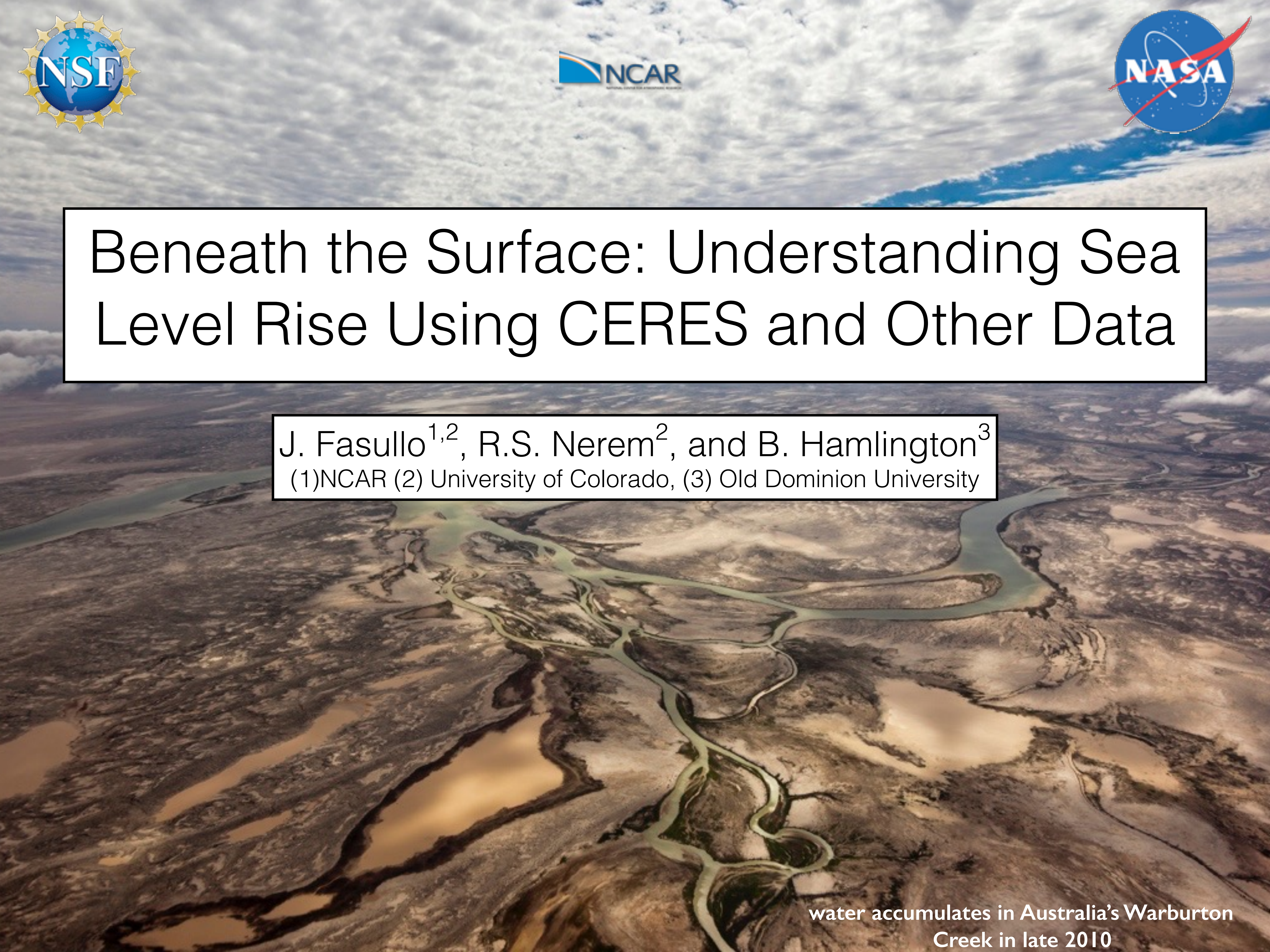
2010-2011 Australian Floods

water accumulates in Australia's Warburton Creek in late 2010


1991 Eruption of Mt. Pinatubo

Beneath the Surface: Understanding Sea Level Rise Using CERES and Other Data

J. Fasullo[1,2], R.S. Nerem[2], and B. Hamlington[3]
(1)NCAR (2) University of Colorado, (3) Old Dominion University



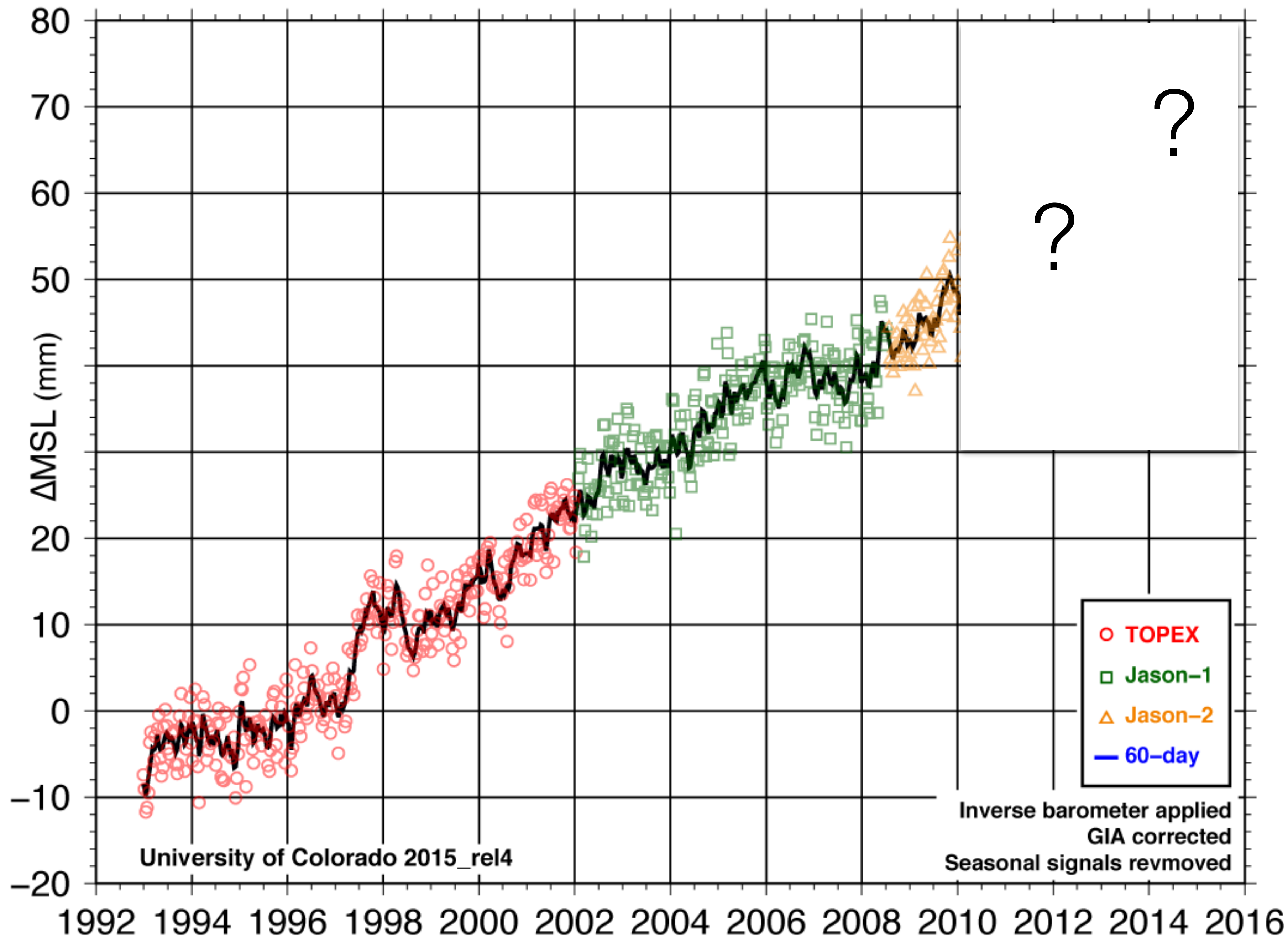
water accumulates in Australia's Warburton Creek in late 2010

Global Mean Sea Level

Trend ≅3 mm yr^{-1}

Less noise than T_S

No “hiatus”



Interpretation requires separation into OHC / mass components.

Sea Level: NASA's Vulnerability

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Research Features

Sea Level Rise Hits Home at NASA

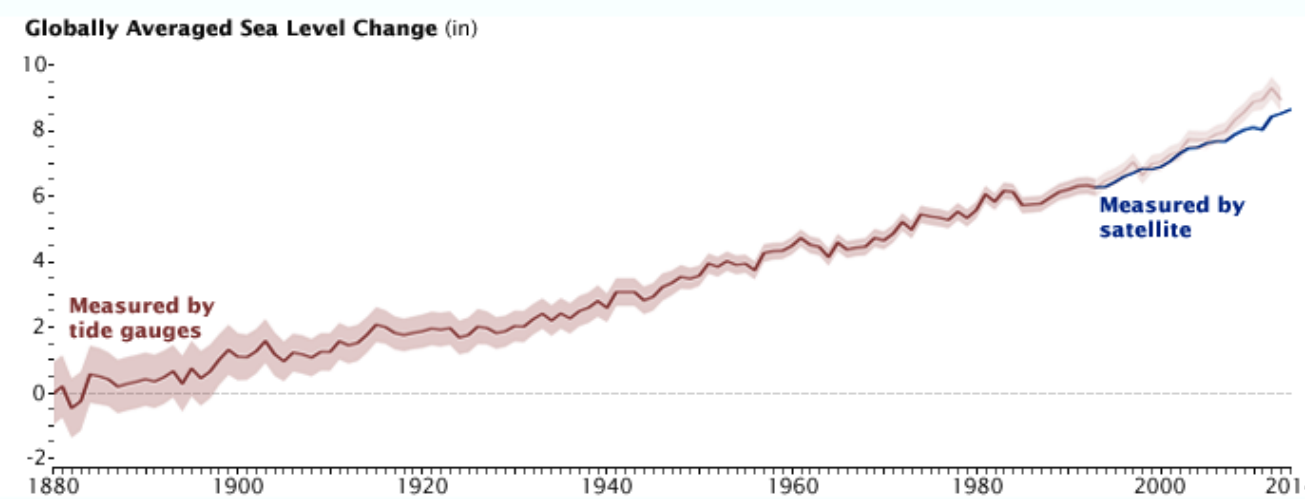
Watching Waters Rise Right Outside the Front Door

By Michael Carlowicz — Design by Joshua Stevens & Paul Przyborski — NASA Earth Observatory
August 26, 2015

The Sun rises at Kennedy Space Center. The sea is steadily doing the same. (Photo by NASA/Andres Adorno)

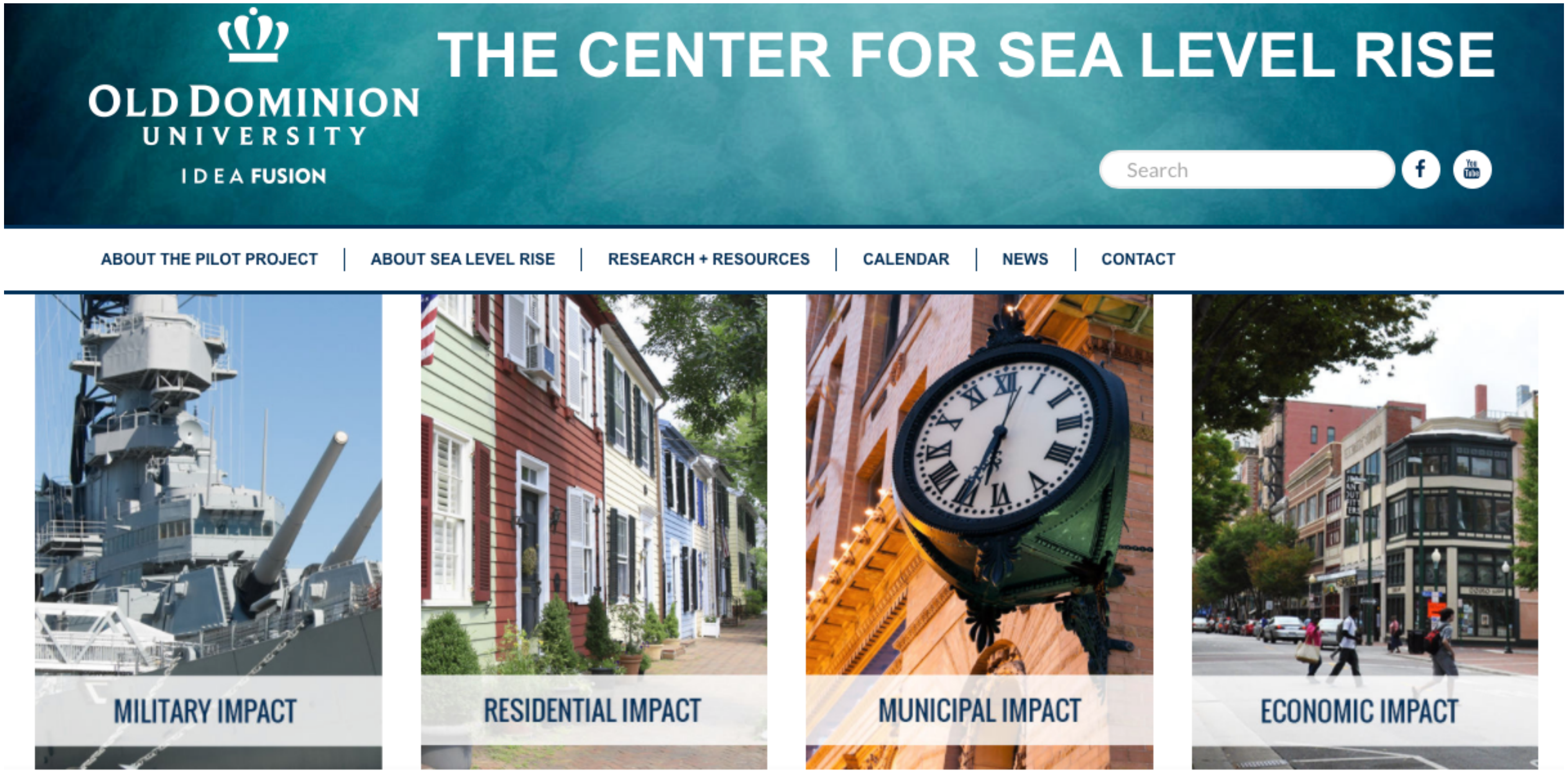
For the past two centuries, two trends have been steady and clear around the United States. Sea level has been rising, and more people have been moving closer to the coast.

As the ocean has warmed, polar ice has melted, and porous landmasses have subsided, global mean sea level has risen by 8 inches (20 centimeters) since 1870. The rate of sea level rise is faster now than at any time in the past 2,000 years, and that rate has doubled in the past two decades.



"**half to two-thirds of NASA's infrastructure and assets stand within 16 feet (5 meters) of sea level**. With at least $32 billion in laboratories, launch pads, airfields, testing facilities, data centers, and other infrastructure spread out across 330 square miles (850 square kilometers)—plus 60,000 employees—NASA has an awful lot of people and property in harm's way."

Sea Level: Hampton Roads Vulnerability

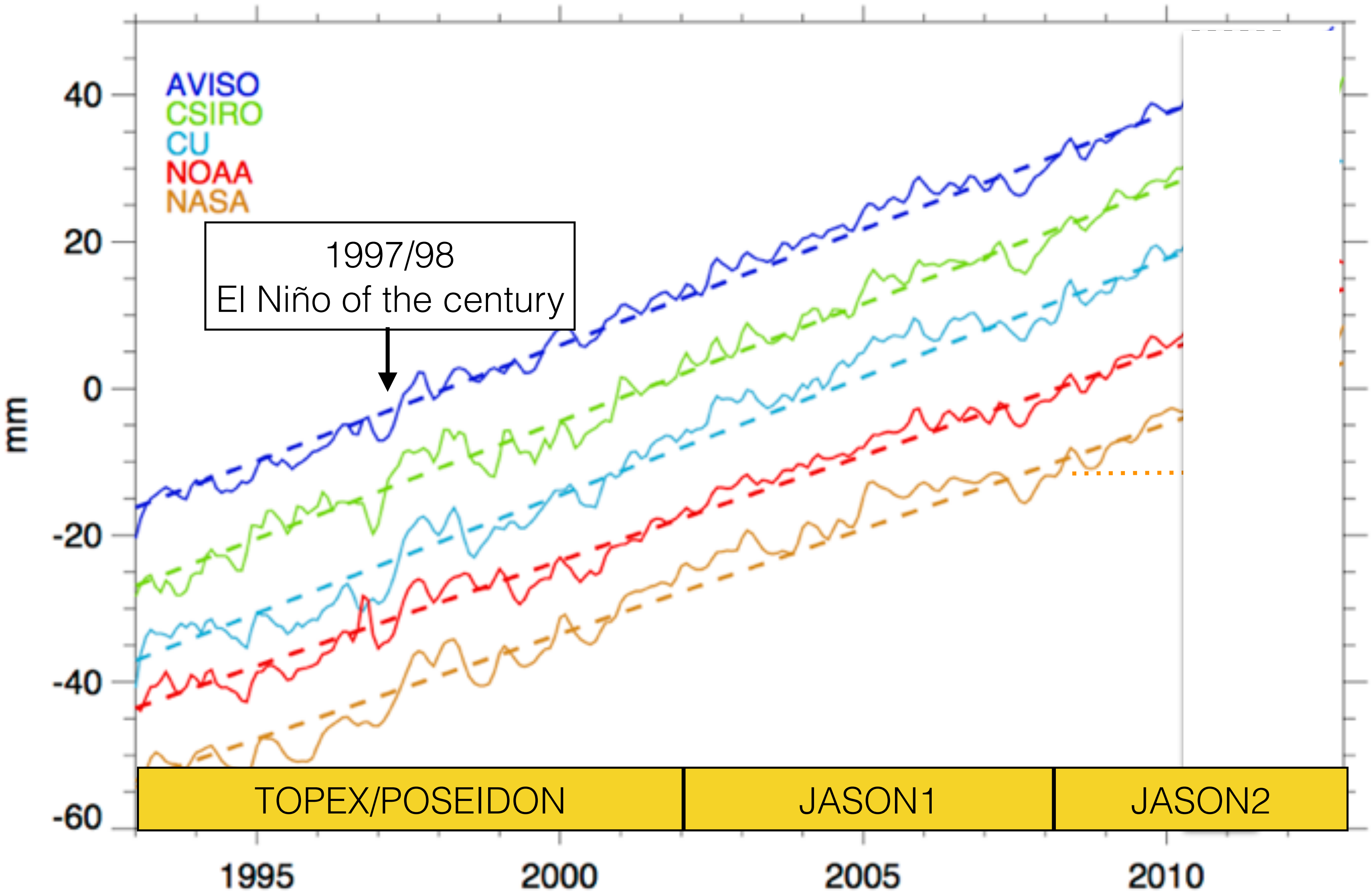


Norfolk Naval Station has 14 WWII era piers that are experiencing significant maintenance problems due to sea level rise. Replacement costs: $35 million per pier.

Norfolk officials estimate the city will need at least $1 billion in the coming decades to replace infrastructure and keep water out of the city's homes / businesses. 877 miles of roads at risk.

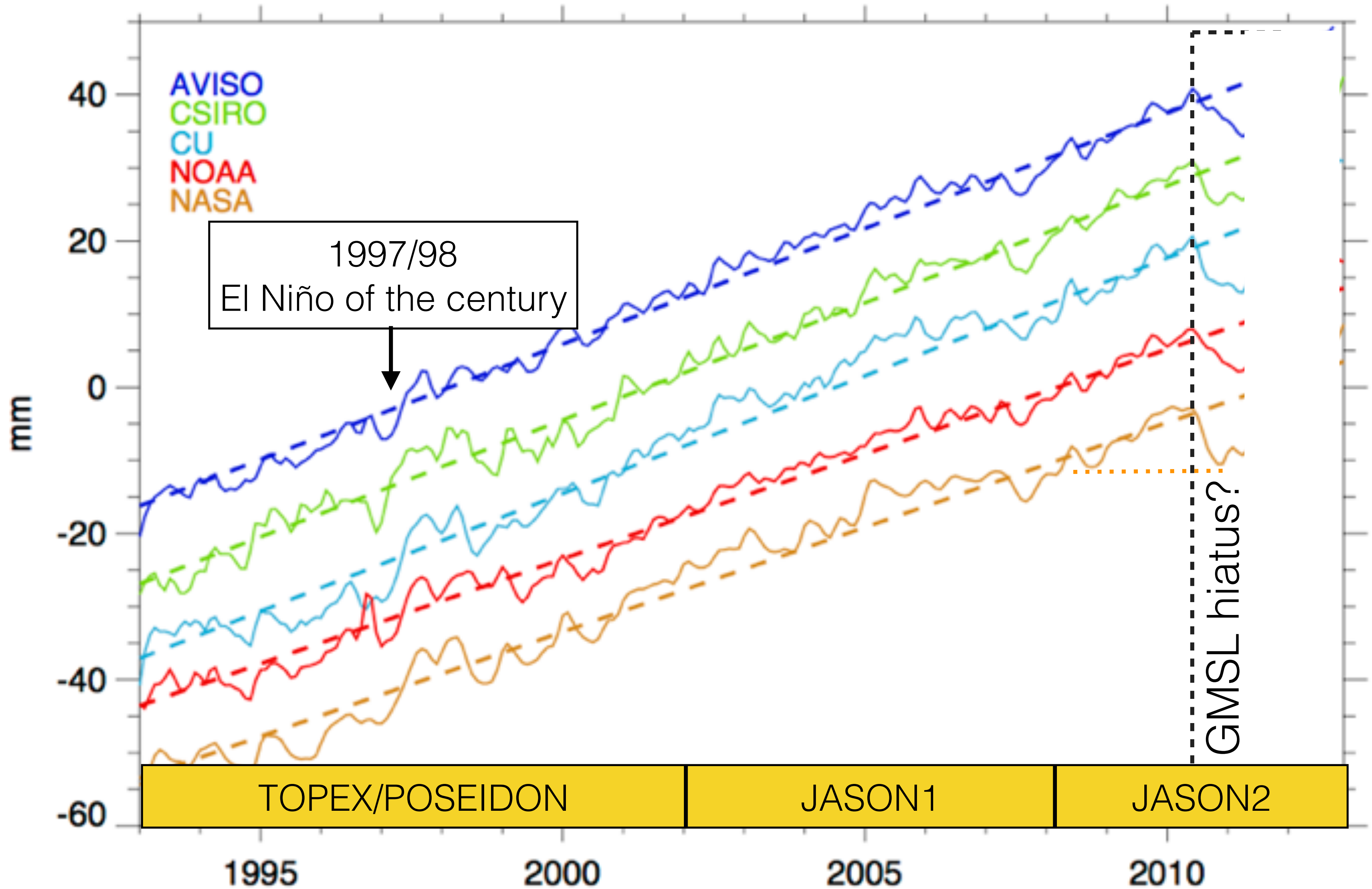
The Virginia Beach-Norfolk Metropolitan Statistical Area ranks 10th in the world in value of assets exposed to increased flooding from sea level rise

Global Mean Sea Level



Trend of ~3 mm yr $^{-1}$; ENSO related variability

Global Mean Sea Level



Trend of ~3 mm yr $^{-1}$; ENSO related variability

Science Question #1

What caused the unprecedented drop in sea level in 2010/2011?

Key Data: ARGO

Strengths

- 3000+ floats presently deployed
- CERES-EBAF depends on ARGO for absolute calibration
- unprecedented sampling 0-2000m

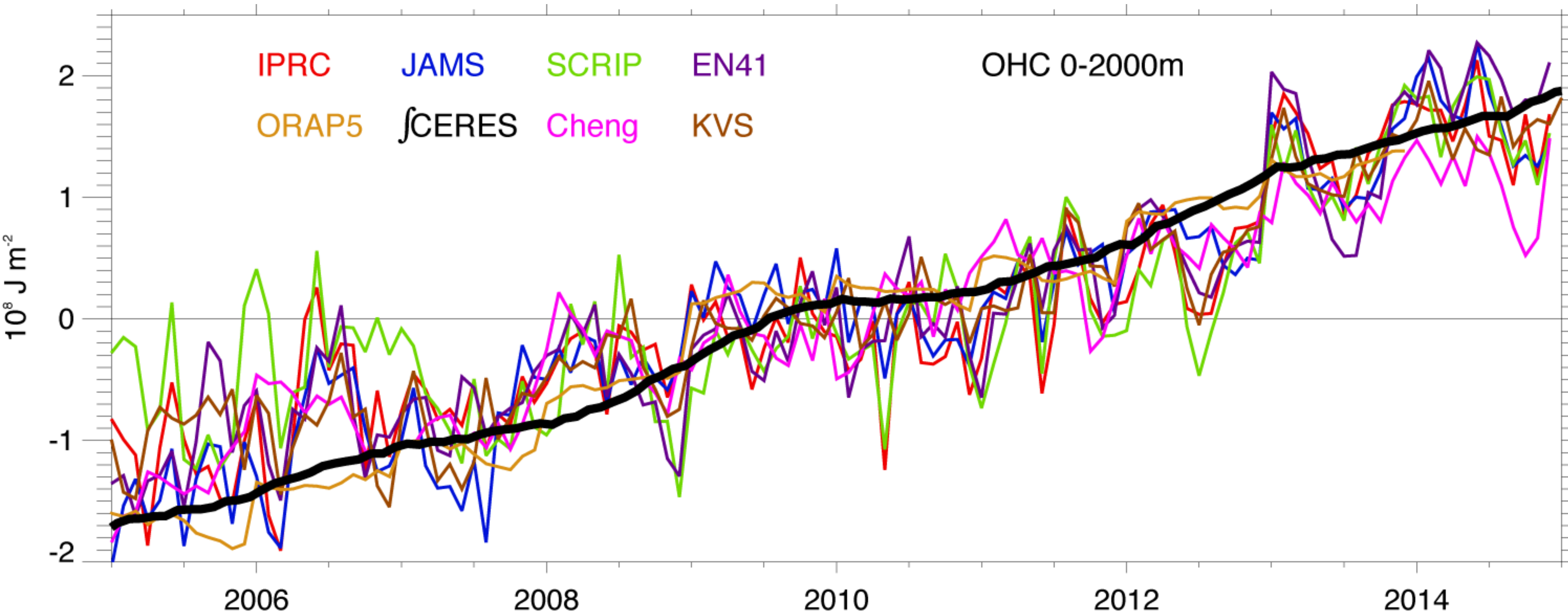
Weaknesses

- does not sample:

1. coastal regions
2. marginal seas
3. ice covered and
4. deep ocean

- **begins in 2005 (for global)**
- **noisy on seasonal timescales**

Key Data: ARGO



Some ARGO OHC estimates show seasonal cooling strong enough to explain a 7 mm GMSL drop (~1.2 10^8 Jm^{-2}).

Integrating CERES at TOA suggests these variations are spurious.

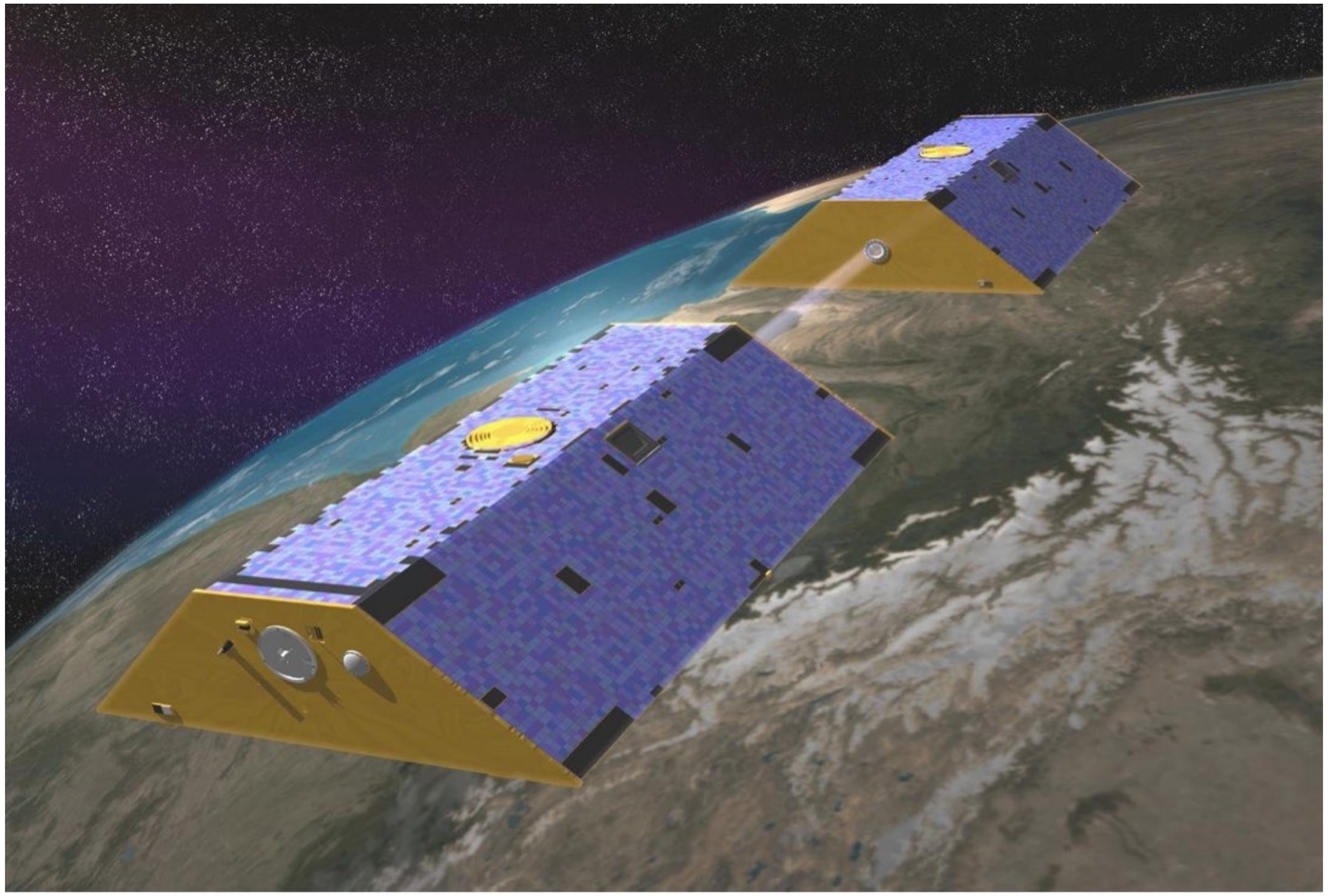
Key Data: GRACE

Strengths

- provides the first ever global estimates of near-surface mass as f(lat,lon,time)

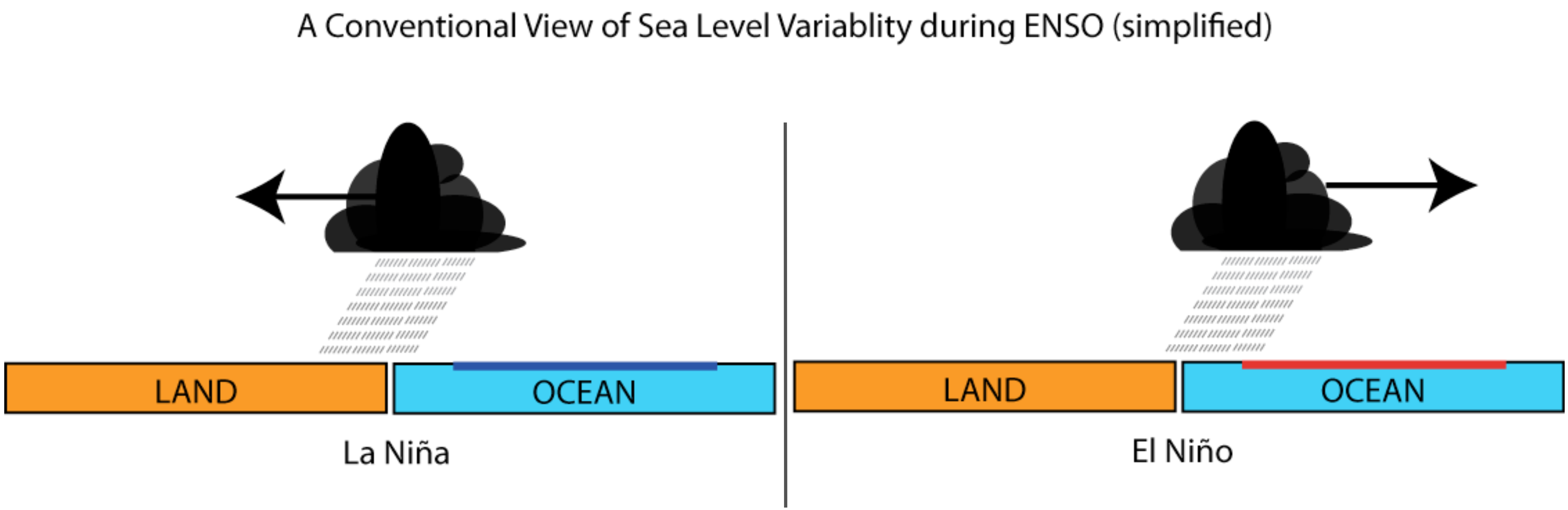
Weaknesses

- cannot resolve surface vertical structure
- synthesized by 3 data centers with sometimes differing results
- begins in 2003
- batteries are currently weak requiring the instrument to be powered down for prolonged intervals; currently near end of life; GRACE-FO in 2017



not to scale; separation is ~200 km
can detect changes of 10 μm

ENSO-GMSL INTERACTION



During **La Niña**, cold tropical oceans decrease convective instability over ocean, favoring terrestrial rainfall, and increasing terrestrial water storage (TWS).

During **El Niño**, warm tropical oceans increase convective instability over ocean, decreasing terrestrial rainfall, and increasing TWS.

Boening et al. 2012, GRL

- closure in the mass budget and altimetry (GMSL ≈ OHC+OM)
- found the event was primarily mass driven (GRACE/ARGO/altimetry/ CERES)
- alluded to the influence of La Niña on the tropical monsoons (sea level during the drop governed primarily by tropical TWS; NOT OHC or melt)

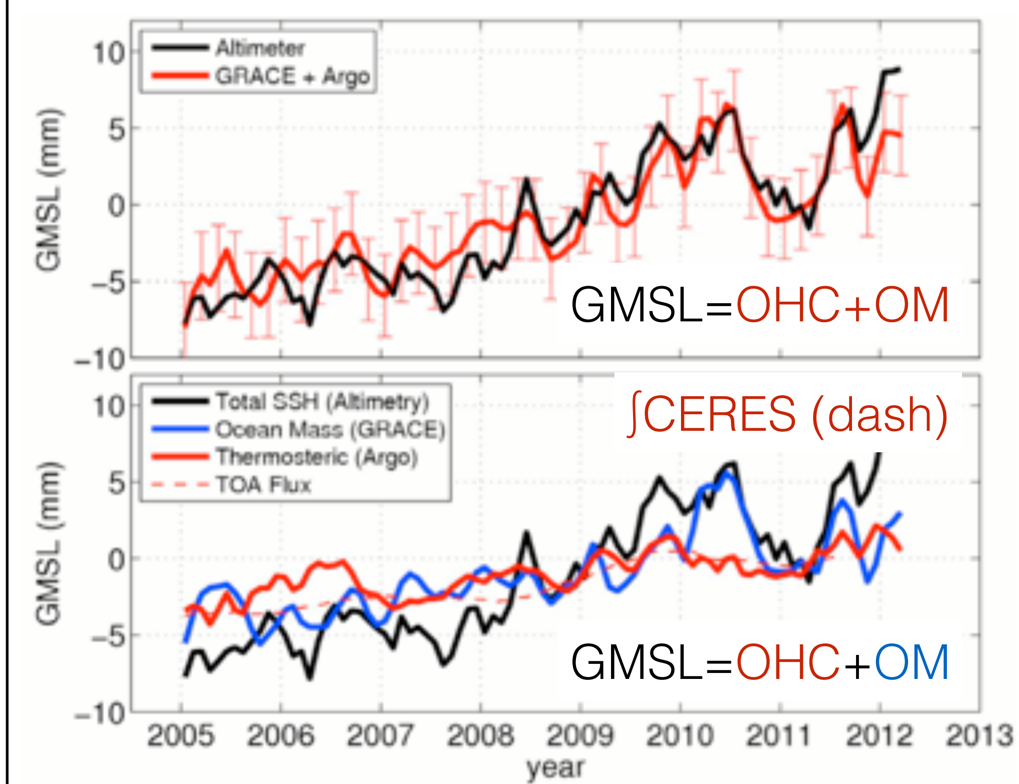


Figure 2. (top) Global mean sea level from altimetry from 2005 to 2012 (black line). The red line shows the sum of the ocean mass contribution (as measured by GRACE) and thermal expansion contribution (as measured by Argo). Error bars are 2.5 mm (as discussed in the Methods Section). (bottom) Contributions to global sea level rise from 2005 to 2012. As in the top panel, the black line shows GMSL as observed by satellite altimeters. Ocean mass changes are shown in blue and thermosteric sea level change is shown in red. The red dashed line shows an estimate of ocean warming based on estimates of radiative imbalance at the top of the atmosphere. The mean warming rate is adjusted to agree with Argo and heat content is scaled assuming that 3×10^{22} J is equivalent to 5 mm of thermosteric sea level rise as in *Church et al.* [2005].

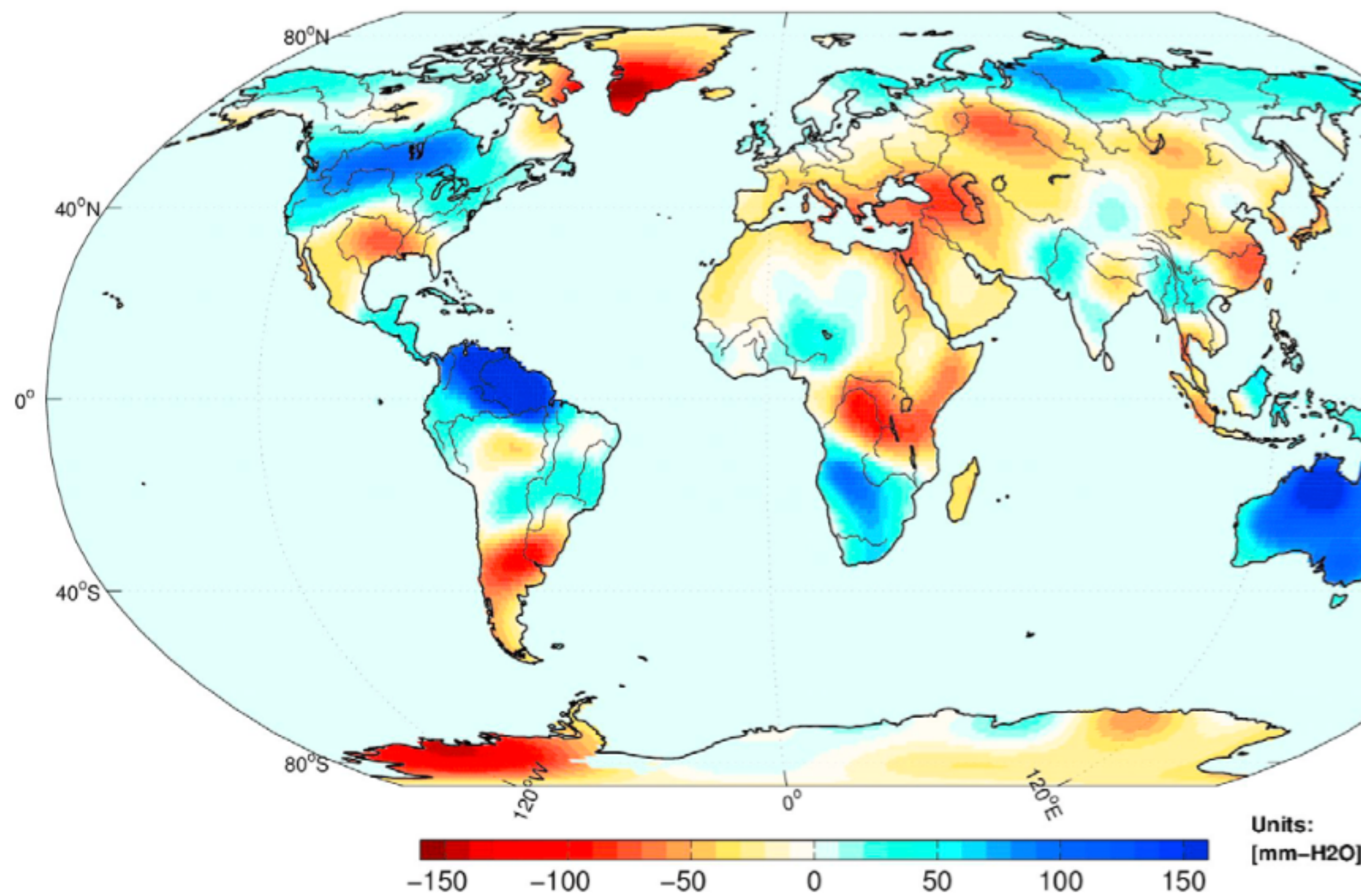
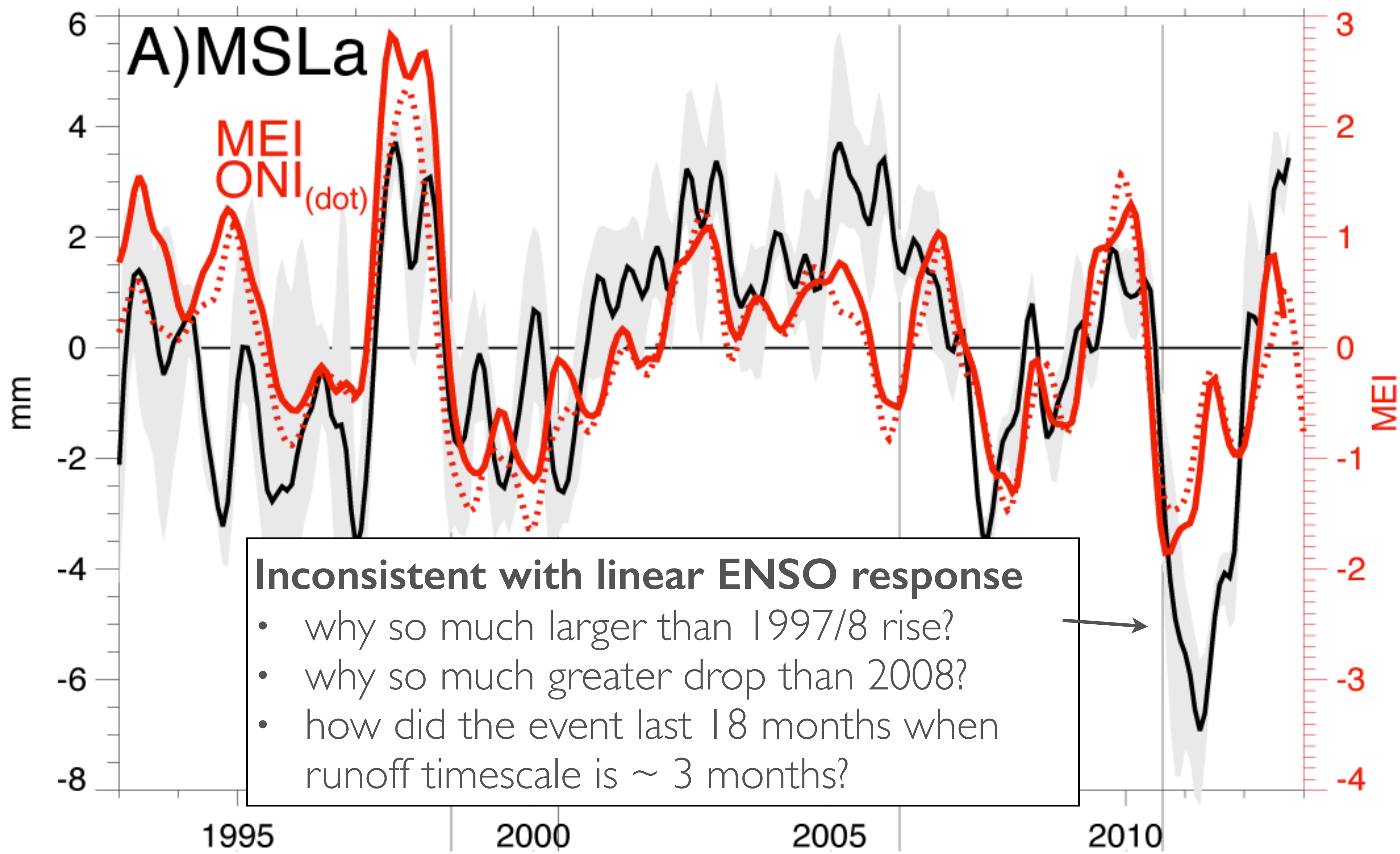


Figure 3. Change in water mass from beginning of 2010 (JFM average) to mid 2011 (MAM average). Blue colors indicate an increase in water mass over the continents.

- Anomalies between 40N-40S, particularly over tropical land, are qualitatively consistent with La Niña-based expectations
- Large decreases over ice sheets driven by the trend, not year to year shifts are therefore do little to contribute to interannual changes.

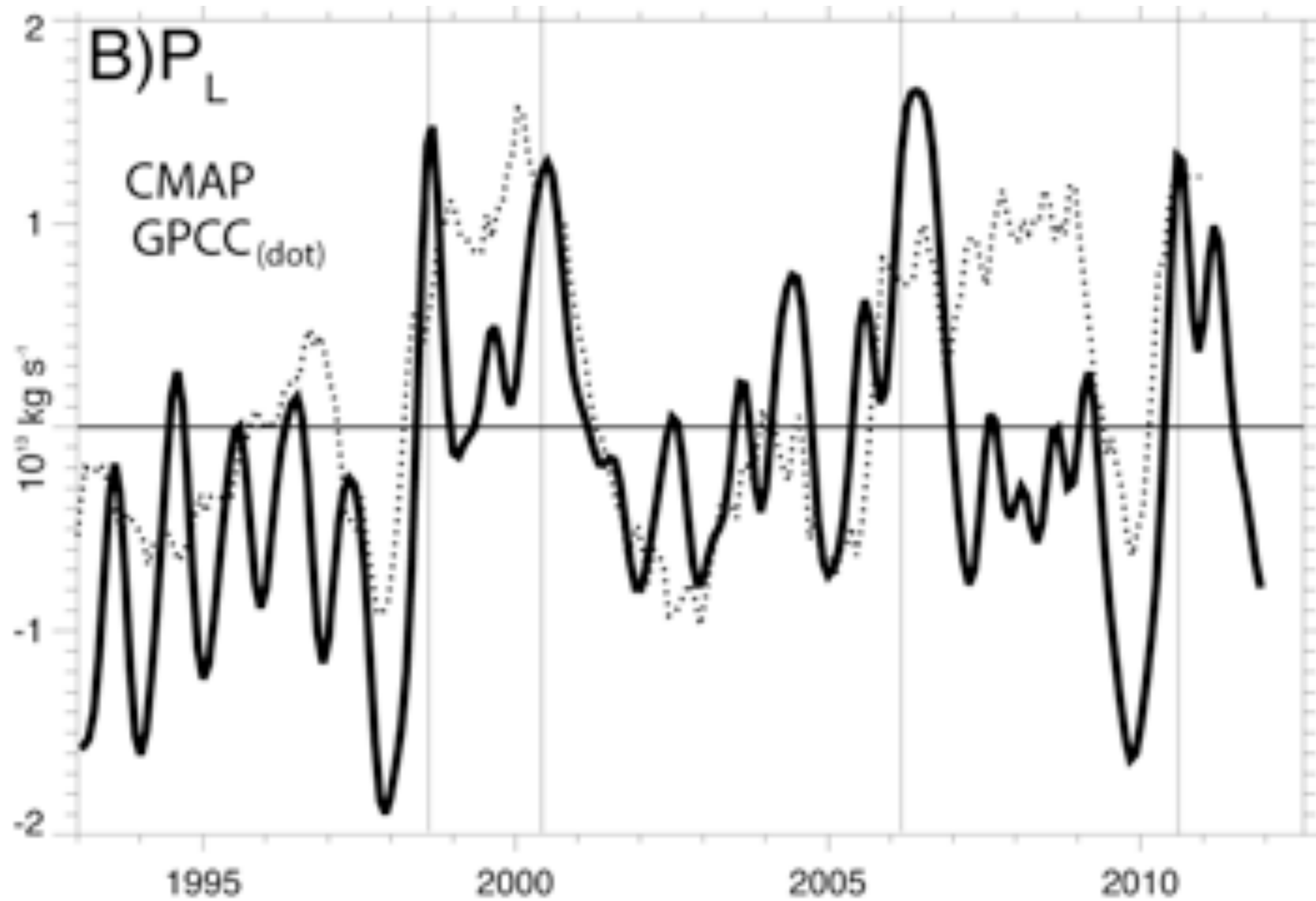
De-trended GMSL vs MEI



Inconsistent with linear ENSO response

- why so much larger than 1997/8 rise?
- why so much greater drop than 2008?
- how did the event last 18 months when runoff timescale is ~ 3 months?

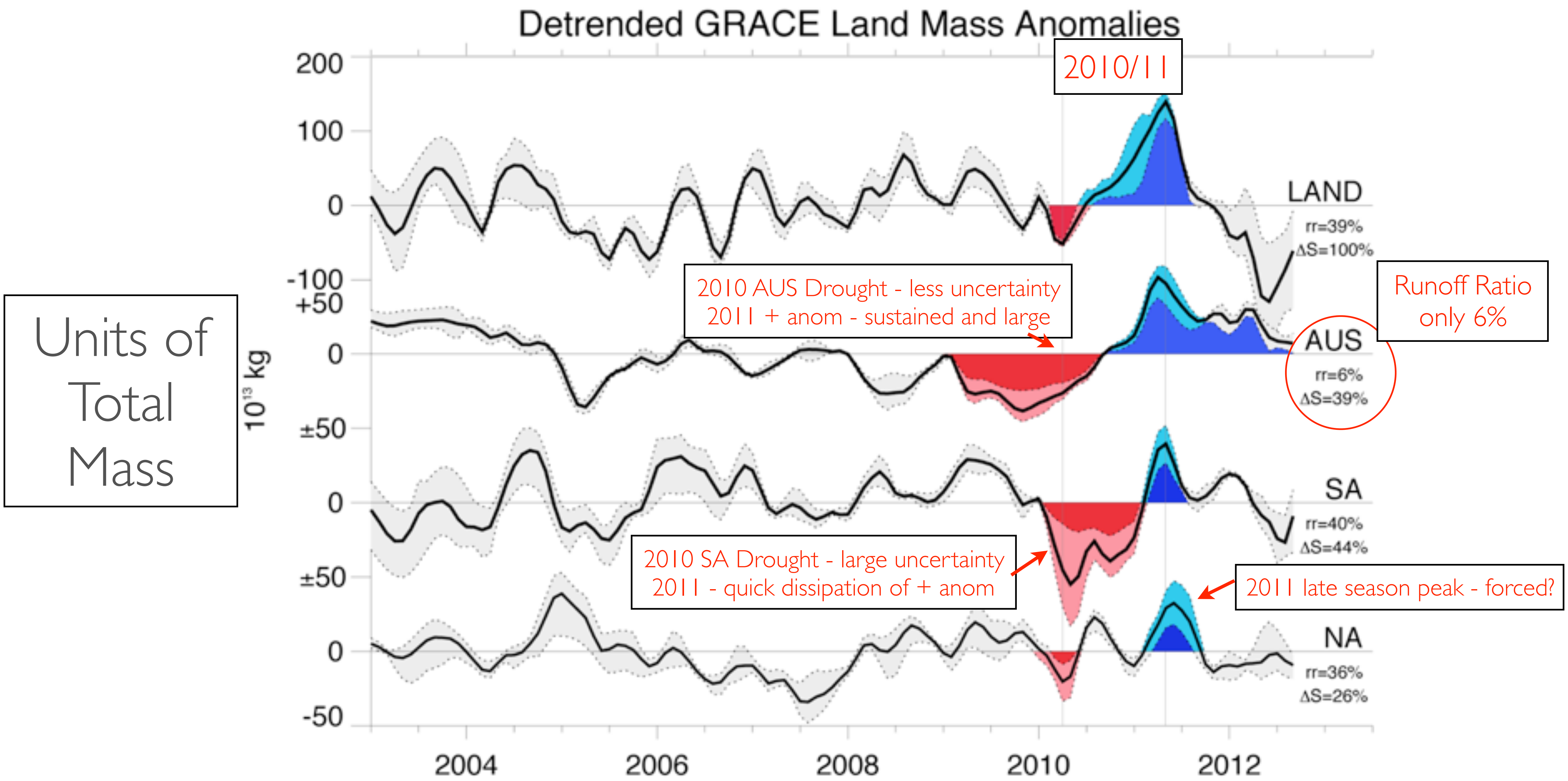
Global Land Rainfall



- Rainfall datasets show 2010-11 P_L to be large but not unique. [also GPCP and TRMM]

- **If P_L not unique, why was GMSL so unique?**

Mass Changes by Continent

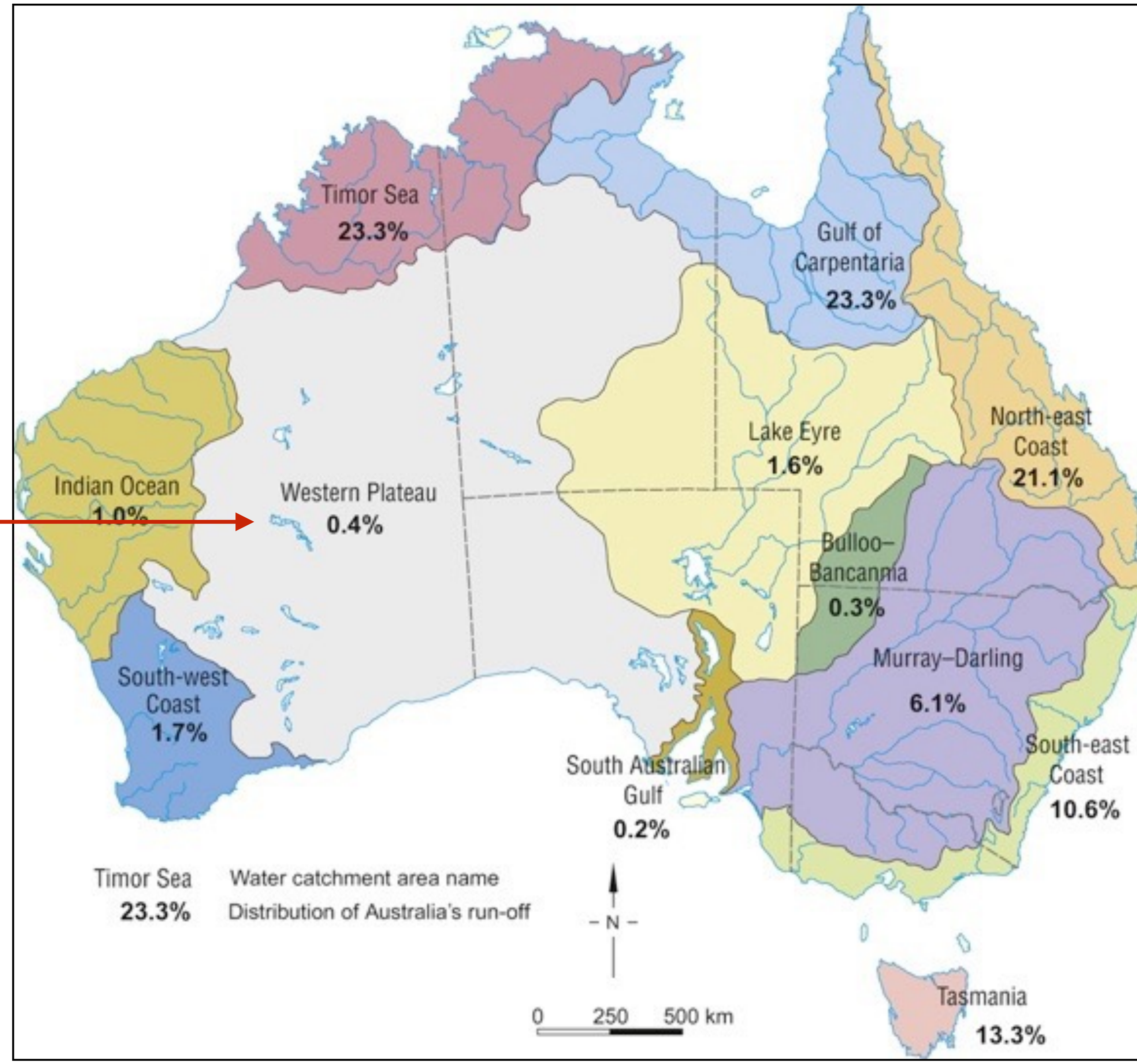


Australia's low frequency contribution to TWS is unequaled by other continents despite being much smaller. Why?

Why is Low Frequency Power in Australian TWS so large?

"what rains in Australia stays in Australia"

- Major arheic and endorheic basins: Western Plateau and Lake Eyre
- Little coordinated runoff to ocean
- In arheic basins (WP), wind rather than rain is the main erosive force (no rivers).
- In endorheic basins (Eyre), flow is inland.
- Increases storage persistence.



Attribution of the GMSL Drop

3234 MONTHLY WEATHER REVIEW VOLUME 137

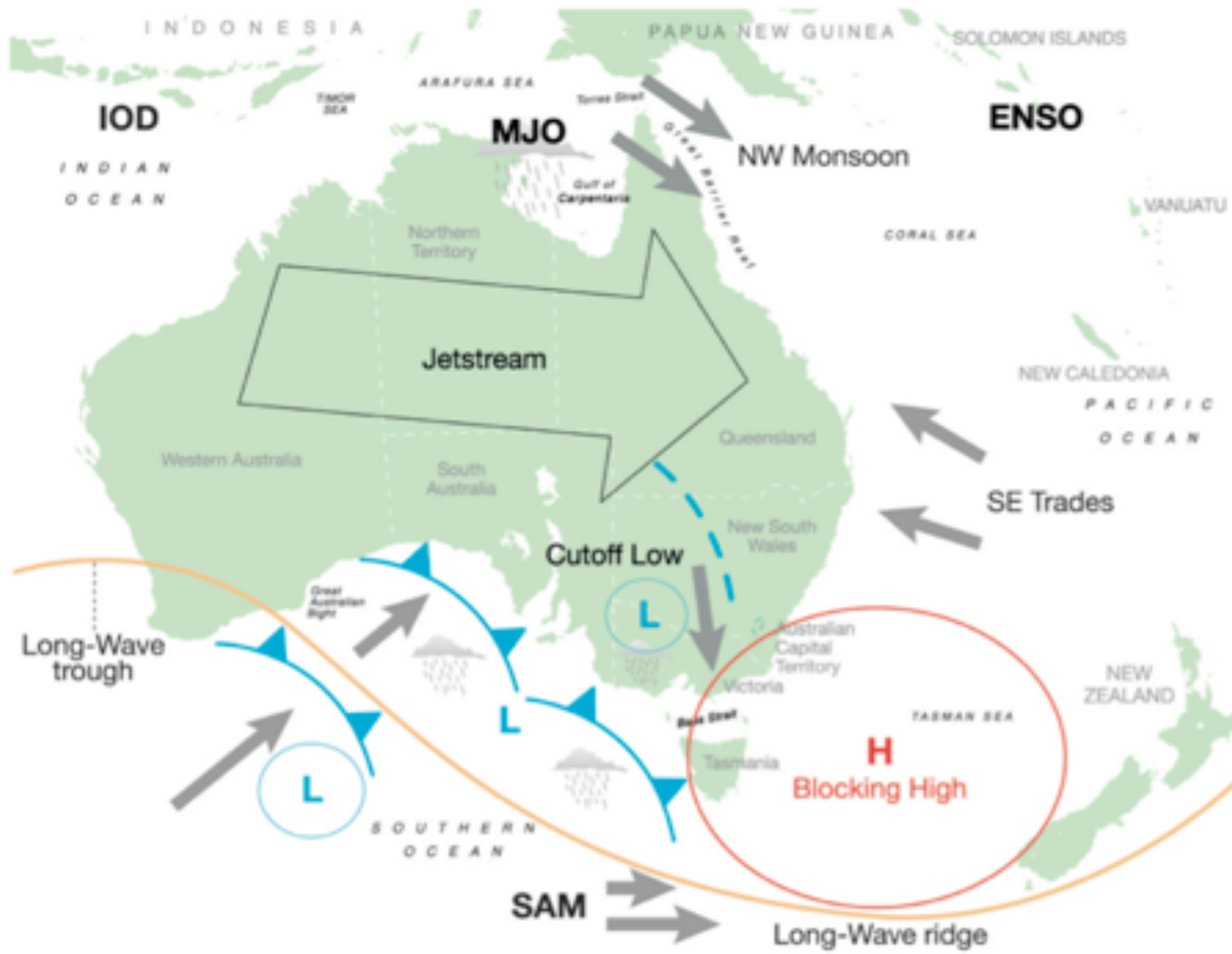


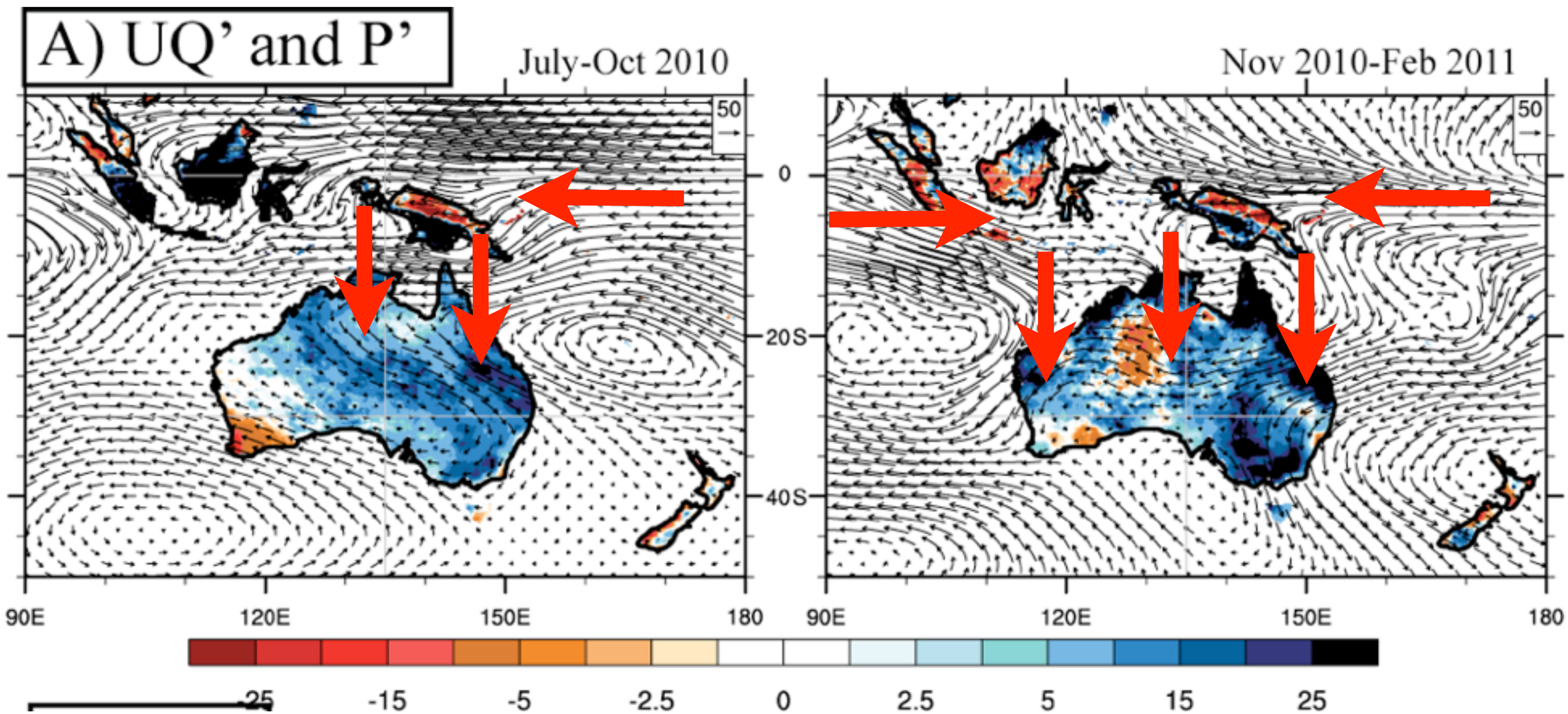
FIG. 1. Schematic representation of the main drivers of rainfall variability in the Australian region. The dominant features are the IOD, MJO, and ENSO in the tropics, and the SAM and blocking in the extratropics. The influence of the subtropical jet is indicated by the "jet stream" arrow. A schematic cutoff low in a typical position to influence southeast Australian rainfall is shown next to the blocking high. The longwave pattern in the midtroposphere consistent with the blocking high is also indicated with a trough over Western Australia and a ridge in the Tasman Sea.

By narrowing the region of interest, GRACE also promotes attribution.

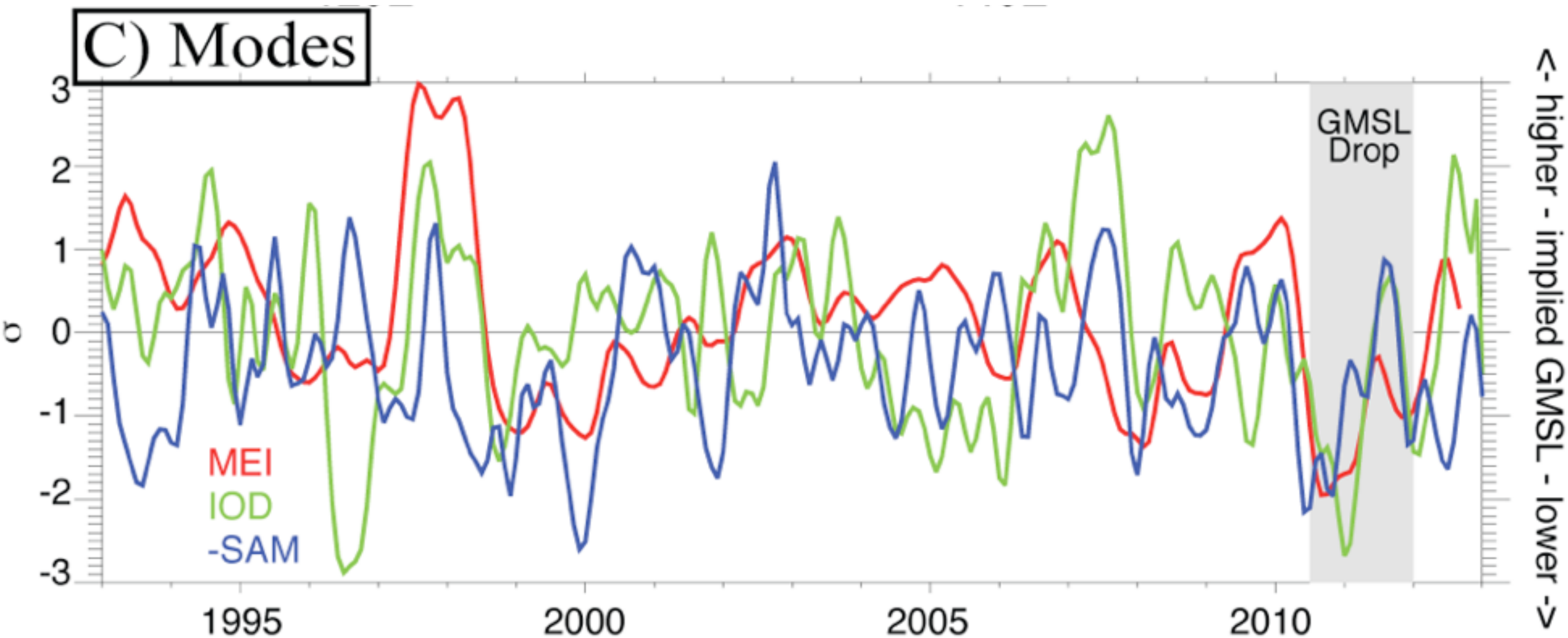
Attribution of the GMSL Drop

- **SAM** pulls tropical easterly moisture transports (La Niña) across the continent.

- **IOD** westerly transport converges with La Niña easterlies, drives them into Australia



Attribution of the GMSL Drop



During the 2011 GMSL drop, extremes in the modes coincided.

A View from MODIS

It's not unusual for a rainy season to transform a landscape, but what's unusual about Australia's Channel Country is that the transforming rains often fall hundreds of kilometers away. Like the Okavango Delta of Botswana, the Channel Country is an inland delta. It is fed by rain that falls on the Mitchell Grass Downs to the north. Instead of flowing to the coast, the rivers arising from these grassy plains flow toward the low-elevation Australian interior, sending water over expansive floodplains.

Just about every year brings some seasonal changes to the Channel Country, though not every year brings the same amount of flooding. The Moderate Resolution Imaging Spectroradiometer (MODIS) on NASA's Aqua satellite captured a dry-season scene on September 26, 2009 (top), and a flooded scene on March 26, 2011 (bottom). These images show floodplains in southwestern Queensland, just west of Australia's Northern Territory and north of the state of South Australia.

Both images use a combination of visible and infrared light to better distinguish between water and land. Water is blue, and darker blue implies greater water depth. Vegetation is bright green and bare ground in pink-beige. The flooding is significant in March 2011, but the water isn't high enough to crest many of the linear dunes that run northwest-southeast in this region.

Much of the water in the Georgina and Diamantina River systems results from monsoonal weather systems. Floods in the Channel Country typically happen between November and June, and flooding is especially likely in February or March.

When the Channel Country floods with water that flowed in from elsewhere, the phenomenon is known as a dry flood. Sometimes rain falls locally, but the region is generally arid, with less than 250 millimeters (10 inches) of rain a year. Either way, where the water flows, plants, fish, and waterfowl follow. Dormant plants quickly revive, as indicated by the abundant green in the March 2011 image. Australia's newly watered interior provides breeding grounds for about 70 bird species, including parrots and pelicans.
The vibrant flood season is fleeting, however, and typically dry conditions quickly return. Some animals don't survive the return to dry weather, but most leave for lakes, water holes, or coastal regions, bolstering populations in those areas.

- http://earthobservatory.nasa.gov/IOTD/view.php?id=80023

2009

2011

Conclusions: The 2011 GMSL Drop

Australia is a key player in global TWS and GMSL budgets due to its unique surface hydrology and proximity to major modes of variability and it played a major role in 2010-11.

La Niña → P_L → Sea Level Drop

Conclusions: The 2011 GMSL Drop

Australia is a key player in global TWS and GMSL budgets due to its unique surface hydrology and proximity to major modes of variability and it played a major role in 2010-11.

~~La Niña → P_L → Sea Level Drop~~

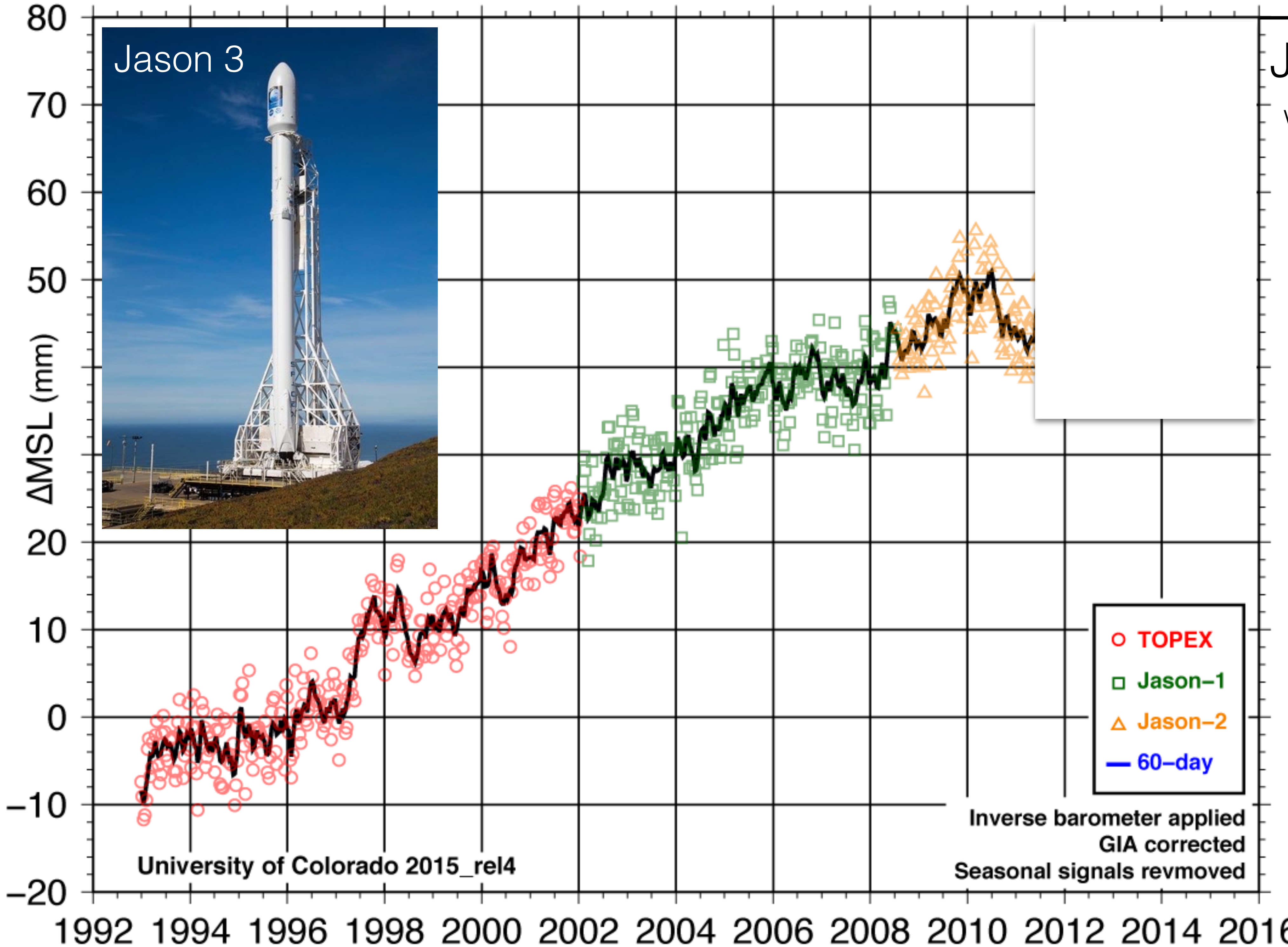
(1) [{2010 El Niño + 2011 La Niña + IOD/SAM} → $P_{\text{AUS Arehic/Endorheic Basins}}$ +

(2) {2010 El Niño+2011 La Niña} → P_{SA}] + P_{NA} (noise?) **(3)**

→ 2011 Sea Level Drop

Best 20th C analogue: 1973/4. We cannot simulate the event in most coupled models. Were we to get the surface hydrology correct, +P biases would fill Australia's interior basins

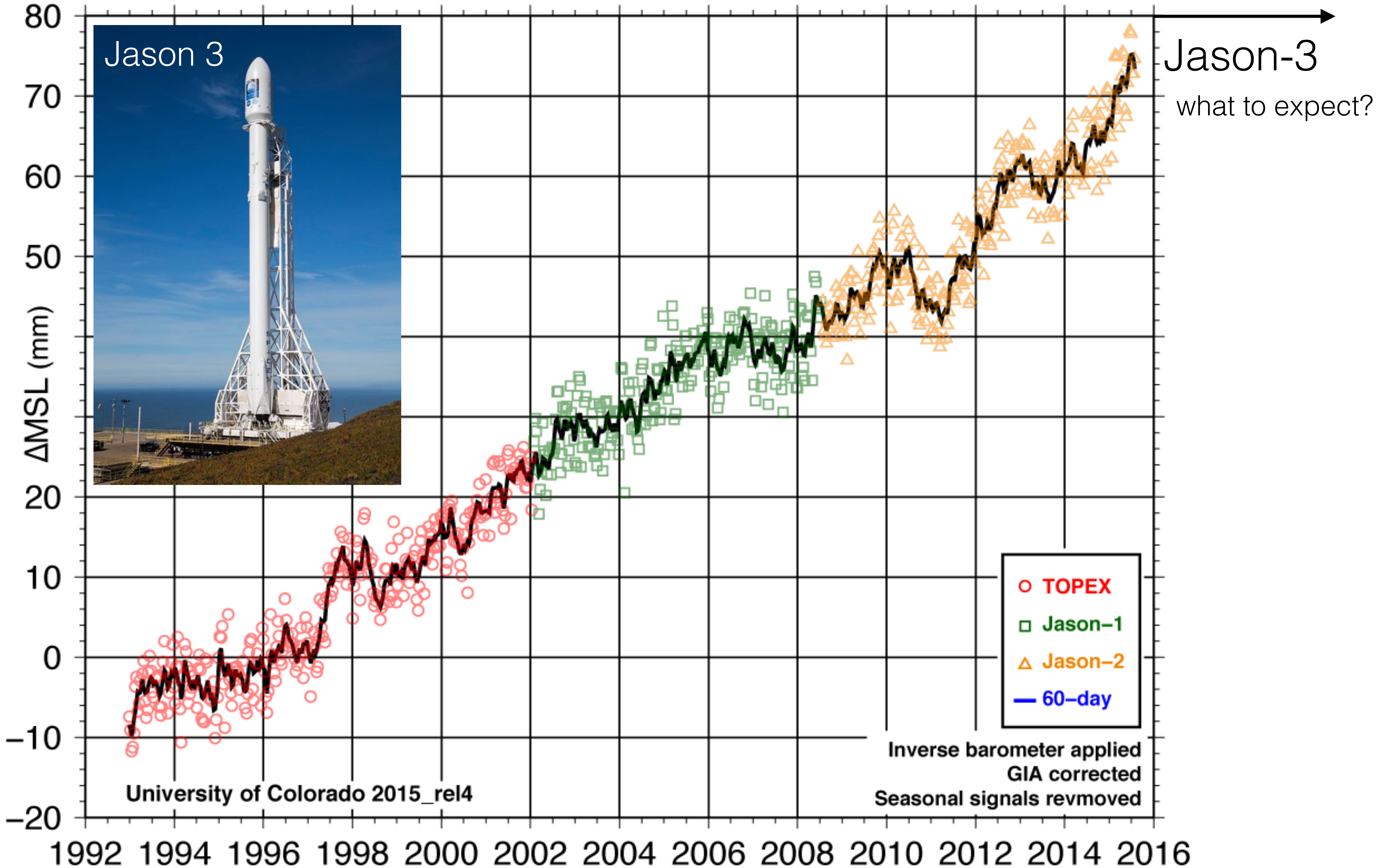
Global Mean Sea Level Anomaly



Jason-3

what to expect?

Global Mean Sea Level Anomaly



Expectation of Acceleration : AR5 Chapter 13

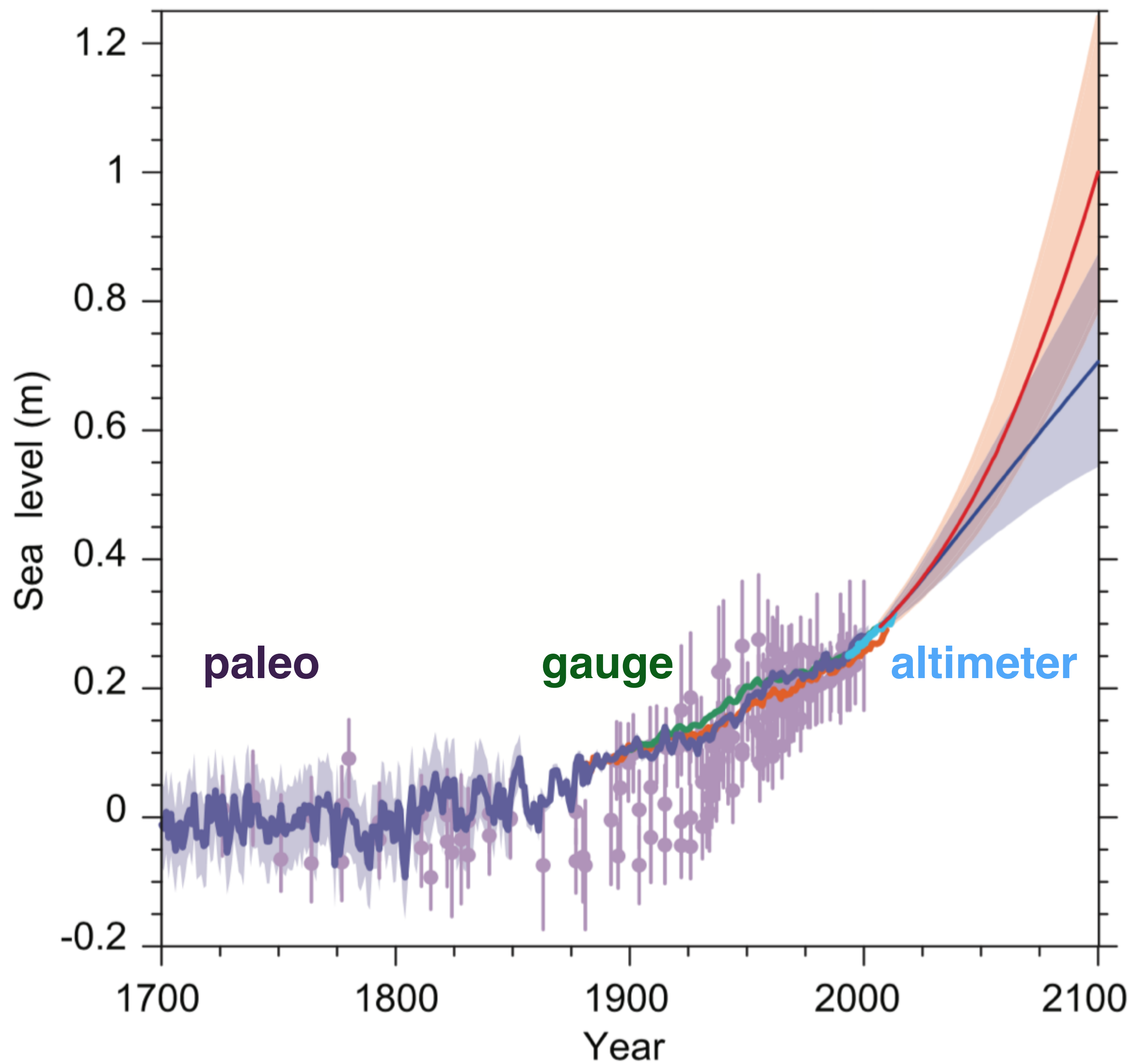


Figure 13.27 | Compilation of paleo sea level data, tide gauge data, altimeter data (from Figure 13.3), and central estimates and *likely* ranges for projections of global mean sea level rise for RCP2.6 (blue) and RCP8.5 (red) scenarios (Section 13.5.1), all relative to pre-industrial values.

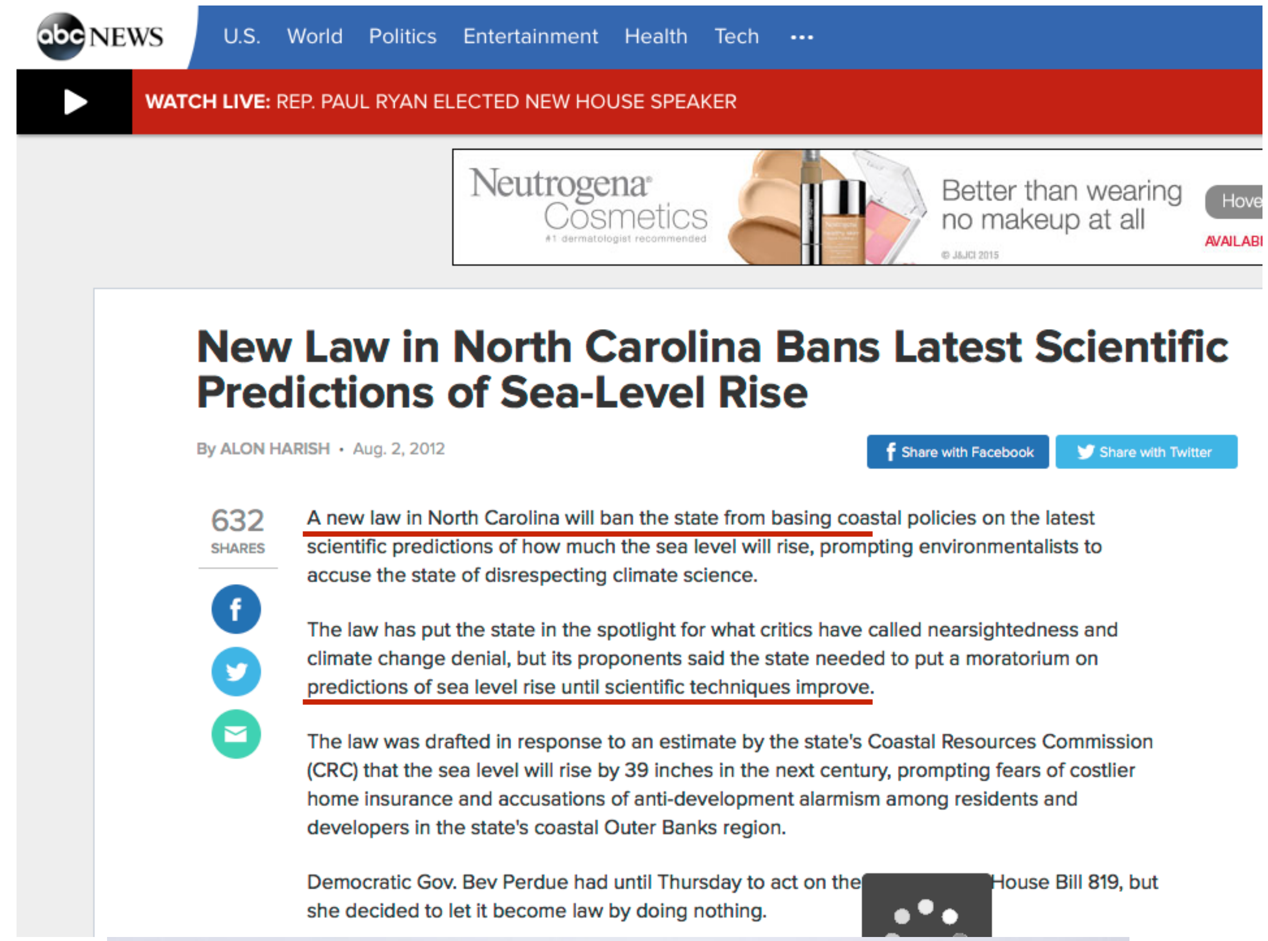
↑GHG⇒

↑ΔOHC+
↑Melt(Ts)

∴↑ΔGMSL

Motivation

- Because of the lifespan of infrastructure (30+ yr), projections of sea level rise have major implications for policy today.
- There is strong resistance in some regions to projections of acceleration (building cost).
- Unanticipated acceleration also has major costs.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WATCH LIVE: REP. PAUL RYAN ELECTED NEW HOUSE SPEAKER

New Law in North Carolina Bans Latest Scientific Predictions of Sea-Level Rise

By ALON HARISH • Aug. 2, 2012

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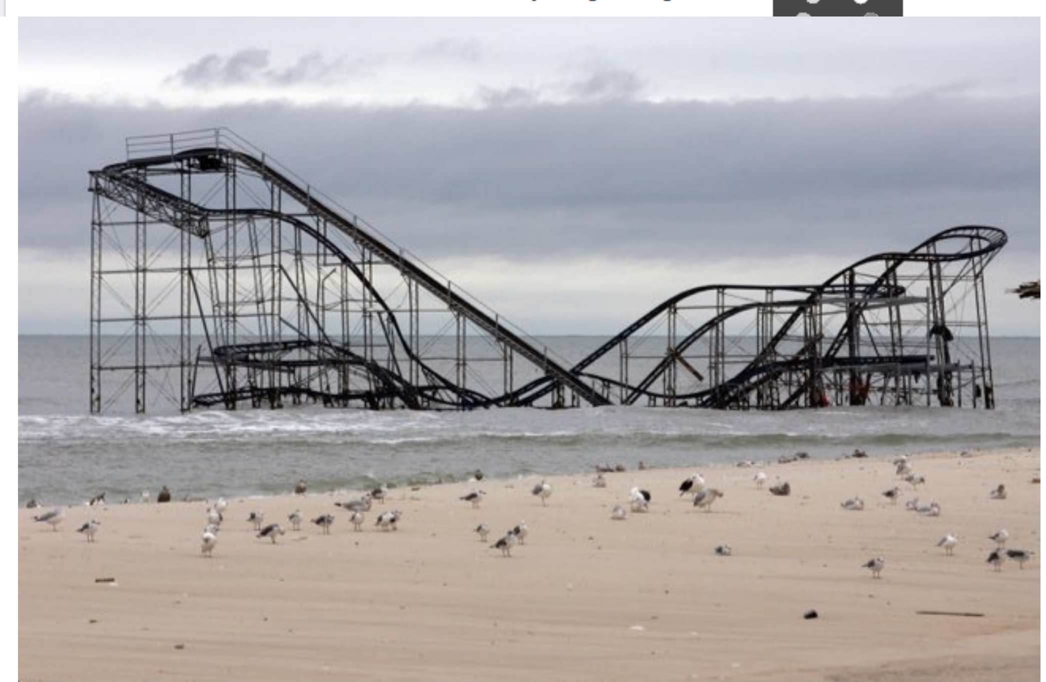
A new law in North Carolina will ban the state from basing coastal policies on the latest scientific predictions of how much the sea level will rise, prompting environmentalists to accuse the state of disrespecting climate science.

The law has put the state in the spotlight for what critics have called nearsightedness and climate change denial, but its proponents said the state needed to put a moratorium on predictions of sea level rise until scientific techniques improve.

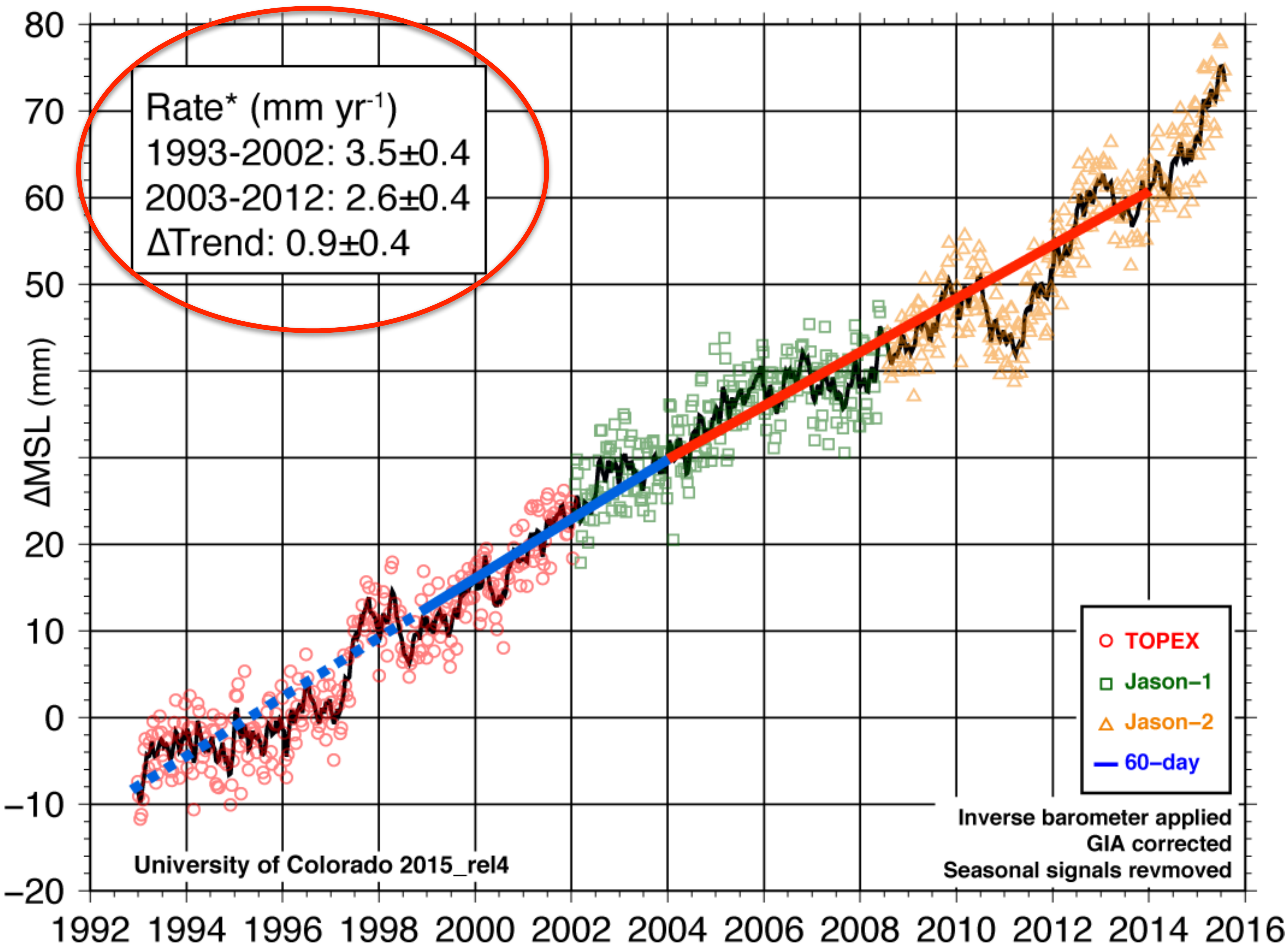
The law was drafted in response to an estimate by the state's Coastal Resources Commission (CRC) that the sea level will rise by 39 inches in the next century, prompting fears of costlier home insurance and accusations of anti-development alarmism among residents and developers in the state's coastal Outer Banks region.

Democratic Gov. Bev Perdue had until Thursday to act on the House Bill 819, but she decided to let it become law by doing nothing.



Sandy : \$50B, Katrina \$128B (\$2015)

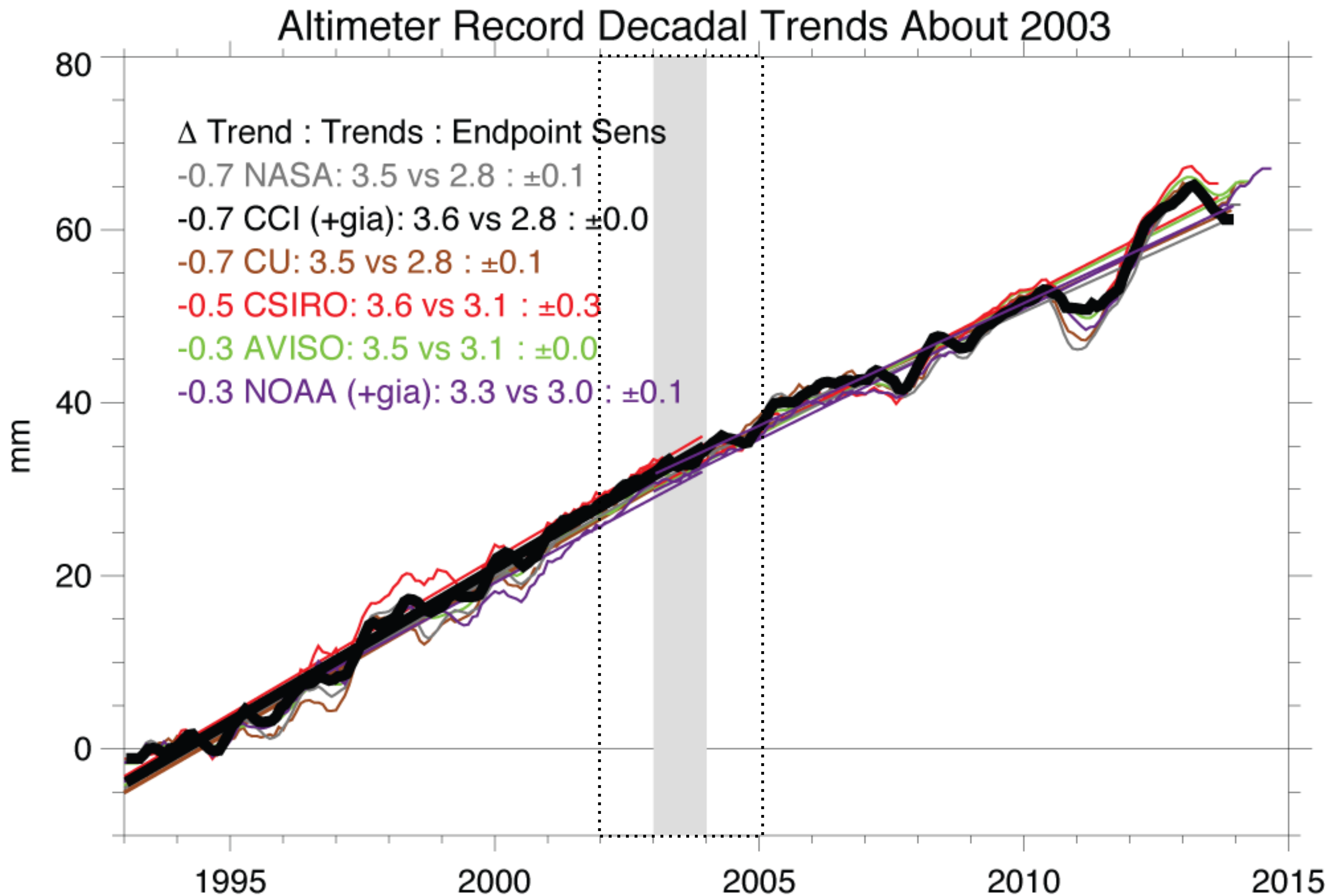
Yet altimetry reports a deceleration. Why?



Science Question #2

Why has sea level not accelerated during the altimeter era?

Does this fundamentally challenge our understanding of climate change?



- 1993-2002 mean rate > 2003-2012 mean rate by 7 mm/decade for 3 products
- some dataset / endpoint sensitivity exists yet deceleration is robust.

Hypotheses for Deceleration

- Increases in TWS in the past decade (Cazenave et al. 2014,NCC) ***…but may arise from changes in the rainfall datasets used. Simulated decadal TWS trends in CLM << 10 mm.***

- Revisions to altimeter bias-drift corrections enabled by GPS VLM data. Particularly important from 1993-1998 (Watson et al. 2015, NCC) ***Large uncertainty in magnitude.***

nature climate change
LETTERS
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The rate of sea-level rise

Anny Cazenave[1*], Habib-Boubacar Dieng[1], Benoit Meyssignac[1], Karina von Schuckmann[2], Bertrand Decharme[3] and Etienne Berthier[1]

Present-day sea-level rise is a major indicator of climate change[1]. Since the early 1990s, sea level rose at a mean rate of ~3.1 mm yr⁻¹ (refs 2,3). However, over the last decade a slowdown of this rate, of about 30%, has been recorded[4–8]. It coincides with a plateau in Earth's mean surface temperature evolution, known as the recent pause in warming[1,9–12]. Here we present an analysis based on sea-level data from the altimetry record of the past ~20 years that separates interannual natural variability in sea level from the longer-term change probably related to anthropogenic global warming. The most prominent signature in the global mean sea level interannual variability is caused by El Niño–Southern Oscillation, through its impact on the global water cycle[13–16]. We find that when correcting for interannual variability, the past decade's slowdown of the global mean sea level disappears, leading to a similar rate of sea-level rise (of 3.3 ± 0.4 mm yr⁻¹) during the first and second decade of the altimetry era. Our results confirm the need for quantifying and further removing from the climate records the short-term natural climate variability if one wants to extract the global warming signal[10].

climate sceptics to refute global warming and its attribution to a steadily rising rate of greenhouse gases in the atmosphere. It has been suggested that this so-called global warming hiatus[11] results from El Niño–Southern Oscillation- (ENSO-) related natural variability of the climate system[10] and is tied to La Niña-related cooling of the equatorial Pacific surface[11,12]. In effect, following the major El Niño of 1997/1998, the past decade has favoured La Niña episodes (that is, ENSO cold phases, reported as sometimes more frequent and more intensive than the warm El Niño events, a sign of ENSO asymmetry[19]). The interannual (that is, detrended) GMSL record of the altimetry era seems to be closely related to ENSO, with positive/negative sea-level anomalies observed during El Niño/La Niña events[2]. Recent studies have shown that the short-term fluctuations in the altimetry-based GMSL are mainly due to variations in global land water storage (mostly in the tropics), with a tendency for land water deficit (and temporary increase of the GMSL) during El Niño events[13,14] and the opposite during La Niña[15,16]. This directly results from rainfall excess over tropical oceans (mostly the Pacific Ocean) and rainfall deficit over land (mostly the tropics) during an El Niño[20] event. The

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Unabated global mean sea-level rise over the satellite altimeter era

Christopher S. Watson[1*], Neil J. White[2], John A. Church[2], Matt A. King[1,3], Reed J. Burgette[4] and Benoit Legresy[2]

The rate of global mean sea-level (GMSL) rise has been suggested to be lower for the past decade compared with the preceding decade as a result of natural variability[1], with an average rate of rise since 1993 of +3.2 ± 0.4 mm yr⁻¹ (refs 2,3). However, satellite-based GMSL estimates do not include an allowance for potential instrumental drifts (bias drift[4,5]). Here, we report improved bias drift estimates for individual altimeter missions from a refined estimation approach that incorporates new Global Positioning System (GPS) estimates of vertical land movement (VLM). In contrast to previous results (for example, refs 6,7), we identify significant non-zero systematic drifts that are satellite-specific, most notably affecting the first 6 years of the GMSL record. Applying the bias drift corrections has two implications. First, the GMSL rate (1993 to mid-2014)

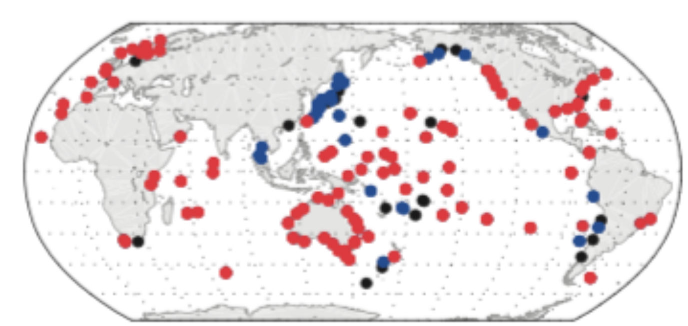


Figure 1 | Map of the initial 122 TGs used in this analysis. Additional quality control procedures (for example, obvious nonlinear VLM) eliminate

The 1991 Eruption of Mt 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, weakening water cycle

What role did Pinatubo play in sea level rise of the 1990's?

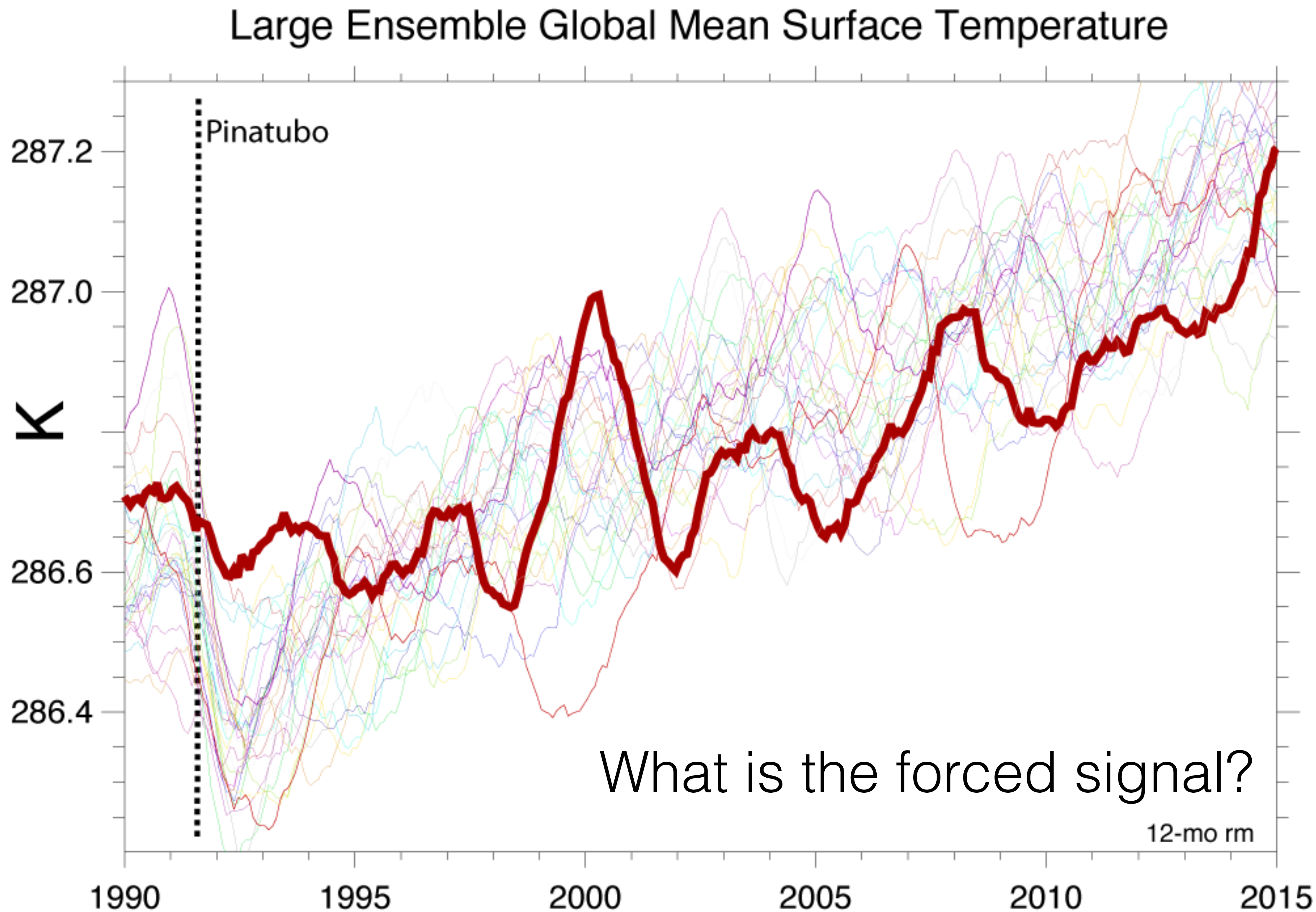
What was the 'forced' response of the climate system?

The NCAR Large Ensemble

- **Motivation**: separating forced-response from internal variability. As variance of internal variability scales as $1/\sqrt{(N-1)}$, in the ensemble mean it is << forced response.
- **42 members:** using the CESM-CAM1 from 1920-2100: *no ice sheet mass changes*
- **Fixed volume ocean** - Church et al. 2005 conversion between OHC and GMSL ($3\ 10^{22}$ J=5 mm)
- **TWS** = ∫SOILLIQ+SOILICE+WA +H2OSNO+H2OCAN+VOLR
- ***Also using 4 "all-but-one(volc)" members of CESM1-CAM5 (run@ NERSC) to estimate non-volcanic variability***.

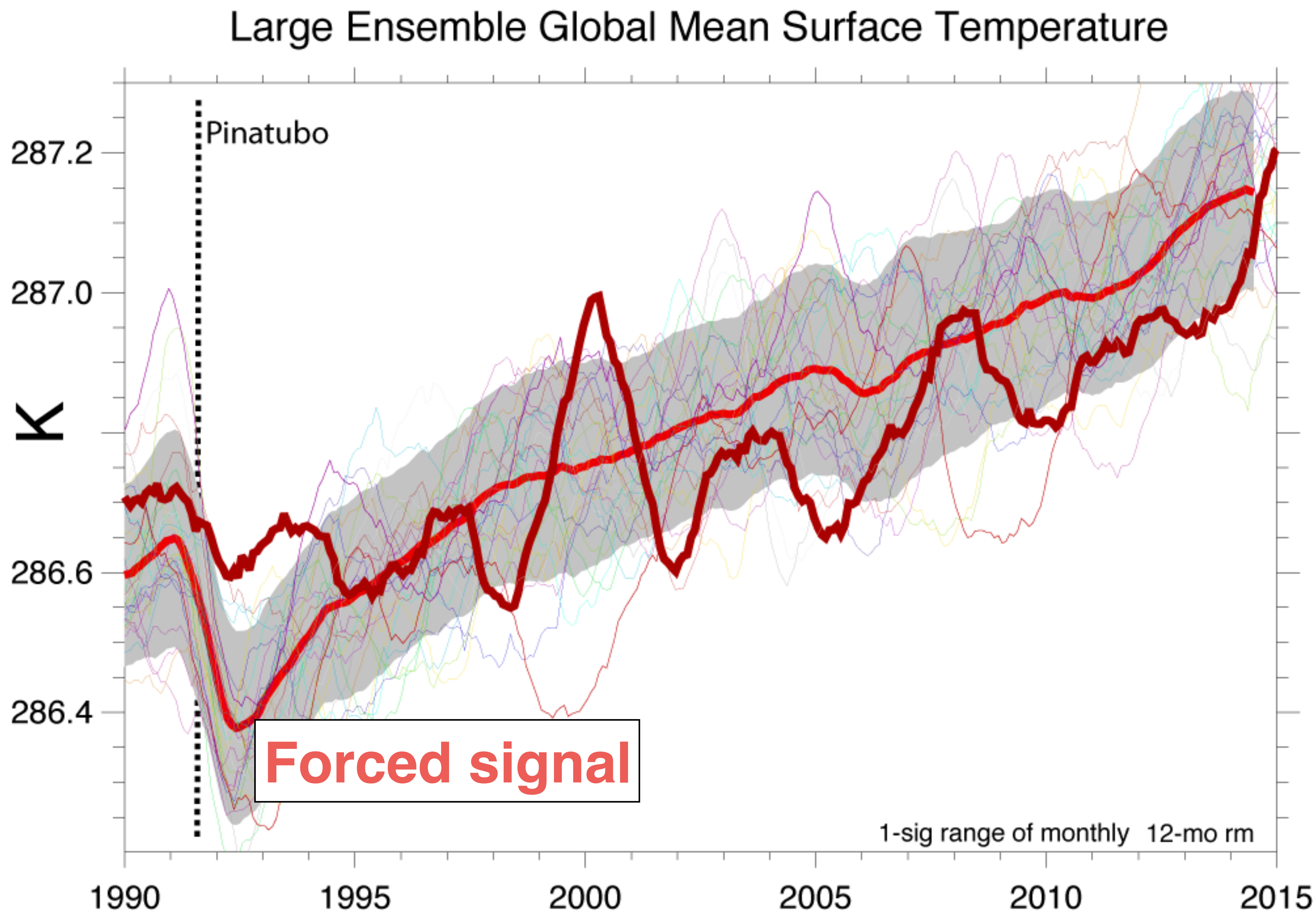
Yellowstone, Wyoming Supercomputing Center

The 1991 Eruption of Mt Pinatubo



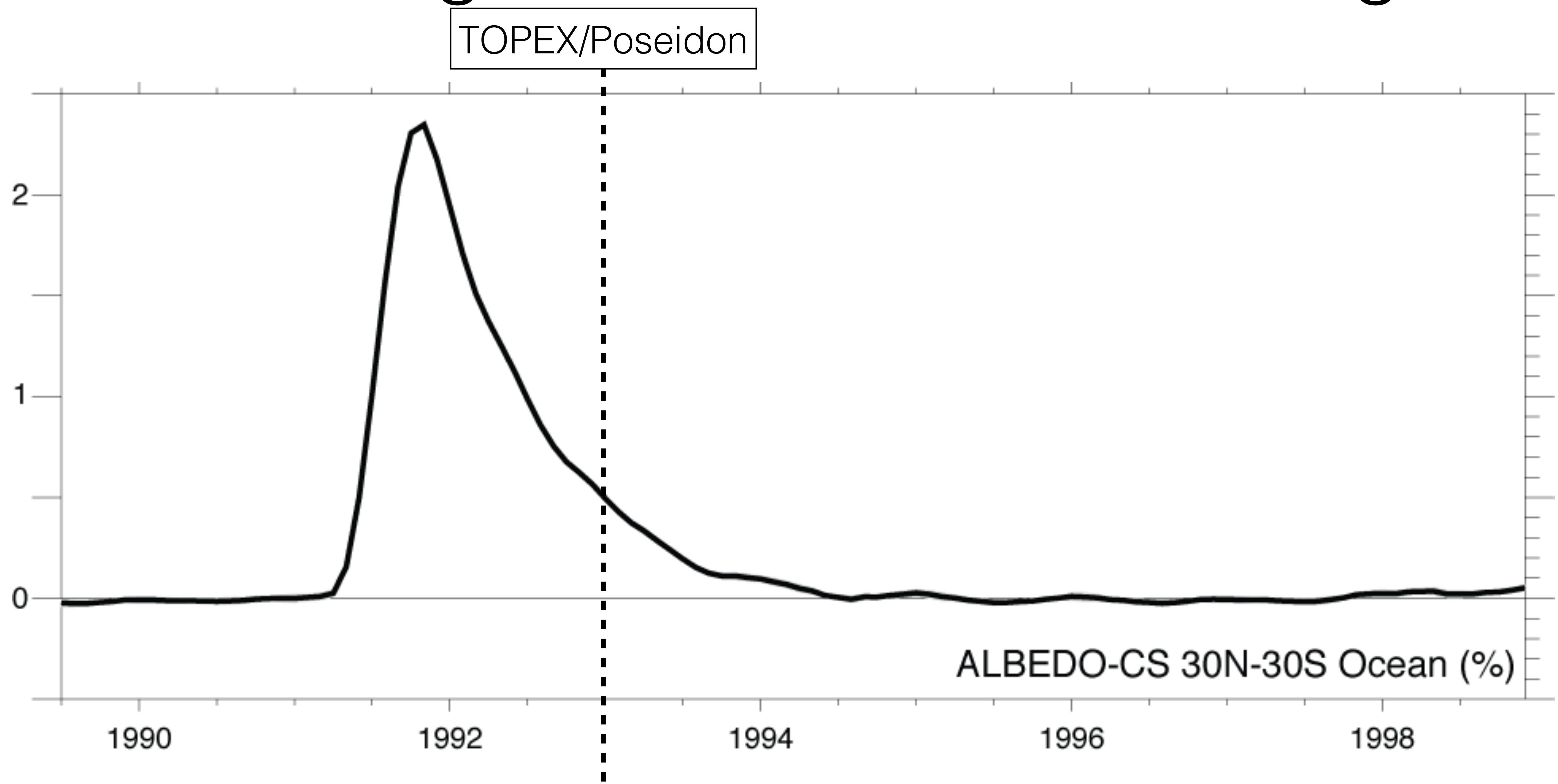
from examining a single member (also obs), it is not possible to quantify forced response
significant spread across ensemble members, including in any apparent "response"

The 1991 Eruption of Mt Pinatubo



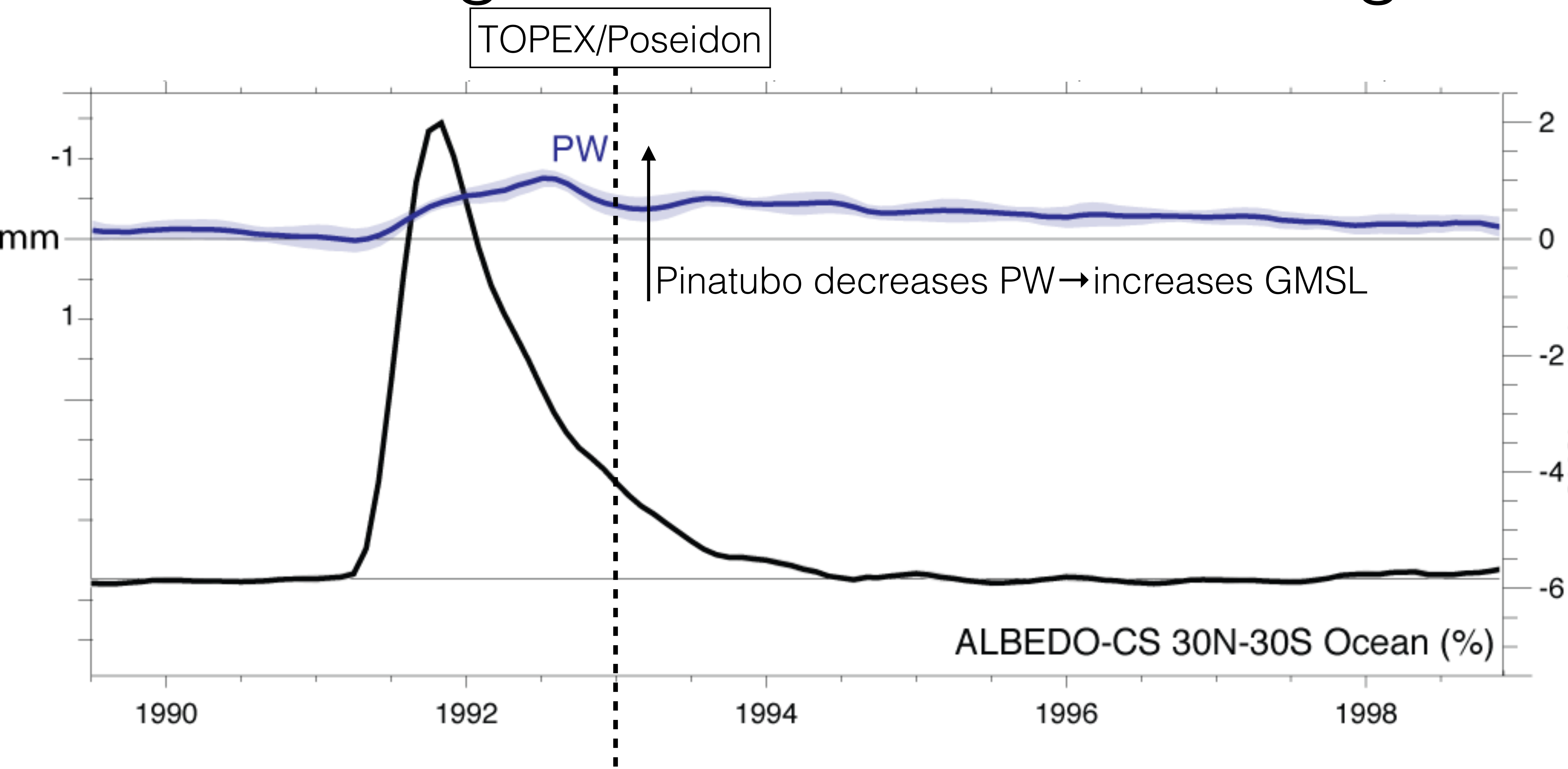
- Temperature Response (ensemble mean, 2 sigma)

The 1991 Eruption of Mt Pinatubo in the Large Ensemble: GMSL Budget



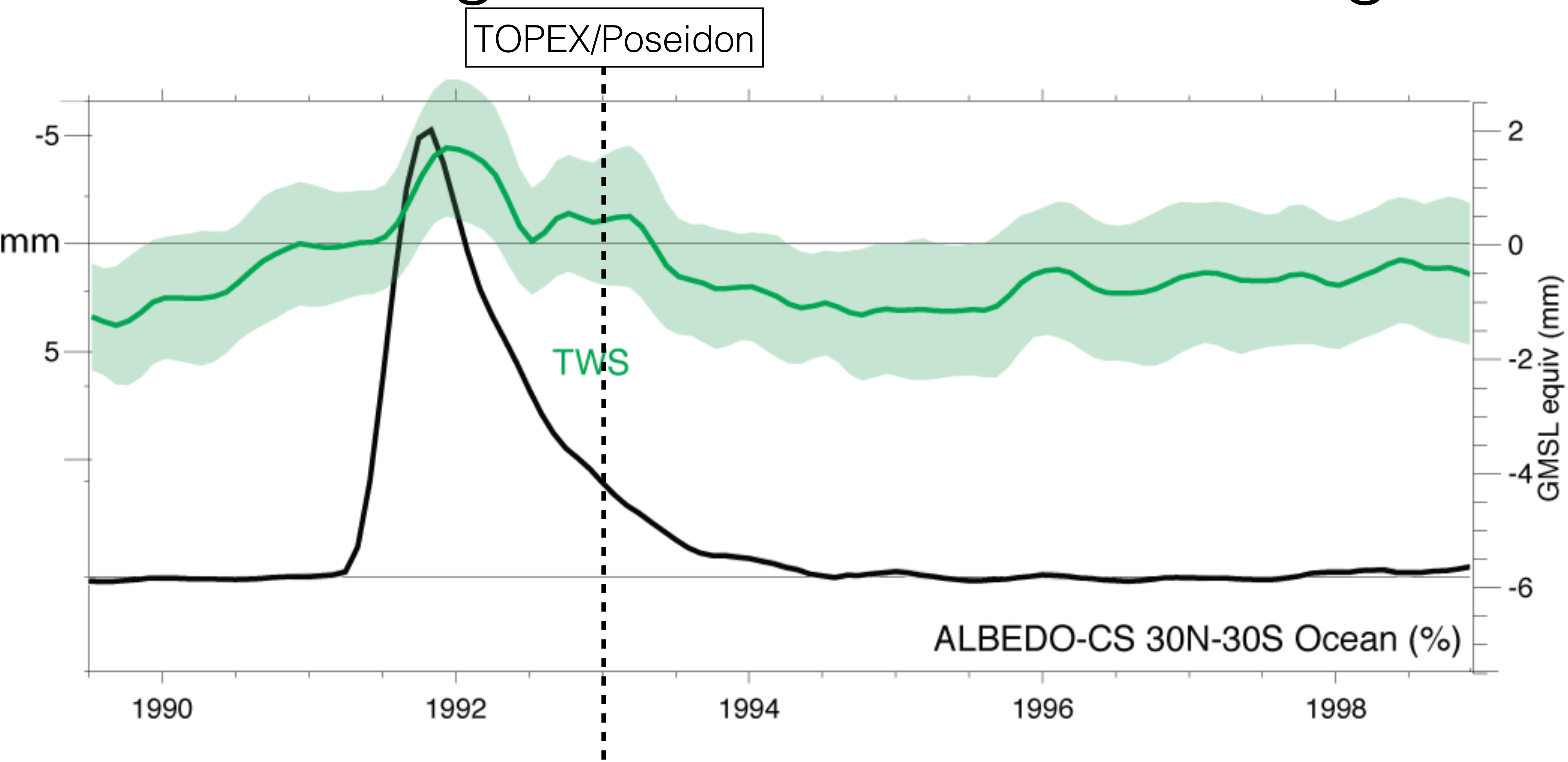
- Ensemble-mean clear sky albedo anomaly is a useful diagnostic for the eruption

The 1991 Eruption of Mt Pinatubo in the Large Ensemble: GMSL Budget



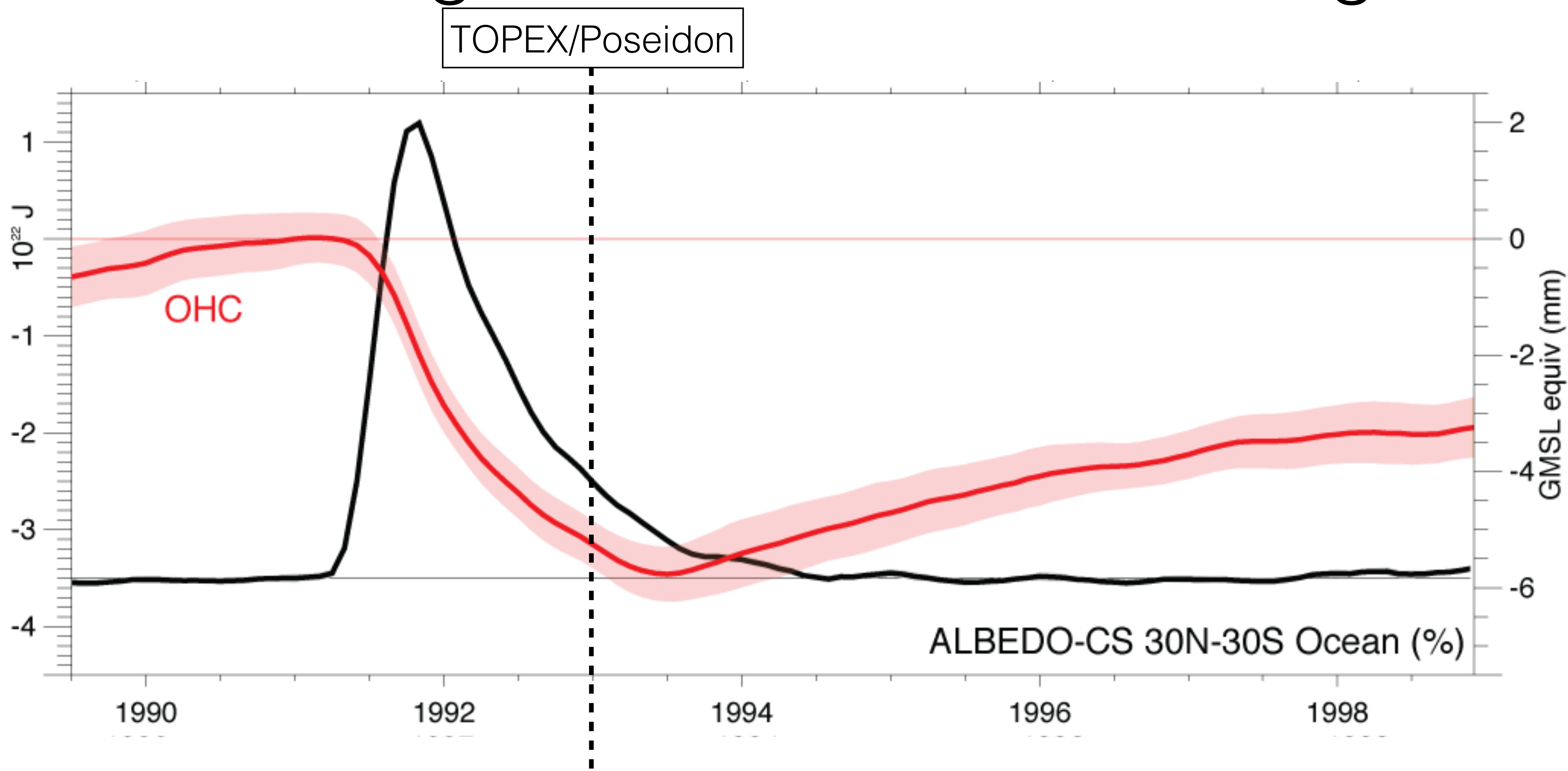
- Atmospheric PW DECREASES (T_S/T cools), contributing to an INCREASE in GMSL

The 1991 Eruption of Mt Pinatubo in the Large Ensemble: GMSL Budget



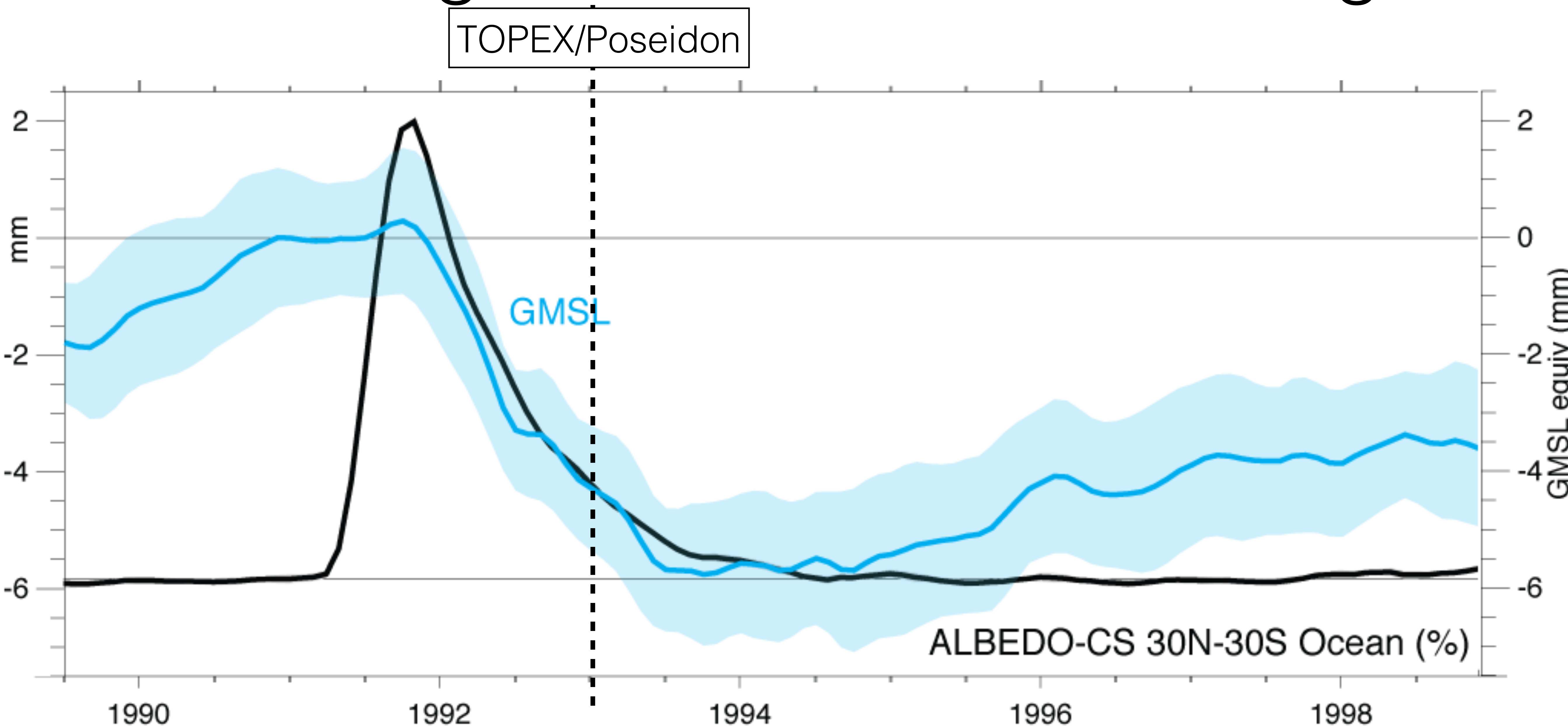
- Terrestrial water also DECREASES, contributing to an INCREASE in GMSL

The 1991 Eruption of Mt Pinatubo in the Large Ensemble: GMSL Budget



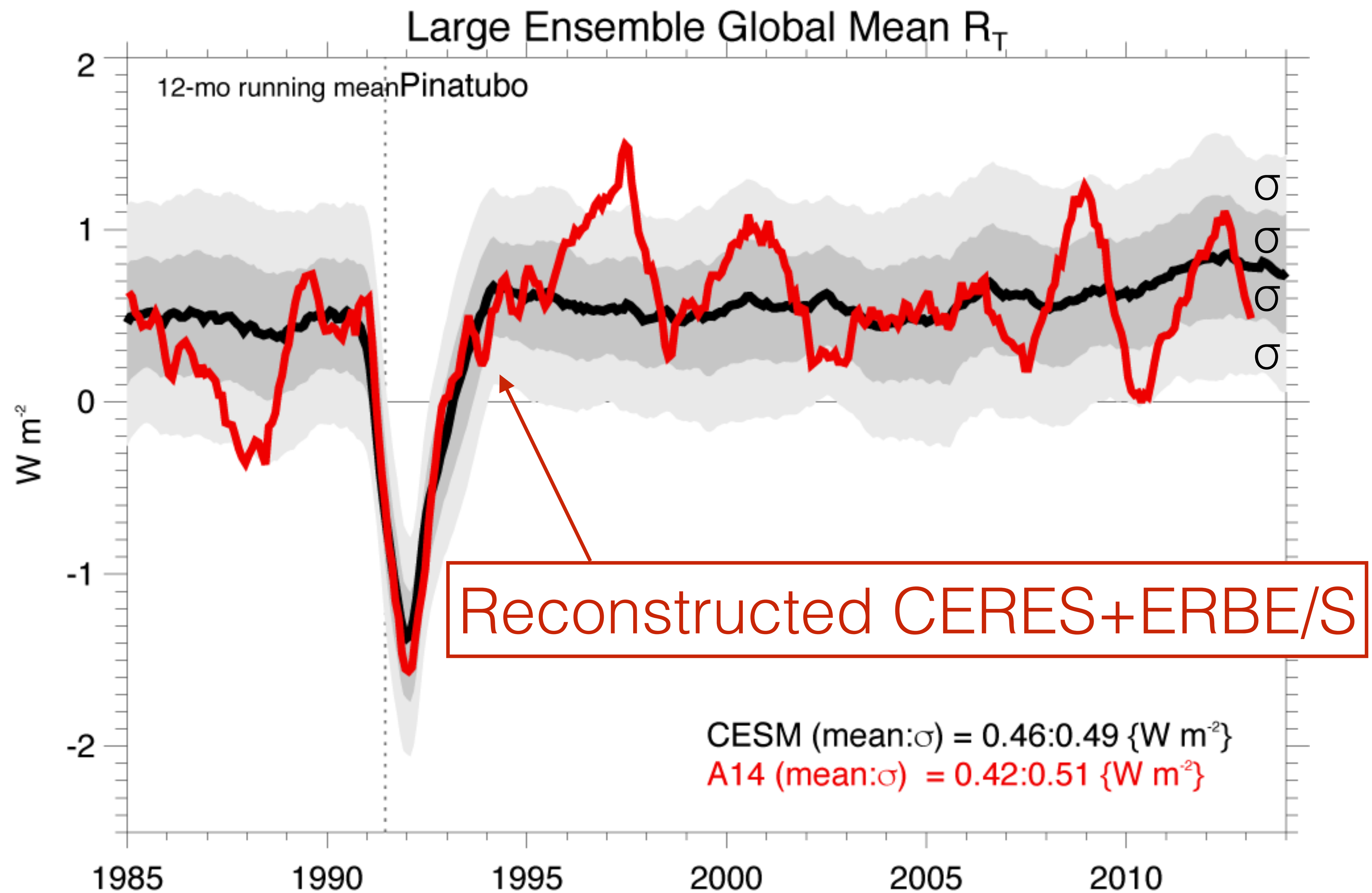
- But the main effect is that ocean heat content drops substantially due to the radiative forcing of the eruption, causing a large and persistent GMSL drop/recovery.

The 1991 Eruption of Mt Pinatubo in the Large Ensemble: GMSL Budget



- The ensemble mean GMSL deficit reaches a minimum in 1993 of 5-7 mm
- **TOPEX/Poseidon was launched in an highly anomalous GMSL environment**.

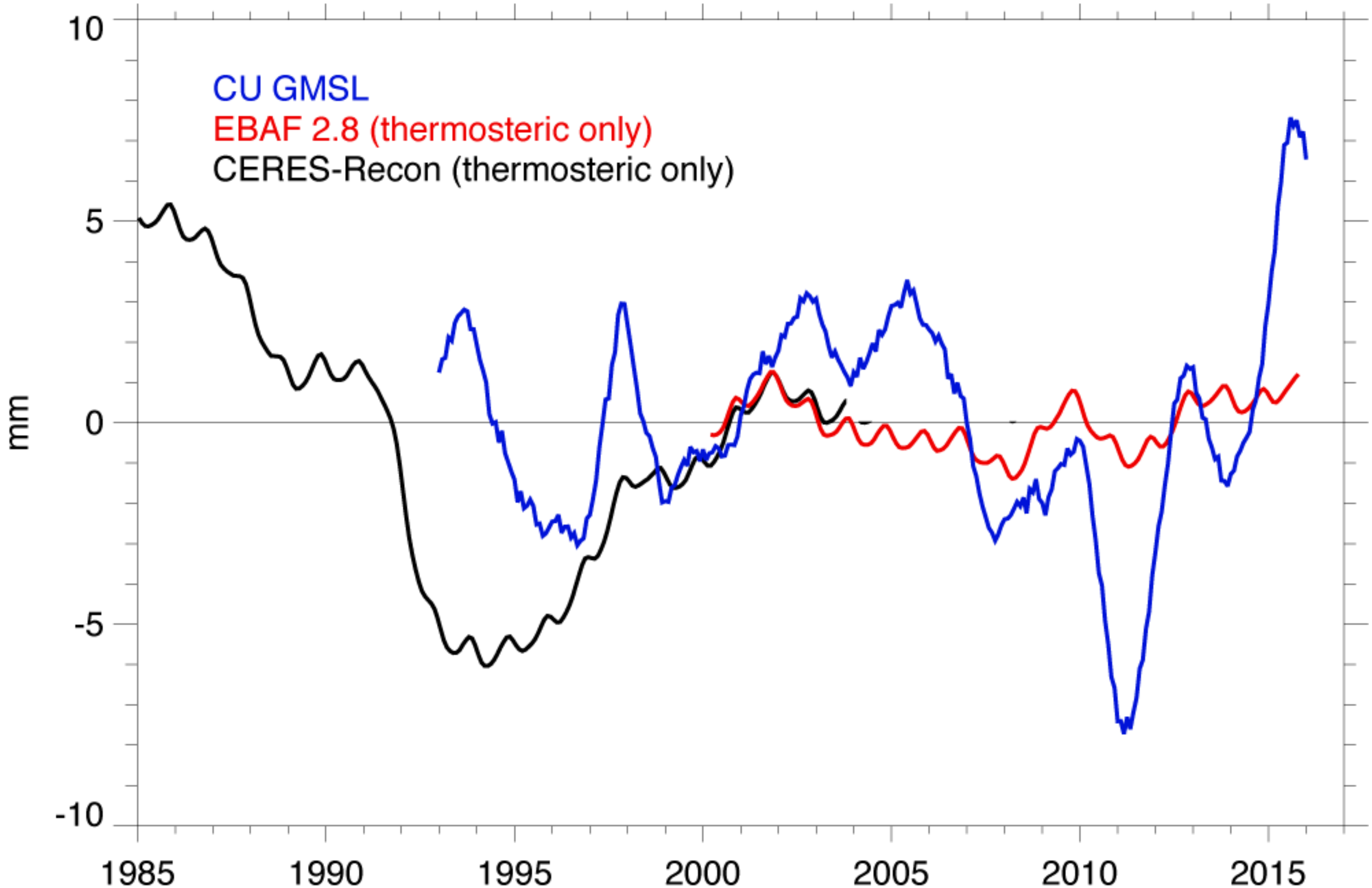
Validation of CESM with CERES



- Can we validate the LE's simulation? Yes - its net TOA flux anomaly matches closely CERES' blended ERBS-CERES data record (combination of CERES/ERBS/ERBE/ERAI/GCM)

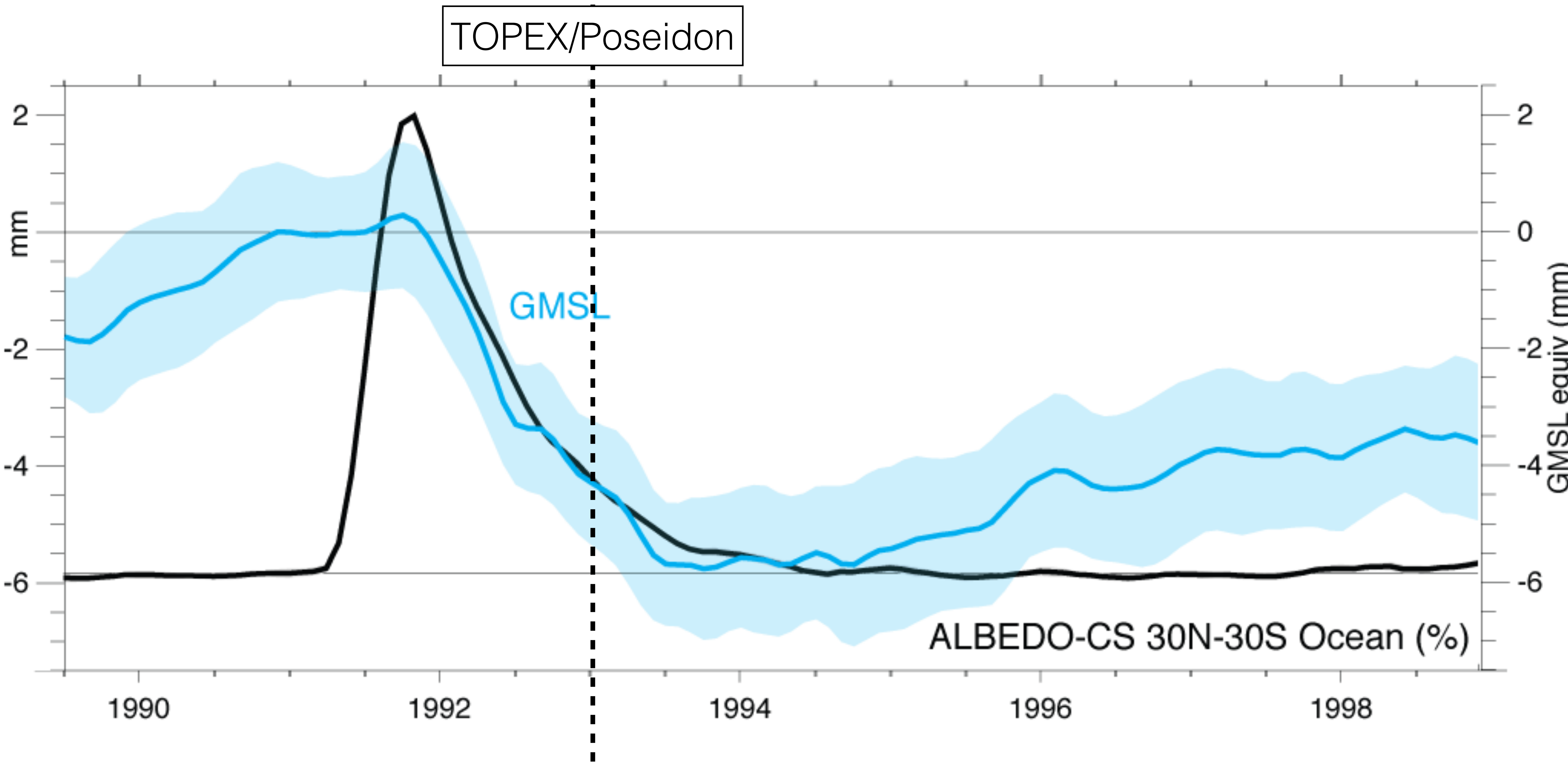
Estimating GMSL From CERES

(Using Church et al. 2005 conversion; 5 mm = 3•10^{22} J)



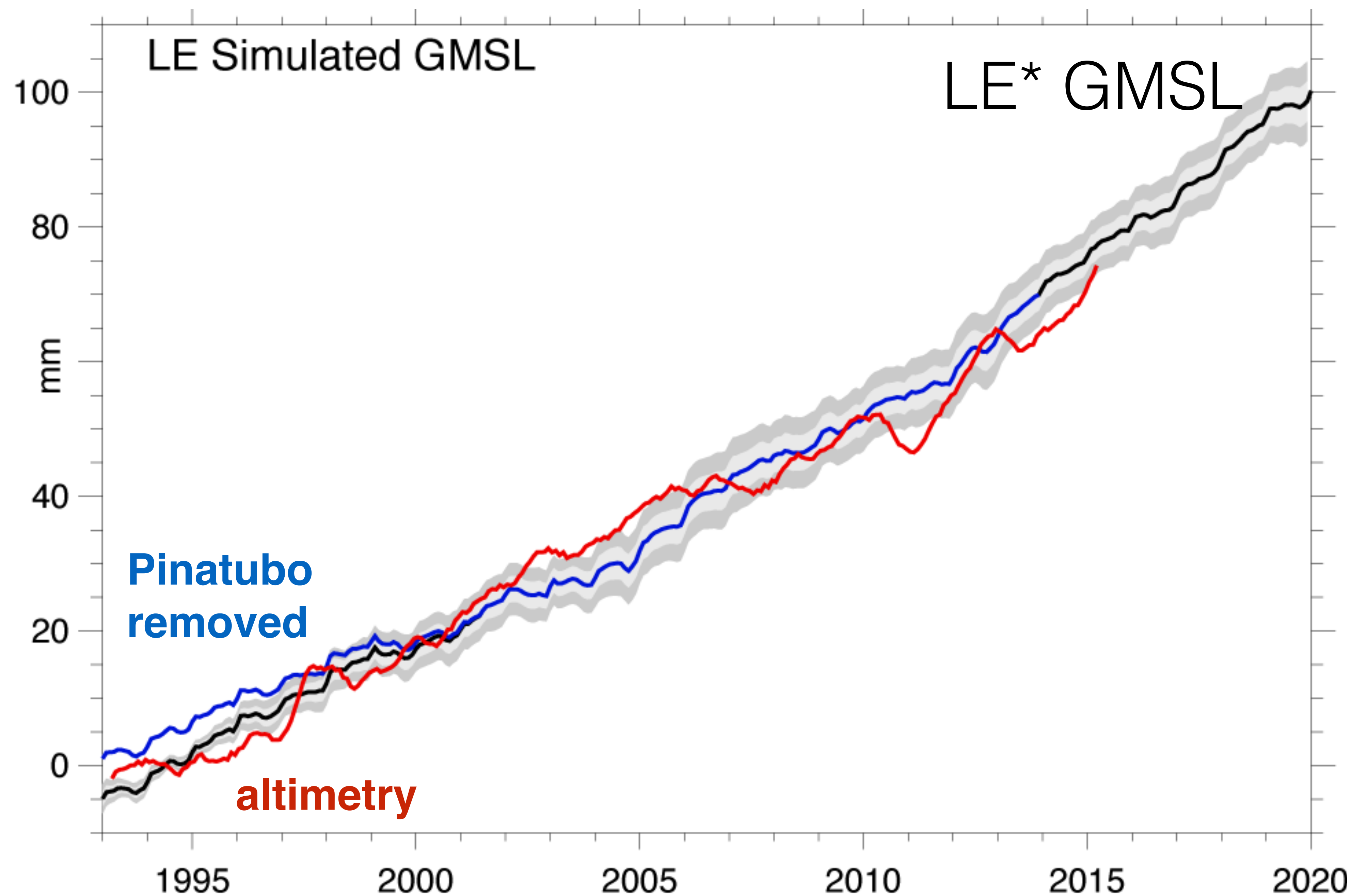
Assuming that $\Delta OHC = 0.9 * \int R_T$

The 1991 Eruption of Mt Pinatubo in the Large Ensemble: GMSL Budget



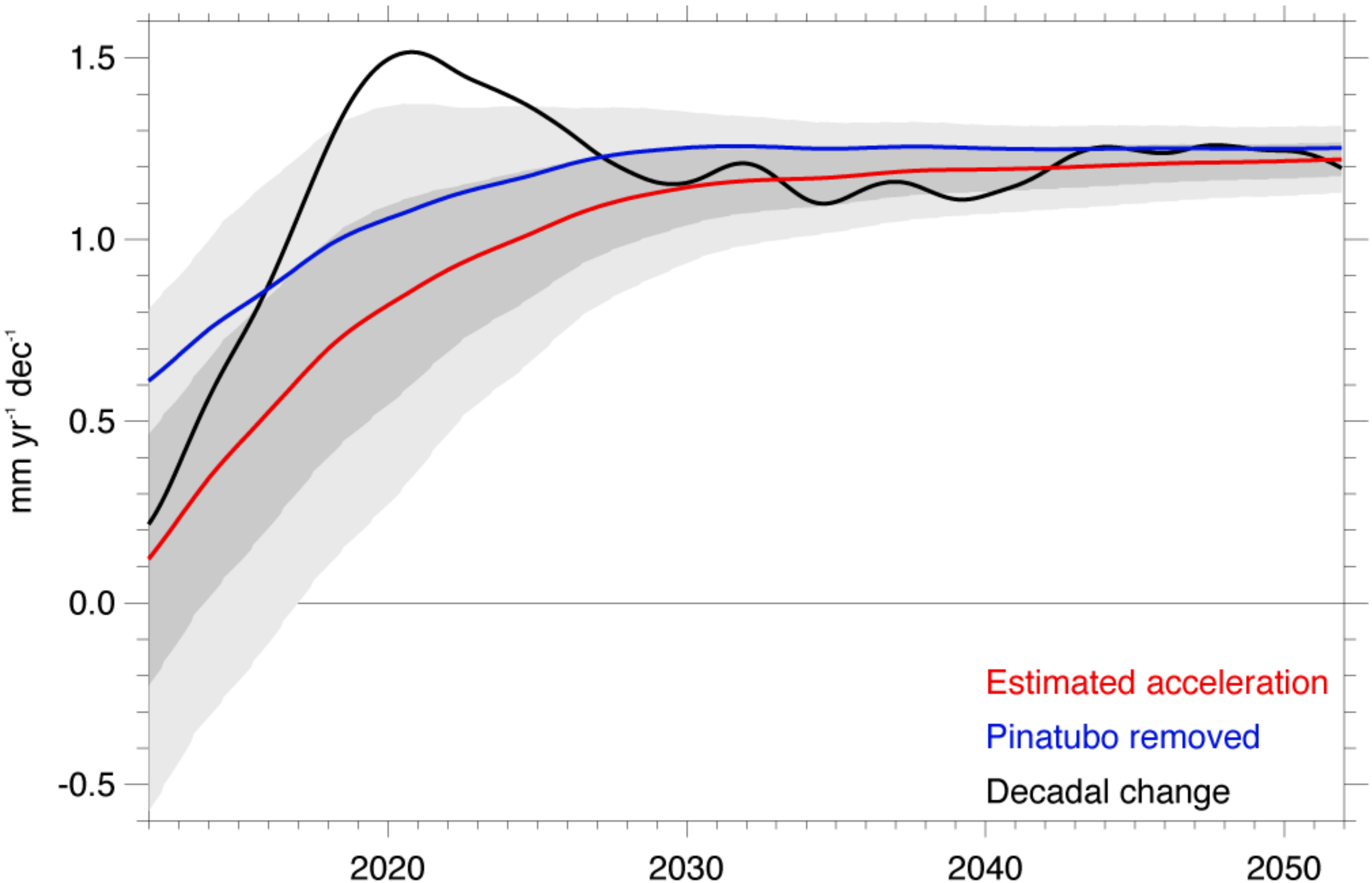
- What are the implications of the forced response in GMSL for acceleration?

Removing Pinatubo's GMSL Influence



*Using AR5 simulated ice sheet contributions (lower bound, Ch 13)

Detecting and Projecting Acceleration



*Using AR5 simulated ice sheet contributions (lower bound, Ch 13)

Conclusions: Part II

- **Altimetry products robustly report GMSL deceleration** (1993-2002 vs 2002-11) ARGO begins in ~2005; XBT OHC estimates lack accuracy. *Reconstructed CERES and models (LE) are thus essential for interpreting the sea level record.*

- **Simulations from the NCAR LE show the 1991 eruption of Mt. Pinatubo to have significantly lowered OHC and GMSL** - reaching a minimum in 1993, the start of the altimeter era, and recovering gradually through the 1990s. *Reconstructed CERES data play a key role in establishing confidence in these simulations.*

- **An anomalous GMSL↑ of 5-7 mm in the decade following 1993 is estimated by the LE** and identified as the dominant driver of observed deceleration. *A similar and independent estimate can be provided directly from CERES data.*

- Removing this signal from altimetry substantially reduces observed decadal variability and suggests that **acceleration should be evident in altimetry within the next decade** (during Jason-3), barring another major volcanic eruption.

End