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What forcing mechanisms affect interannual sea level co-variability between the Northeast and Southeast Coasts of the United States?

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StoryMap by Annette deCharon: https://ecco-group.org/storymaps.htm?id=96

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Motivation

- Sea level anomalies (SLA) in the northeast (**NE**) and southeast (**SE**) U.S. coasts co-vary within each sector, but not between the two sectors.

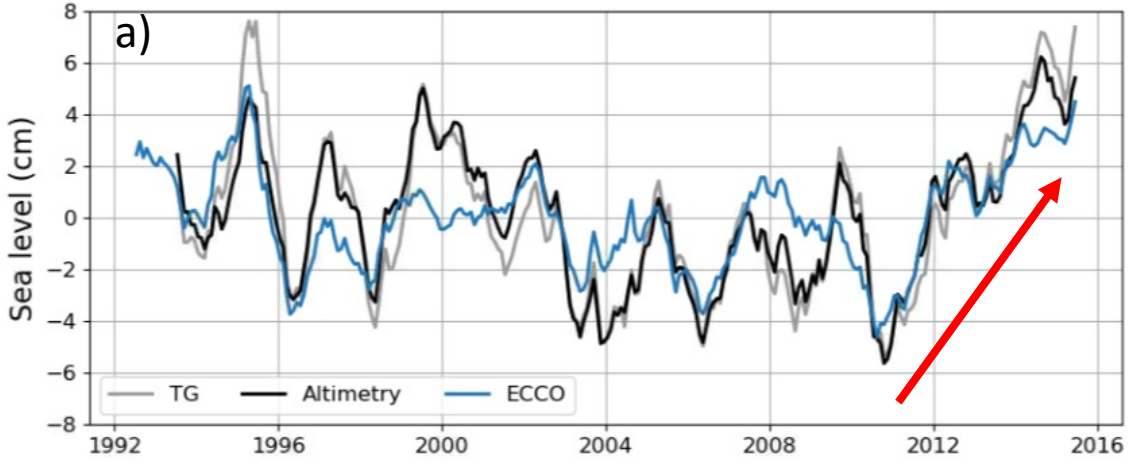
- The forcing mechanisms causing this behavior are not well understood. Studies that use correlation-based analysis and simple models suggest potential factors. These include local and remote wind and buoyancy forcing, the Gulf Stream and its precedent currents, AMOC, climate modes including NAO, AMO, ENSO.

- Here we use **ECCO** ocean state estimation and adjoint sensitivity analysis to investigate the causes, focusing on interannual time scales.

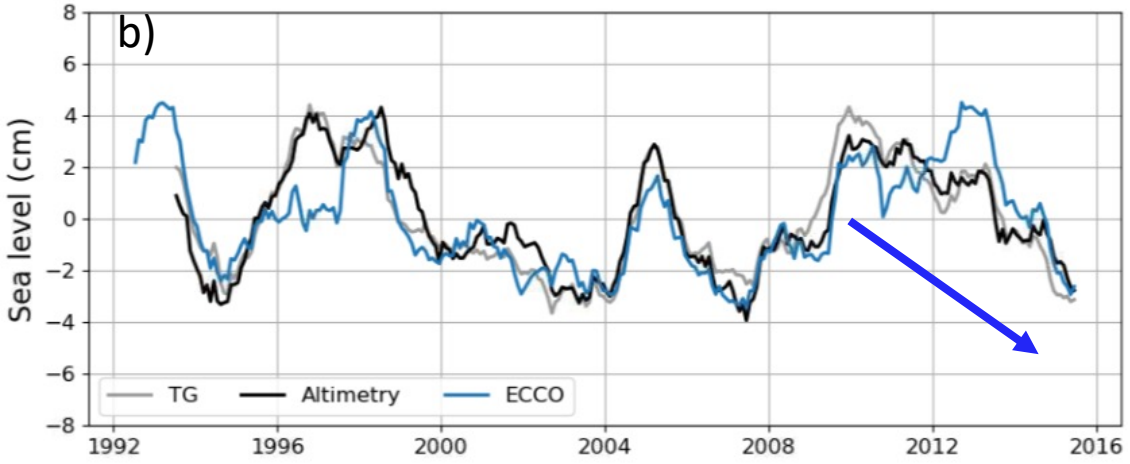
- Improving this understanding is important for sea level prediction and evaluation of climate models.

SLA comparison: tide gauge, altimetry (AVISO), and ECCO estimate

Charleston
(proxy for U.S. Southeast Coast)



Nantucket
(proxy for U.S. Northeast Coast)

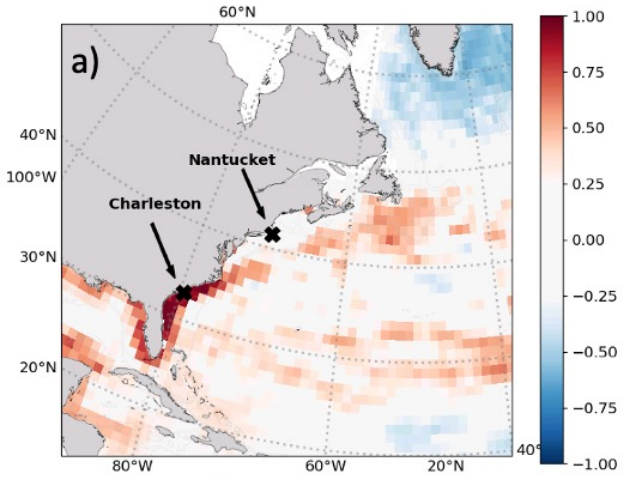
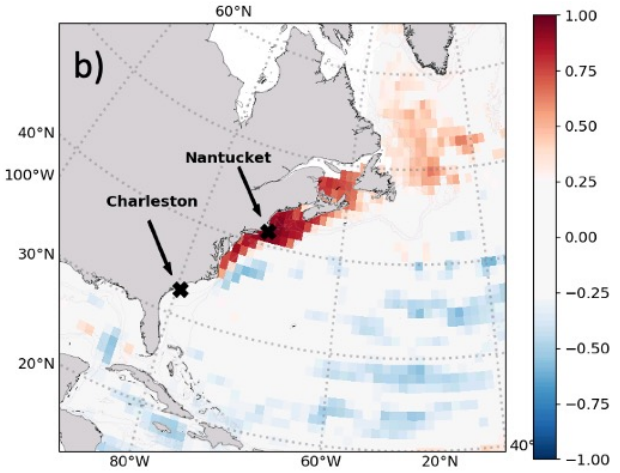
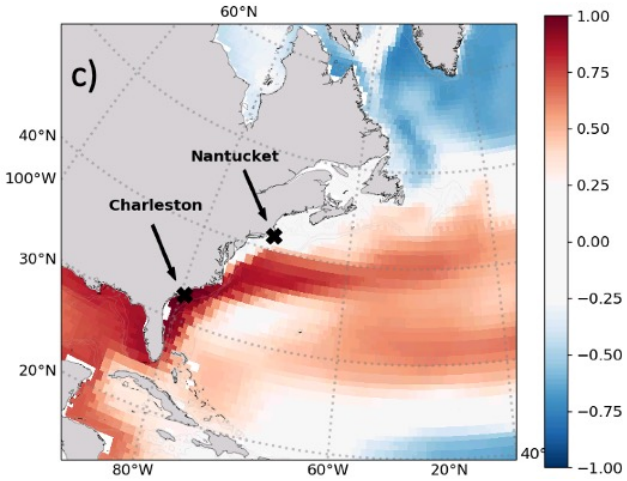
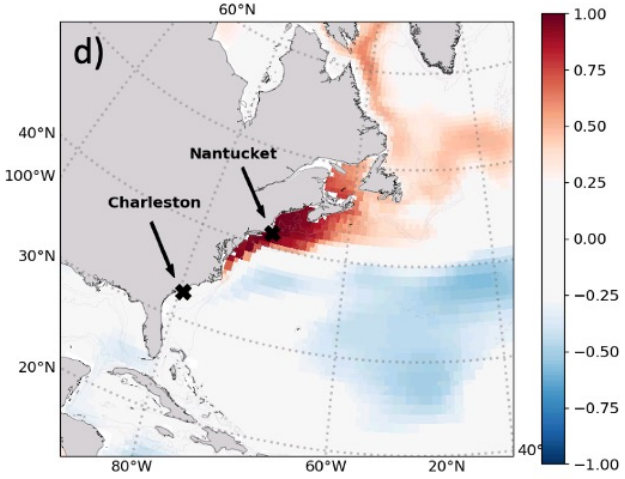


- Sea level anomalies (SLA) at Charleston and Nantucket are not correlated
- ECCO estimate is similar to tide gauge and altimetry

ECCO estimate is from V4r3 (LLC90). SLAs are ocean dynamic SLAs, referenced to the global mean and 1992–2015 time mean. A linear trend and the mean seasonal cycle have also been removed. The time series are 13-month low-pass filtered.

SLA in the NE & SE U.S. coasts are well correlated within NE or SE, but not between NE & SE

Correlation Coefficients of SLAs

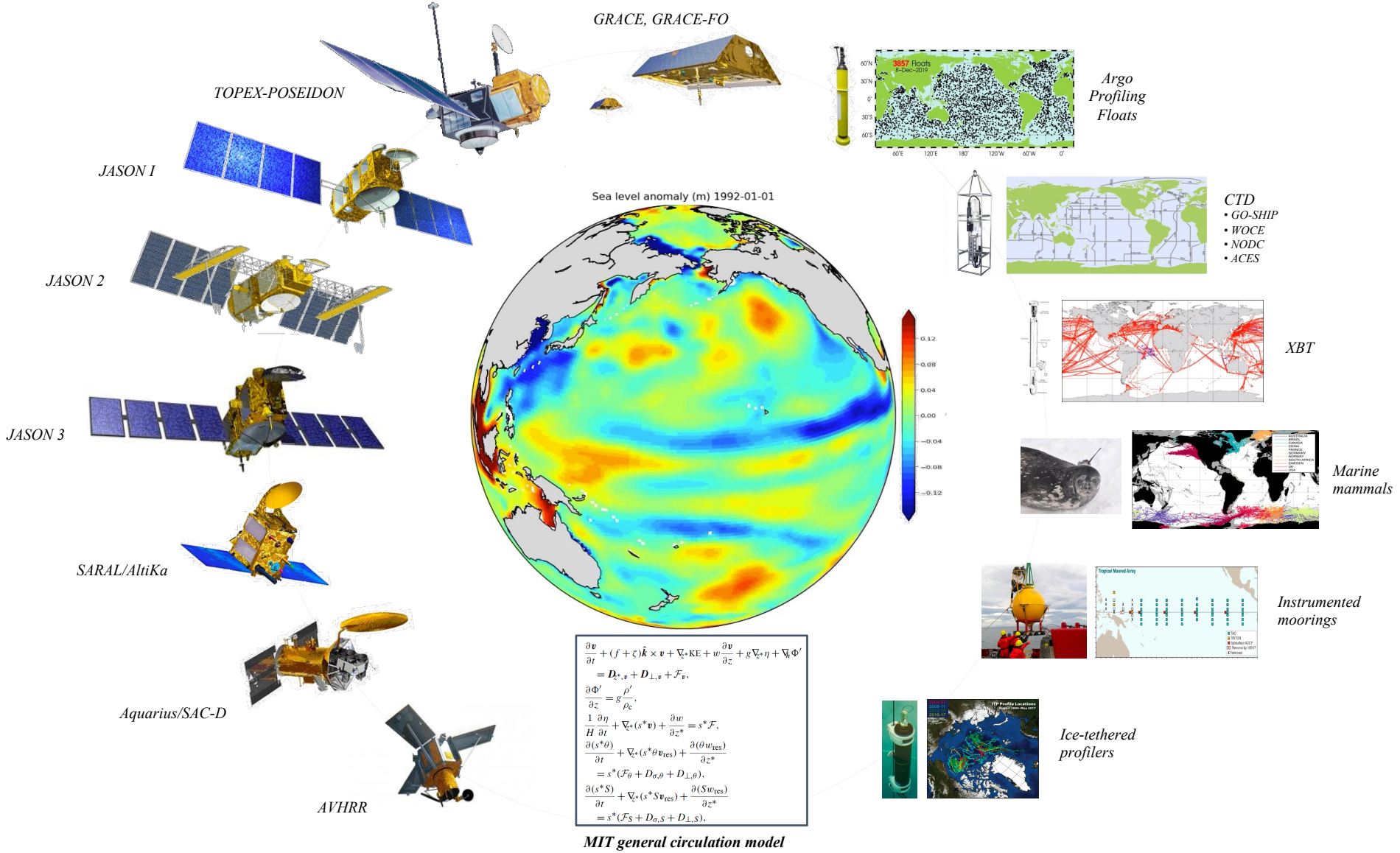
	Charleston and Elsewhere	Nantucket and Elsewhere
Altimetry (**AVISO**)		
ECCO		

- Both altimetry and ECCO indicate that SLAs co-vary within each sector, but not between the two sectors.

(A 13-month low-pass filter applied to the monthly mean SLAs after removing the global mean and the mean seasonal cycle)

Estimating the Circulation & Climate of the Ocean (ECCO) ocean state estimates:

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



Adjoint-based Reconstruction Method

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

SLA

Forcing type i

Location s

Lead time Δt

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

Forcing anomaly at prior time $t-\Delta t$ and location s

- Two assumptions:
  - Ocean response to forcing is assumed ***linear***
  - Adjoint sensitivity is assumed ***stationary*** in time

- *Forcing F includes* zonal and meridional wind stress, heat flux, and freshwater flux (the latter two combined are buoyancy forcing.)

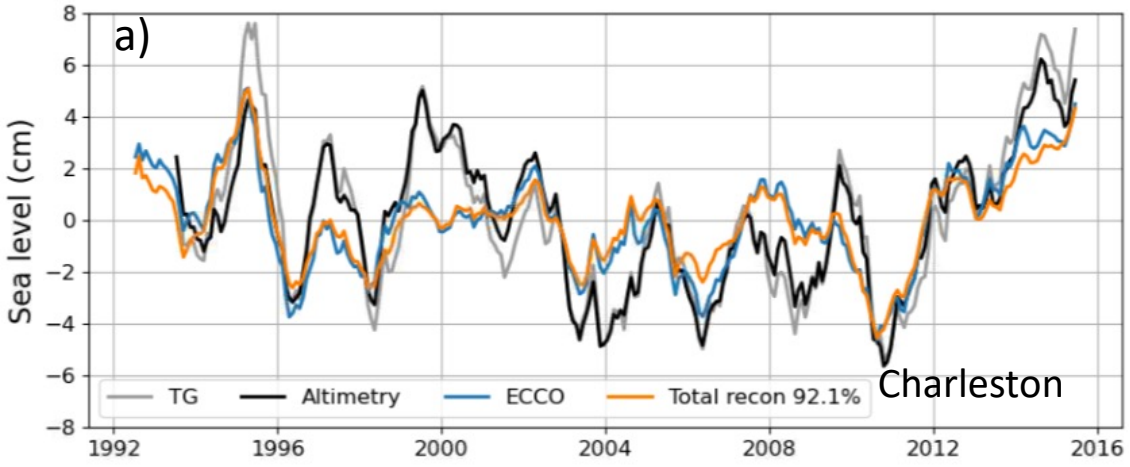
(for details: Fukumori et al., 2015; Wang, Lee, & Frederikse et al. 2024; Wang, Lee, & Piecuch et al. 2022)

Steps for Adjoint-based Analysis of Charleston-Nantucket SLA Co-Variability

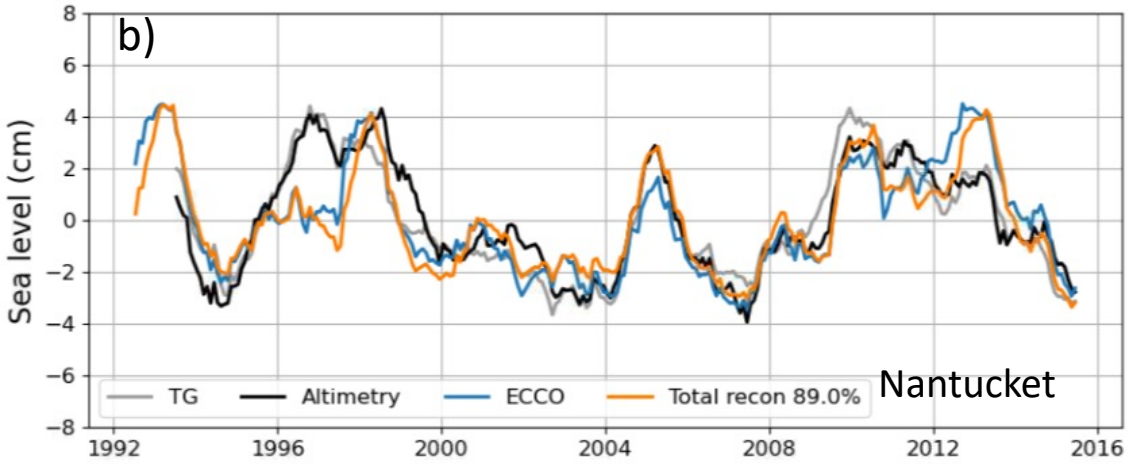
- Use the ECCO adjoint model to compute the adjoint sensitivity of objective function *J* (sea level at Charleston or Nantucket) with respect to wind stress, heat flux, and freshwater flux
- Reconstruct *J* by convolving adjoint sensitivity with forcing anomaly across forcing types and locations, summing all contributions
- Confirm reconstruction (RHS) reproduces model-simulated J (LHS)
- Decompose reconstructions by forcing type, location, and lead time
  - Assess the relative contributions of wind stress and buoyancy forcing
  - Contrast regional atmospheric forcing contributions (called “Forcing Influence Maps”)
  - Quantify which regional forcings improve or degrade the co-variability between Charleston and Nantucket SLA

SLA comparison: tide gauge, altimetry (AVISO), ECCO estimate, and adjoint-based reconstruction

Charleston



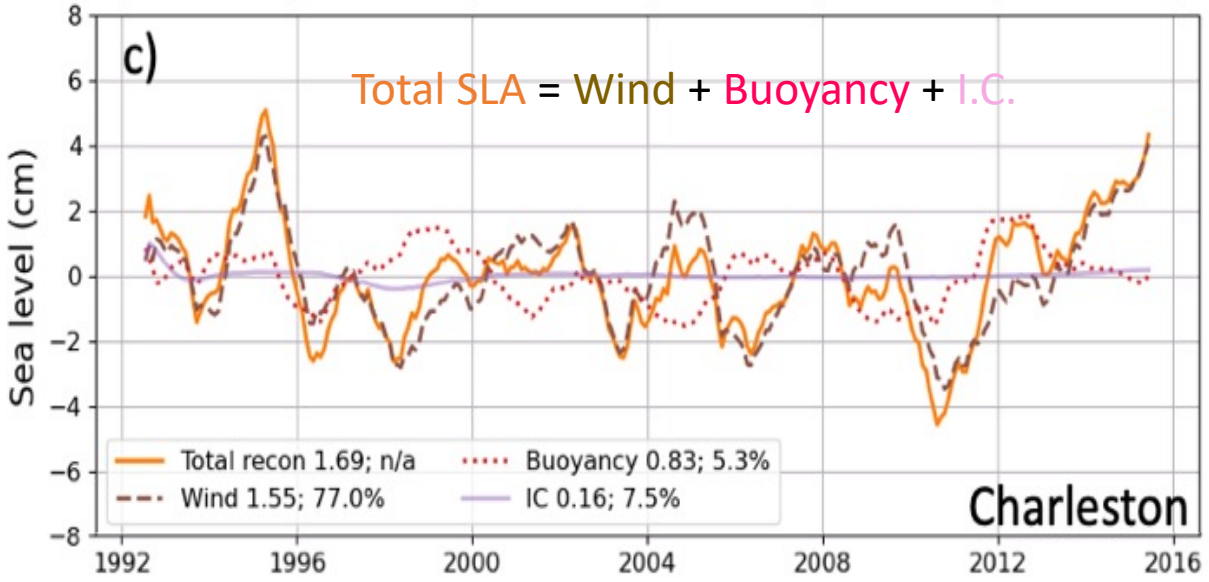
Nantucket

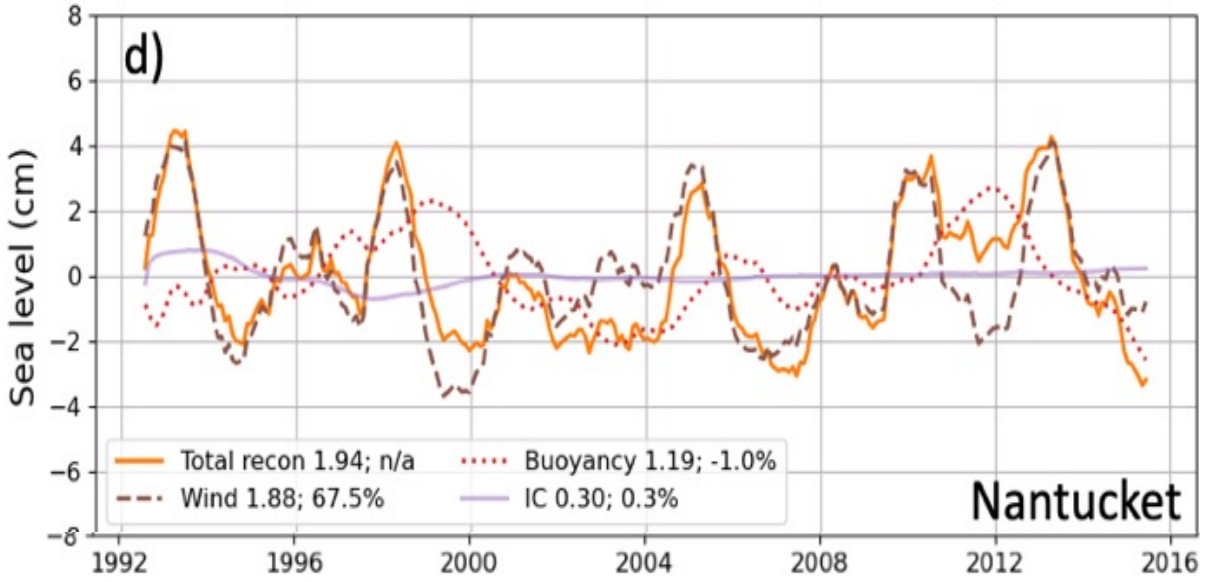


- Adjoint-based reconstruction reproduces ECCO estimate

Contributions to SLA by Forcing Type (Wind Stress vs. Buoyancy Forcing)

Wind stress explains 80% of the interannual SL variance for Charleston and 70% for Nantucket

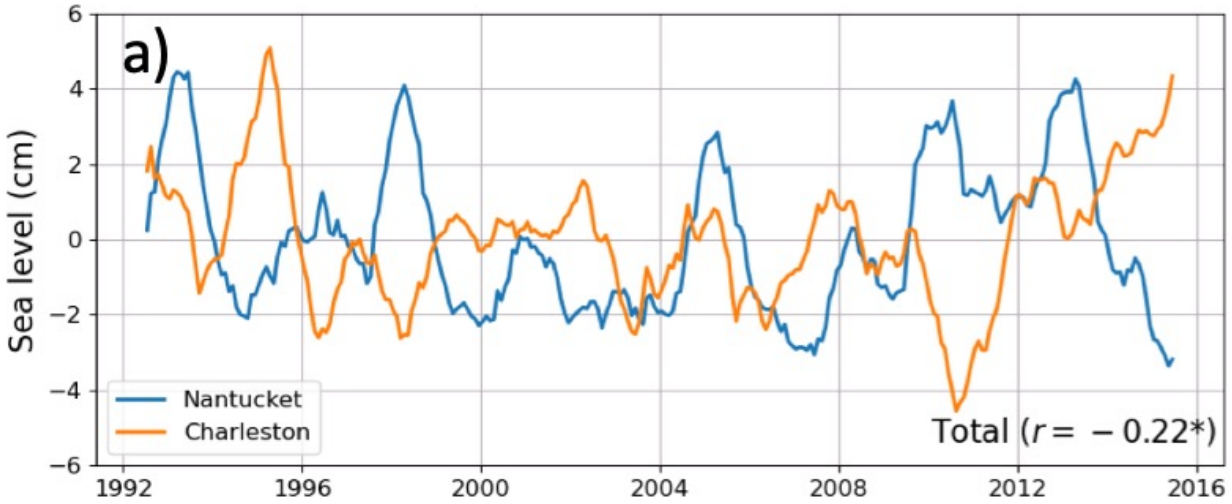


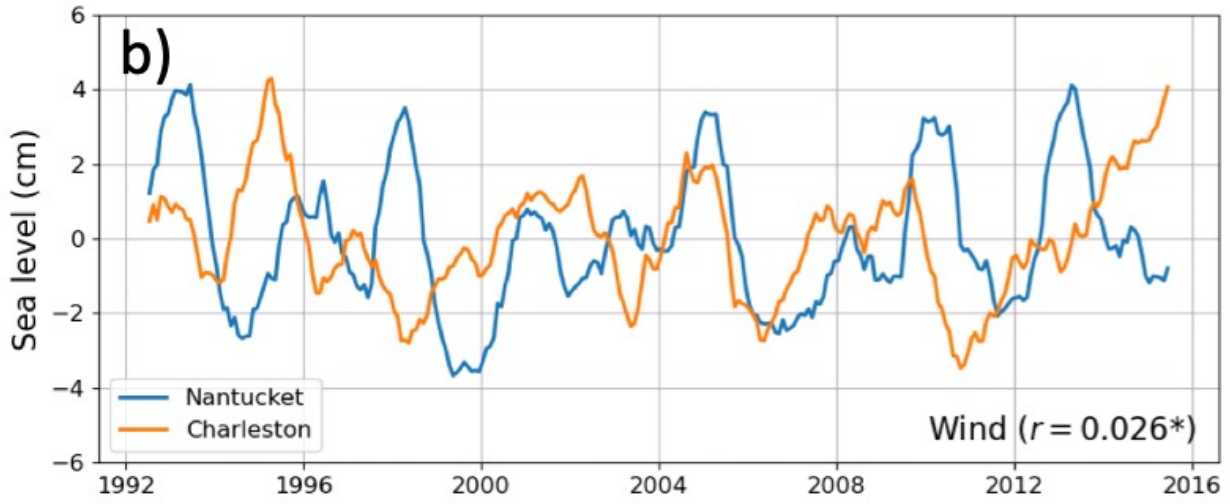


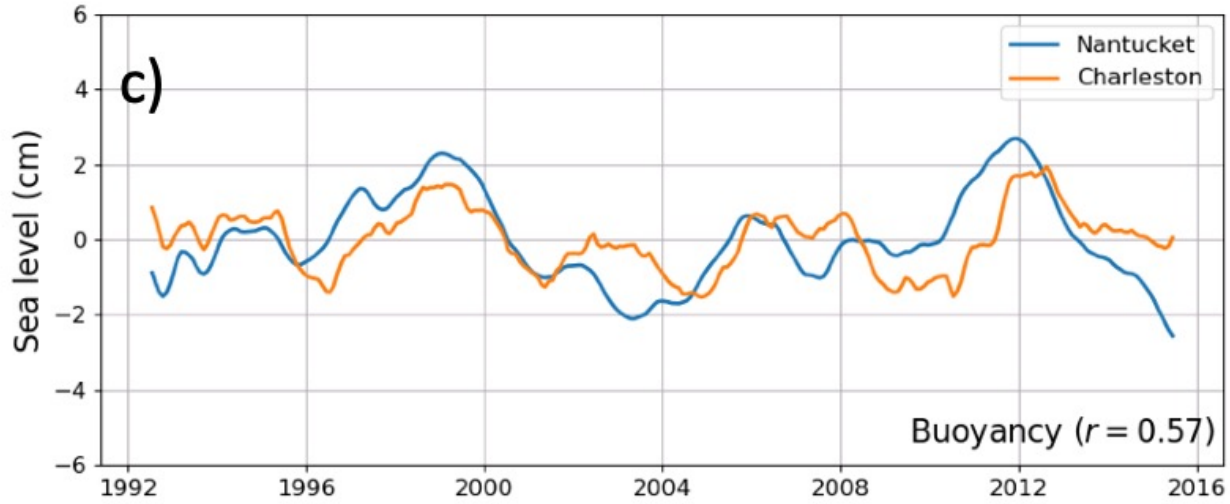
Panels (c) and (d) show decomposition of the total reconstruction of SLA into wind and buoyancy forcing contributions for (c) Charleston and (d) Nantucket. The two numbers in the legend are standard deviation (cm) and explained variance of the total reconstruction by each contribution.

Which Forcing Makes Interannual SLA Less Correlated between Nantucket and Charleston?

- Wind stress tends to make Nantucket & Charleston interannual SLA less correlated.
- Buoyancy forcing tends to make Nantucket & Charleston interannual SLA more correlated.







Comparison of SLAs (cm) between Charleston and Nantucket reconstructed using (a) all forcings, (b) wind stress, and (c) buoyancy forcing.

(The *r* numbers are the correlation coefficients for each pair; * indicates insignificant correlation coefficient at the 95% confidence level)

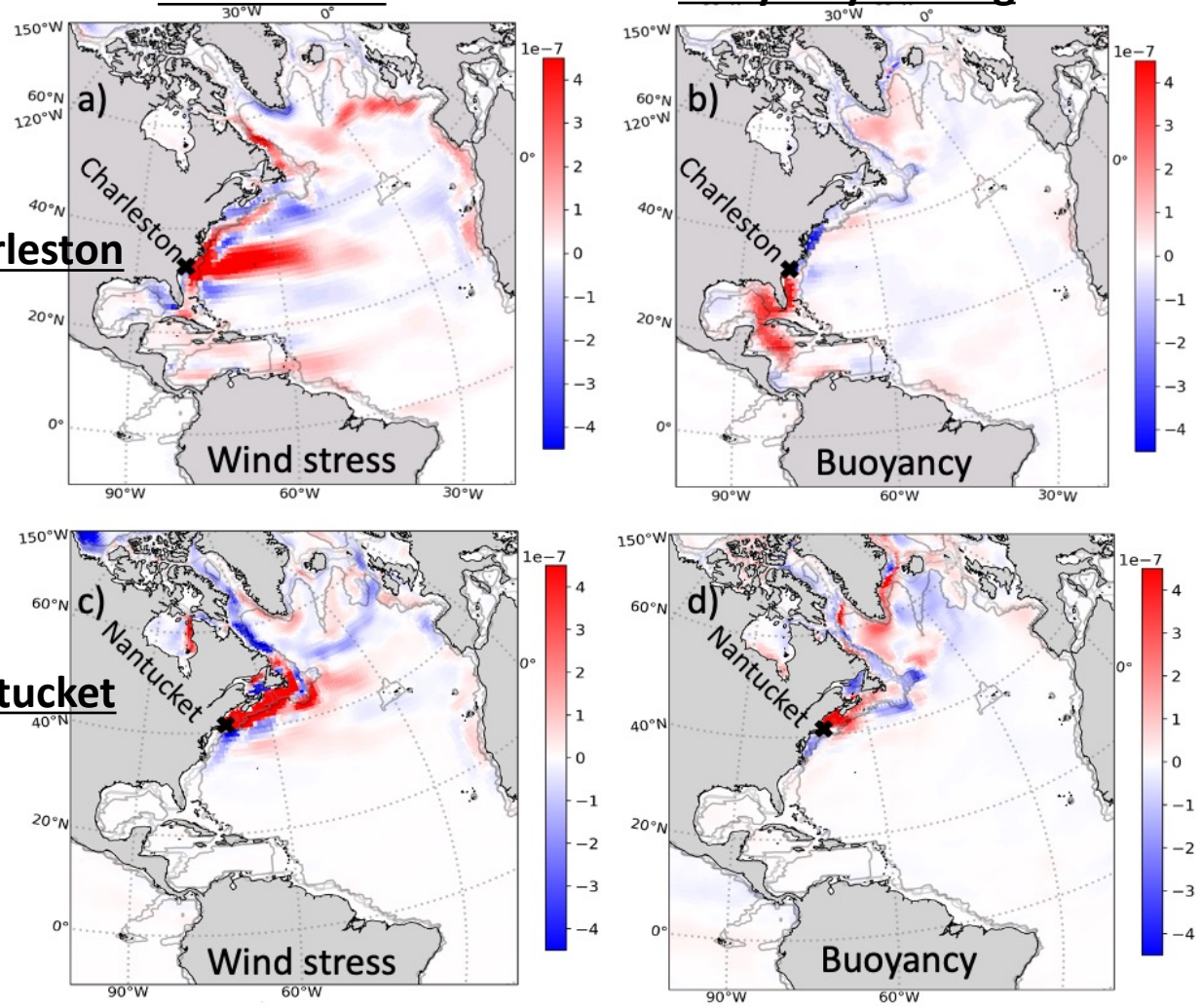
Forcing Contributions as a Function of Space

Forcing Influence Maps

Wind Stress | **Buoyancy Forcing**

Charleston

Nantucket



- Onshore winds north of Cape Hatteras & buoyancy forcing both cause Nantucket & Charleston SLA to co-vary
- Offshore winds contribute much more to interannual SLA at Charleston than to that at Nantucket
- **Offshore winds are the major factor causing incoherent interannual SLA between Nantucket and Charleston**
  - **Open-ocean wind stress curl forces Rossby waves propagating slowly towards Charleston, in contrast to onshore winds that force coastal waves propagating down the coast rapidly**
  - **Important info for ML-based SLA prediction**

Forcing influence maps for Charleston SLAs due to a) wind stress and b) buoyancy forcing. Panels c) and d) are the same as a) and b) but for Nantucket. The values represent fractions per unit area (km^{-2}) of variance of total reconstructed interannual SLA variations at Charleston or Nantucket explained by reconstructed SLA using forcing at each location.