Understanding Forced Climate Signals in the 30-year Satellite Altimeter Sea Level Record

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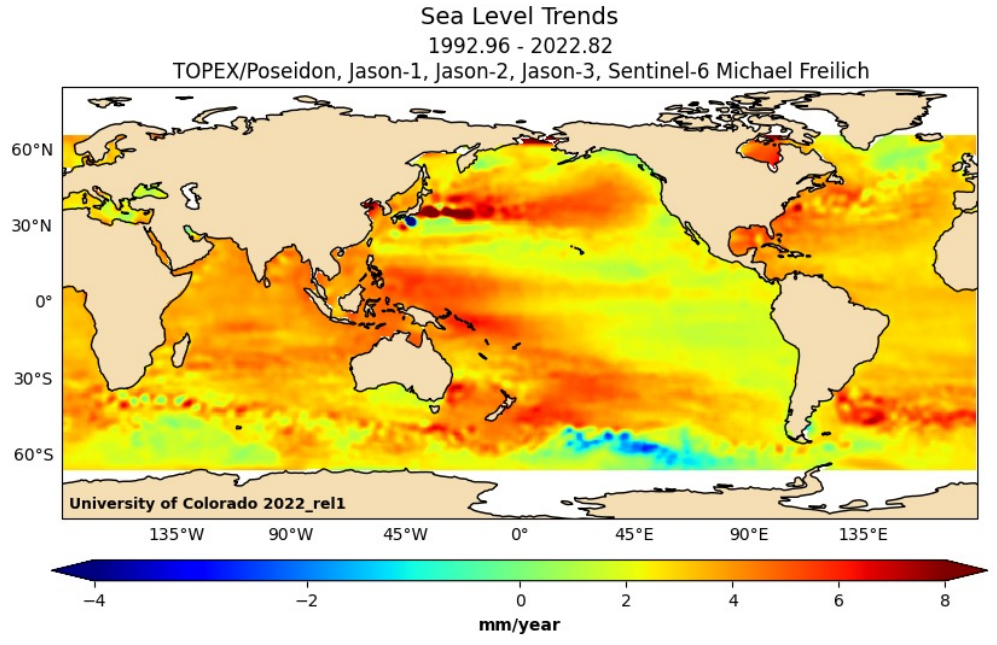

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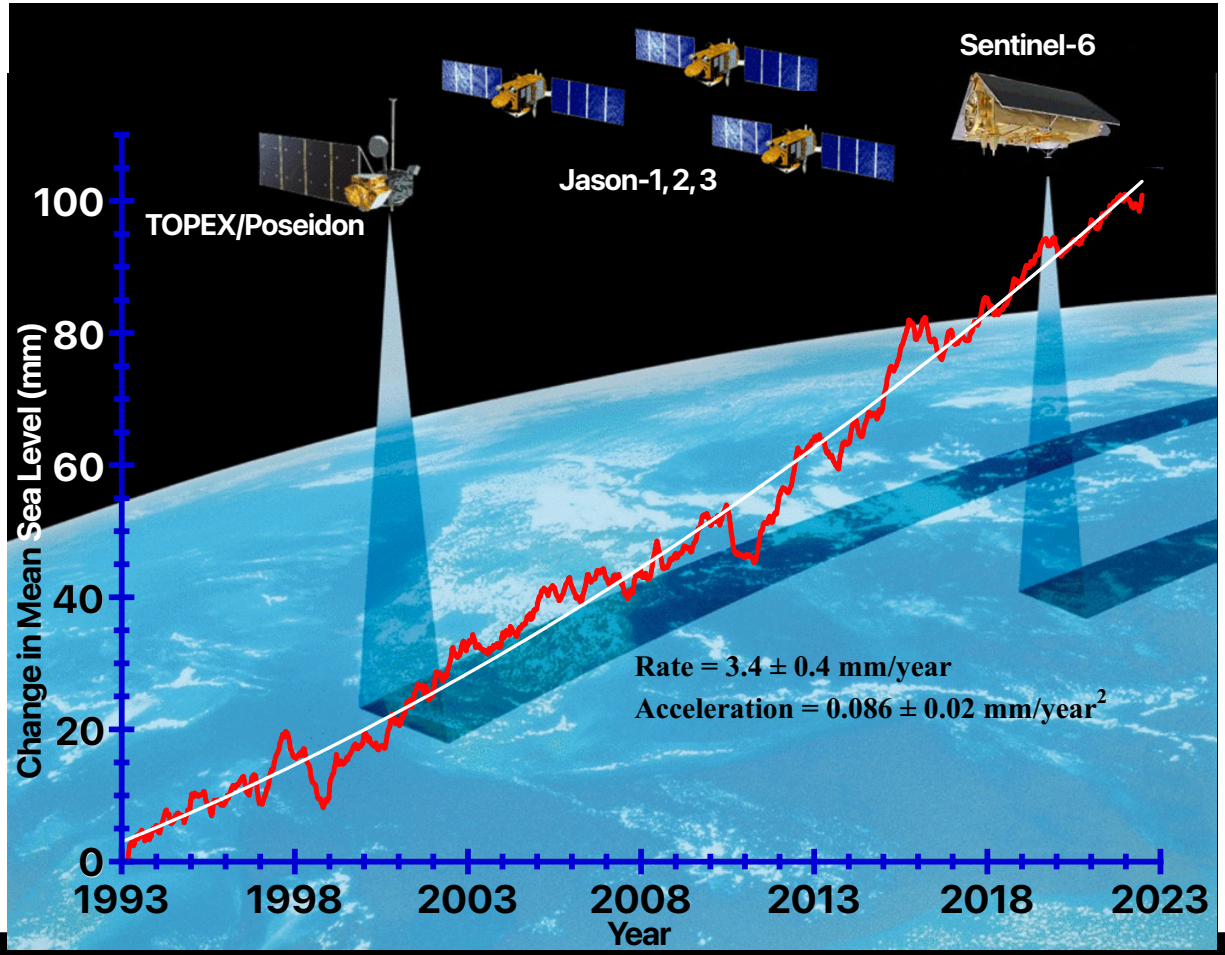
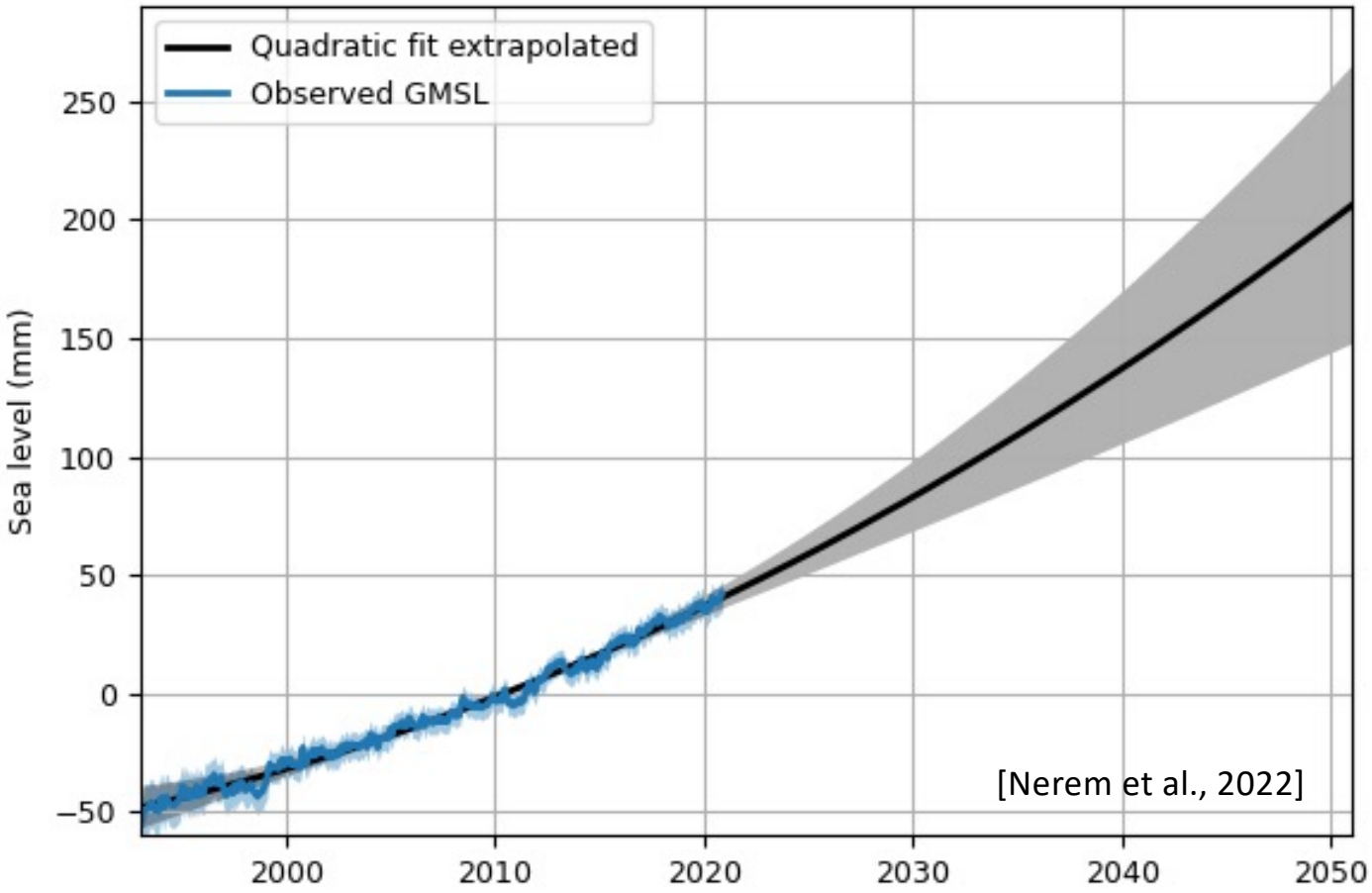
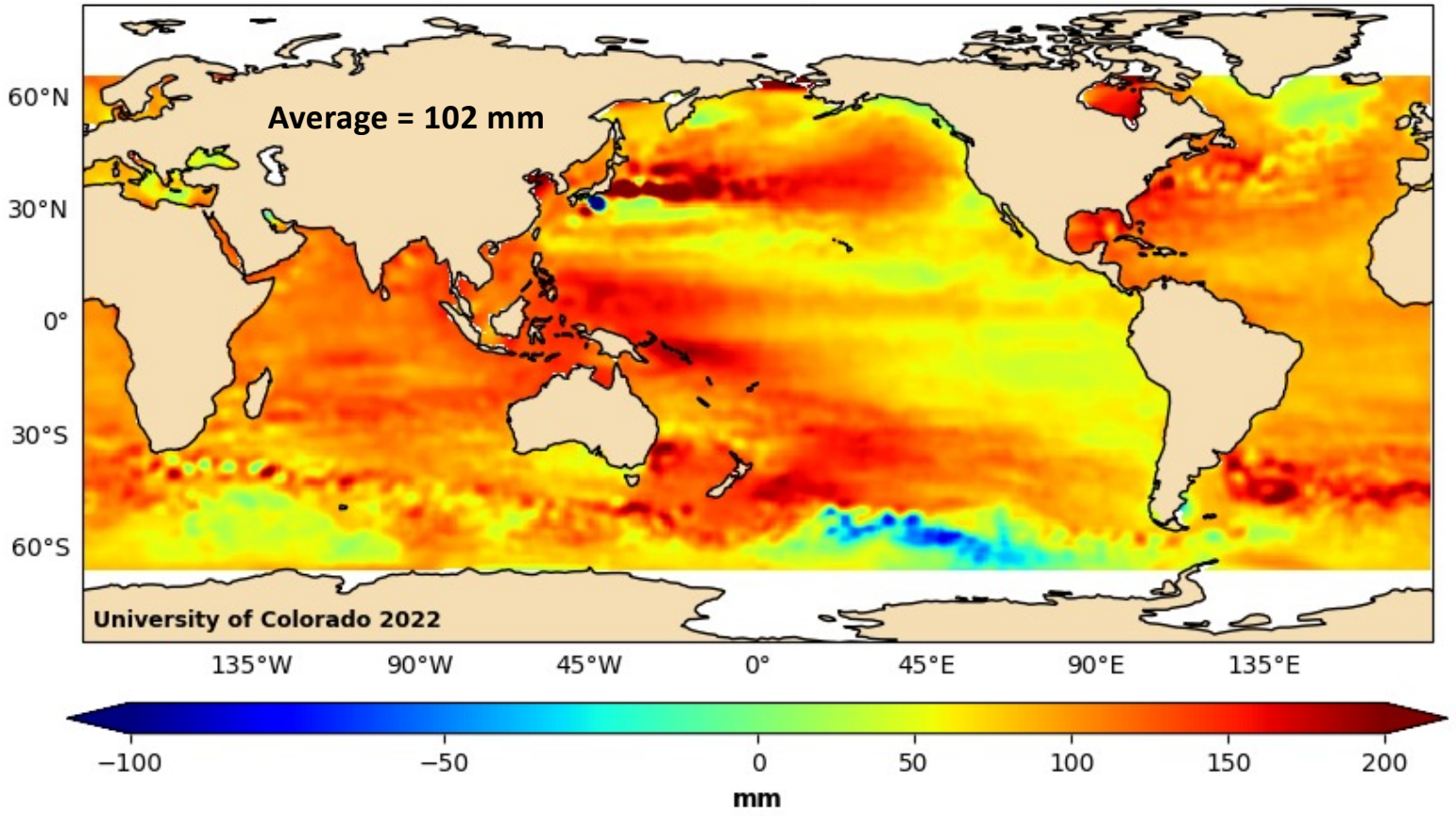
Global Mean Sea Level Variations



Extrapolation of Global Mean Sea Level Change



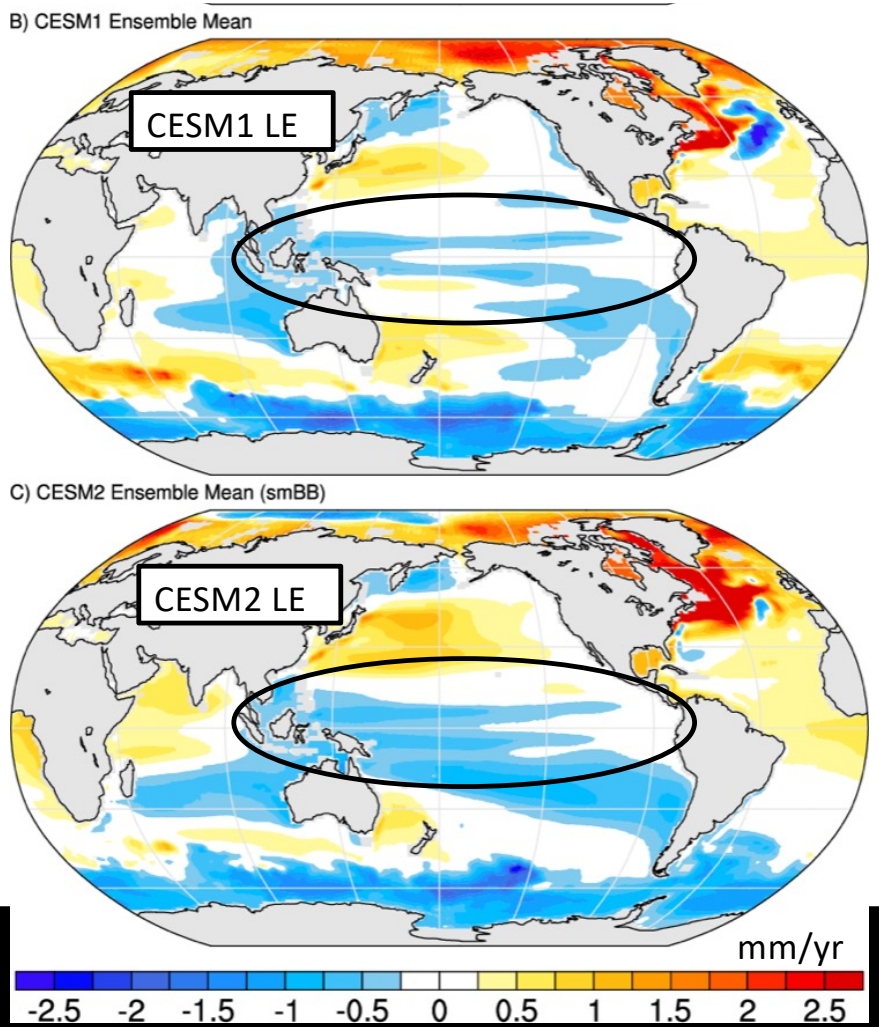
Total Regional Sea Level Change (1993-2022)

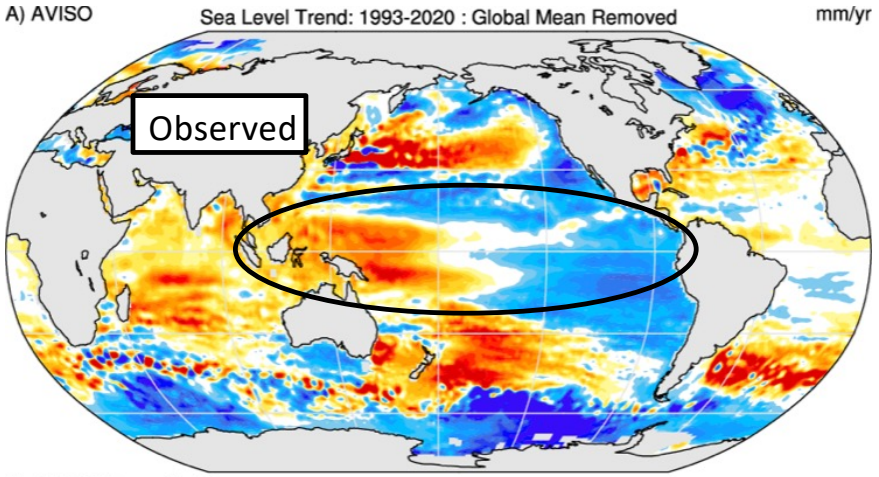


Regional Sea Level Change

- Observed 30-year regional sea level changes are telling us how ocean and atmospheric dynamics are changing due to climate change and contain information about future sea level changes.
- Climate models large ensembles can assist us in interpreting the 30-year sea level record and suggest that the forced response due to climate change should be emerging in the observations.
- How to include observations of regional sea level change in data-driven projections of future sea level change?
  - Understand the physics driving the observed regional changes.
  - Understand the differences between the observed regional changes and those seen in different climate models.
- A variety of approaches are being pursued to use the observed regional changes to understand future changes. We are exploring:
  - Extrapolations of regional sea level change aided by results from climate models.
  - Machine learning approaches that train on output from climate models and then operate on the observed regional sea level trends.

Modeled and Observed Sea Level Trends (1993-2020)

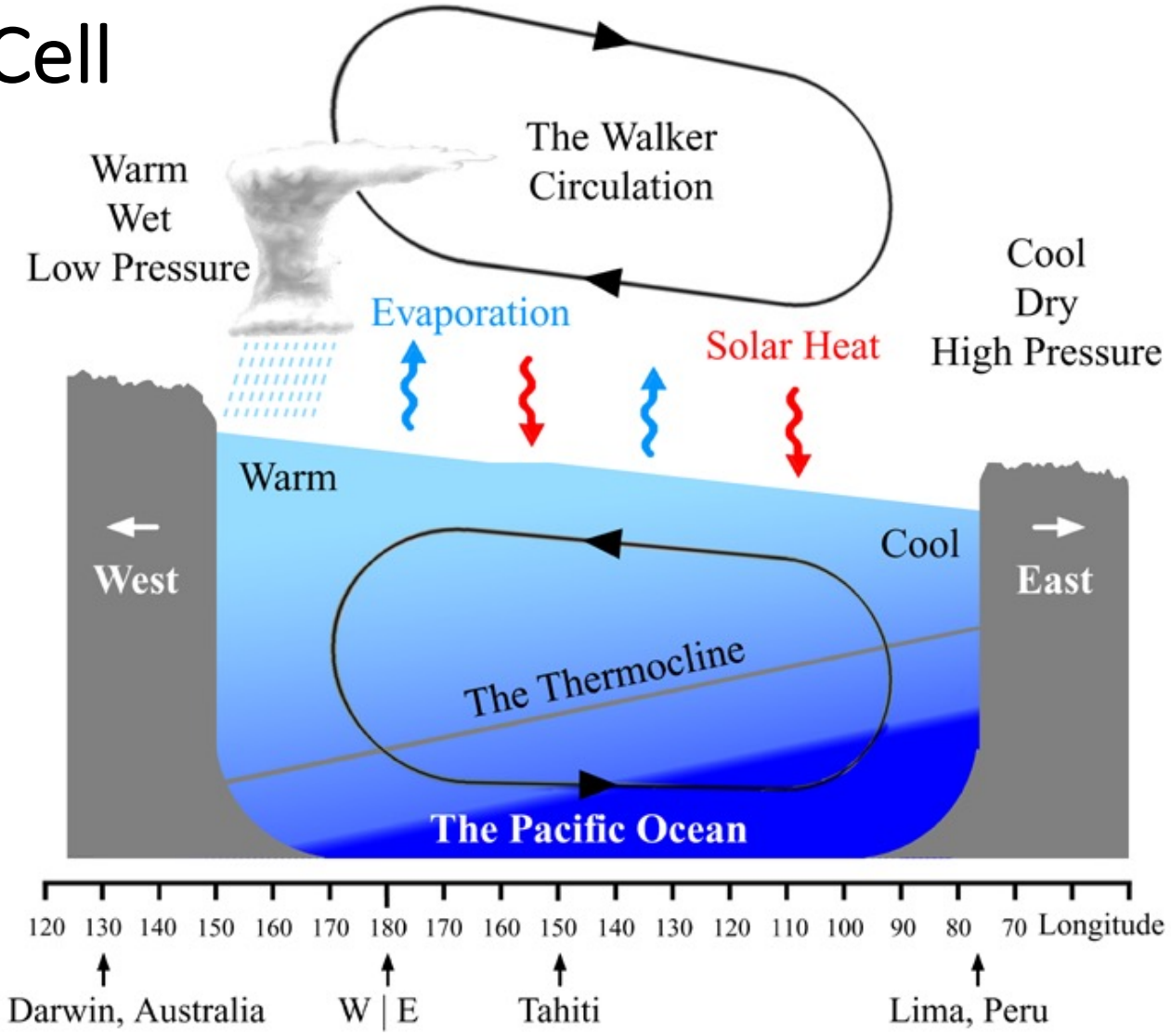




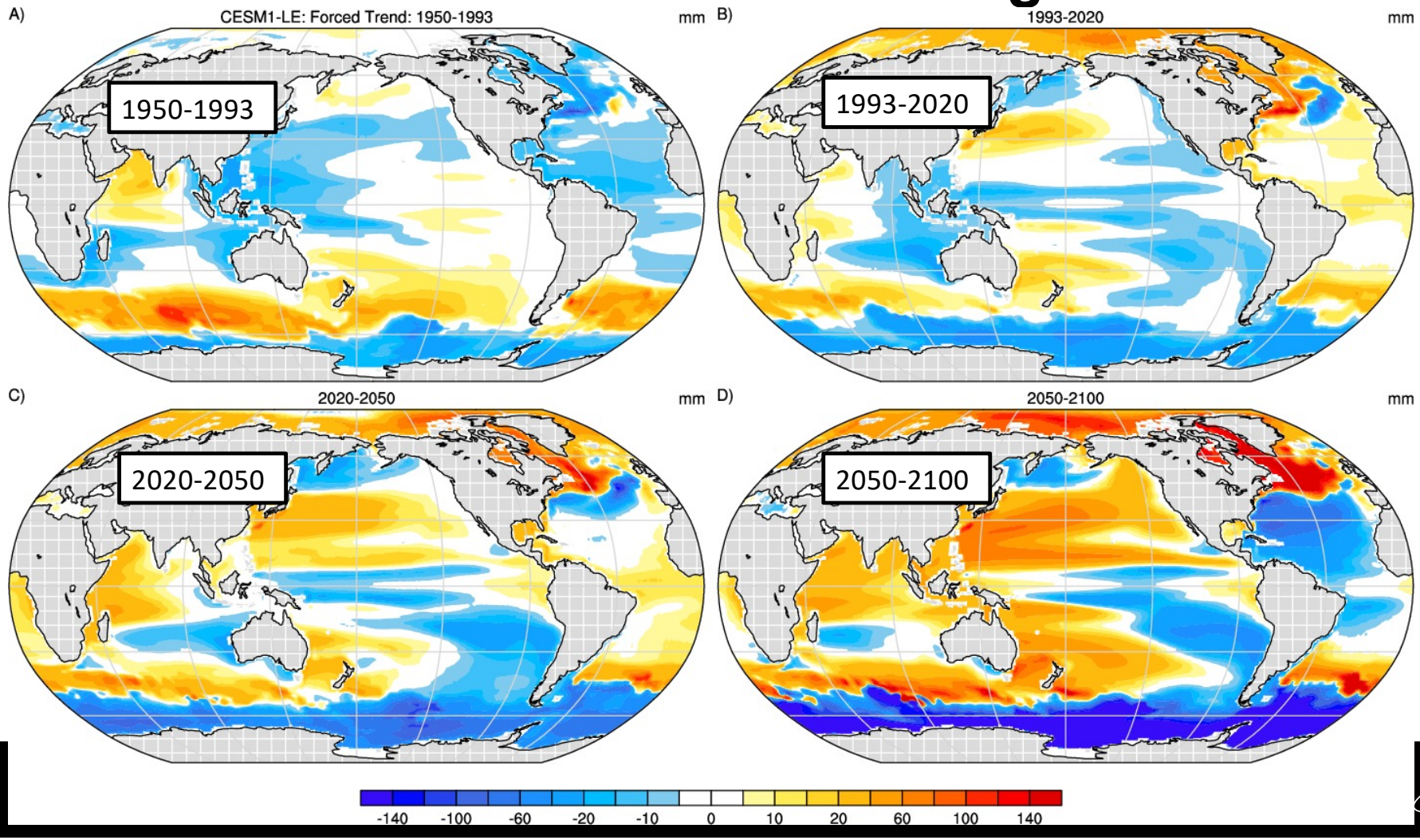
- Global mean trend removed
- Modeled trends are generally smaller than observed trends
- Gradient across the tropical Pacific is missing in the models
- We are decomposing this using single-forcing model experiments.

The Walker Cell

There are some indications that the climate models can be "tuned" to increase the Walker circulation and the sea level gradient across the Pacific to better agree with the altimeter observations.



Forced Trends in the CESM1 Large Ensemble



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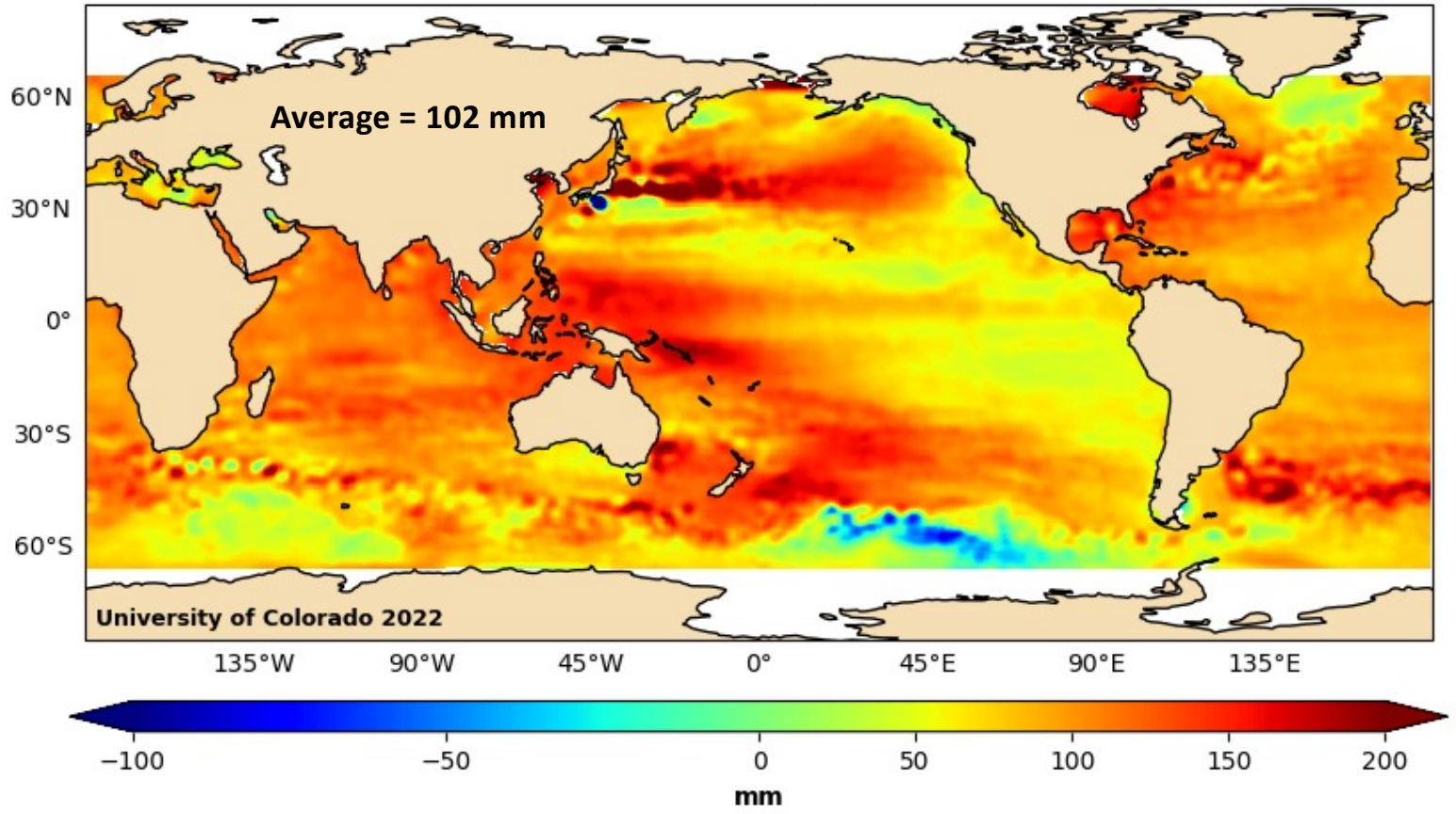
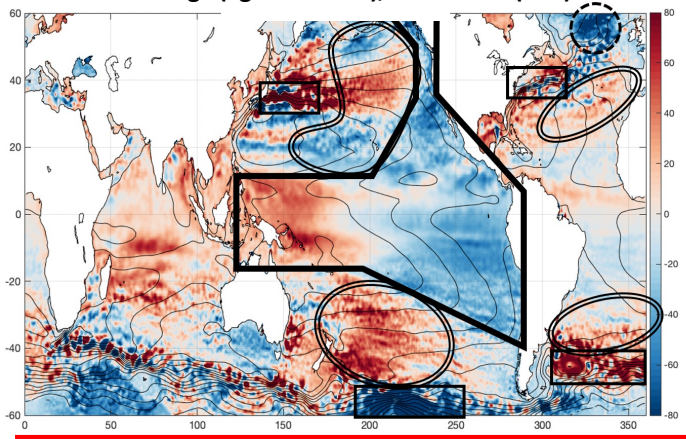
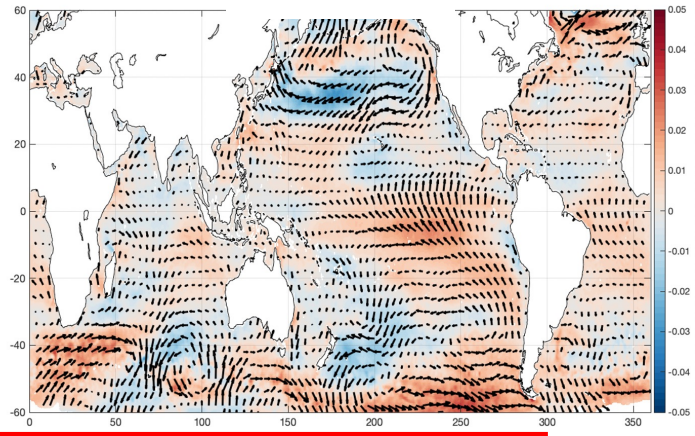


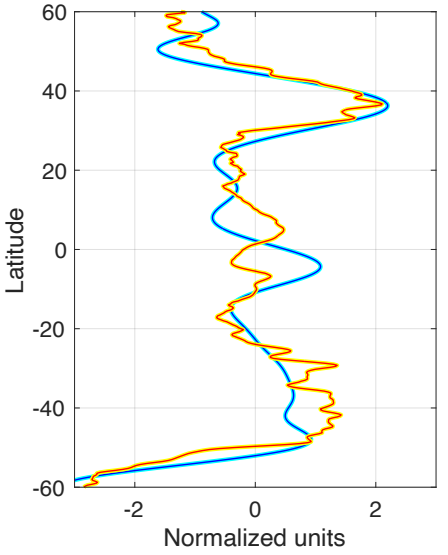
Unraveling Regional Patterns of Sea Level Rise over the Altimeter Era

SLA change (–global mean), 1993–2020 (mm)



Wind stress trend, 1993–2020 (m/yr)





— Small latitudinal shifts near strong mean gradients = large local trend
- Poleward shifts in Northern Hemisphere WBC systems
- Latitudinal shifts in Antarctic Polar Front

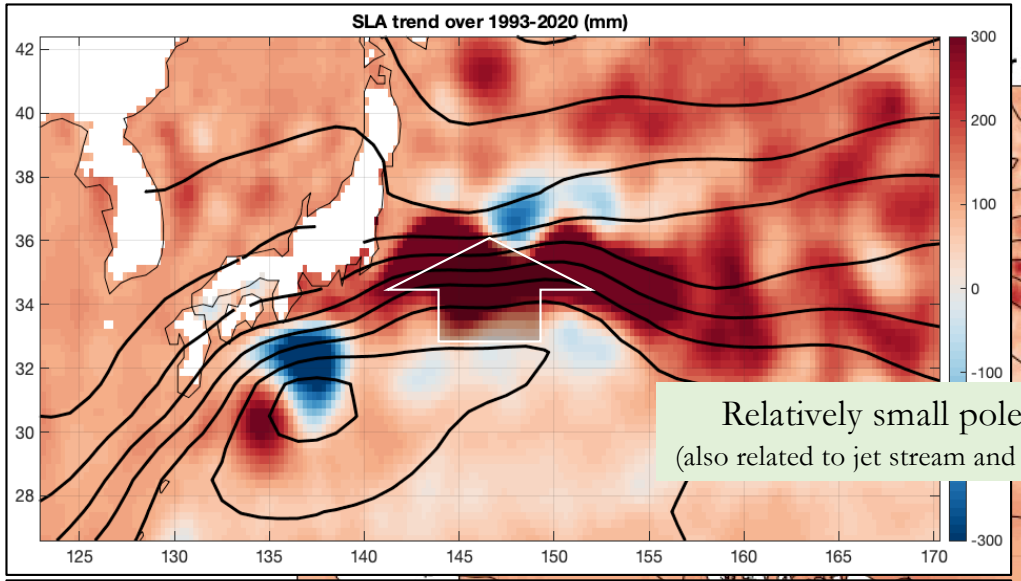
— Strengthening of the trade wind system in the tropical+ Pacific (basically Ekman dynamics)
- Stronger coastal upwelling on the eastern boundary along U.S. west coast (more related to the subtropical highs)
- Stronger zonal gradient (tilt) of tropical thermocline depth (more related to the easterly trades)

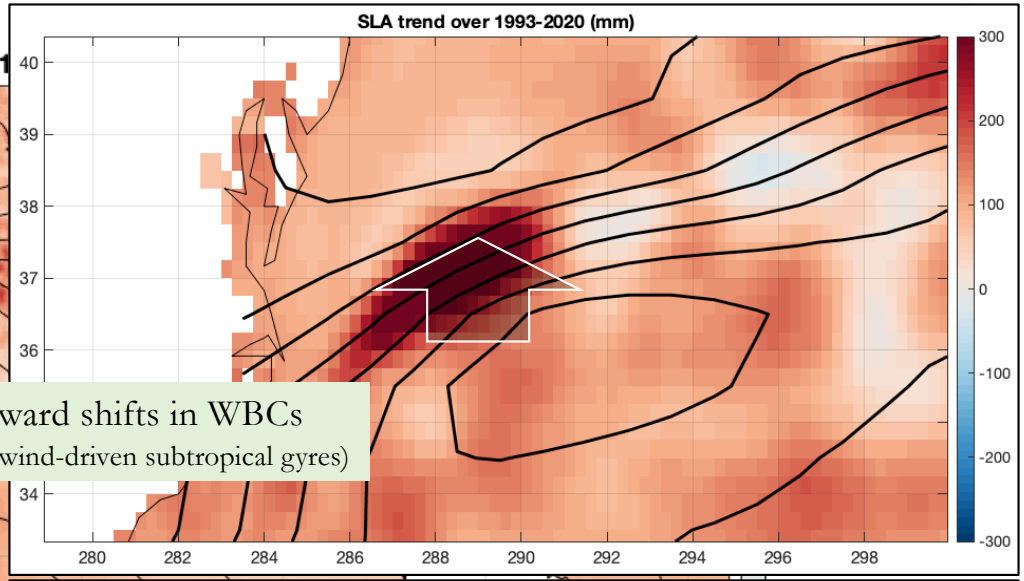
$$\frac{\partial}{\partial y}\left(\frac{1}{\rho\beta}\frac{\partial \tau_x}{\partial y}\right)$$

═ Ocean circulation response to wind forcing (Sverdrup transport convergence) outside of the tropics
- Related to the latitudinal structure of the zonal winds, including the jet stream, etc.

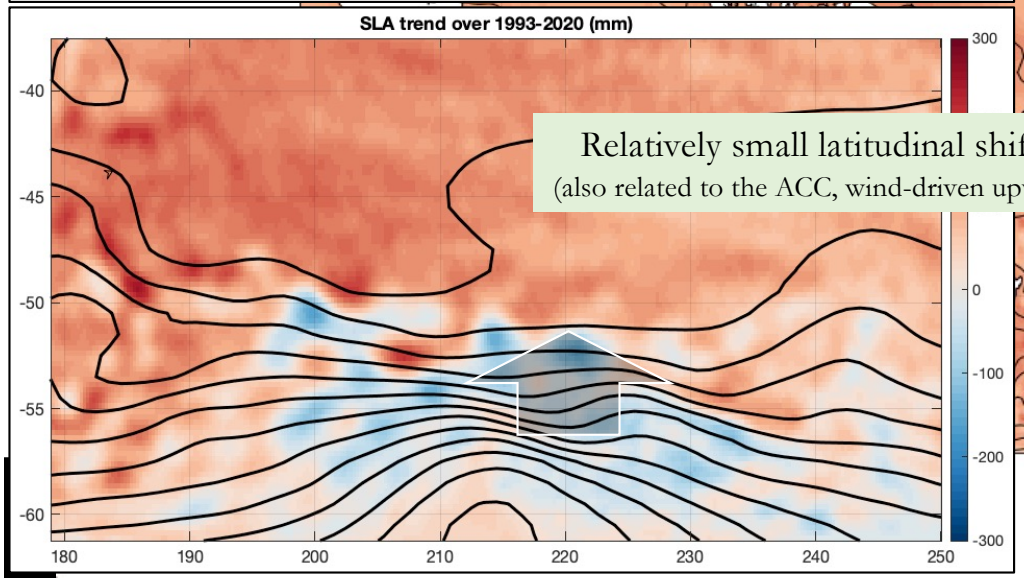
----- Reduction of poleward heat transport by AMOC

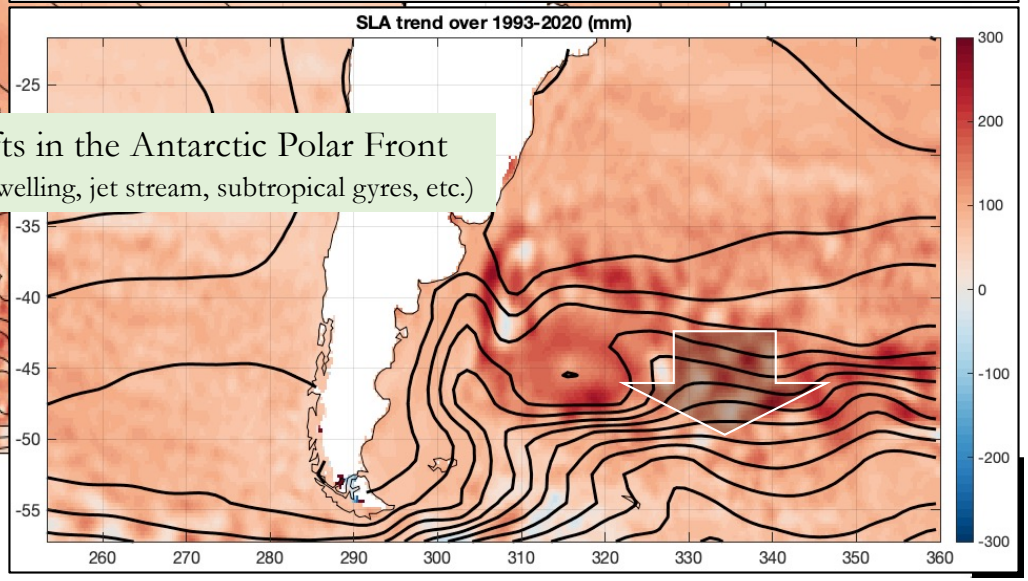
[Karnauskas et al., 2022, in preparation]





Relatively small poleward shifts in WBCs
(also related to jet stream and wind-driven subtropical gyres)

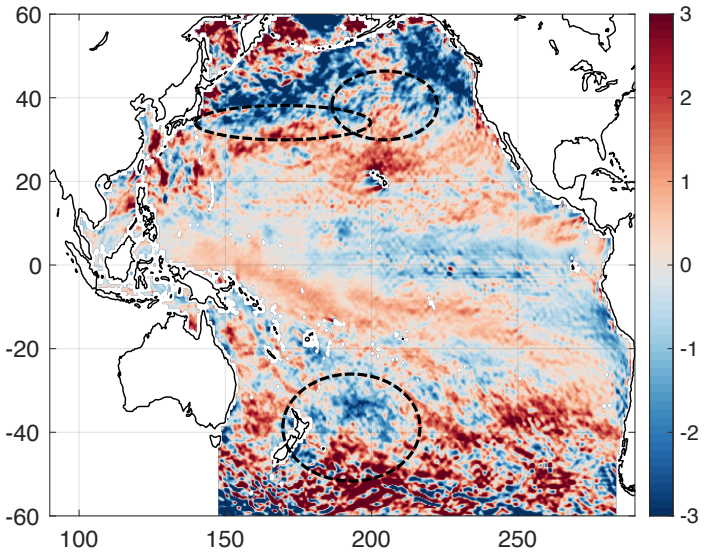


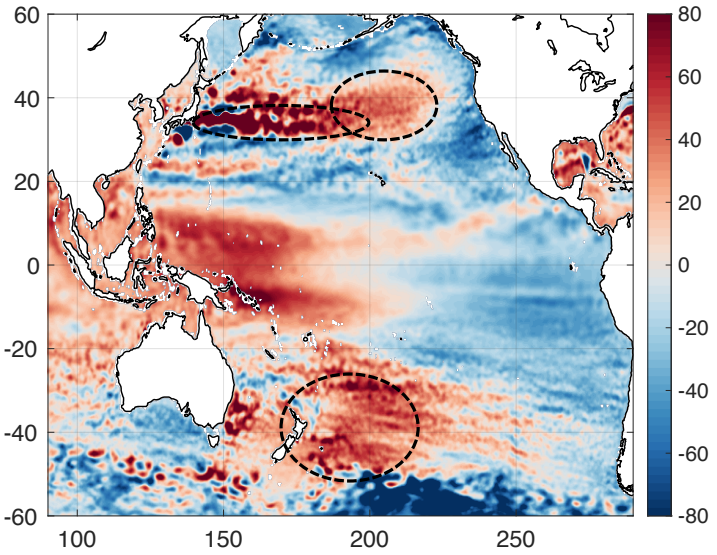


Relatively small latitudinal shifts in the Antarctic Polar Front
(also related to the ACC, wind-driven upwelling, jet stream, subtropical gyres, etc.)

Sverdrup transport

$$M^{y}_{sv} = \frac{1}{\rho_0 \beta} \nabla \times \vec{\tau}$$





Where the Sverdrup transport trends are converging, sea level rise is higher than average.

Unraveling Regional Patterns of Sea Level Rise over the Altimeter Era

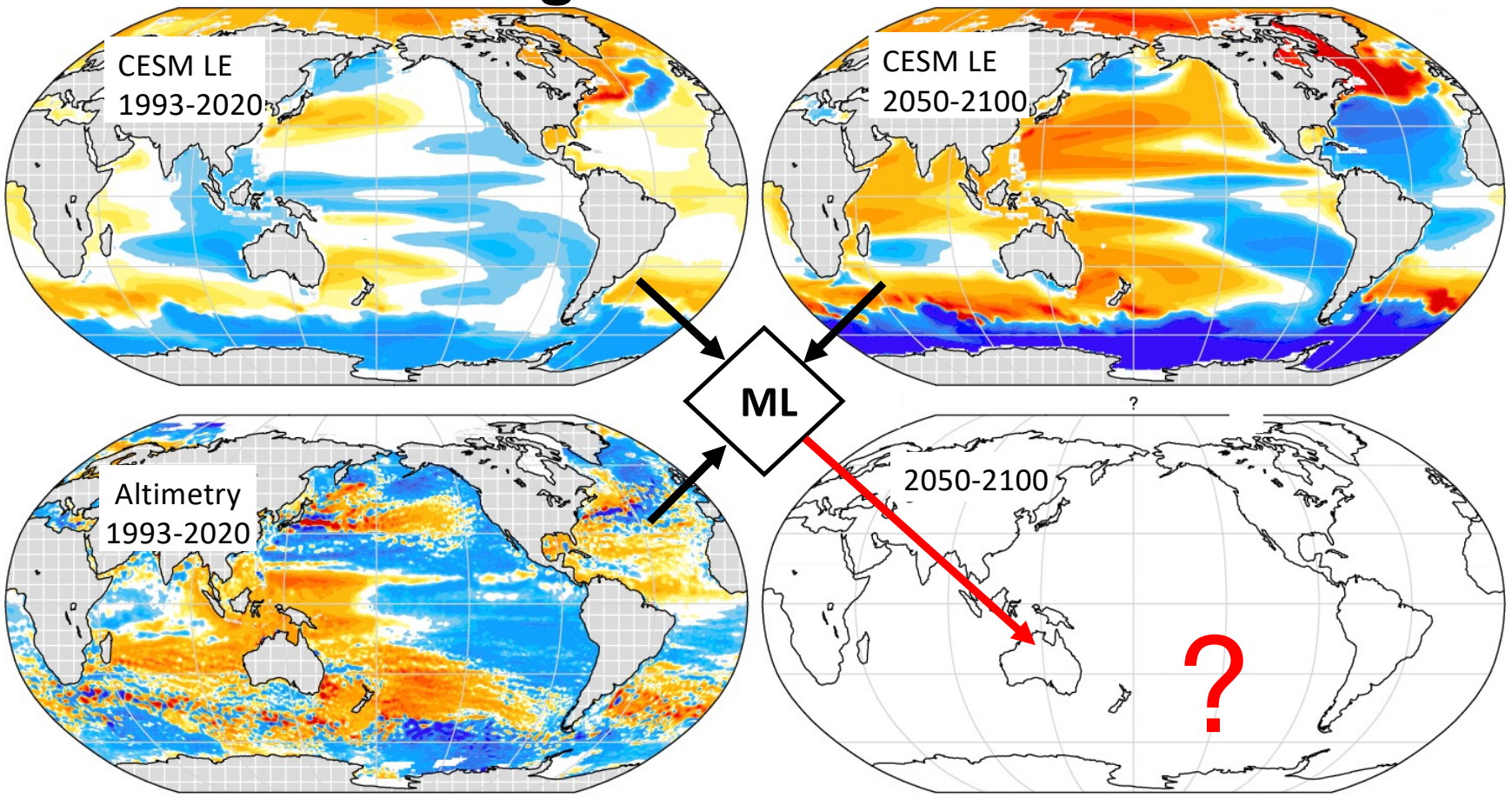
- We argue that the global pattern of sea level rise since 1993 is set, to leading order, by changes in the wind-driven ocean circulation and their influence on sea surface height via **ocean heat transport.**
- "Wind-driven" needn't be synonymous with internal variability. Much of the observed global pattern is **recovered by global climate models** subject to historical anthropogenic forcings.
- The latitudinal structure may be explained by changes in zonal wind driving a redistribution of mass (with role for OHC) via **Sverdrup dynamics**.
- The *zonal* structure outside of the tropics is probably explained by a combination of western intensification and **Ekman dynamics**.
- Zonal gradients in the tropics (esp. Pacific) are probably Ekman and coupled dynamics driving a zonal redistribution of heat content.
- The wind patterns may themselves be driven by patterns of ocean warming, making the interpretation complex……...
- These patterns are largely **thermosteric in origin** – they will fundamentally change in the future as the **ice sheets** (and their sea level fingerprints) start to dominate regional sea level change.

[Karnauskas et al., 2022, in preparation]

Next Steps

- With an understanding of how ocean and atmospheric dynamics are changing due to climate change, how might we incorporate this information in projections of regional sea level change?
- Climate models offer a path forward, but there are still disagreements with the observations that need to be resolved.
- Data-driven approaches likely need a longer observational record before they can be implemented.
- Can the insight from the observations and climate models be combined?

Machine Learning – A Path Forward?

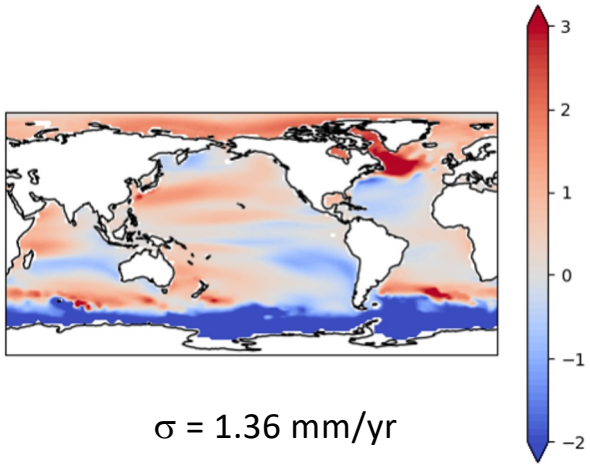


Predicting Sea Level Change Using Machine Learning

Combining climate models and satellite observations

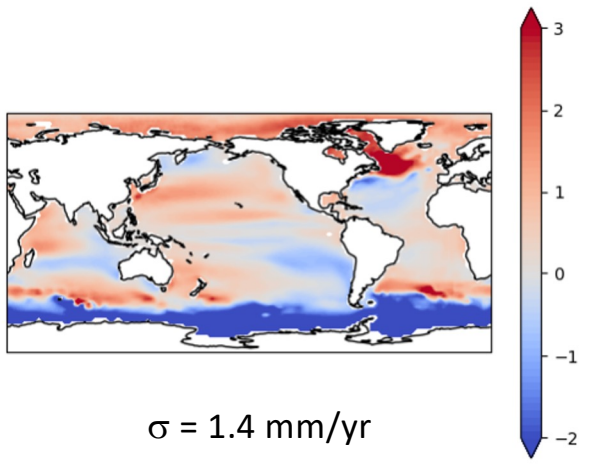
Training Data for ML: CESM1 SSH trend data over 1930-2010
Input for Prediction: CESM1 SSH trend data over 1993-2020

CESM1
Trends over 2041 - 2070



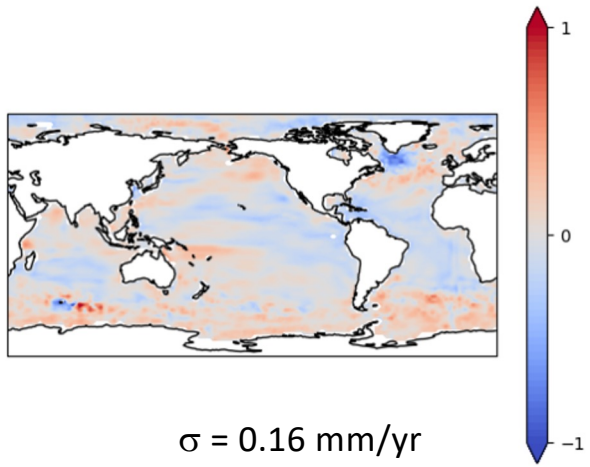
σ = 1.36 mm/yr

ML Prediction
Trends over 2041 - 2070



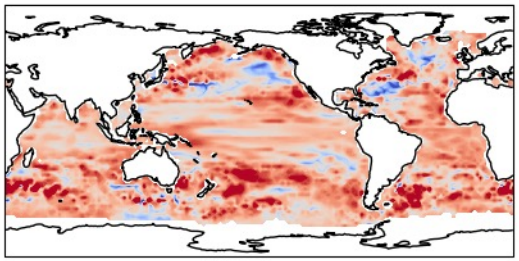
σ = 1.4 mm/yr

Difference
Trends over 2041 - 2070

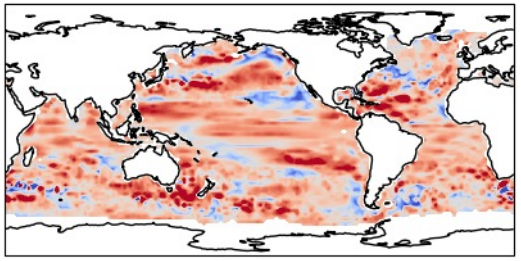


σ = 0.16 mm/yr

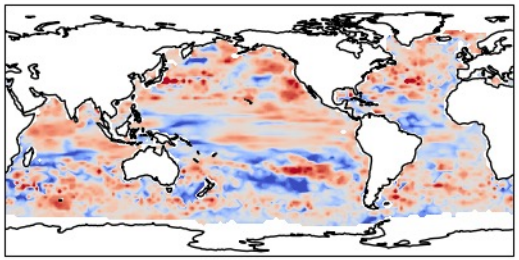
Multiple Regression of Climate Models on the Altimeter Observations



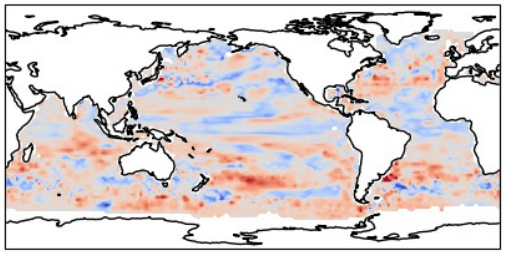
CESM1LE



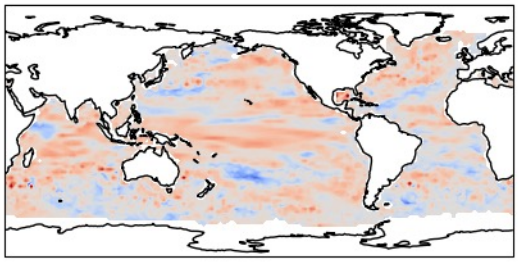
CESM2LE



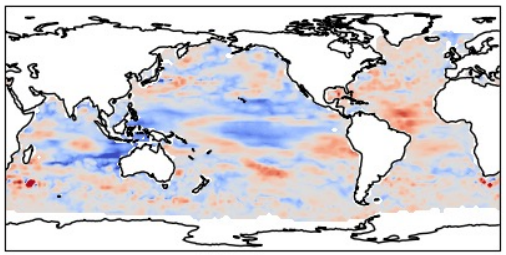
MPIGE



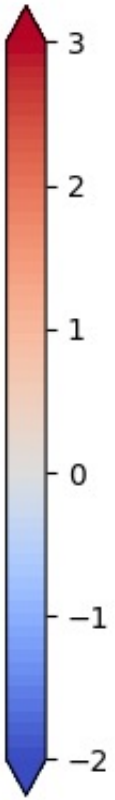
GFDLESM2M

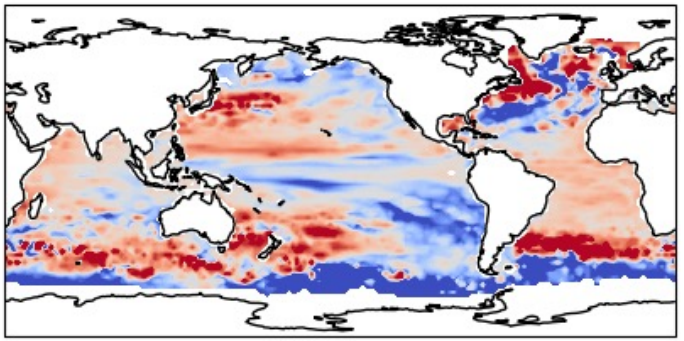


MPI-ESM1-2-HR



MPI-ESM1-2-LR





Predicted altimeter trend for 2023-2049,

Summary

- Climate models suggest that the forced response due to climate change is emerging in the altimeter-observed 30-year sea level trends.
- Observations of regional sea level change from satellite altimetry are providing valuable insight into the climate-induced changes in ocean and atmospheric dynamics, which helps inform future regional sea level changes.
- Large-scale ocean dynamics, particularly those that govern the wind-driven ocean circulation, play the predominate role in determining where heat is being stored in the ocean and setting the currently observed spatial pattern of sea level change.
- Machine learning may offer a way to combine altimeter observations and climate models to understand what the currently observed patterns of sea level change are telling us about the future.