodic vortex and (ii) preliminary US Atlantic coast case
- MOM6-WW3 codes w/ FMS merged into same git versions as SHiELD-MOM6 w/ FMS to facilitate the three-way coupling
- SHiELD-MOM6-WW3 grids generated and used to complete proof-of-concept atmosphere-ocean-wave run for idealized double-periodic cyclone

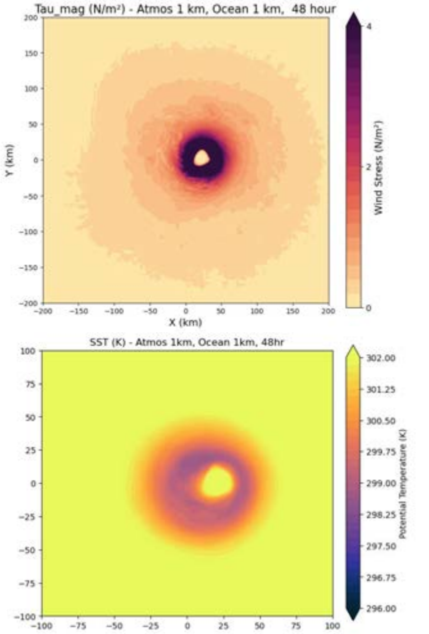


Fig 1: (a) SHiELD Idealized vortex wind stress used to force (b) MOM6 ocean SST evolution in coupled MOM6-SHiELD configuration.

3. SHiELD-MOM6-WW3: Kilometer-scale coupling yields more accurate fluxes

What benefits are realized by developing a high-resolution coupled model?

- Ocean response to a strong wind event is sensitive to having adequate resolution in both ocean and atmosphere components
  - Atmosphere resolution needed to represent peak air-sea fluxes that cause intense SST cooling (e.g., Fig1a vs 1b)
  - Ocean resolution needed to represent the ocean vertical mixing and km-scale lateral current effects (e.g., Fig 1b vs 1c)
- Similar responses can be found in the atmosphere's dynamical response to ocean forcing at various scales (not shown)
- To capture the important feedbacks between the atmospheric dynamical response and oceanic dynamical response requires simulating both MOM6 and SHiELD at ~1 km resolution.

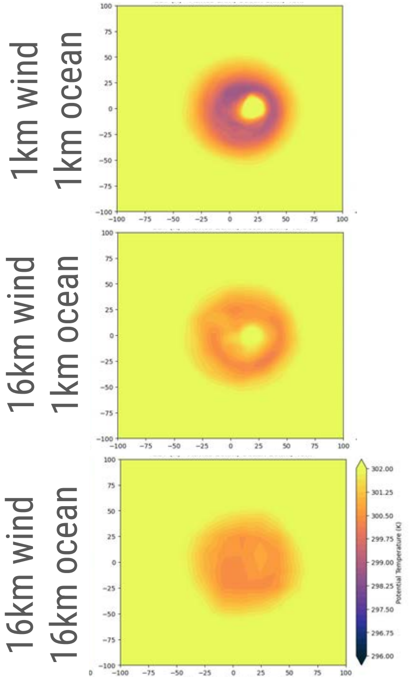


Fig 1: MOM6 SST driven by output of SHiELD idealized vortex with wind at (a) 1km and coarsened to (b,c) 16km. MOM6 simulated at both (b) 1 km and (c) 16 km.

4. SHiELD-MOM6-WW3: Ocean waves modify air-sea fluxes and ocean mixing

What benefits are realized by including a wave component?

- WAVEWATCH III (NOAA/EMC) spectral wave model component simulates direction-frequency distribution of wave energy.
- The coupled model can use the spectrum to better parameterize:
  - Air-sea fluxes (e.g., momentum, heat, moisture, and gases)
  - Upper ocean current simulation (via wave-averaged equations)
  - Upper ocean mixing (for Langmuir turbulence scheme, see Fig1b)
- Including WW3-coupling requires novel model development threads that include both technical and scientific aspects
- By considering surface waves we are able to more accurately represent the physics of air-sea interactions
- Aspects of this work done in collaboration with partners throughout NOAA and academia including operational groups (NCEP, AOML)

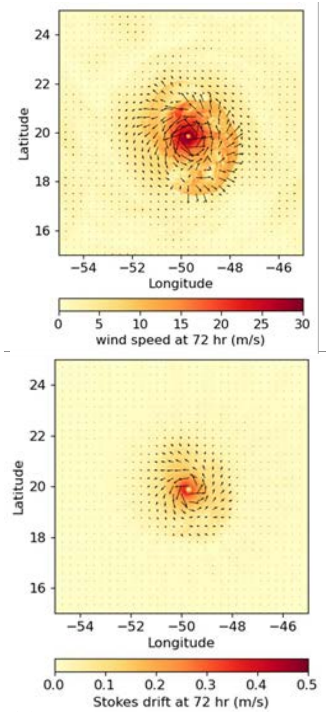


Fig 1: (a) SHiELD Idealized vortex wind field used to drive (b) Stokes drift in WW3 , which is used for Langmuir mixing in the coupled SHiELD-MOM6-WW3 configuration

5. SHiELD-MOM6-WW3: Recent breakthrough on implementing w/ land

Recent Highlight

- Proof-of-concept implementation of SHiELD-MOM6 model simulated using a prototype 3km US east coast domain.
- Realistic ocean current response to development initialized extreme cyclone events.

Next steps

- Ocean initialization for realistic application (in progress following work by partners at NOAA/NCEP/EMC/J. Meixner)
- Ocean wave coupling implementation for realistic domains
- Complete merging the SHiELD, MOM6, FMS, and WW3 modifications back to parent git repositories (in progress)
- Evaluation of model skill against observations and parameter sensitivities for real world case studies

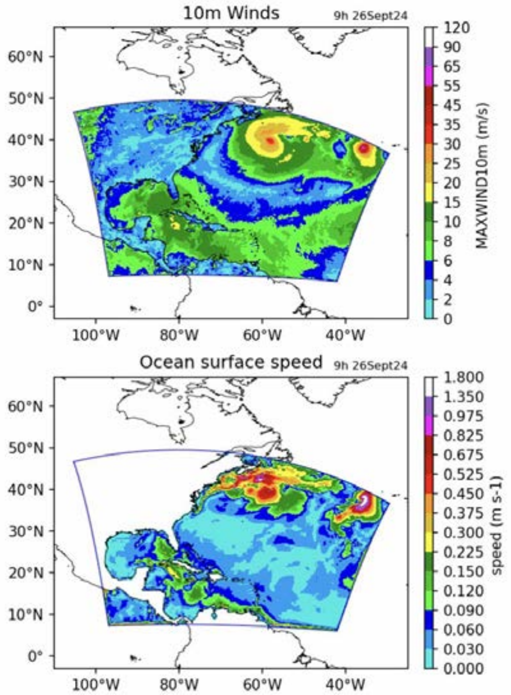


Figure 1: Prototype coupled SHiELD-MOM6 model w/ realistic SHiELD initial condition/boundary condition coupled to a simple uninitialized MOM6 ocean model

6. Explicit Tides in MOM6

- Modeling explicit tides in MOM6 for sea-level projections and rectified effect in climate simulations
- Porous barriers give robust global tides across resolutions (Wang et al., 2024)
- MOM6 now offers consistent and realistic on-line gravitational self-attraction and solid-earth loading effects on tidal sea-levels (done via spherical harmonics)
- Tides will change with a changing climate; this new MOM6 capability gives GFDL and NOAA the ability to explore this.

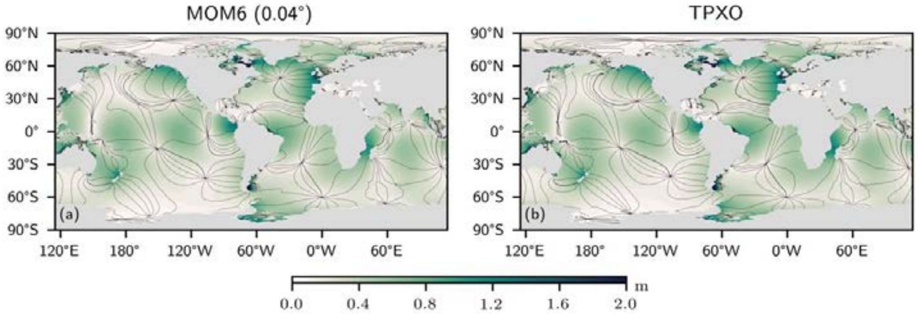


Figure 1: Evaluation of tidal amplitudes in 1-layer 1/25° MOM6 model with M_2 tidal potential as forcing compared to TPXO.

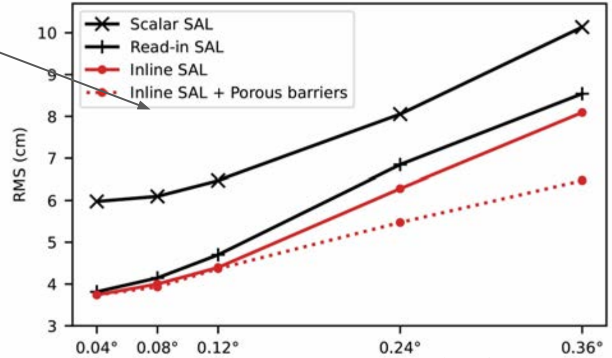
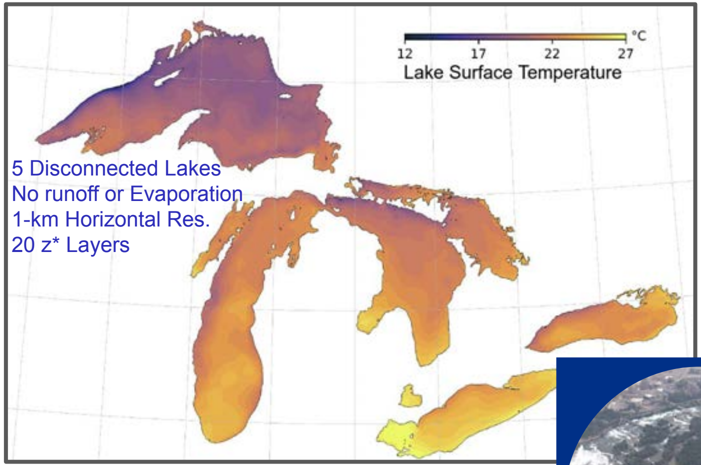


Figure 2: Inline self attraction and loading (SAL) w/ porous representation of topography reduces RMS bias in sea level even at coarse lateral resolution

7. Great Lake modeling using MOM6



August 2023 Lake Surface Temperatures from a regional Great Lakes configuration being developed by He Wang using MOM6.

Niagara Falls, C. M. Highsmith 2018

Niagara Falls is represented using a hydraulic jump, where the velocity is capped at a value proportional to the upstream supercritical flow. Porous barriers represent the subgrid scale channels and rivers that connect the Great Lakes to each other and the ocean.

Direct simulation of the U.S. Great Lakes in coupled configurations

- Improve regional predictions and projections of the North-central U.S. weather, climate and water levels.
- Challenge - representing the 5 Great Lakes in a single interconnected model. MOM6 now has the ability to:
  - Represent hydraulic control points (waterfalls)
  - Include porous barriers (Wang et al 2024)
  - Future work includes expanding the set of represented lakes to include the Caspian Sea, large Canadian Lakes, Lake Baikal, and the African Great Lakes.

8. Connecting development threads for the simulation of coastal sea level

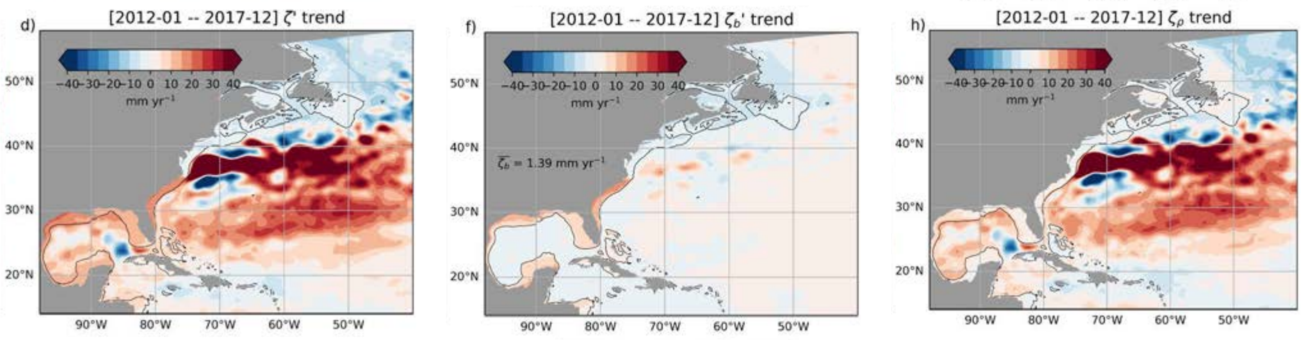
Many recent ocean, wave, and atmosphere model developments result specifically in the improved representation of sea level processes. These enable new studies seeking an improve understanding and increase in predictive skill of the patterns and drivers of coastal inundation, flooding, and climate variability realized at the coast. From a stakeholder perspective, this work enhances model realism and facilitates the attribution of past/present/future changes to physical processes. Recent and ongoing sea level relevant developments include:

- Enhanced simulation of waves, storm surge, and tides (km scale coupled ocean-wave-atmosphere simulations)
  - this work enables process studies relevant for interpretation and improvement of existing, less complex, NOAA storm surge modeling (UFS)
- Simulation of waves and high-wind air-sea fluxes in shallow water
- Incorporation of a dynamic coastline allowing for wetting and drying of land
- Explicit tide representation in MOM6

9. Sub-seasonal to Interannual Sea Level Variability

From global to regional ocean modeling - assessment of the patterns and drivers of sea level change - projects:

- Sub-seasonal coastal sea level forecasting (enhanced horizontal resolution via dynamical downscaling of SPEAR)
- Understanding the physical processes connecting coastal sea level and offshore sterodynamic (density and circulation driven) variability:
    - Attribution of differing patterns of variability north/south of Cape Hatteras (and the role of ocean heat content)
    - Cross-shore subsurface density driven mass redistribution
    - A mechanistic understanding can be utilized to reduce prediction uncertainty (adding a dynamical perspective, ocean memory)



left: sea level, manometric, and steric height trends that reveal a link between subtropical gyre-scale changes and continental shelf mass loading (coastal sea level rise)

[Steinberg et al. 2024. "A Link Between US East Coast Sea Level and North Atlantic Subtropical Ocean Heat Content" JGR: Oceans"]
[Ross et al. 2023. "A high-resolution physical–biogeochemical model for marine resource applications in the northwest Atlantic (MOM6-COBALT-NWA12 v1.0)"]

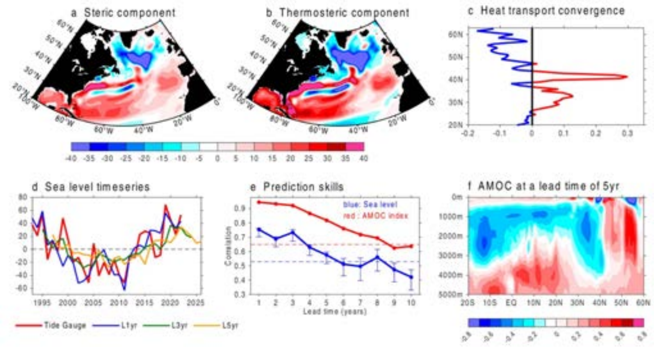
10. Global-to-Regional-to-Local

As part of a larger strategy to improve sea level prediction along US coastlines, we are downscaling global ocean simulations (hindcasts and forecasts) to consider variability across sub-seasonal to interannual timescales. This work is part of an integrated effort to carry out nested downscaling where regional model out serves as a boundary condition for a higher resolution coastal ocean model (SCHISM, collaborations with NOAA PSL). Together, SPEAR, NWA12, and SCHISM simulations improve coastal sea level forecast skill, link local- and climate-scale processes, and provide opportunity to improve our understanding of coastal and open-ocean connectivity

Identifying sources of predictability [SPEAR]

[Gu et al. 2024. “Exploring multiyear-to-decadal North Atlantic sea level predictability and prediction using machine learning”]

[Zhang et al. 2024. “Causes and multiyear predictability of the rapid acceleration of U.S. Southeast Sea level rise after 2010”] →



Dynamical downscaling (from 1 degree ocean model) reveals the importance of resolving boundary and slope currents as well as and shelf/slope bathymetry. This results in more realistic simulation of coastal dynamics.

[Koul et al. 2024. “A Predicted Pause in the Rapid Warming of the Northwest Atlantic Shelf in the Coming Decade”]

11. Sea Level Focused Collaborations within GFDL

Recent and ongoing:

- In collaborating with MED and S2D divisions, we assess the effects of downscaling in a seasonal forecasting framework and leverage understanding of ocean circulation in quantifying drivers of sea level variability

  [Koul et al. 2024. “A Predicted Pause in the Rapid Warming of the Northwest Atlantic Shelf in the Coming Decade”]
- Building an ensemble of high temporal resolution seasonal forecasts

Next steps:

- With a new ensemble, we have begun quantifying US east coast seasonal variability, focusing on changes in hourly distributions of sea level (will yield an assessment of forecast skill dependence on initialization state and time)
- We are continuing analyses revealing when and where downscaling improves prediction

12. Sea Level Focused Collaborations Outside GFDL

At GFDL, sea level related development and analysis is carried out in an integrated manner with NOAA's Coastal Inundation at Climate Timescales Initiative. Model developments and use to explore sea level questions has led to engagement and collaboration with the community. Ongoing and new community/professional group involvement includes:

- Participation on the U.S. Clivar Phenomena, Observations, and Synthesis Science Panel
- Collaboration with the NASA Sea Level Change Team
- U.S. CLIVAR Ocean Model Development Panel
- NOAA/NASA RISE program (and transition to the Coastal Inundation Task Force (pilot array location planning))
- 2023 Sea Level Symposium (brought together researchers using GFDL models to study sea level - hosted by GFDL)
- Inter-agency technical report (2022) and development of sealevel.globalchange.gov (2024)

13. Relevance to Ongoing Model Developments

Recent and ongoing ocean model developments have led to the improved representation of sea level processes including:

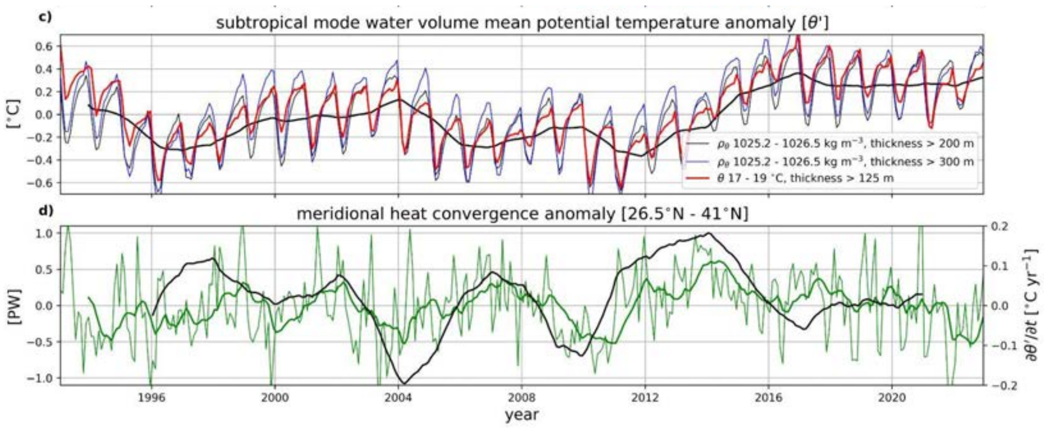
- Non-Boussinesq configuration (sea level changes now include effects of thermohaline expansion/haline contraction - offline correction calculations are no longer necessary and ocean circulation response to salinity and temperature changes is now more accurate - removes ambiguity of choice to make this correction in regional Boussinesq models)
- Coupled atmosphere - ocean - sea ice - ice sheet model development - Simulations newly enable a full assessment of the sea level budget (local/remote contributions from ocean mass change and sterodyanmic change can be directly assessed - relevance for projections)
- Reduced temperature drift with increased horizontal resolution [CM4X, Griffies et al. submitted]

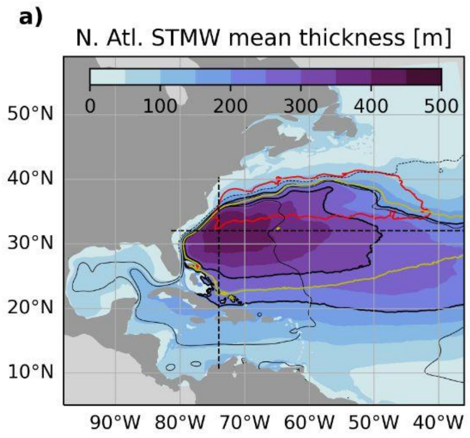
14. Process Studies: Linking Sea Level to Ocean Heat Content and Water Mass Transformation (towards improved prediction)

In seeking to understand the patterns and drivers of sea level change across regional scales, we identify key links to ocean circulation, ocean heat content change, and water mass transformation

[e.g. Krasting et al. 2024 "Steric Sea Level Rise and Relationships with Model Drift and Water Mass Representation in GFDL CM4 and ESM4"]

[example below: U.S. East Coast sea level rise south of Cape Hatteras and links to North Atlantic subtropical mode water, Steinberg et al. 2024]





15. Connections to Stakeholders and Development of Partnerships

- Results from dynamical downscaling reveal sub-seasonal to interannual sea level changes to increase in amplitude (particularly south of Cape Hatteras). Increases in model horizontal resolution likewise reveal unique sub-regional scale impacts. Downscaling has also resulted in the improved representation of sea level variability in the Gulf of Mexico (connections to the National Academy of Sciences Understanding Gulf Ocean Systems gorup)
- In ongoing collaborations with NOAA's National Ocean Service (Center for Operational Oceanographic Products and Services) and PSL, these simulations are helping to improve understanding of operational/applied forecast skill and biases
- Sea level related work is being done alongside CEFI led operational forecast system development