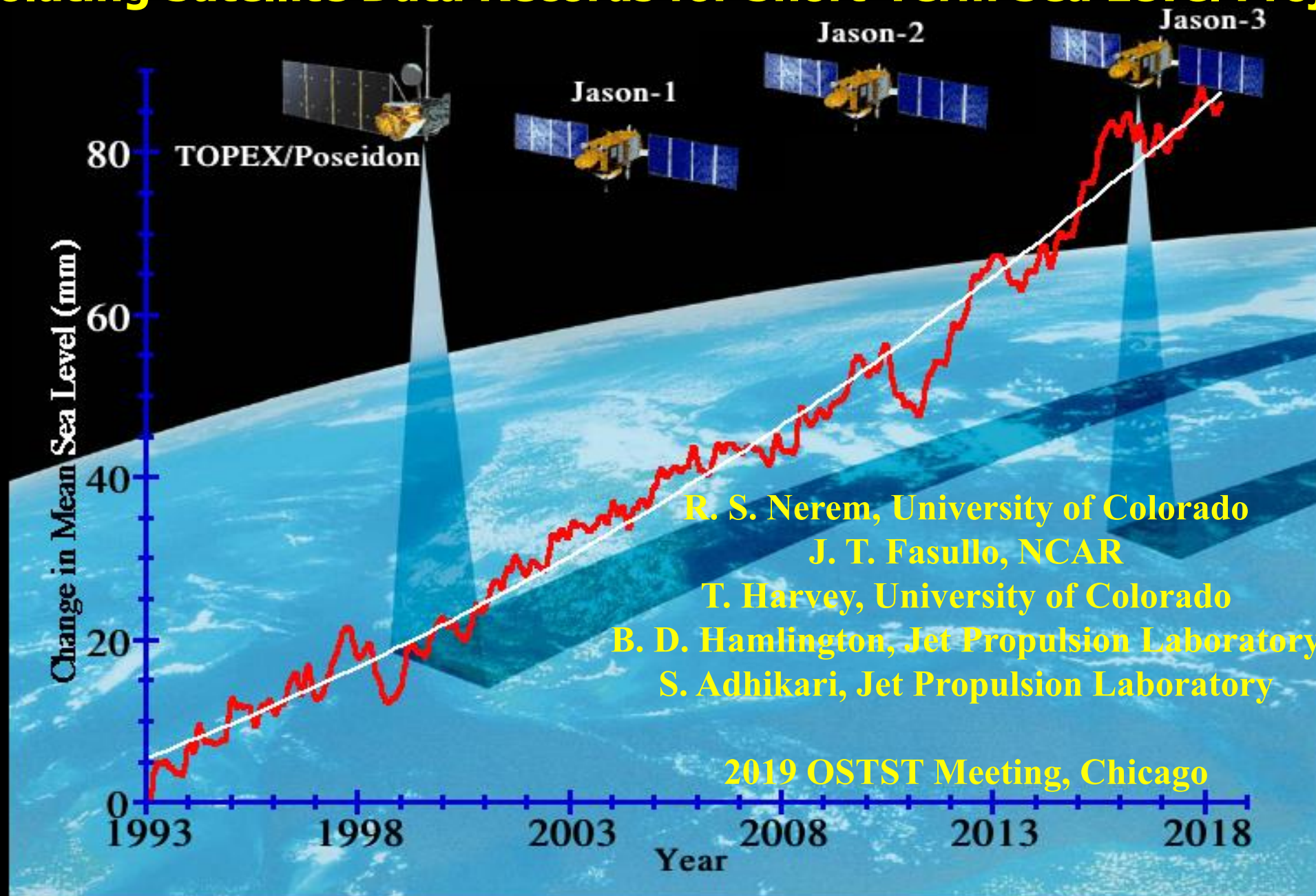
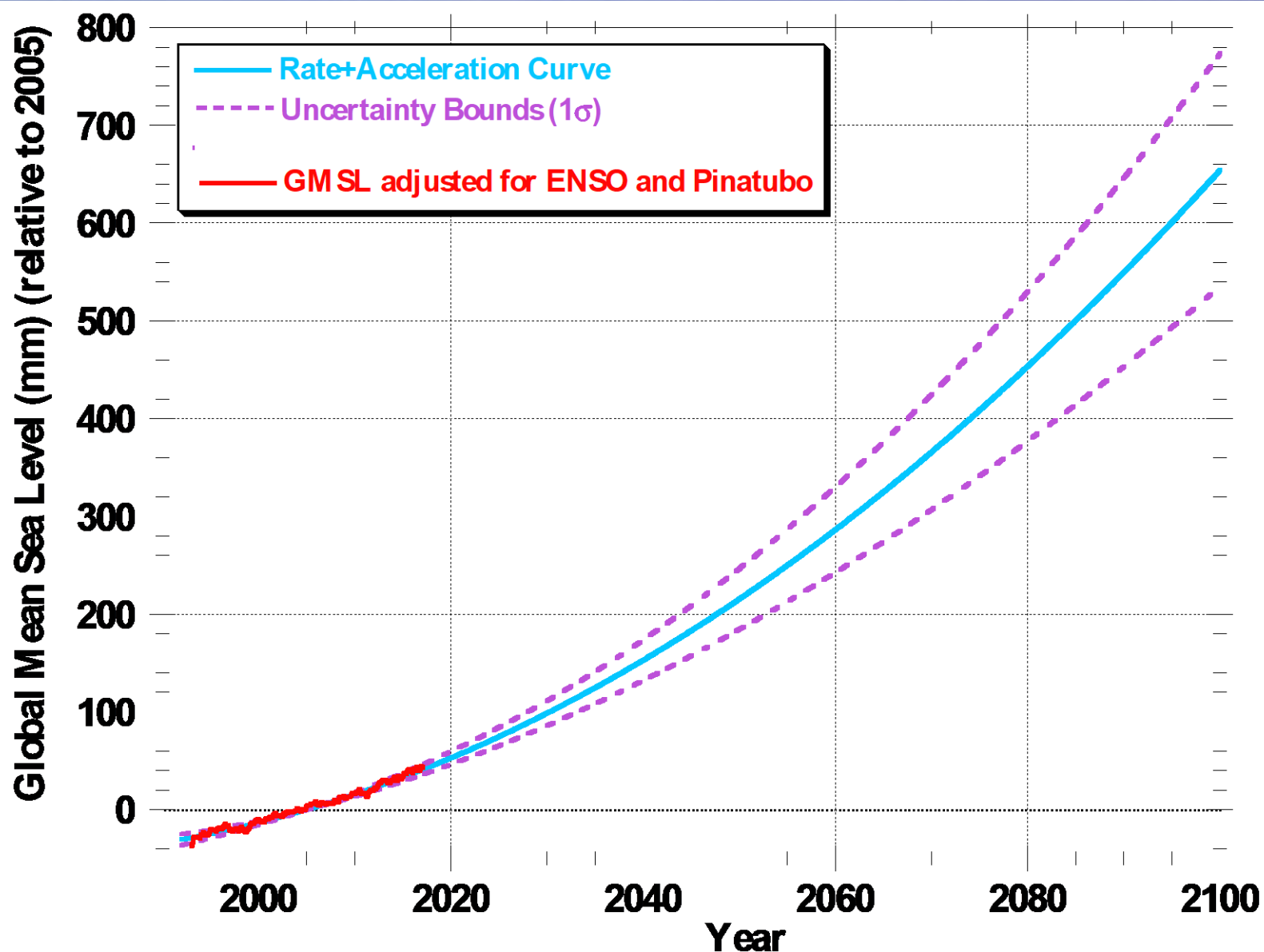


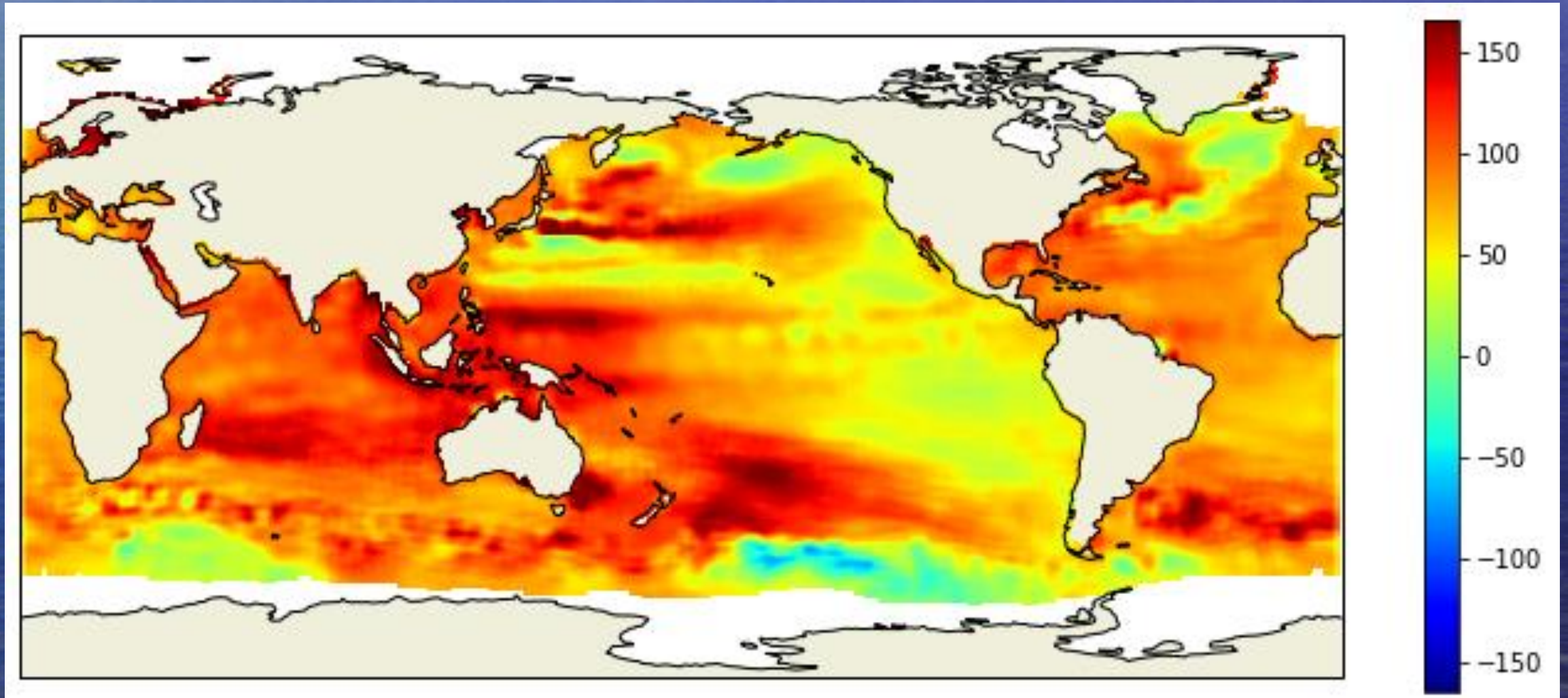
Extrapolating Satellite Data Records for Short-Term Sea Level Projections



Extrapolation of Satellite Era GMSL Rate & Acceleration



Observed Sea Level Change (1993 - 2019)



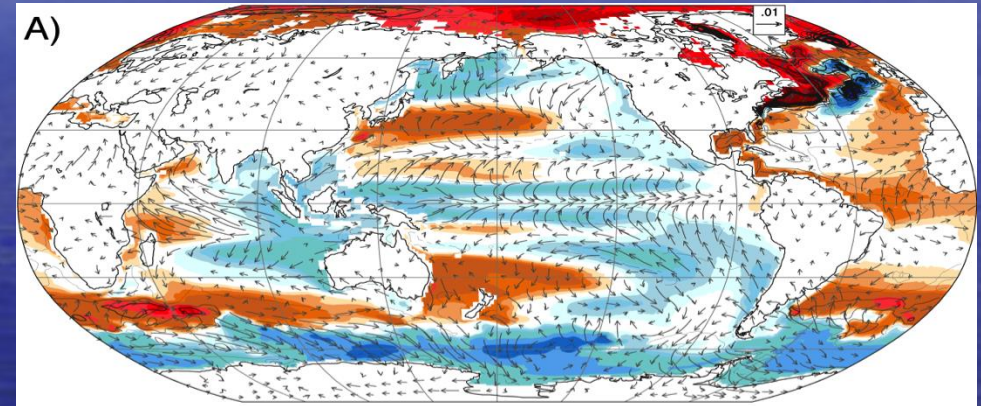
Global Average: 83 mm

Climate Model LEs & Regional Sea Level Change

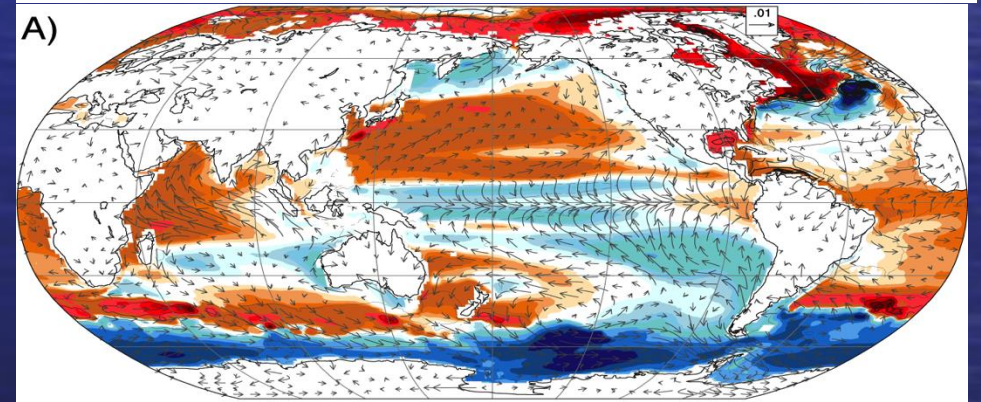
- Large ensembles (LEs) of climate models show that the Force Response (FR) of regional sea level change should be emerging from the 25-year altimeter data record.
- The LEs also predict that this pattern of regional sea level change will continue through the next century, thus the altimeter trend pattern can be used as a blueprint (scaling pattern) for future regional sea level change.

Forced Response Sea Level Trends

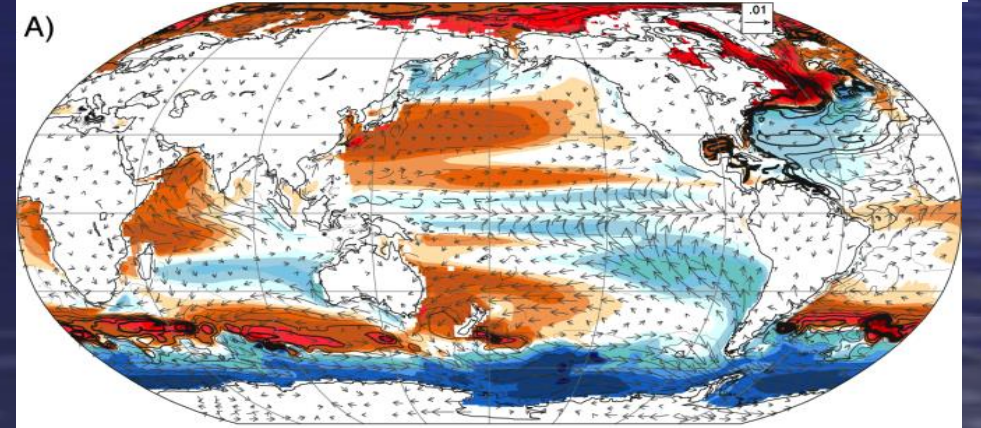
1993-2018

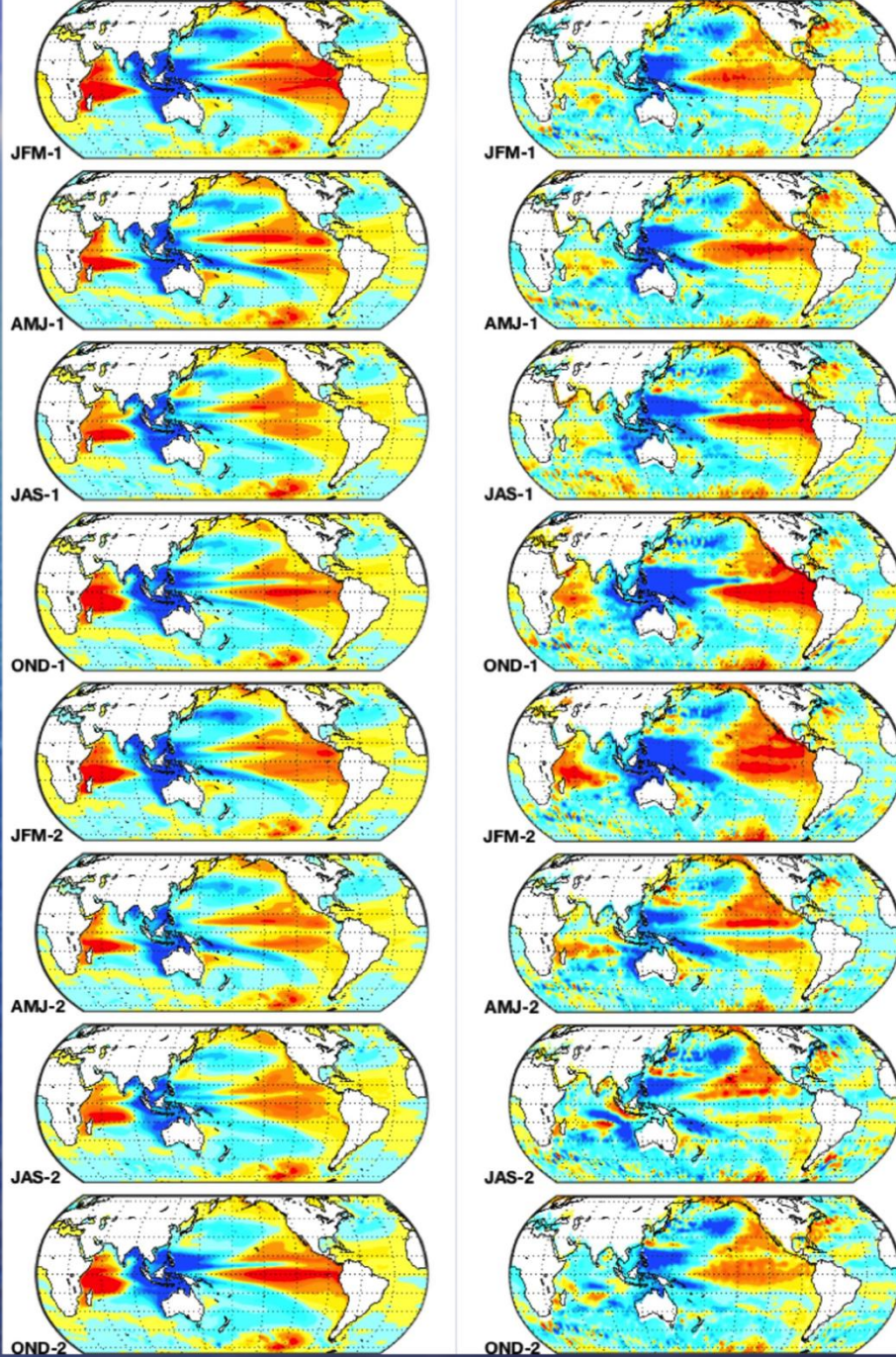


2020-2045



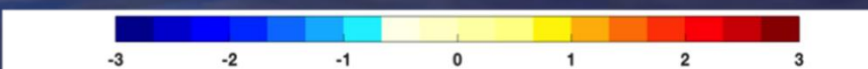
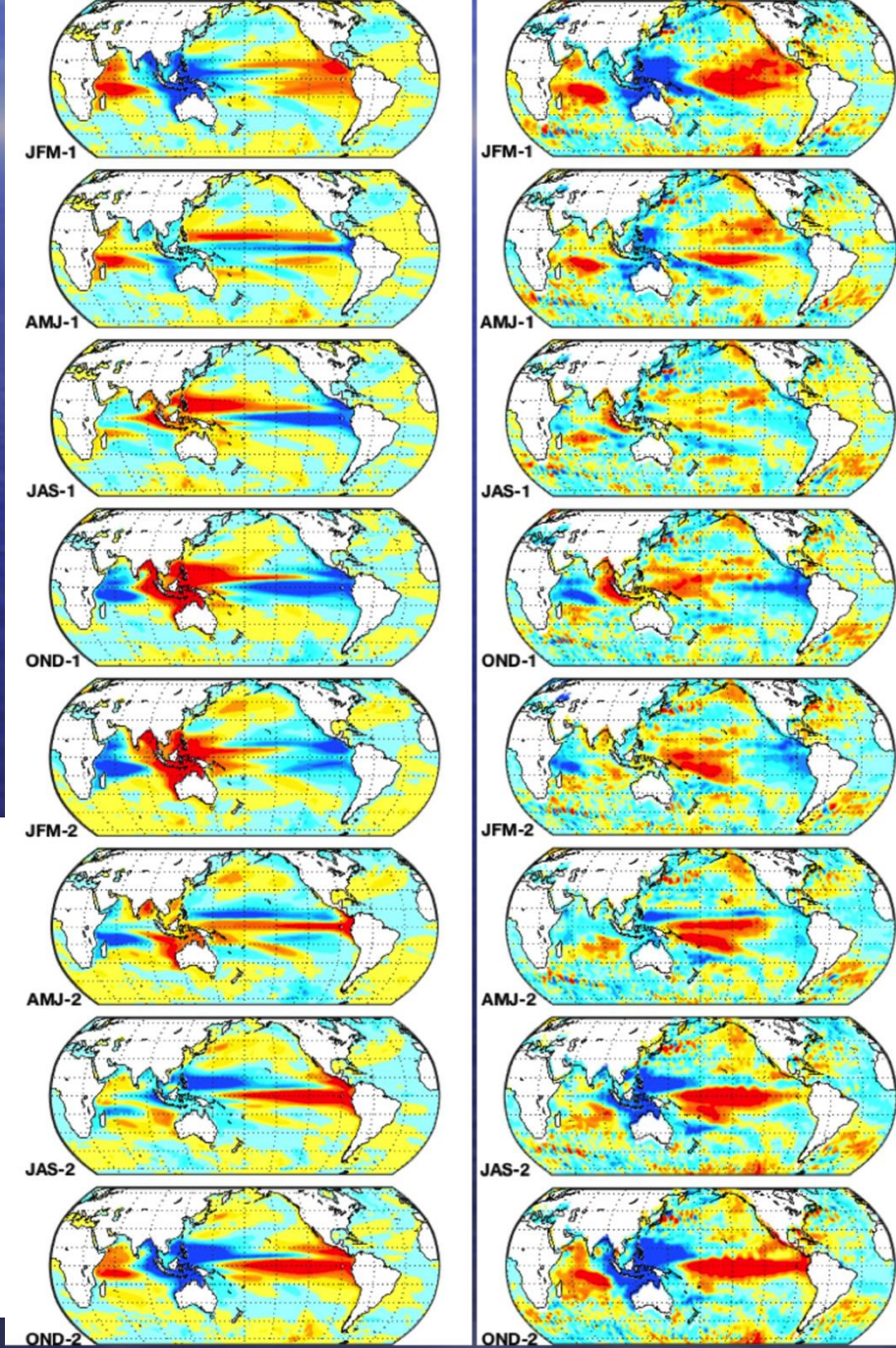
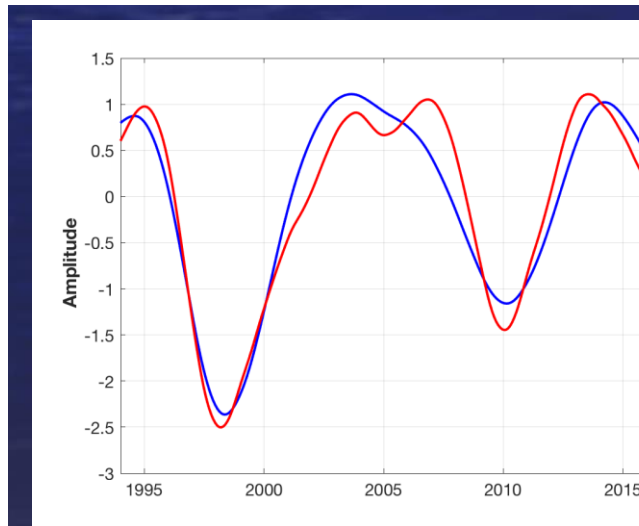
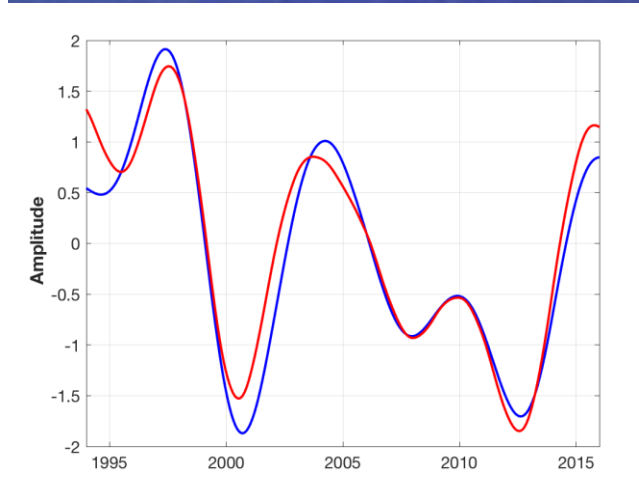
1950-2100



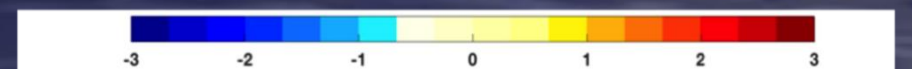


Removing Natural Variability

< Low Freq ENSO & PDO >



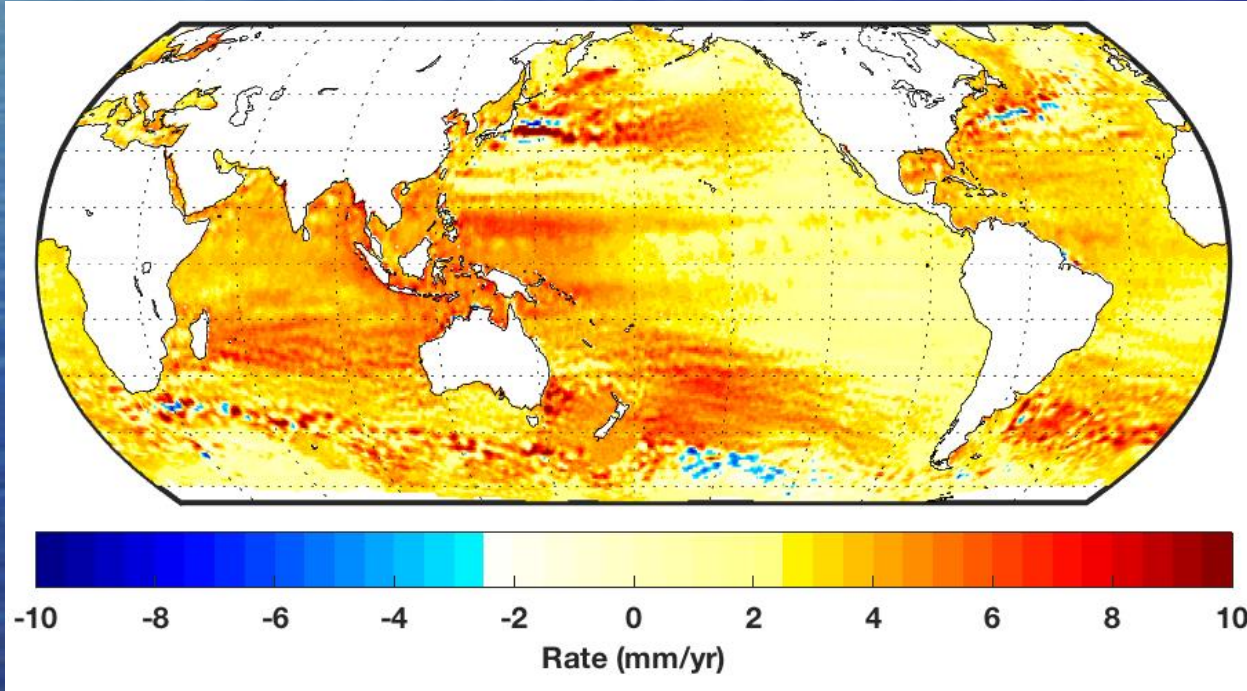
[Hamlington et al., 2019]



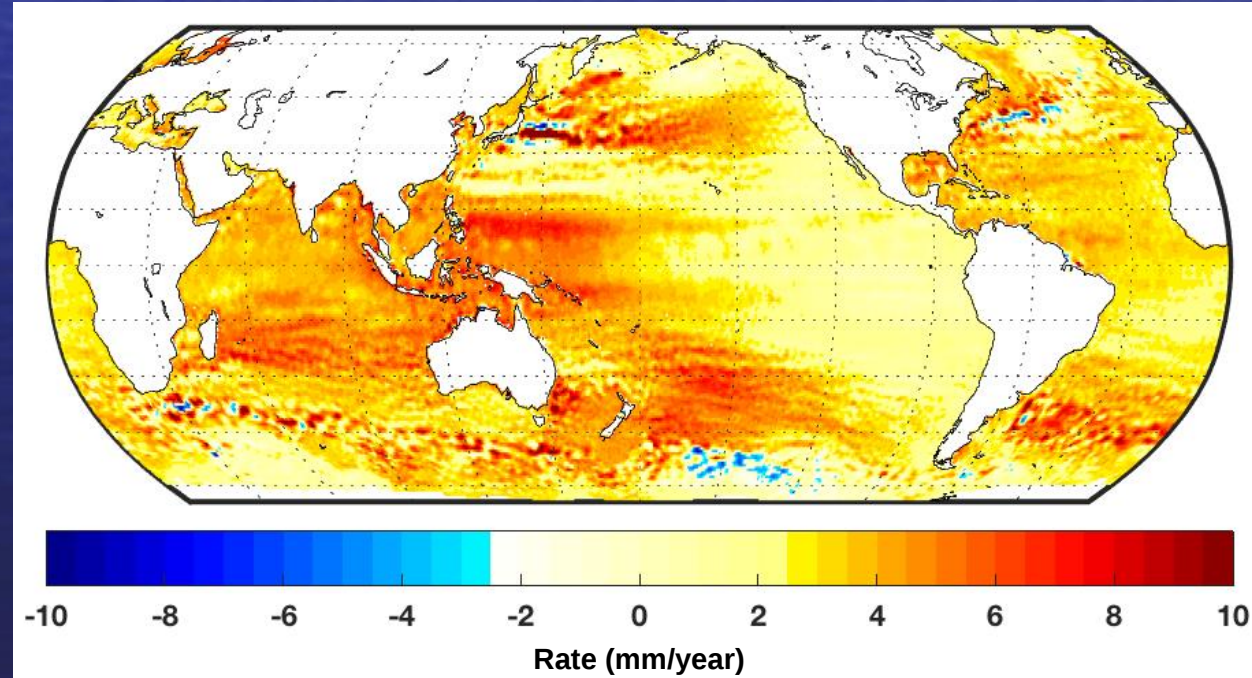
Regional Trends from Satellite Altimeter Record

- Removing natural variability associated with ENSO, PDO, IOD and NAO in the 26-year record...doesn't do much to the spatial pattern

Rate, Original Data: 1993-2018

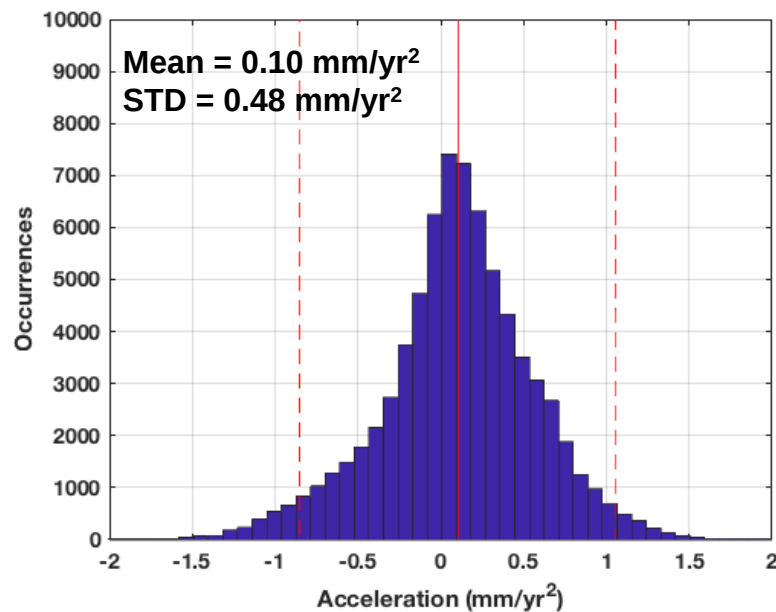
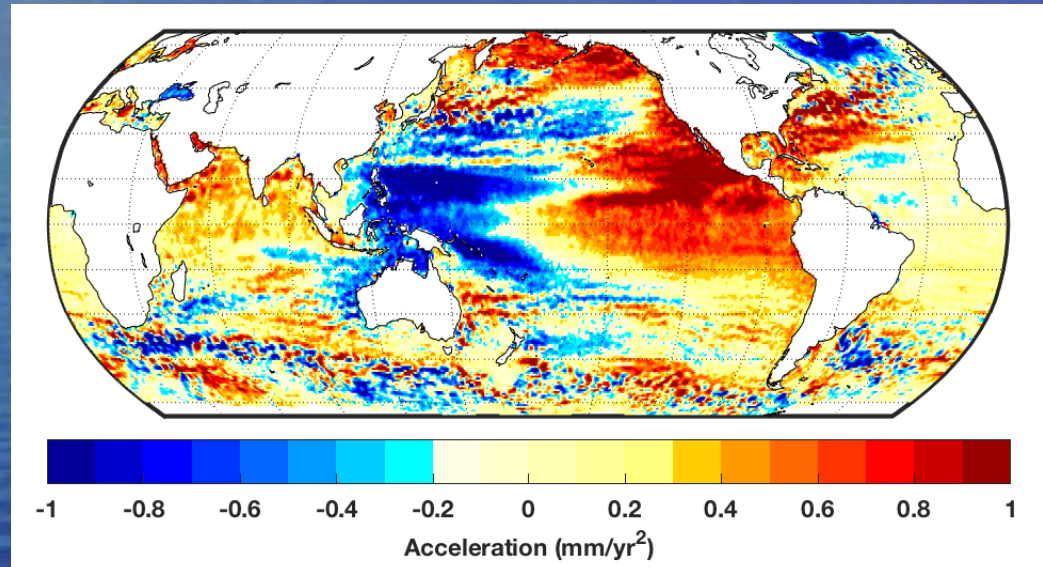


Rate, Natural Variability Removed: 1993-2018

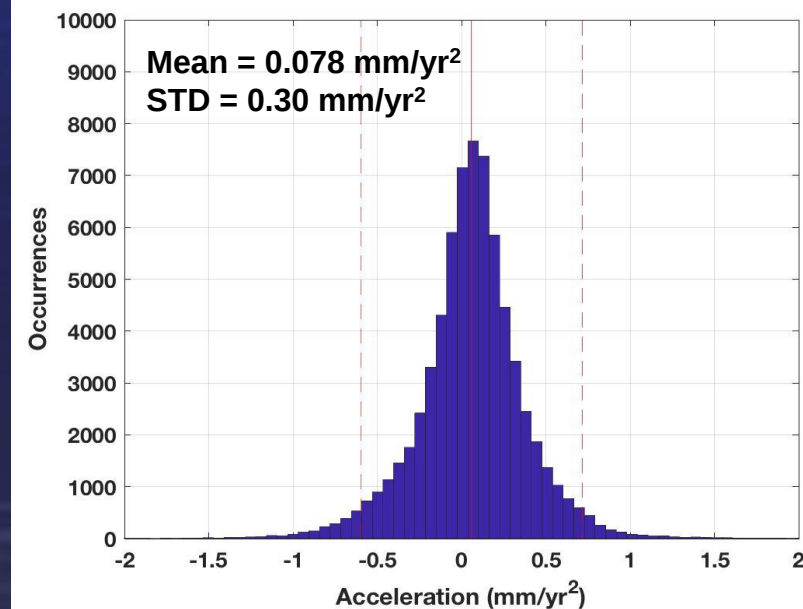
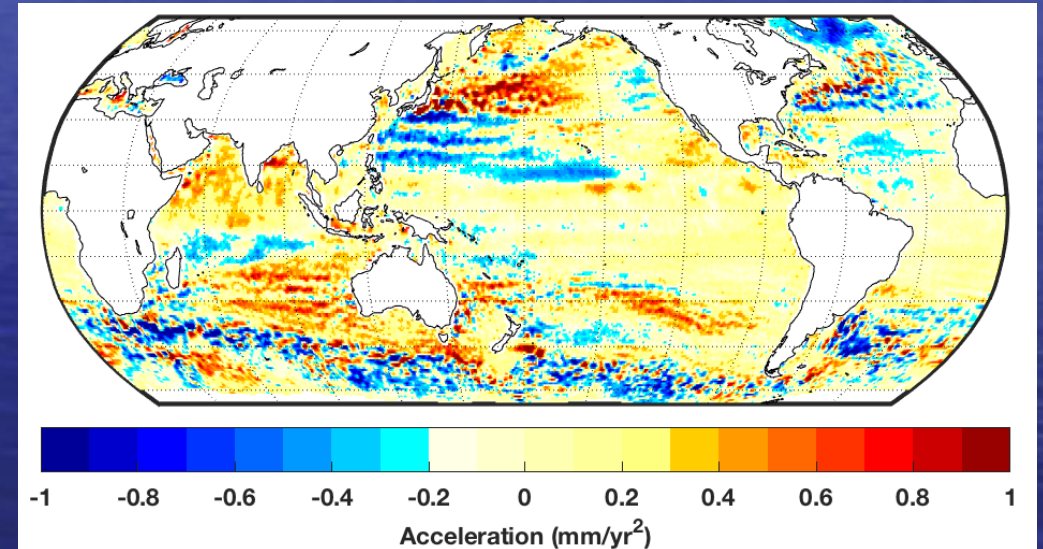


Regional Accelerations from the Satellite Altimeter Record

Acceleration, Original Data: 1993-2018

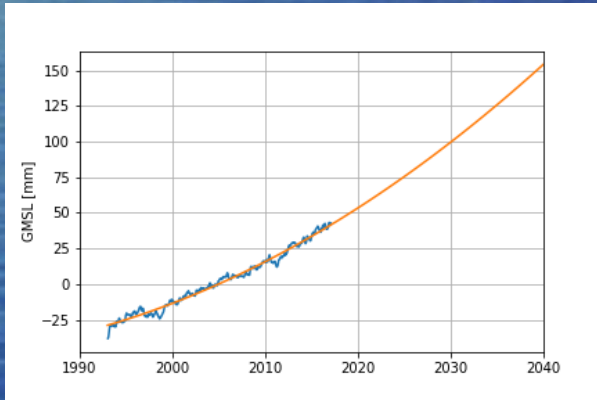


Acceleration, Natural Variability Removed: 1993-2018



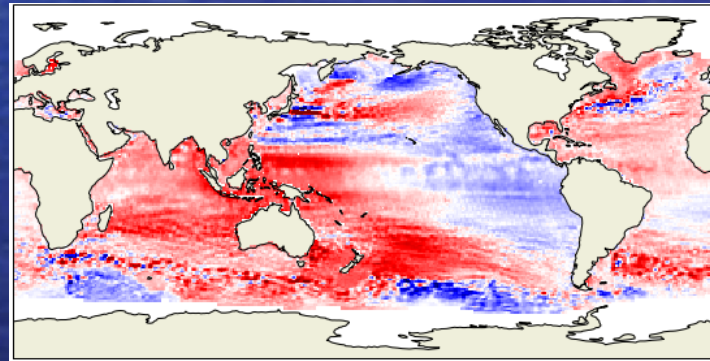
A Data-Driven Path Towards Short-Term Regional Sea Level Extrapolations

Residual Altimeter-Observed GMSL (ENSO & Pina. Corrected)

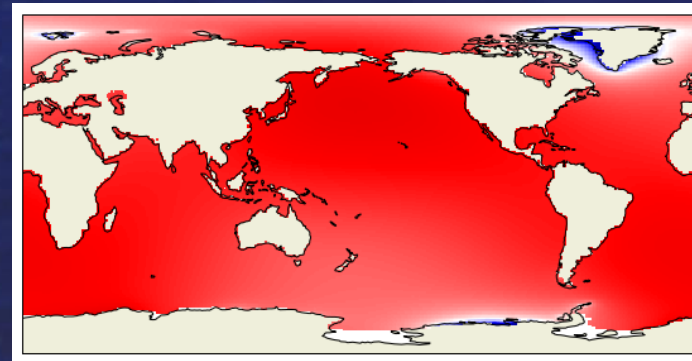


+

Altimeter-Observed Regional Sea Level Trend Pattern (minus GRACE-derived ice sheet fingerprints)



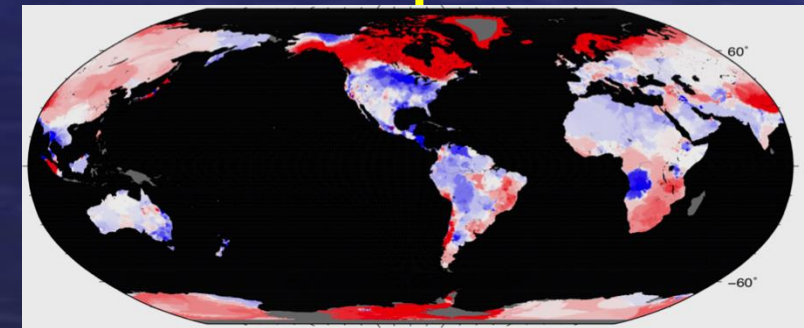
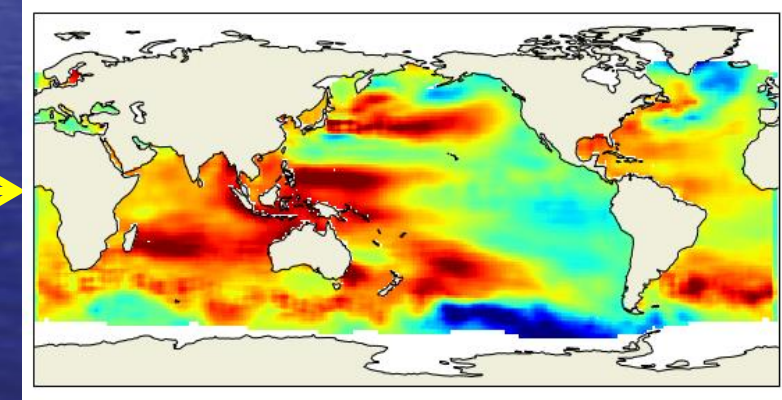
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GRACE-based mass loss

Ice Sheet Fingerprints (based on GRACE)

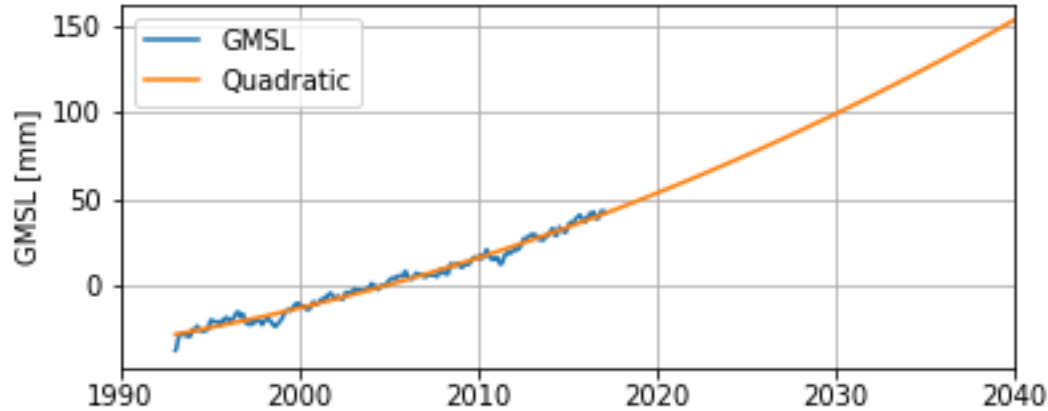
Regional Relative Sea Level Projections



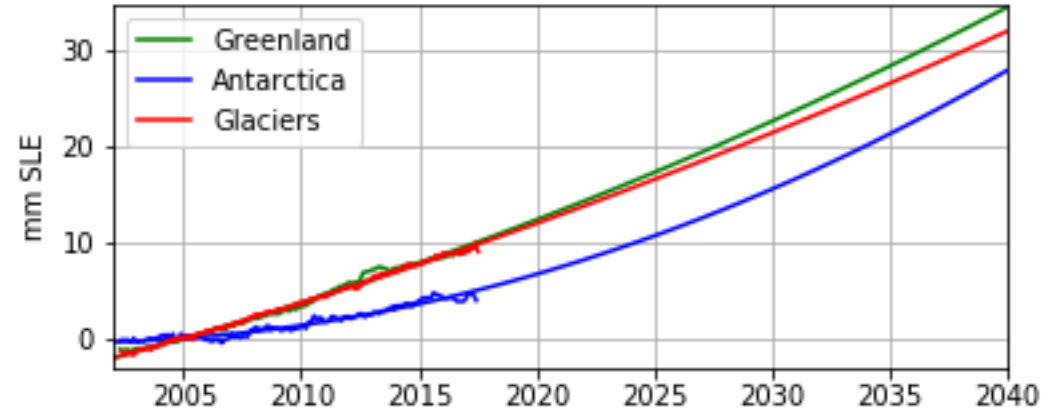
Vertical Land Motion

Removing Mass Signals from GMSL Using GRACE

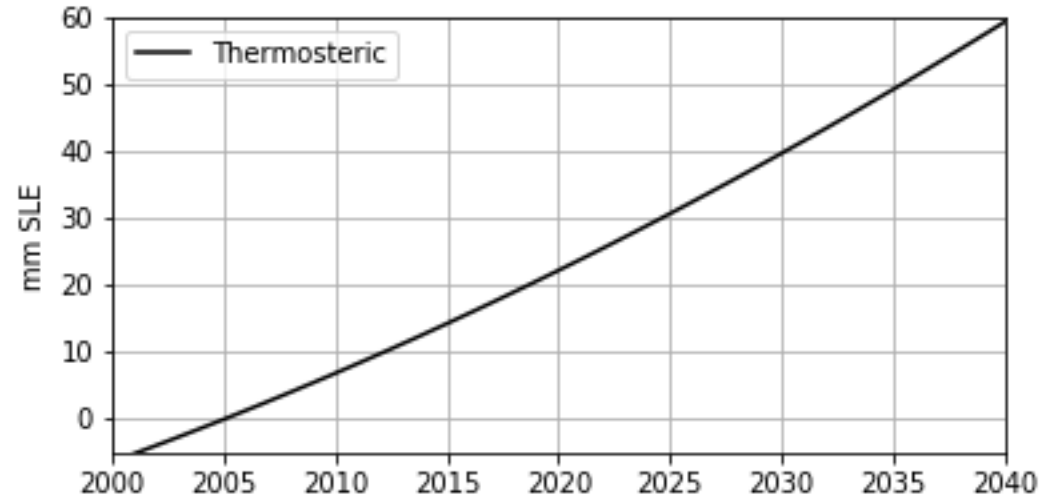
GMSL Record from Altimetry



GMSL contributions from glaciers and ice sheets (GRACE)



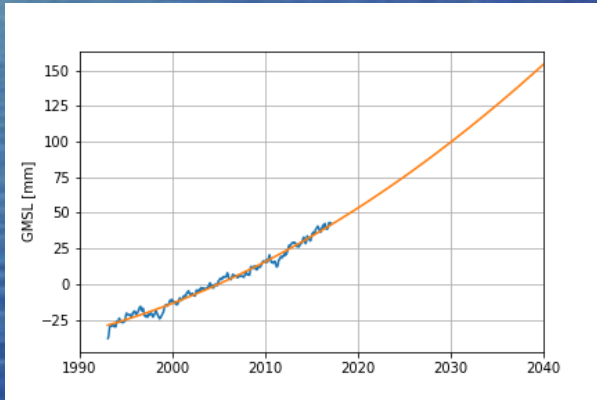
==



“Thermosteric”

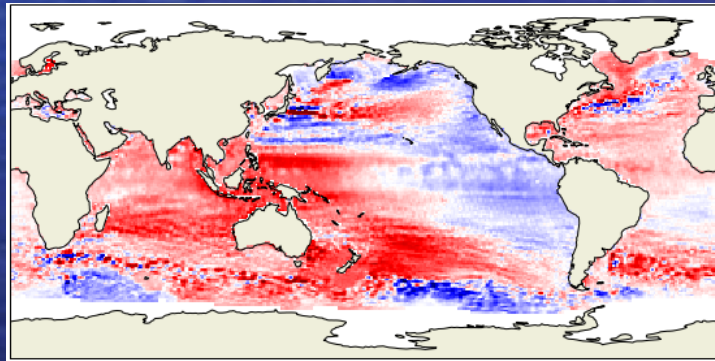
A Data-Driven Path Towards Short-Term Regional Sea Level Extrapolations

Residual Altimeter-Observed GMSL (ENSO & Pina. Corrected)

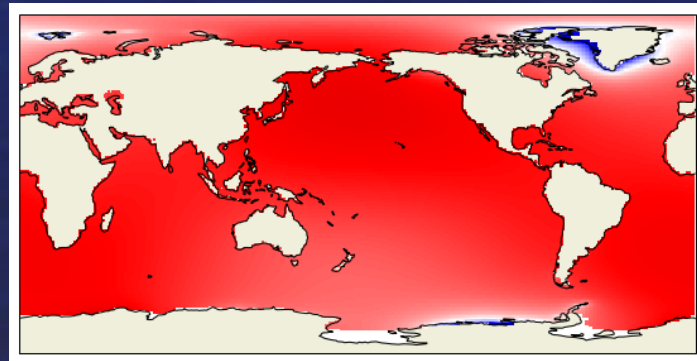


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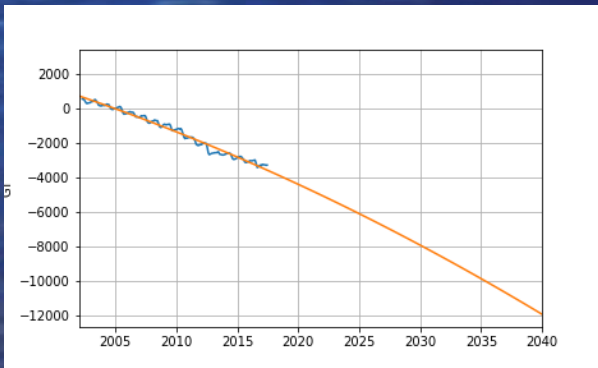
Altimeter-Observed Regional Sea Level Trend Pattern (minus GRACE-derived ice sheet fingerprints)



+

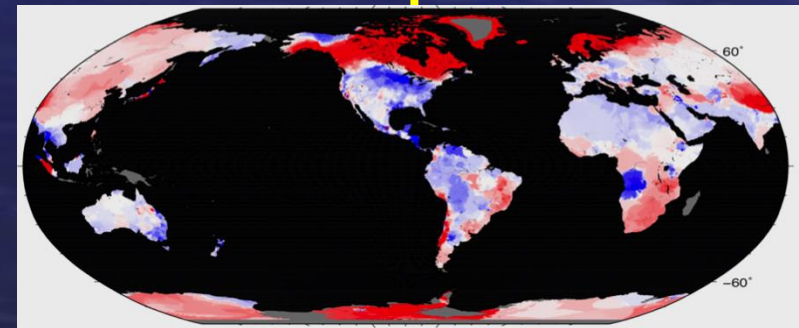
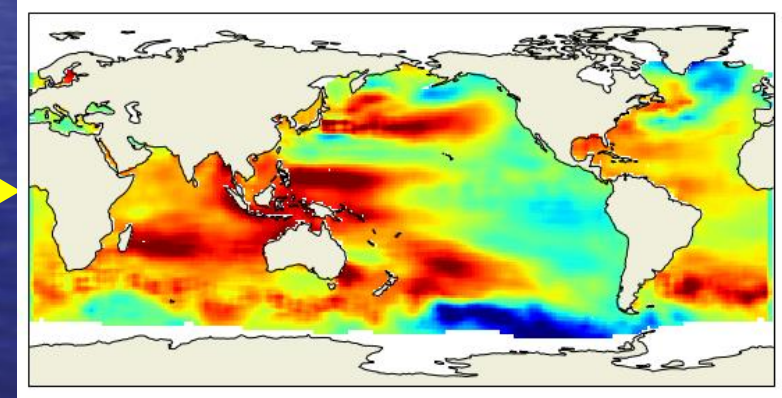


GRACE-based mass loss



Ice Sheet Fingerprints (based on GRACE)

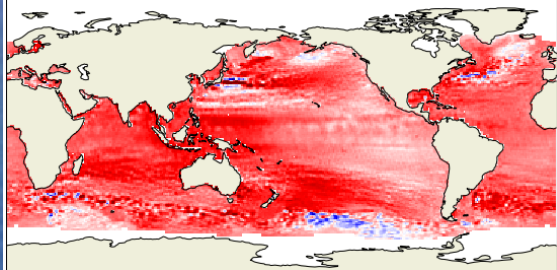
Regional Relative Sea Level Projections



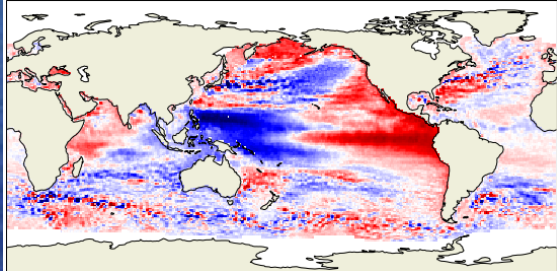
Vertical Land Motion

Regional Thermosteric Sea Level Pattern

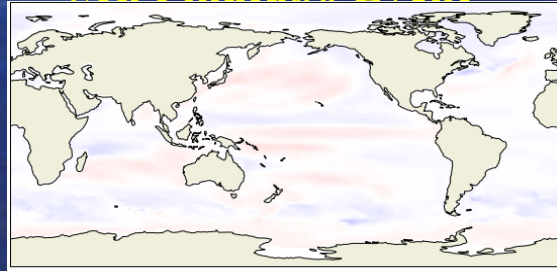
Altimeter Trends (1993-2018)



ENSO/PDO/IDO Signal



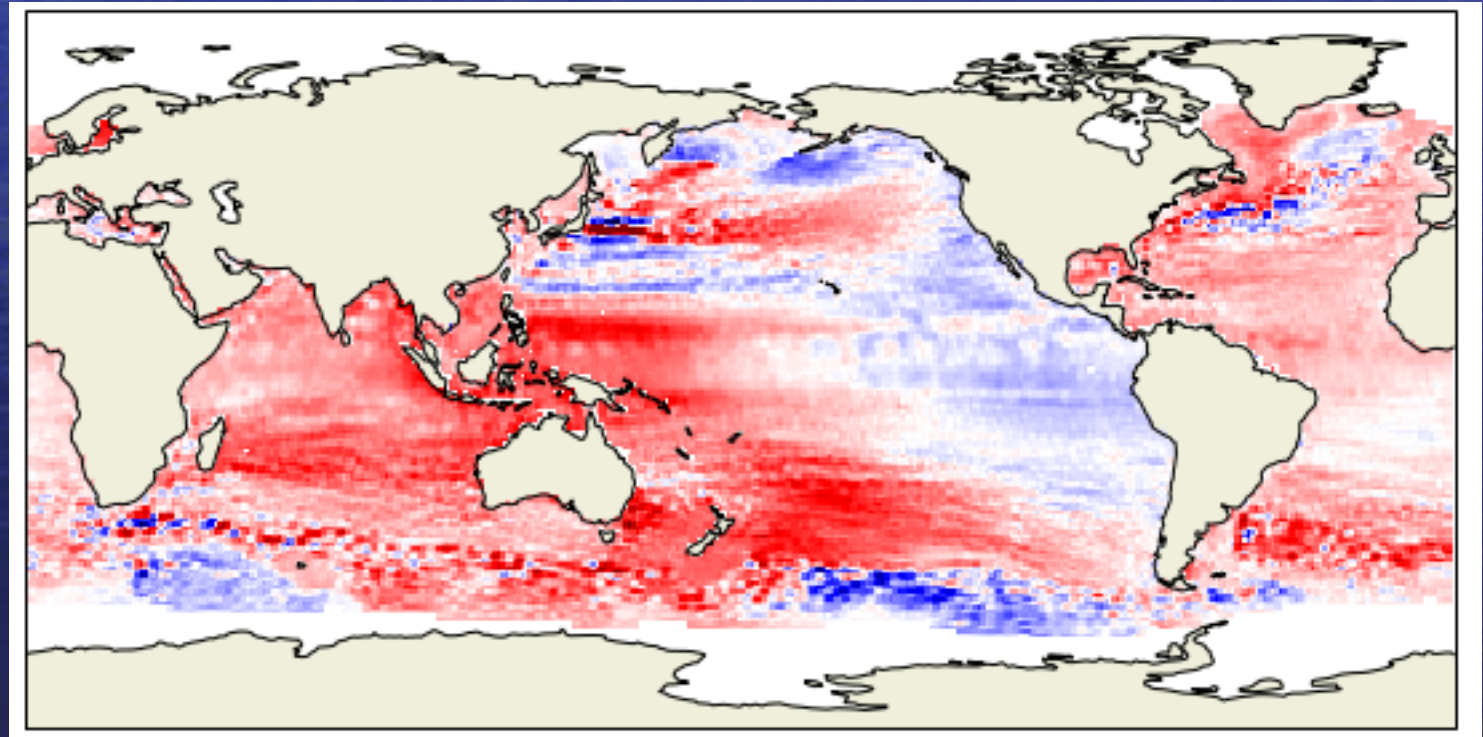
Mt. Pinatubo Event



Global Ice Sheet Fingerprints

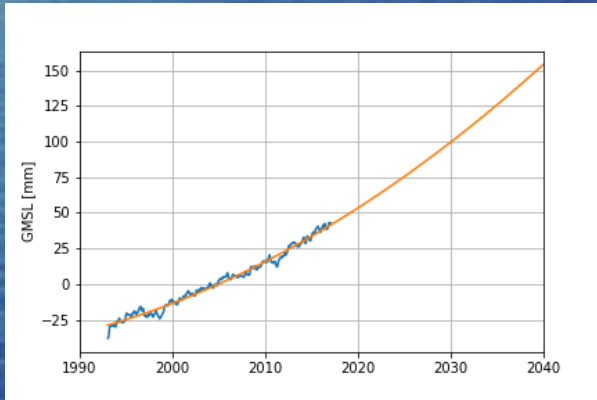


Residual Sea Level Trend Pattern



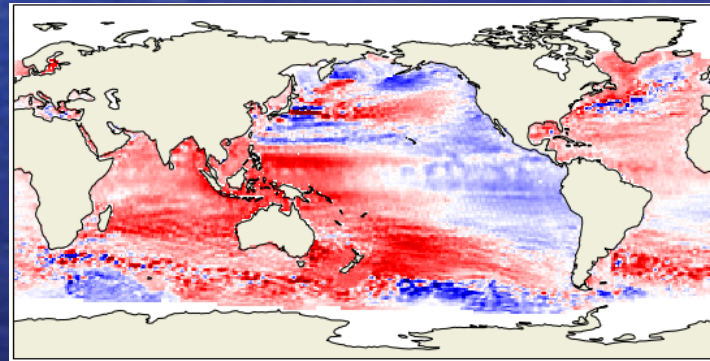
A Data-Driven Path Towards Short-Term Regional Sea Level Extrapolations

Residual Altimeter-Observed GMSL (ENSO & Pina. Corrected)

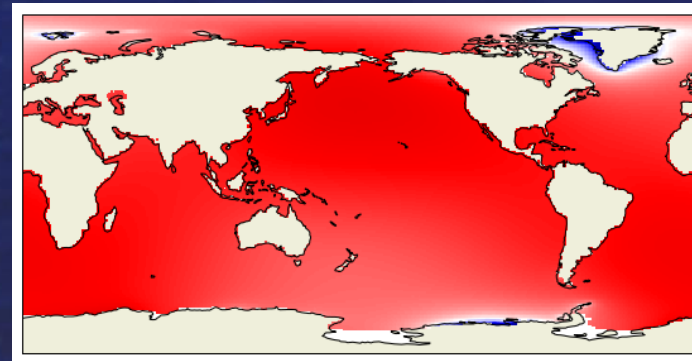


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Altimeter-Observed Regional Sea Level Trend Pattern (minus GRACE-derived ice sheet fingerprints)



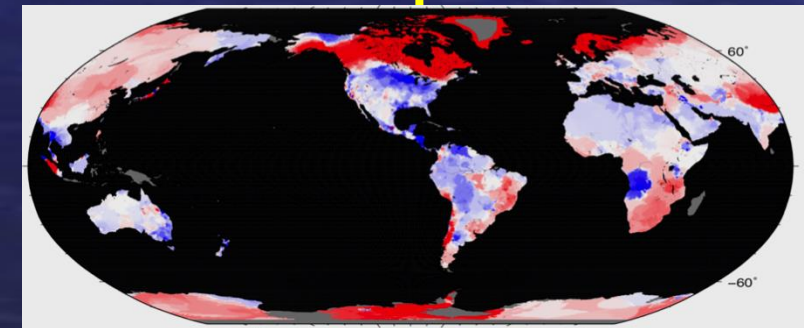
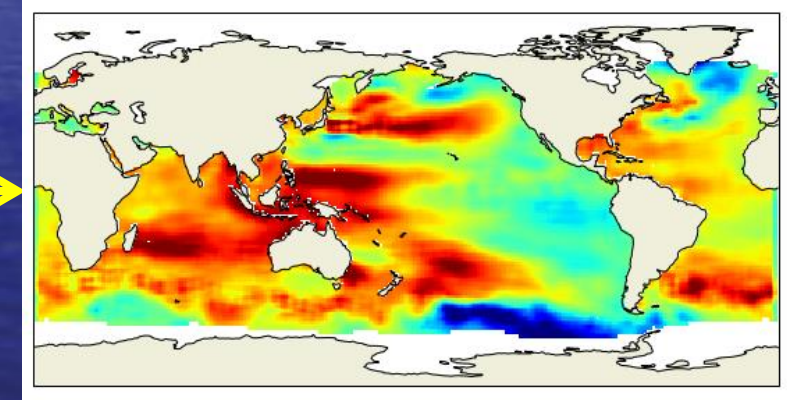
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GRACE-based mass loss

Ice Sheet Fingerprints (based on GRACE)

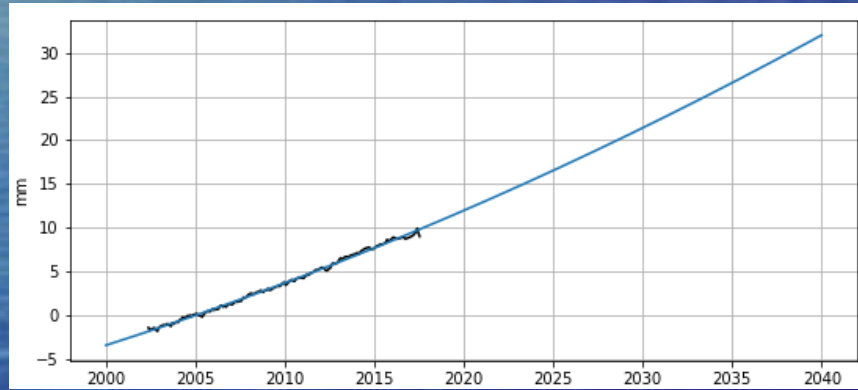
Regional Relative Sea Level Projections



Vertical Land Motion

Ice Contributions from GRACE Extrapolation

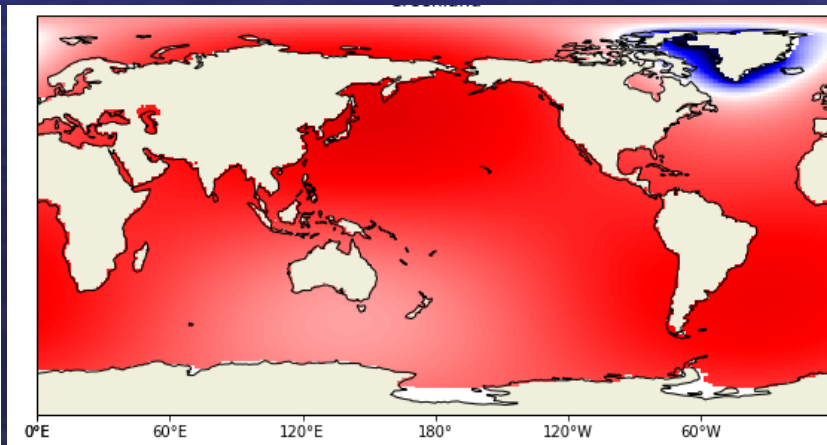
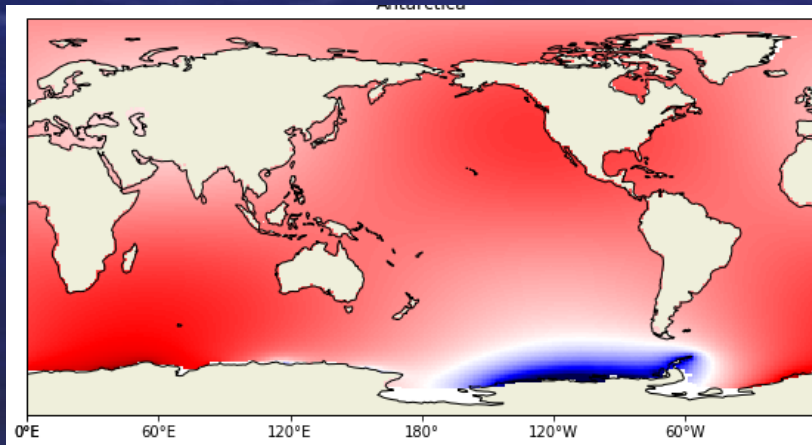
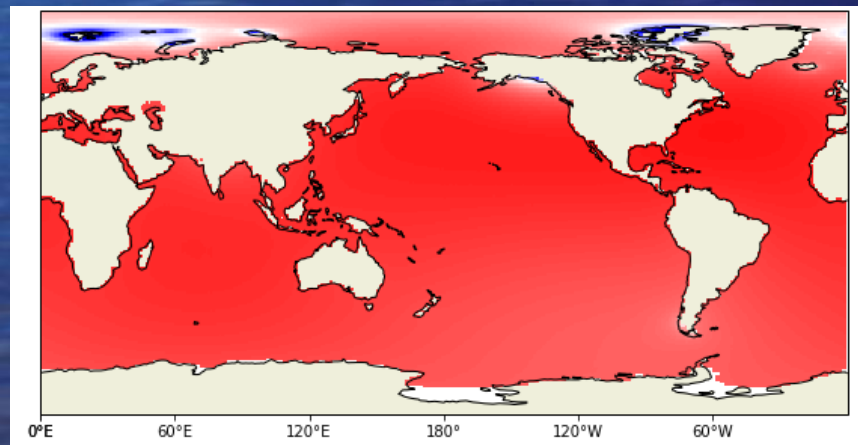
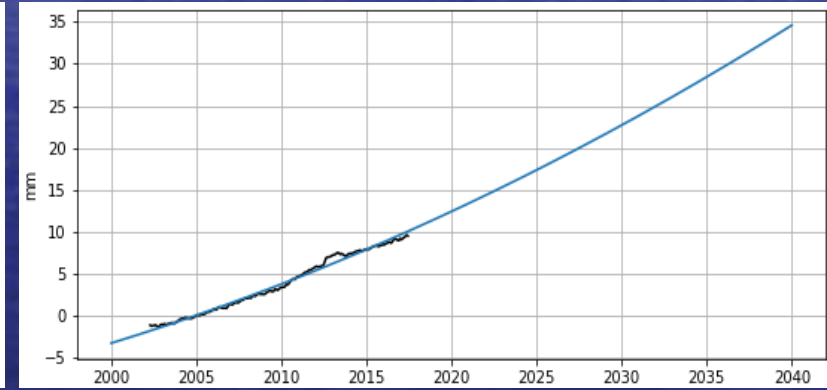
Glaciers



Antarctica

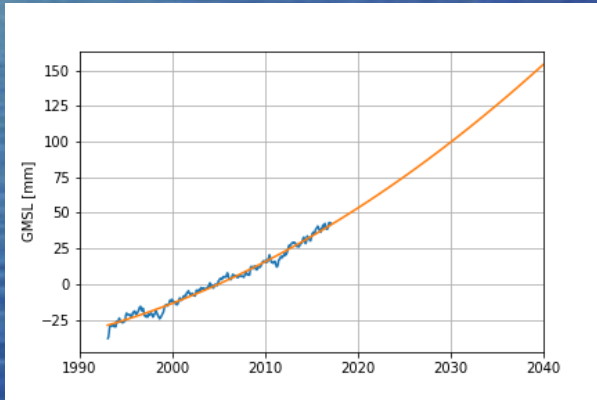


Greenland



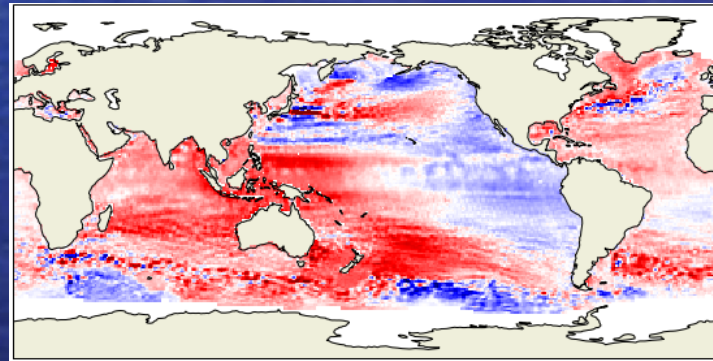
A Data-Driven Path Towards Short-Term Regional Sea Level Extrapolations

Residual Altimeter-Observed GMSL (ENSO & Pina. Corrected)

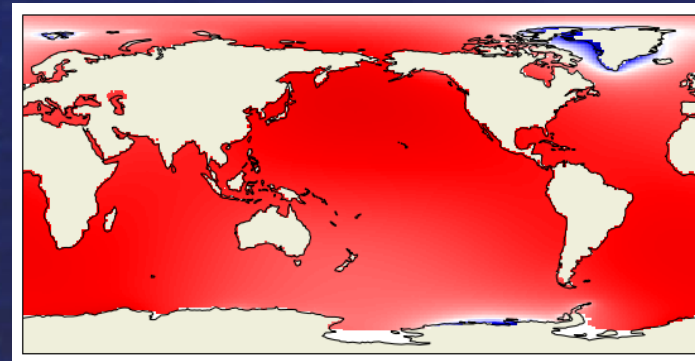


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Altimeter-Observed Regional Sea Level Trend Pattern (minus GRACE-derived ice sheet fingerprints)



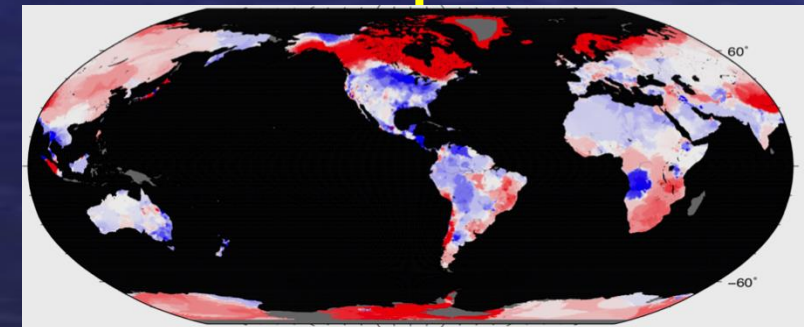
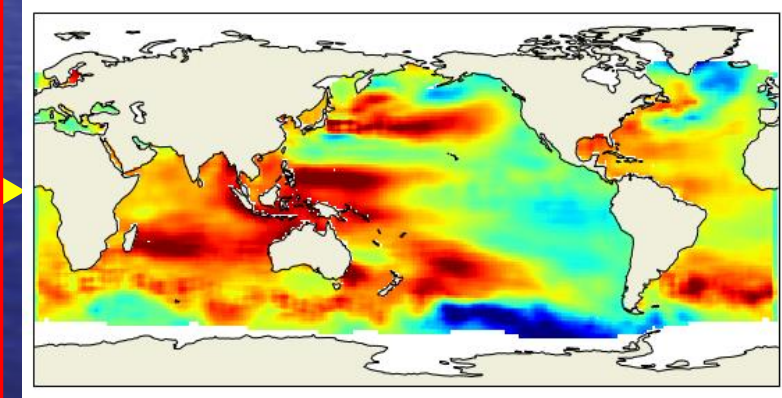
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GRACE-based mass loss

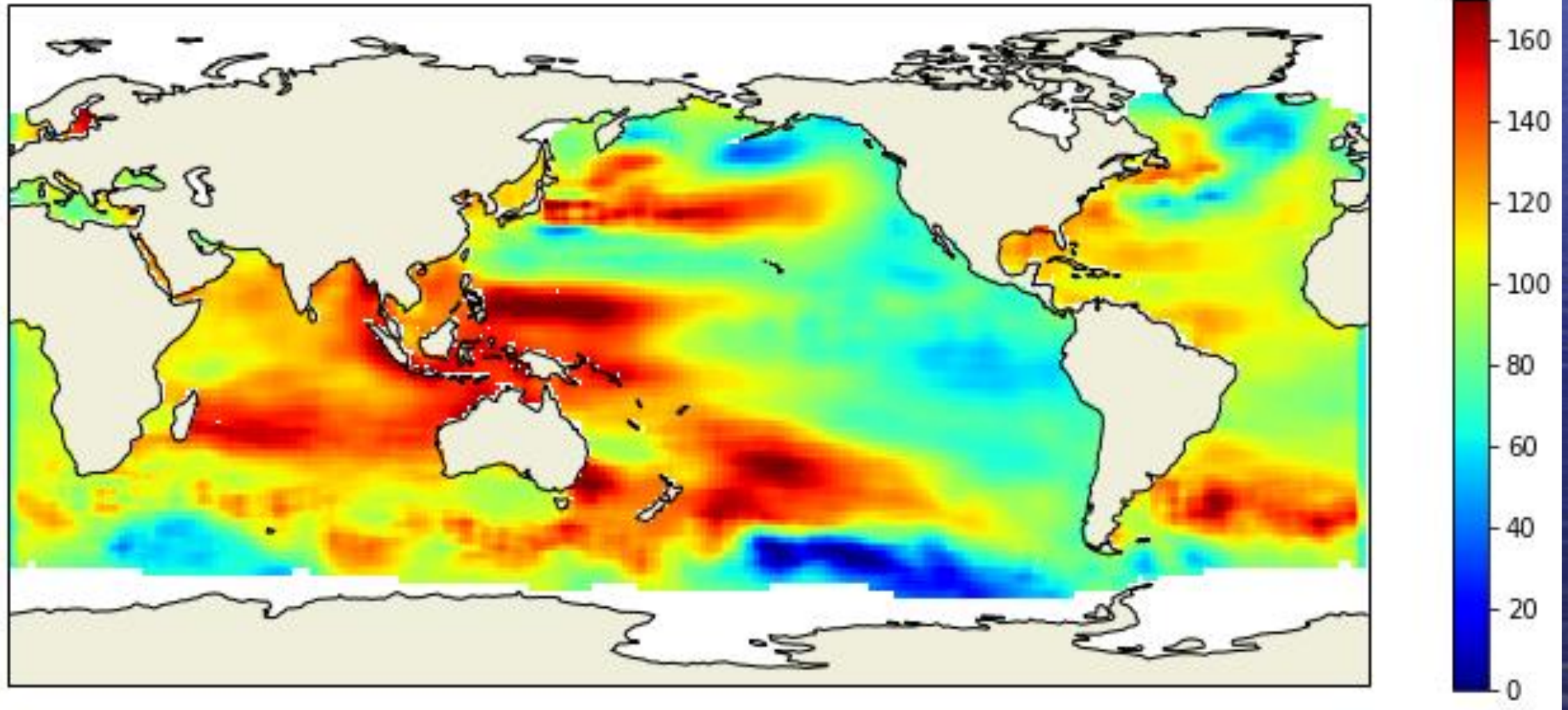
Ice Sheet Fingerprints (based on GRACE)

Regional Relative Sea Level Projections



Vertical Land Motion

2040 Sea Level Extrapolation (relative to 2019)

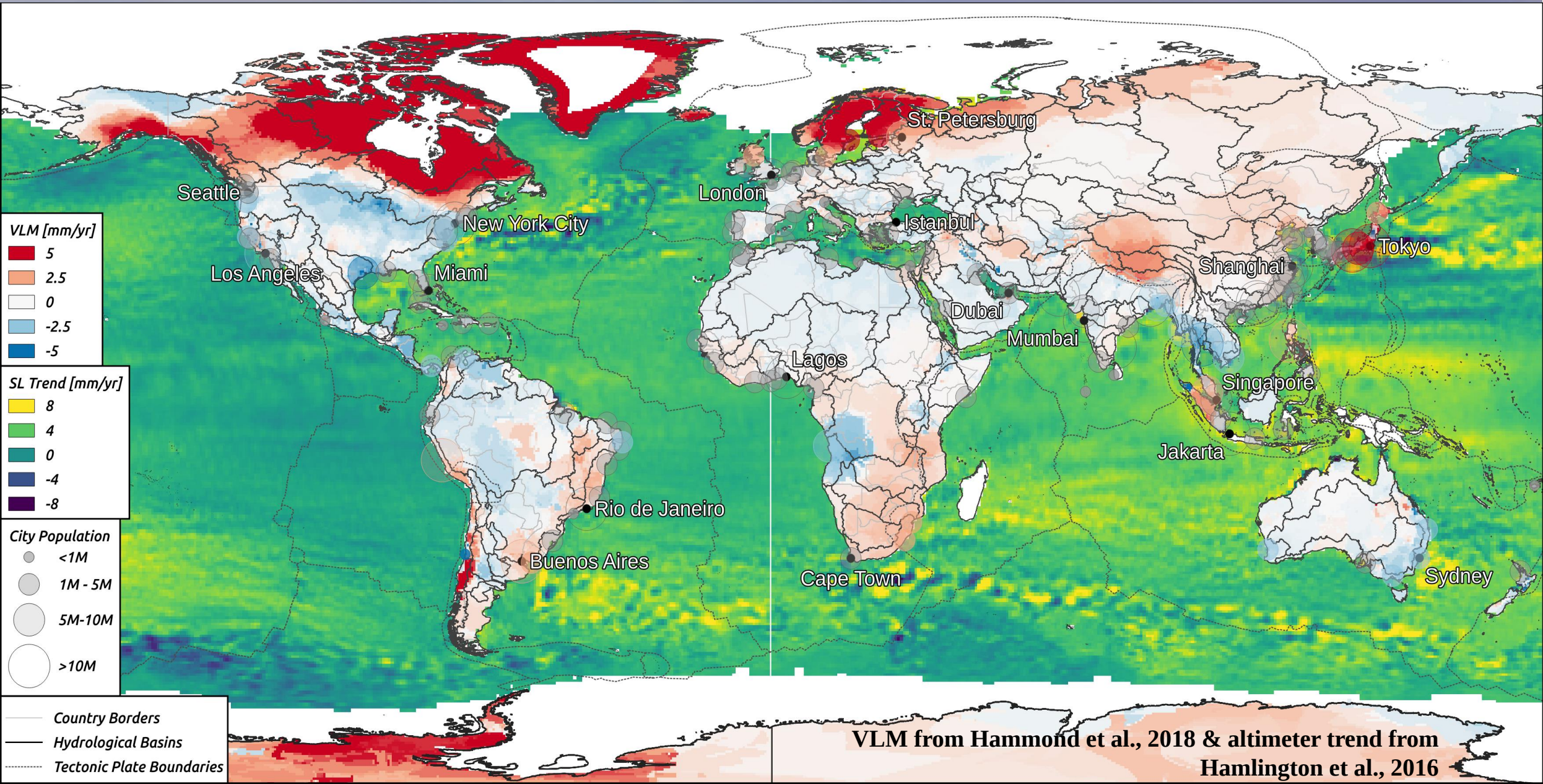


Global Average: 104 mm

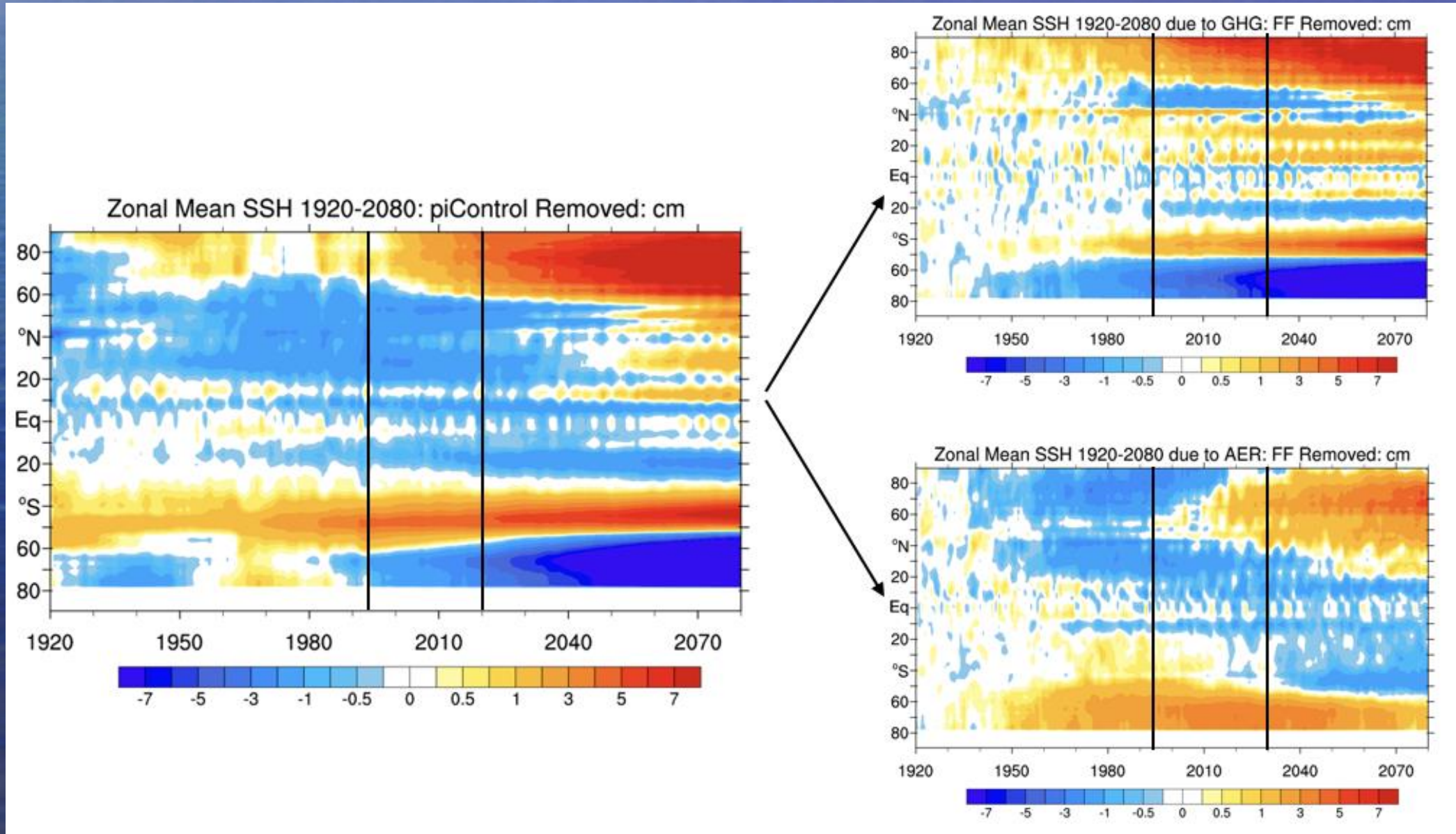
2040 Sea Level Extrapolation

Source	GMSL Contribution (mm) (relative to 2019)
Greenland	22
Antarctica	22
Glaciers	21
Thermosteric	39
Total	104

GPS-Inferred Vertical Land Motion



More Results from the Large Ensemble (LE)



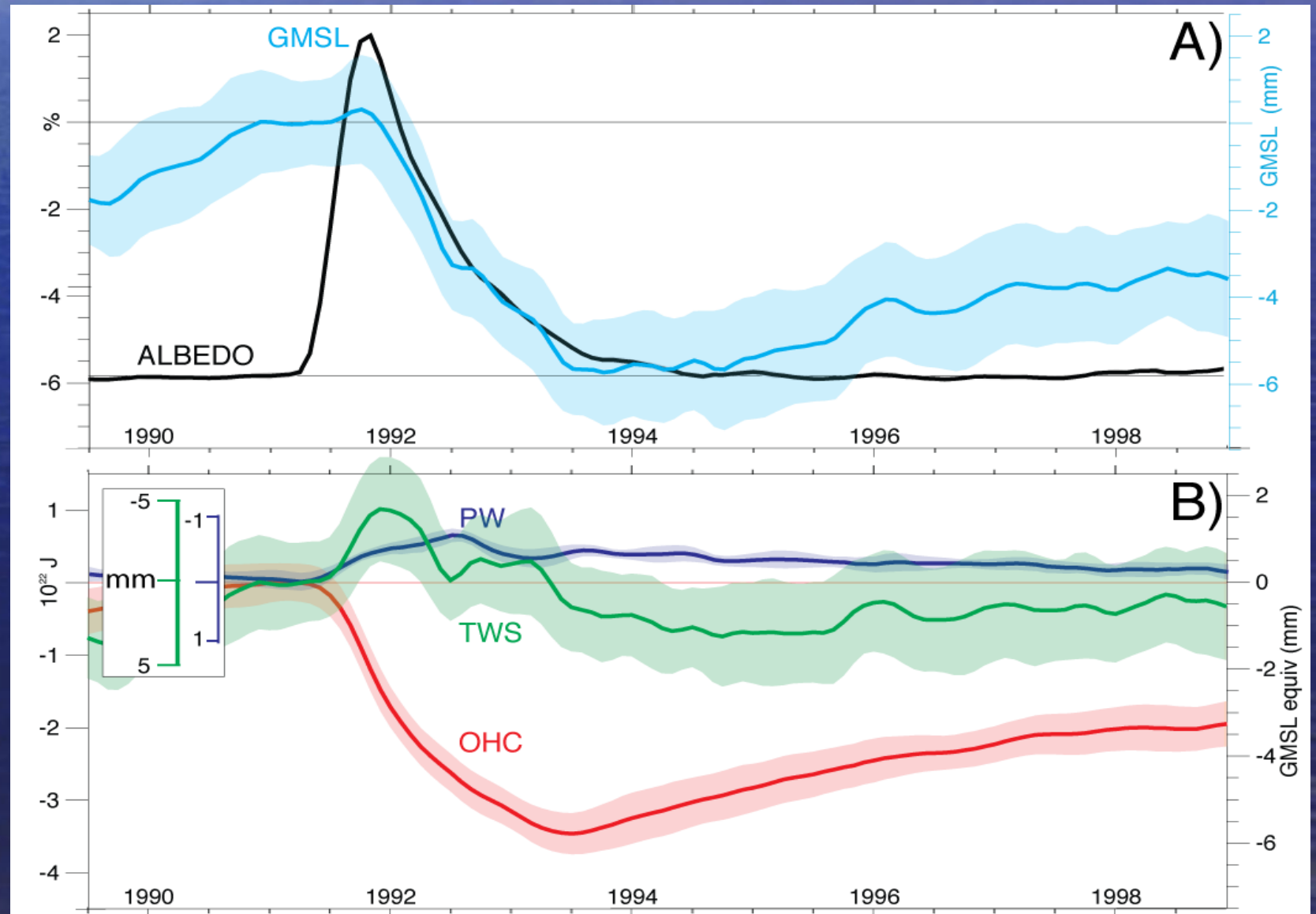
Summary

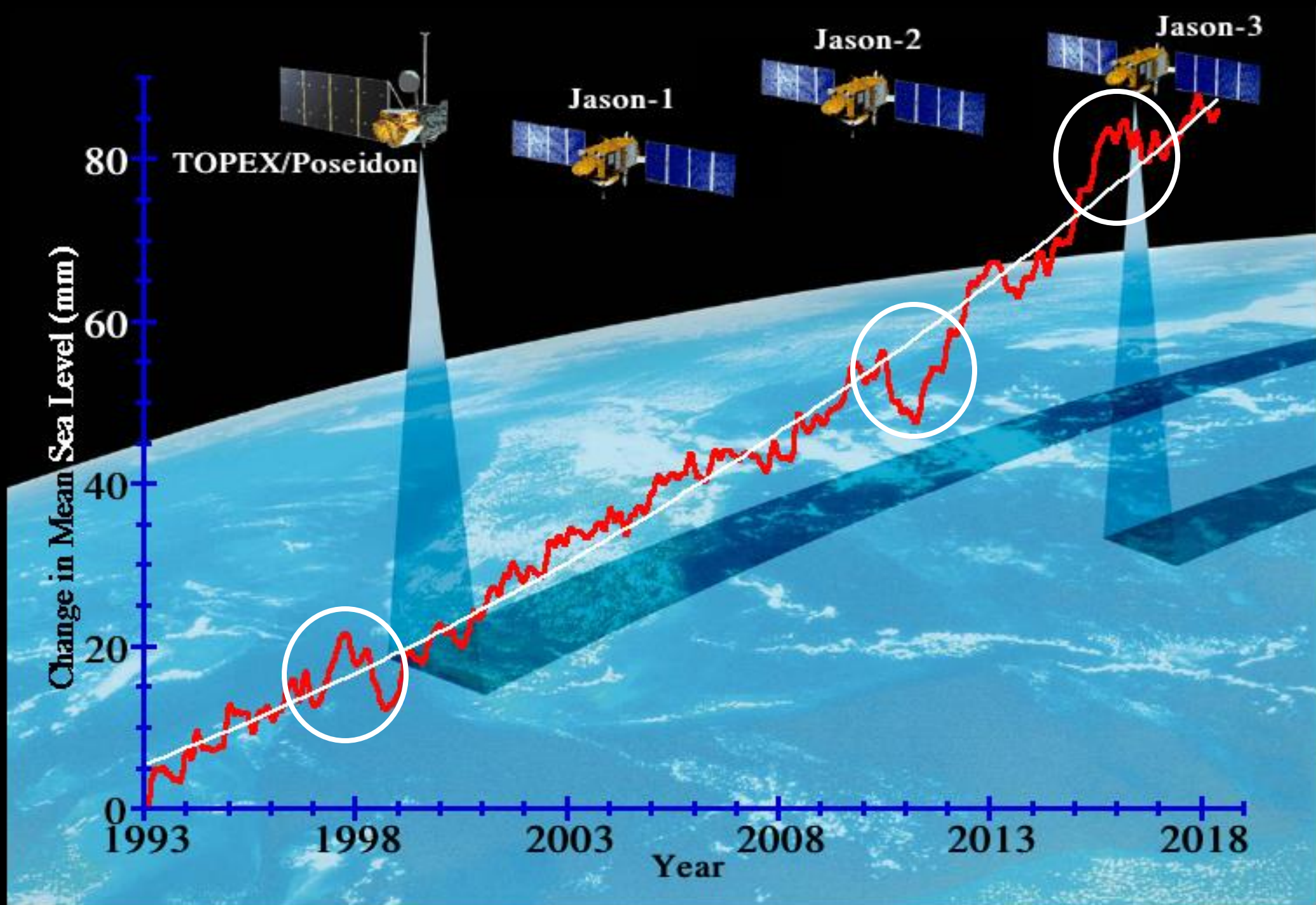
- Satellite altimeter and GRACE data are used to extrapolate regional sea level to 2040.
- The 26-year altimeter trend pattern, which is dominated by the Forced Response (FR) of aerosols and GHGs, is used to inform the patterns of regional sea level change in 2040.
- Climate model large ensembles (LEs) can be very useful for identifying the FR and helps with interpreting the relatively short altimeter record.
- The altimeter record occurs at a transition from aerosol-dominated forcing to GHG-dominated forcing, and thus care must be taken when interpreting the results.
- Future work will focus on further dissecting the altimeter trend map and estimating error bars for the 2040 extrapolation.



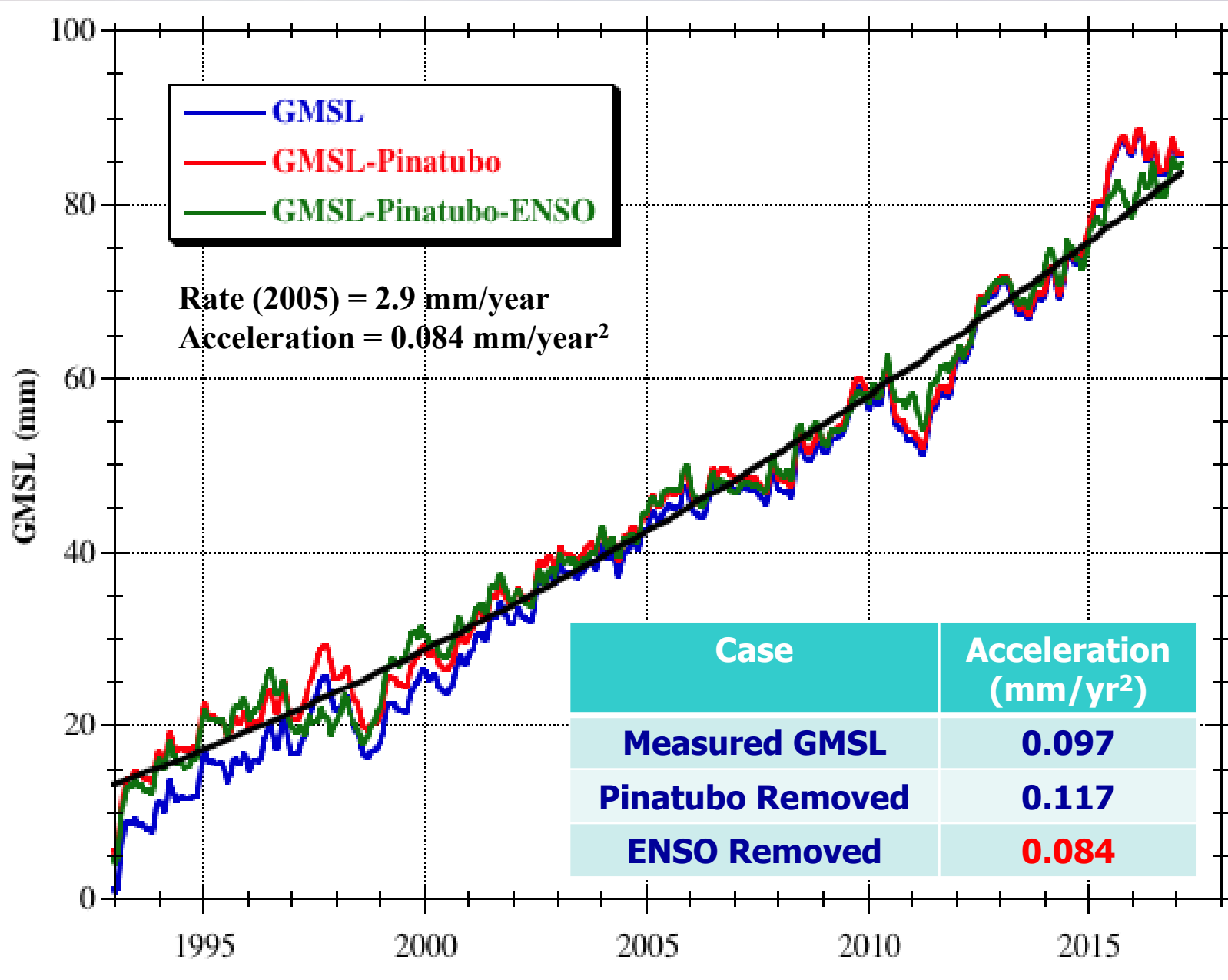
Thanks! Questions?

Effects of Mt. Pinatubo Eruption in 1991





Correcting GMSL for Pinatubo and ENSO



Acceleration Error Assessment

Error	Source	Acceleration Error (mm/yr ²) 1 σ
Altimeter Measurement Errors	Tide Gauge Calibration	0.011
Decadal Variability	Cryosphere (Wouters et al., 2013)	0.014
	TWS (NCAR LE)	0.0054
	Thermosteric (NCAR LE)	0.0075
	Precipitable water (NCAR LE)	0.0013
Pinatubo Correction Error	NCAR LE	0.01
ENSO/PDO Correction Error	Coupled EOF Analysis	0.01
Total	RSS	0.025

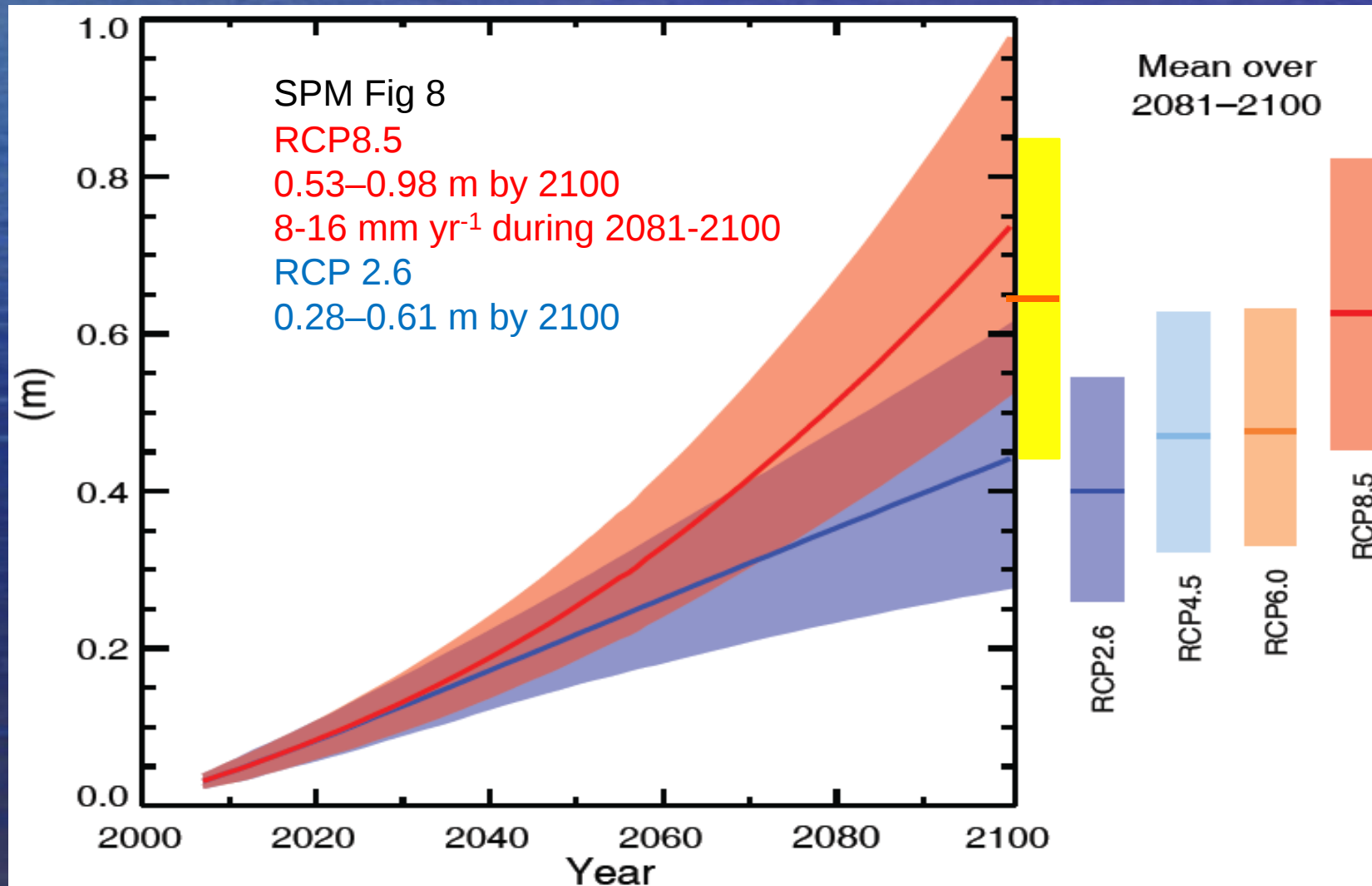
Climate Change-Driven GMSL Acceleration = 0.084 ± 0.025 mm/yr²

Validating the Observed GMSL Acceleration

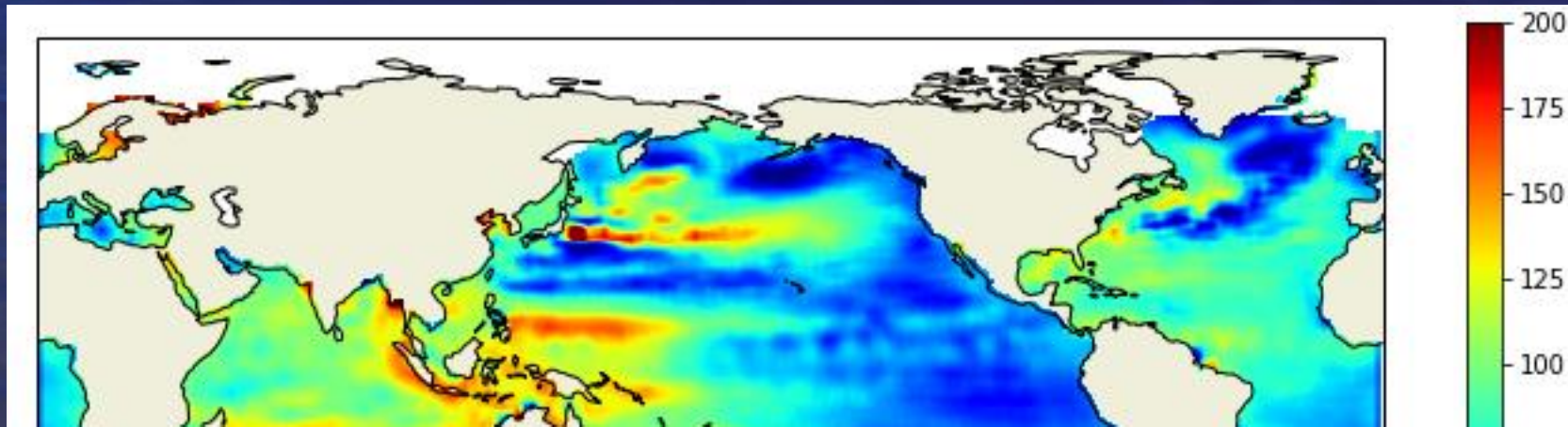
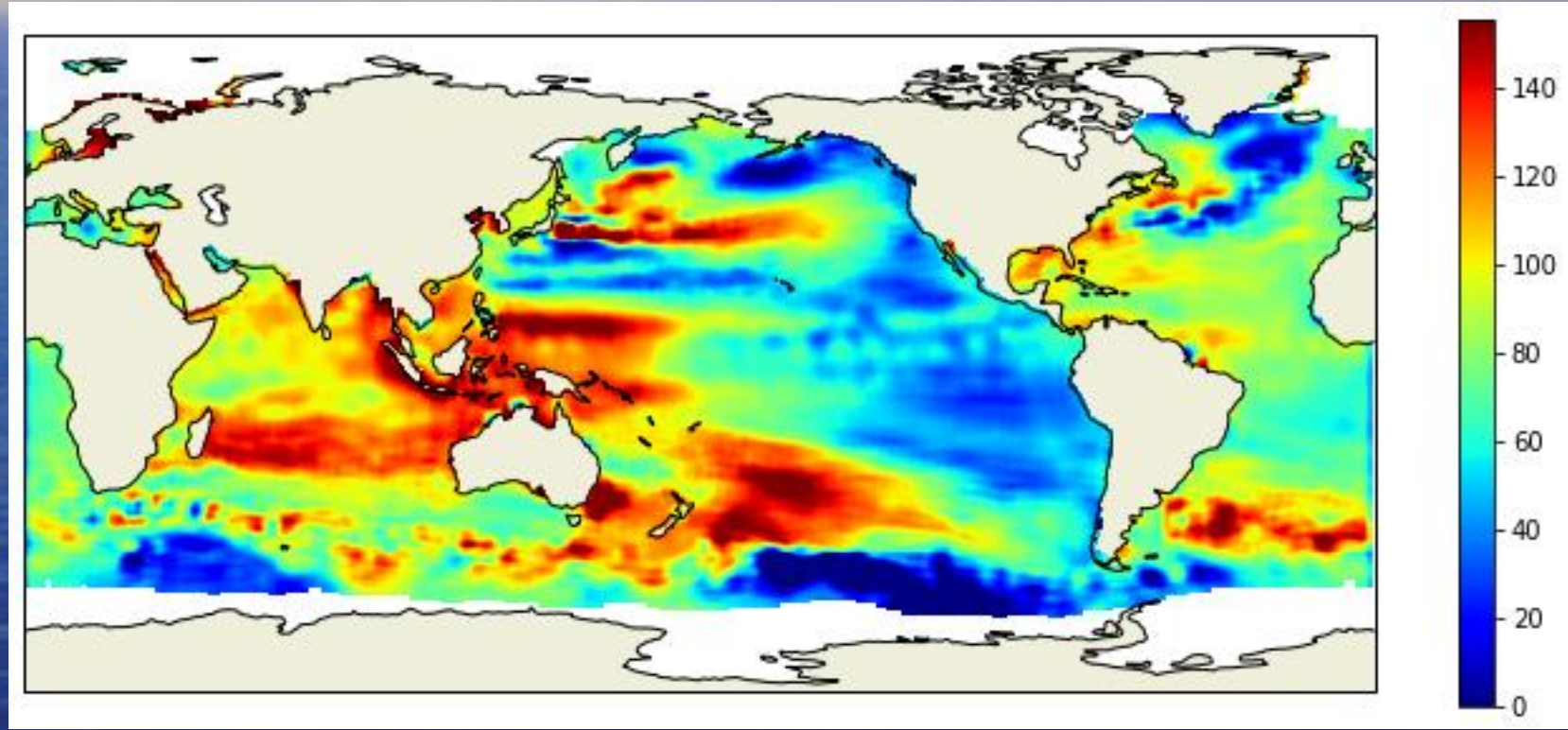
Component	Time Period	Rate (mm/yr) Epoch 2005	Acceleration (mm/yr ²)
Greenland	2002-2017	0.66	0.0236
Antarctica	2002-2017	0.19	0.0332
Mountain Glaciers & Small Ice Caps	2002-2017	0.51	0.0094
Thermosteric (no Pin.)	1993-2015	1.65	0.0076
Components Total		3.0	0.078
Altimeter Observed	1993-2017	2.9	0.084

Projections of 21st-century GMSLR under Different RCPs from the IPCC 5th Assessment Report

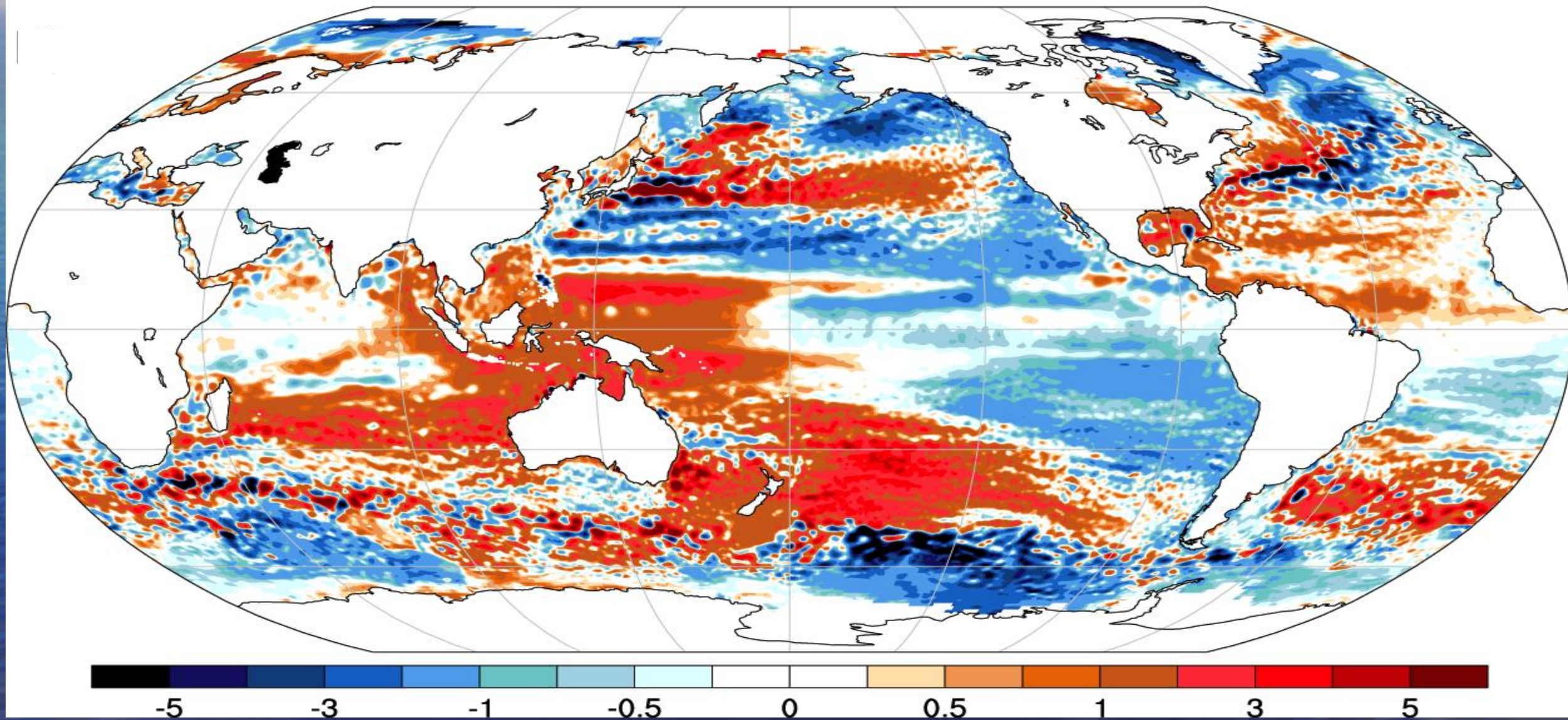
Medium confidence in likely ranges. Very likely that the 21st-century mean rate of GMSLR will exceed that of 1971-2010 under all RCPs.



Observed Sea Level Change (1993-2019)



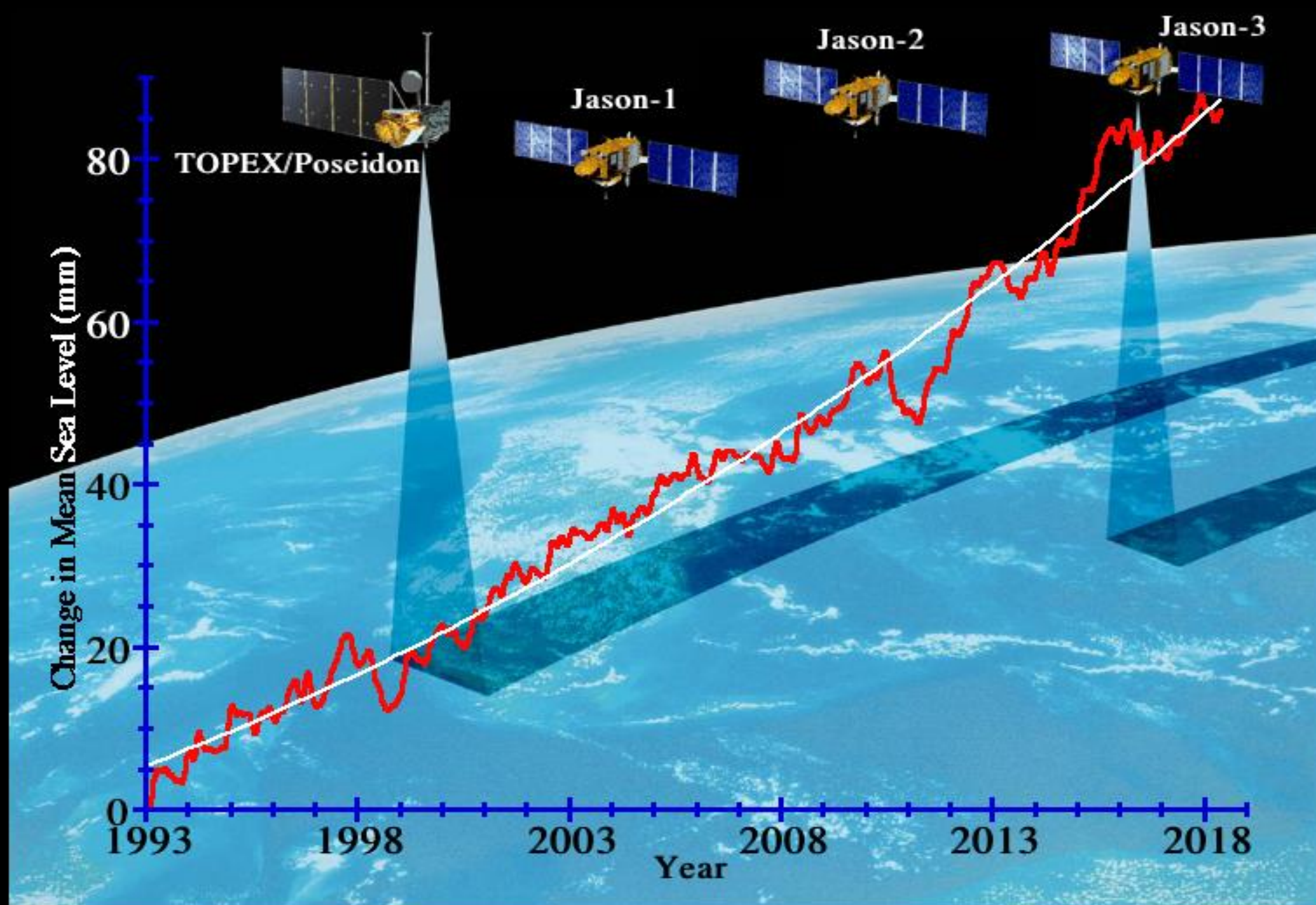
Altimeter Regional Sea Level Trends



Altimeter-observed sea level trends (1993-2018) minus the GMSL mean trend.

Talk Summary

- 1) An acceleration has been detected in the 26-year long satellite record of global mean sea level change.
- 2) An analysis of climate model large ensembles (LEs) shows that the Forced Response (FR) due to greenhouse gases and aerosols should be emerging in the regional trend map from the satellite record.
- 3) A separate analysis that removes natural variability from the satellite regional sea level record supports both (1) and (2).
- 4) Together these results suggest a path forward for using the satellite record to do short-term (20 year) projections of regional sea level change.



2040 Projection (epoch 2005)

