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Origin of Interannual Variability in Global Mean Sea Level

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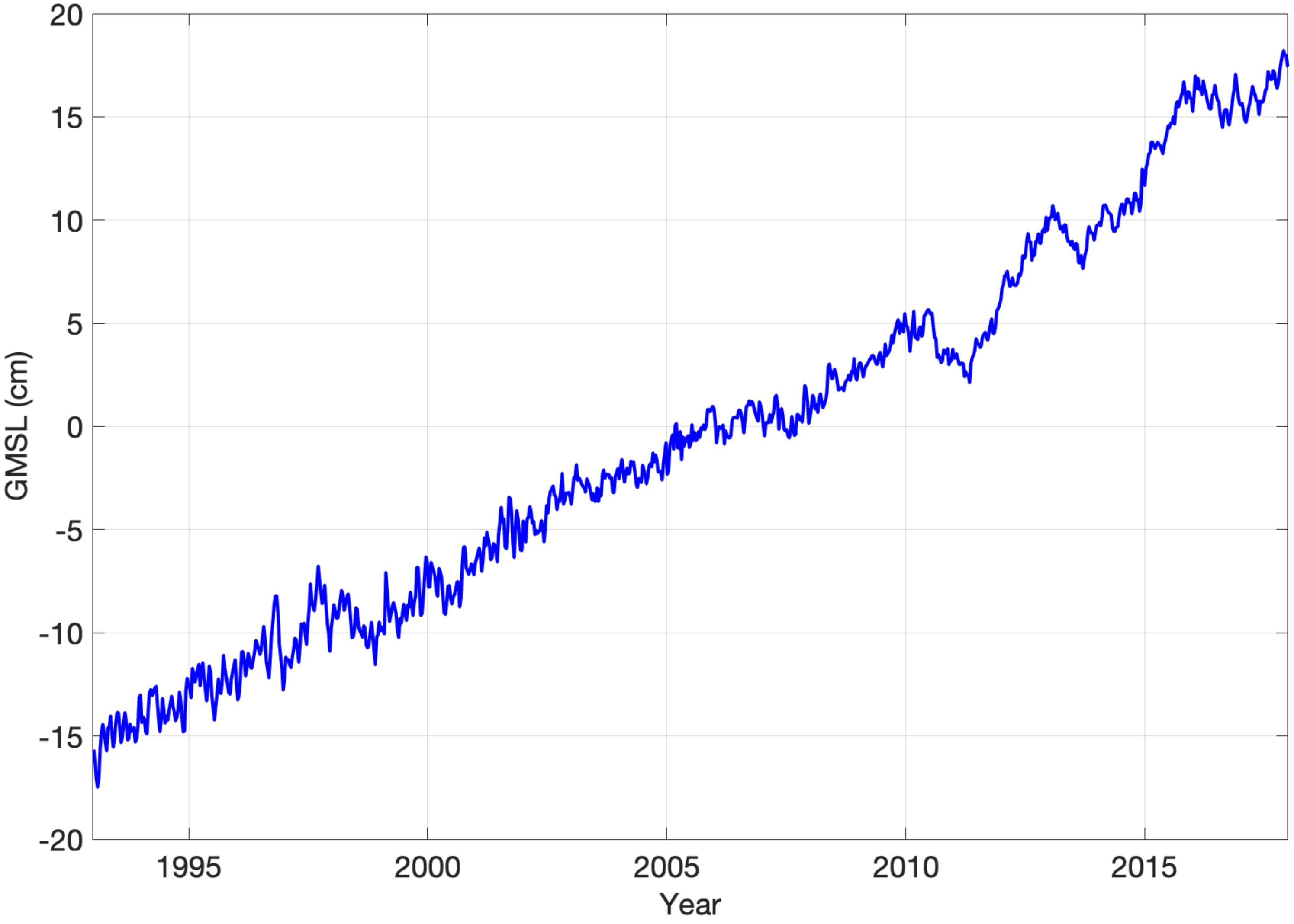
Satellite Altimetry Global Mean Sea Level

- Two main drivers of trend in global mean sea level (GMSL):
    1. **Thermal expansion** (referred to here at steric sea level change)
    2. **Changes in ocean mass associated with the movement of water between land and ocean** (referred to here as barystatic sea level change)

- The relative contributions of these drivers has been investigated using modern sea level records over the past decade → “sea level budget”.
    - GRACE satellites → record of barystatic sea level since 2002.
    - Argo profiling floats → record of steric sea level since 2005.
- ”Budget closure” has been discussed and demonstrated in several recent studies using these records (for summary, Cazenave et al., 2018).



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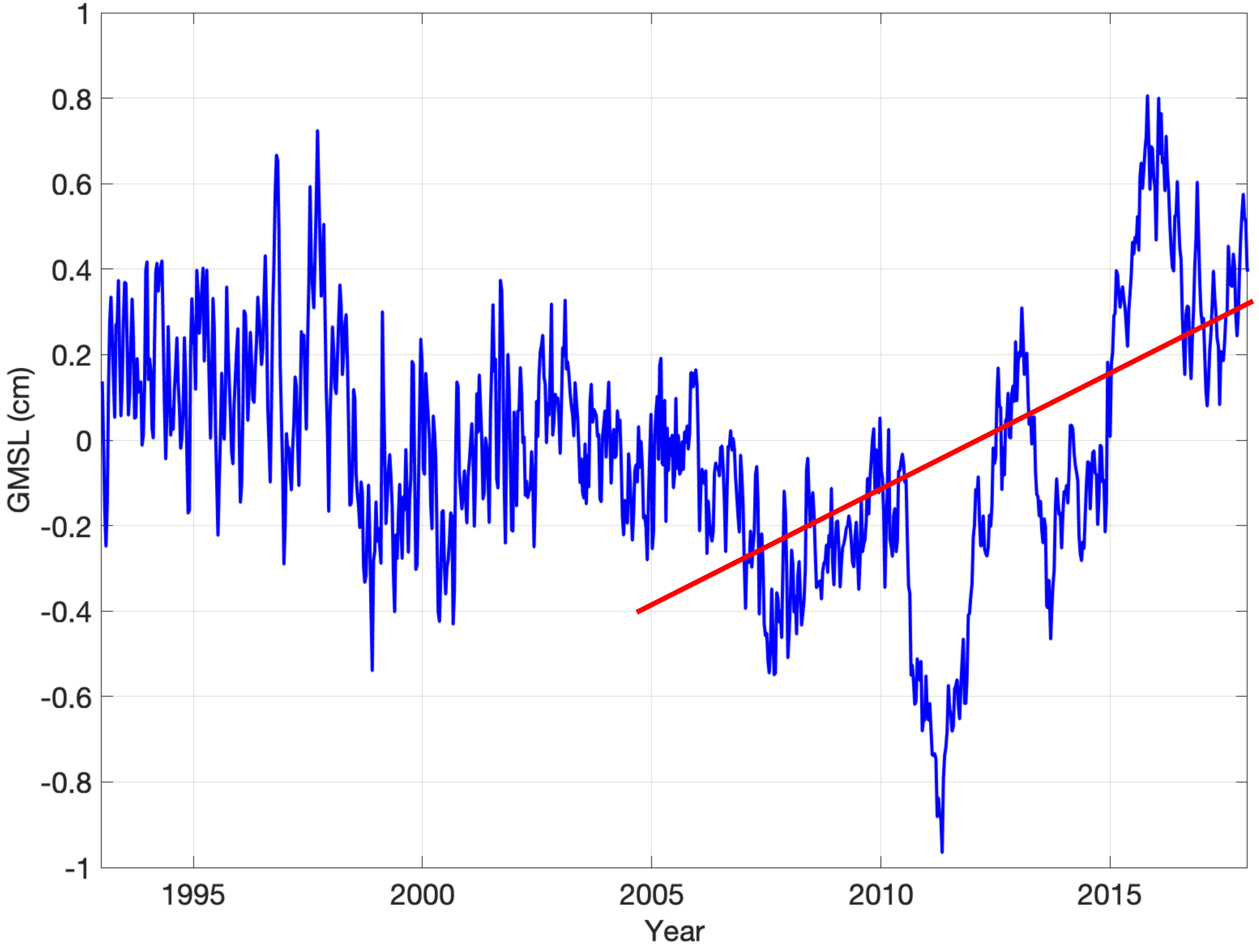
Satellite Altimetry Detrended Global Mean Sea Level

- Once the trend is removed, large interannual to decadal variability becomes apparent (annual cycle removed).
- What do we know about the origins of this variability?
  - Investigation of contributors is problematic using only Argo and GRACE.
  - Prior to 2005, ability to study is very limited.

1. Large disagreement in literature on the relative importance of barystatic and steric changes, particularly as related to ENSO.*
2. Changes in interannual to decadal variability in GMSL reflect changes in global water cycle and Earth's energy budget.
3. This variability serves to obscure background trends that might be associated with anthropogenic forcing.

GOAL: Extend GRACE (TWS) and Argo records into past to improve understanding of interannual to decadal changes in GMSL



*e.g. Piecuch and Quinn, 2016, Dieng et al., 2014 Fasullo and Nerem, 2016, Cazenave et al., 2014, Llovel et al., 2011, Boening et al., 2011

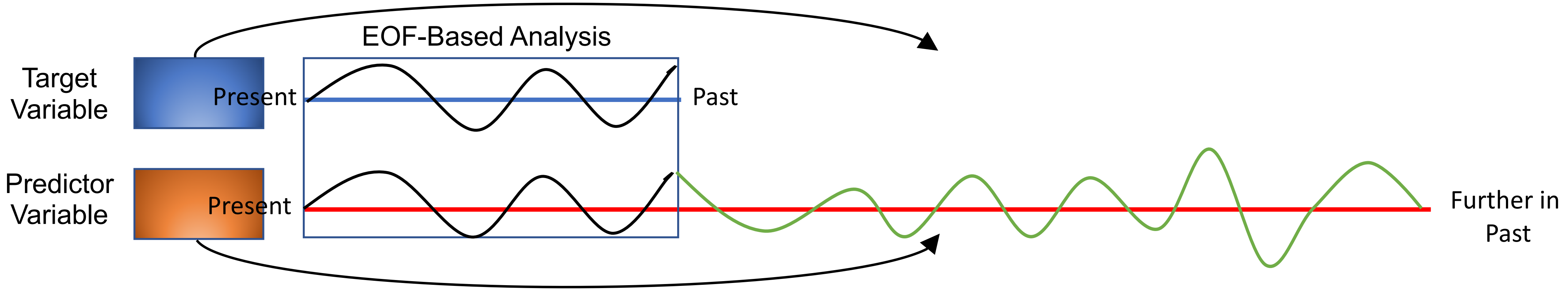
Extending Modern Sea Level Records

- **Method for extending steric and TWS datasets based on *Smith et al.* [2009] and *Hamlington et al.* [2012]:**

1. Using a modern record of a "target" variable and a longer, overlapping record of a physically-related "predictor" variable, compute combined statistical EOF-based modes of variability of both datasets during the overlapping period → spatial patterns in both variables with common temporal evolutions.

2. Project the spatial patterns of the predictor variable back onto the full dataset of the predictor to obtain the temporal evolution of each pattern over the full length of the record.

3. Finally, recombine the spatial patterns of target variable from the (1) with the longer time series in (2).



Extending Modern Sea Level Records

Target Variable	Modern Record	Predictor Variables (all 1982-2018)	Resulting Dataset
Terrestrial Water Storage	GRACE Land only (JPL-RLO6), 2003-2016	Precipitation (GPCP v2.3) 2-m Temperature (ERA5)	TWS, 1982 to 2019
Steric Sea Level	Argo (SI0), 2005-2018	SST (OISST v2) OHC (IAP)	Steric Sea Level, 1982 to 2019

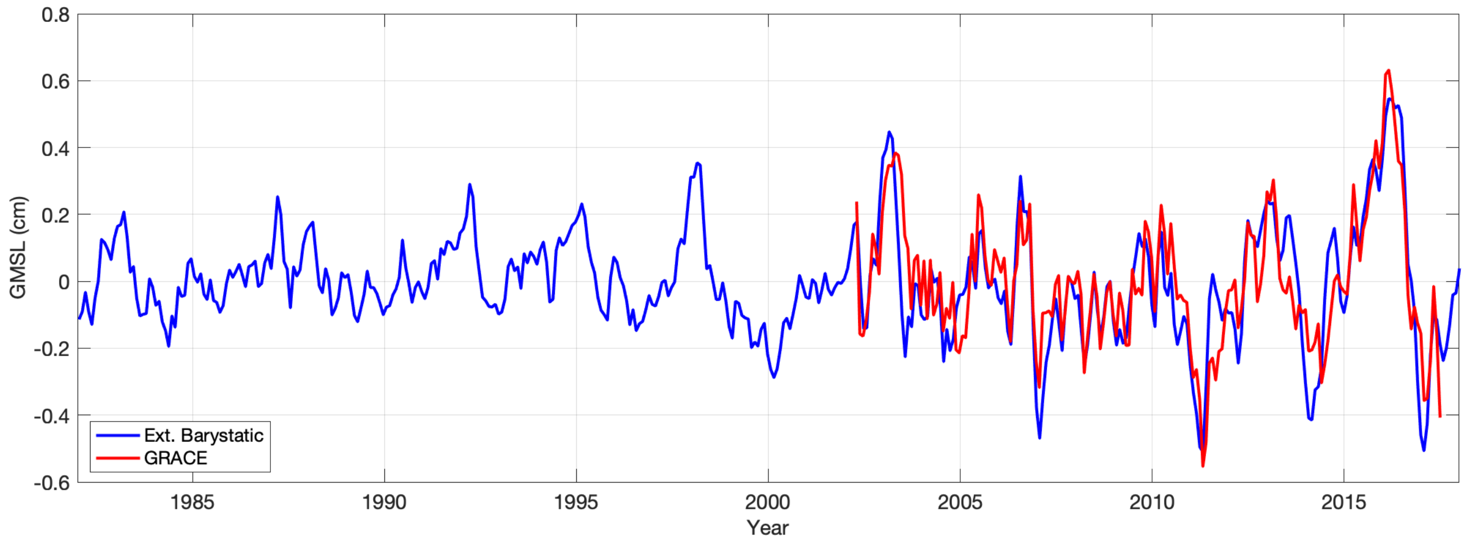
- **For budget studies and comparisons, we also use two additional products:**

  1. **Satellite Altimetry GMSL, 1993 to 2019, (ensemble average of NOAA, CSIRO, U. Colorado, AVISO and JPL)**
  2. **Reconstructed GMSL, 1982 to 2019 (from Hamlington et al., 2014)**

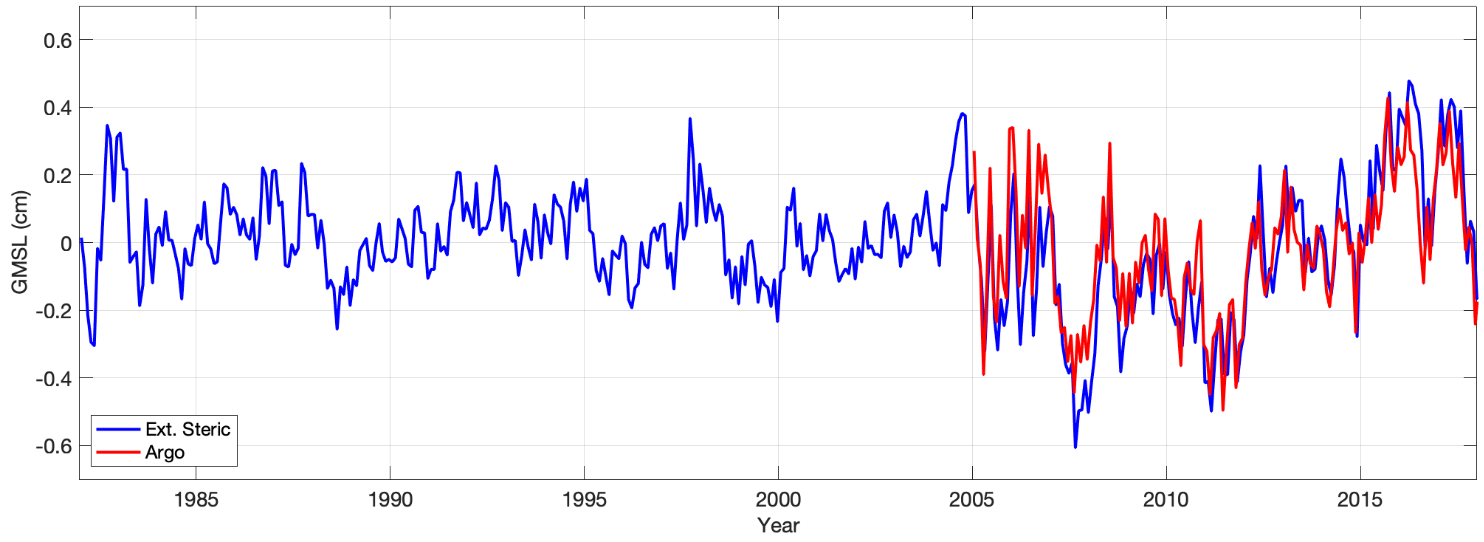
(Note: We are extending the GRACE record of TWS, but subsequent plots will show barystatic sea level, which here is the negative of globally averaged TWS).

Extending Modern Sea Level Records

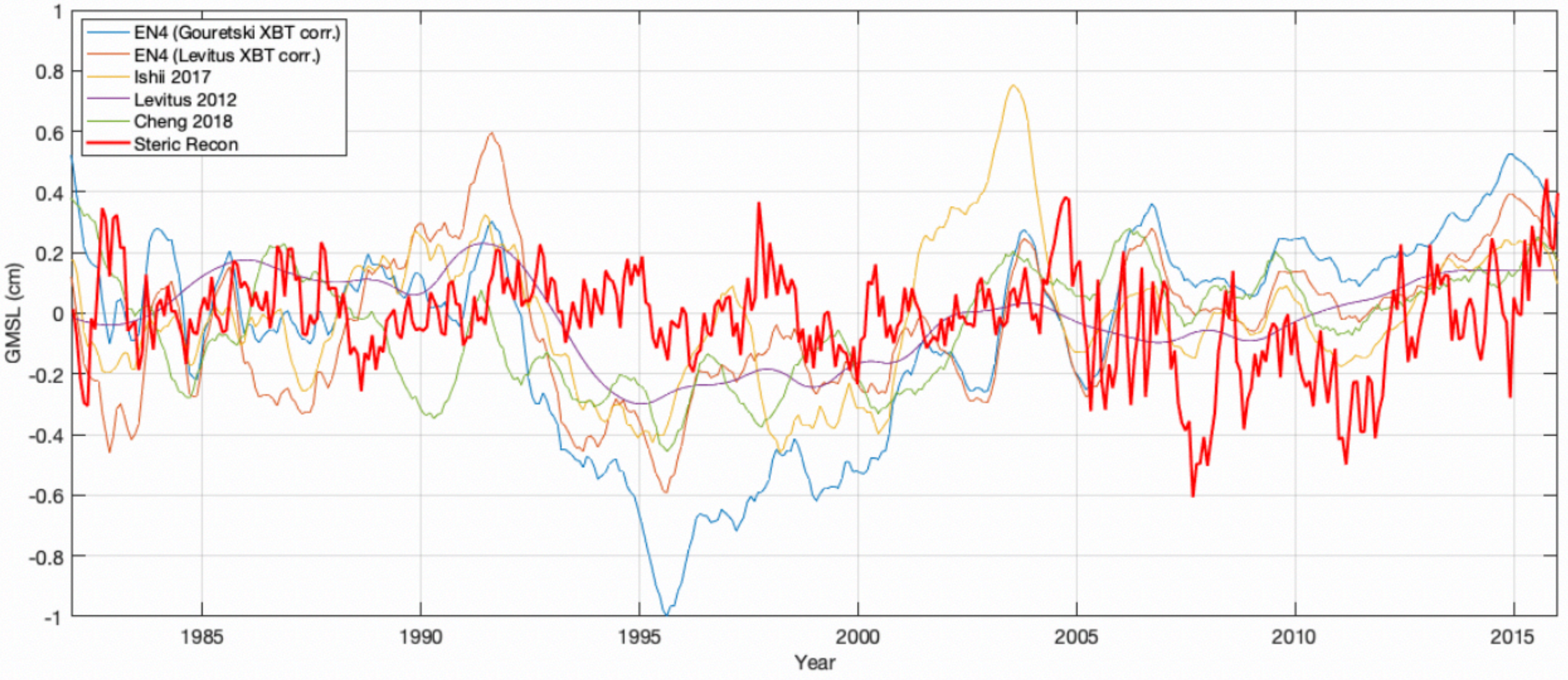
Comparison of barystatic (-TWS) GMSL contribution from GRACE and extended dataset



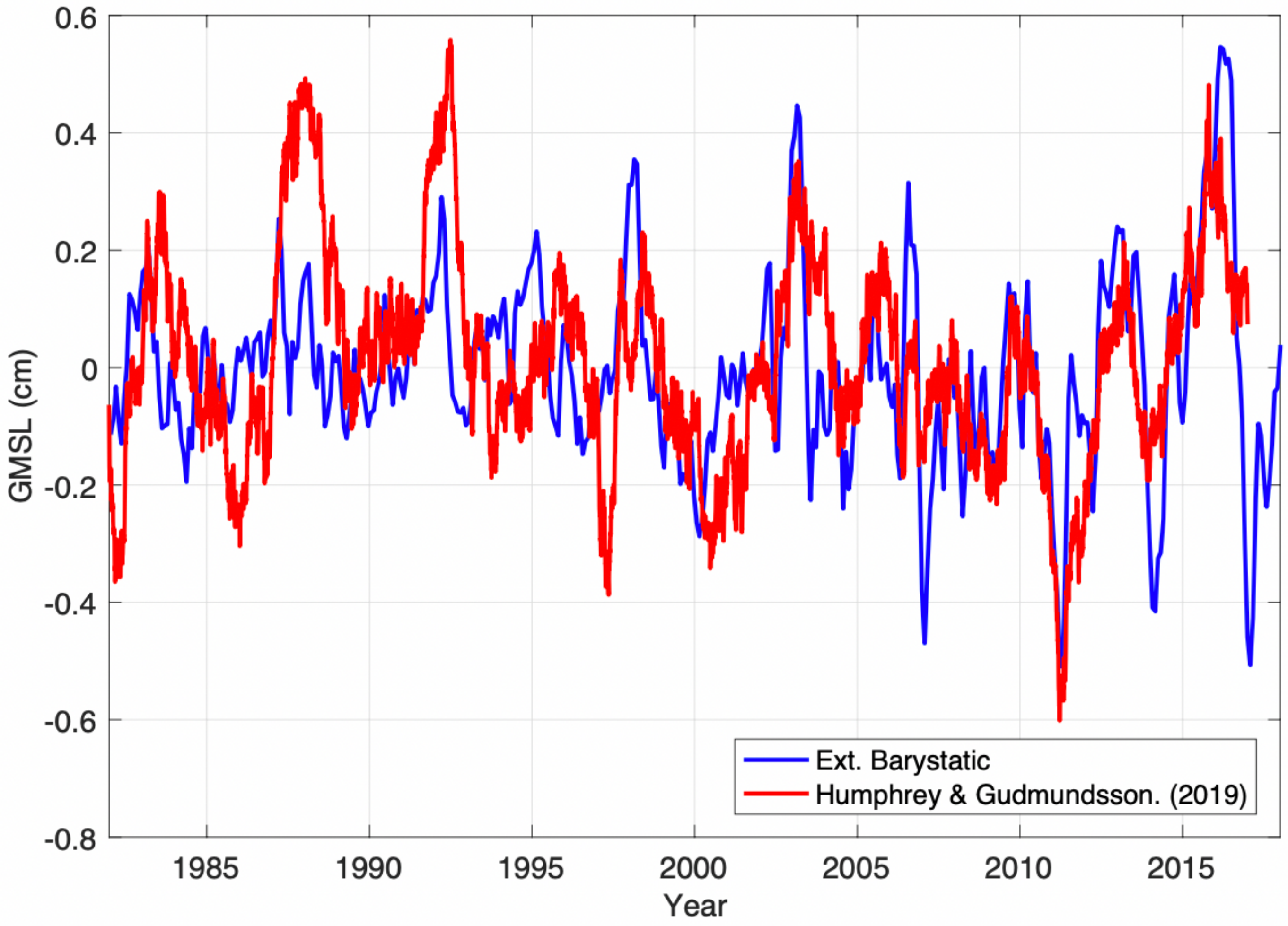
Comparison of steric GMSL contribution from Argo and extended dataset



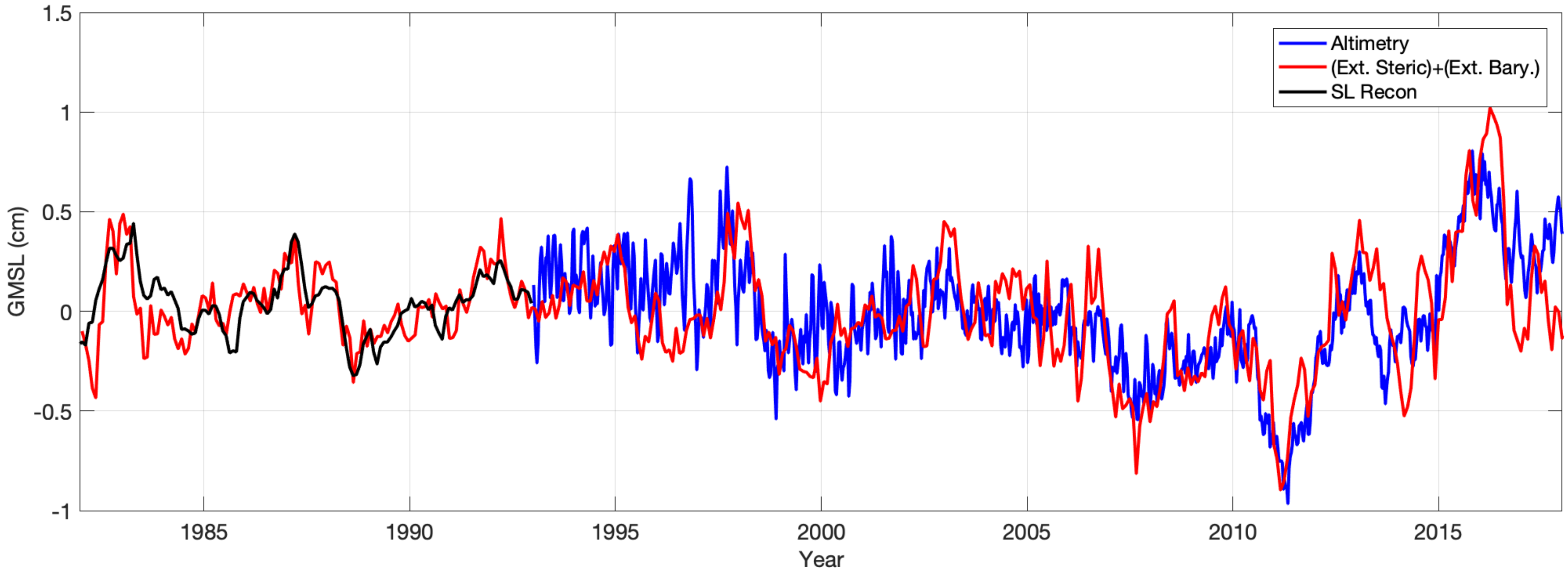
Extending Modern Sea Level Records



Extending Modern Sea Level Records



Comparison to Satellite Altimetry

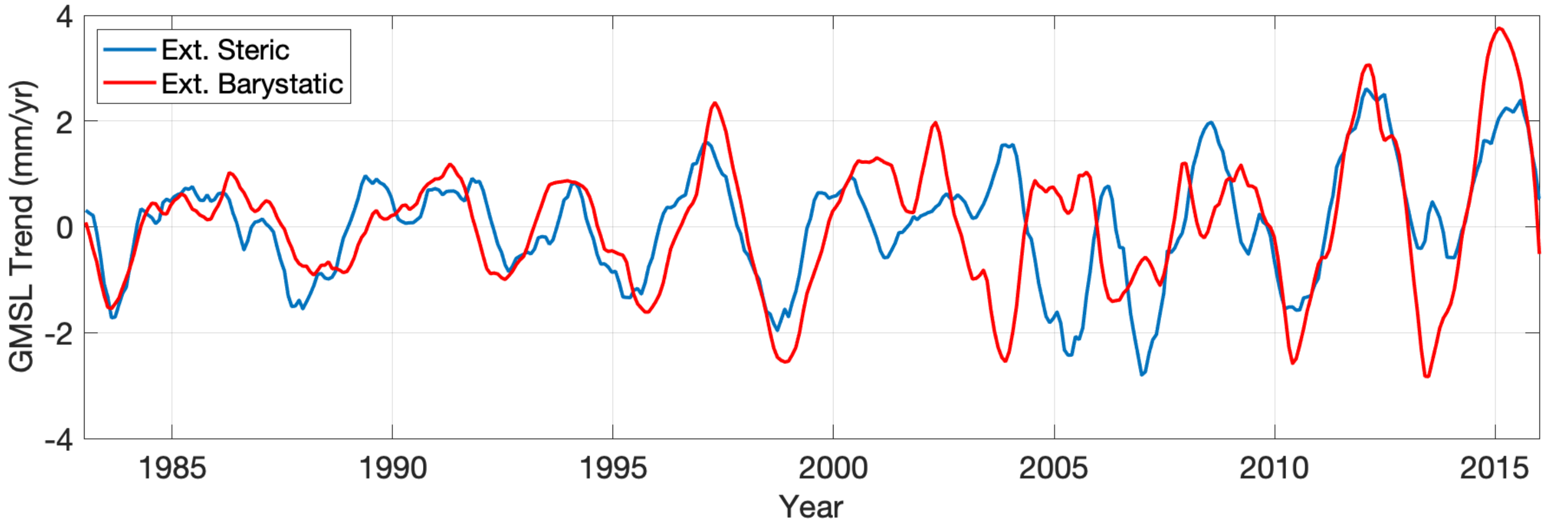


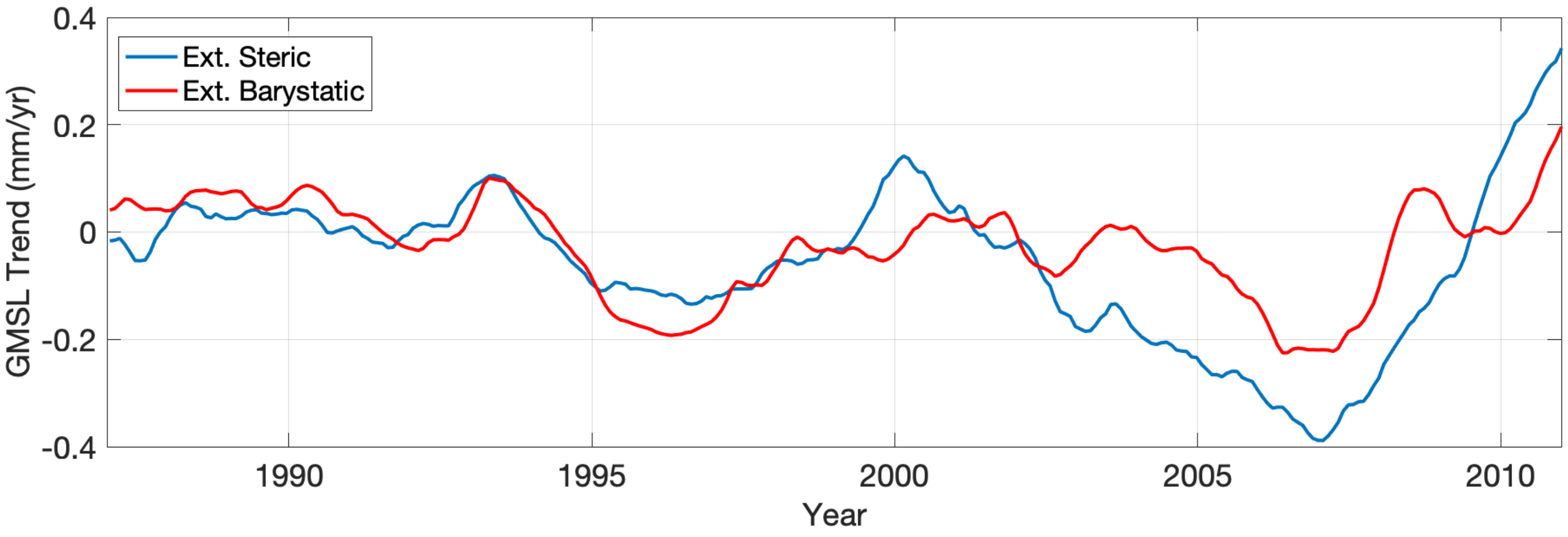
Variance of total GMSL time series explained over different time periods

	2005-2019	1993-2019	1982-2019
Steric	**73%**	**65%**	**65%**
Barystatic	**43%**	**42%**	**45%**
Steric + Barystatic	**83%**	**76%**	**77%**

Impact on Interannual to Decadal Variability

- We can now examine the relative steric and barystatic contributions to GMSL over different timescales.
- To do this, running two-year, and ten-year trends are computed from the GMSL time series.

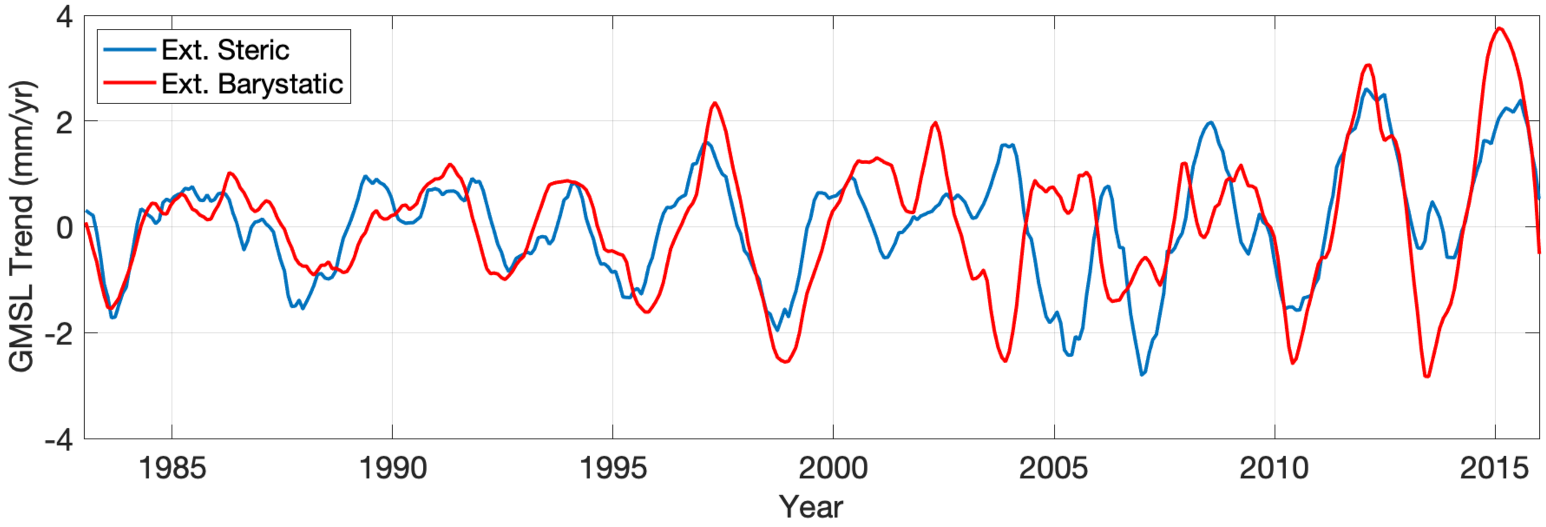


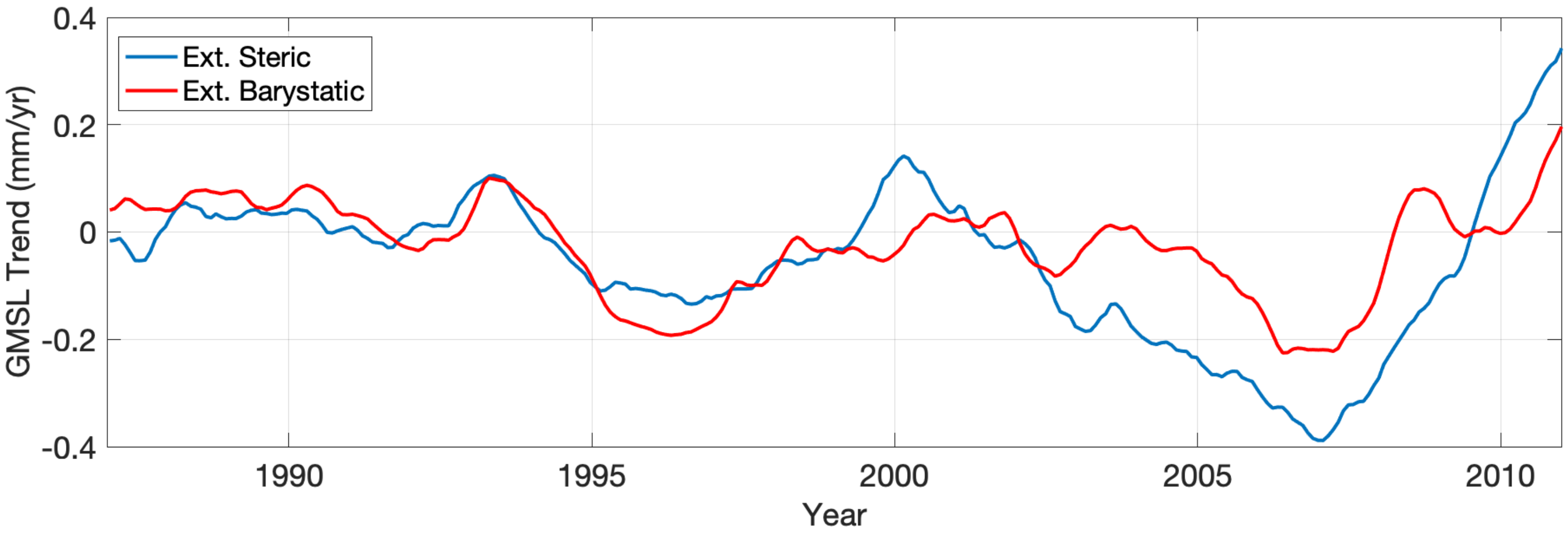


Impact on Interannual to Decadal Variability

- Based on this analysis, 3 key takeaways:
  1. Barystatic and steric contributions are near-equal in magnitude;
  2. Barystatic and steric contributions are generally correlated;
  3. Both contributions are strongly connected to variations in ENSO.

Question: Is there a physical expectation for these results?





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What should be expected? A Simple Scaling Experiment

Change in barystatic sea level driven by anomalous air-sea freshwater flux:

$$\frac{\partial \eta_F}{\partial t} = \frac{1}{A}\iint_A \frac{1}{\rho_0}(E + P + R)dA$$

The change in global mean steric sea level is given by:

$$\frac{\partial \eta_Q}{\partial t} = \frac{1}{A}\iint_A \frac{\alpha}{\rho_0 c_p}(Q_E + Q_H + Q_L + Q_S)dA$$

1. Based on recent study (Piecuch et al., 2019), anomalous latent evaporative heat fluxes are important driver of heat flux on interannual and longer timescales.

2. This heat flux is proportional to anomalous evaporation → ocean will lose water mass at same time evaporative cooling occurs ($Q_E = \Lambda \mathrm{E}$, where Λ is the latent heat of vaporization of seawater).

3. Anomalous evaporation offset in part by precipitation (increased evaporation leads to increased precipitation). Based on GPCP, ~25% of this precipitation will fall over land (range between 20% and 30% for El Nino and La Nina).

- Relative contributions of barystatic and steric variability can then be given as:

$$\frac{\partial \eta_F/\partial t}{\partial \eta_Q/\partial t} \approx \frac{0.25 c_p}{\alpha \Lambda} \approx 1.25$$

Summary and Conclusions

- By extending the records of steric sea level and TWS over a longer time period, advances in our understanding of the variability in GMSL can be obtained:

  1. Strong agreement between the GMSL contributions estimated from the extended steric and TWS datasets, the satellite altimetry data, and the tide gauge reconstructions, serve as validation for each dataset and the underlying method.

  2. We have shown that there are correlated barystatic and steric GMSL contributions of similar magnitudes from 1982 to 2018.

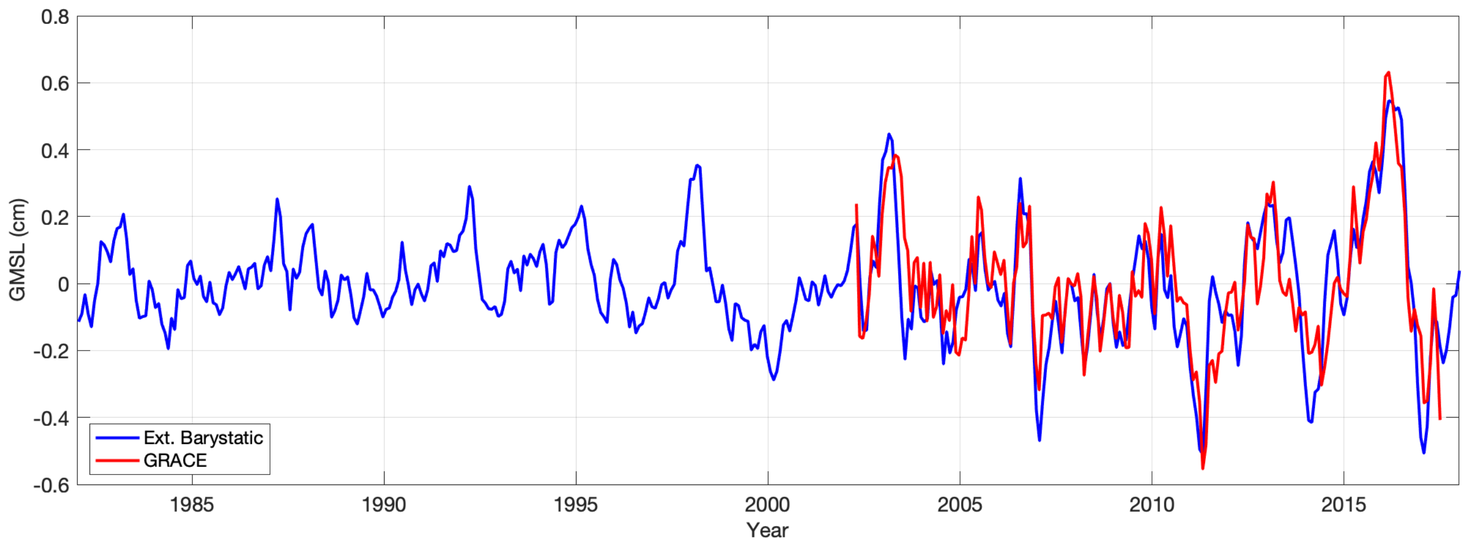
  3. These variations are closely related to ENSO and provide observational support for past studies indicating important steric and barystatic contributions to GMSL associated with ENSO → confirms the result of Piecuch and Quinn (2016) with longer observational support.

What's Next?

1. The extended datasets are gridded and support both regional and global studies → allow for the investigation of drivers of TWS variability over past 3+ decades.

2. The improved explanation of the drivers of the variability about the long-term trend could allow for a better estimate of the forced trend in regional and global sea level.

3. Scaling experiment can be expanded and assumptions tested to provide an improved physical explanation for what is seen in the observations.



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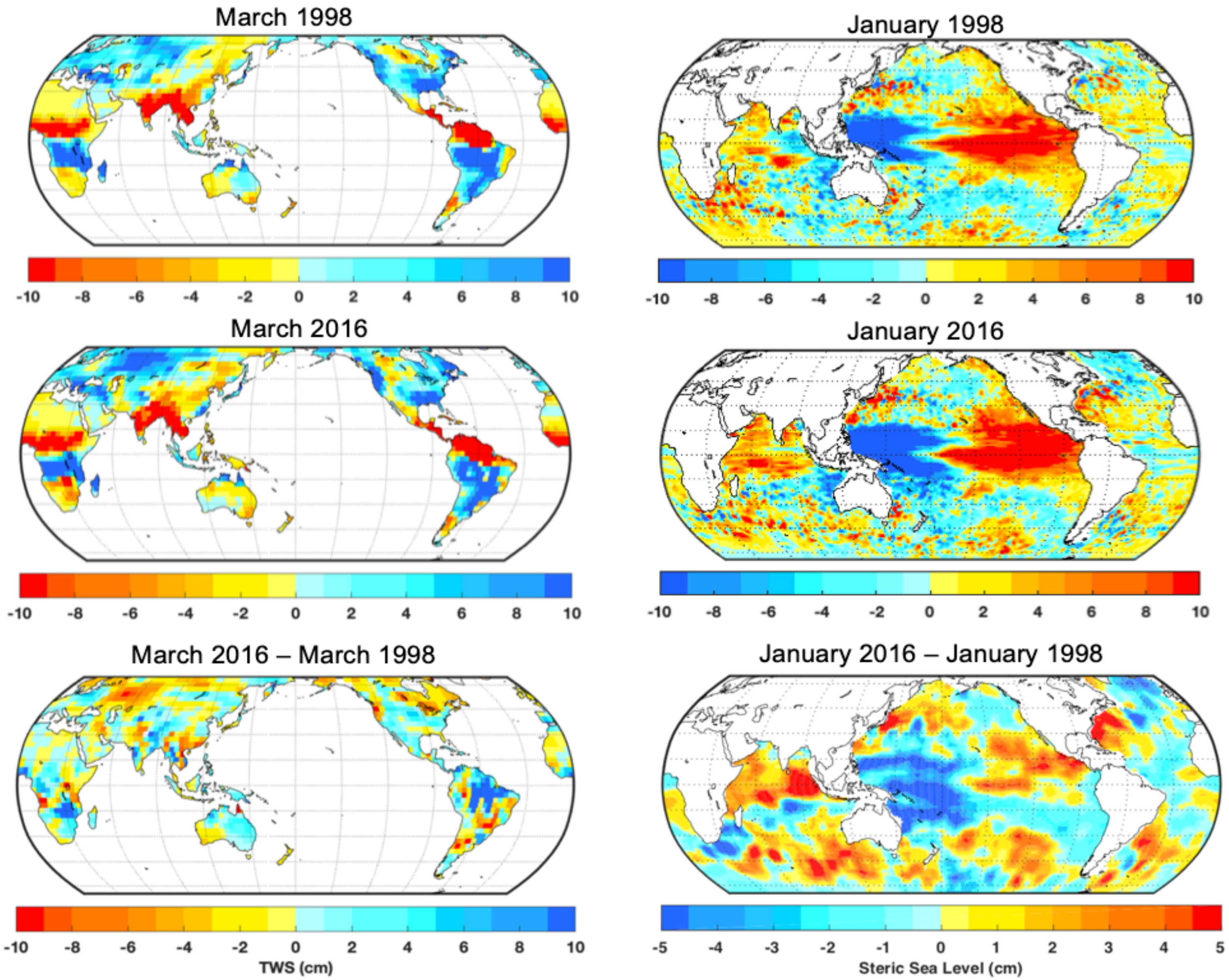

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