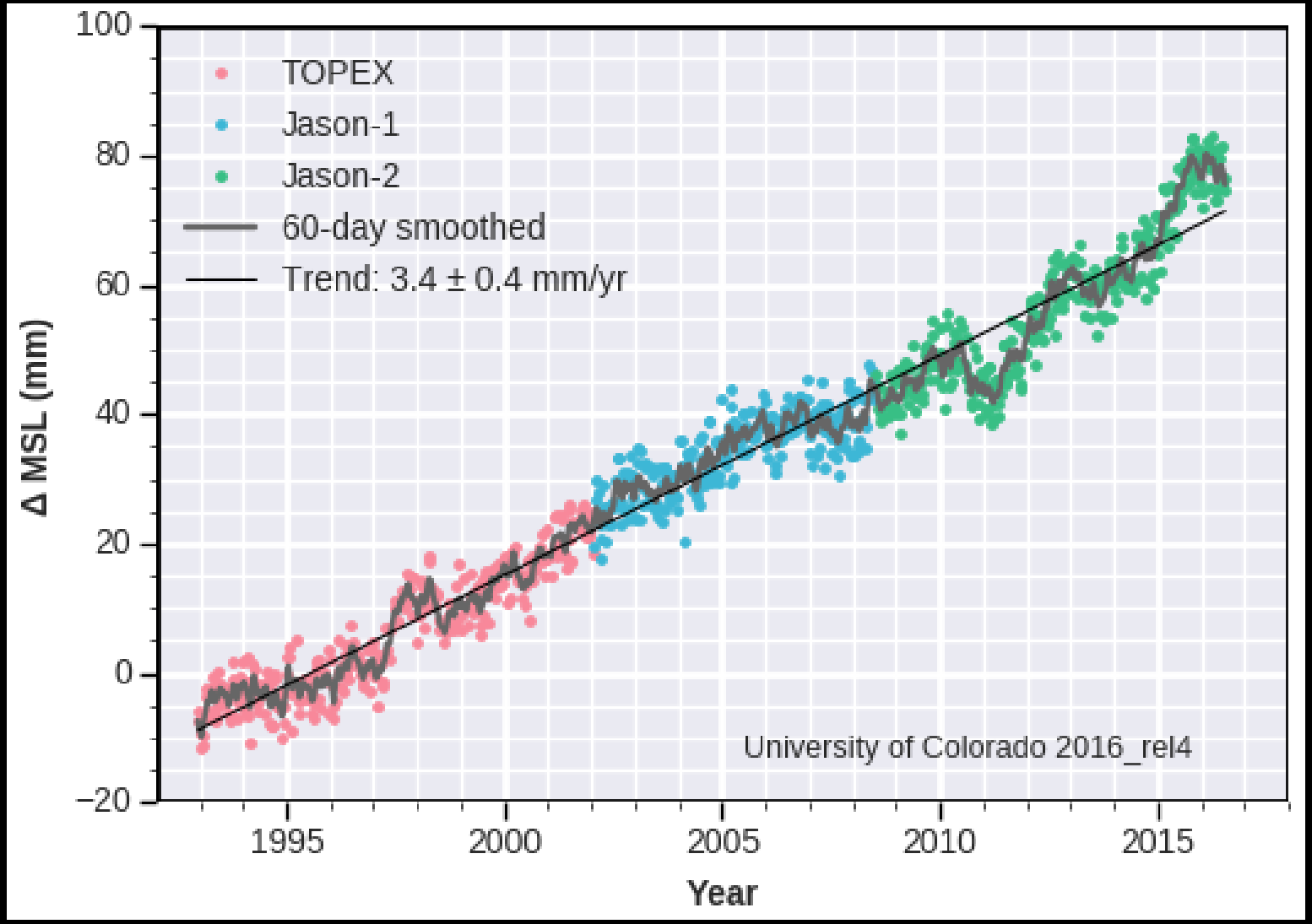
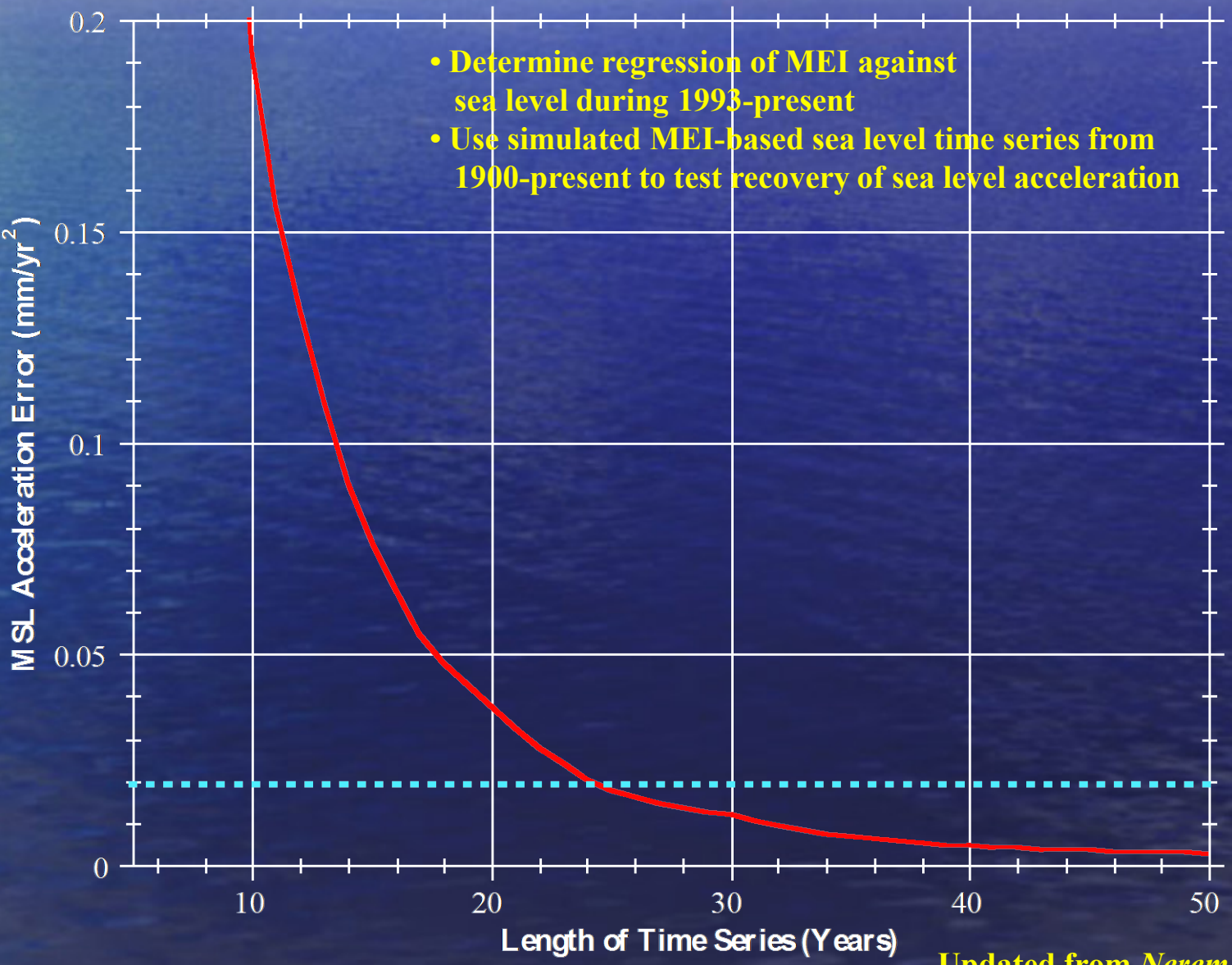
Has the Rate of Sea Level Rise Accelerated During the Altimeter Era?



R. S. Nerem, J. Fasullo, B. Hamlington, D. Masters, M. Merrifield, G. T. Mitchum, and P. Thompson

Simulated GMSL Acceleration Recovery



Updated from *Nerem et al.* [1999]

Questions to be Addressed

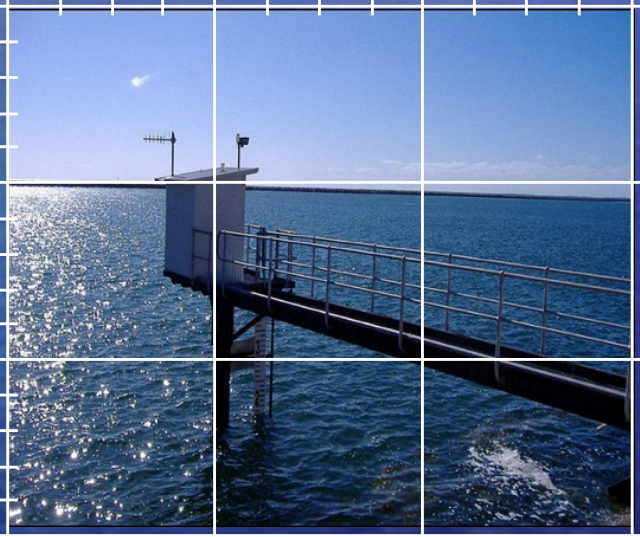
- How large of an acceleration in GMSL might we expect to see?
- Could another sea level signal be masking the acceleration we expect to see? (e.g. decadal variability)
- If there has been an acceleration, is it statistically significant?
- What have we observed in the altimeter record?

Some Comments about Acceleration

- "Don't estimate acceleration by fitting a quadratic if your data does not look like a quadratic" (Rahmstorf)
- "Fitting a quadratic to test for change in the rate of sea-level rise is a fool's errand" (Tamino)
- A quadratic may not be a good model to use to describe sea level – other models may be better.
- For the 24-year altimeter record, we often just look at the difference in the decadal rates, but for this talk we will discuss acceleration for convenience.
- $SL(t) = a + bt + ct^2$
  - SL Rate (t) = b + 2ct
  - 2c is often referred to as the "acceleration"

How large of an acceleration might we expect to see?

Reconstructed Tide Gauge GMSL Variations



100
50
0
-50
-100
-150
-200
ΔMSL (mm)
1880
1900
1920
1940
1960
1980
2000
Year

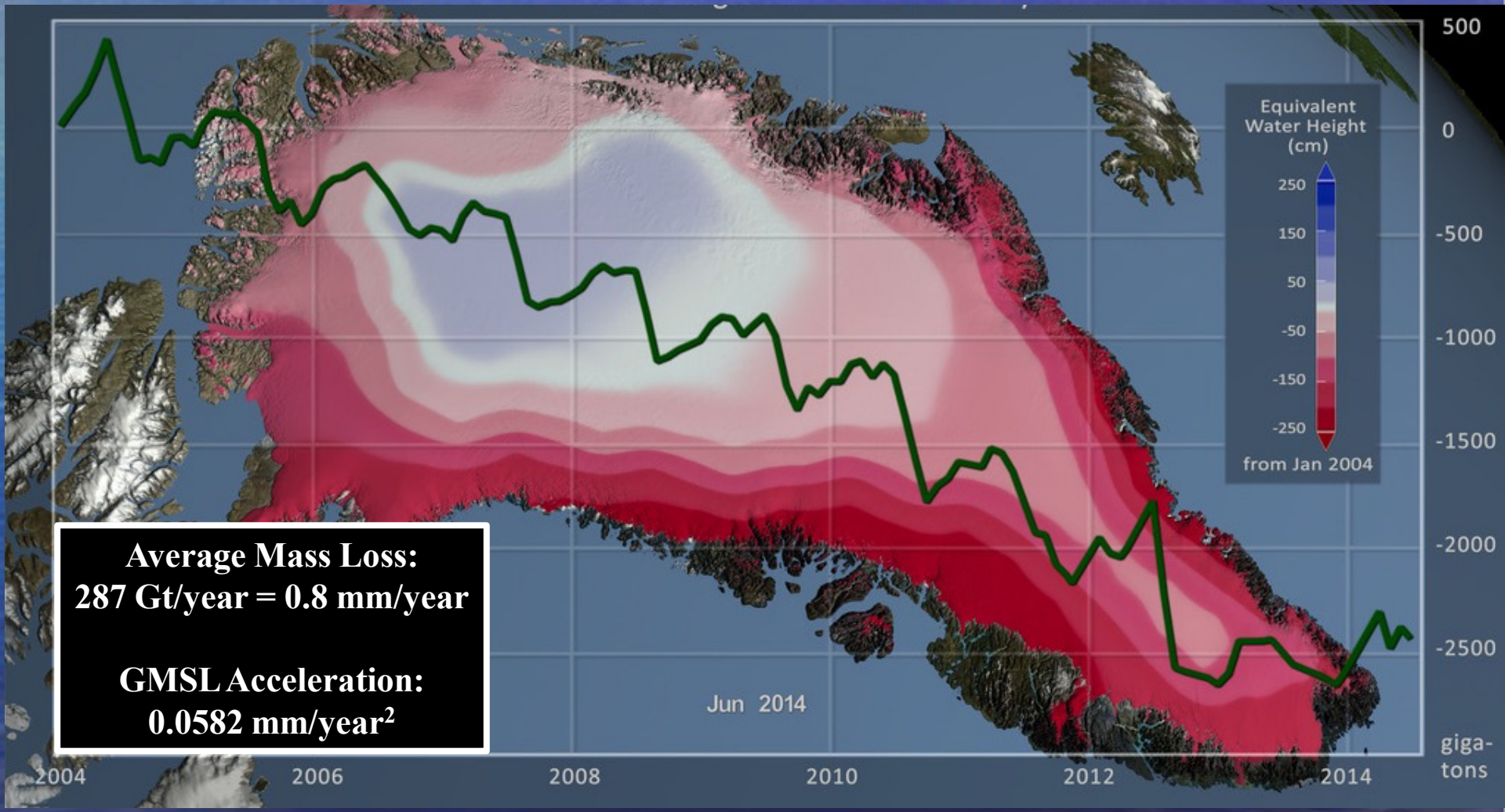
Average Rate (1950-2010): ~1.8 mm/year

Acceleration (1880-2009): 0.009 mm/year ^{2}

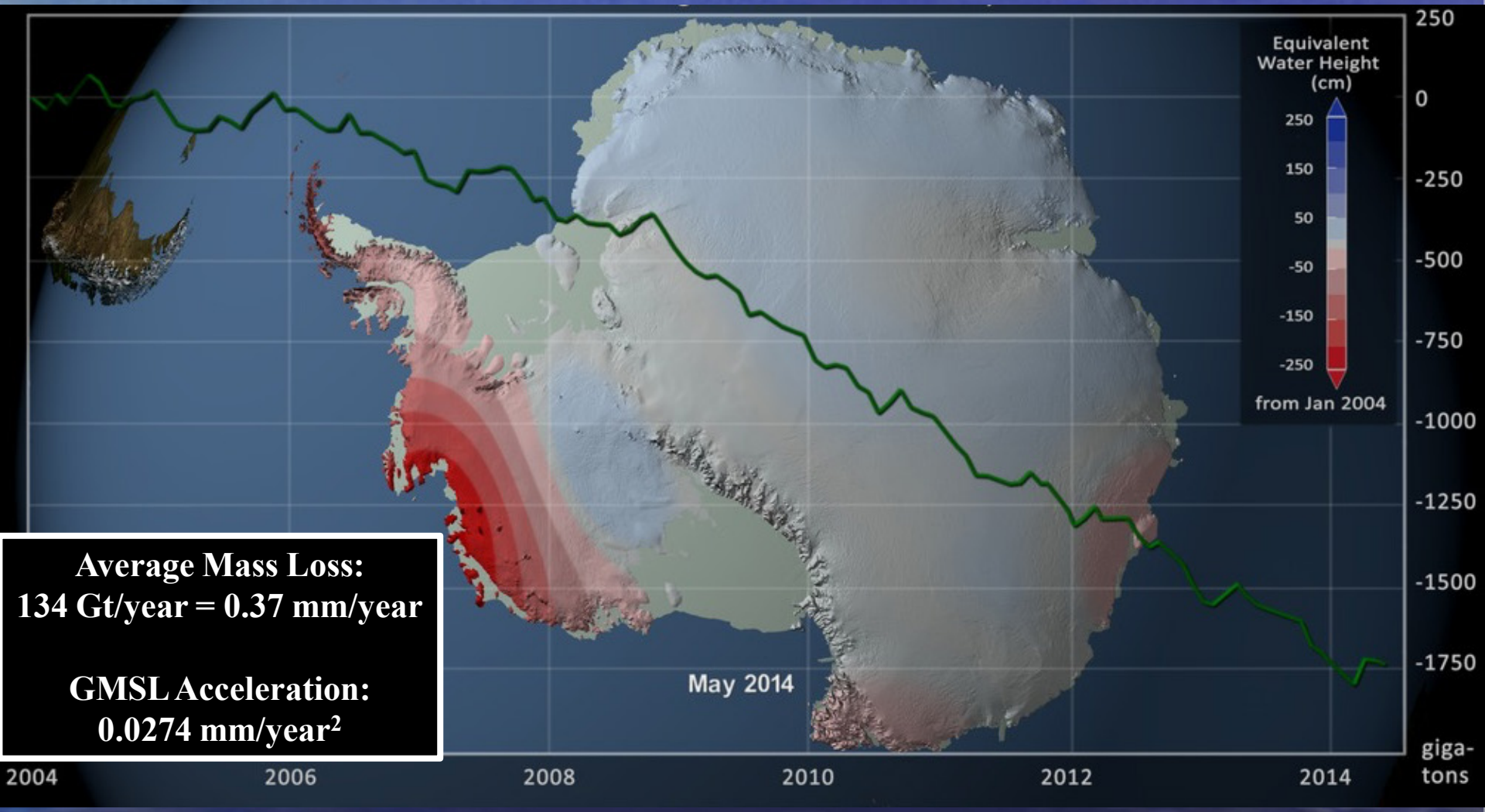
Acceleration (1950-2009): 0.02 mm/year ^{2}

[Church and White, 2011]

Greenland Mass Change from GRACE Data



Antarctic Mass Change from GRACE Data



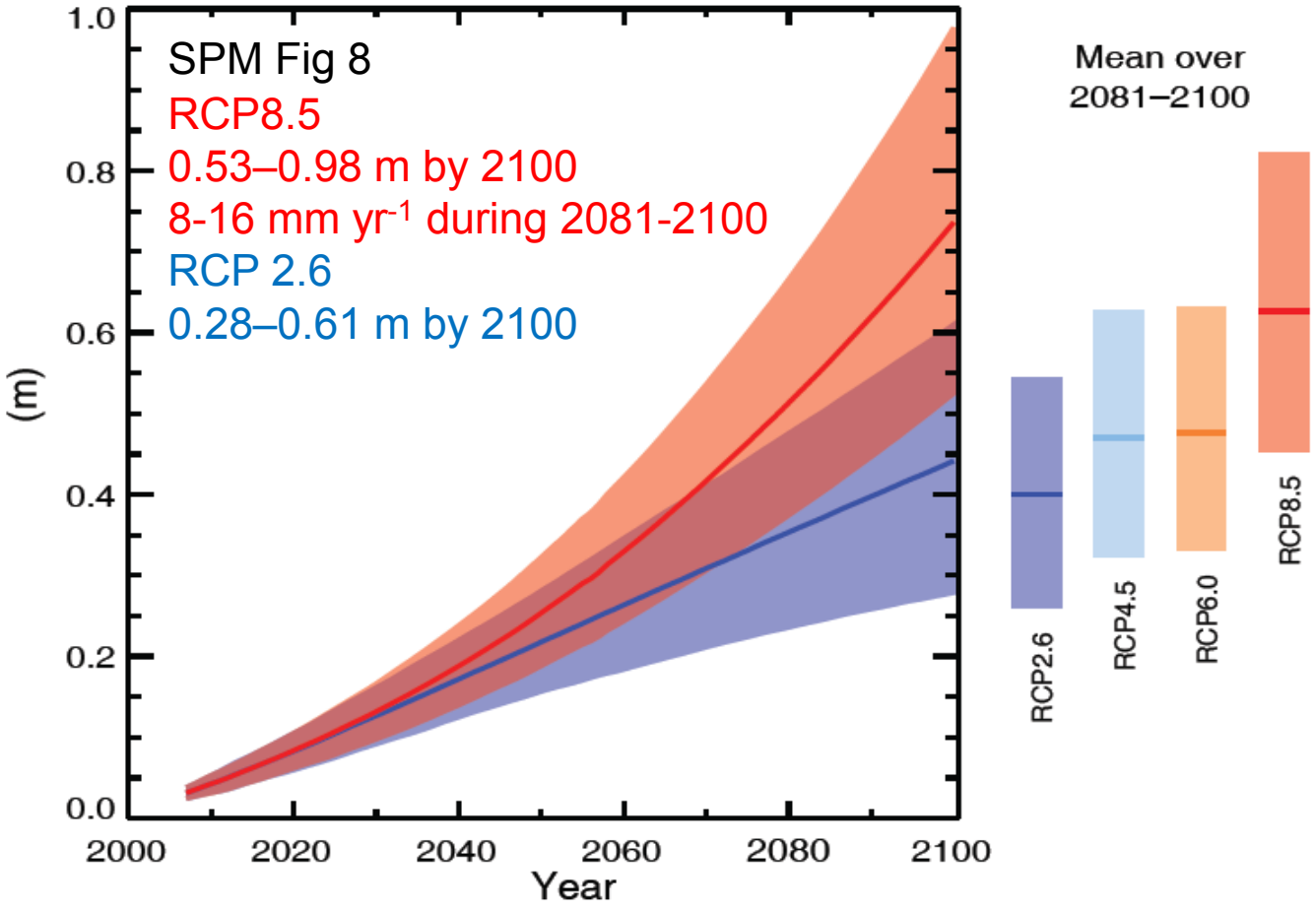
Average Mass Loss:
134 Gt/year = 0.37 mm/year

GMSL Acceleration:
0.0274 mm/year^2

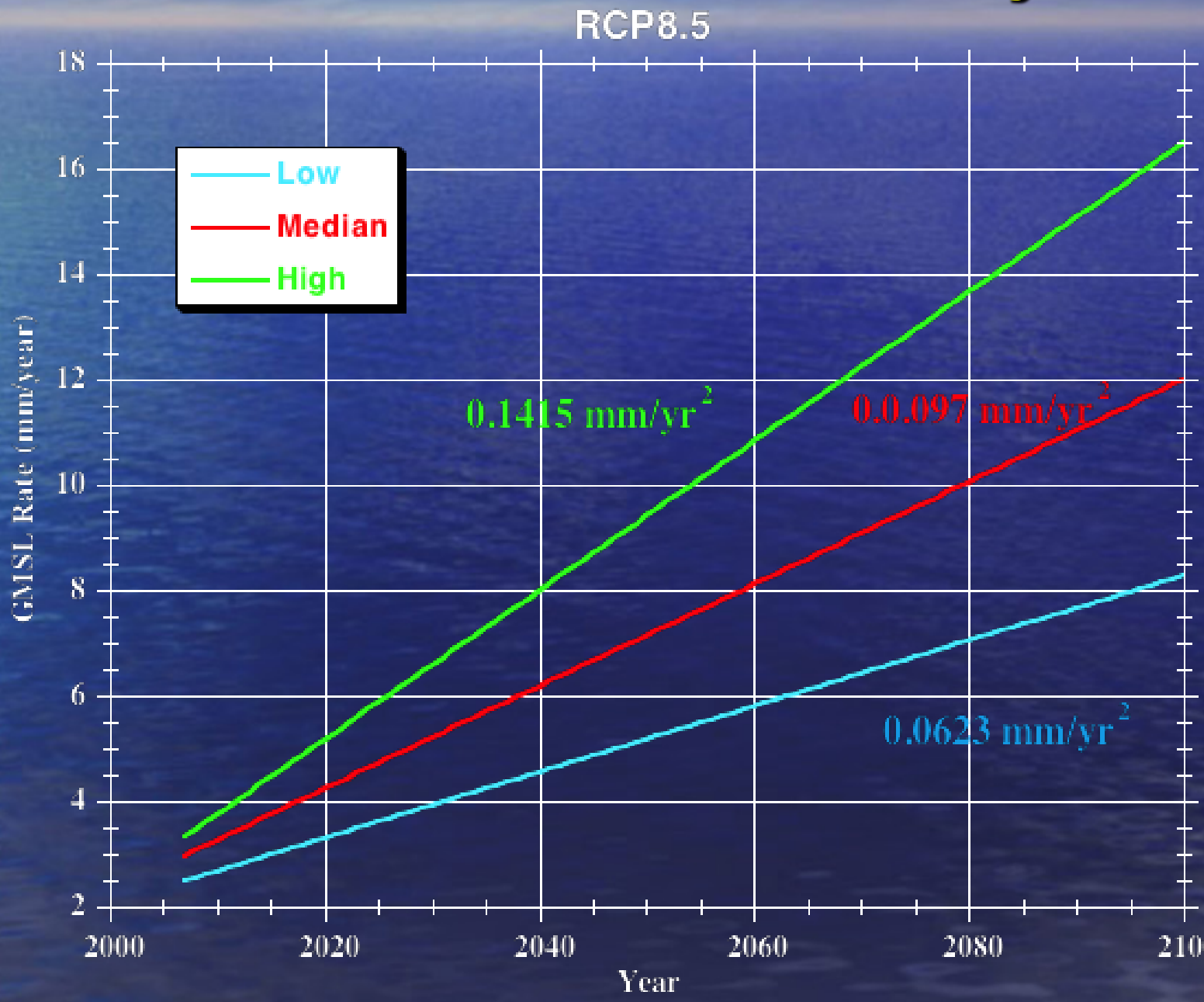
Acceleration from ice sheet alone over 2002-2016 is 0.085 mm/year^2

Projections of 21st-century GMSLR under RCPs

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



Rate of IPCC AR5 Sea Level Projections



Accelerations from the IPCC AR5 Projections

2007 – 2100 (mm/yr^2)

RCP	Low	Median	High
2.6	-0.0149	0.0184	0.0185
4.5	0.0095	0.0306	0.0532
6.0	0.0286	0.0515	0.0767
8.5	0.0624	0.0975	0.1415

Could another sea level signal be masking the acceleration we expect to see?

(e.g. decadal variability impacting a short altimeter record)

The 1991 Eruption of Mount Pinatubo

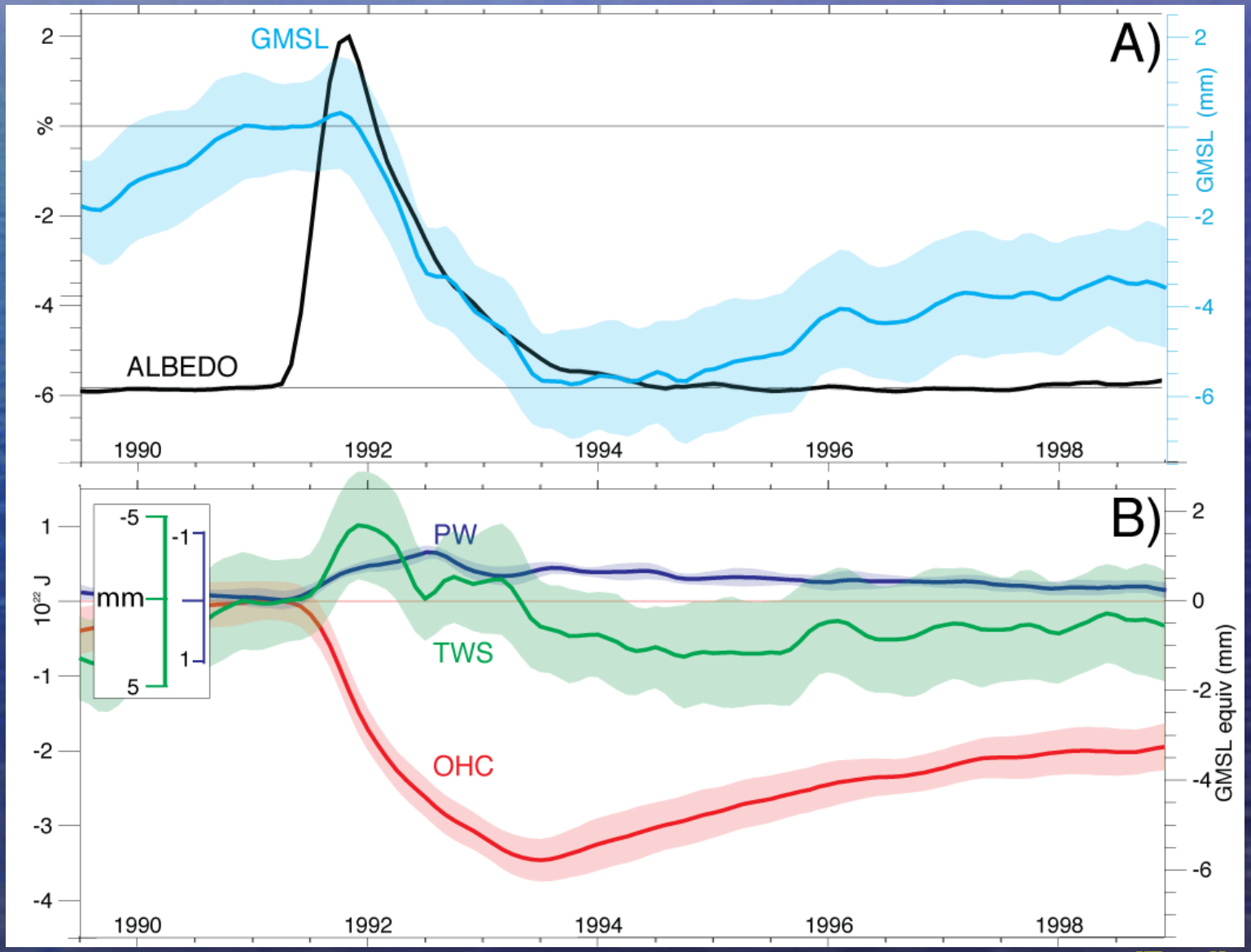
- June 15, 1991
- 2nd largest eruption of the 20th Century
- ~25 Tg of stratospheric aerosol loading
- Global cooling of ~0.5 C, substantial ozone depletion

The NCAR Large Ensemble (LE)

- **Motivation**: identifying the forced-response of the climate system requires distinguishing it from internal variability
- **CMIP archives** do not allow for a such a distinction due to model structural differences (ensemble mean ≠ forced response)
- **The NCAR LE** consists of **40 members** of simulation using the CESM-CAM1 from 1920-2100
- Fixed volume ocean - using the Church conversion between OHC and GMSL.
- As variance of internal variability scales as $1/\sqrt{(N-1)}$, the ensemble mean it is << forced response.

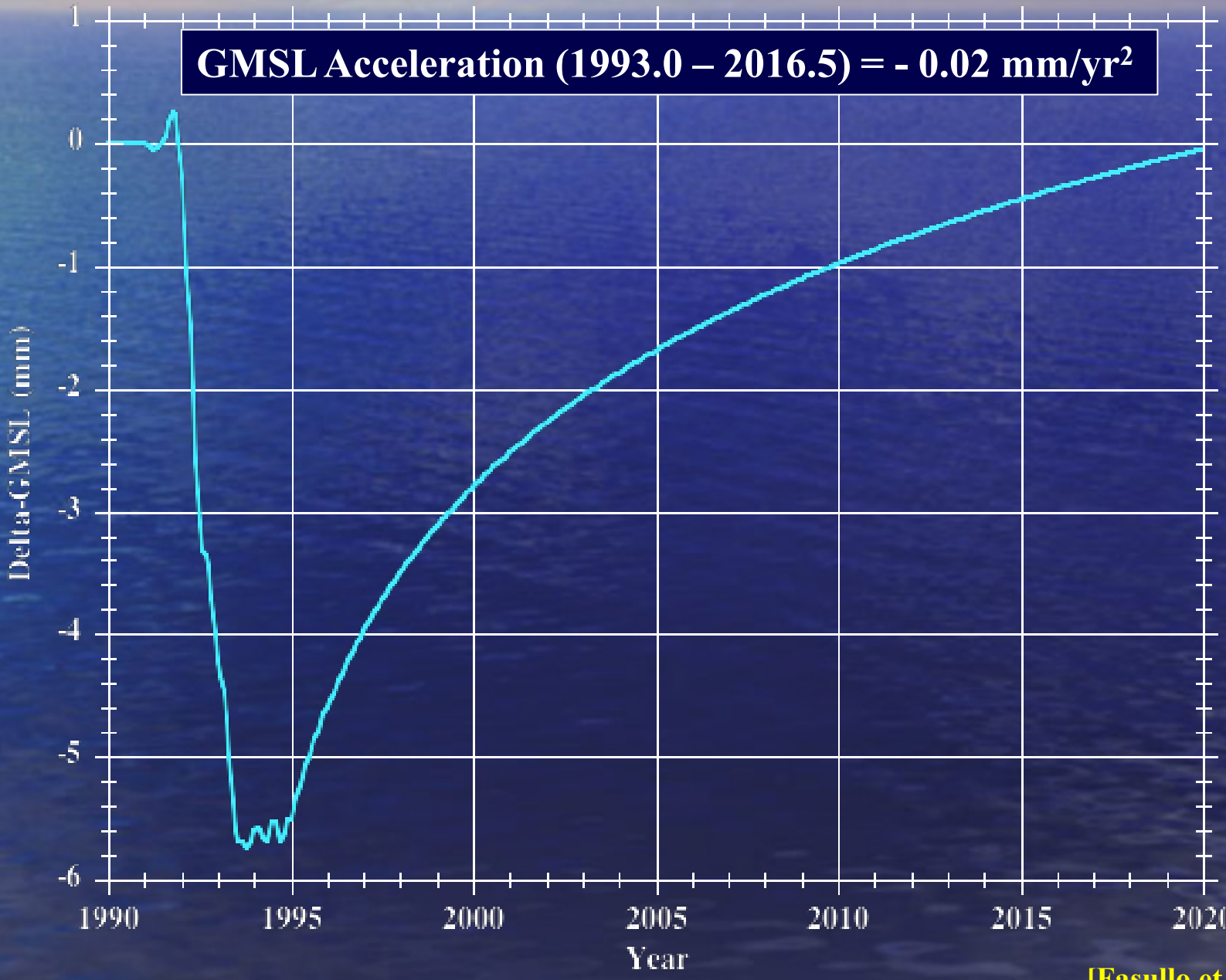
Yellowstone, Wyoming Supercomputing Center

Effects of Mt. Pinatubo Eruption in 1991



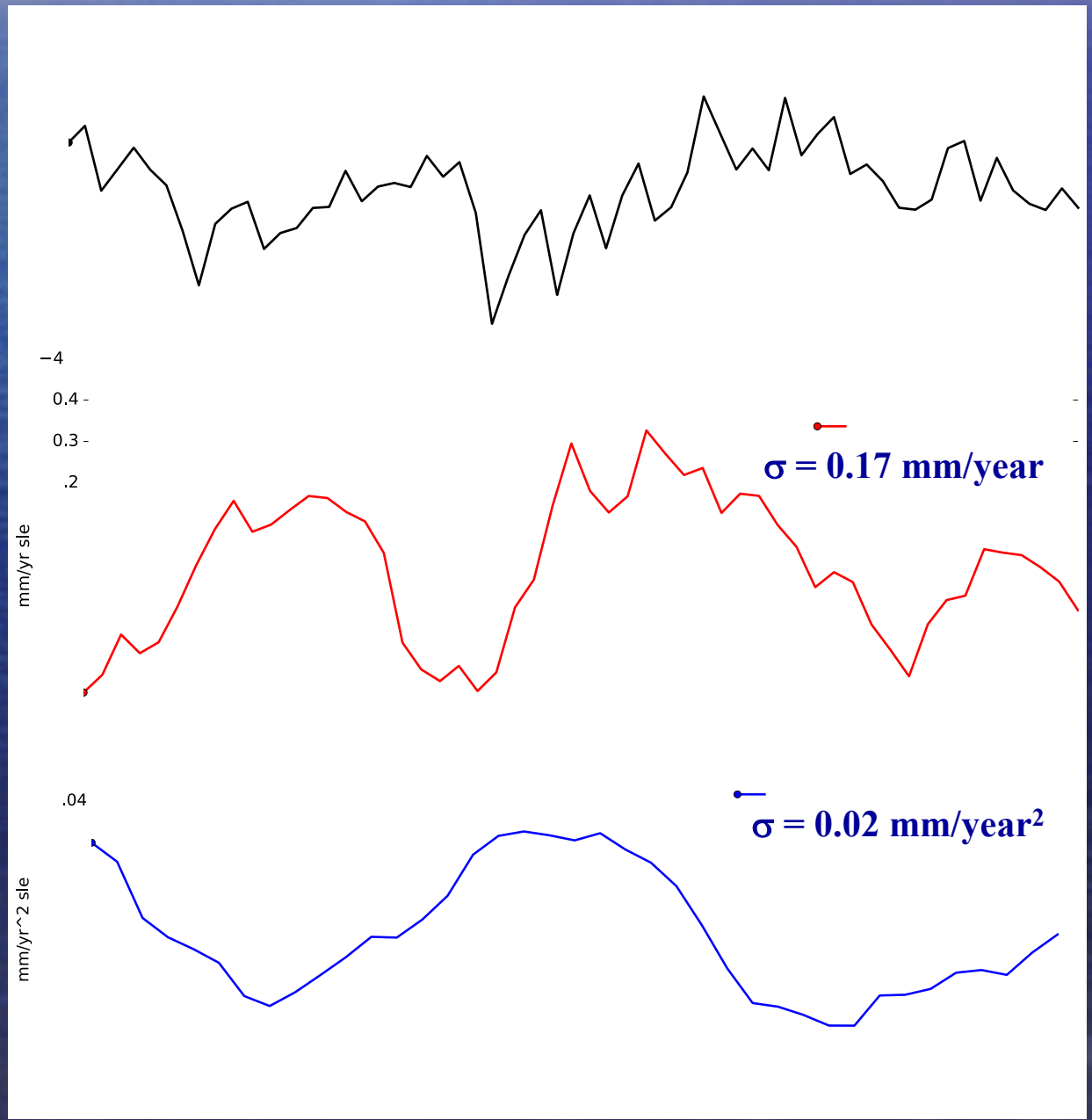
[Fasullo et al., 2016]

Effects of Mt. Pinatubo Eruption in 1991

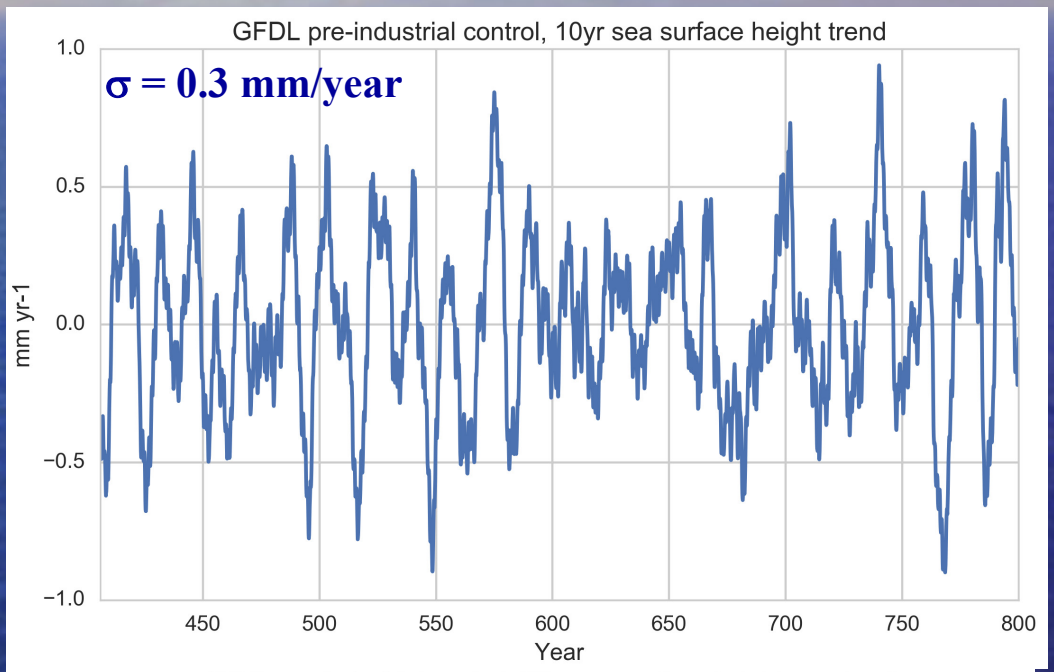


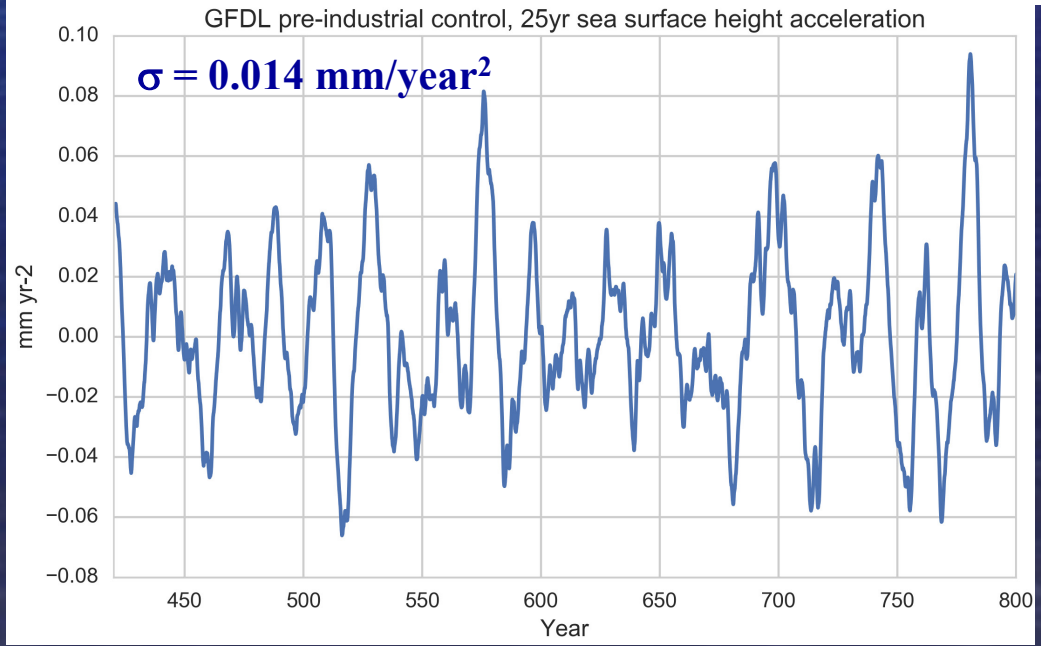
[Fasullo et al., 2016]

TWS-driven GMSL Variations from GLDAS-2



Thermosteric Variability – GFDL Model



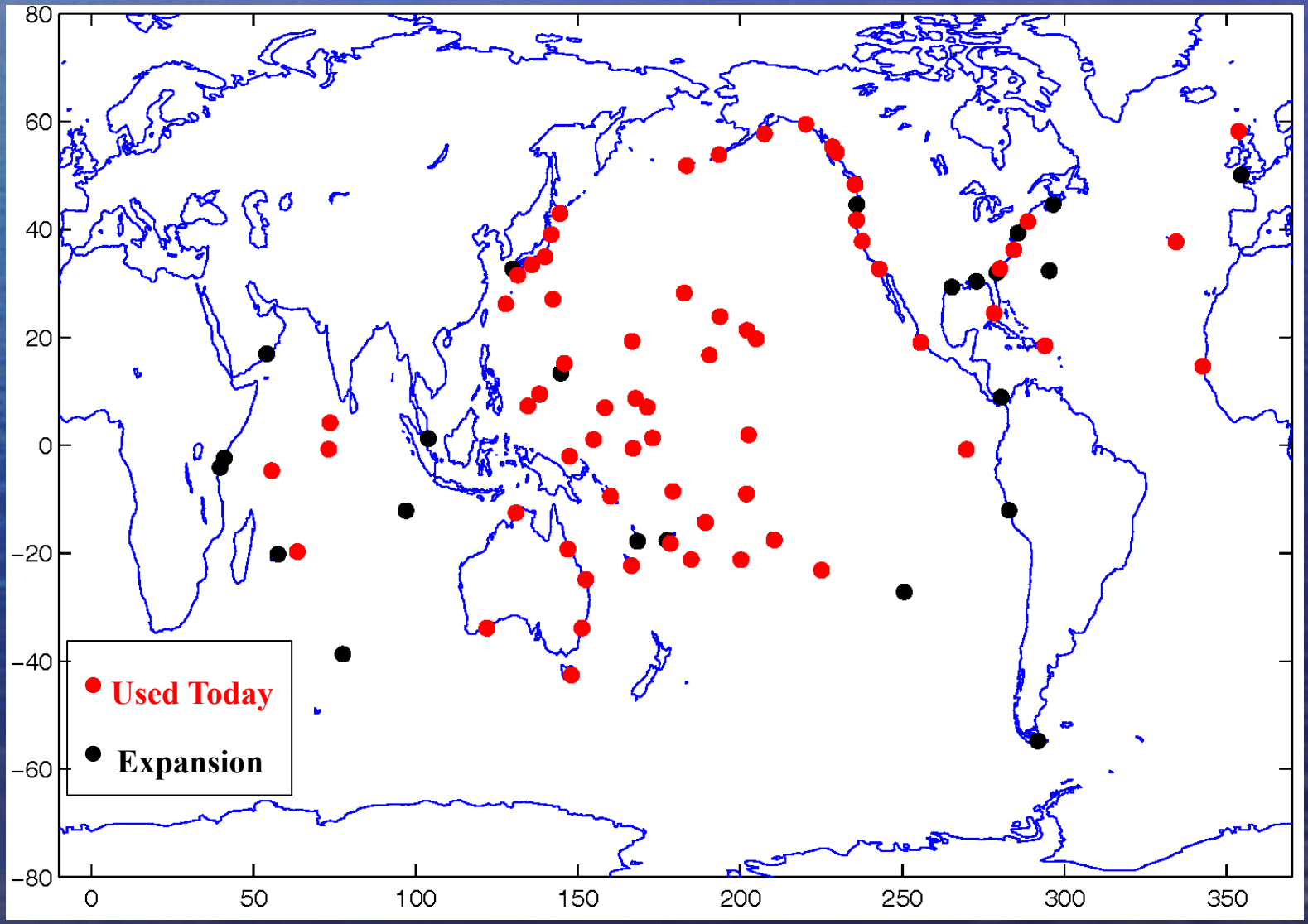


If there has been an acceleration, is it statistically significant?

Altimeter Data Issues

- Tide gauge validation can be used to establish uncertainty bounds for the GMSL acceleration estimate.
- Watson et al. (2015) suggested potential problems in the altimeter data record, mostly with TOPEX. Also saw differences depending on how land motion at the tide gauges are treated.
- Wallops Calibration Mode Correction for TOPEX
  - Tide gauge calibration suggests it should not be applied
- Bias between TOPEX Side A and Side B
  - Estimated from the tide gauge calibration

Tide Gauges Used for Cal/Val

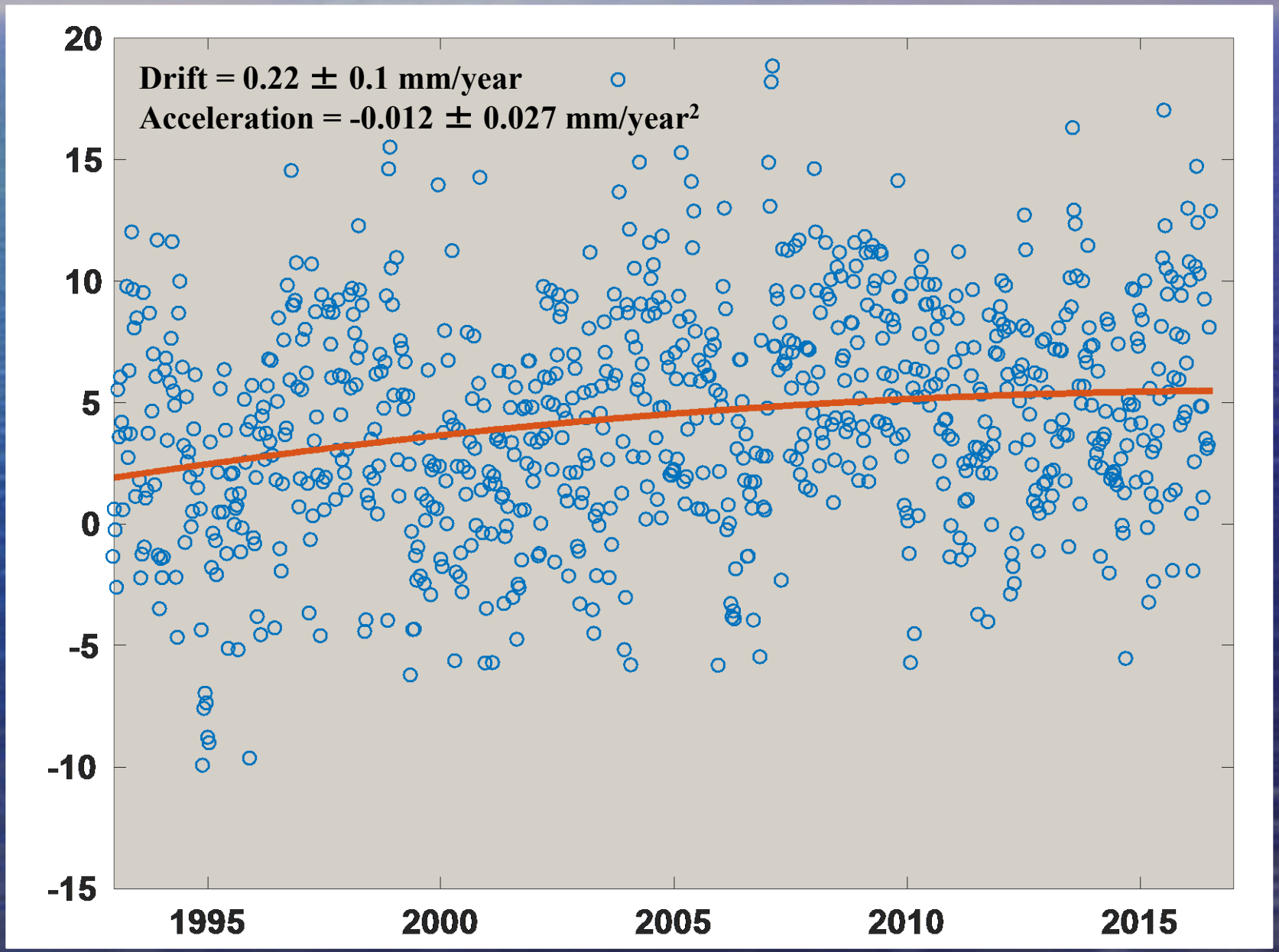


Updated from [Mitchum, 2000]

Tide Gauge Validation

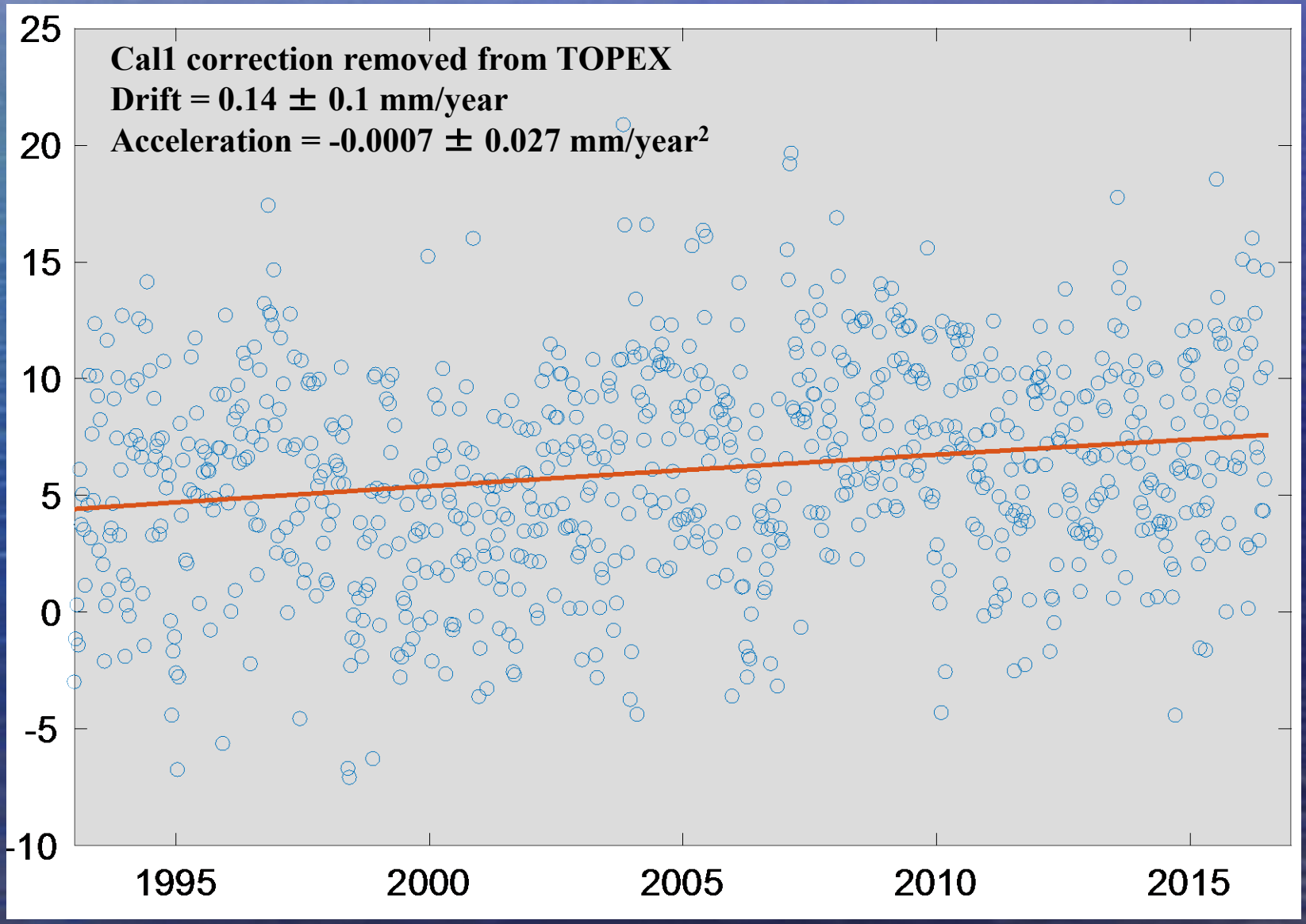
- Used altimeter – tide gauge as altimeter error estimate.
- AR1 error model applied to the full time series as well as to each mission individually.
- Get same answer for acceleration error if altimeter time series are treated individually (with biases estimates) or as a single time series.
- Uncertainty of bias estimates is 0.75 mm for TOPEX A/B, 0.52 mm for TOPEX B/Jason-1, and 0.17 mm for Jason-1/Jason-2 (all 1σ).
- Acceleration error (2σ) = 0.027 mm/year^2

Altimeter – Tide Gauge Validation Results



[Mitchum et al., 2016]

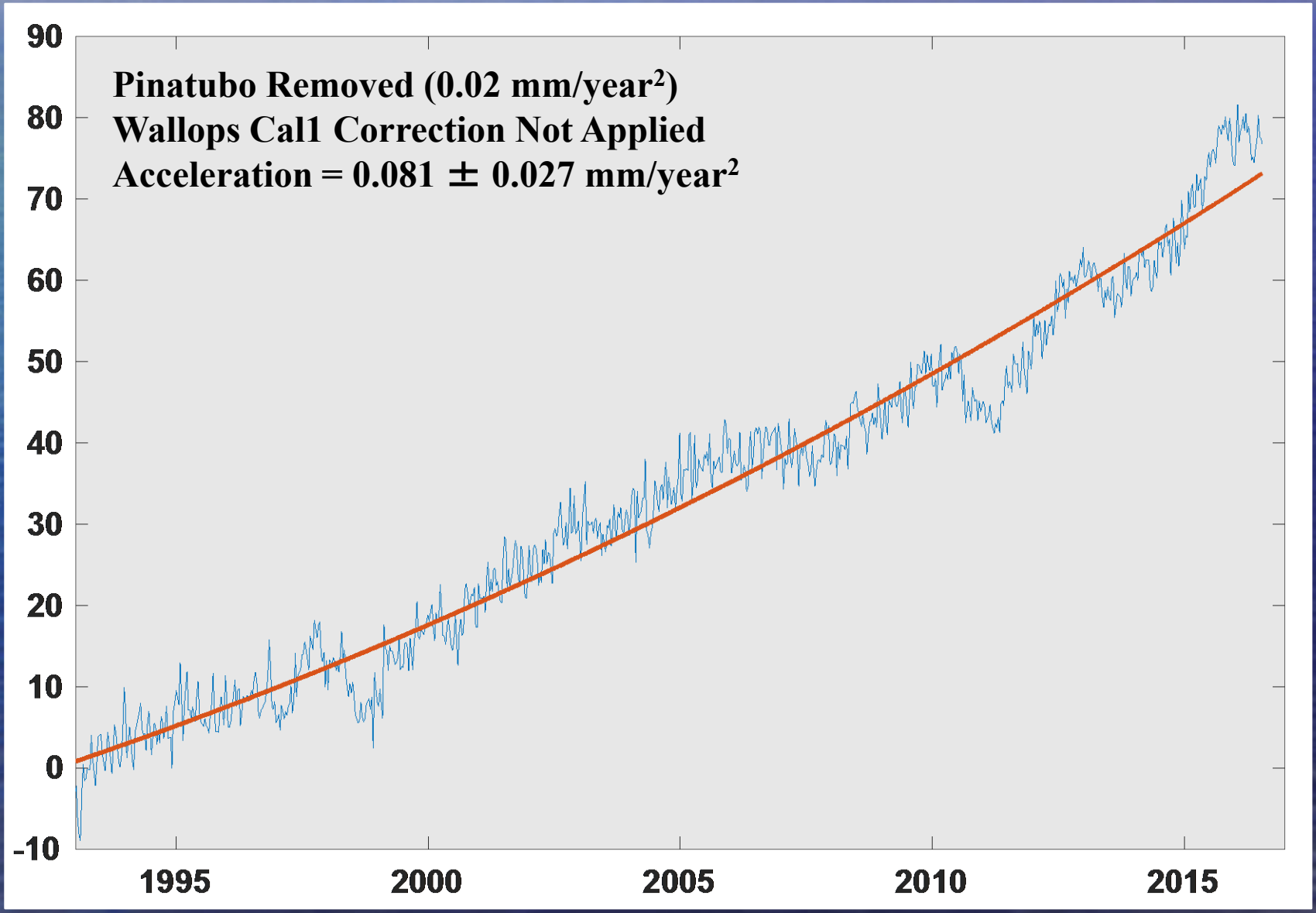
Altimeter – Tide Gauge Validation Results



[Mitchum et al., 2016]

What have we observed during the altimeter era?

Global Mean Sea Level Variations



http://sealevel.colorado.edu

GMSL Acceleration Estimates

Case	Acceleration (mm/yr^2)	Formal Error (mm/yr^2 2σ)	Tide Gauge Validation (mm/yr^2 2σ)
Nominal	0.046	0.013	0.027
Wallops Cal1 removed	0.061	0.013	0.027
Cal1 and Pinatubo removed	0.0811	0.013	0.027

These accelerations may be influenced by thermosteric and TWS decadal variability at the level of 0.025 $mm/year^2$ (1σ). Decadal variability in the cryosphere may add to this.

GMSL Projections Based on Acceleration

Rate (2000.0) (mm/year)	Acceleration (mm/yr^2)	GMSL at 2100 (mm)
3.0	0.02	400
3.0	0.04	500
3.0	0.06	600
3.0	0.08	700
3.0	0.10	800
3.0	0.12	900
3.0	0.14	1000

Summary

- The cryosphere has seen an acceleration of mass loss during the GRACE era of (~0.085 mm/yr^2), but the impacts of decadal variability in the cryosphere remain to be determined.
- The eruption of Mount Pinatubo in 1991 has masked an acceleration of ~0.02 mm/year^2 in the altimeter record [Fasullo et al., 2016].
- TWS and thermosteric variability contributes ~0.025 mm/year^2 to the acceleration estimates.
- The tide gauges are critical for understanding the errors in the altimetry and establishing an error bar for the acceleration estimates.
- Our best estimate for the acceleration of GMSL over 1993-2016 after removed the Pinatubo effect is 0.081 $\pm$ 0.027 mm/year^2.

Future Work

- Develop a better understanding of the errors in TOPEX (retracking effort, the A/B bias, etc.).
- Develop improvements to the tide gauge calibration (understand influence of errors in land motion corrections).
- Use GRACE to better understand the interannual variability in GMSL after 2002.
- Develop a better understanding of the impacts of decadal variability on the GMSL acceleration estimates from the relatively short altimeter record.
- Develop a more rigorous error budget based on all these considerations.
- Projections of future GMSL?