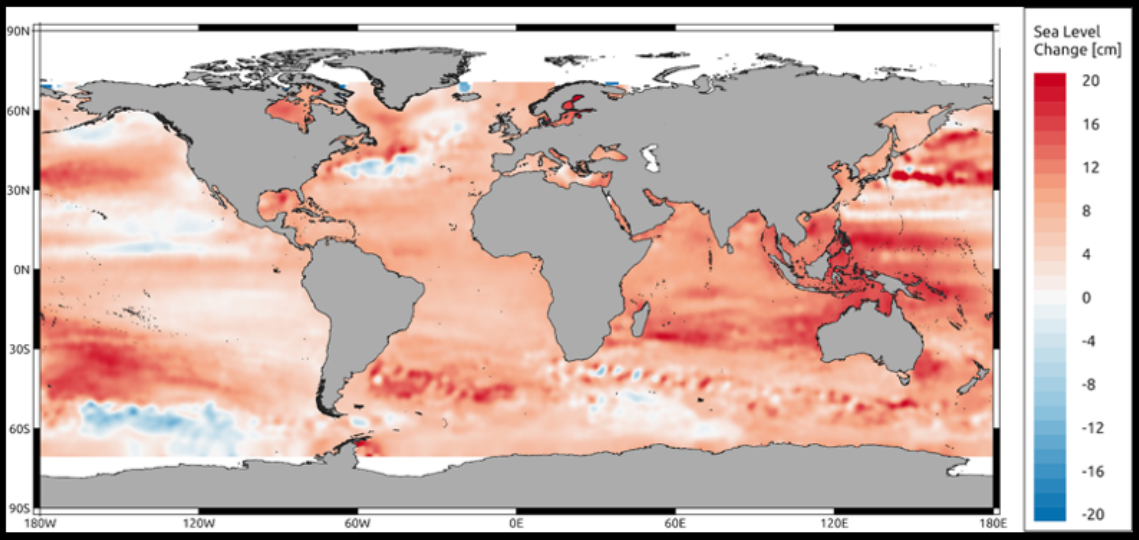
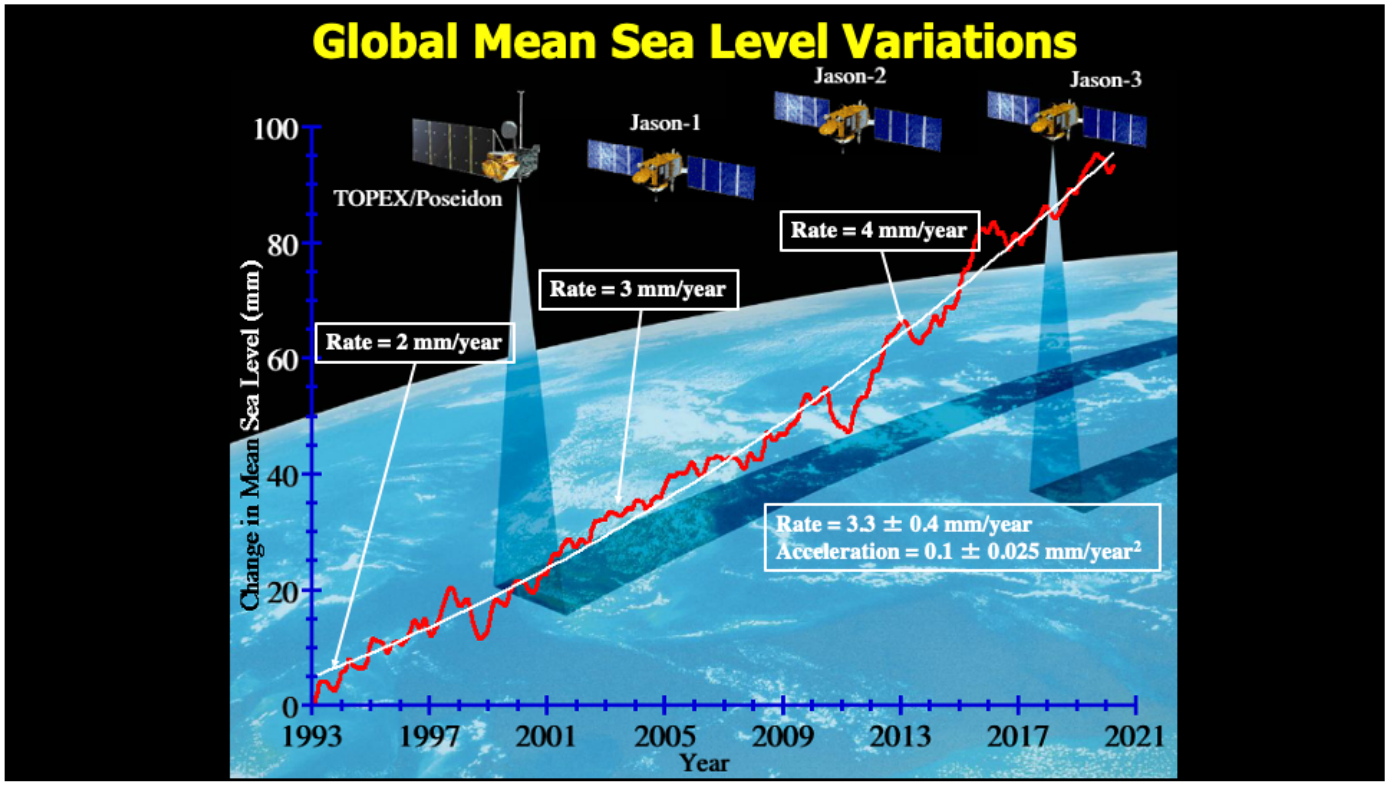
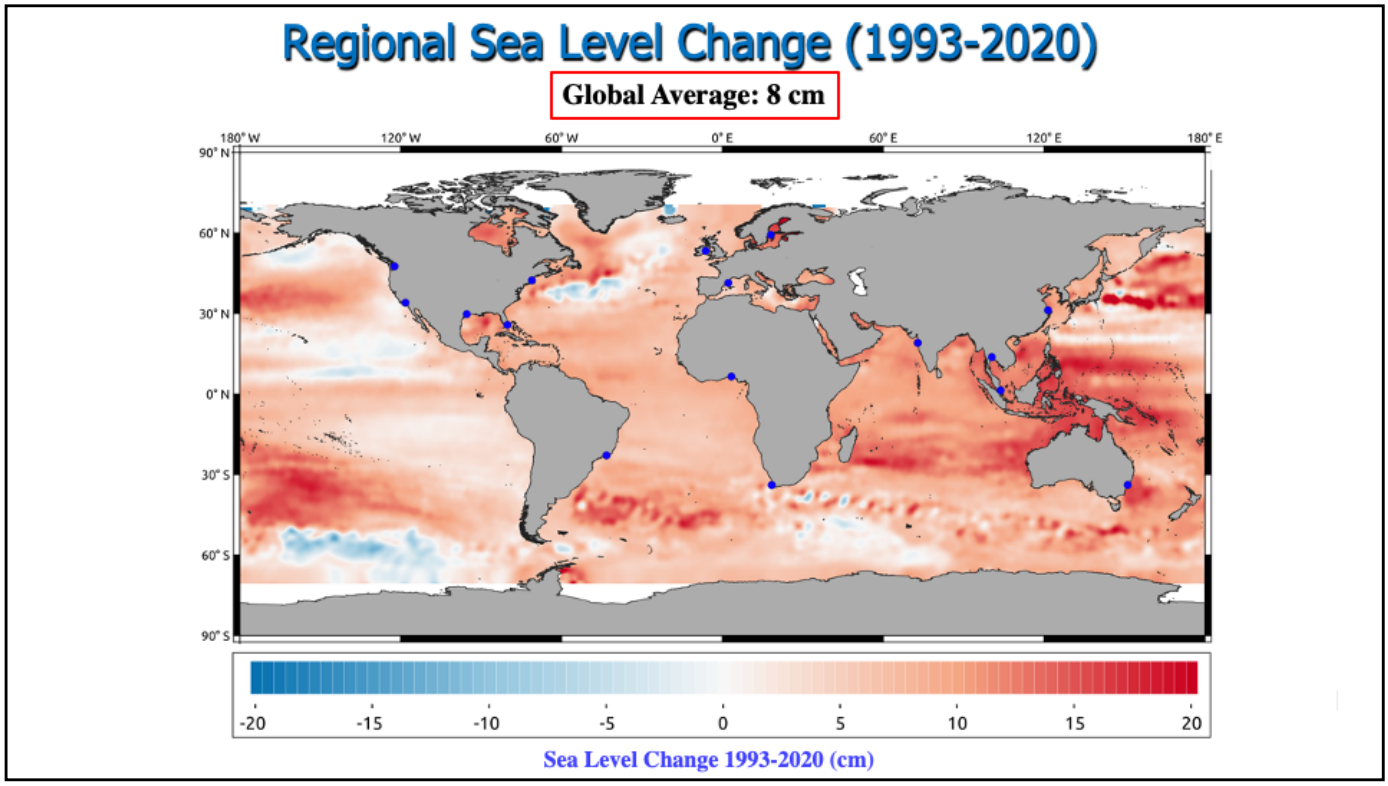
The Emergence of the Forced Response of Climate Change in the Altimeter Sea Level Record



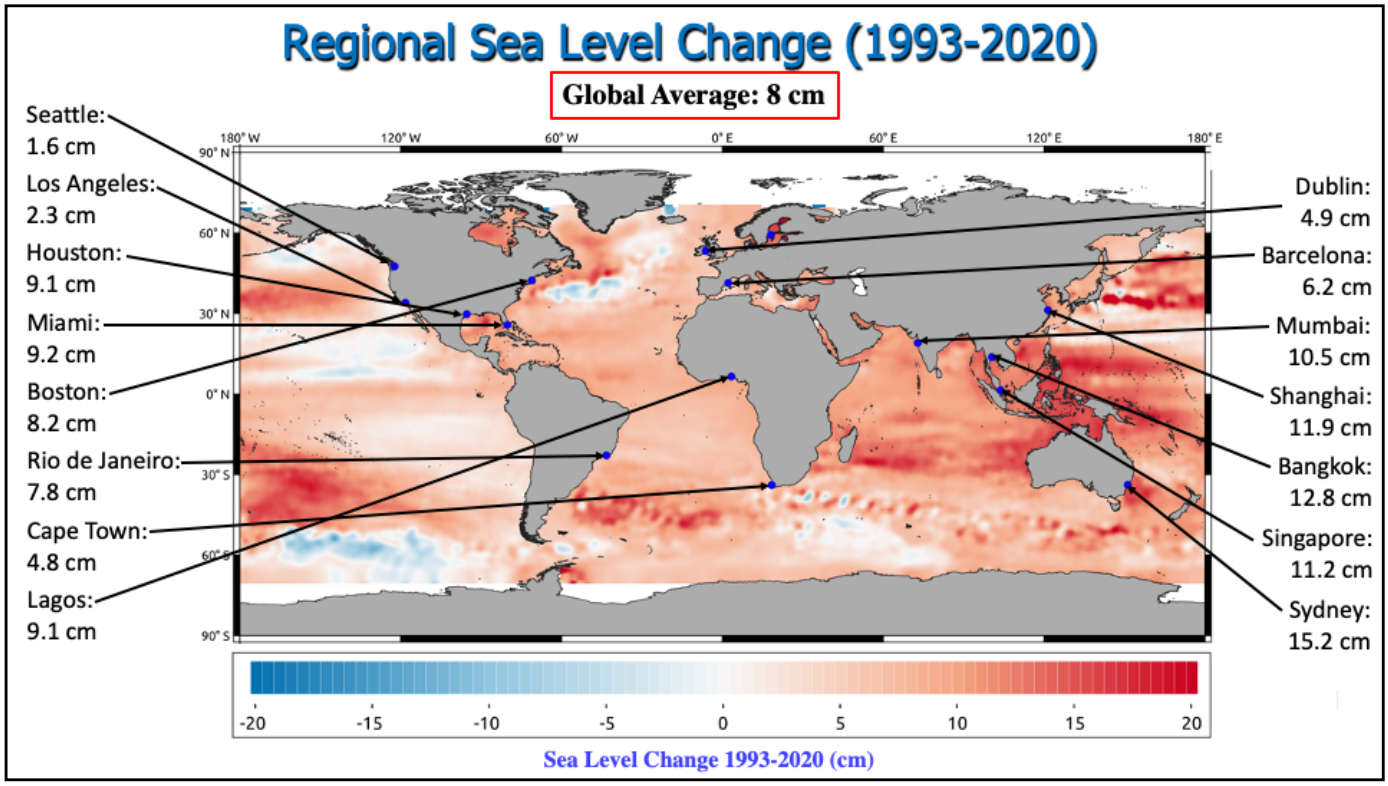
R. Steven Nerem, University of Colorado, CCAR, CIRES
J. Fasullo, NCAR
B. Hamlington, JPL



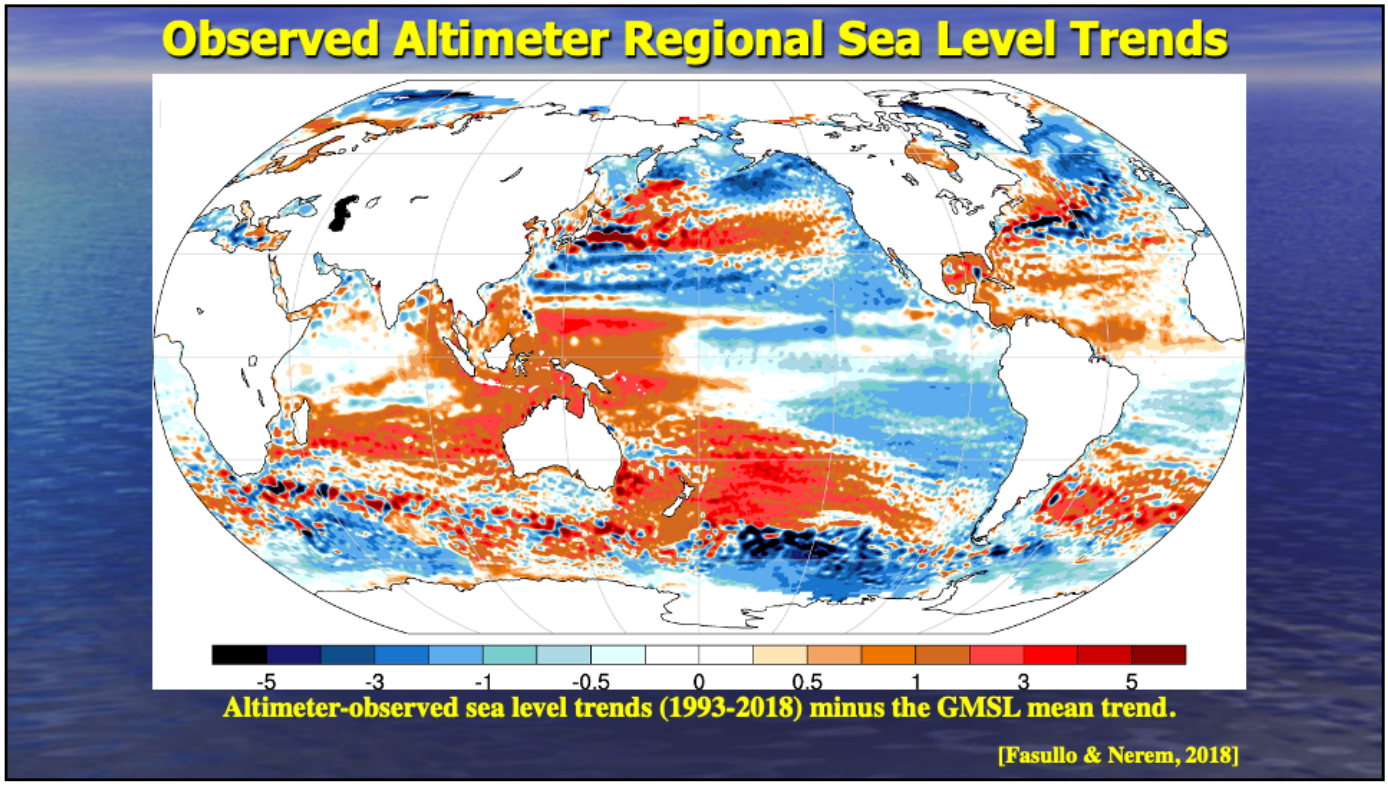
Global mean sea level update: GMSL continues to accelerate (updated from Nerem et al., 2018]

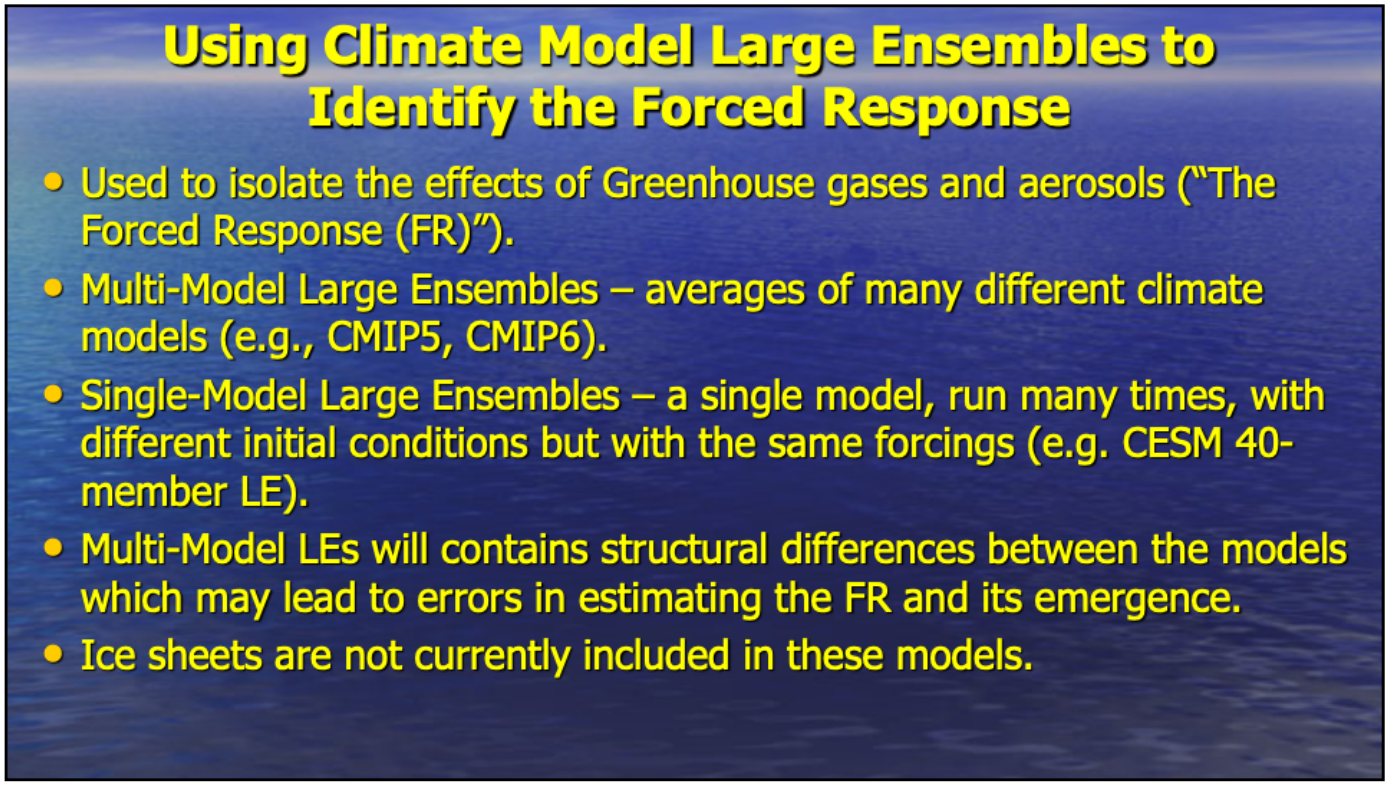


Total regional sea level change obtained by taking the sea level trends (mm/year) and multiplying by 28 years.

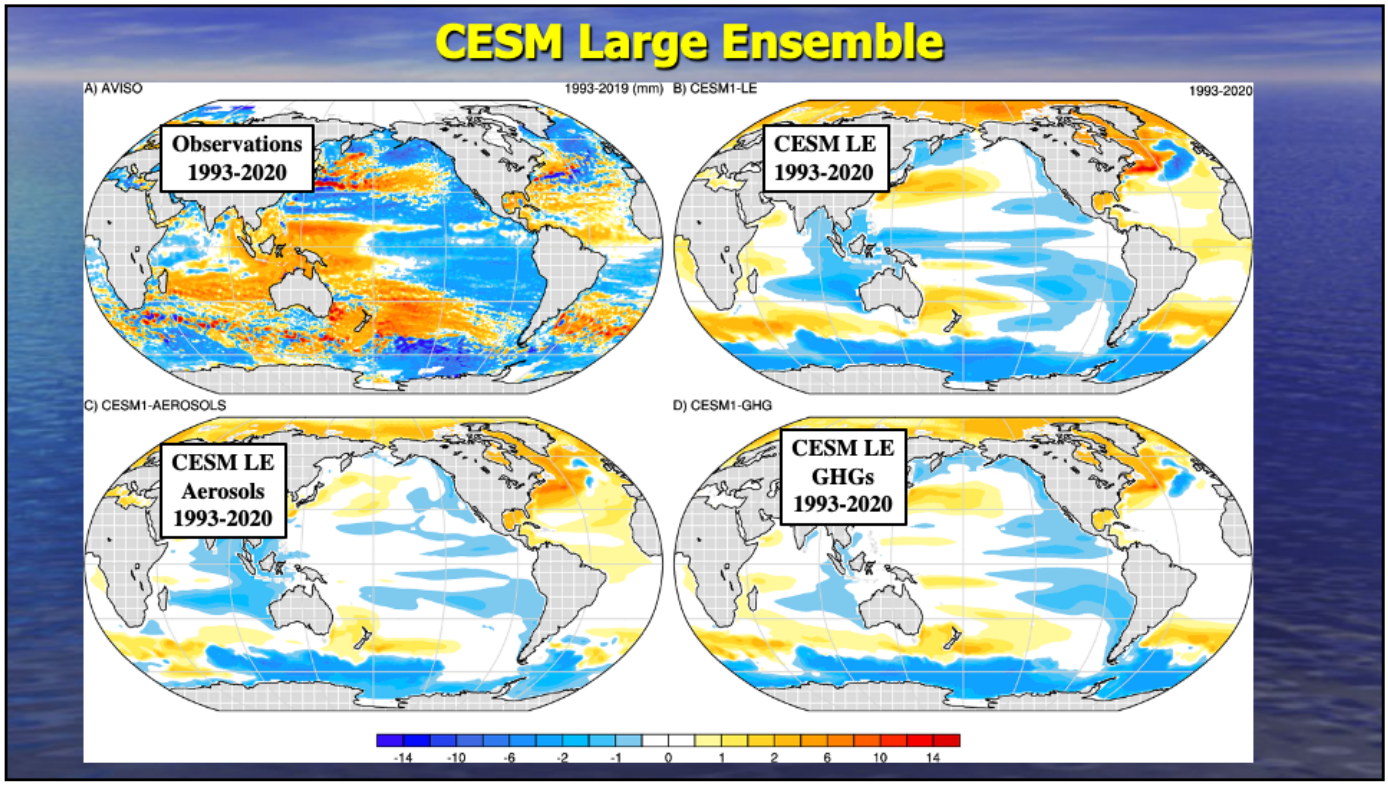


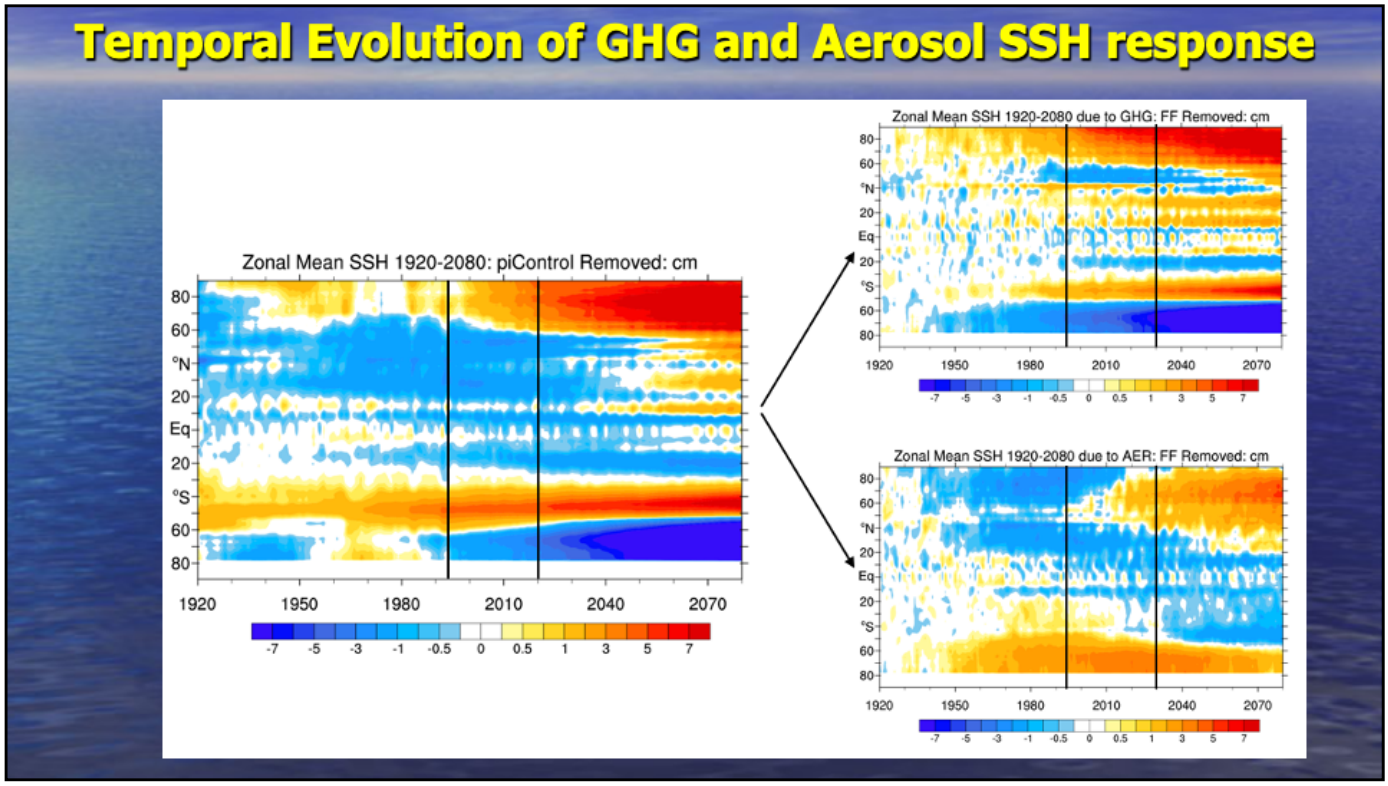
There is substantial regional variability in the amount of sea level rise seen over the last 28 years – will this variability continue into the future?


Observed Altimeter Regional Sea Level Trends
-5
-3
-1
-0.5
0
0.5
1
3
5
Altimeter-observed sea level trends (1993-2018) minus the GMSL mean trend.
[Fasullo & Nerem, 2018]

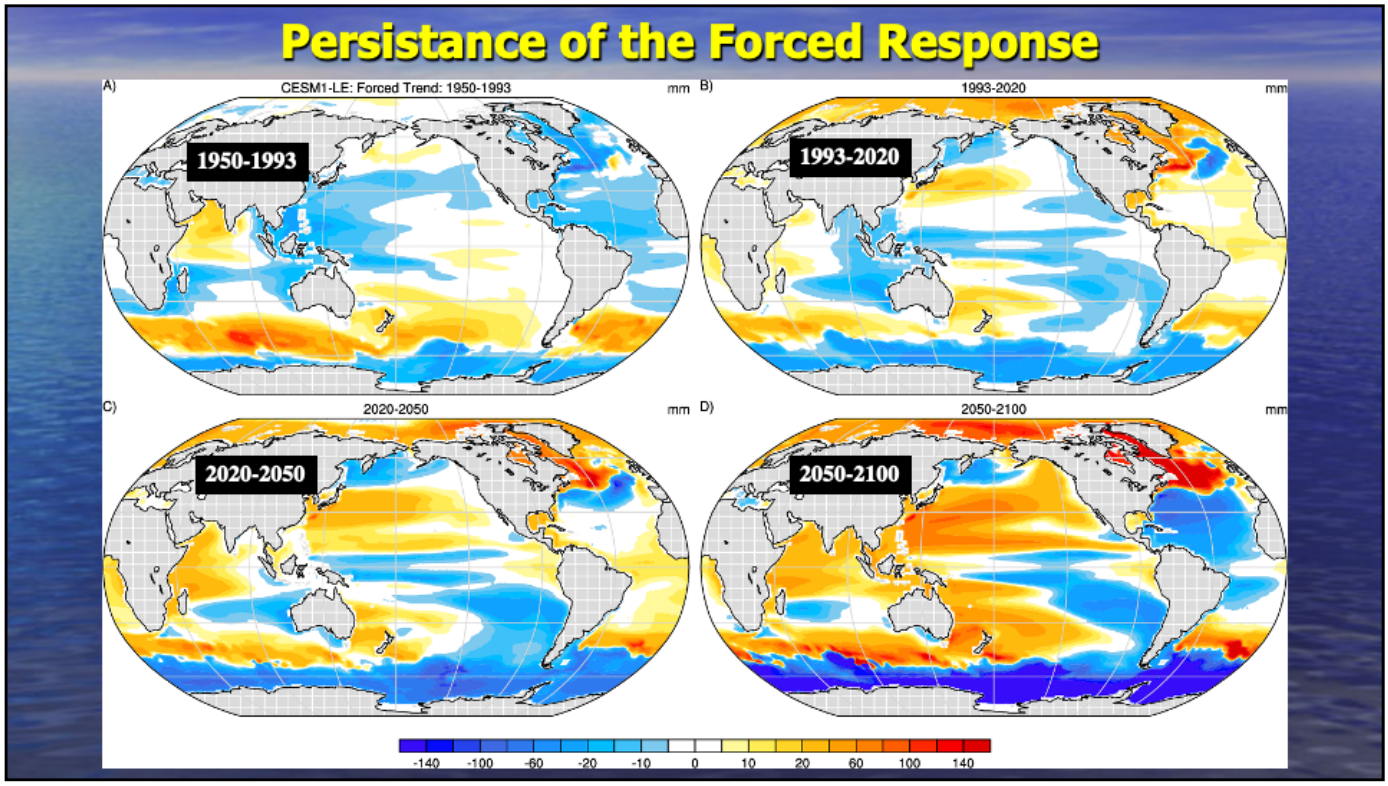


Large Ensemble (LE) runs of a single climate model are better for estimating the FR than multi-model ensembles (e.g. CMIP5, CMIP6), because the latter contains structural differences between the models that make the detection of the FR more difficult.


CESM Large Ensemble
A) AVISO
1993-2019 (mm)
B) CESM1-LE
1993-2020
Observations
1993-2020
CESM LE
1993-2020
C) CESM1-AEROSOLS
D) CESM1-GHG
CESM LE
Aerosols
1993-2020
CESM LE
GHGs
1993-2020
-14
-10
-6
-2
-1
0
1
2
6
10
14

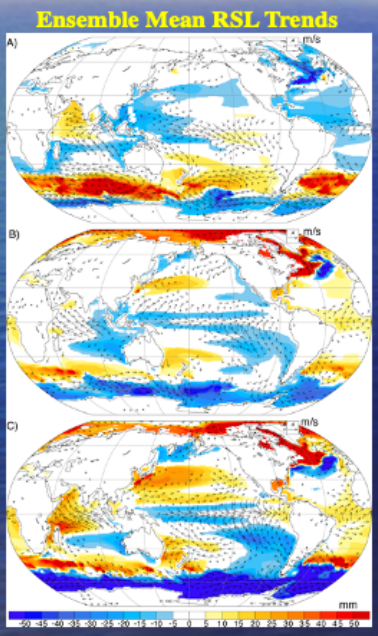


The altimeter era is shown between the black bars. The results show that while the altimeter era is dominated by both aerosols and GHGs, GHGs will become more dominant in the future.



There is evidence that the Forced Response (FR) has some persistence into the future, suggesting we might be able to use the observed sea level trends as a predictor for future regional sea level change.

Forced Trends in SLR in CESM1 from 1920-2100



1950-1993

1993-2020

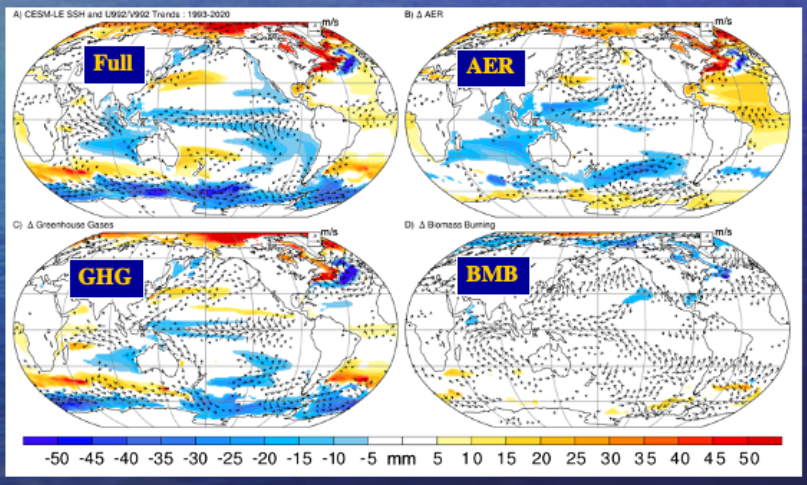
2020-2050

- Science Question: Have past regional sea level rise patterns been driven by external forcing or are they merely internal variability?
- Data & Results: Using the CESM1 large ensemble we find strong regional forced trends as a function of lat/lon. In some regions these are larger than internal variability (e.g. SH). The pattern is also non-stationary, changing significantly across decades due to shifts in the FR in winds and steric (i.e. OHC) contributions.
- Significance: There is strong regional and hemispheric structure to the patterns 1) not accounted for in tide gauge reconstructions, 2) is predictable in principle, 3) modulates regional structure of trends in extremes (Piecuch) and other aspects.

Fasullo, J. T., Gent, P. R., & Nerem, R. S. (2020a). Forced patterns of sea level rise in the community earth system model large ensemble from 1920 to 2100. Journal of Geophysical Research: Oceans, 125, e2019JC016030. https:// doi.org/10.1029/2019JC016030

Sea Level Rise in the CESM Single Forcing Large Ensemble

CESM1 Ensemble Mean Trends 1993-2020 in RSLR

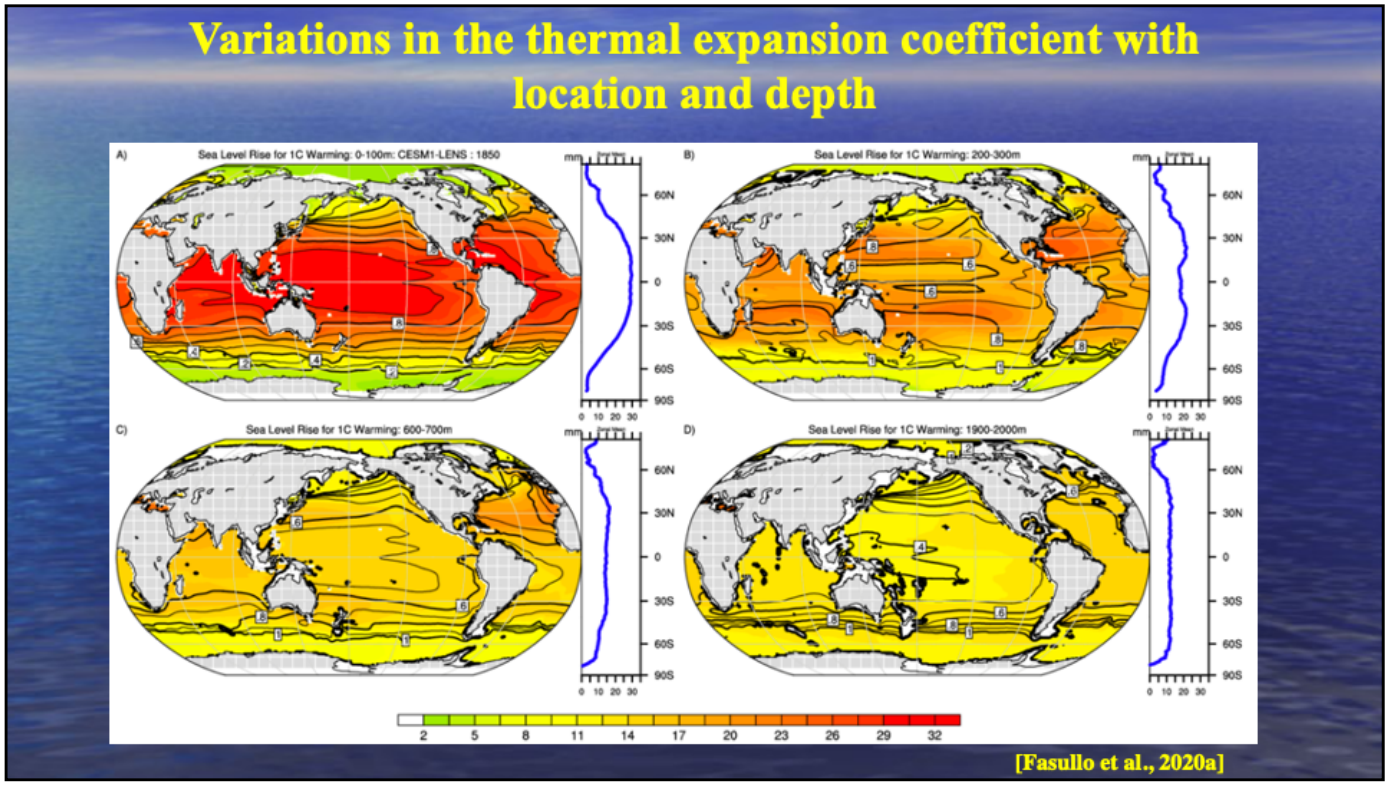


For full-forcing (FULL), aerosol forcing (AER), greenhouse gases (GHG), and biomass burning (BMB).

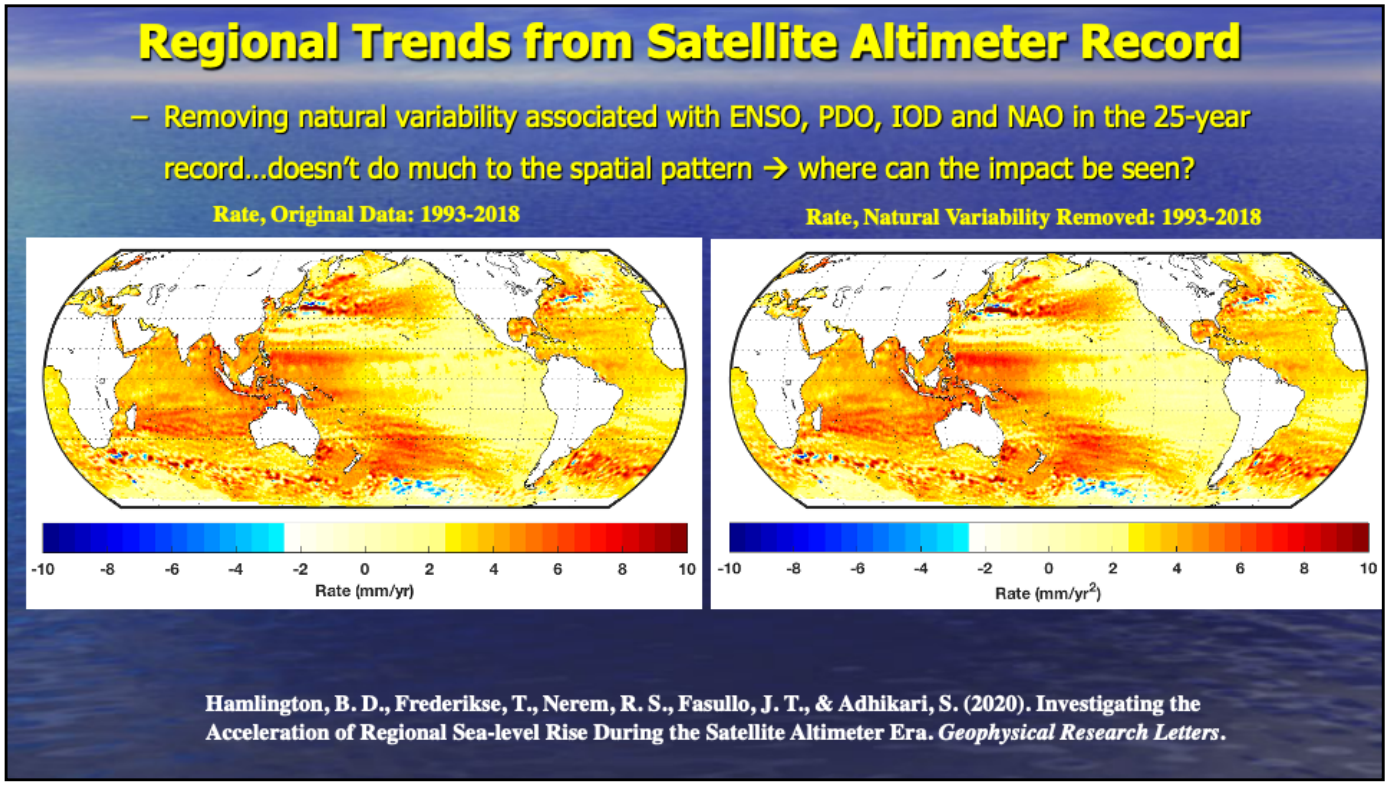
- **Science Question: What drives the patterns that are evident in the altimeter record?**
- **Data & Results: The main features are attributable to greenhouse gases and industrial aerosols forcings via 1) expansion coefficient dependence on T/P, 2) pattern of ocean warming/cooling, 3) changes in winds (southern ocean – also ozone, not shown). Atlantic features influenced by both U/V, and T/S, particularly mid 20th C.**
- **Significance: Allows for attribution of recent RSLR (e.g. AER in Atlantic) and anticipation of regional features under a range of future emissions scenarios.**

Fasullo, J. T., Gent, P. R., & Nerem, R. S. (2020b). Sea Level Rise in the CESM Large Ensemble: The Role of Individual Climate Forcings and Consequences for the Coming Decades. Journal of Climate, 33(16), 6911-6927.

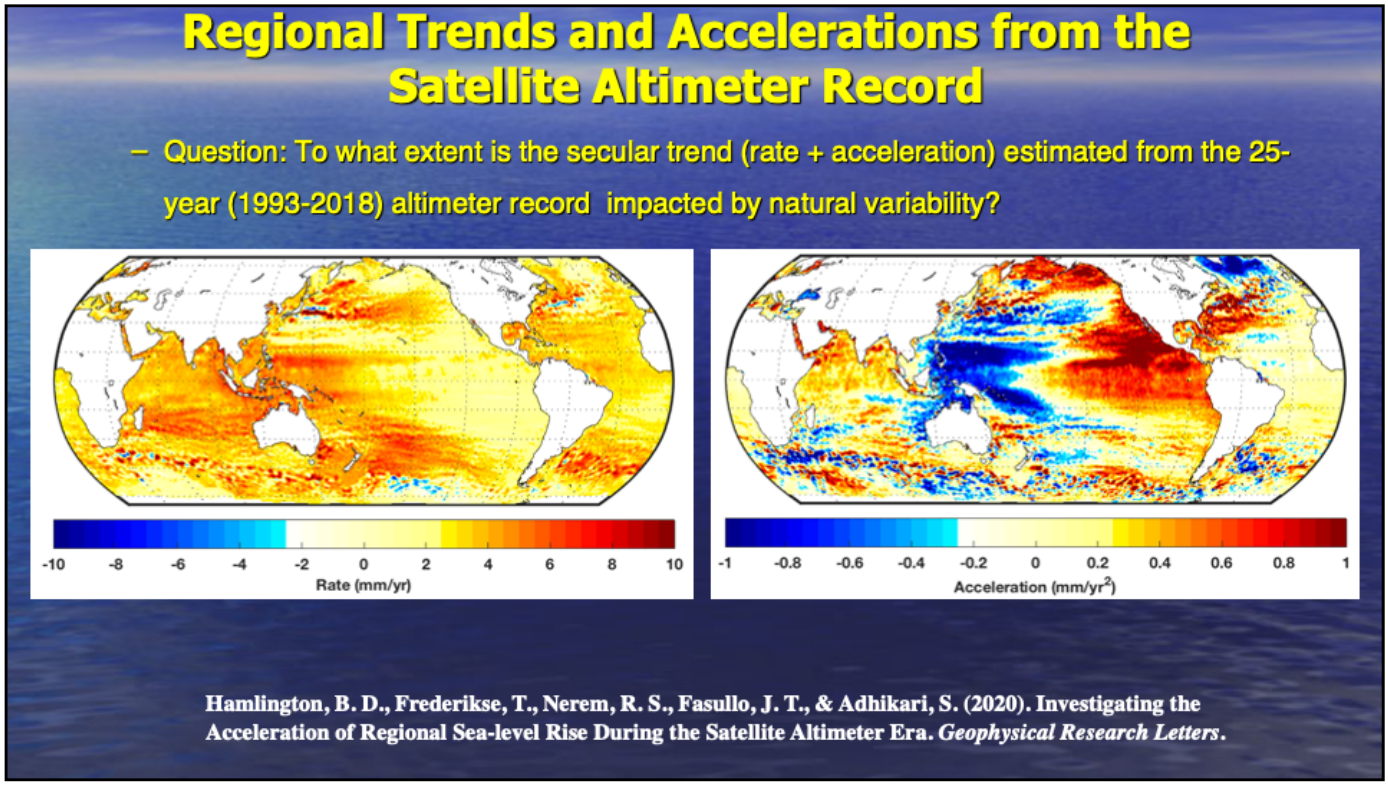
You may add comments here to clarify the work or the results.



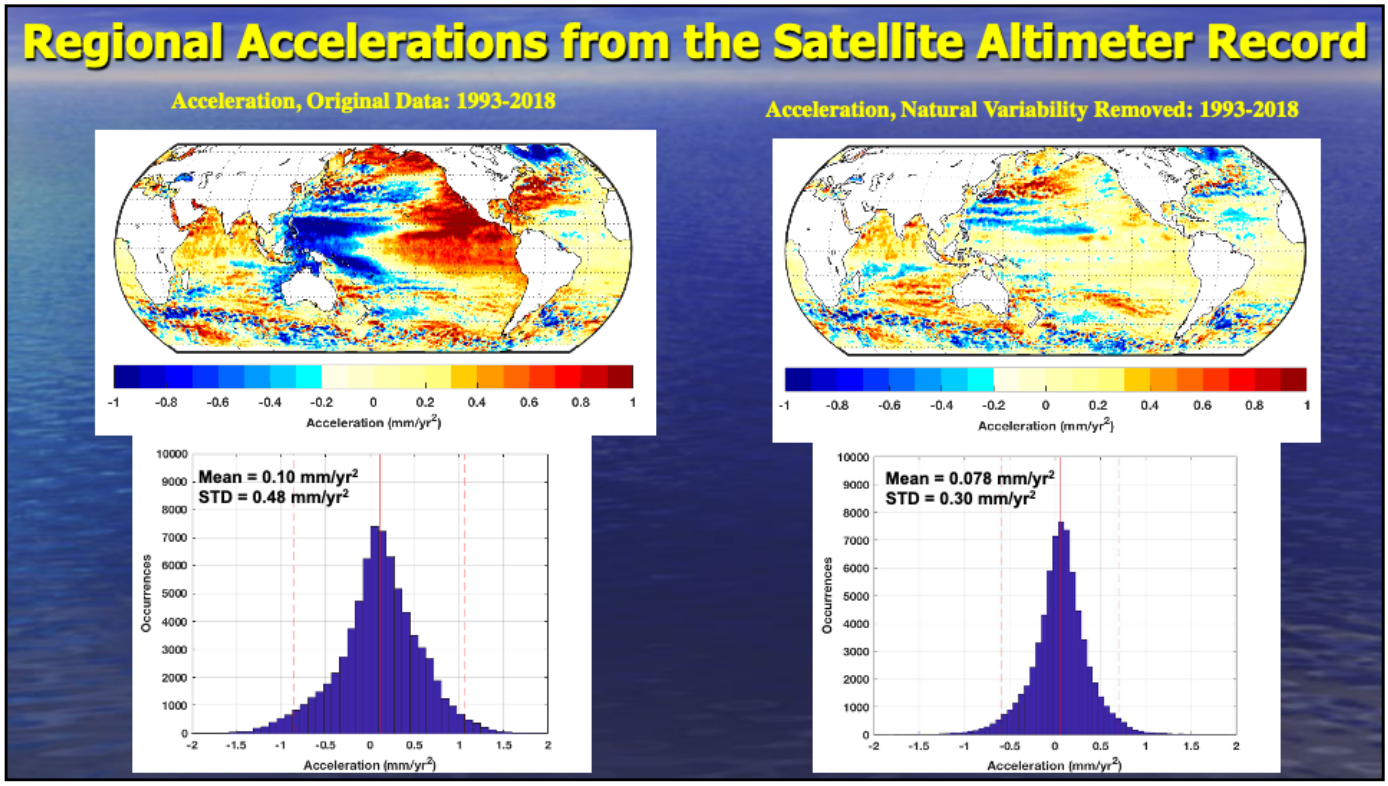
Estimated change in sea surface height (mm) for a 100m deep 1C warming across various ocean depths based on the simulated LENS 1850 control state and the equation of state (McDougall et al. 2009). Corresponding zonal means are plotted as blue lines. In (A), contour lines indicate the fraction of rise relative to the western equatorial Pacific maximum. In (B-D), contour lines indicate the fraction of rise relative to the 0-100m layer amount (A) at the same latitude and longitude (at 0.1 intervals from 0 to 1).



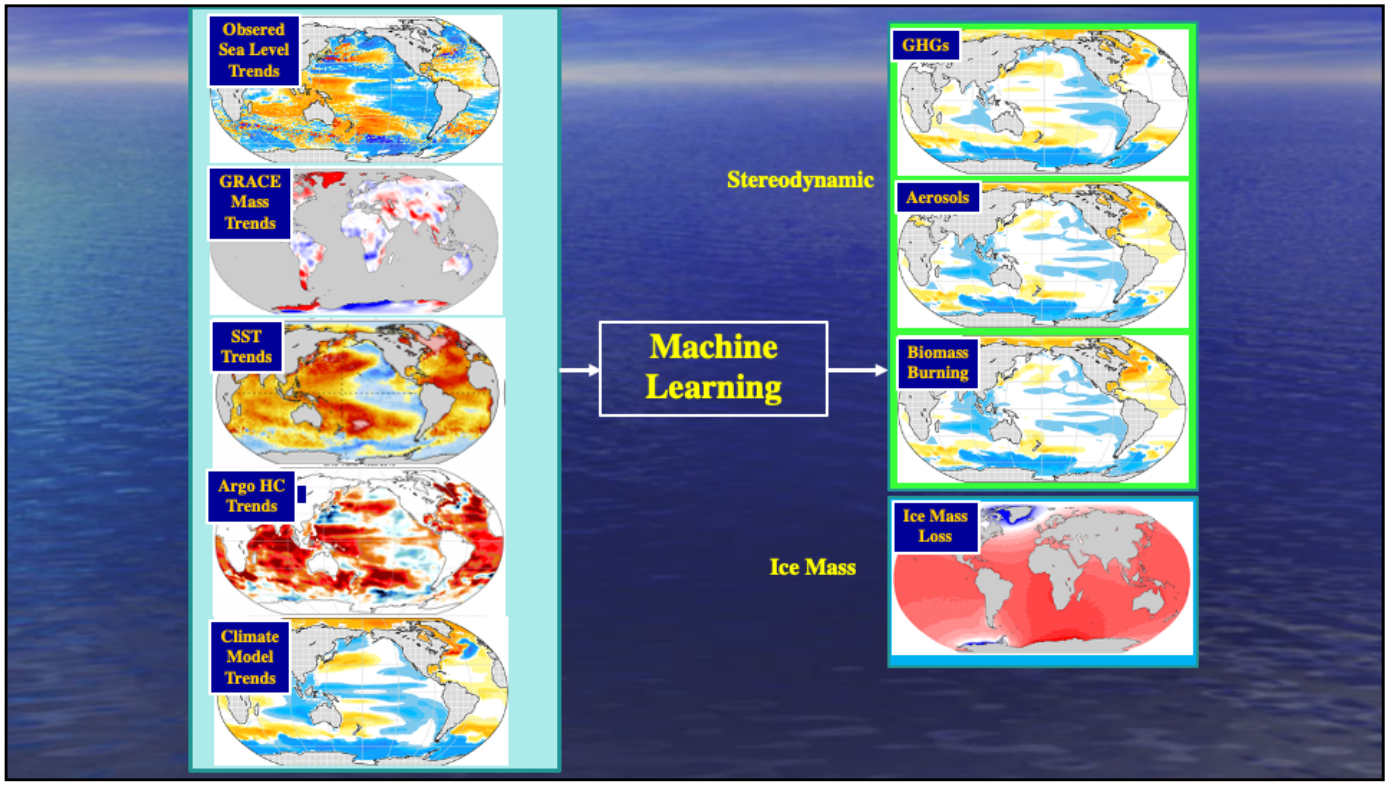
Removing natural variability does not impact the regional trend map from altimetry – another indication that the Forced Response should be emerging from the natural variability.



Hamlington, B. D., Frederikse, T., Nerem, R. S., Fasullo, J. T., & Adhikari, S. (2020). Investigating the Acceleration of Regional Sea-level Rise During the Satellite Altimeter Era. *Geophysical Research Letters*.



Estimates of regional variability in the acceleration of SSH are still strongly impacted by natural variability. Removing the natural variability improves the regional map substantially [Hamlington et al., 2020].



We are investigating a machine learning approach to untangling the contributions to the observed regional sea level change during the altimeter era.

Conclusions

- Single-model large ensembles have been used to show that the Forced Response (FR) of sea level change due to GHGs and aerosols is emerging in the altimeter record.
- The results also suggest some persistence in the FR into the future, which may allow the altimeter data to be used to predict future patterns of regional sea level change.
- The regional patterns of the FR are driven by variations in the thermal expansion coefficient, winds, ocean circulation, in addition to diversity and transient evolution of climate forcing agents.
- Machine learning approaches may offer a tool for disentangling the different contributions to the observed sea level change during the altimeter era.

References

- Fasullo, J. T., & Nerem, R. S. (2018). Altimeter-era emergence of the patterns of forced sea-level rise in climate models and implications for the future. *Proceedings of the National Academy of Sciences of the United States of America*, *115*(51), 12944–12949.
- Fasullo, J. T., Gent, P. R., & Nerem, R. S. (2020a). Forced Patterns of Sea Level Rise in the Community Earth System Model Large Ensemble from 1920 to 2100. *Journal of Geophysical Research, C: Oceans*. https://doi.org/10.1029/2019JC016030
- Fasullo, J. T., Gent, P. R., & Nerem, R. S. (2020b). Sea Level Rise in the CESM Large Ensemble: The Role of Individual Climate Forcings and Consequences for the Coming Decades. *Journal of Climate*, *33*(16), 6911–6927.
- Hamlington, B. D., Fasullo, J. T., Nerem, R. S., Kim, K., & Landerer, F. W. (2019). Uncovering the Pattern of Forced Sea Level Rise in the Satellite Altimeter Record. *Geophysical Research Letters*, *46*(9), 4844–4853.
- Hamlington, B. D., Frederikse, T., Nerem, R. S., Fasullo, J. T., & Adhikari, S. (2020). Investigating the Acceleration of Regional Sea-level Rise During the Satellite Altimeter Era. *Geophysical Research Letters*.
- Nerem, R. S., Beckley, B. D., Fasullo, J. T., Hamlington, B. D., Masters, D., & Mitchum, G. T. (2018). Climate-change-driven accelerated sea-level rise detected in the altimeter era. *Proceedings of the National Academy of Sciences of the United States of America*, *115*(9), 2022–2025.