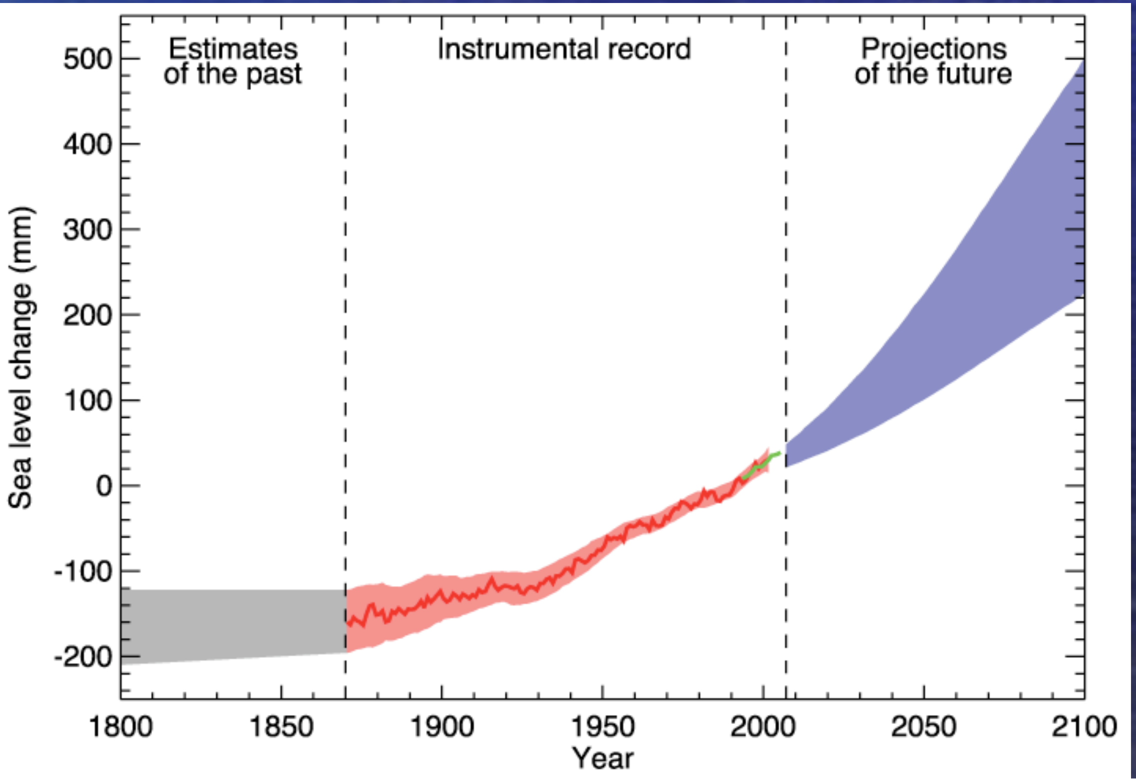
Sea Level Change: Past, Present, Future

R. S. Nerem, University of Colorado

(with input from Anny Cazenave, Don Chambers, John Church, Catia Domingues, Ben Hamlington, Bob Leben, Eric Leuliette, Mark Merrifield, Gary Mitchum, Neil White, Josh Willis, Carl Wunsch, and many others)



OSTM 2009

Paleo Sea Level

The last time the Arctic was 3 to 5°C warmer than present, global sea level was 4 to 6 meters higher than present

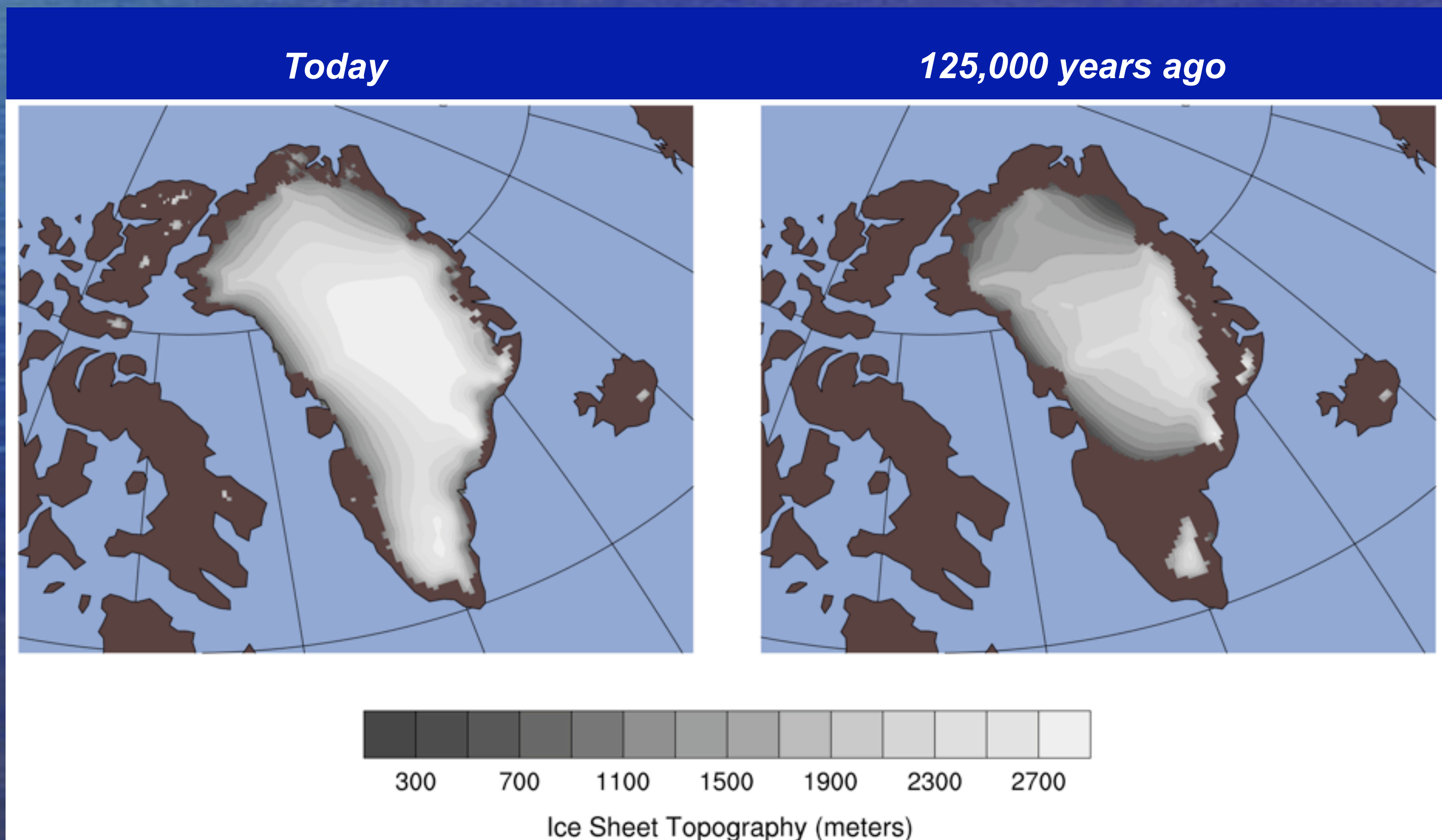
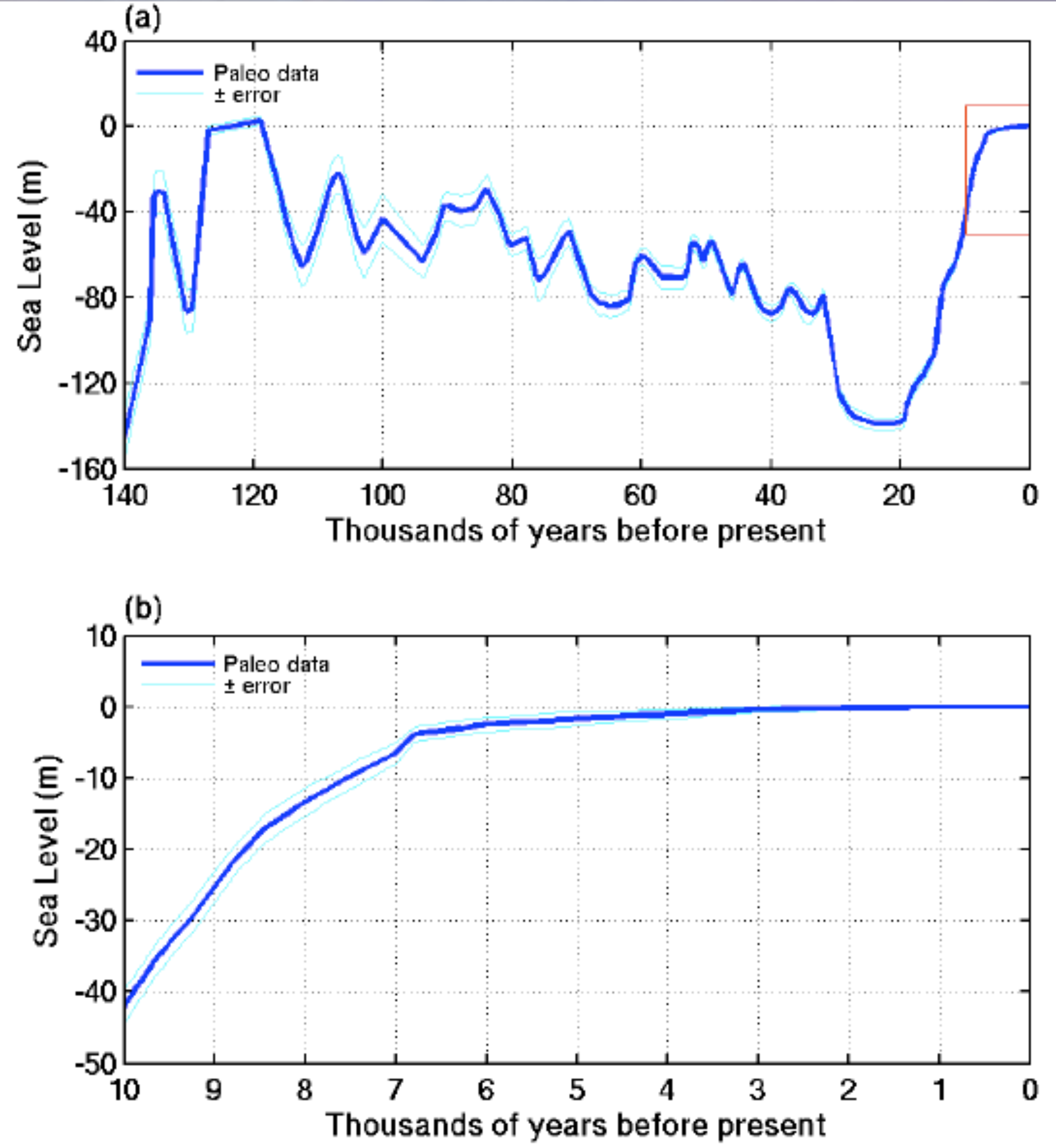


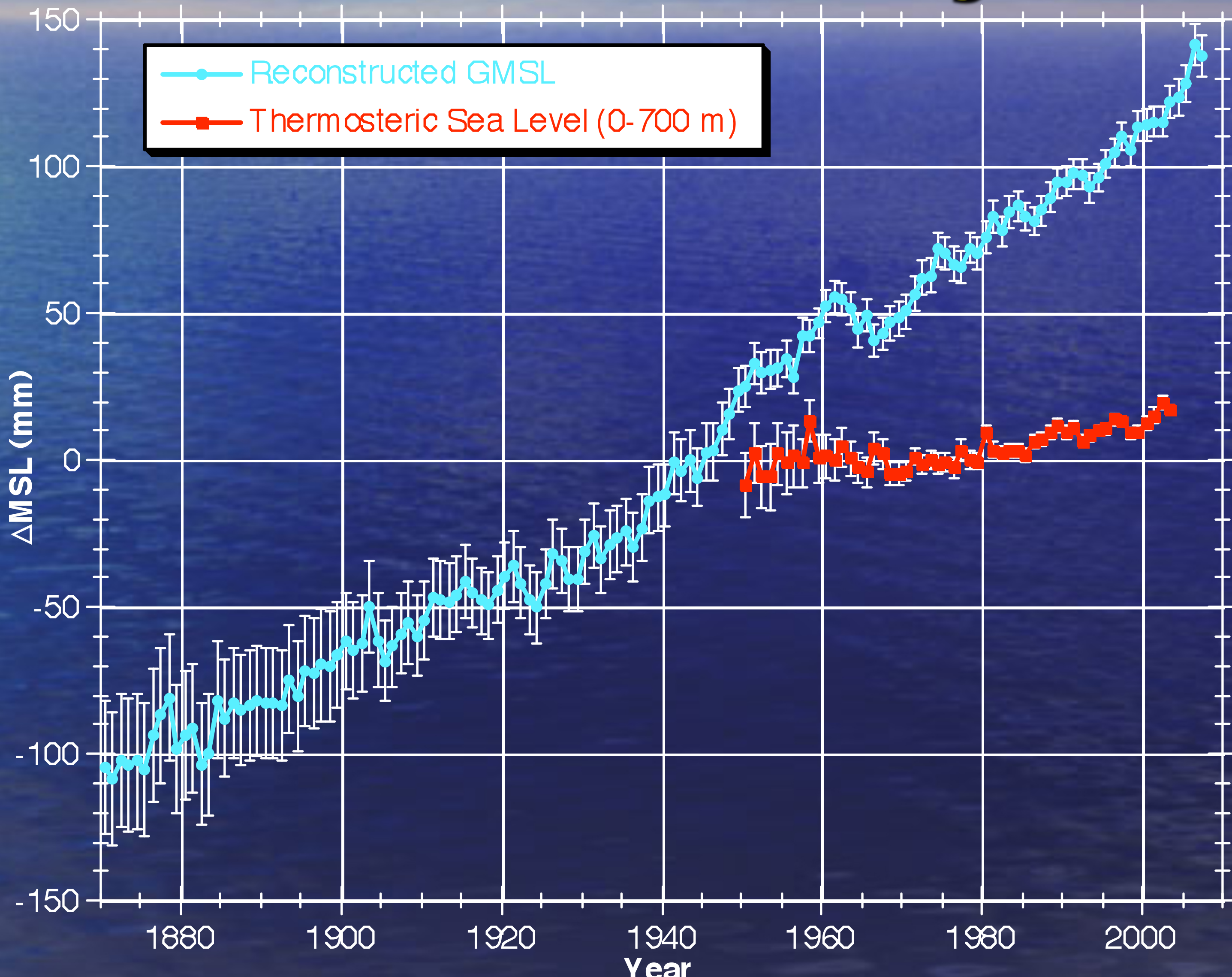
Image from Bette Otto-Bliesner, National Center for Atmospheric Research

Paleo Sea Level



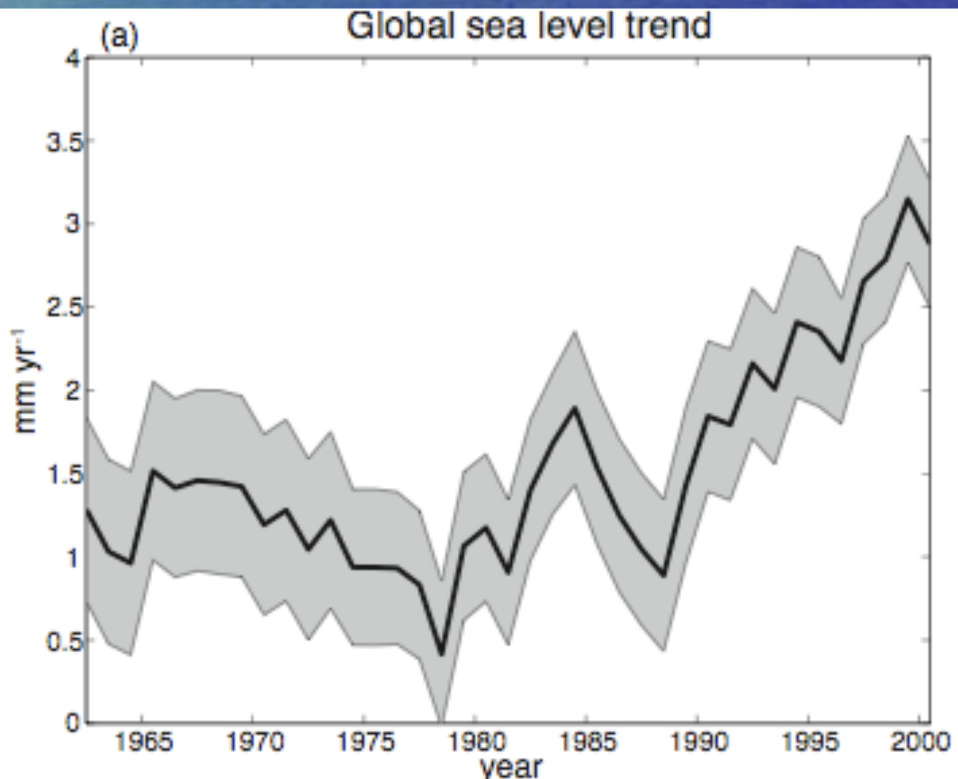
[Lambeck et al., 2002; Church et al., 2009]

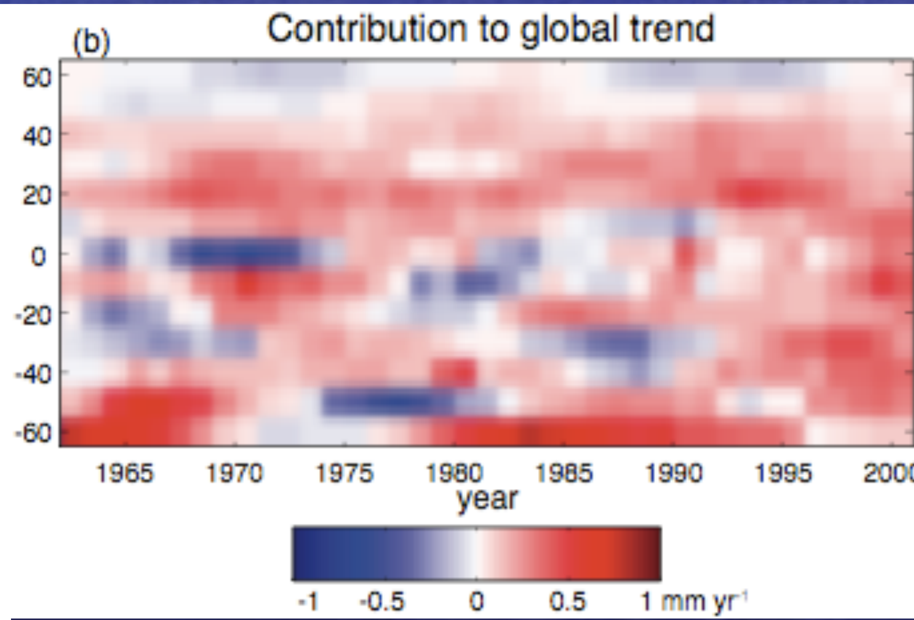
Past Sea Level Change



[Church and White, 2006; Domingues et al., 2008]

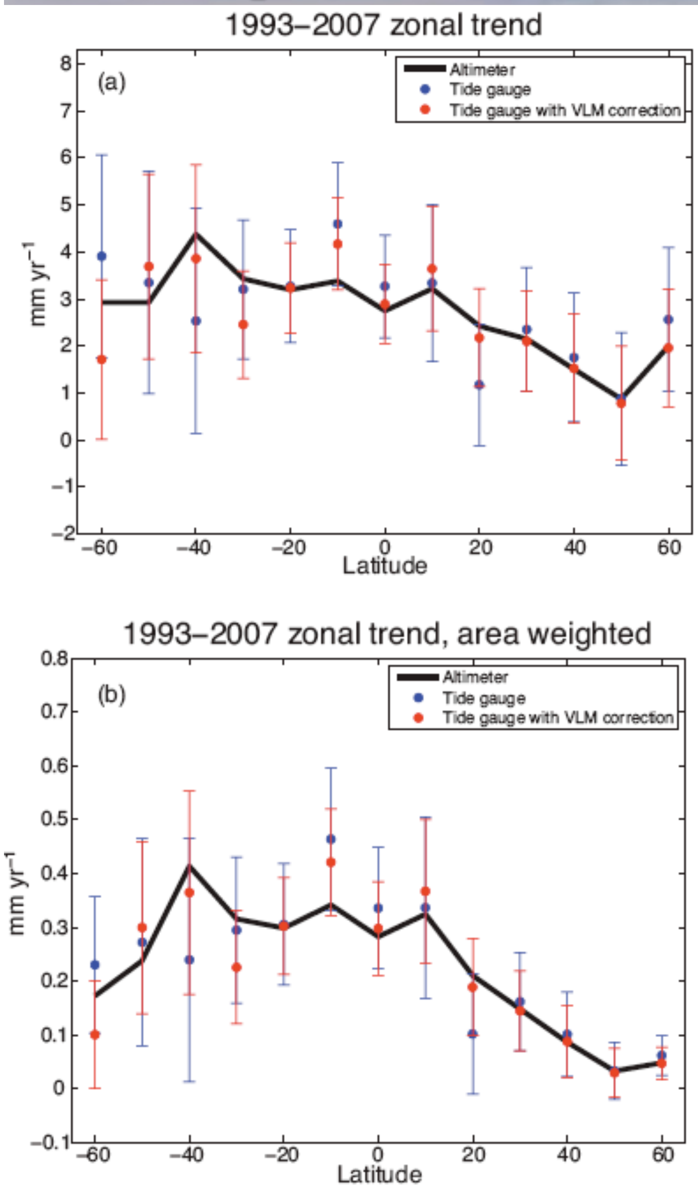
15-year Global Sea Level Trends from Tide Gauges

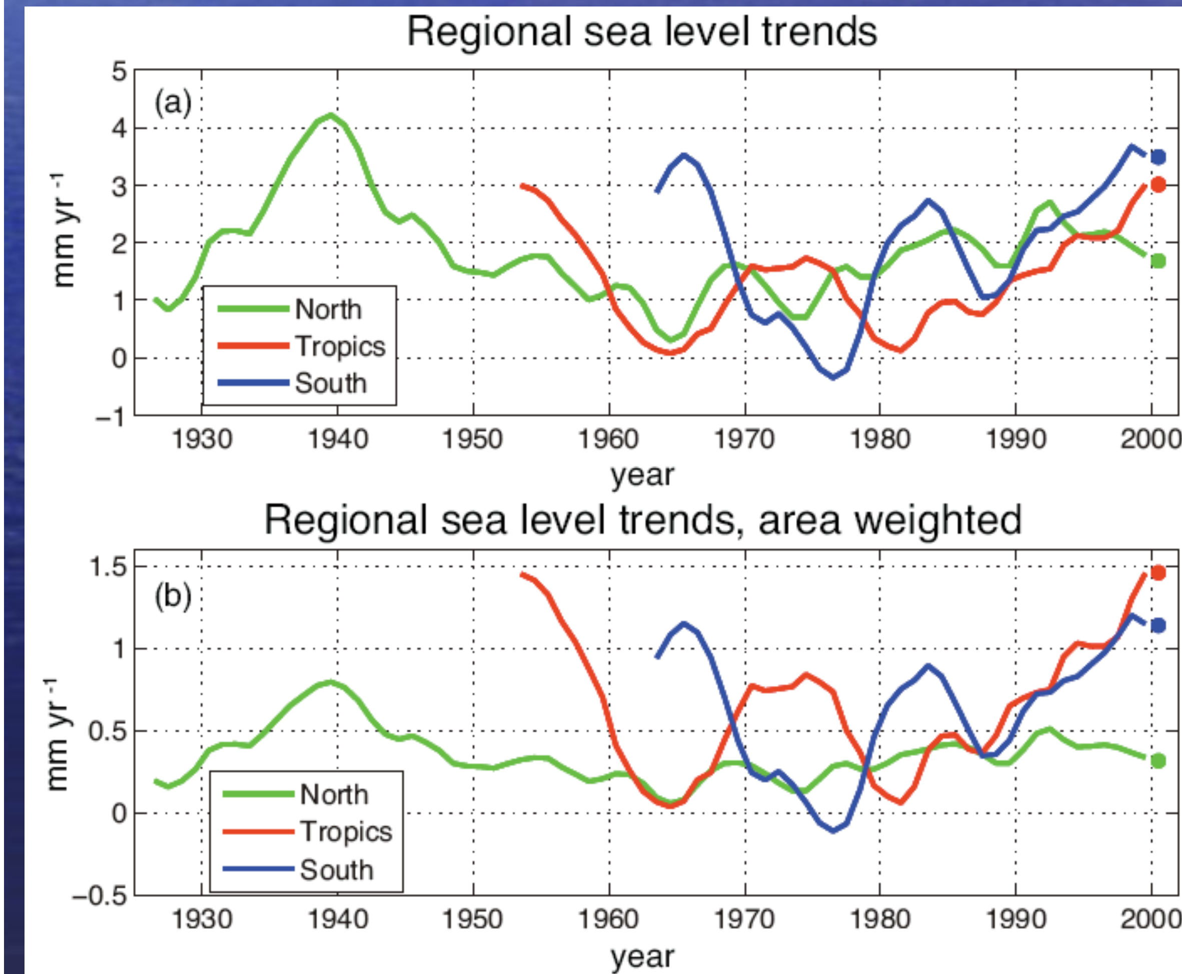




[Merrifield, Merrifield, and Mitchum, J. Climate, in press, 2009]

15-year Sea Level Trends from Tide Gauges

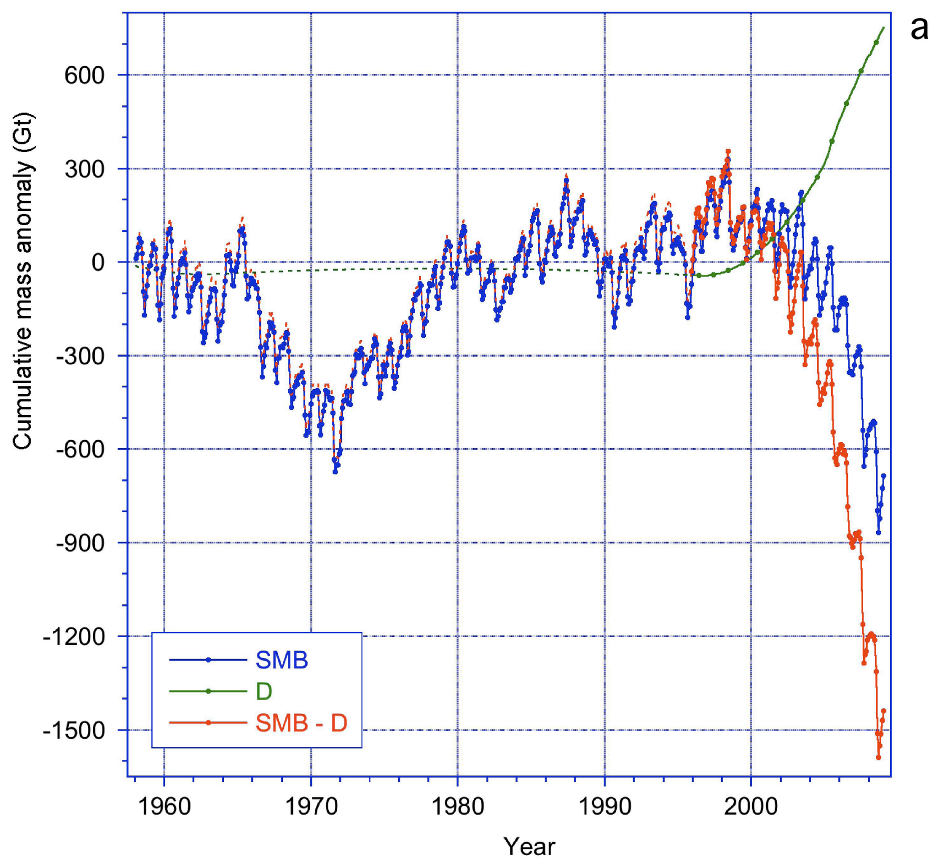




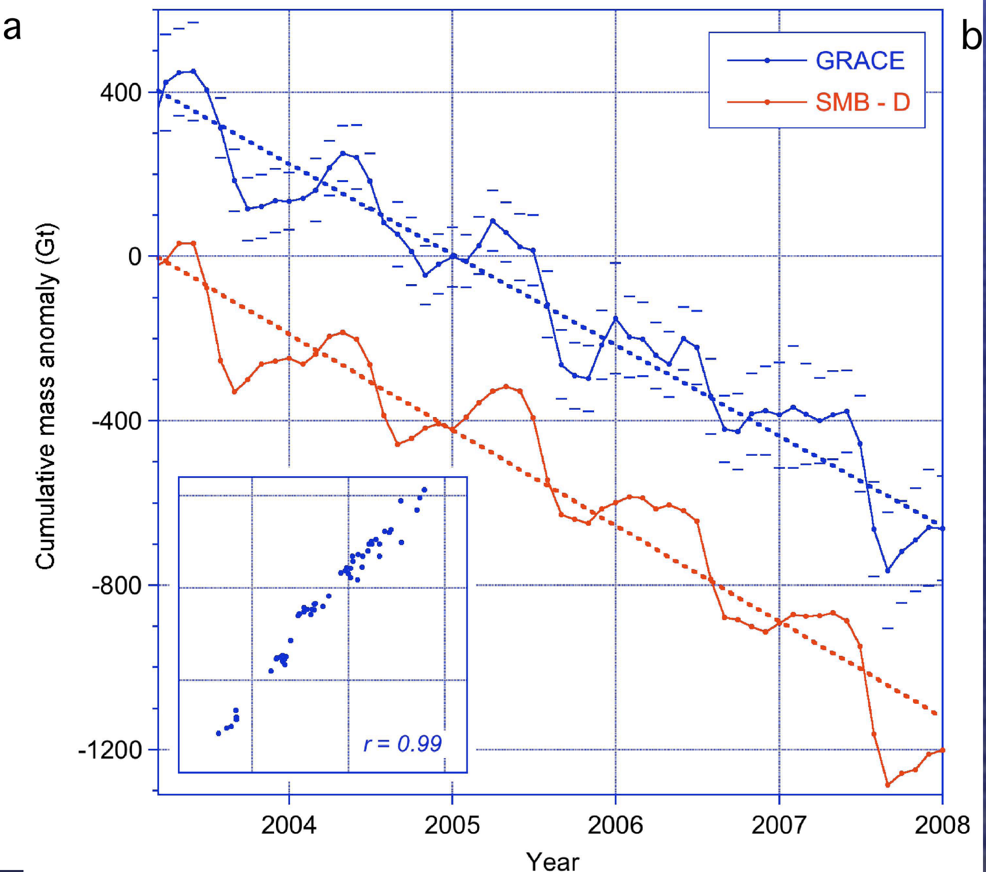
[Merrifield, Merrifield, and Mitchum, J. Climate, in press, 2009]

Greenland Ice Mass Change

Model forced by ERA40



Model vs GRACE



[Vanden Broeke et al., 2009]

Antarctic Ice Mass Changes

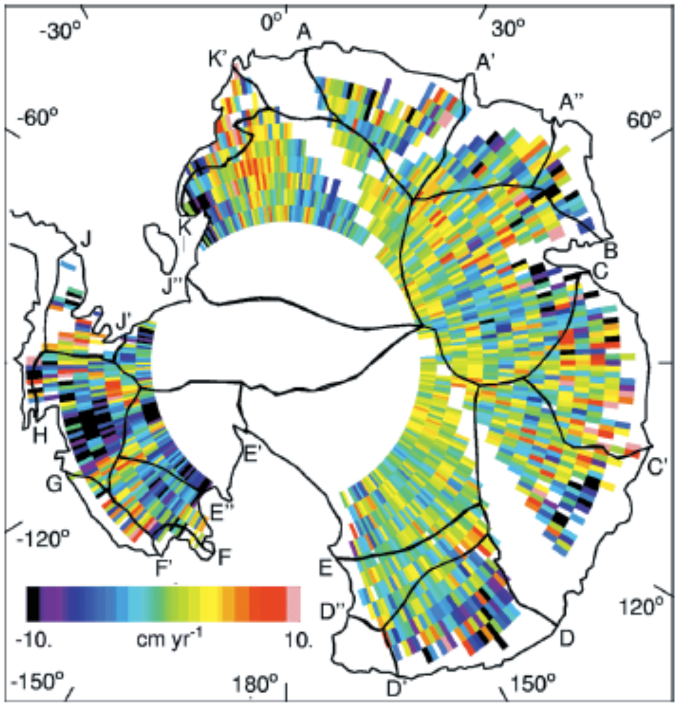
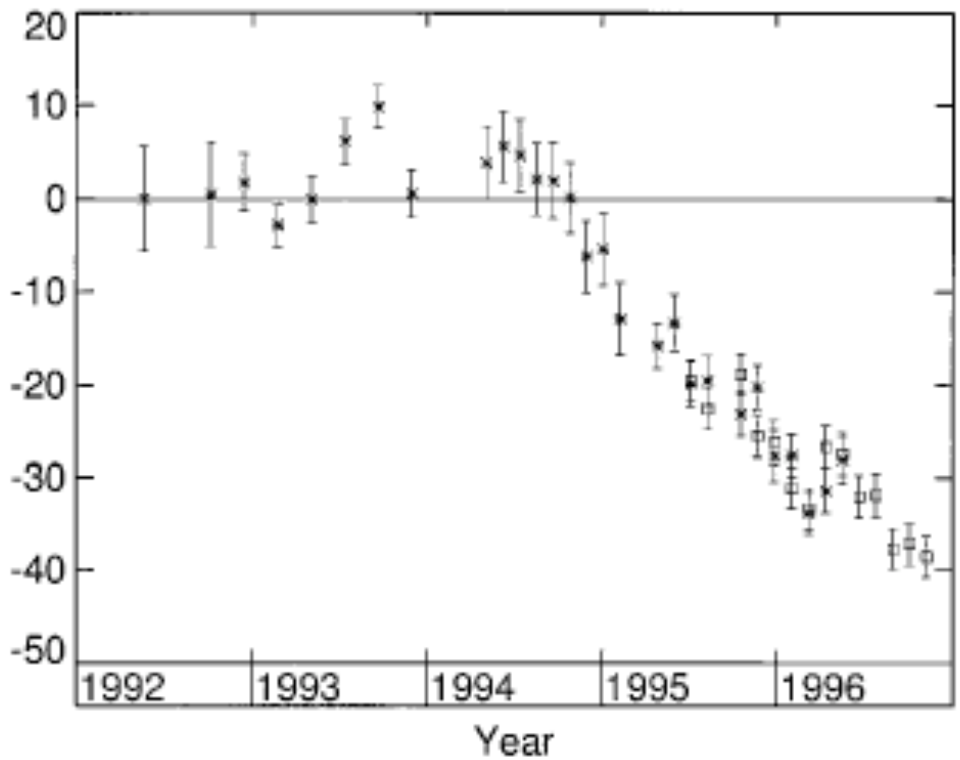
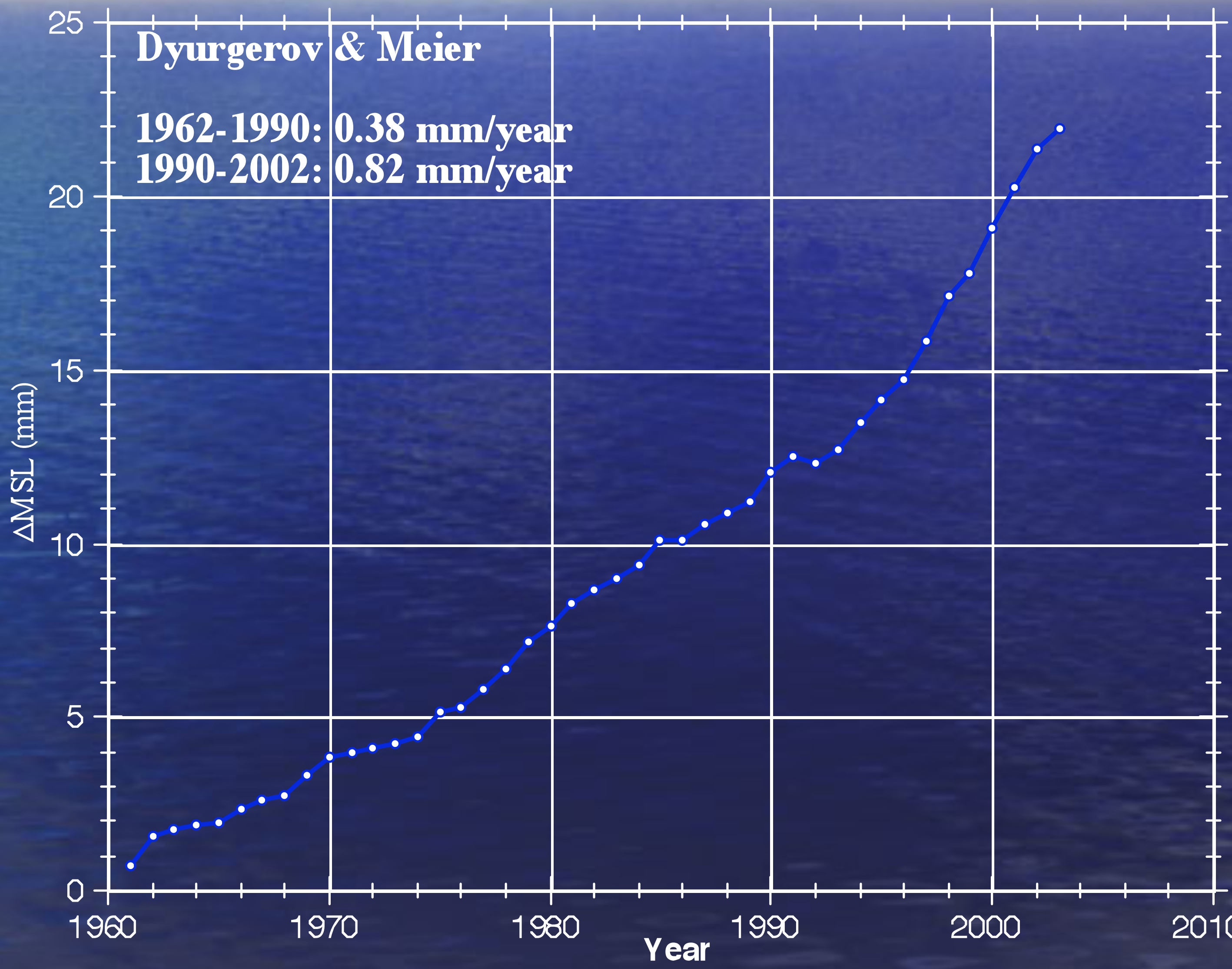


Fig. 2. The change in elevation from 1992 to 1996 (expressed in centimeters per year) of 63% of the grounded Antarctic Ice Sheet at a resolution of 1° by 1°, determined from ERS satellite altimeter measurements. Superimposed are the boundaries of the major drainage basins derived from ERS observations (*33*). The data gaps affecting basins K′-A, A′-A″, and C′-D result from tape-recorder limitations. The change of basin G-H appears to fall within the boundaries of the Thwaites Glacier Basin, and there is perhaps reason (*34*) to suppose that the Thwaites Glacier is drawing down its basin. However, the change in elevation of the basin is not unusual in comparison with the expected snowfall variability (Table 1). In addition, the change is unsteady (Fig. 1); a snowfall fluctuation is certainly implicated in the volume reduction.



[Wingham et al., 1998]

Mountain Glacier Contribution to GMSL



Glacier Mass Balance

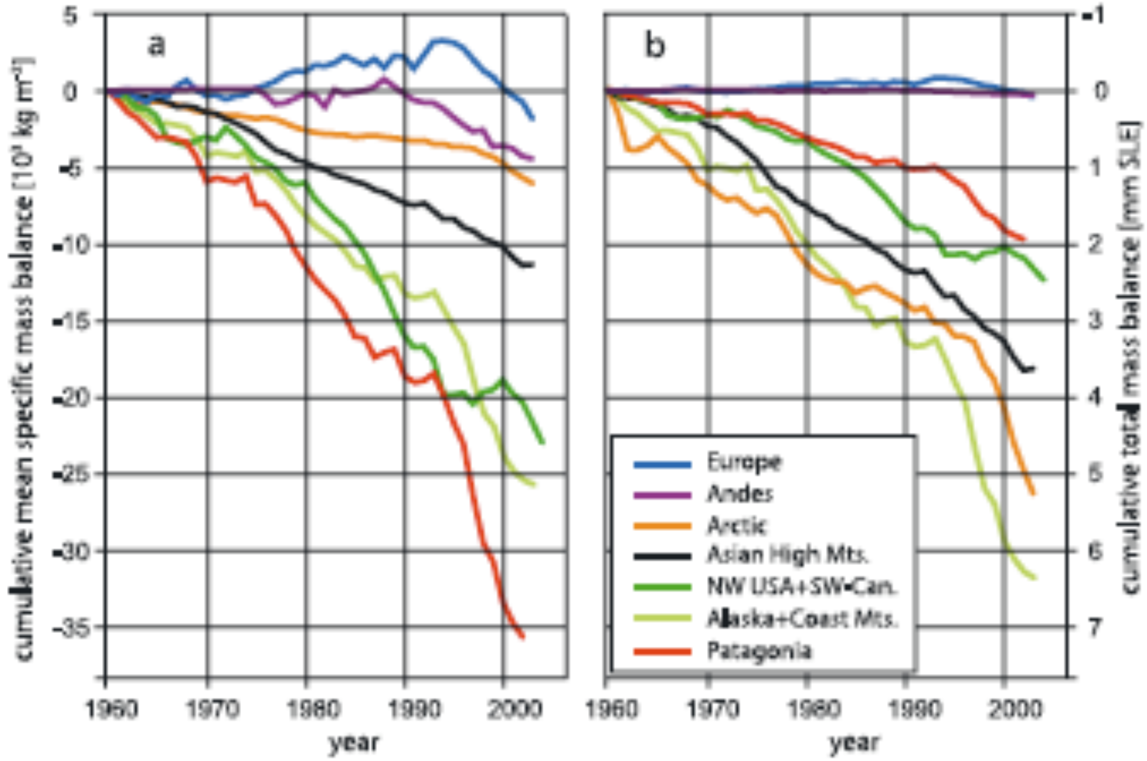
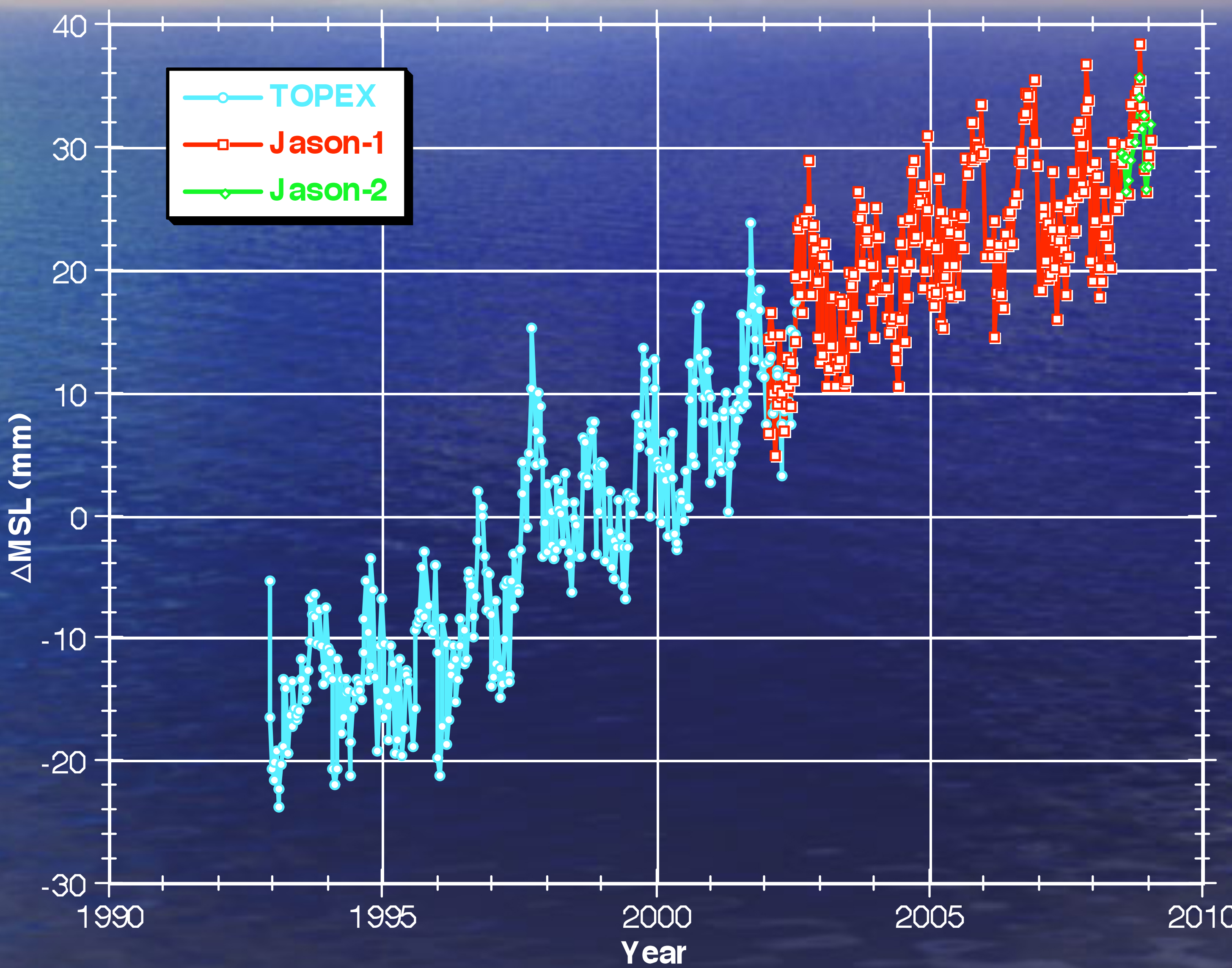


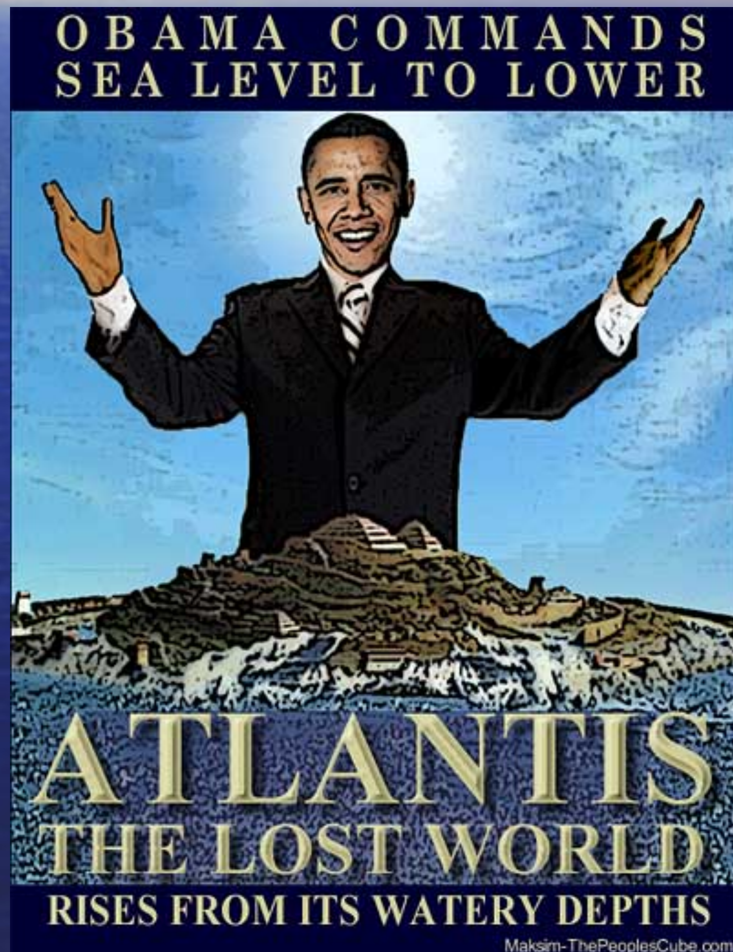
Figure 1. Cumulative (a) specific and (b) total mass balances of glaciers and ice caps, calculated for large regions [*Dyurgerov and Meier*, 2005]. Specific mass balances signalize the strength of the glacier response to climatic change in each region. Total mass balances indicate each region's contribution to sea level.

[Kaser et al., 2006]

Present-Day Sea Level Change



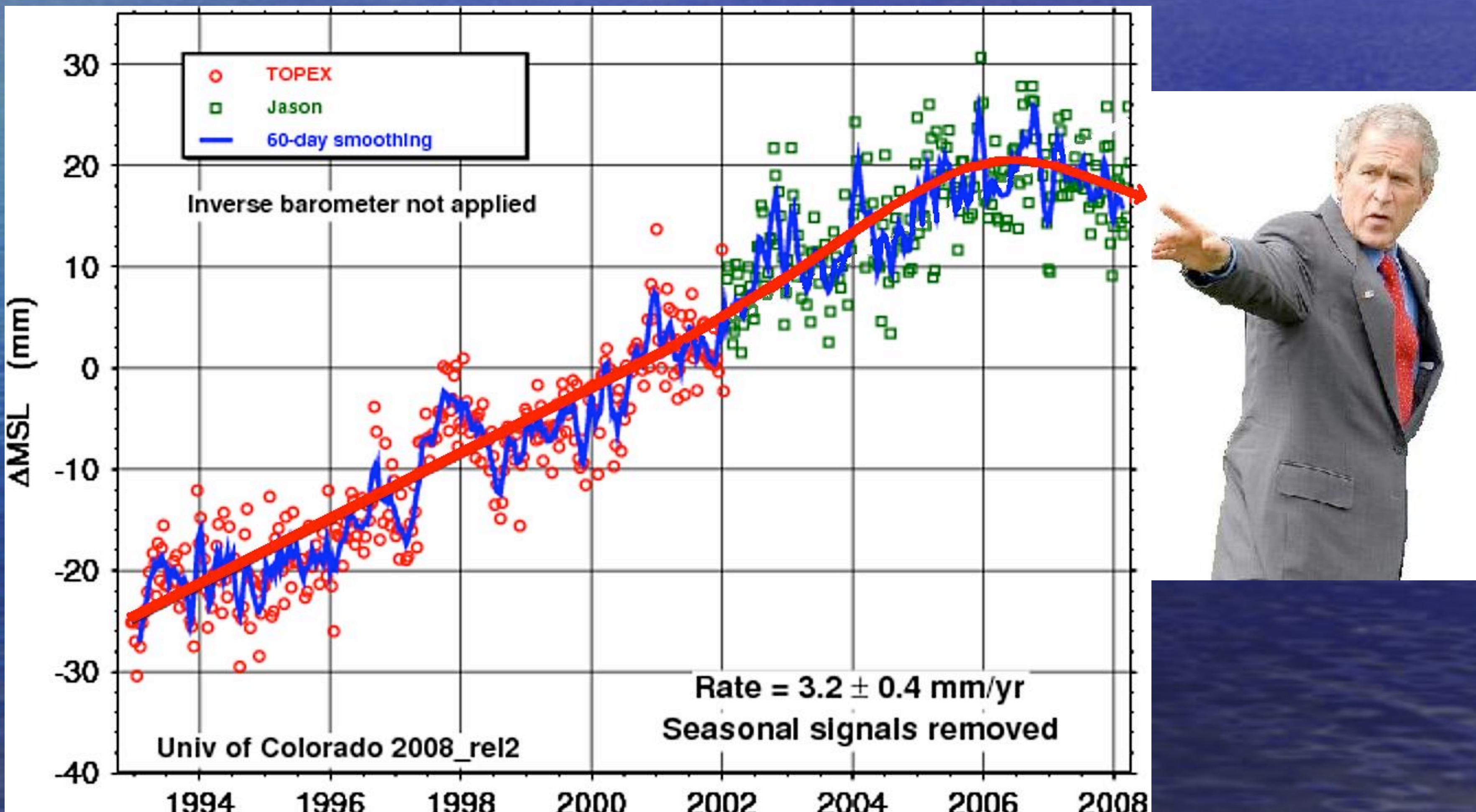
Can this guy lower the seas ?



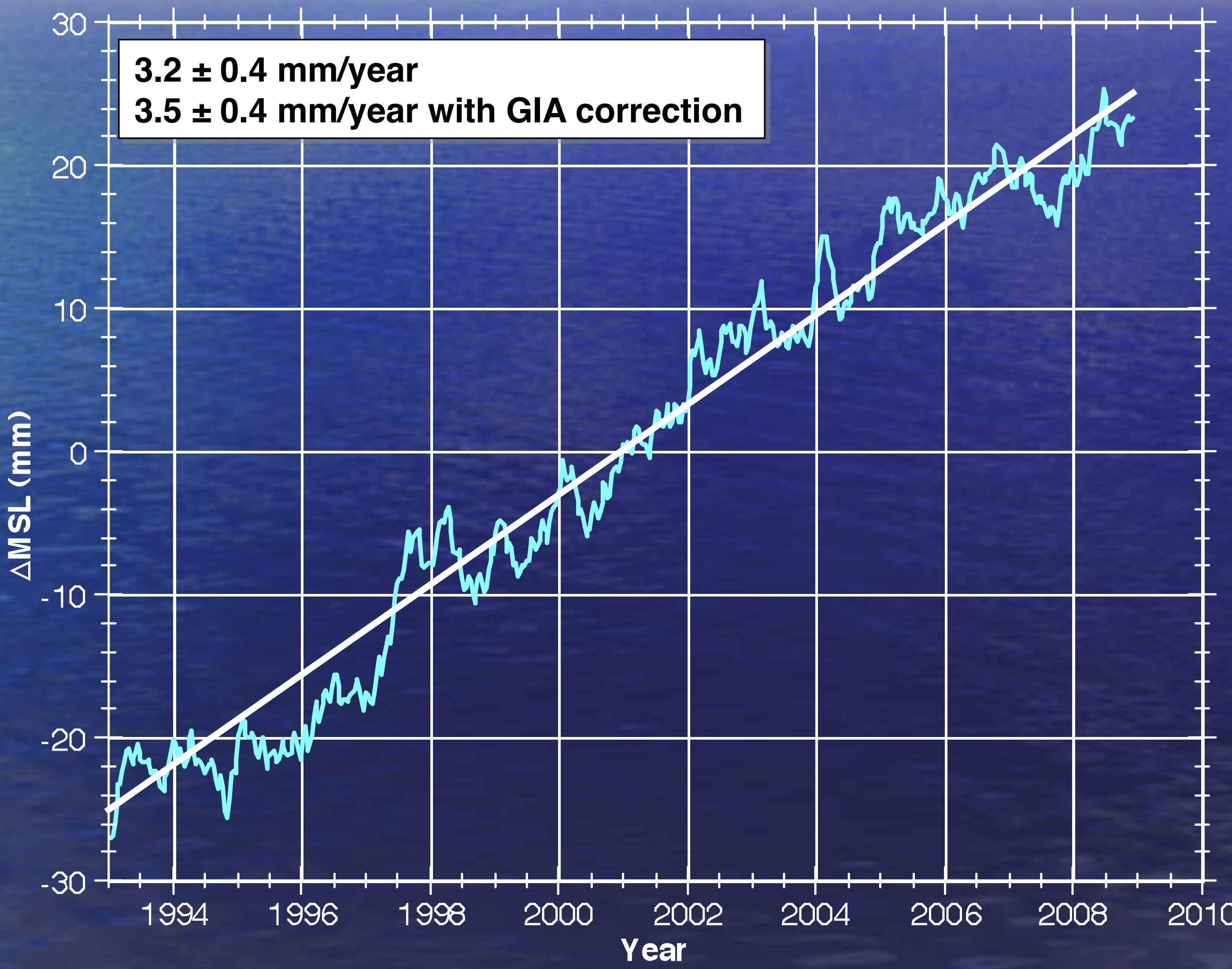
"I am absolutely certain that generations from now, we will be able to look back and tell our children that this was the moment when the rise of the oceans began to slow and our planet began to heal."

- Barack Obama, June 3, 2008

Why not? This guy did….

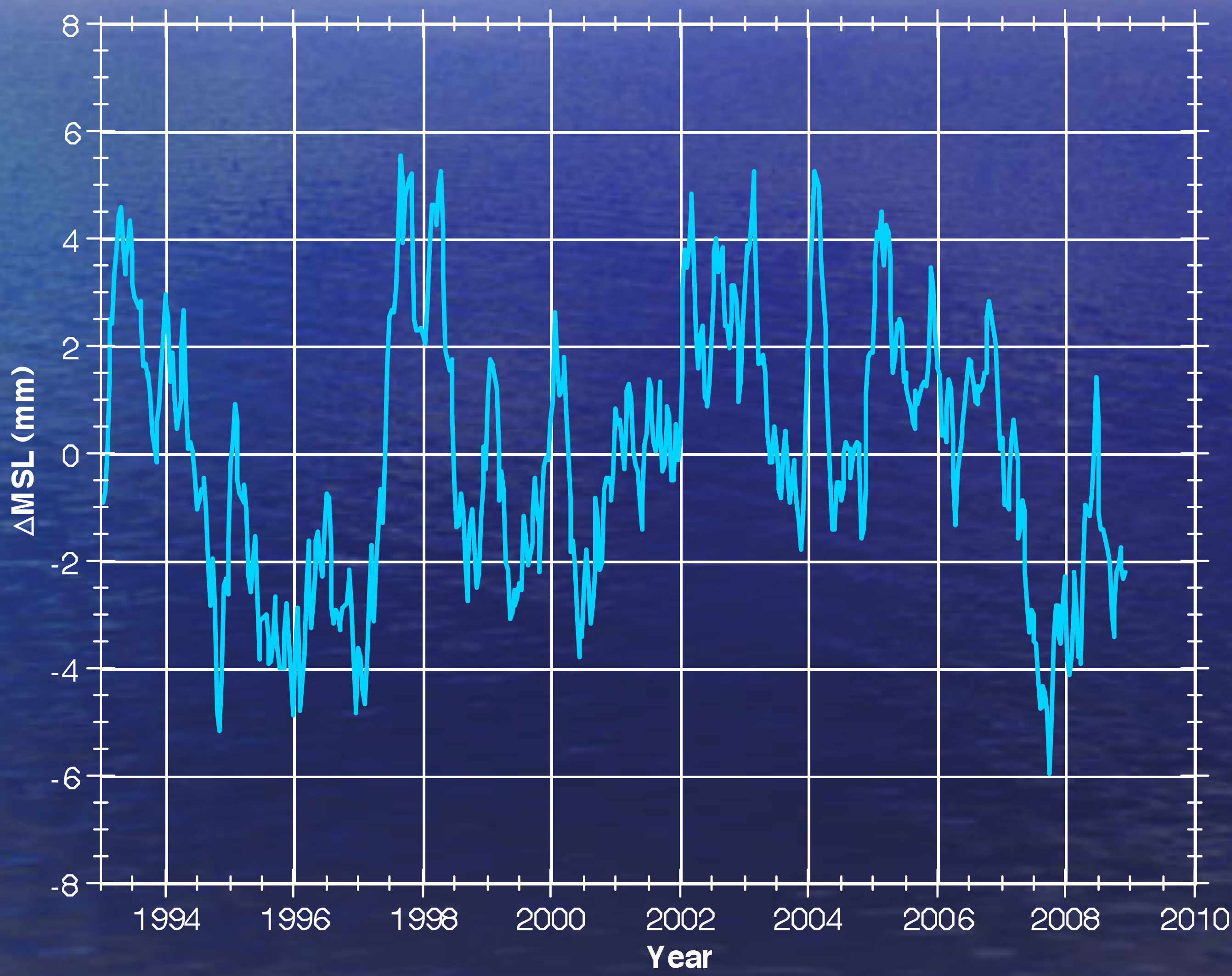


Present-Day Sea Level Change

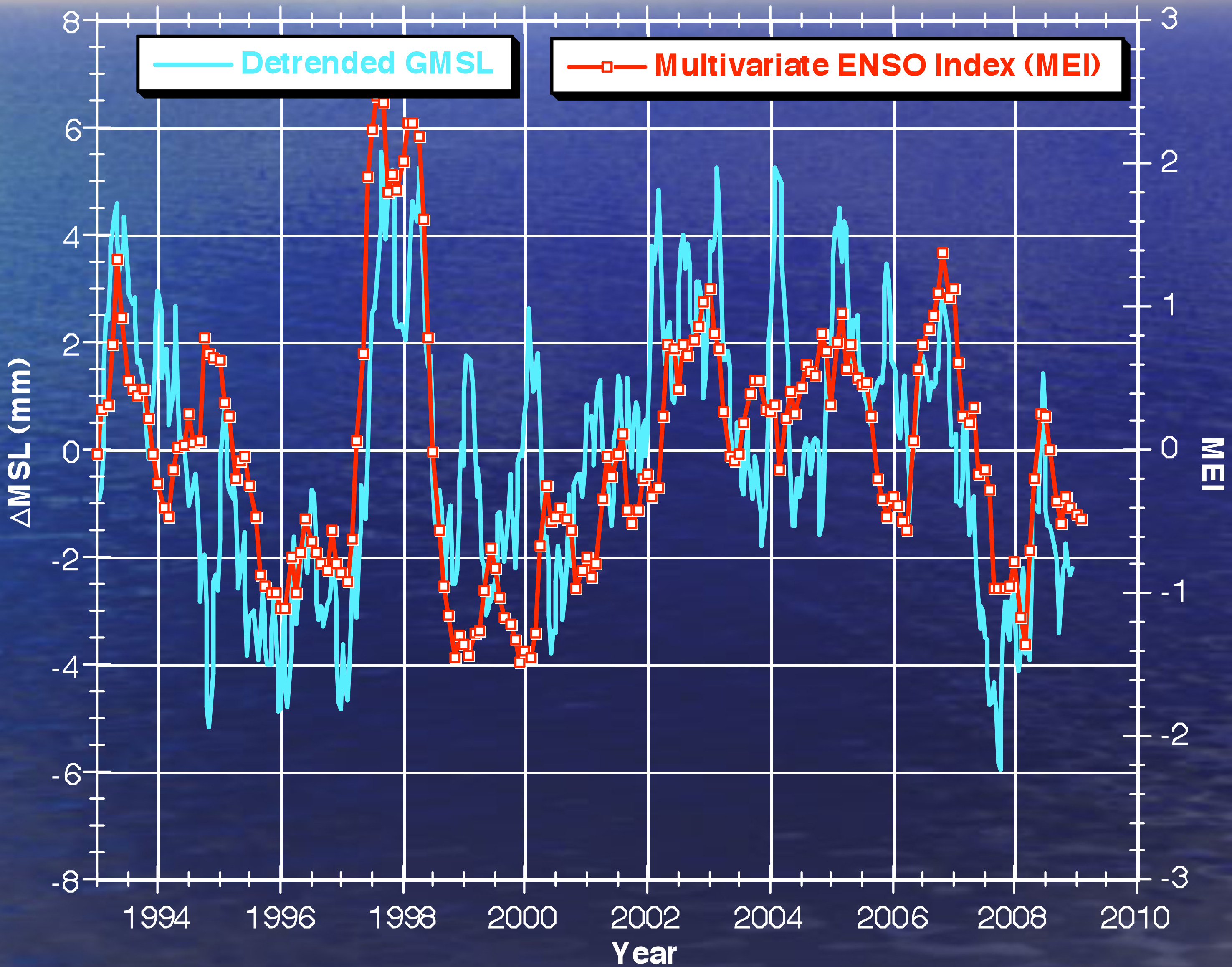


Global Mean Thermosteric Contribution

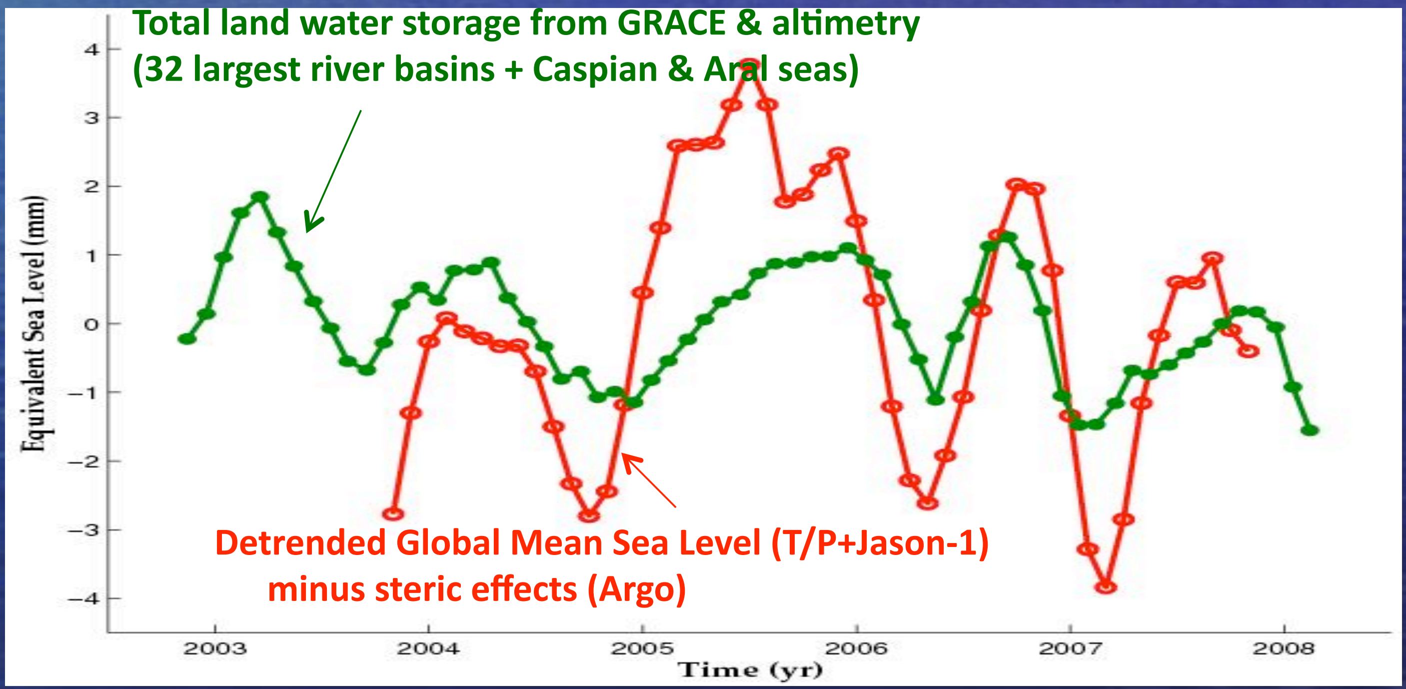
Detrended Global Sea Level Change



Detrended GMSL and MEI

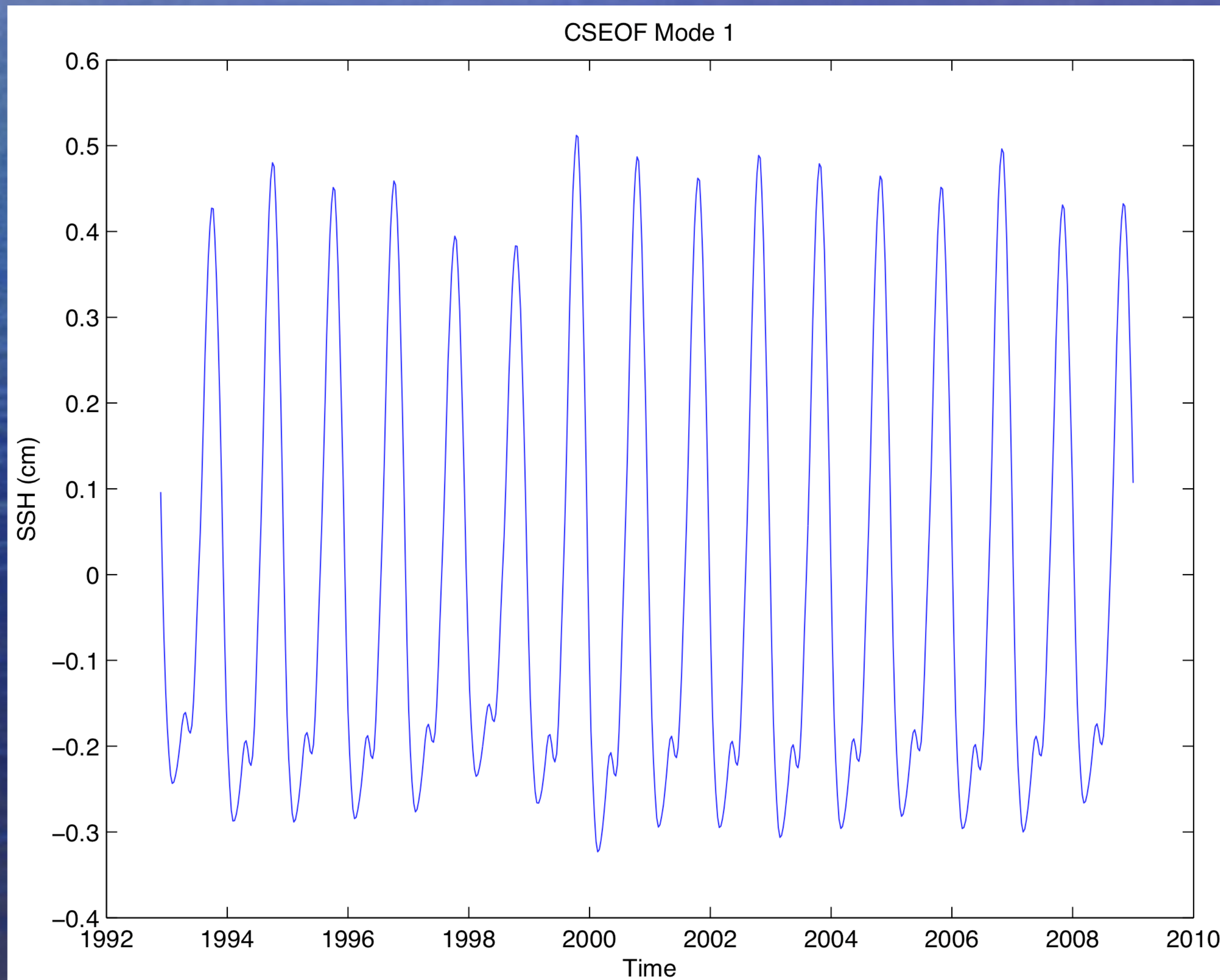


Changes in Land Water Storage?

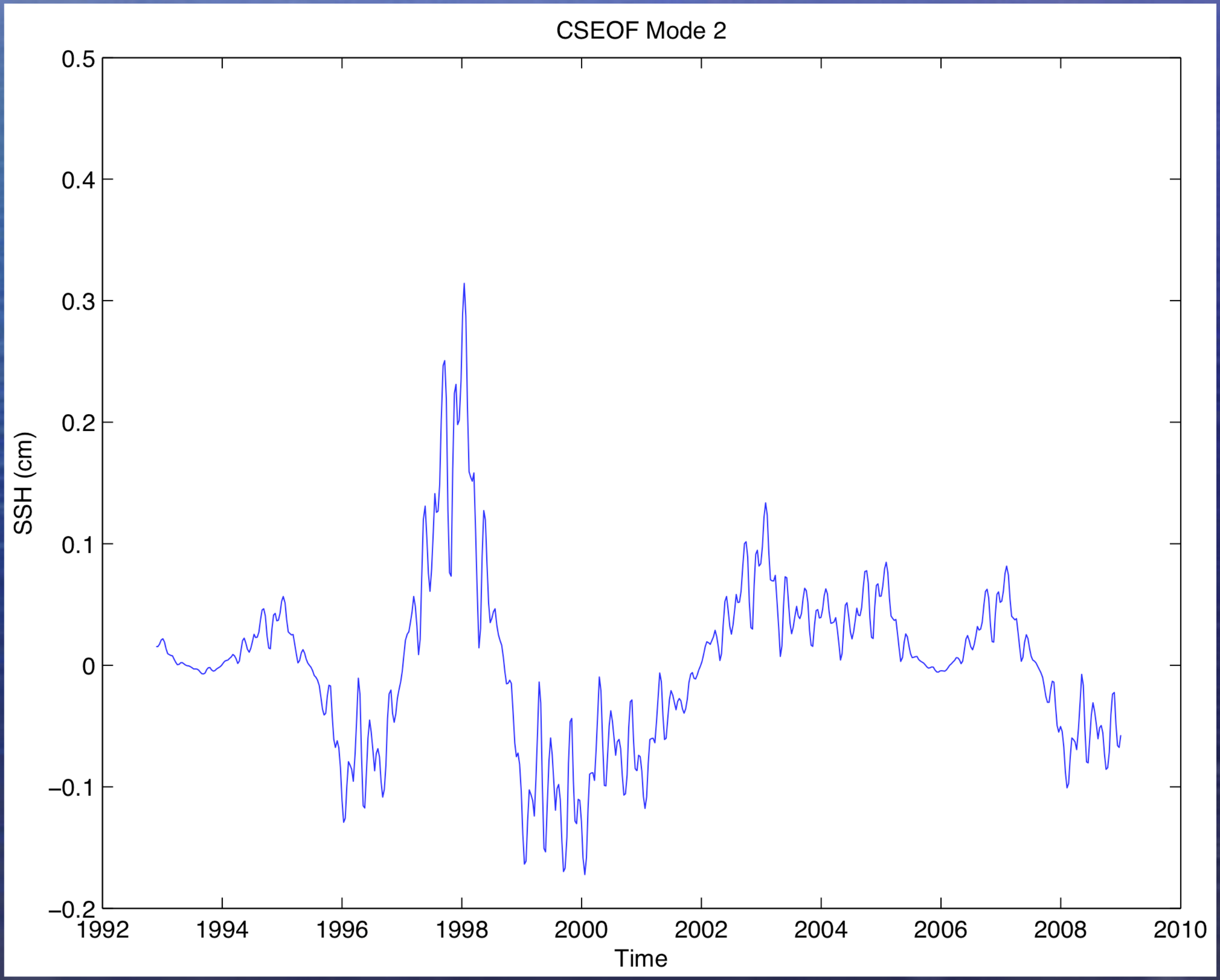


[Cazenave et al., 2009]

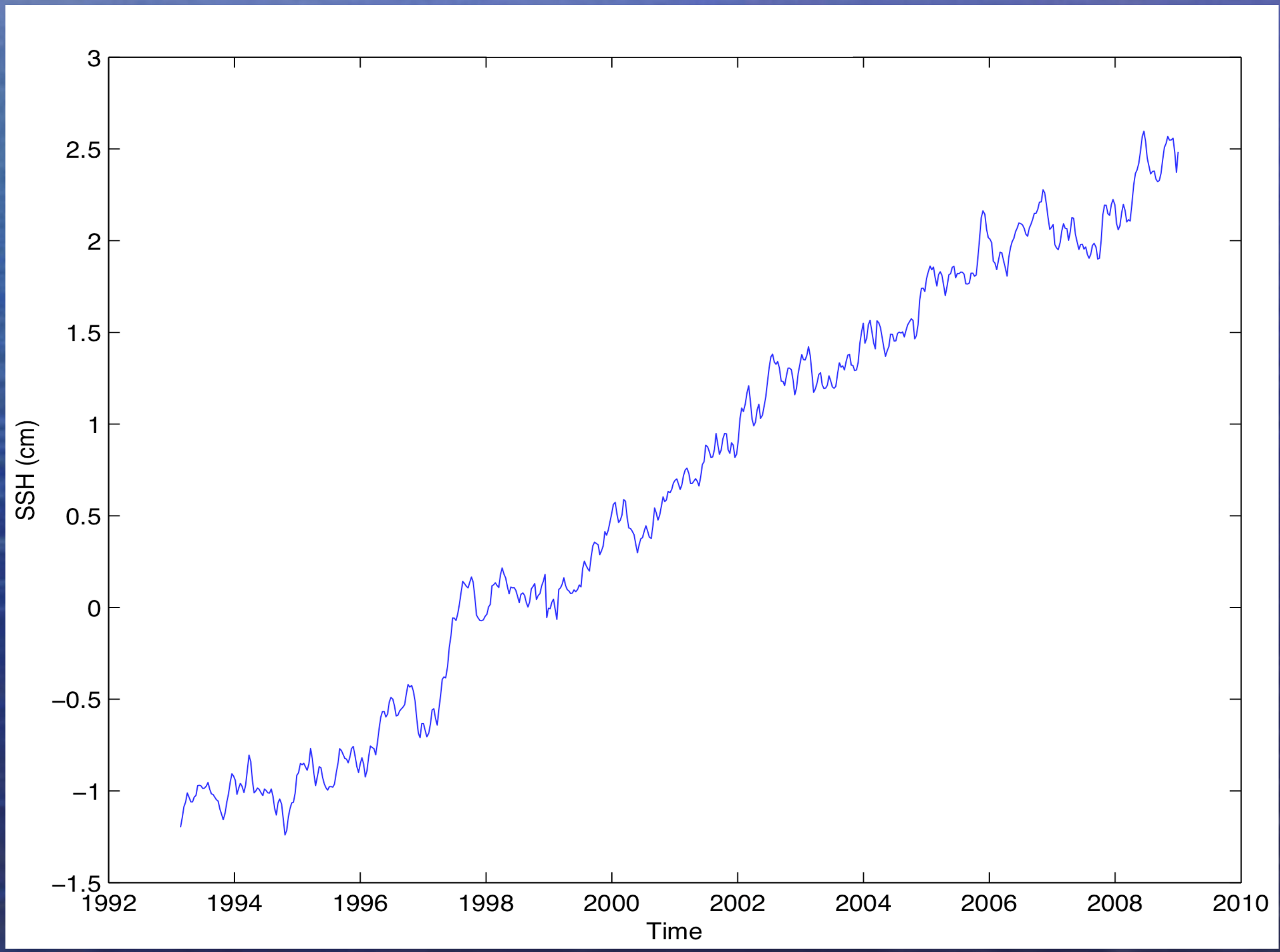
Cyclostationary Empirical Orthogonal Functions



Cyclostationary Empirical Orthogonal Functions

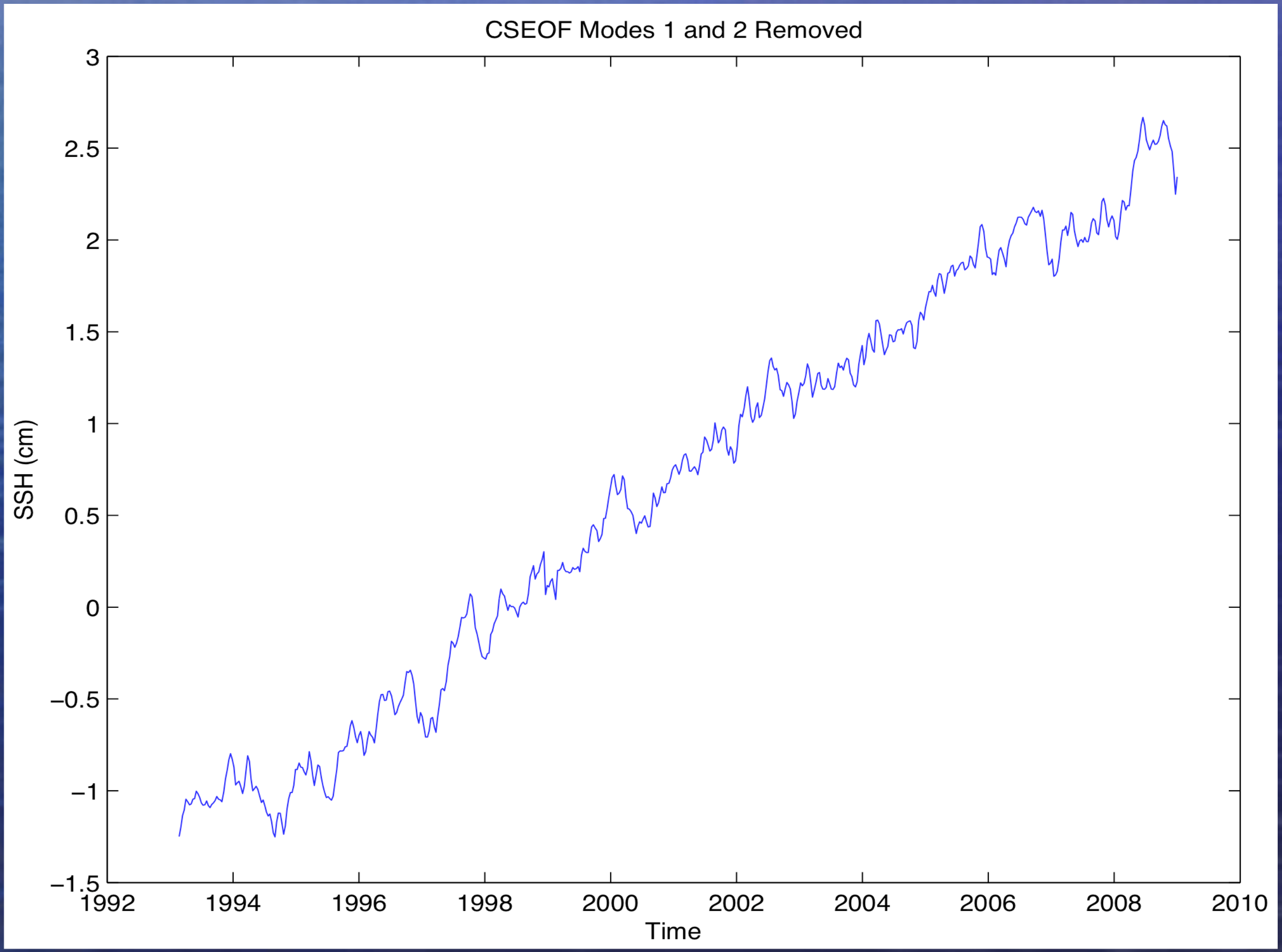


Global Mean Sea Level Variations

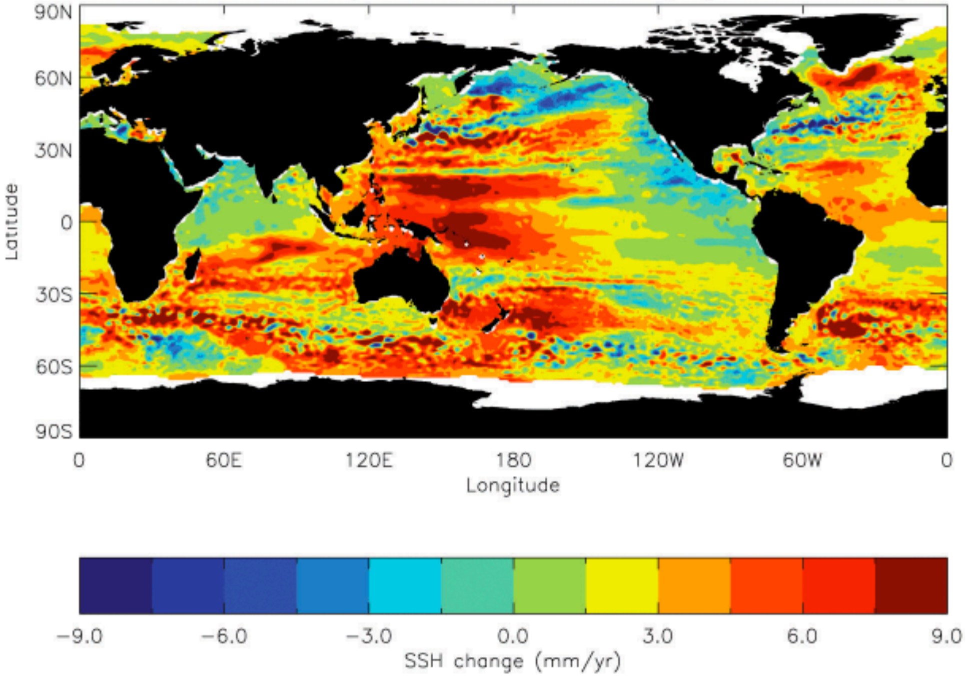


Global Mean Sea Level Variations

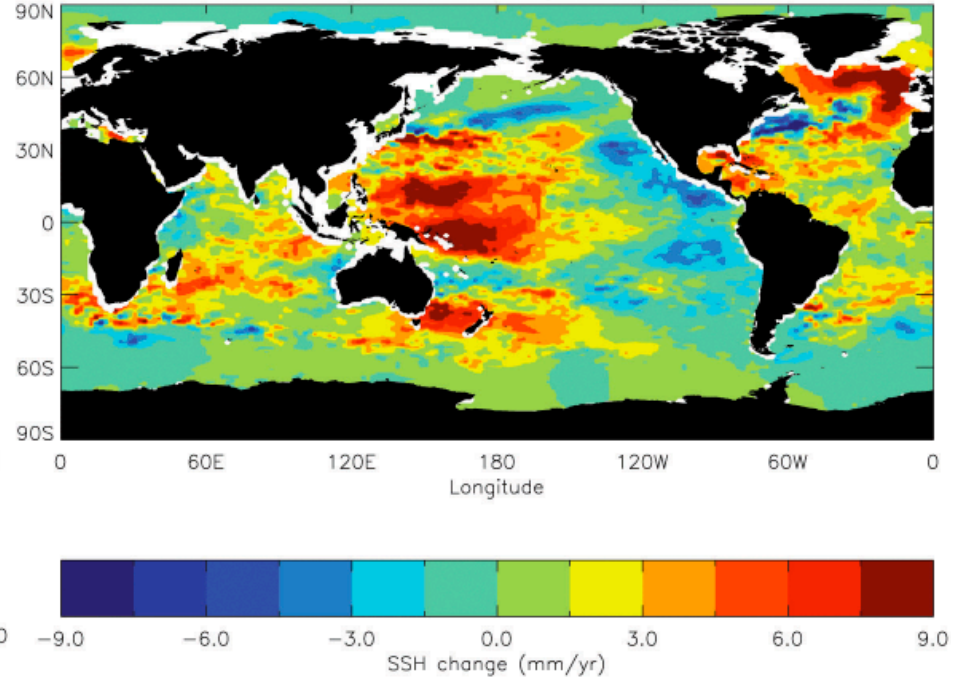
Global mean time series with first and second CSEOF modes removed.



Observed Sea Level Trends: 1993-2006

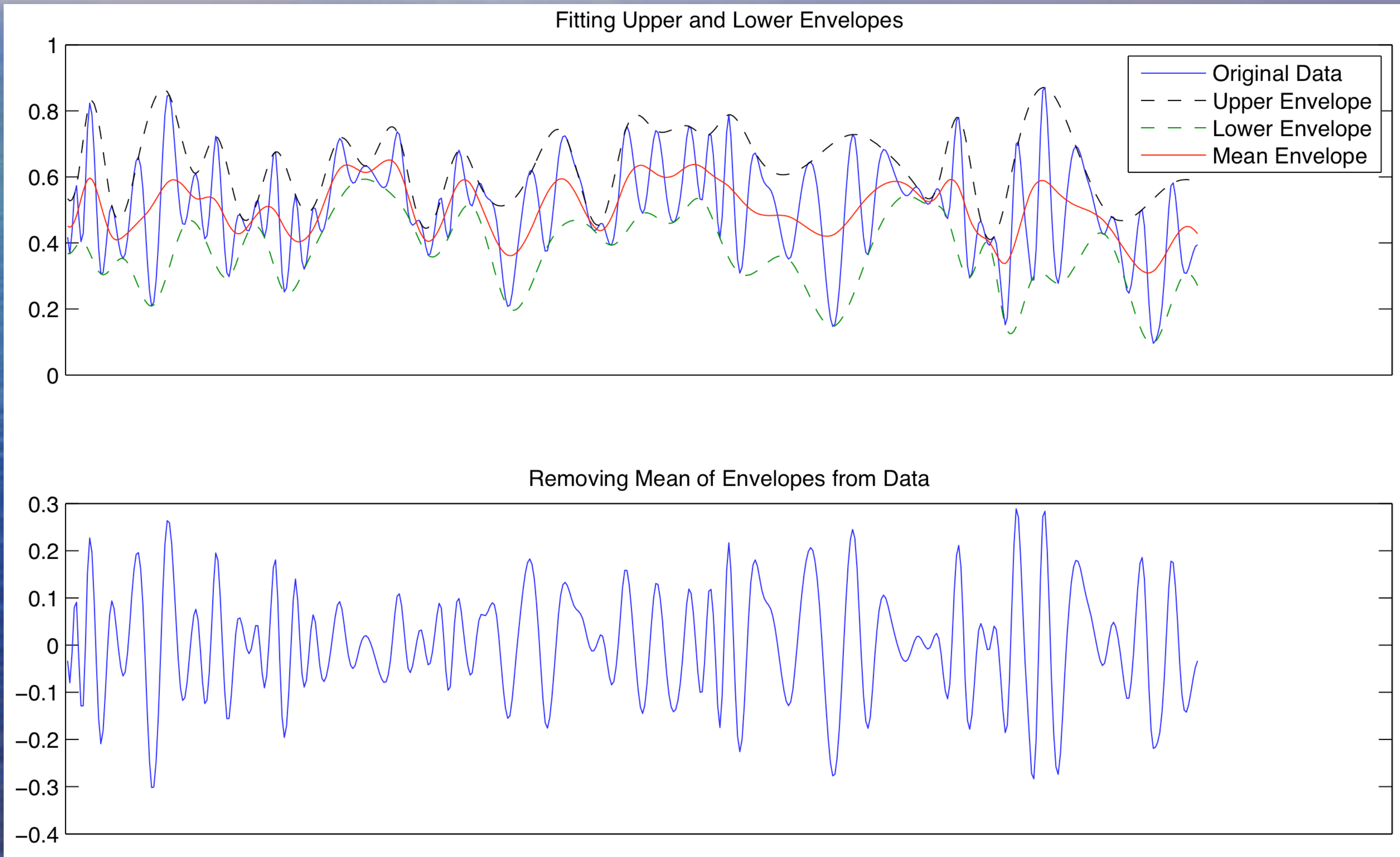


Total Sea Level (Altimetry)



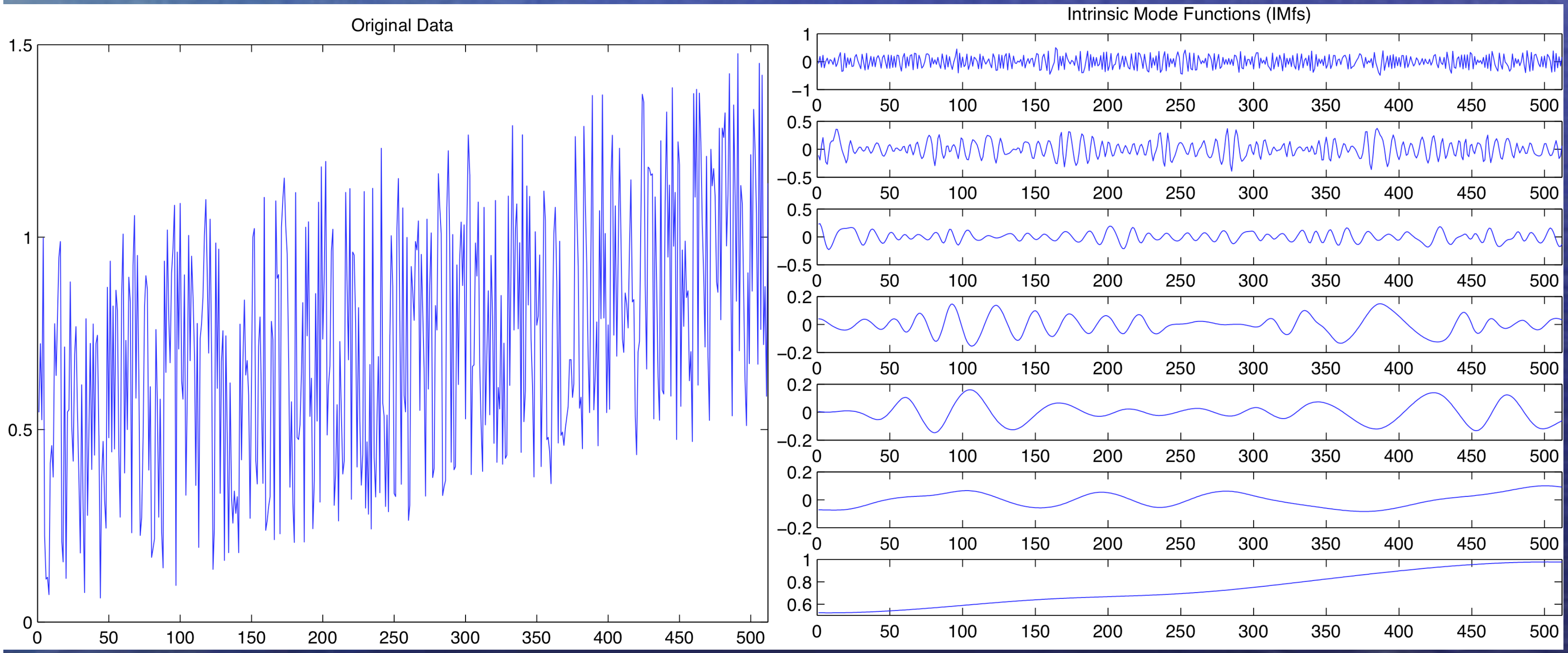
Thermosteric Sea Level (XBTs, Argo, etc.)

Empirical Mode Decomposition



[Huang et al., 1998]

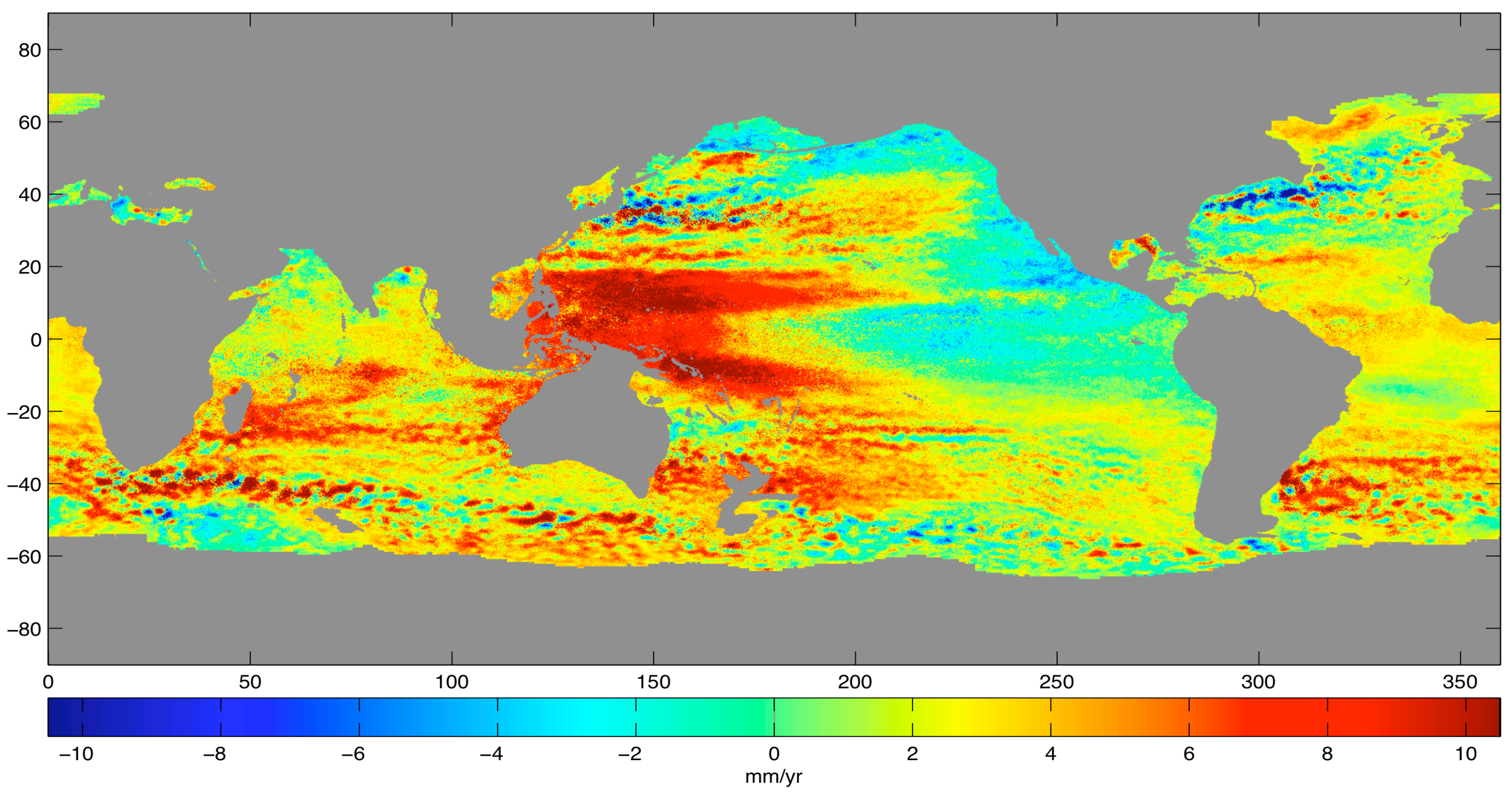
Empirical Mode Decomposition



[Huang et al., 1998]

Sea Level Trends over the Altimeter Era

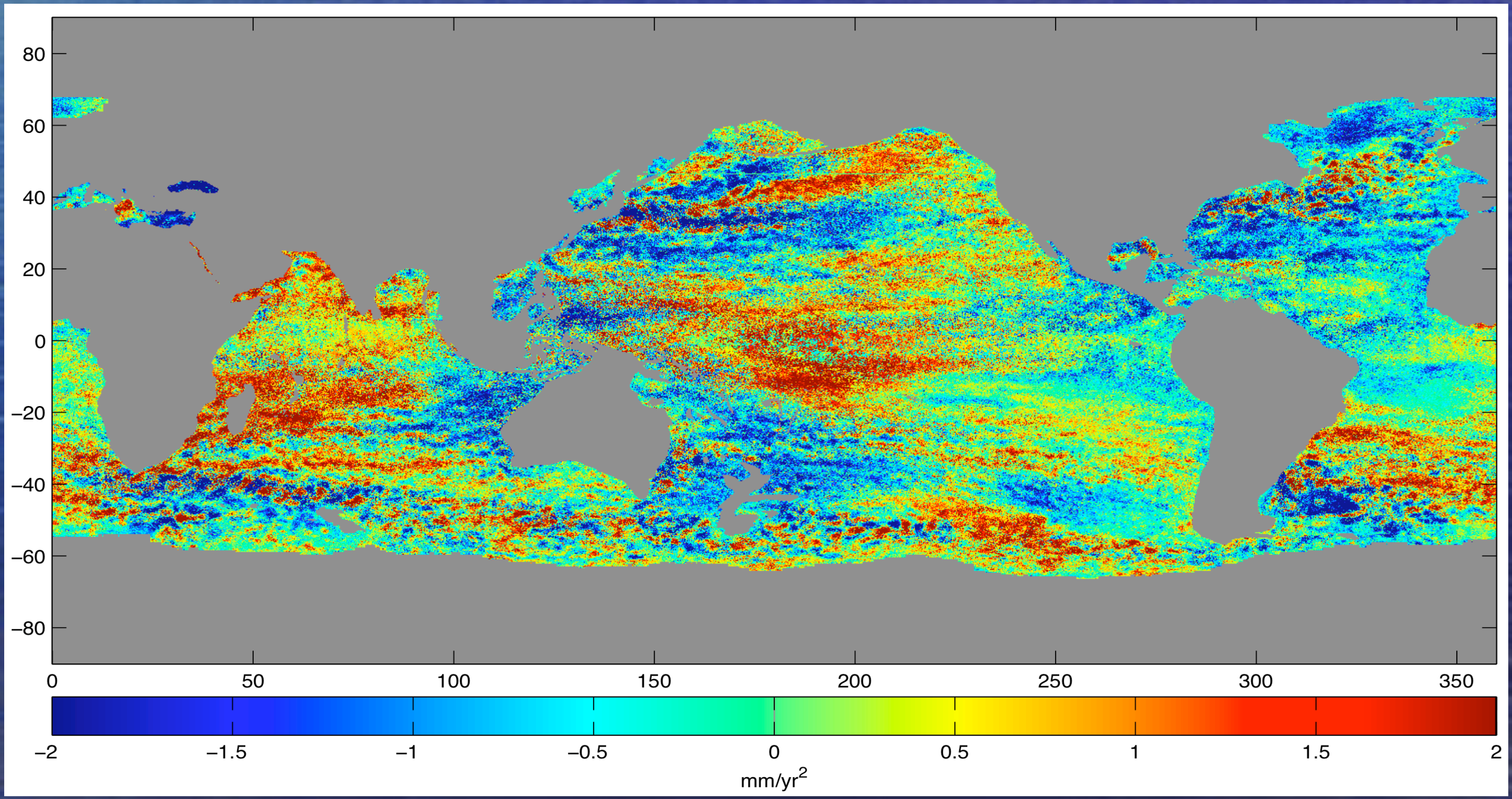
Using combined EMD/EOF method, rate of global mean sea level rise is determined to be 2.6 mm/yr.



[Hamlington et al., 2009]

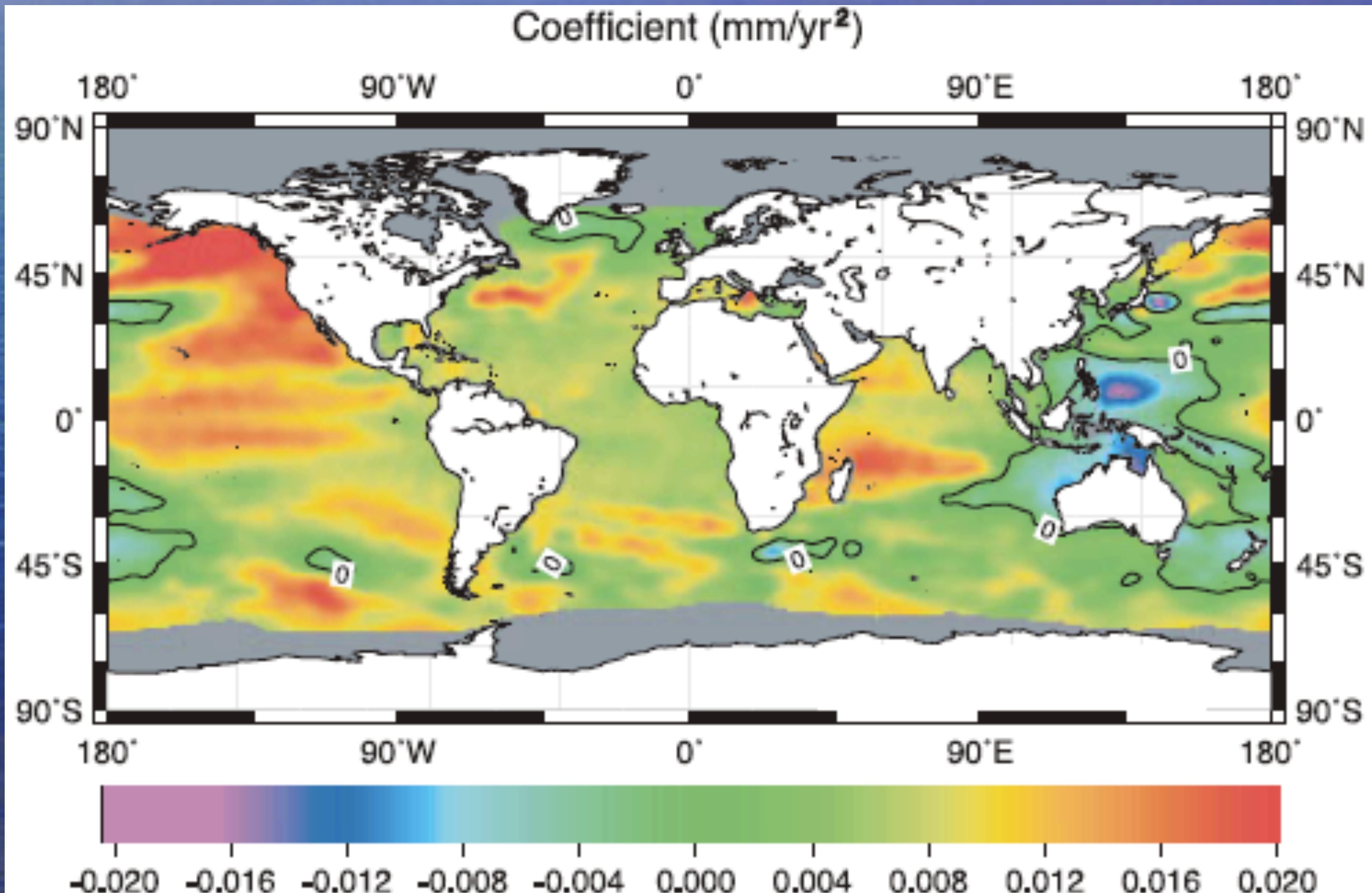
Sea Level Acceleration during Altimeter Era

Global mean sea level acceleration was found to be 0.01 mm/yr^2.



[Hamlington et al., 2009]

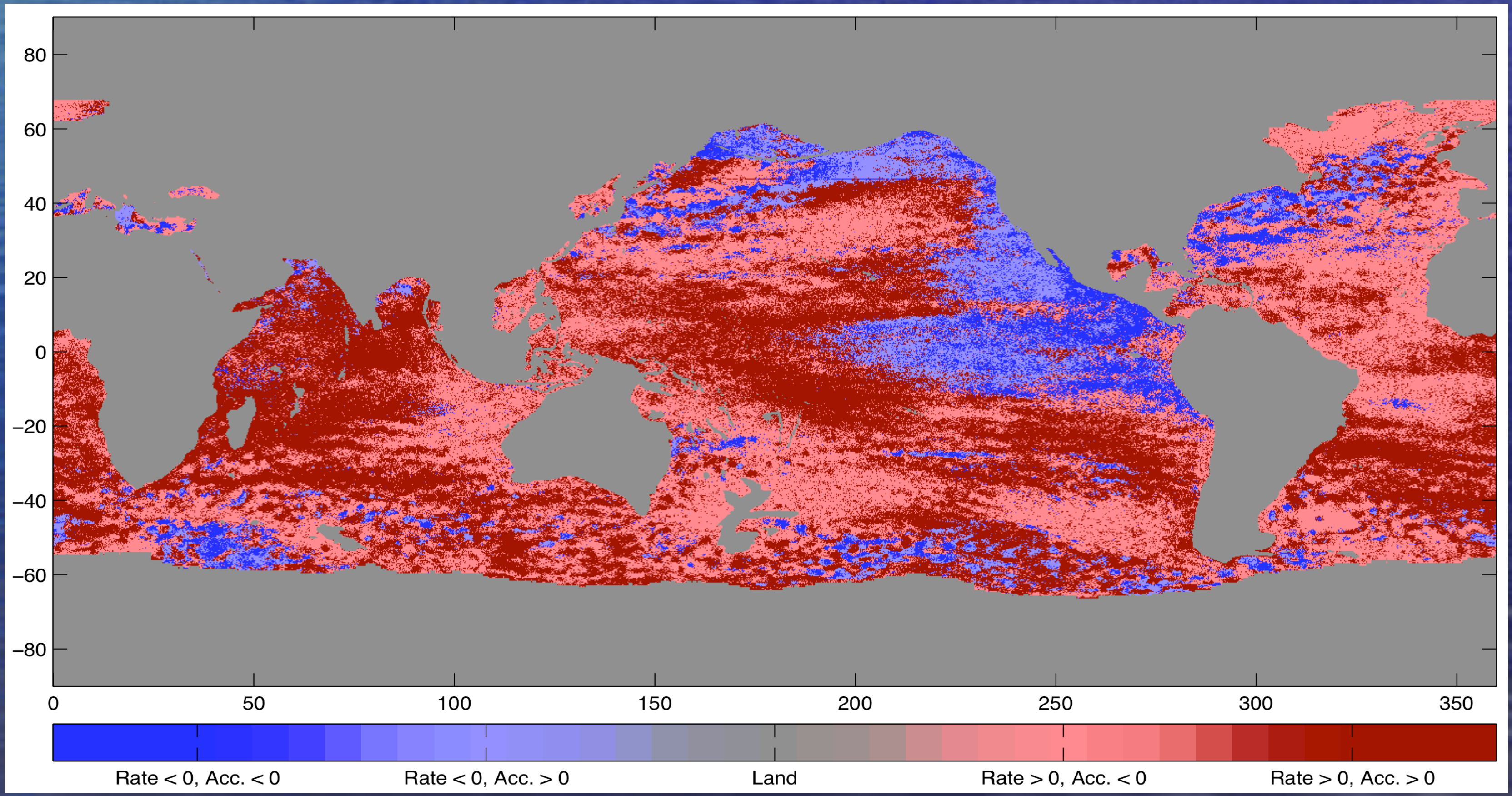
Sea Level Acceleration: 1870-2000



[Woodworth et al., 2009; based on Church and White, 2006]

Sea Level Acceleration and Rate

We classify each gridpoint into one of four categories: 1) positive rate, acceleration; 2) positive rate, deceleration; 3) negative rate, acceleration; 4) negative rate, deceleration. 42.8% of the ocean has a positive rate and acceleration, while only 8.4% has a negative rate and deceleration. In total, 83% of the ocean is undergoing a positive rate of sea level rise based on our results, while 51.5% of the ocean is undergoing an acceleration of sea level rise.



[Hamlington et al., 2009]

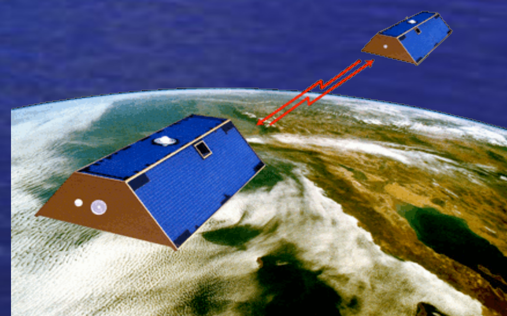
Combining Data to Study Sea Level Change

Addition of Heat

Argo

+

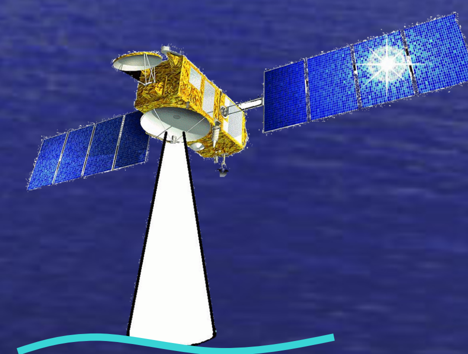
Addition of Freshwater



GRACE

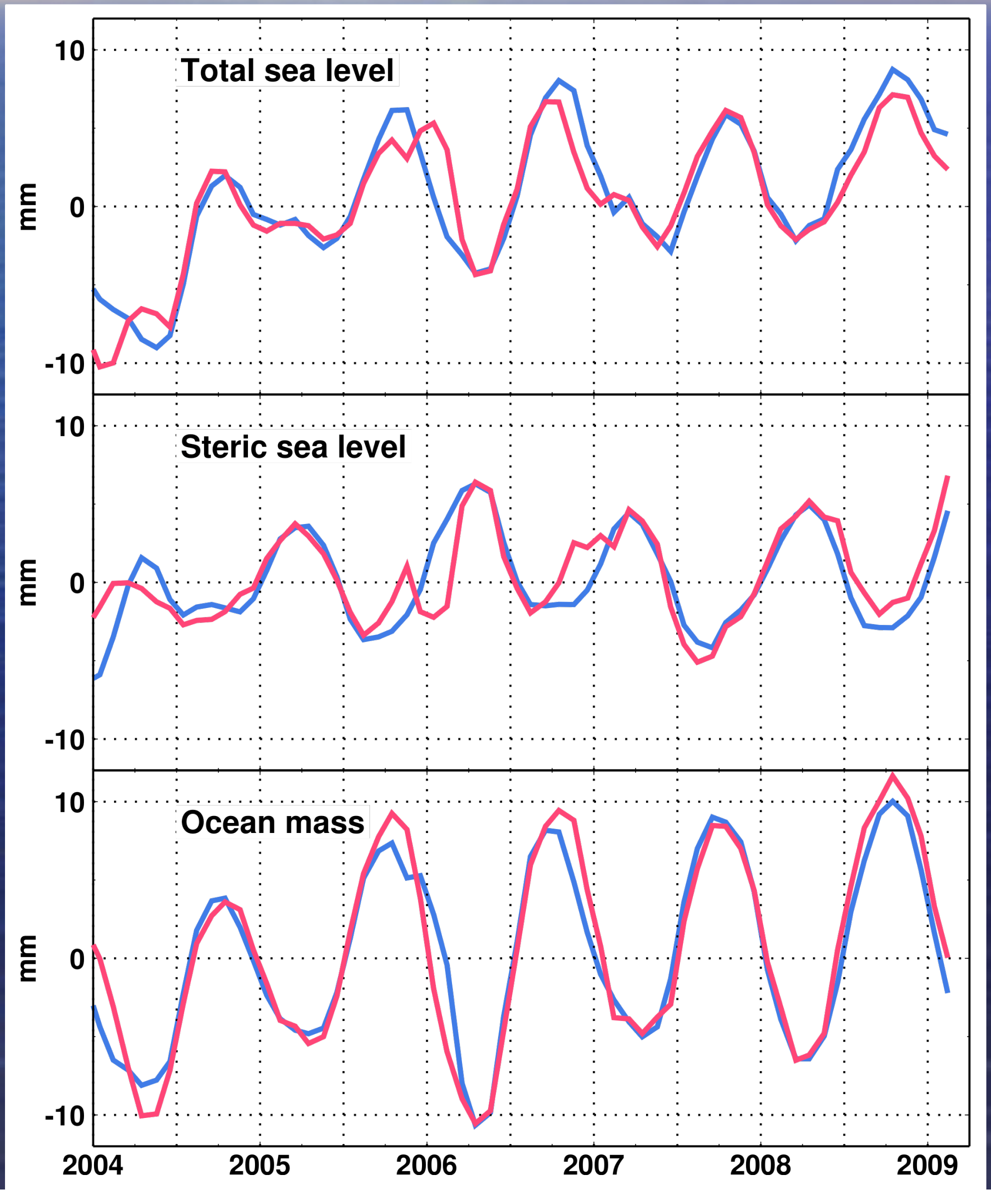
=
(roughly)

Total Sea Level Rise



Jason

Closure of GRACE, Argo, and Altimetry

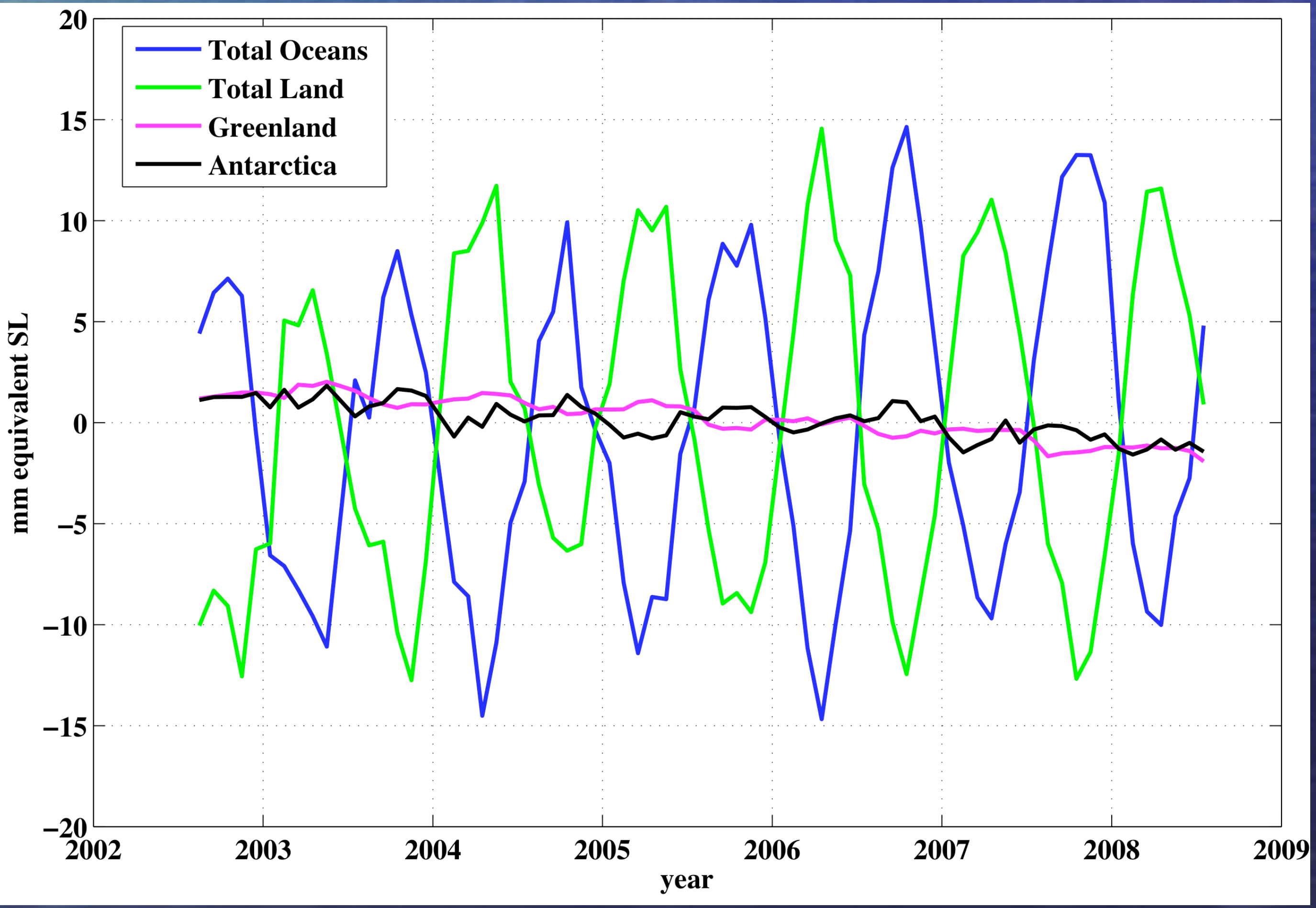


[Leuliette and Miller, 2008]

Land Water Storage and Sea Level

Monthly storage anomalies as equivalent mean sea level

$$\Delta S_{OCEAN} + \Delta S_{LAND} + \Delta S_{ICE} + \Delta S_{ATM} = \Delta S_{GLOBAL} = 0$$



Trends (mm/yr):

Ocean = 1.2 ± 0.4

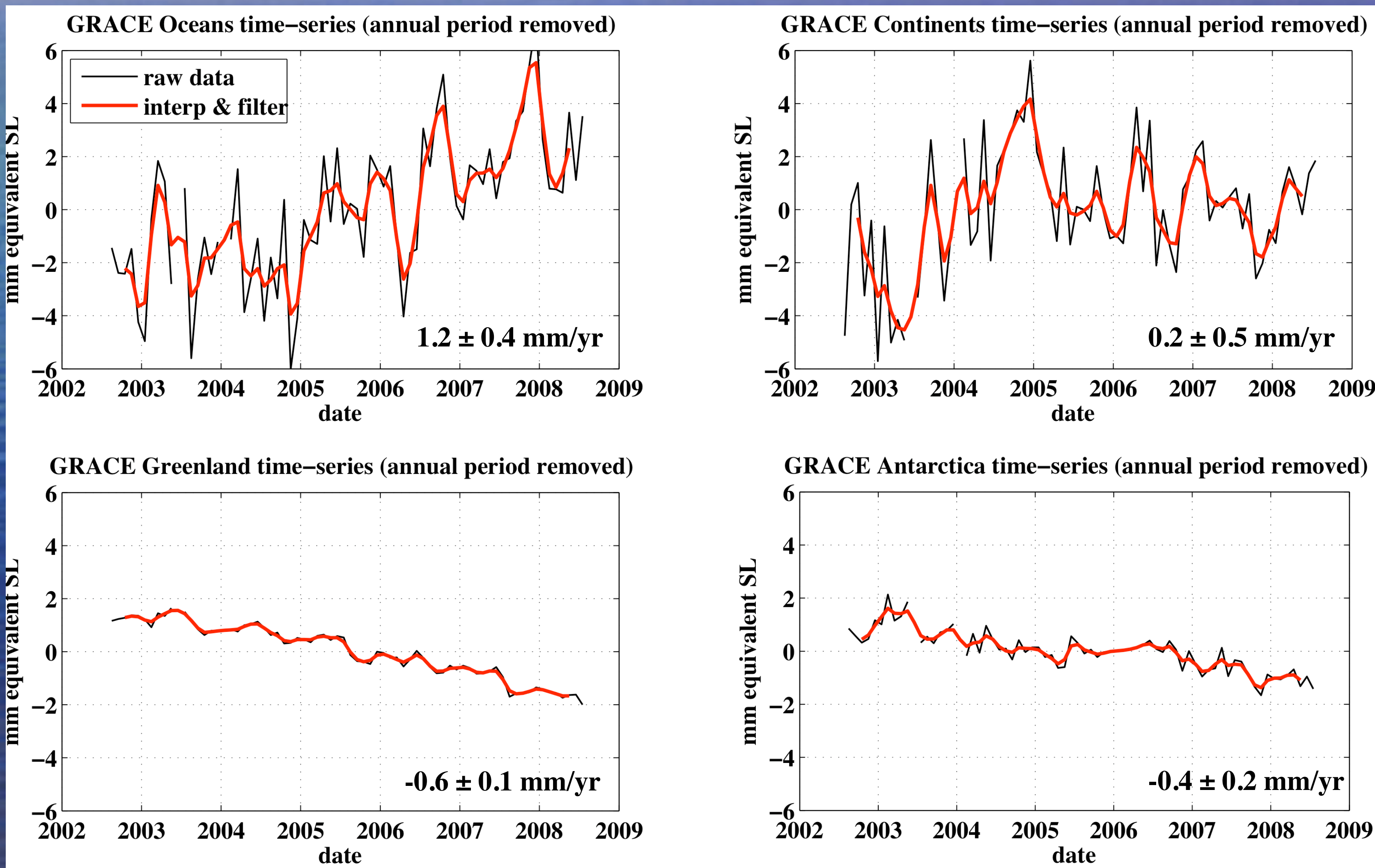
Land = 0.2 ± 0.5

Greenland = -0.6 ± 0.1

Antarctica = -0.4 ± 0.2

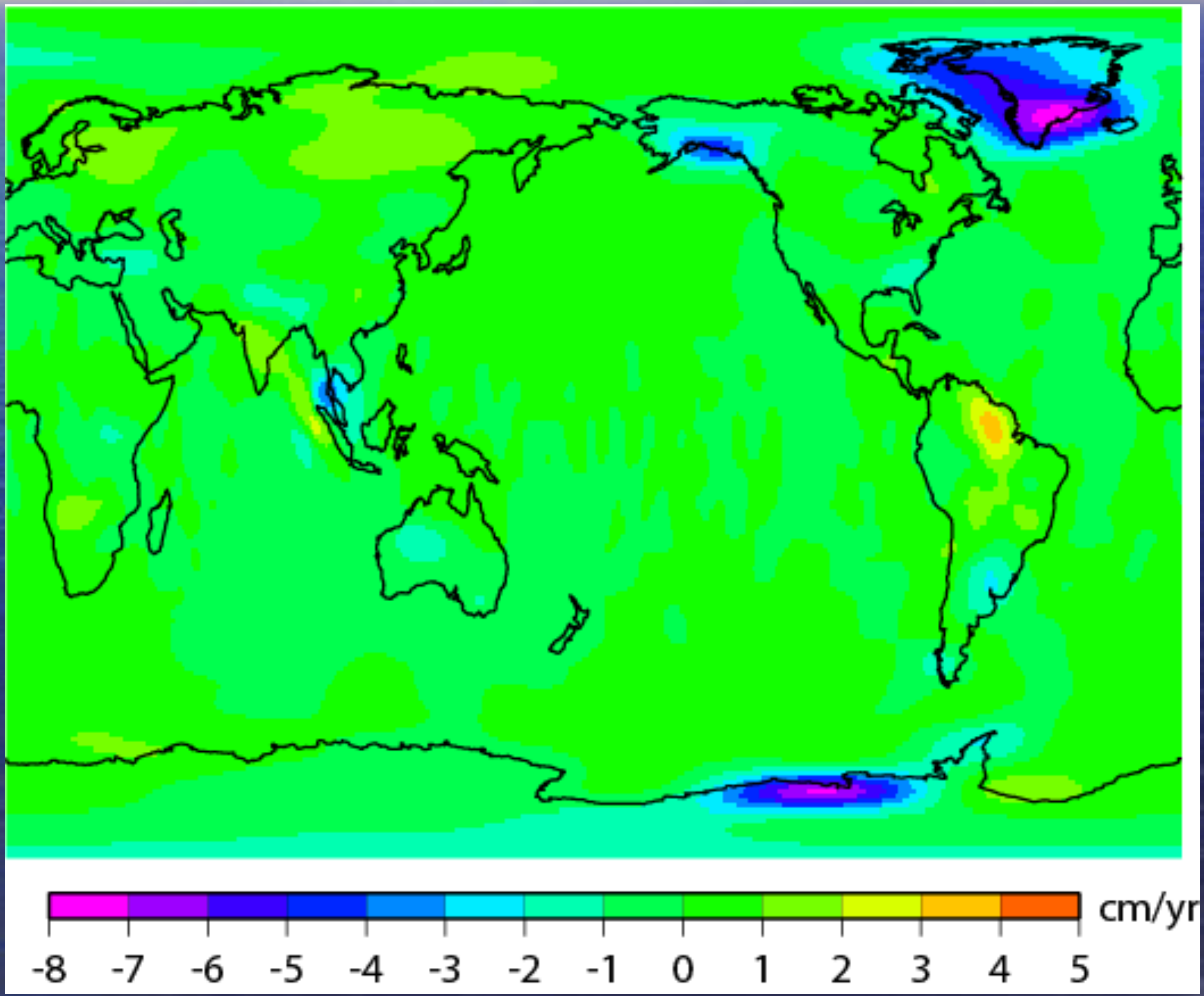
[Famiglietti et al., in review, 2009]

Land Water Storage and Sea Level



[Famiglietti et al., in review, 2009]

GRACE Secular Trends (2002-2009)



GIA Model Removed

[Wahr, 2009]

Greenland Mass Change from GRACE

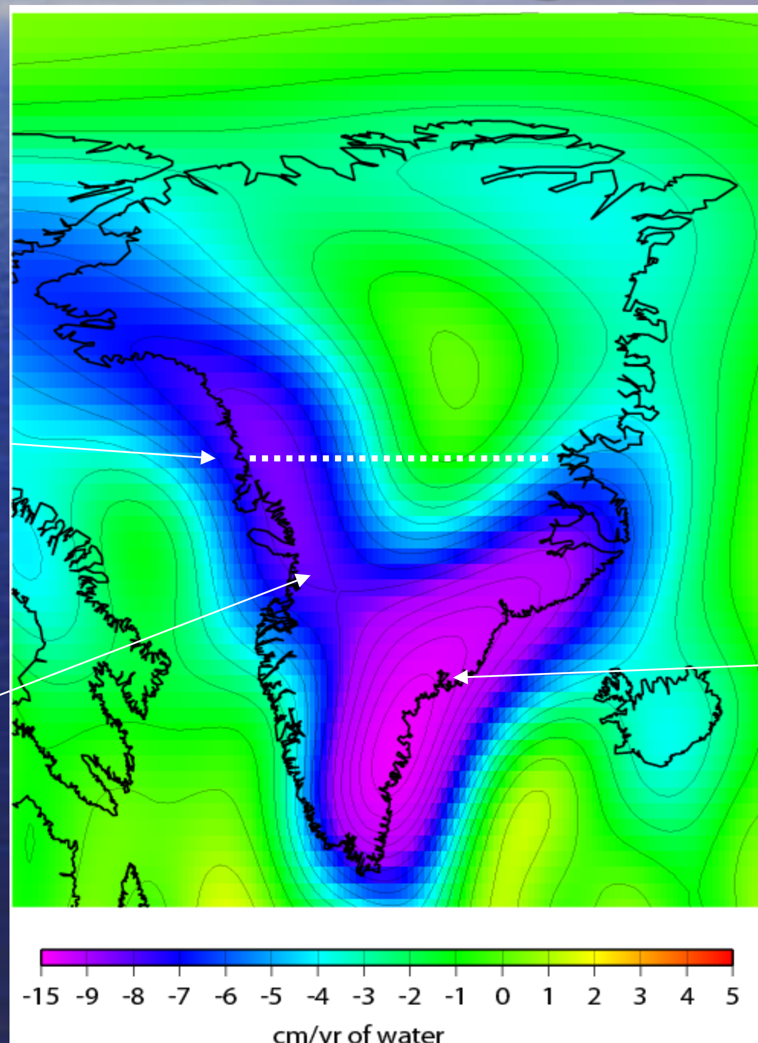
Rate of mass change during April, 2002 – February, 2009

Rate of mass change:

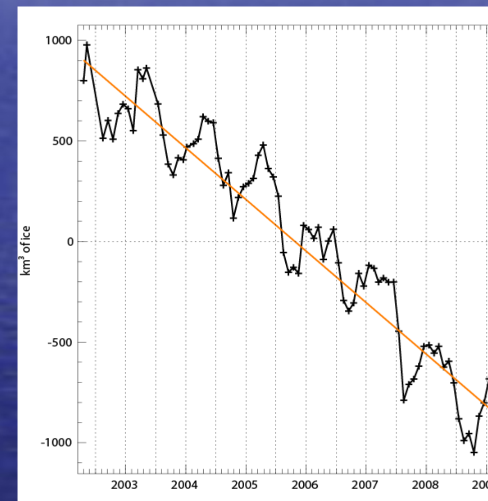
All Greenland: -235 Gton/yr

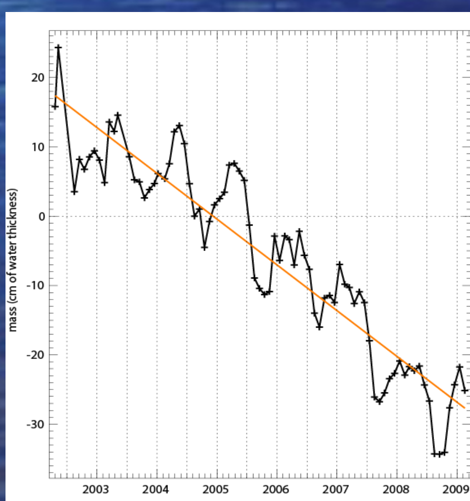
South Greenland: -169 Gton/yr

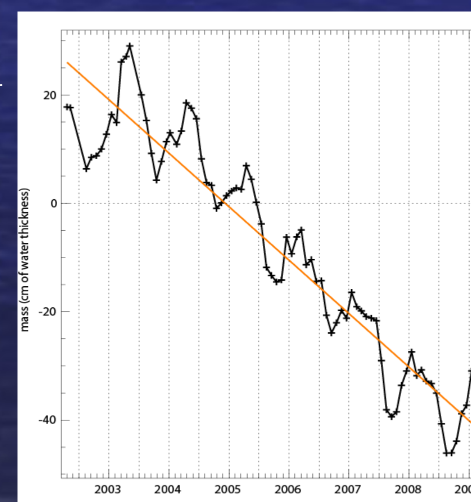
North Greenland: -65 Gton/yr



Total Greenland ice volume





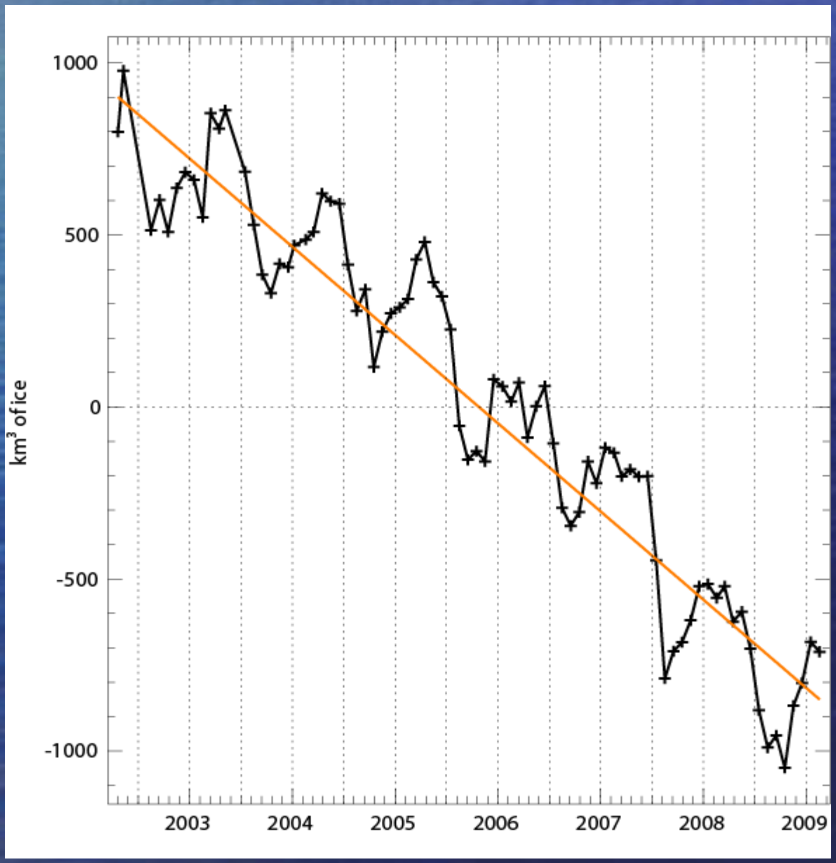


-235 Gton/yr = 0.65 mm/yr sea level rise

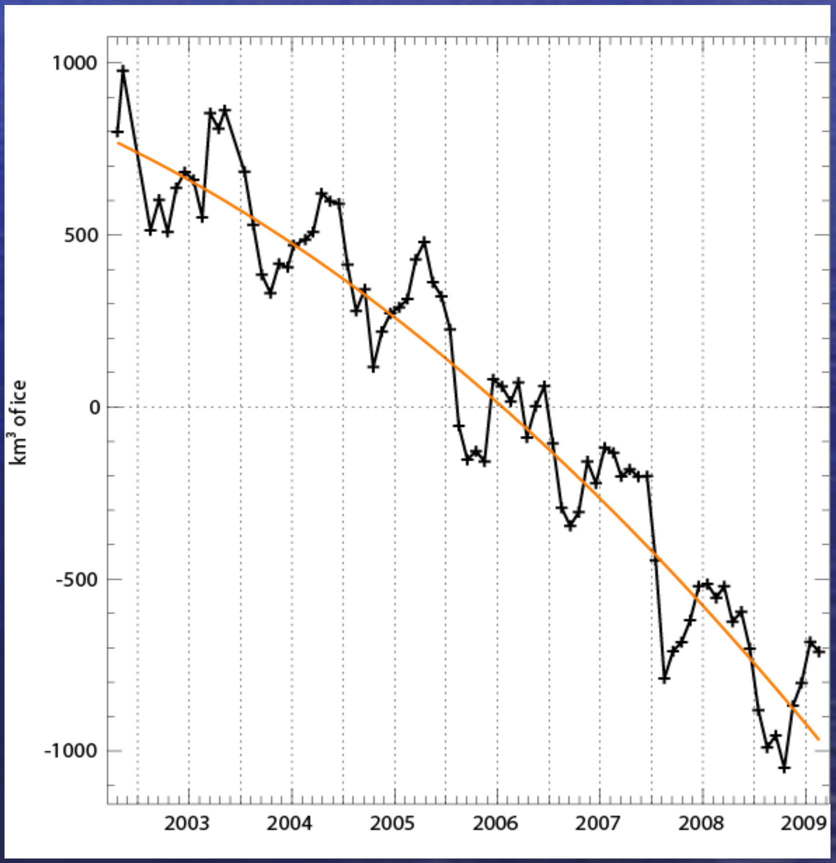
[Wahr, 2009]

Greenland Mass Change from GRACE

Best-fitting linear trend



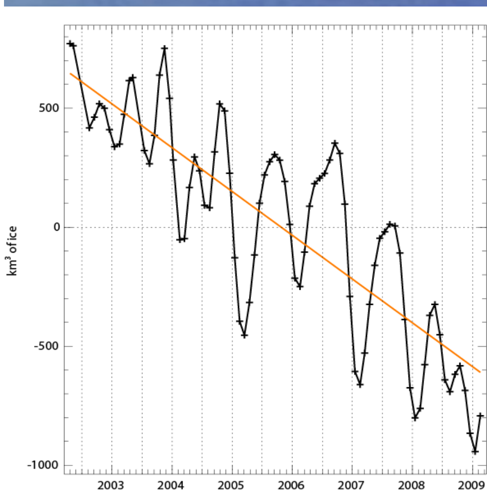
Best-fitting linear and quadratic terms



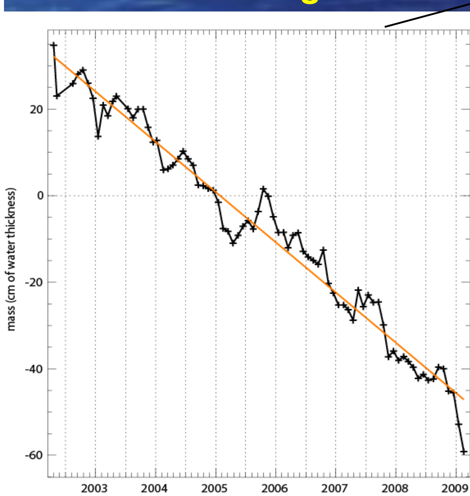
[Wahr, 2009]

Antarctica Mass Change from GRACE

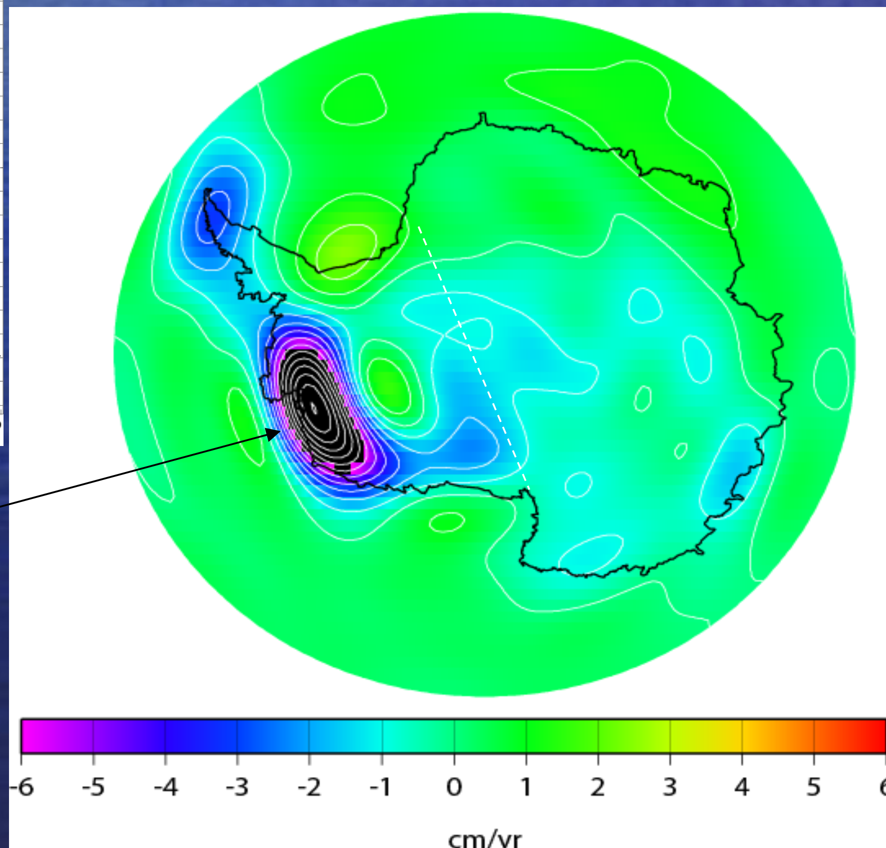
Total Antarctic ice volume.



Amundsen Sea glaciers



April, 2002 – February, 2009



-169 Gton/yr = 0.47 mm/yr sea level rise

Rate of mass change after removing ICE5G rebound model:

All Antarctica: -169 Gton/yr

West Antarctica: -128 Gton/yr

East Antarctica: -36 Gton/yr

Uncertainty of post-glacial rebound correction:

All Antarctica: ± 75 km^3/yr

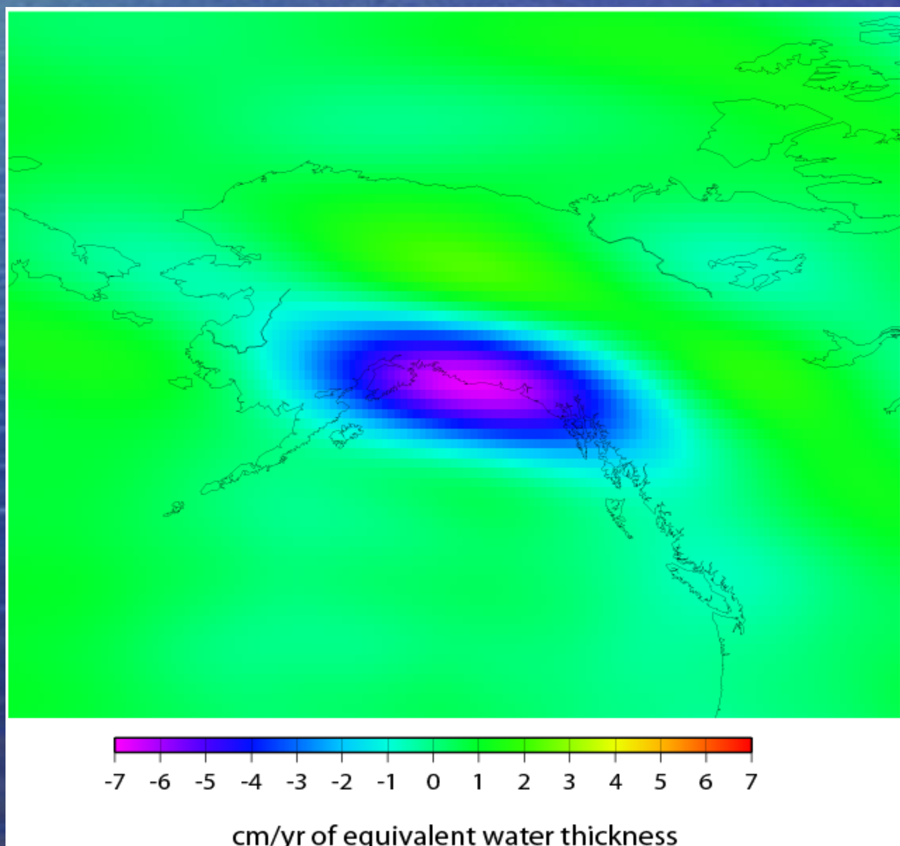
West Antarctica: ± 20 km^3/yr

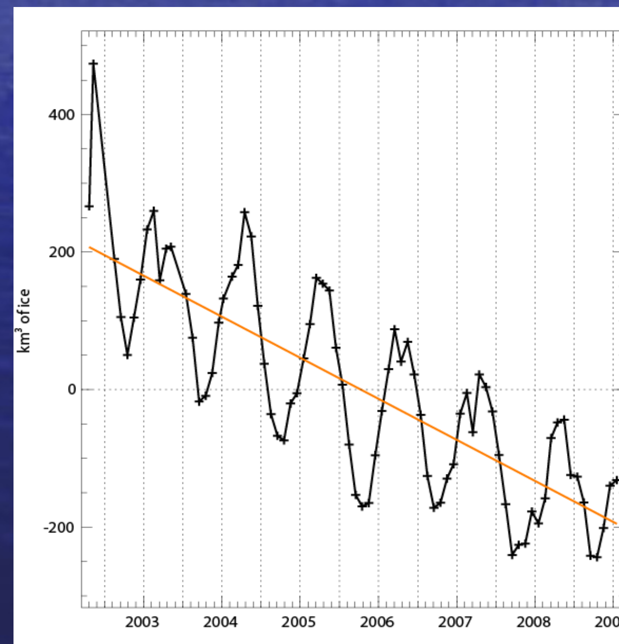
East Antarctica: ± 50 km^3/yr

[Wahr, 2009]

Alaskan Glaciers

Rate of mass change from GRACE between April, 2002 and February, 2009





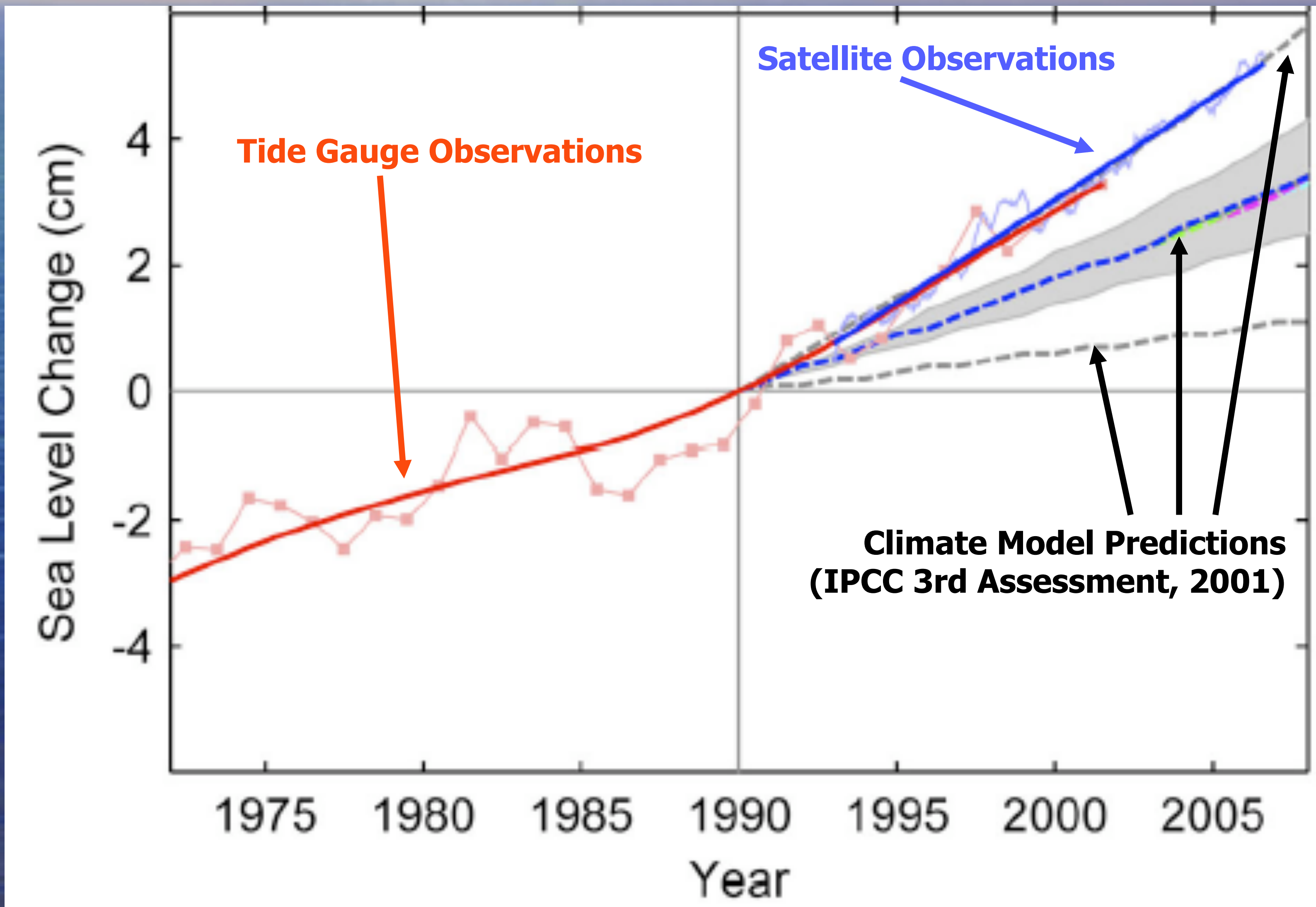
Rate of ice volume change:

-51 gton/yr = 0.15 mm/yr sea level rise

[Wahr, 2009]

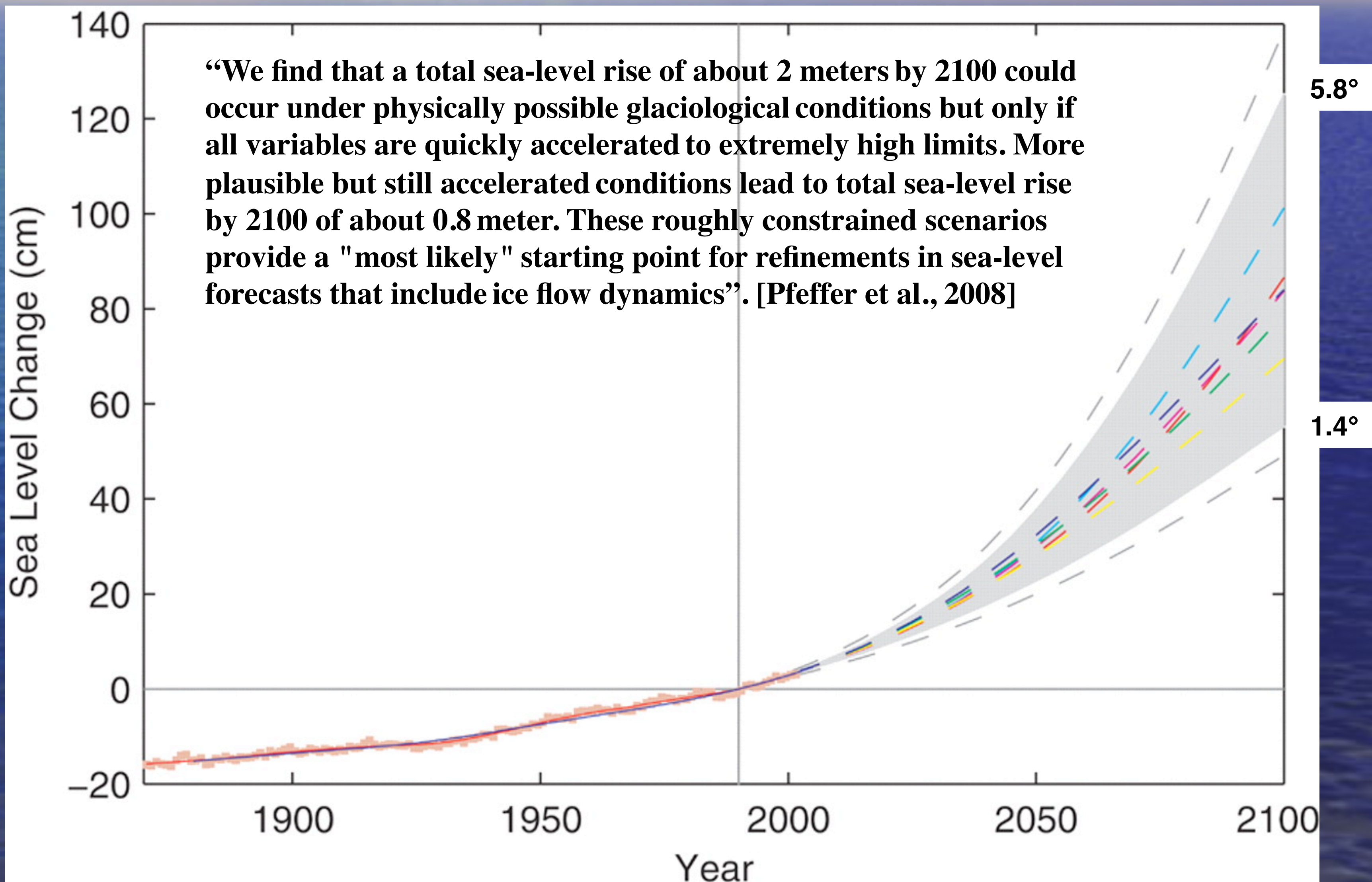
Future Sea Level in Boulder

Sea Level Observations versus Predictions



[Rahmstorf et al., 2007]

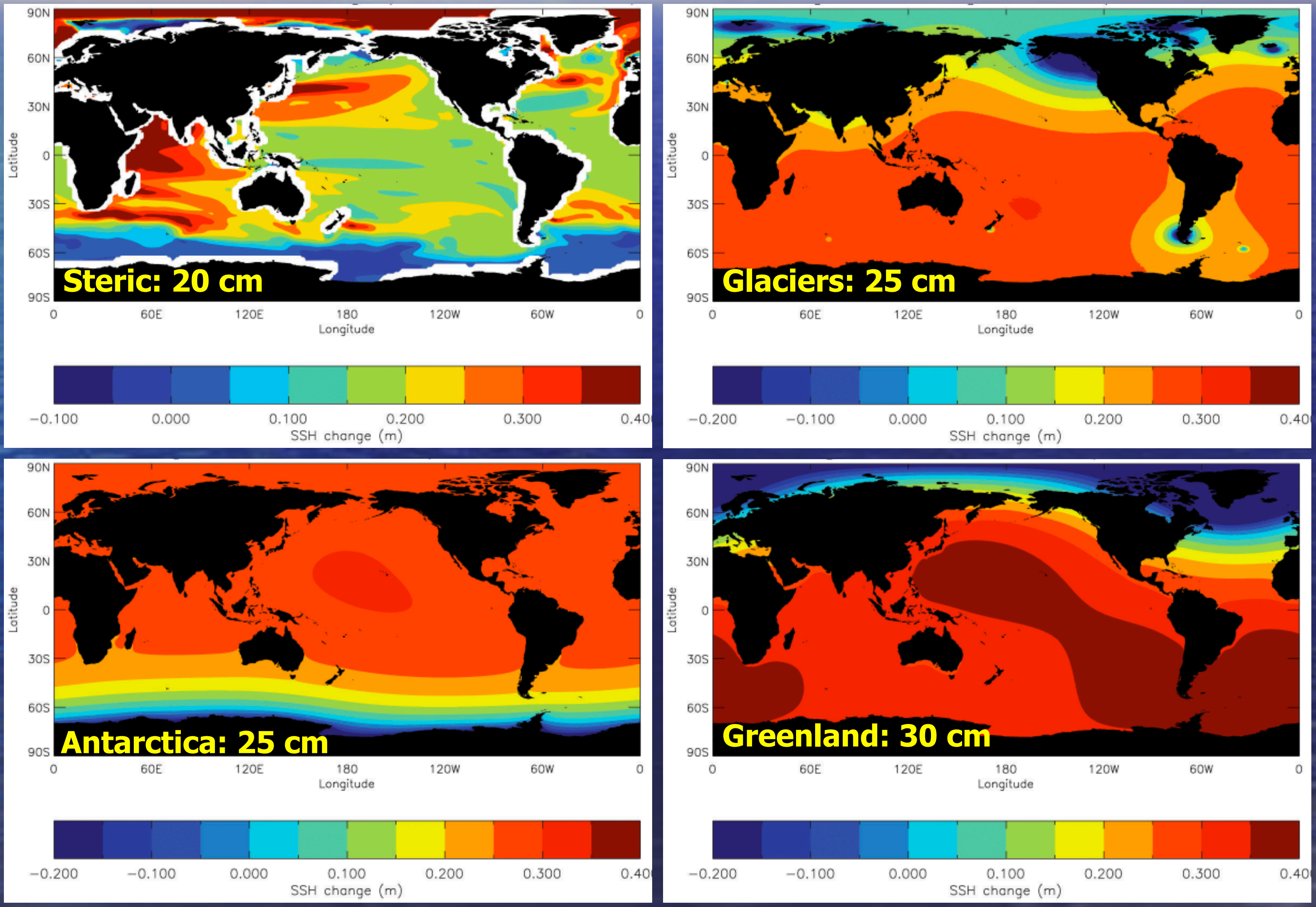
Future Sea Level Change



"We find that a total sea-level rise of about 2 meters by 2100 could occur under physically possible glaciological conditions but only if all variables are quickly accelerated to extremely high limits. More plausible but still accelerated conditions lead to total sea-level rise by 2100 of about 0.8 meter. These roughly constrained scenarios provide a "most likely" starting point for refinements in sea-level forecasts that include ice flow dynamics". [Pfeffer et al., 2008]

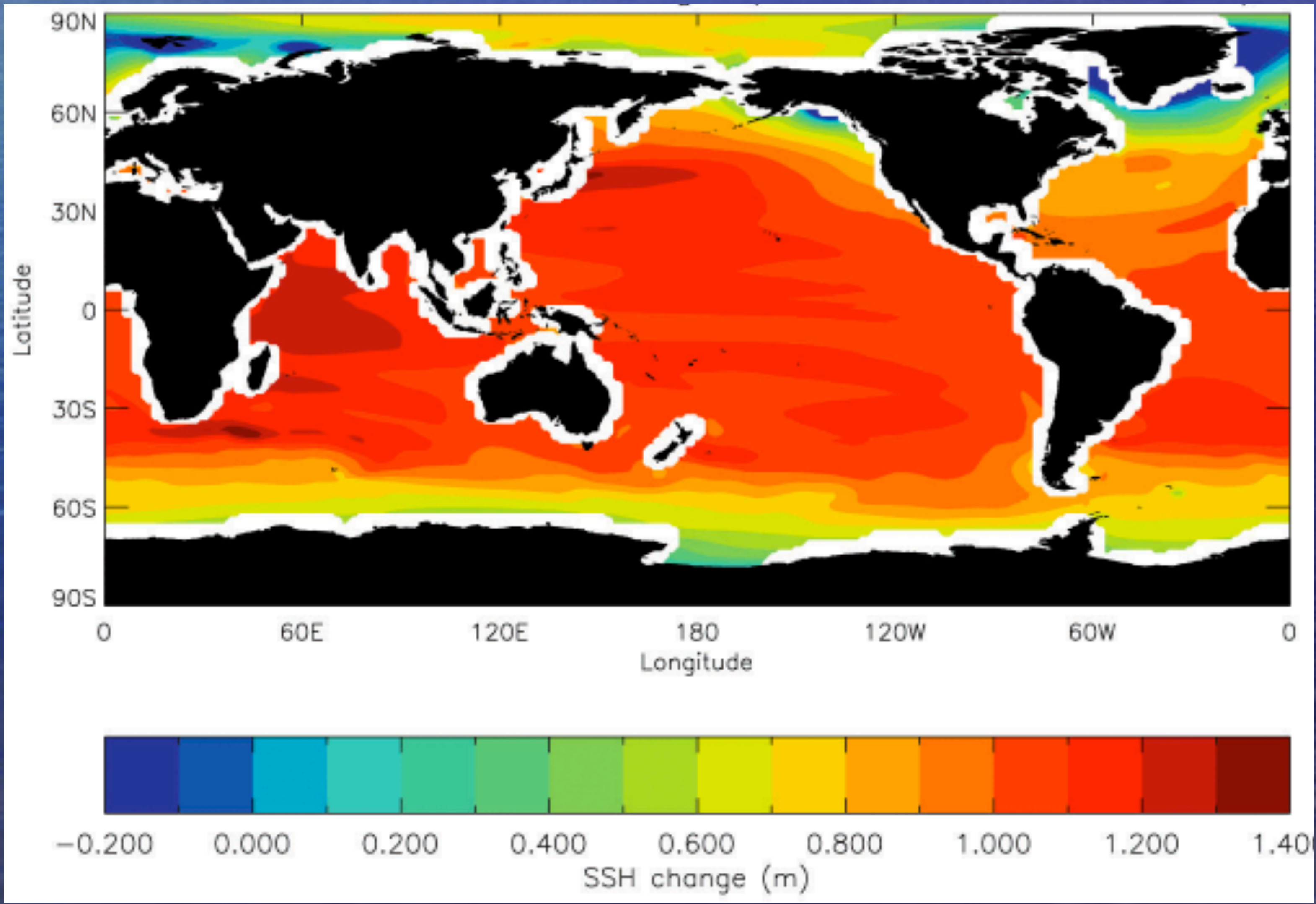
[Rahmstorf, 2007]

Contributions to Sea Level Change

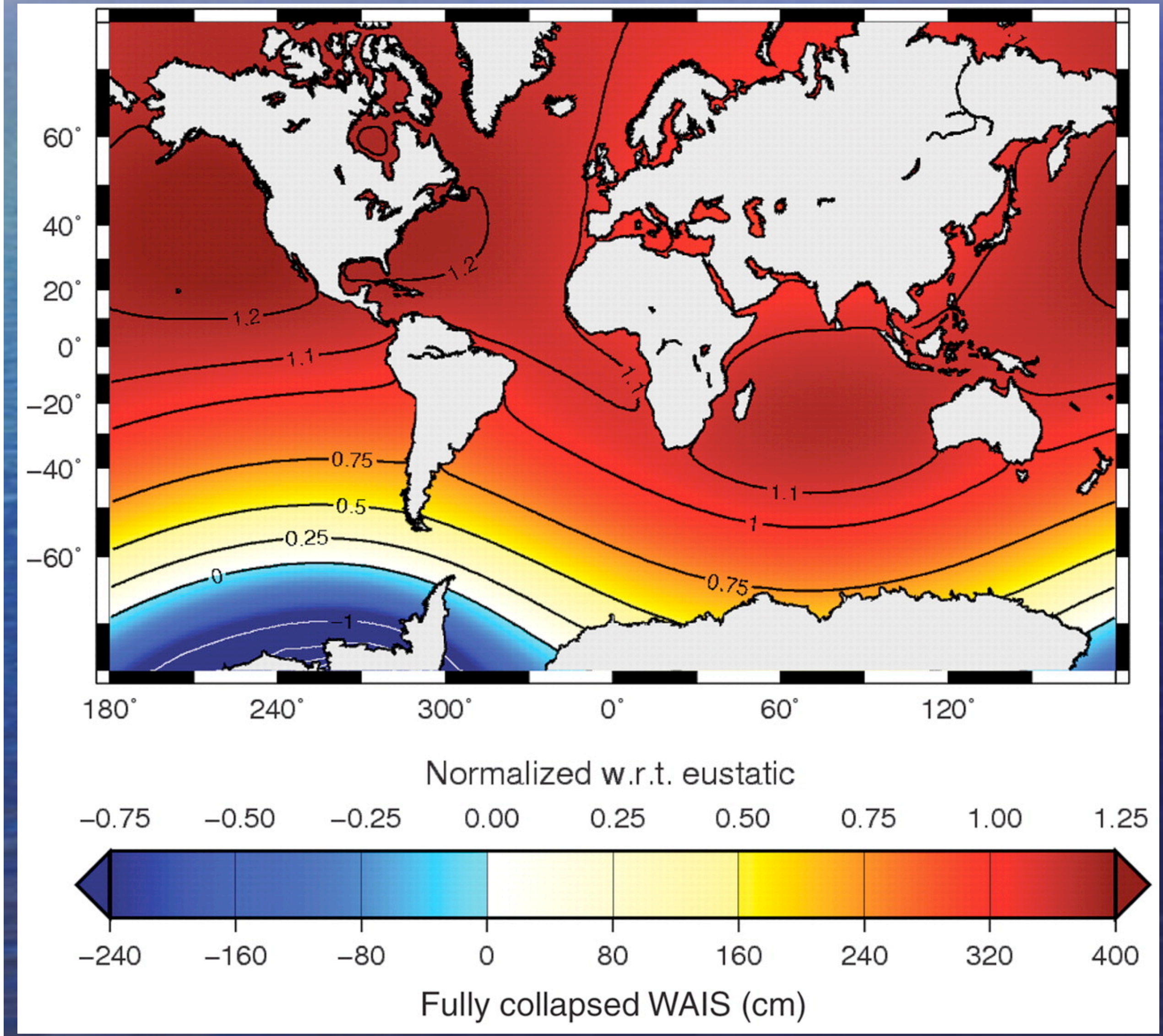


Regional Change by 2100 for 1 m Total

Steric: 20 cm   Glaciers: 25 cm   Greenland: 30 cm   Antarctica: 25 cm

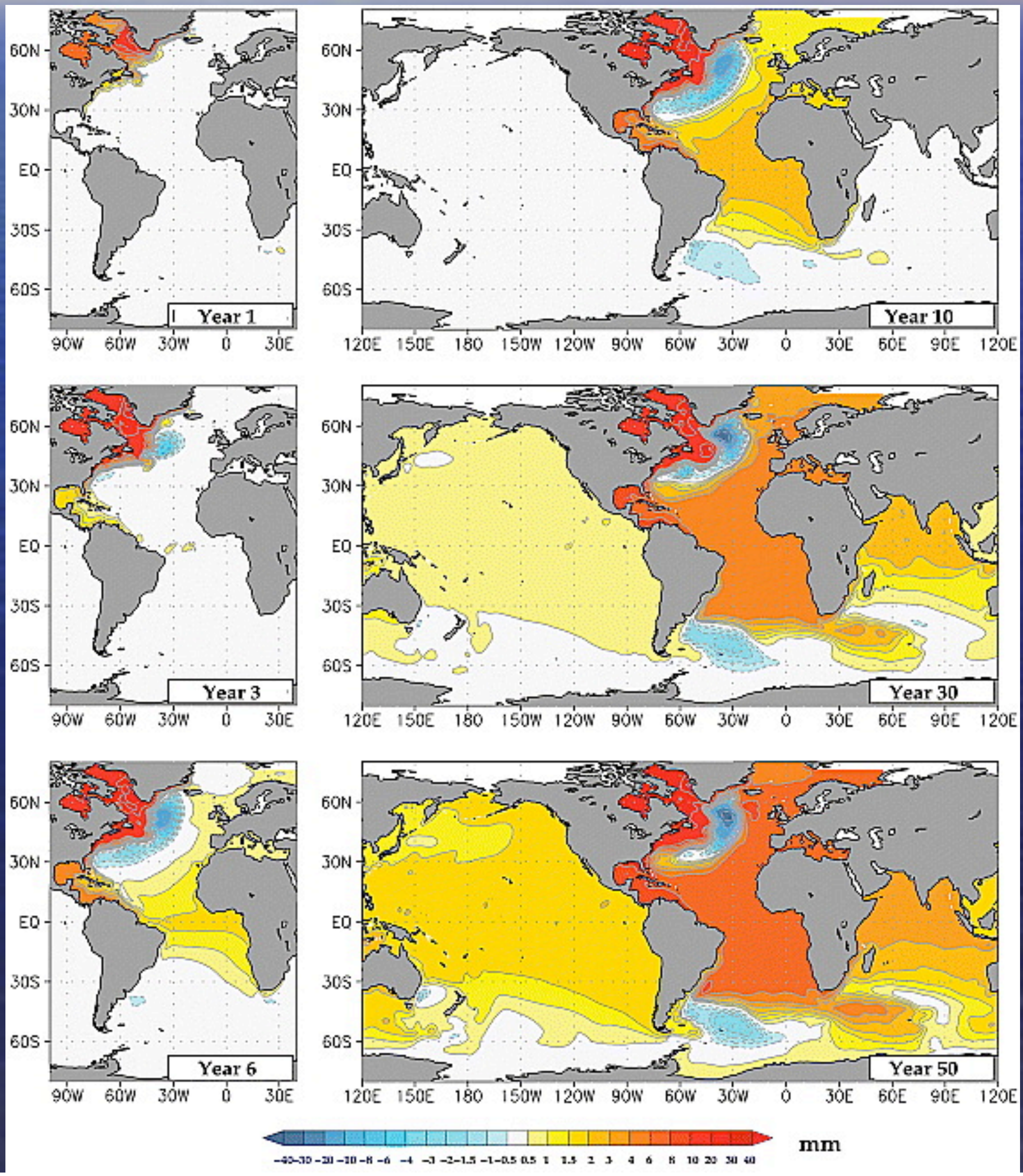


West Antarctic Sea Level Potential: 3.3 m



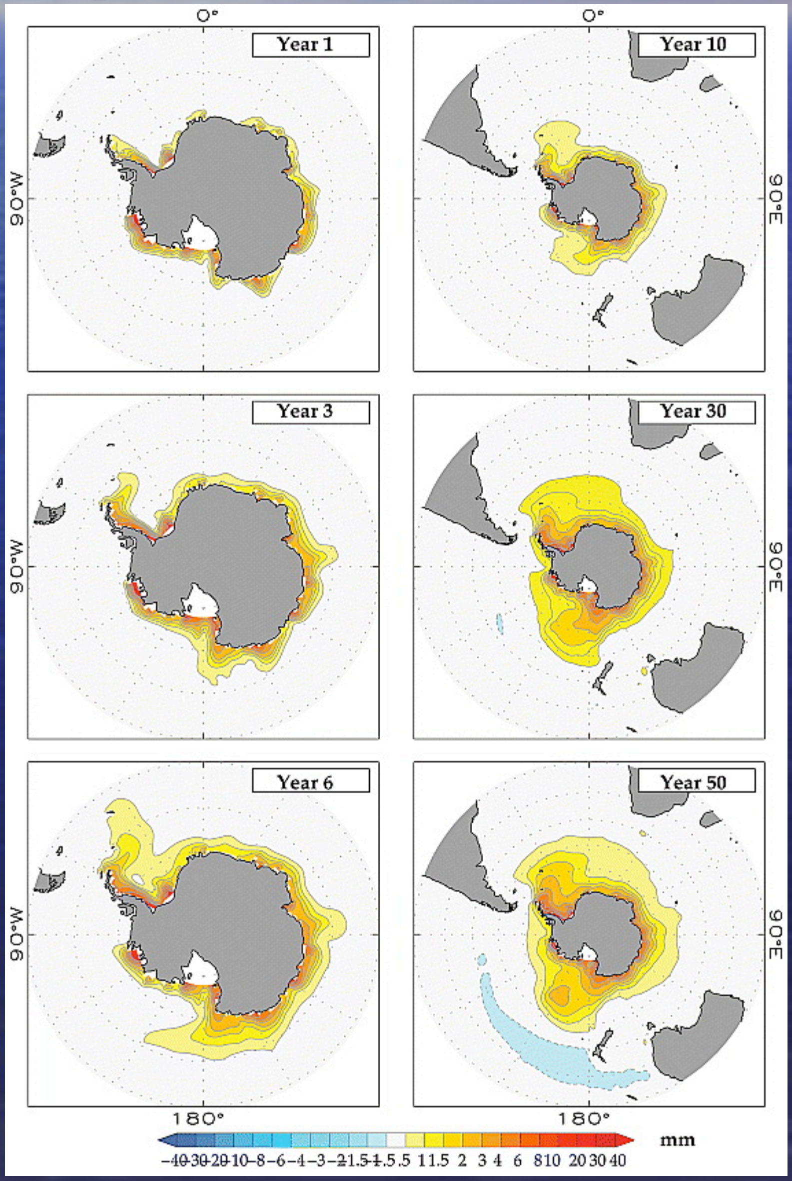
[Bamber et al., 2009]

Ocean Response to Greenland Ice Melt



[Stammer, 2008]

Ocean Response to Antarctic Ice Melt



[Stammer, 2008]

Conclusions

- There are large interannual variations in global mean sea level related to ENSO, thus one must be careful when interpreting the sea level change record during the altimeter error.
- The rate of sea level change has roughly doubled (from ~1.5 to ~3 mm/year), and there is evidence that this increase started just prior to the precision altimeter era (early 1990s).
- The increase in the rate of sea level change has been driven mainly by changes in the cryosphere as opposed to thermal expansion.
- Sea level is rising faster in the tropics and southern ocean than in the northern ocean.

Recommendations

- Continuing satellite altimeter and gravity measurements, as well as in situ measurements such as Argo and the tide gauges, are critical for understanding present-day changes in sea level, and predicting future changes.
- Developing better predictions/projections of future sea level change should be a high priority goal for future reserach.
- Understanding the regional variation of future sea level change, which is important for the socio-economic consequences of the change as well as for the identification of sea level “fingerprints”, should be considered a grand challenge problem for future research.