Subpolar North Atlantic heat flux drives projected U.S. East Coast sea-level trend in a climate model

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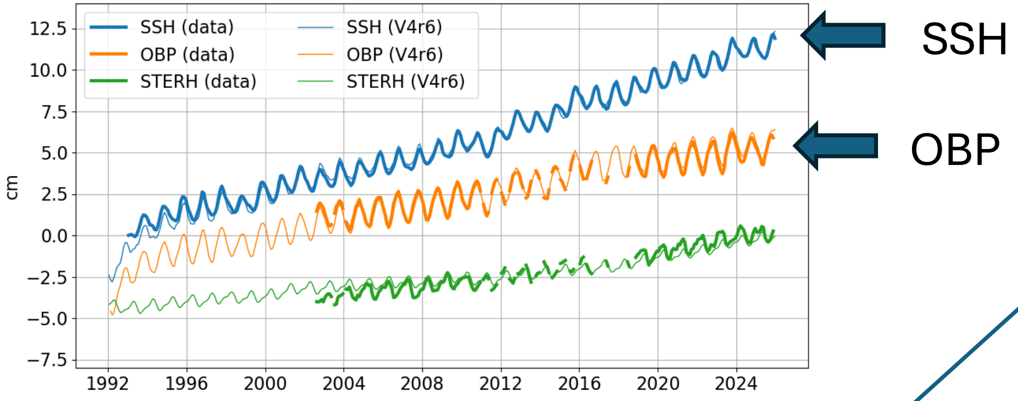
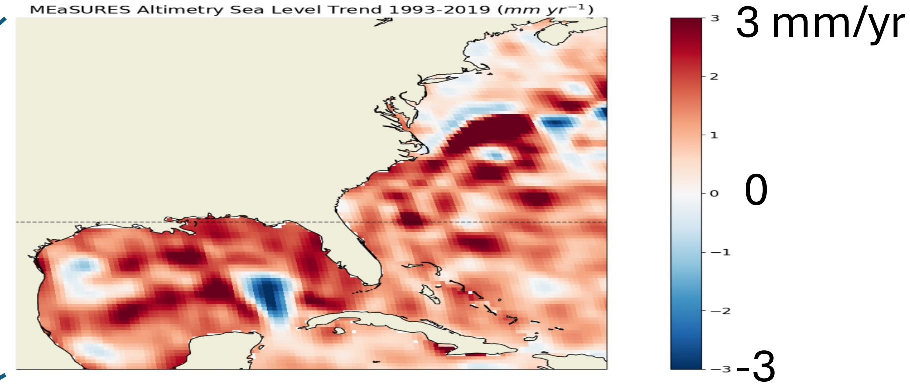
Sea Level Changes over the Past Three Decades

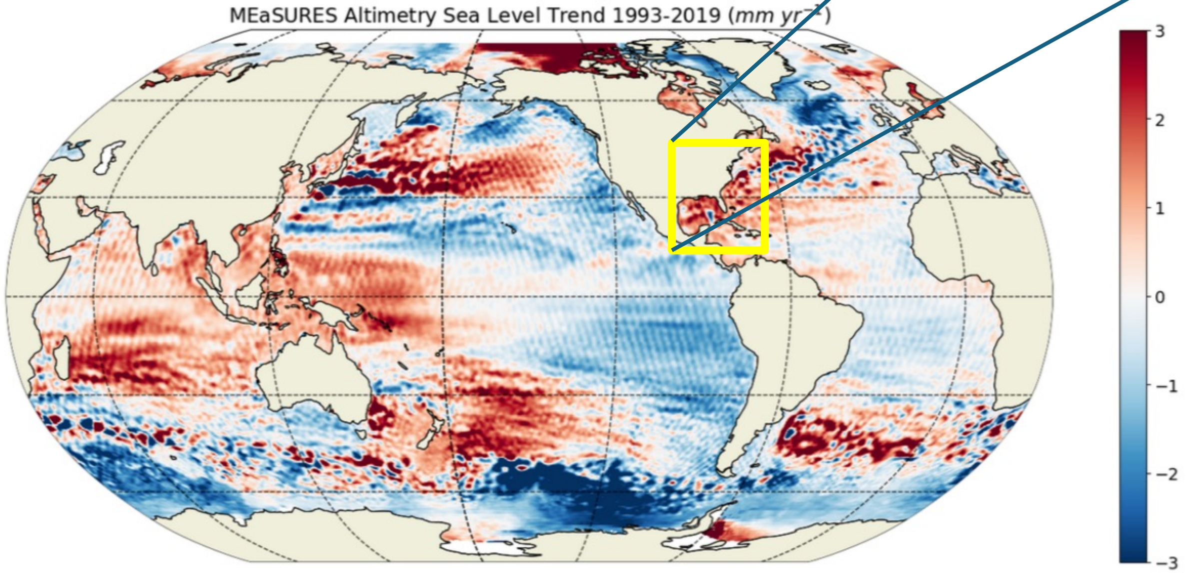
Global Mean



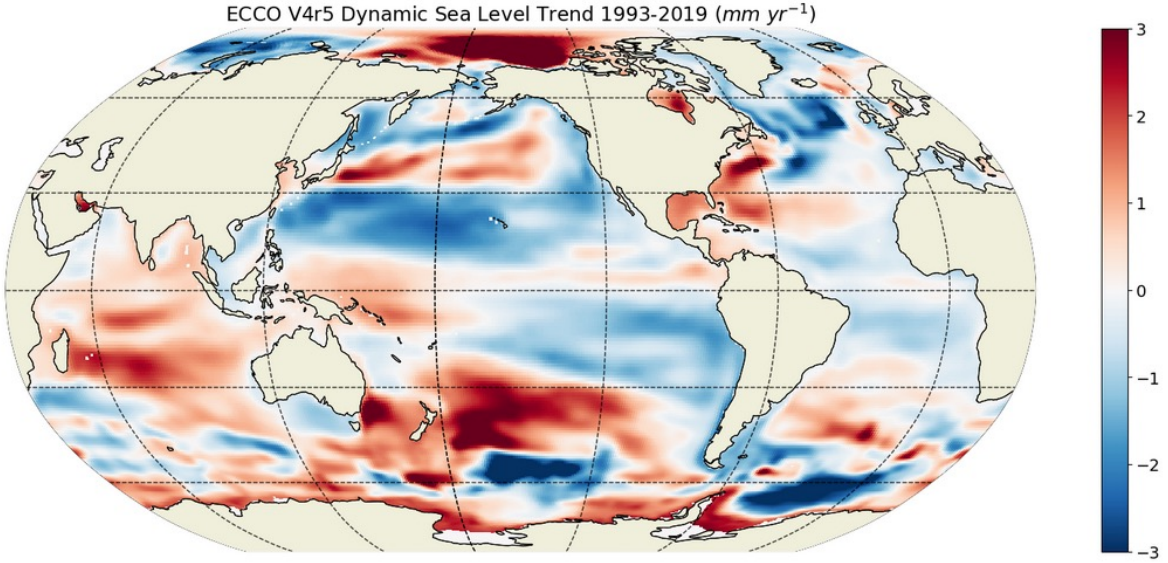


Regional Sea Level Trend – Global Mean Trend

Observation



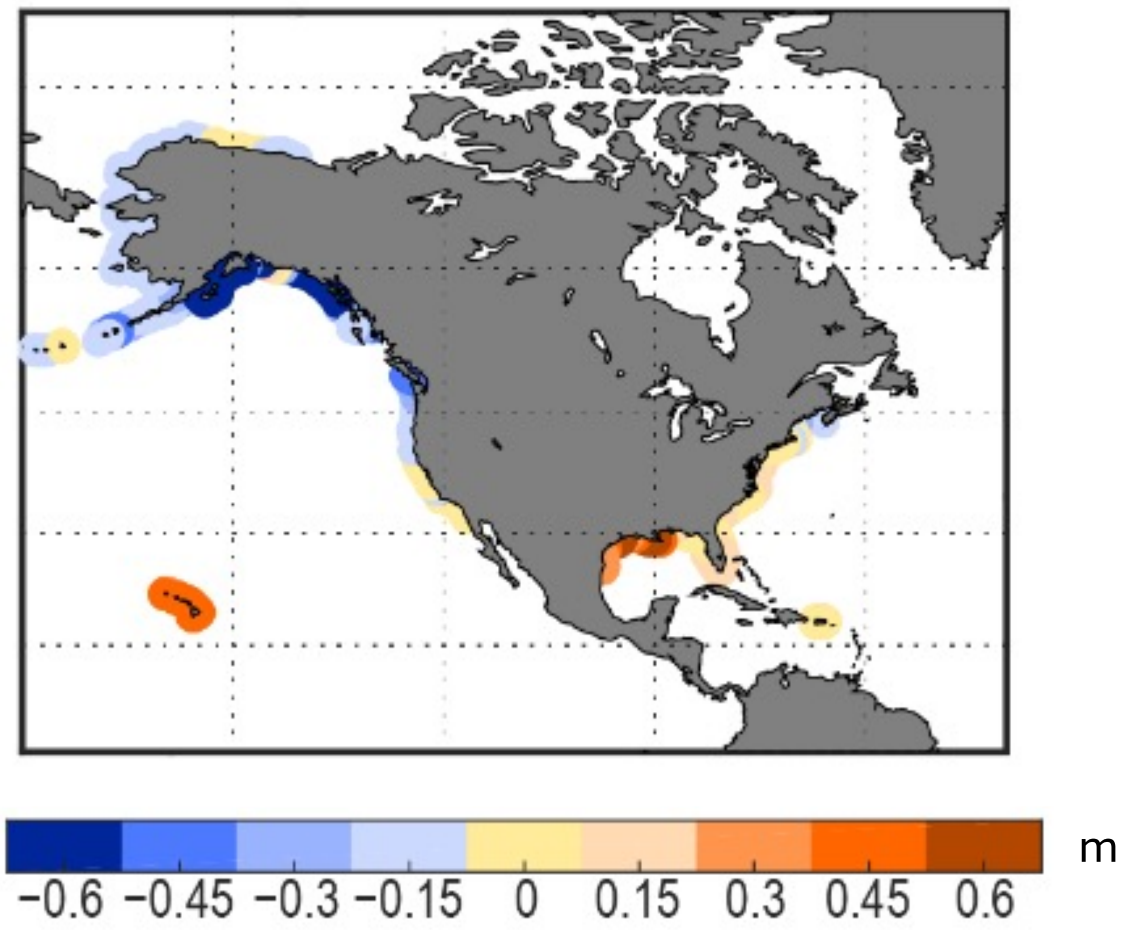
ECCO



Based on MEaSURES altimetry data

Sea Level along the U.S. East Coast Is Projected to Continue Rising

Relative Sea Level Rise between 2000 and 2100
In addition to the projected GMSL Rise

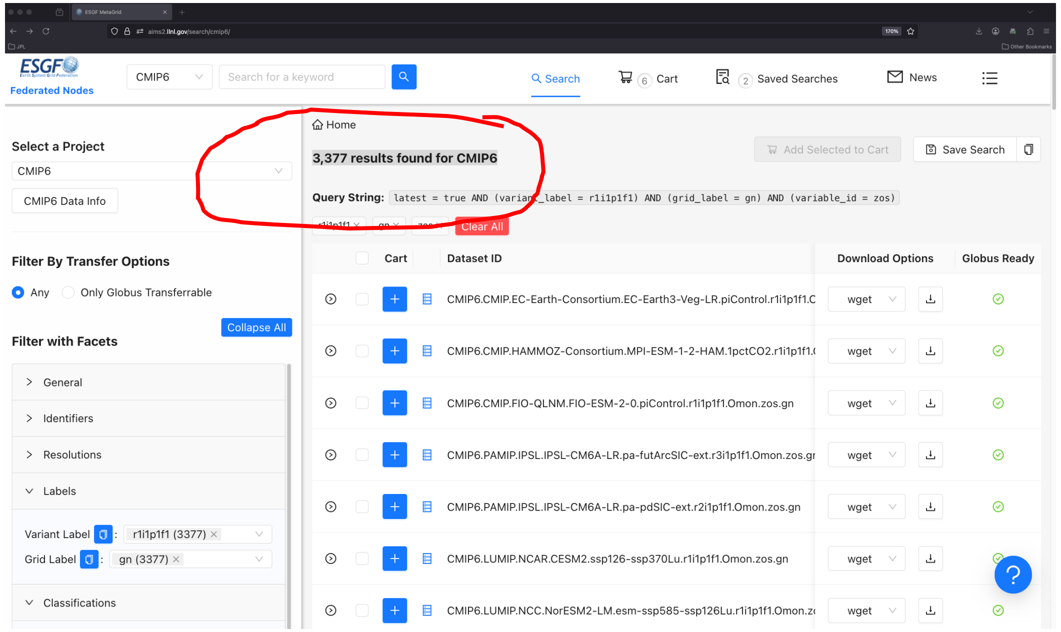


Modified from Sweet, Hamlington, Kopp et al. (2022)

Our focus is **dynamic sea level changes**, that is, sea level changes relative to the global mean arising from the ocean's dynamic response to surface forcings.

CMIP6 Coupled Climate Models

> 3000 files for dynamic sea levels for one ensemble member r1i1p1f1



- CMIP6 coupled models are useful tools for projecting dynamic sea-level (and other climate) changes
- Knowing the **causality**—which ocean forcings cause the projected sea-level changes, and where they are most important—is critical for improving projections
- Correlation-based analysis cannot establish causality

CMIP6: Coupled Model Intercomparison Project, Phase 6

Forward Perturbation Experiment

- **Method:** Perturb surface forcing (by type or region) to investigate the ocean response
- **Example:** Flux-Anomaly-Forced Model Intercomparison Project (FAFMIP)
- **Pros:**
  - Reveals physical mechanisms
  - Captures impacts on all model variables across the entire domain
- **Cons:**
  - Computationally expensive;
  - Deciding what and where to perturb is at best an educated guess
- **Alternative:** Adjoint-based attribution

Climate Dynamics (2021) 56:155–187
https://doi.org/10.1007/s00382-020-05471-4

Check for updates

What causes the spread of model projections of ocean dynamic sea-level change in response to greenhouse gas forcing?

Matthew P. Couldrey[1] · Jonathan M. Gregory[1,2] · Fabio Boeira Dias[3,4,5,6] · Peter Dobrohotoff[4,5] · Catia M. Domingues[4,6,7] · Oluwayemi Garuba[8] · Stephen M. Griffies[9,10] · Helmuth Haak[11] · Aixue Hu[12] · Masayoshi Ishii[13] · Johann Jungclaus[11] · Armin Köhl[14] · Simon J. Marsland[4,5,6] · Sayantani Ojha[15] · Oleg A. Saenko[16] · Abhishek Savita[4,5,6] · Andrew Shao[16] · Detlef Stammer[14] · Tatsuo Suzuki[17] · Alexander Todd[18] · Laure Zanna[18,19]

Climate Dynamics (2023) 60:2003–2039
https://doi.org/10.1007/s00382-022-06386-y

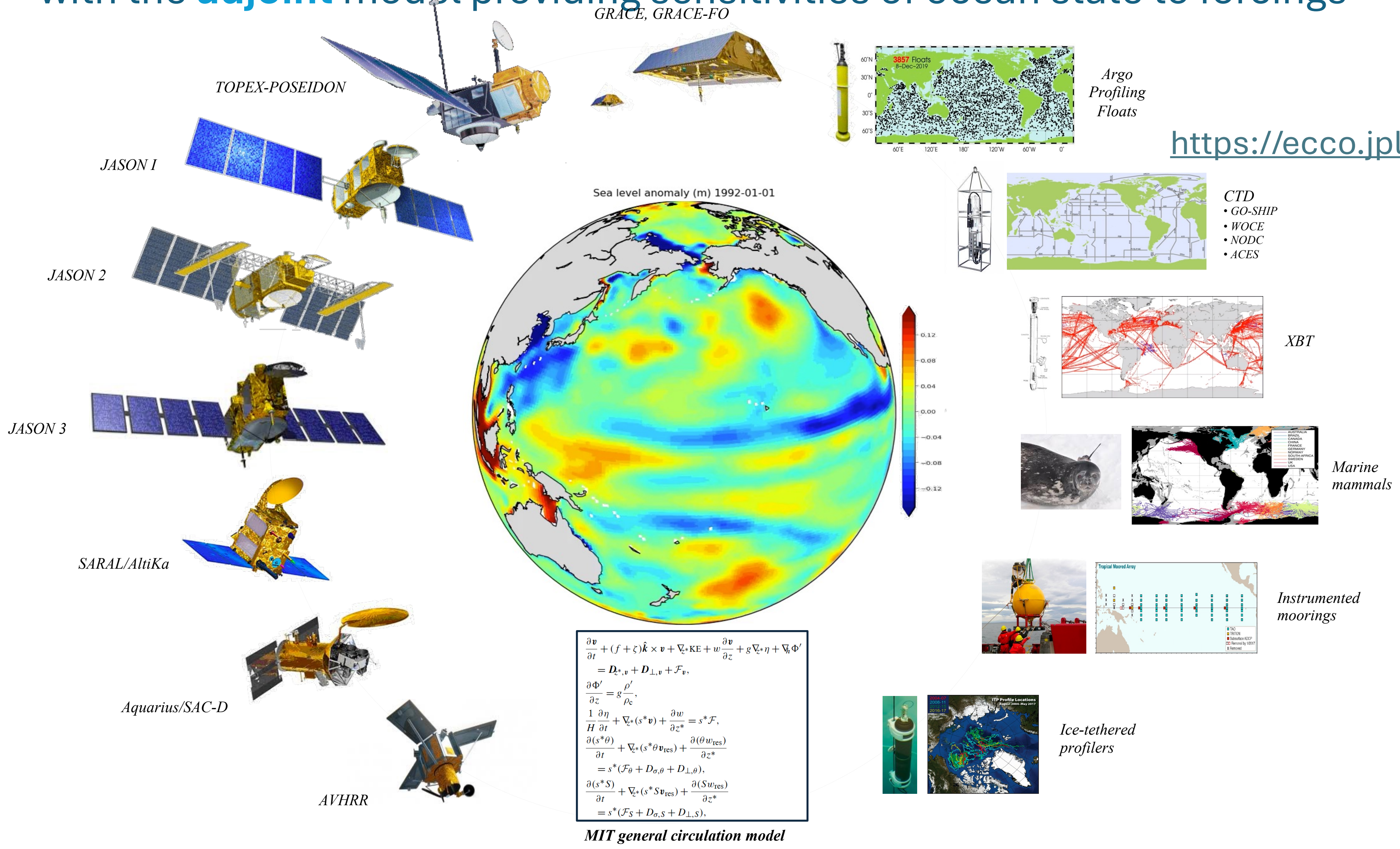
Check for updates

Greenhouse-gas forced changes in the Atlantic meridional overturning circulation and related worldwide sea-level change

Matthew P. Couldrey[1] · Jonathan M. Gregory[1,2] · Xiao Dong[3] · Oluwayemi Garuba[4] · Helmuth Haak[5] · Aixue Hu[6] · William J. Hurlin[7] · Jiangbo Jin[3] · Johann Jungclaus[5] · Armin Köhl[8] · Hailong Liu[9] · Sayantani Ojha[10] · Oleg A. Saenko[11] · Abhishek Savita[12,13,14,15] · Tatsuo Suzuki[16] · Zipeng Yu[9] · Laure Zanna[17]

Estimating the Circulation & Climate of the Ocean (ECCO) Ocean State Estimation

Synthesis of global ocean data with MITgcm using an **adjoint**-based inverse estimation method, with the **adjoint** model providing sensitivities of ocean state to forcings



https://ecco.jpl.nasa.gov

Adjoint-Based Attribution Method

$$\delta J(t) \approx \sum_{i} \sum_{s} \sum_{\Delta t} \frac{\partial J}{\partial F_i(s, \Delta t)} \delta F_i(s, t - \Delta t)$$

SLA

Forcing type

Location

Lead time

Sensitivities (i.e. gradients) of *SLA* to forcing F_i at lead time Δt and location *s* (calculated by ECCO adjoint model)

Forcing anomaly at prior time t-Δt and location *s*

- In essence, the equation is a Taylor expansion of *SLAs*, with all terms except for the first derivative term dropped:

$\delta J(x) = dJ/dx_{x0}(x-x_0)$ + ~~…higher-order terms…~~

- Validate the reconstruction by comparing it with sea-level changes simulated by the model
- Linearity of the equation allows sea-level change to be attributed to different forcing types, location, and lead time
- Method successfully applied to regional sea-level changes worldwide, e.g., Fukumori, Menemenlis, & Lee, T. (2007); Fukumori et al., 2015; Wang, Lee, et al. 2024; Wang, Lee, & Piecuch et al. 2022

What is New: Extending Adjoint Attribution Beyond ECCO

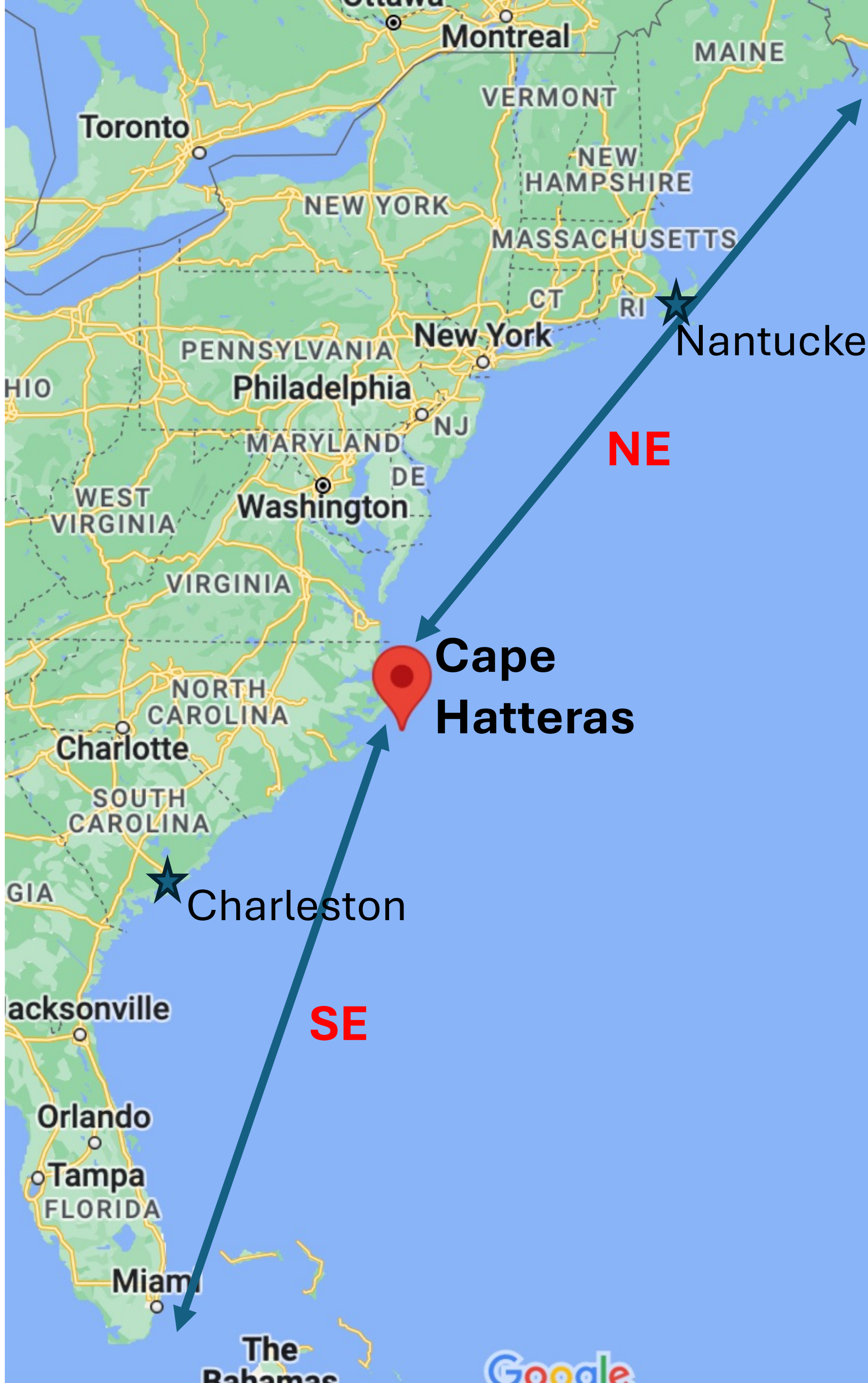
$$\delta J(t) \approx \sum_i \sum_s \sum_{\Delta t} \frac{\partial J}{\partial F_i(s, \Delta t)} \delta F_i(s, t - \Delta t)$$

- ECCO adjoint model computes gradients ***∂J/∂F***
- In previous studies, forcing anomalies ***δF*** also come from the ECCO model
- Adjoint-based attribution methods have proven powerful, but climate models do not have adjoint models to compute these gradients

- **What is new?**
  - We will convolve ECCO adjoint gradients with forcing anomalies taken from climate models (rather than ECCO forcing anomalies)

Study Objectives

- Can sea-level changes along the U.S. East Coast simulated by a climate model be reconstructed by convolving ECCO adjoint sensitivities with climate-model surface forcings?
- What forcings drive the projected sea-level changes along the U.S. East Coast—heat, freshwater, wind? Local or remote?



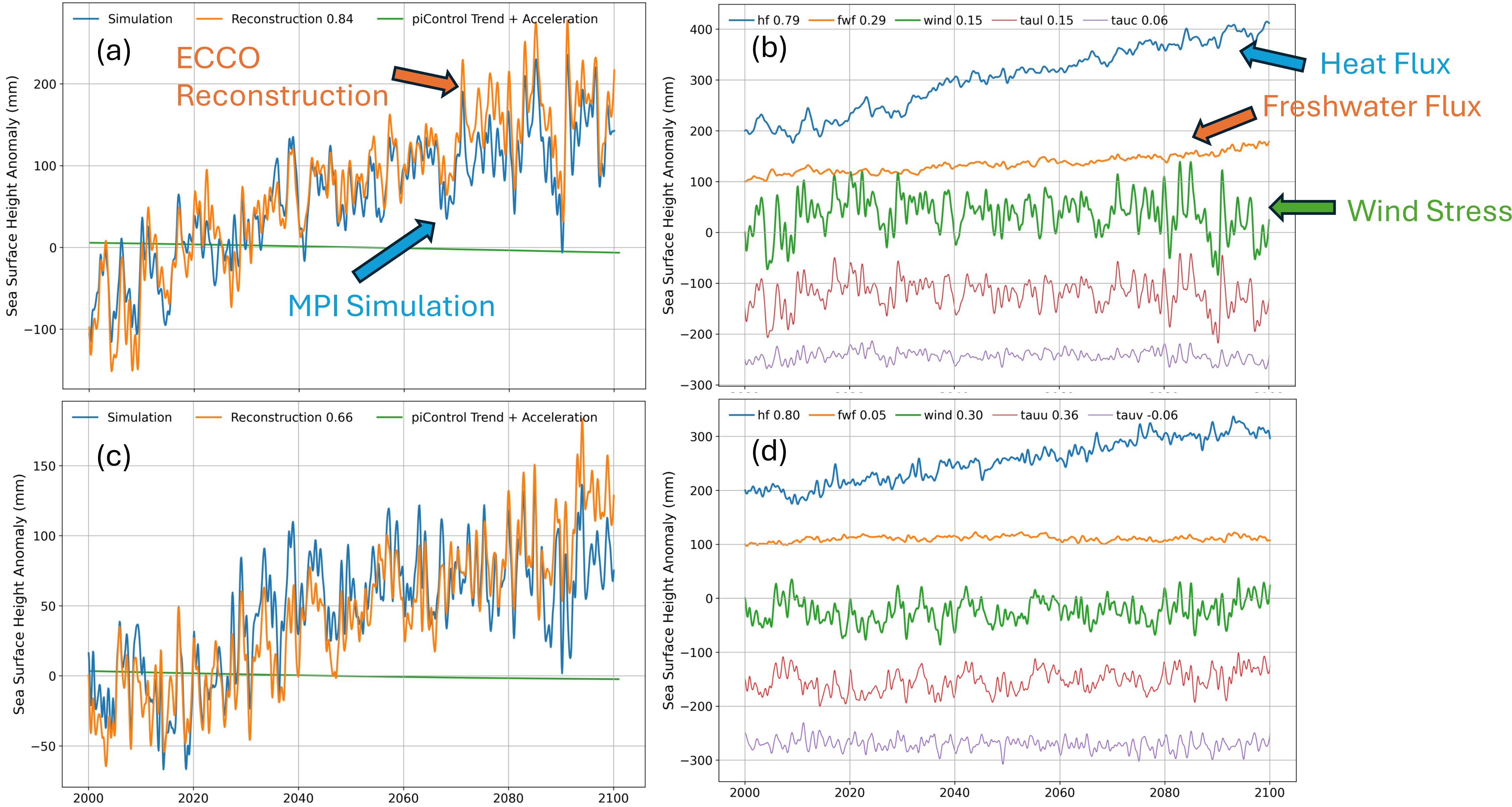
CMIP6 Model Used

- MPI-ESM1.2-HR
- The ocean model in MPI-ESM1.2-HR is the Max Planck Institute Ocean Model (MPIOM), a primitive equation model with a horizontal resolution of 0.4° and 40 vertical levels (compared to a nominal 1° horizontal resolution and 50 vertical levels)
- Ocean surface forcings include heat flux, freshwater flux, wind stress
- Focus on the period 2000-2100 and the SSP5-8.5 scenario

Reconstructing CMIP6 Sea-Level Changes

Nantucket

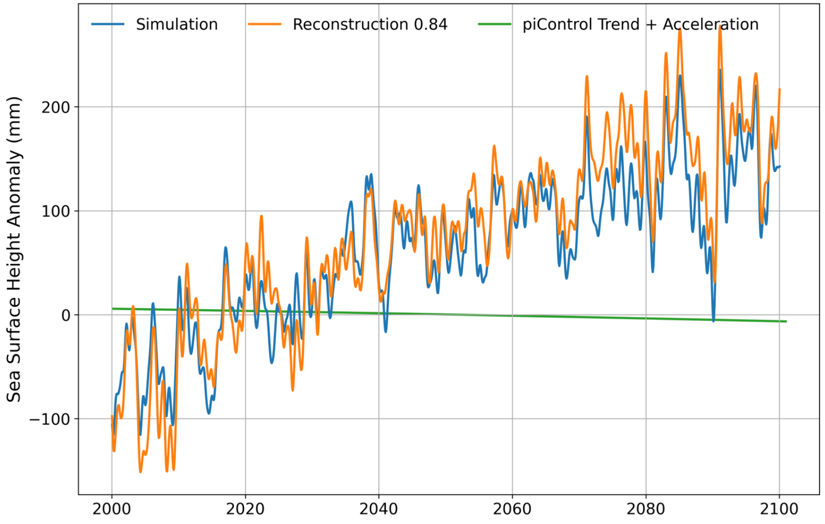
Charleston



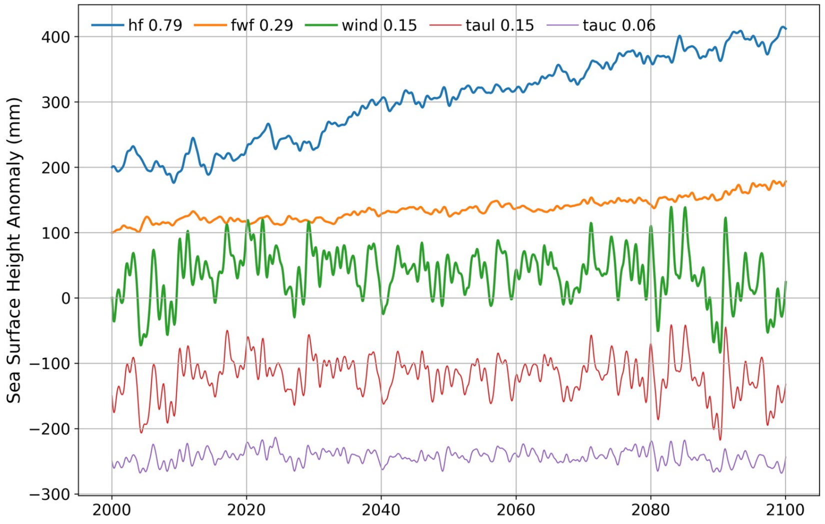
Sea level anomaly relative to the global mean; seasonal cycle removed and 13-month low-pass filtered; Curves in (b) and (d) are vertically shifted for clarity.

Summary for Reconstructing CMIP6 Sea-Level Changes

- CMIP6 sea-level changes along the U.S. East Coast can be reproduced by convolving ECCO adjoint sensitivities with CMIP6 forcings



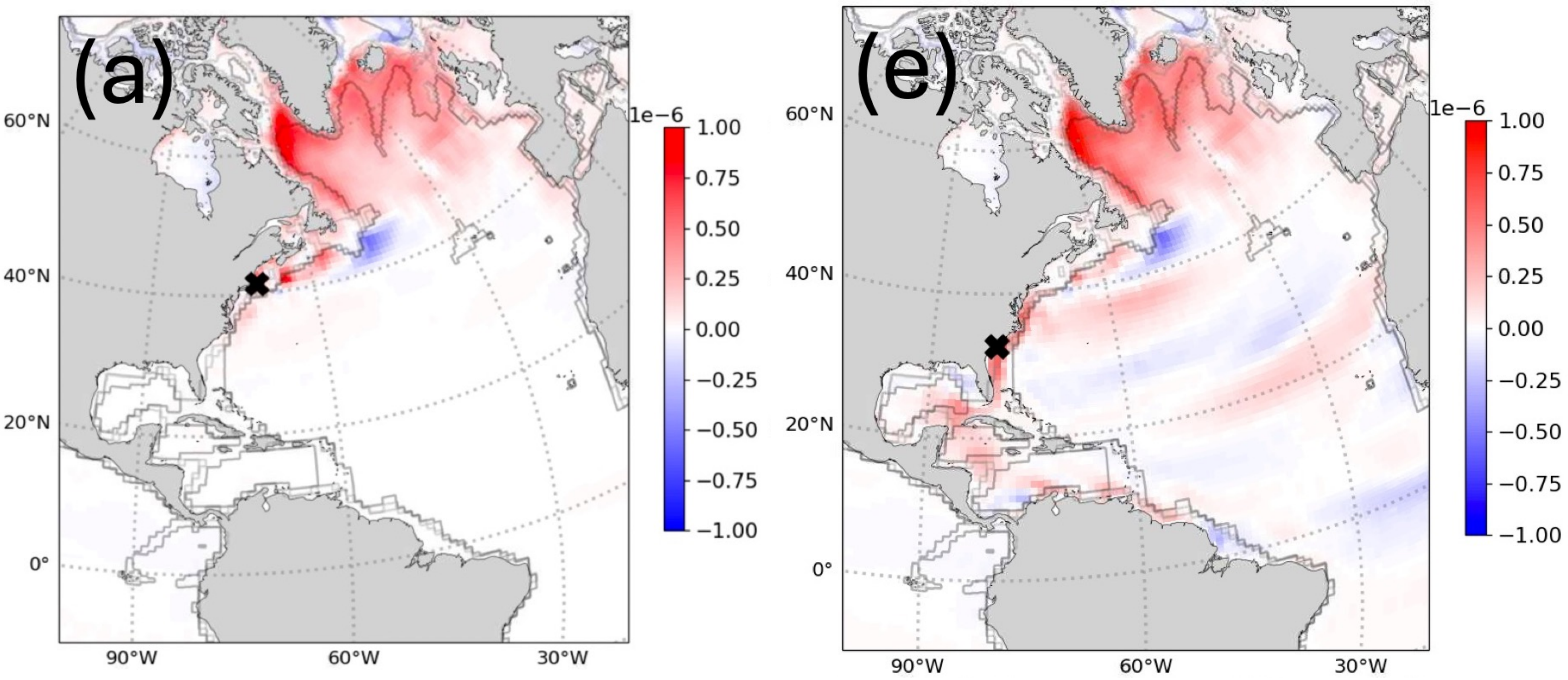
- Heat flux is the dominant contributor to the secular sea level trend over 2000-2100
- Wind stress is the main contributor to interannual-to-decadal sea-level variability



Where do the forcing contributions come from?

Heat Flux Contributions as a Function of Space

Nantucket | **Charleston**

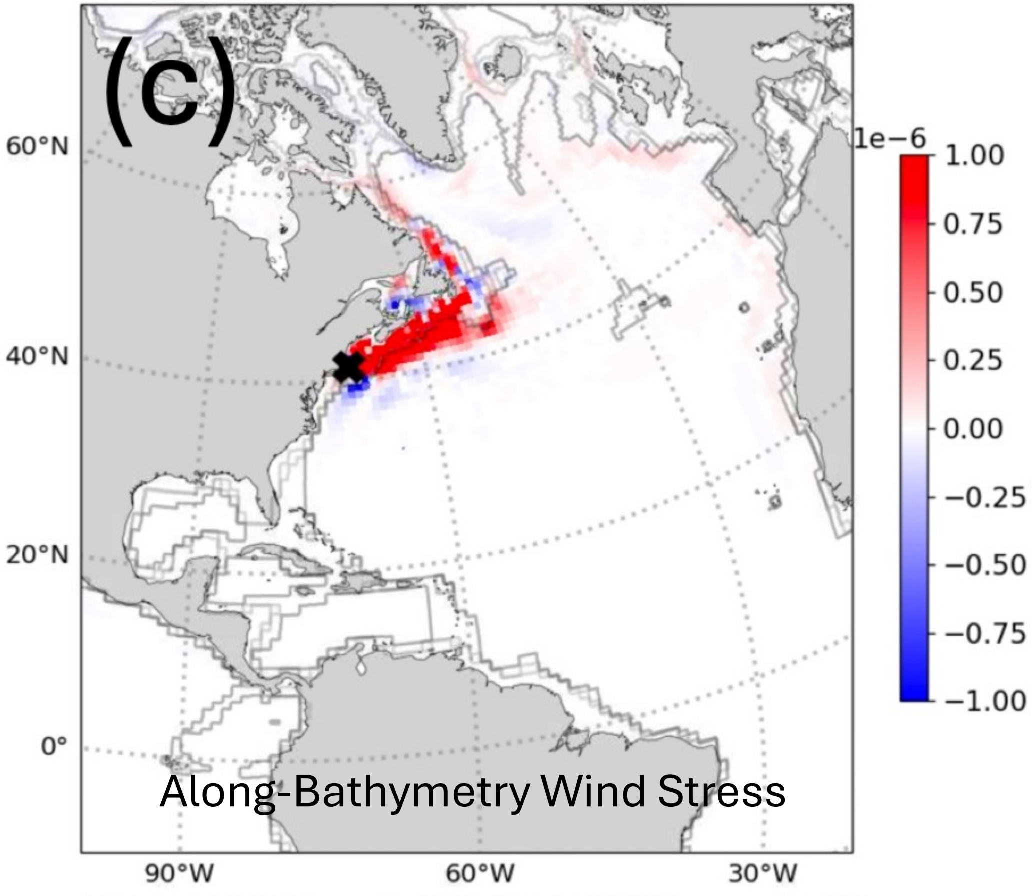


- Heat flux from the subpolar North Atlantic is the key forcing for the 21st century sea level trend along U.S. East Coast

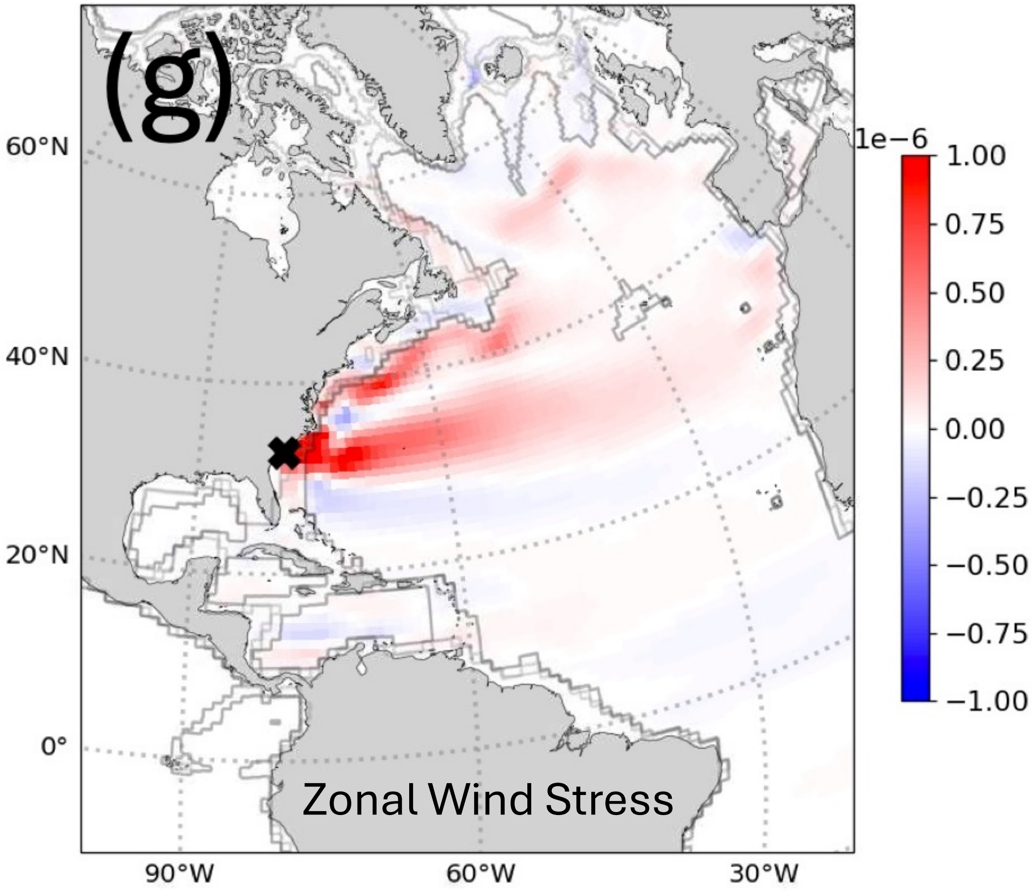
The values represent fractions per unit area (km^{-2}) of variance of reconstructed sea-level anomaly (SLA) by heat flux forcing from all locations, explained by SLAs reconstructed using heat flux at each location.

Wind Stress Contributions as a Function of Space

Nantucket



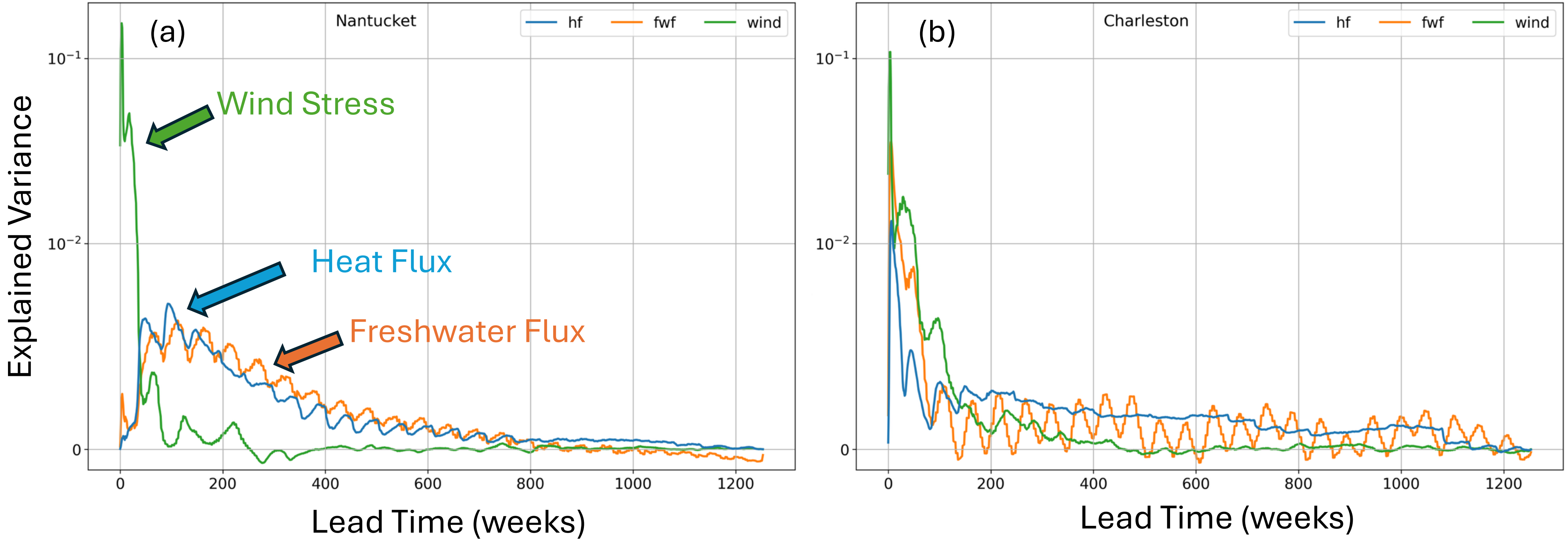
Charleston



- Nantucket: Along-bathymetry wind stress north of Nantucket dominates, indicating southward propagating coastally trapped waves
- Charleston: Offshore zonal wind stress is the major contributor, indicating westward propagating Rossby waves

Contributions as a Function of Lead Time

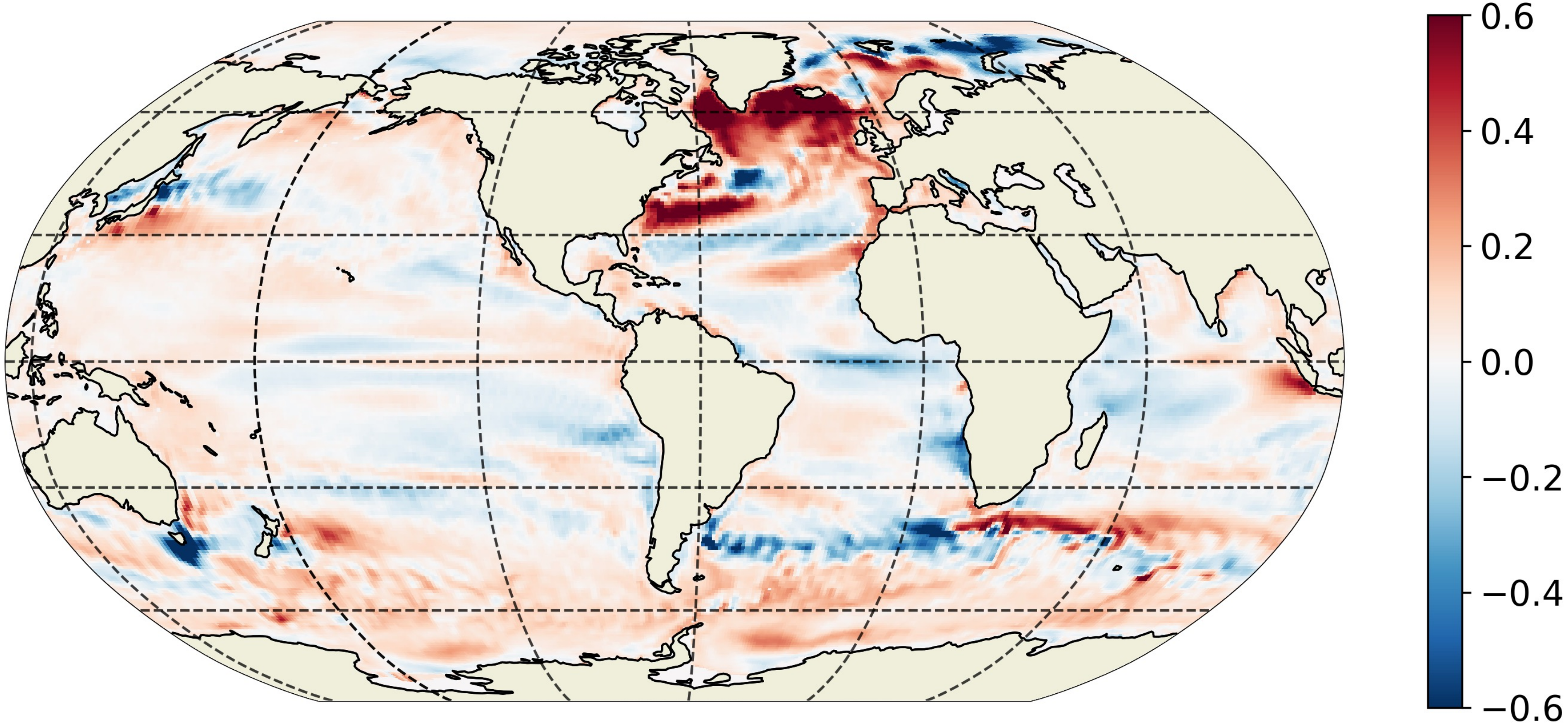
Nantucket | Charleston



- Wind stress contributions peak at a short lead time (a few weeks), reflecting the effect of fast-propagating coastally trapped waves
- Heat flux and freshwater flux contribute over much longer lead times (decades)
- Wind stress contributions for Charleston have longer decay time than those for Nantucket, reflecting impact of slow-propagating Rossby waves for Charleston
- For Charleston, both heat and freshwater fluxes also peak at a short lead time, reflecting the impact of heat and freshwater forcings advected by the Gulf Stream and the Loop Current

Why Heat Flux in Subpolar North Atlantic?

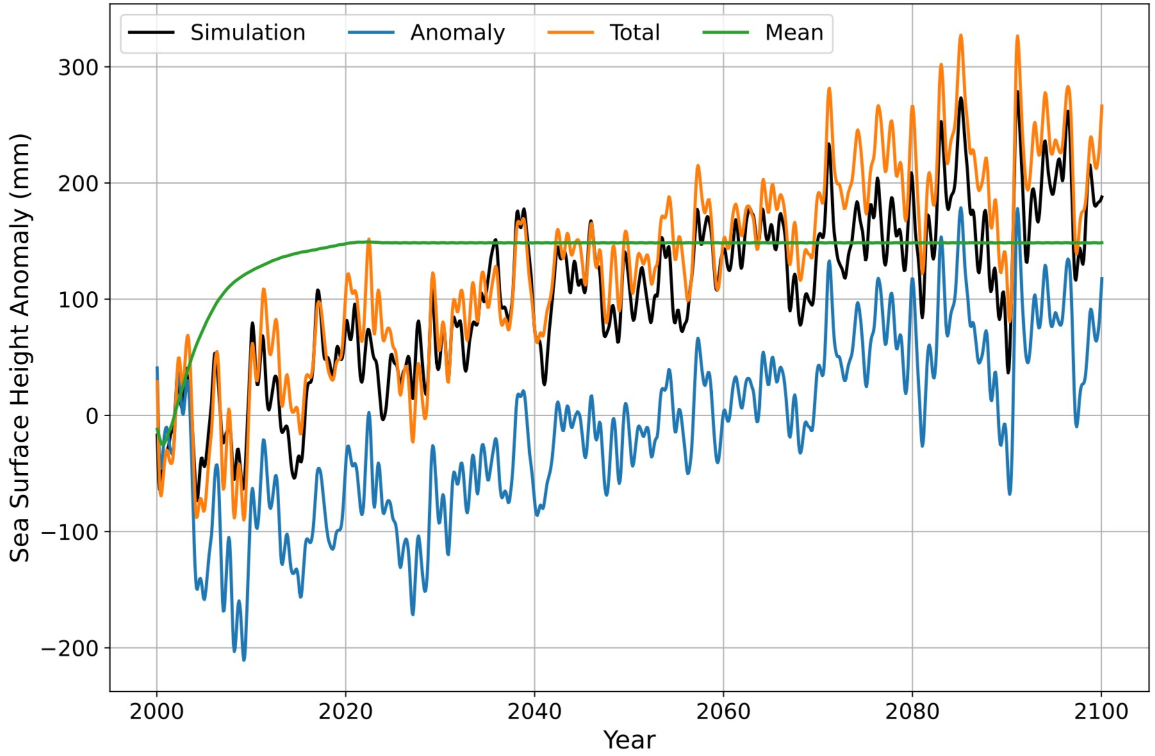
Downward heat flux trend (W m^{-2} per year from 2000 to 2100)



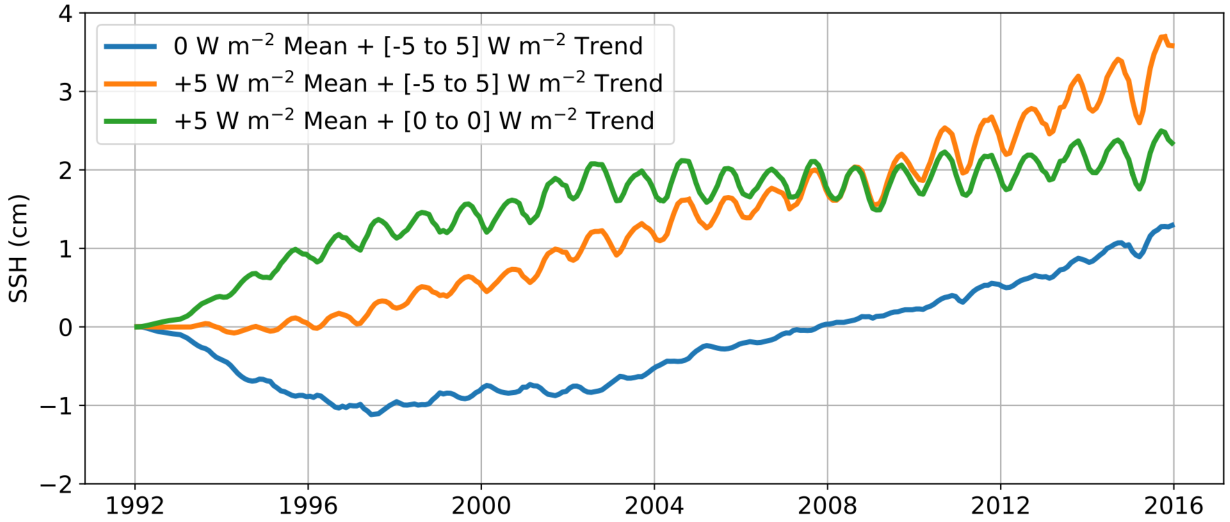
- The subpolar North Atlantic is projected to have the largest increase in downward heat flux between 2000 and 2100 in the SSP5-8.5 scenario.

Both time-mean increase and linear trend in heat flux are important for U.S. East Coast sea-level rise

Nantucket SLA reconstructed using different forcing changes: total, time-invariant and time-varying



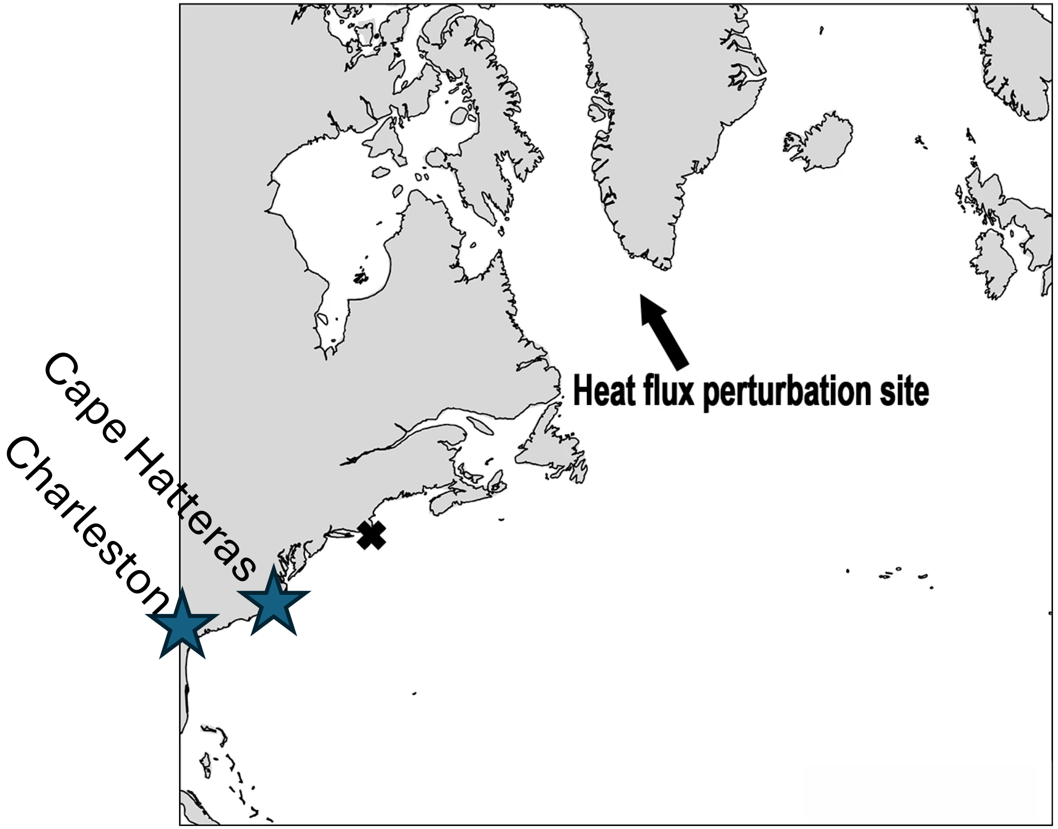
Perturbed Nantucket SLA from forward perturbation experiments



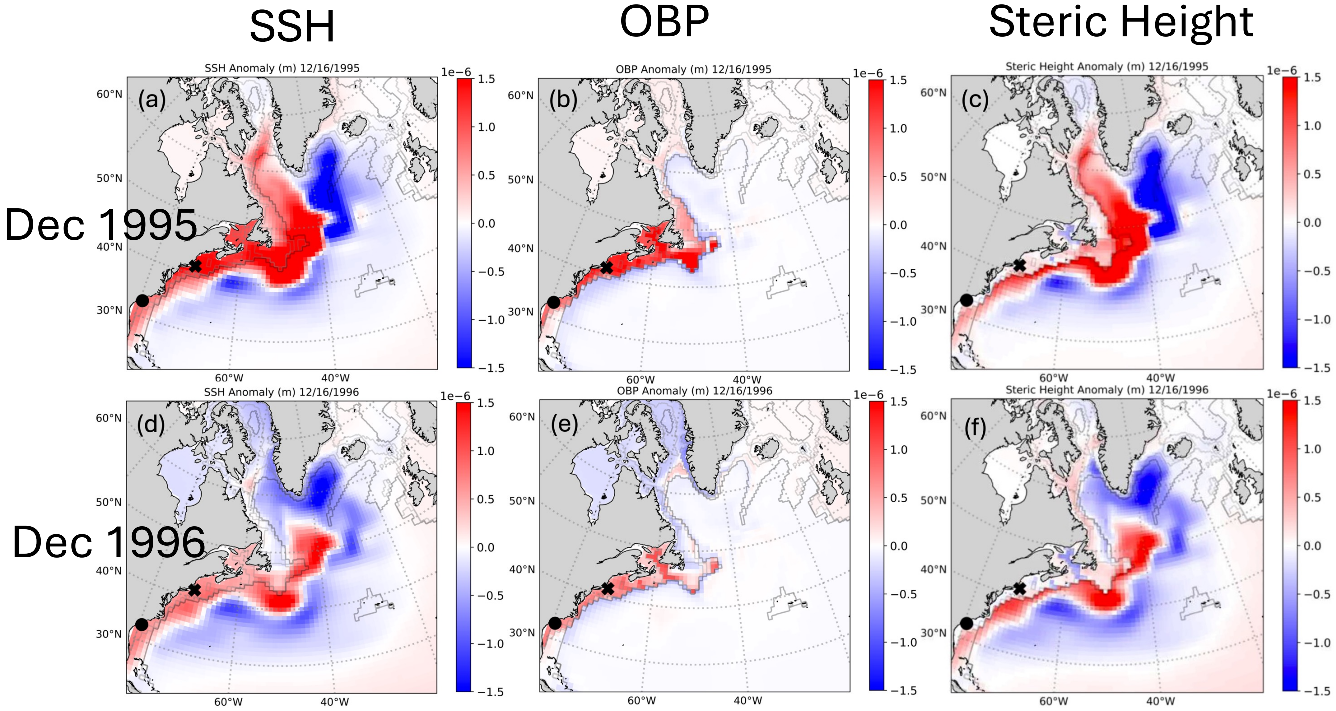
- Both time-mean and temporal forcing changes contribute to projected sea-level changes, but only their combined effect reproduces the projected magnitude and temporal evolution.

How Heat Flux in Subpolar North Atlantic Affect Sea Level South of Cape Hatteras?

SSH after Perturbing Heat Flux in the Subpolar North Atlantic



With improvements by A. deCharon
https://ecco-group.org/storymaps.htm?id=73



- Arrested Topographic Waves are likely responsible for how heat flux in the subpolar North Atlantic affects sea level south of Cape Hatteras, including at Charleston.

Conclusions

- Our proof-of-concept demonstrates that ECCO adjoint sensitivities can be used to attribute regional sea-level changes on interannual-to-centennial timescales in climate models
- Subpolar North Atlantic surface heat flux is the key forcing for the 21st century sea-level trend along U.S. East Coast
- Both the time-mean increase and the linear trend in heat flux are important for U.S. East Coast sea-level rise
- Wind stress plays a major role in interannual-to-decadal (13 months to 50 years) sea-level variability on U.S. East Coast