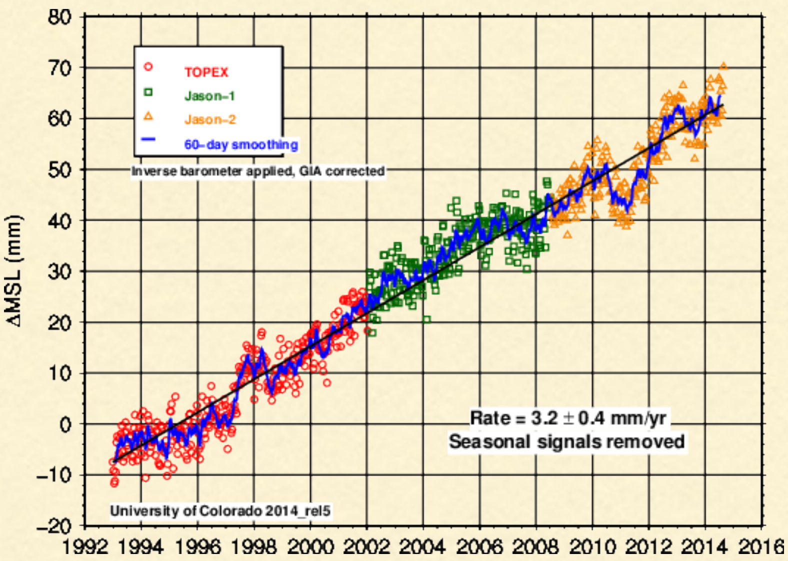

UNDERSTANDING GLOBAL MEAN SEA LEVEL

AS AN INDICATOR OF CLIMATE VARIABILITY AND CHANGE

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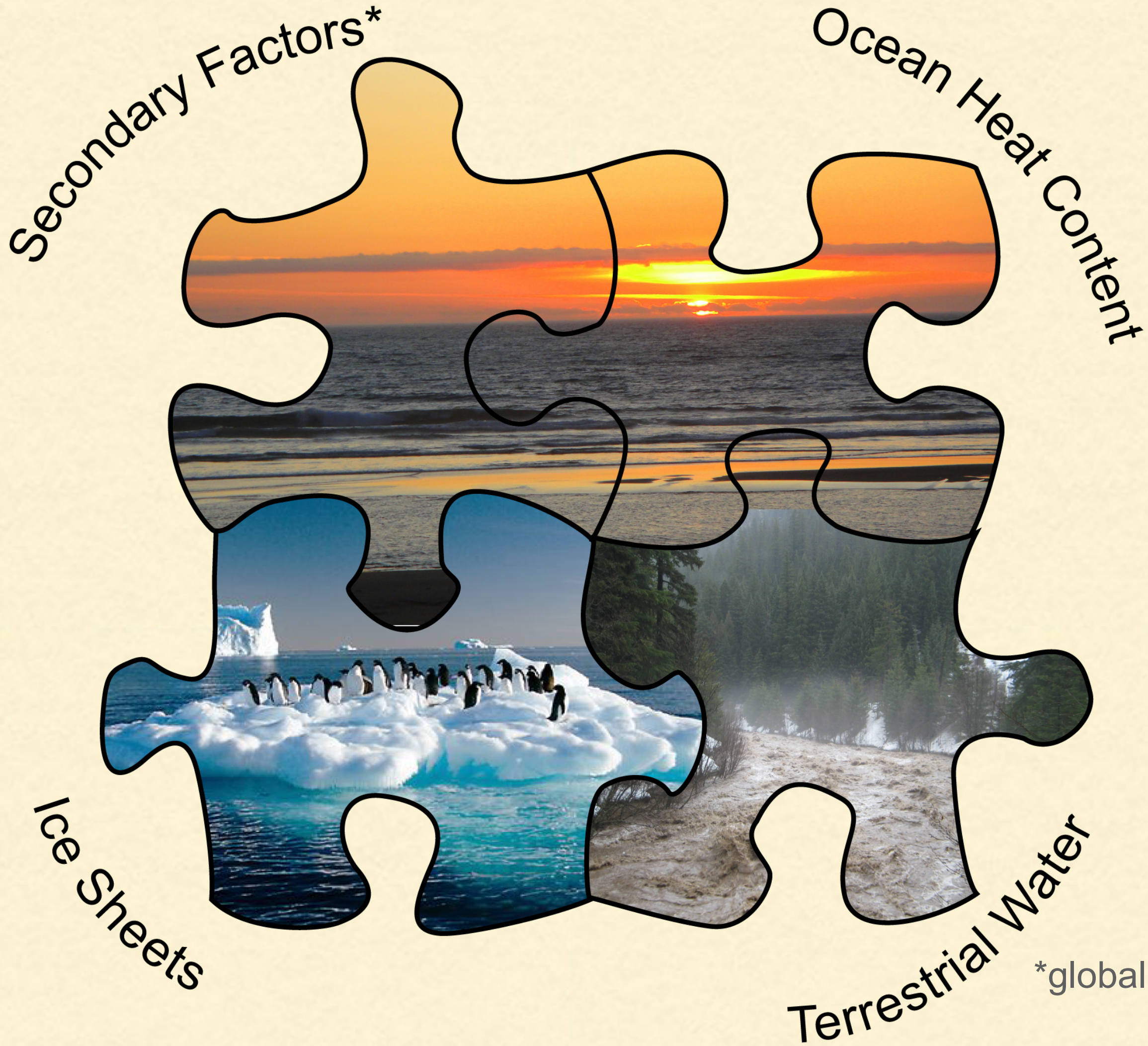
NCAR / University of Colorado - Boulder

NCAR Climate Change and Variability Working Group Meeting, Boulder, CO, Feb. 9, 2015

Outline

- Background and Data Sources
- Insights from the GRACE decade GRACE/Altimetry/ARGO/CERES - 2004-2013
- Using Models to Extend Understanding of GMSL
  - ENSO-driven variability from the CESM1-CAM5 Large-Ensemble
  - Understanding the Altimeter Era/Hiatus with the CLM4.5+
  - Improving gauge reconstructions with simulated variability
- Summary

BACKGROUND: THE SEA LEVEL PUZZLE

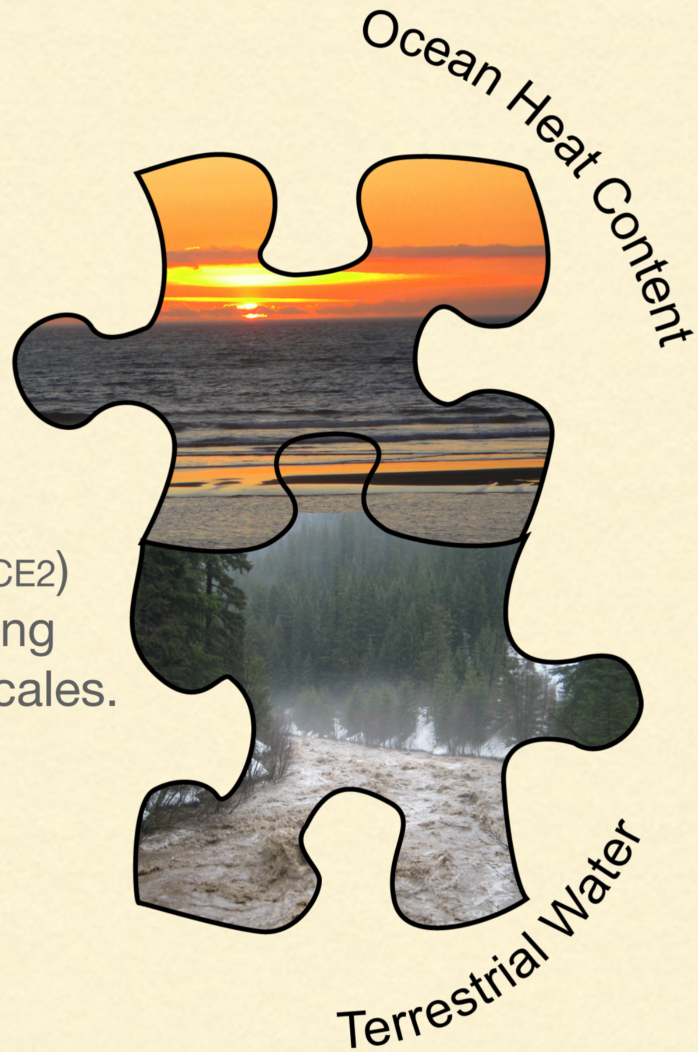


*global isostatic rebound (GIA)
atmospheric water

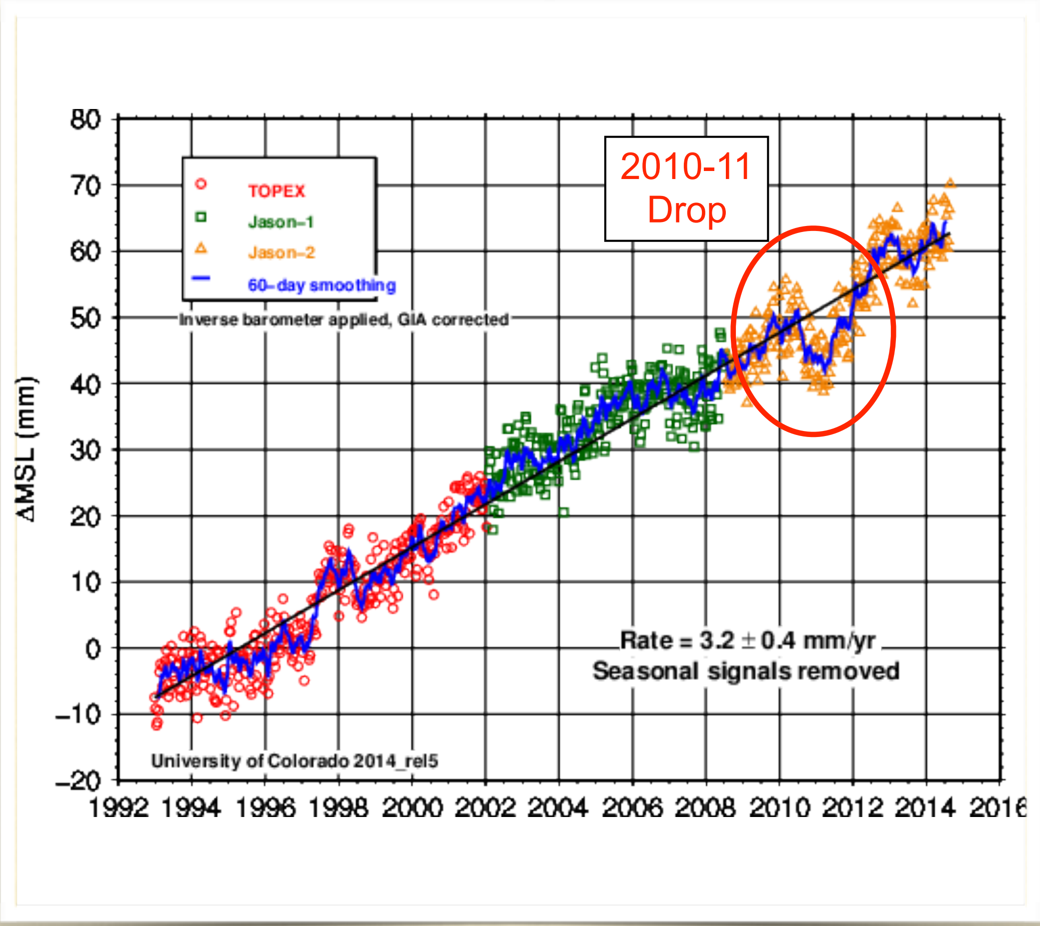
BACKGROUND: THE SEA LEVEL PUZZLE

Based on estimates from GRACE, interannual variability is dominated by OHC and TWS anomalies.

A longer record of GRACE (including GRACE2) is going to be essential for understanding variability in melt/TWS on longer timescales.

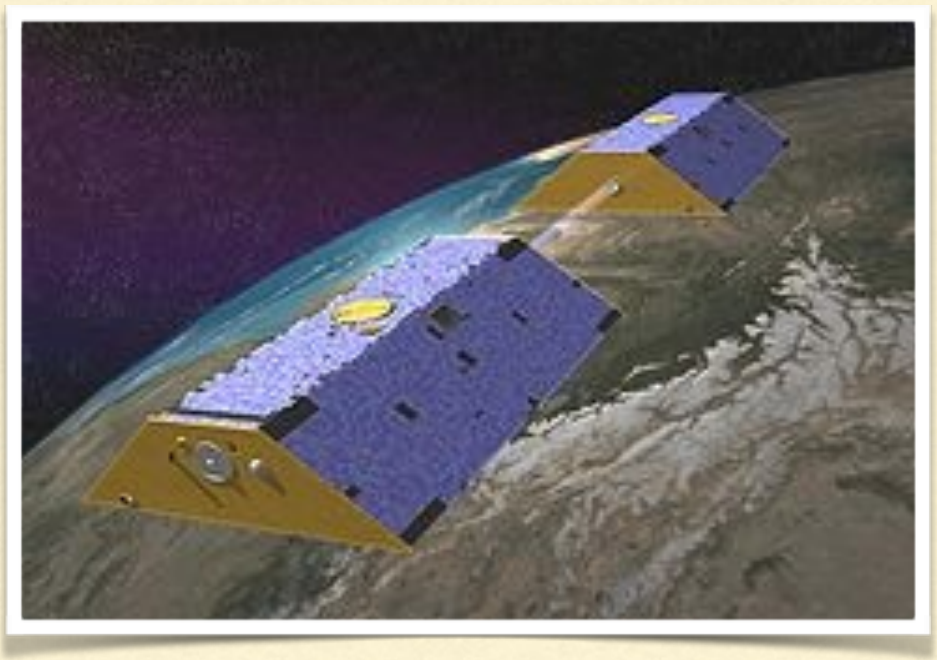


THE ALTIMETER RECORD



- begins in 1993 through present
- derived from multiple radar altimeters calibrated against tide gauges
- mean rise ≅3.2±0.4 mm/yr
- a major drop from mid 2010-2012
- accuracy is about ±1 mm (annual)
- only includes 66N-66S (95% ice free oceans)

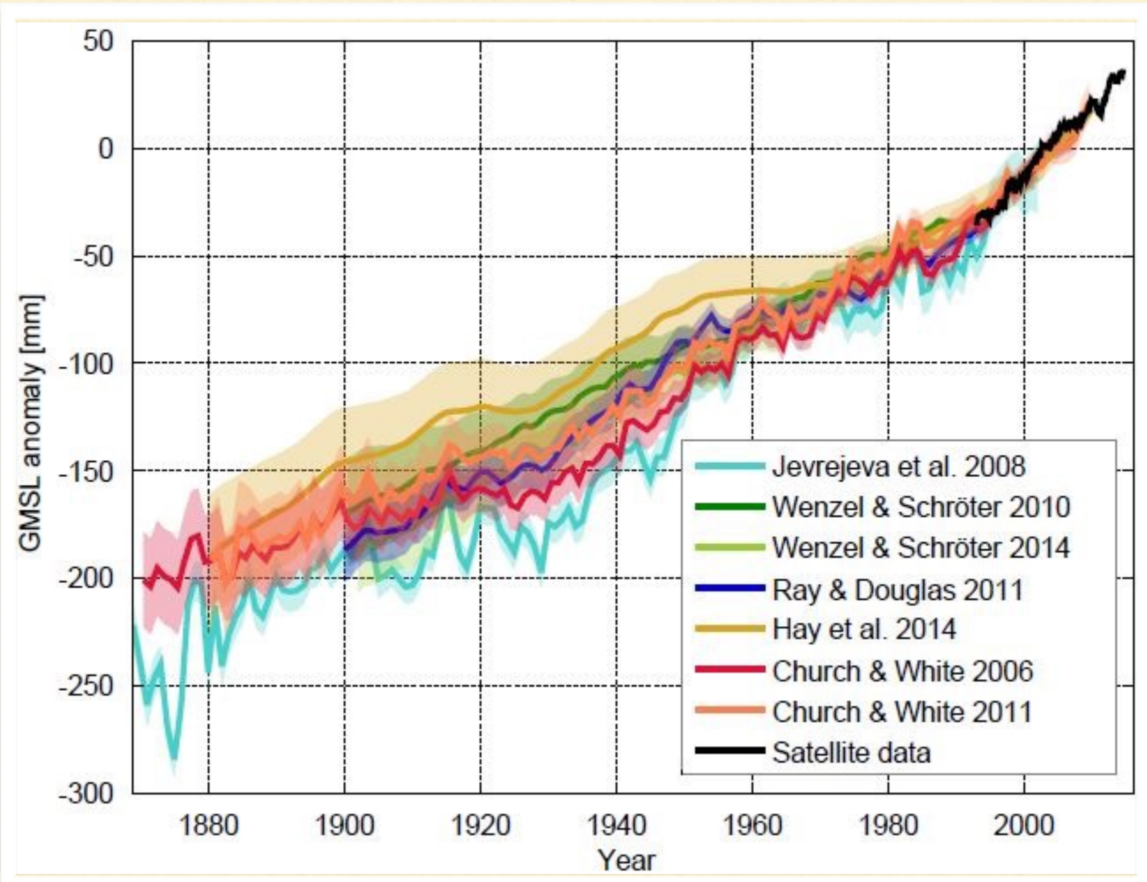
GRACE: GRAVITY RECOVERY AND CLIMATE EXPERIMENT (2003-2013)



Not drawn to scale.
Actually ~220 km apart. 10 micrometer sensitivity

- The “GRACE satellite” is actually a twin satellite constellation able to detect small changes in surface mass.
- The first Earth monitoring mission that doesn’t “look” at Earth.
- Uses microwave ranging to detect the precise distance and relative speed of the satellites (Tom and Jerry).

THE GAUGE RECORD



Hay et al. 2015

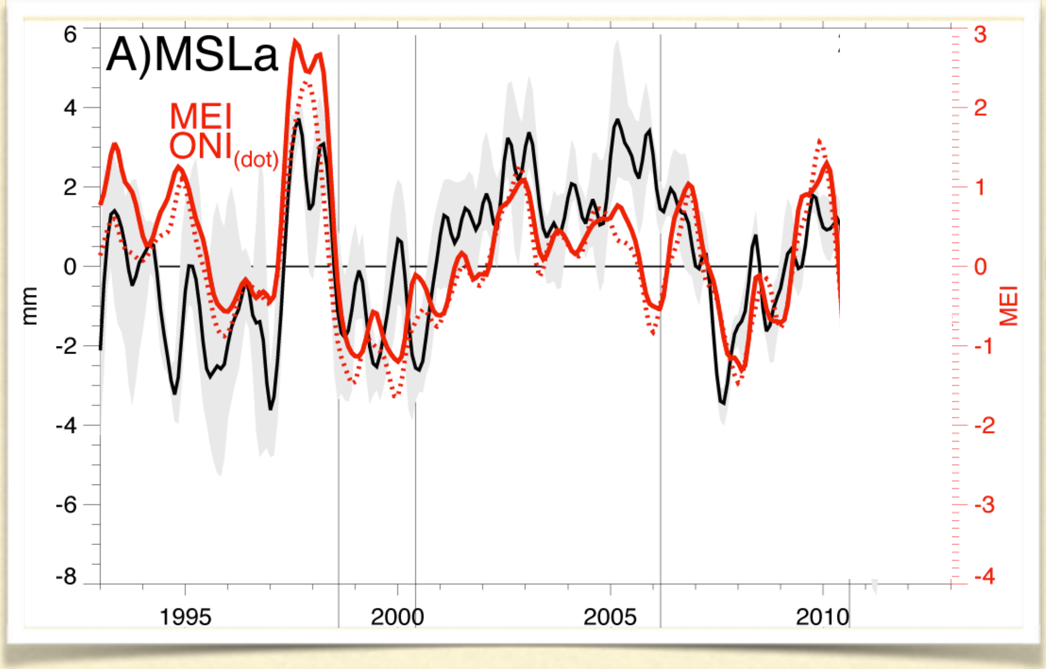
- **Ultimate goal**: to understand the variability and intrinsic uncertainties/limitations of gauge-based reconstructions.
- **Substantial uncertainty remains** estimates lie outside of each other's error bars, some over overly smoothed, the impact of sampling issues remains unexplored, insights based on known influence of climate modes remains underutilized.

QUESTIONS

Given that GMSL is a “catchall” of multiple aspects of climate variability and change, how can we disentangle the various contributions to it?
f(timescale, time period)

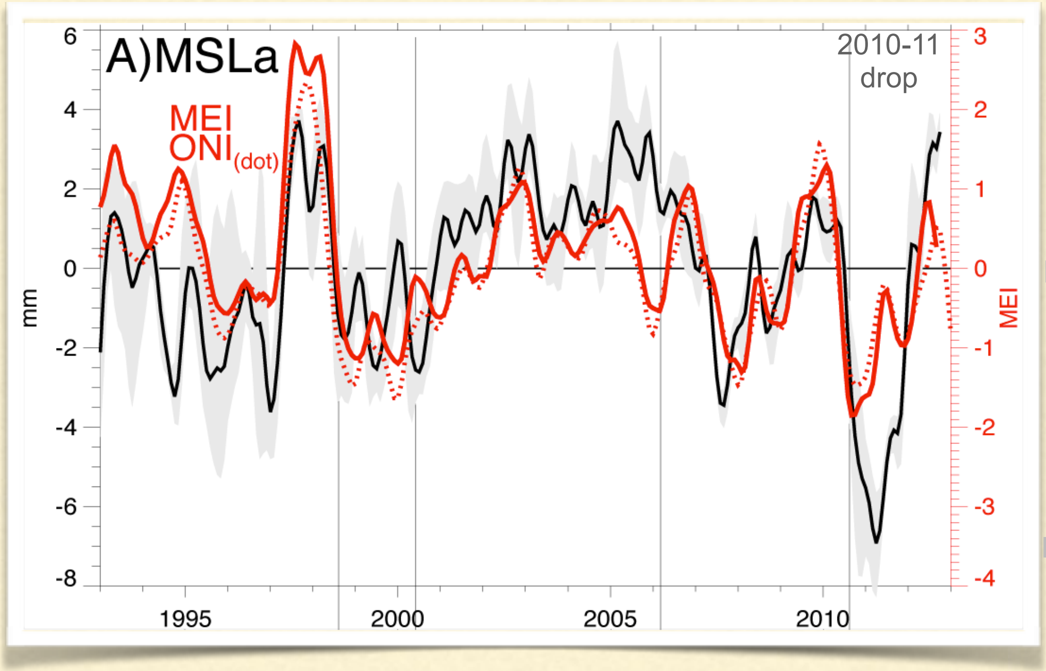
- What insights can be gained from the GRACE decade?
- Given these, what is our understanding of the altimeter era (1993→)?
- What viable approaches exist for inferring CVC from the gauge record?

QUESTIONS: ROLE OF ENSO?



- Early thinking (2005): ENSO and de-trended GMSL appear tightly correlated
- Why? How tight should one expect this relationship to be? What might be mitigating factors?

QUESTIONS: ROLE OF ENSO?



- Early thinking (2005): ENSO and de-trended GMSL appear tightly correlated
- Why? How tight should one expect this relationship to be? What might be mitigating factors?
- The 2010-2011 event, while confirming a role for ENSO, suggests a more complex interaction (e.g. 2008). Note: accompanied the hiatus).

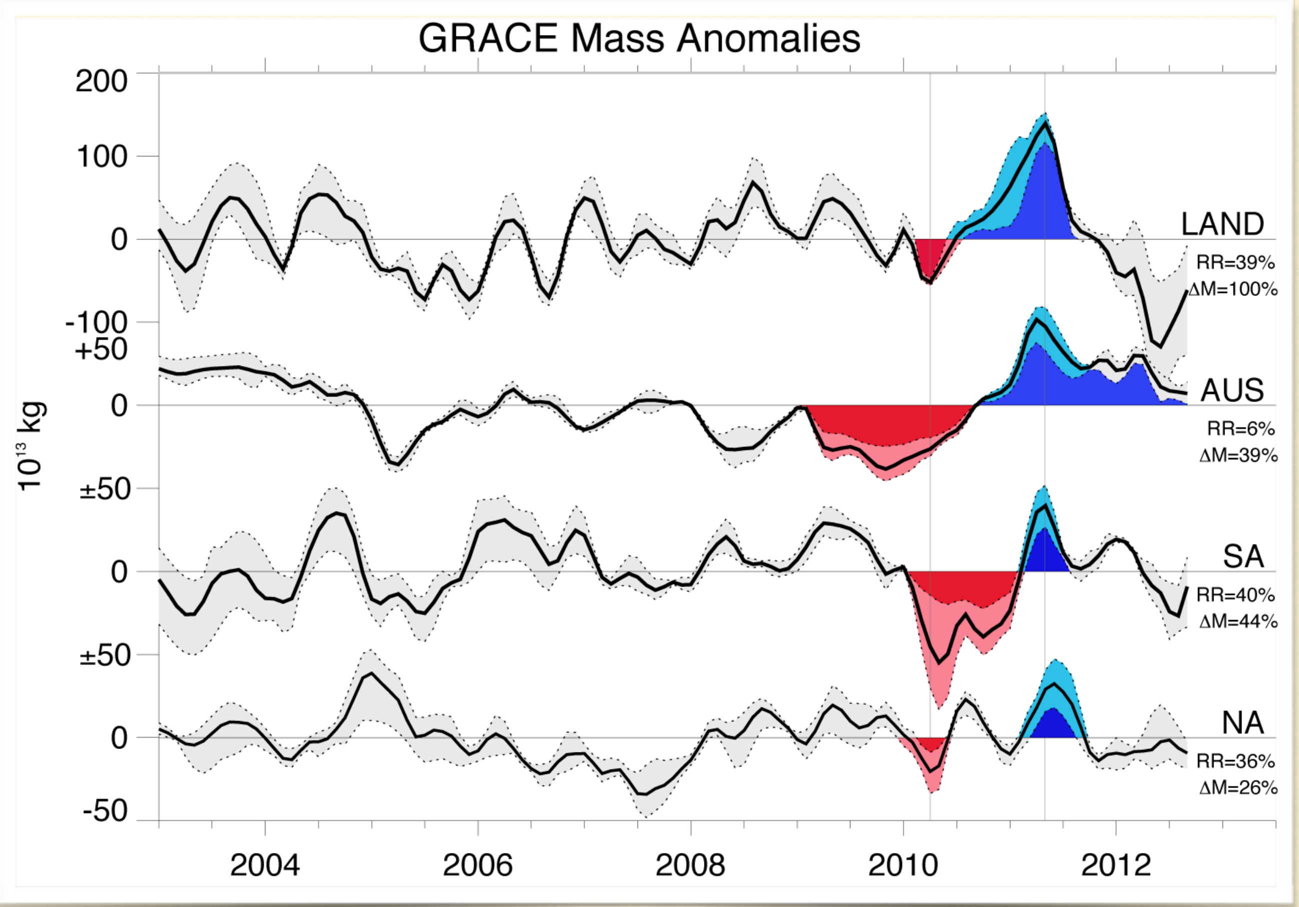
THE 2010-2011 SEA LEVEL DROP

Fasullo et al. 2013

Questions

- What really "caused" the drop?
- Why was the 2010-11 drop so much larger than other La Niña events in the altimeter era?
- How could the drop last over a year when the runoff timescale is generally about 3 months?

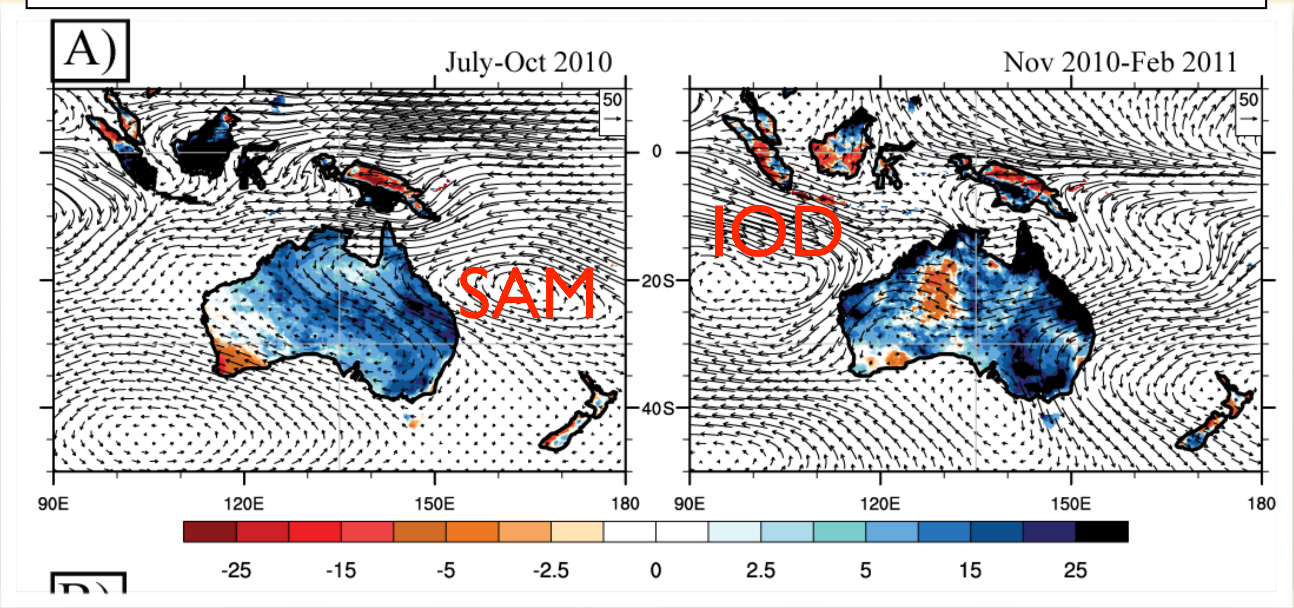
THE 2010-2011 SEA LEVEL DROP



- Global-land TWS nearly balanced the drop in sea level
- Australia dominated the TWS anomaly in both magnitude and duration
- Contrast with 2008

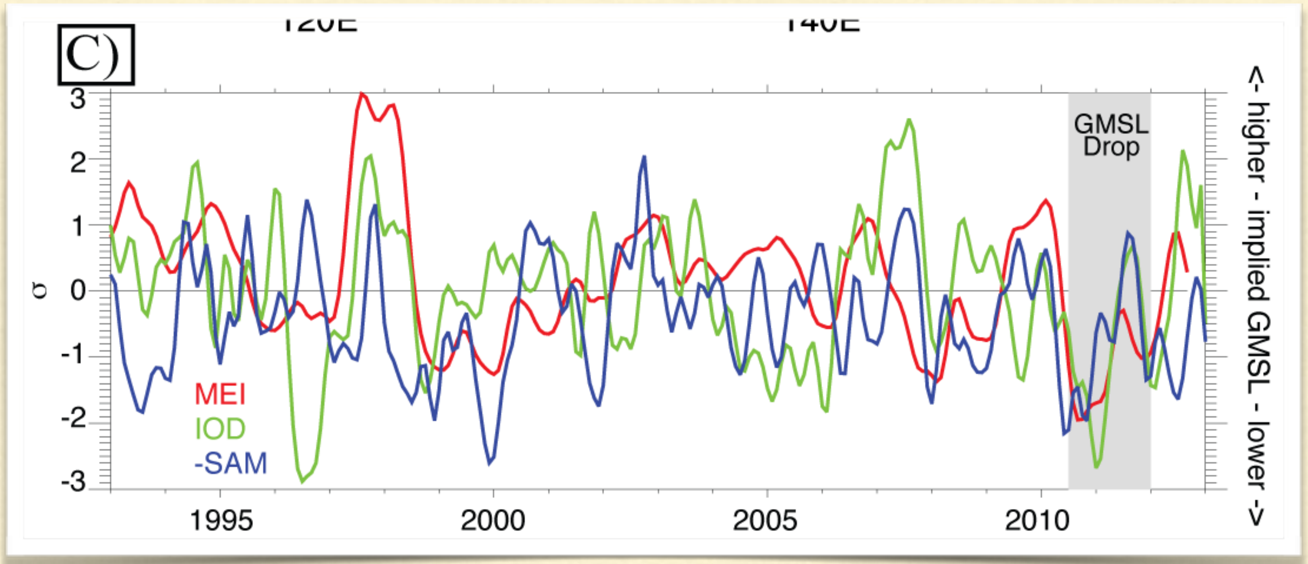
THE 2010-2011 SEA LEVEL DROP

ERAI - Vertically Integrated Moisture Advection and TRMM P



- Atmospheric moisture budgets show a key role not only of La Niña but also of the SAM (A) and IOD (B)
- Unique Australian interior hydrology provided a source of TWS persistence.

THE 2010-2011 SEA LEVEL DROP



- 2010-11 was unique in that it coincided not only with a strong La Niña but also prolonged -IOD/+SAM anomalies.
- Land surface characteristics play a key role in TWS, not just total rainfall.
- Large variability in GMSL response to ENSO. Observations are too brief to adequately sample. How can this be quantified?

GMSL in LE: Methods and Caveats

- **NCAR Large Ensemble**: 30-member ensemble of coupled simulations using CMIP5 historical forcing spanning 1920-2005 and RCP8.5 2006-2100.
- ENSO events are identified using Niño3.4 SST anomalies, composited by intensity (0.5-1.5, 1.5-2.5, 2.5+, 120-month running mean removed to deal with trends, 1/4°C weaker thresholds for La Niña)
- Ocean heat content (OHC) changes are scaled to GMSL by Church conversion ($6 \bullet 10^{22}$ J = 1 cm), slightly less than what is computed directly using equation-of-state in CCSM4).
- Ice-sheet mass variability is not considered. GRACE suggests IA-var to be small (< 0.2 mm).
- The validity of TWS anomalies depends on ENSO teleconnections depicted in the model. While all models have shortcomings, CESM is one of the better models. Validation ongoing.
- The validity of OHC anomalies depends on the structure and intensity of the CESM's ENSO (likely too strong). Binned by intensity.
- The land model is CLM4 not 5. TWS variability is likely to improve in 5. Ongoing work.

GMSL in LE: Methods and Caveats

TWS

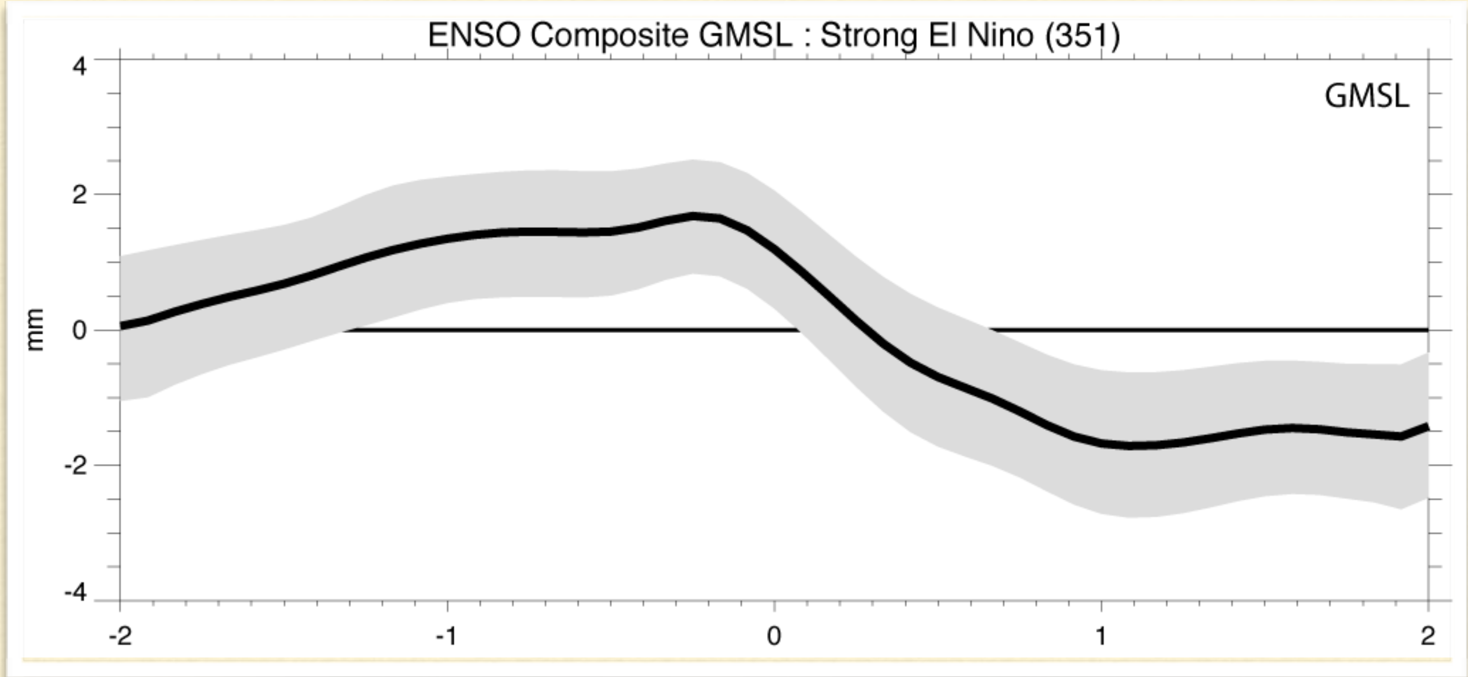
= (∫ (SOILLIQ+SOILICE)dz+WA+H20SNO+H2OCAN) + VOLR

OHC

= ∫ (THEATO*1026 kg/m3*3990 J/kg)

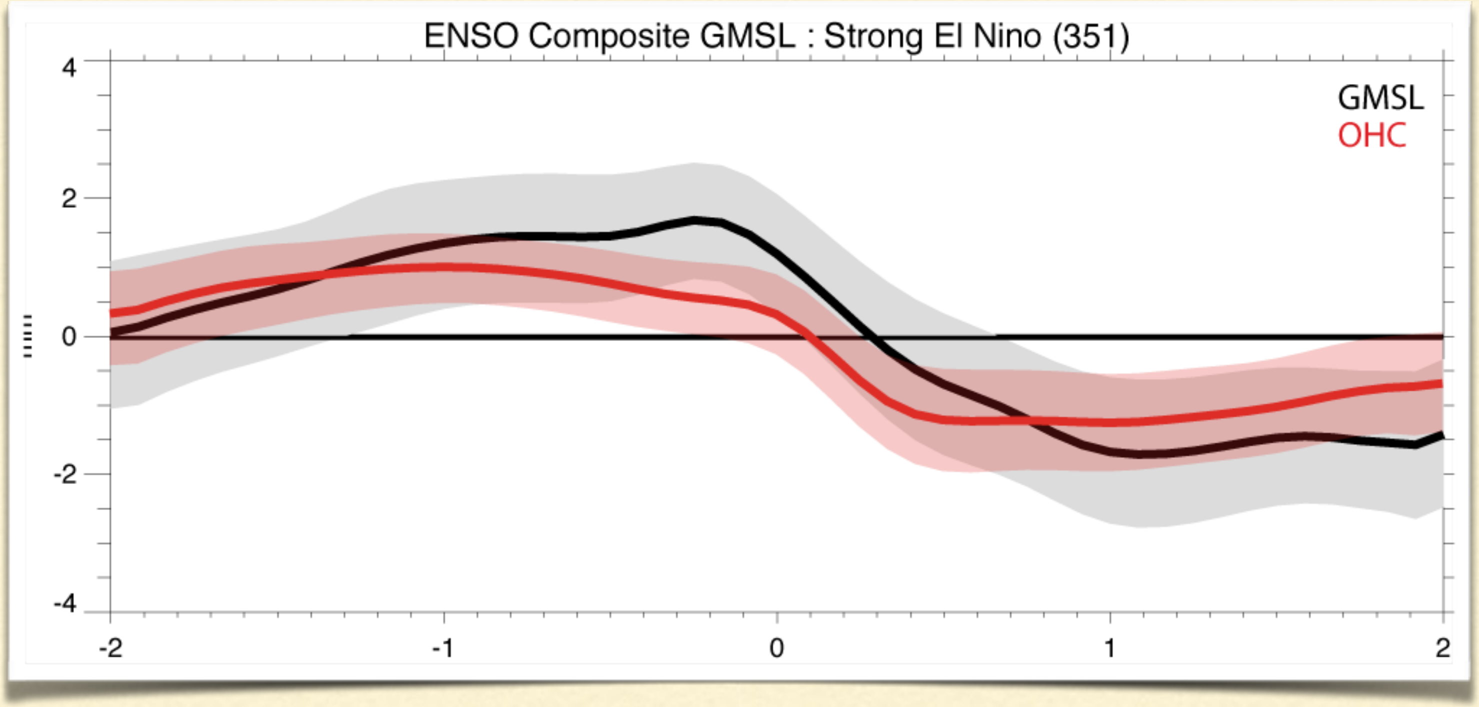
Conventional Wisdom : TWS' dominates

GMSL in LE: El Niño



- As observed, sea level ↑ during El Niño onset and ↓ afterward (La Niña).

GMSL in LE: El Niño



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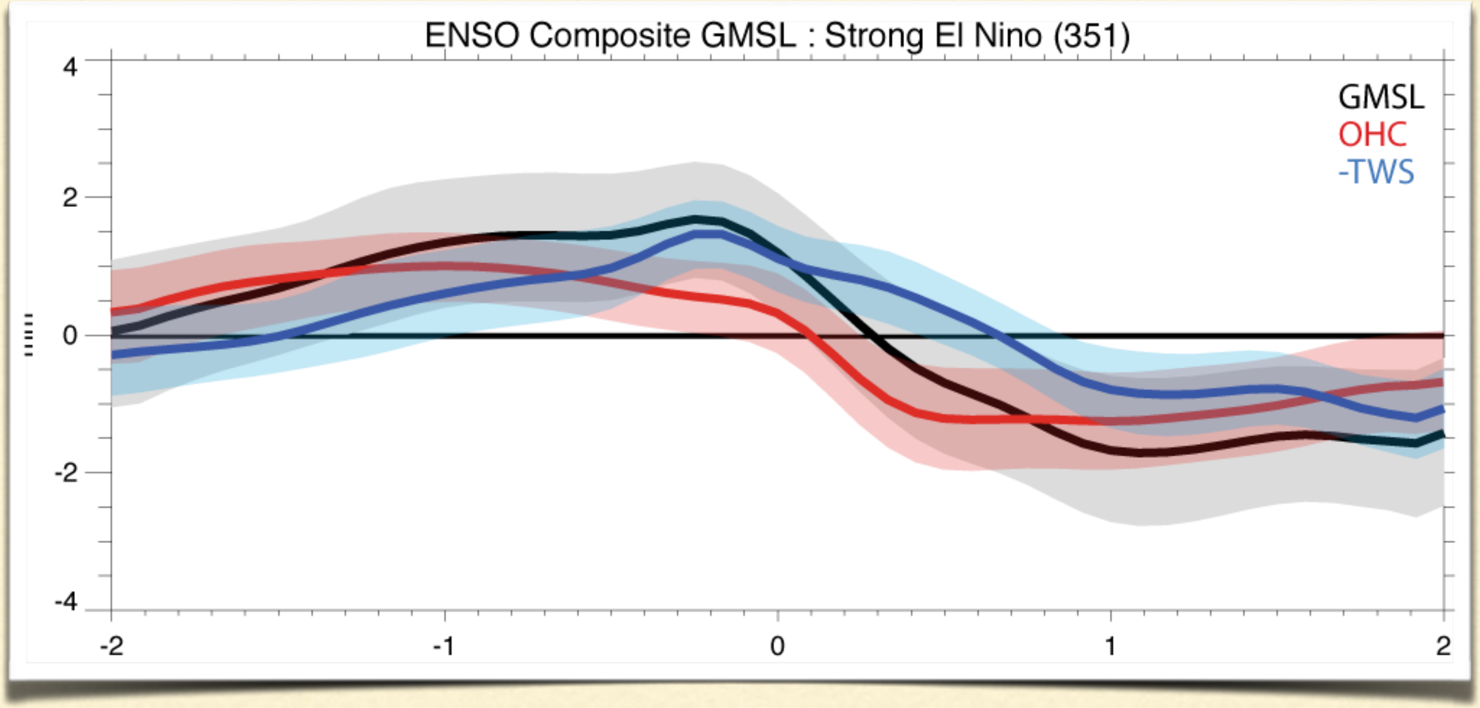
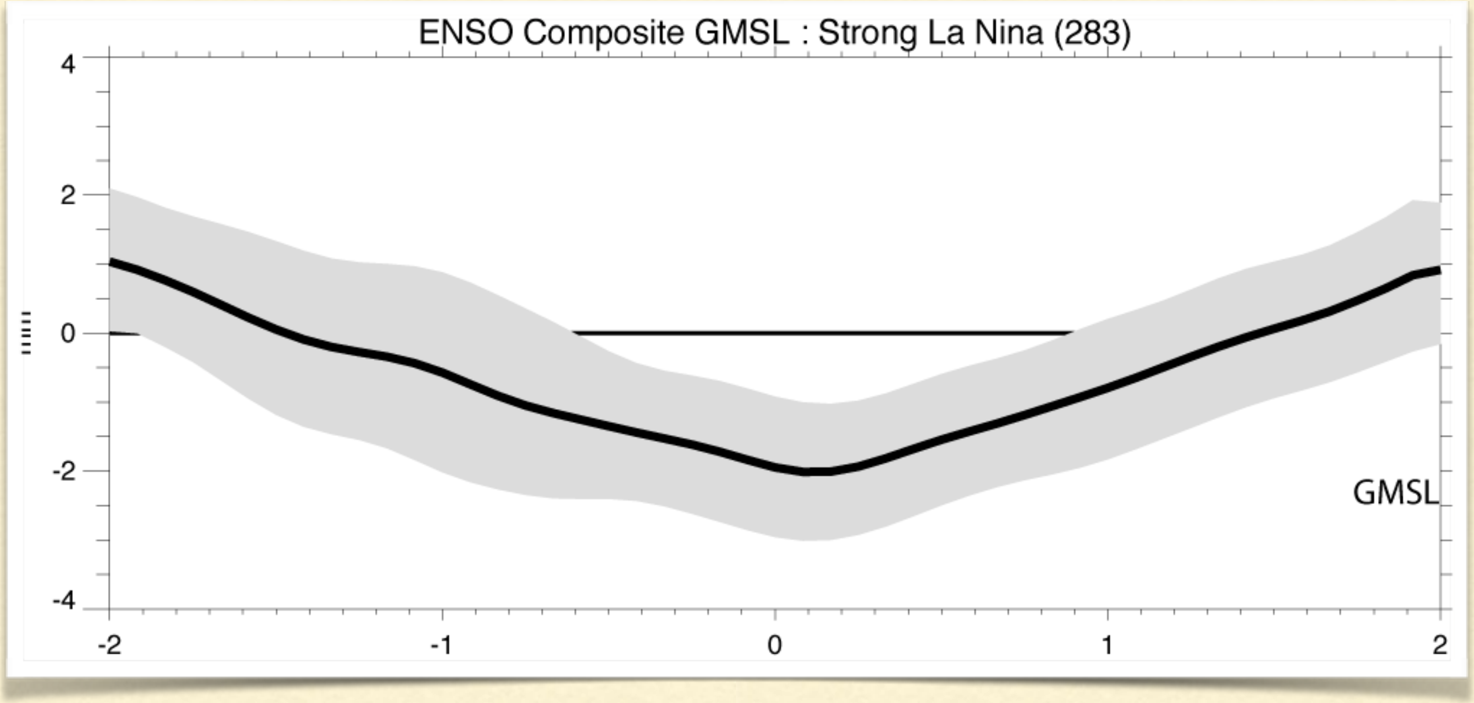
GMSL in LE: El Niño



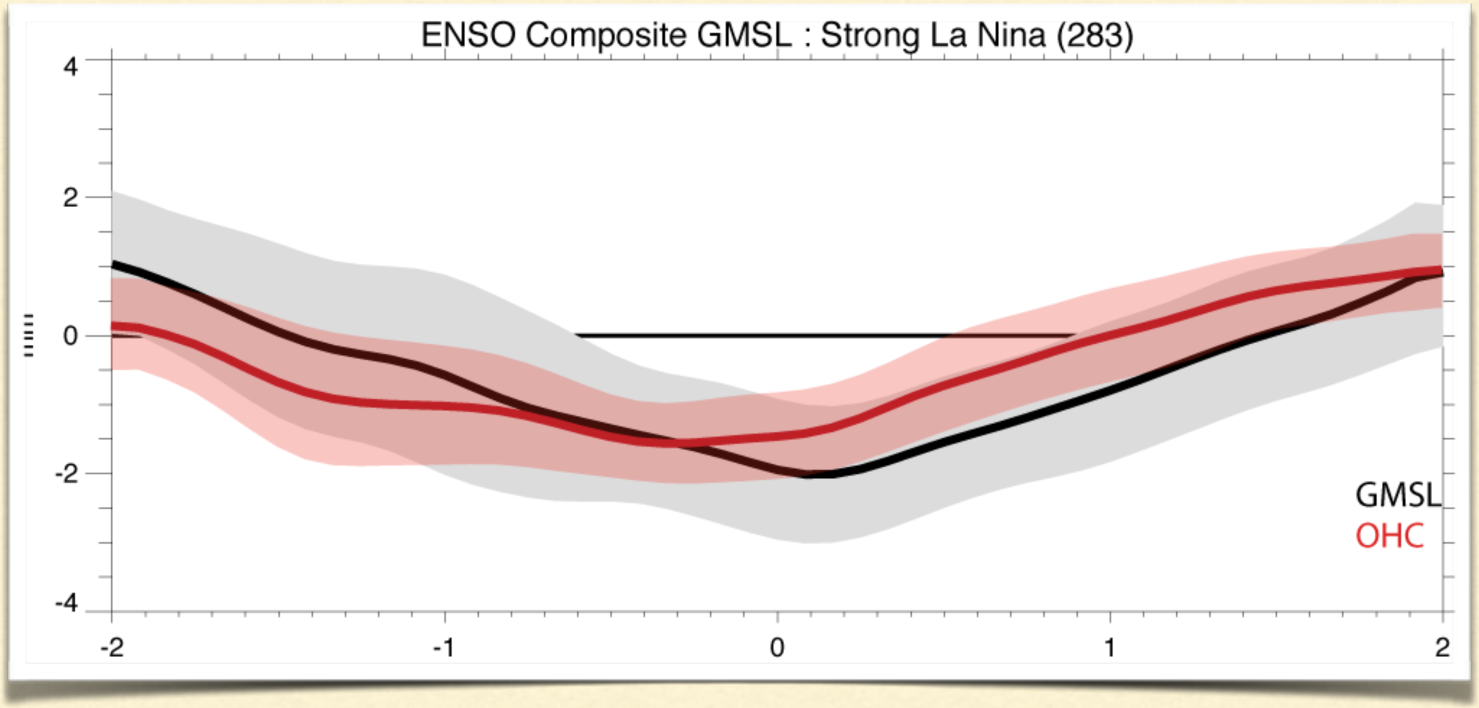
- As observed, sea level ↑ during El Niño onset and ↓ afterward (La Niña).
- The initial increase is caused by ↑OHC, ↓ during and after.
- -TWS is approximately in phase with SST, peaking near El Niño peak.

GMSL in LE: La Niña



- As observed, sea level ↓ at onset and peak of La Niña and ↑ afterward.

GMSL in LE: La Niña



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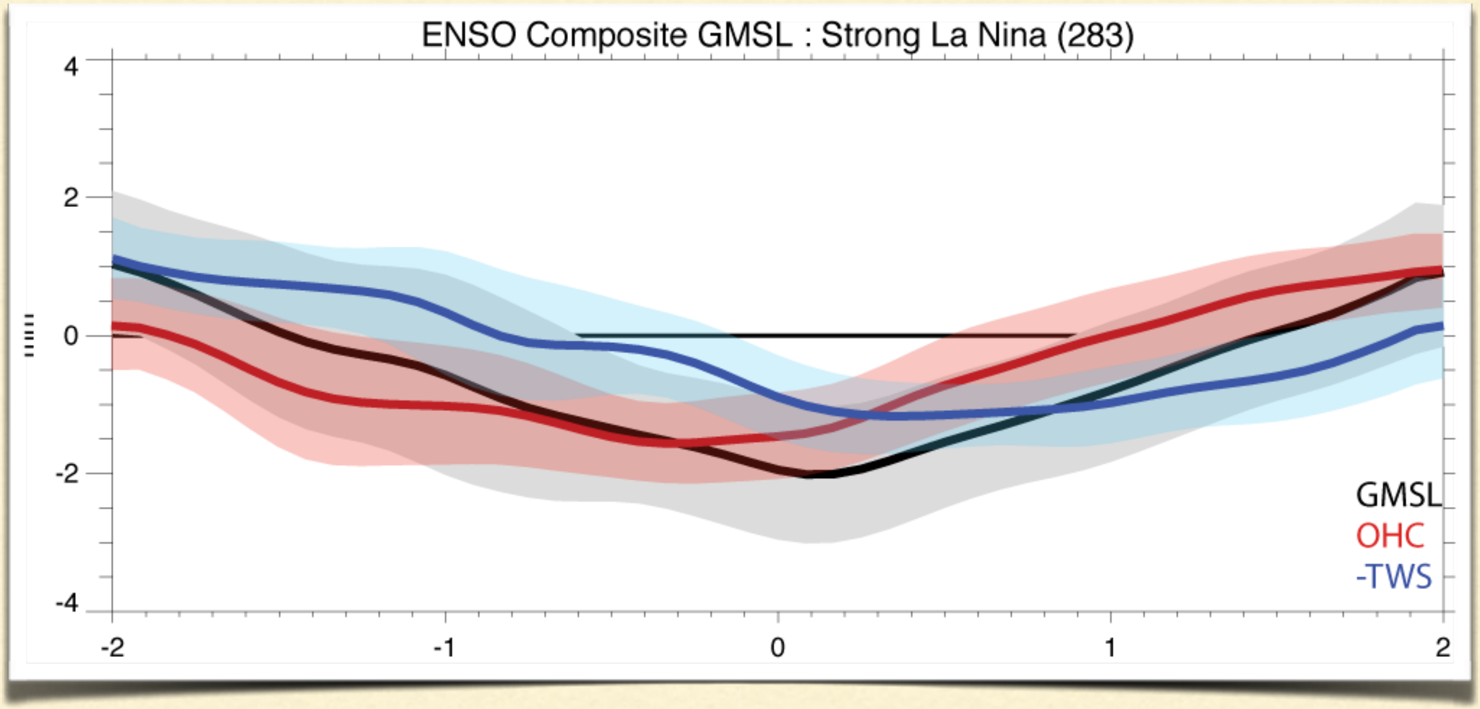
GMSL in LE: La Niña



- As observed, sea level ↓ at onset and peak of La Niña and ↑ afterward.
- The initial ↓ is caused by ↓ OHC (prior El Niño), ↑ during and after.
- -TWS lags SST, peaking in the months after La Niña's peak.

ENSO - GMSL Interactions in the LE: Summary

The asymmetric aspects of ENSO are fundamental to understanding GMSL-ENSO variability (e.g. 2010 El Niño set the stage for the 2011 La Niña).

In the LE, both TWS and OHC play important and complementary roles in GMSL variability during ENSO - in contrast to most of the diagnostic studies that have recently been done emphasizing TWS. (within the error bars of OHC obs)

Large GMSL drops are exceptionally rare. In the LE, they occur roughly once every 75 years and this is probably an overestimate of their frequency in nature due to CESM's excessive ENSO strength.

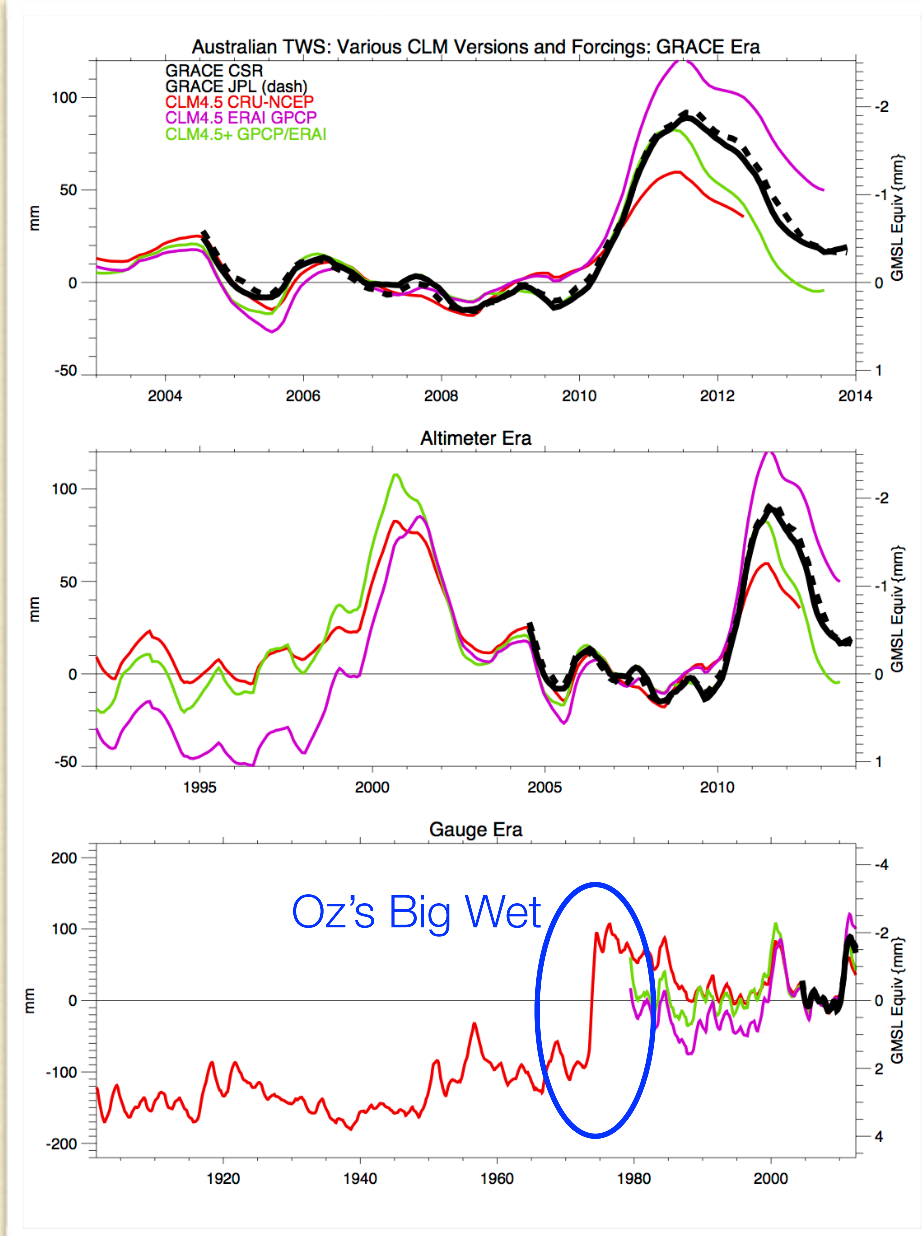
Fasullo et al. 2015

Understanding the Altimeter/Gauge Records: Reconstructing GRACE with the CLM 4.5+

In collaboration with the land modeling group, the **most recent runs with CLM4.5+** agree closely with **GRACE** and are improved over those with **CRU-NCEP forcing** and **CLM4.5 physics**.

Refinements in CLM 4.5+ include an improved characterization of 1) the surface soil skin and 2) aquifers, in conjunction with improved forcing datasets being used.

Substantial historical variability suggested! The gauge record likely must capture such features to be viewed as useful.



CONCLUSIONS

- **Sea level is among the most promising metrics** for estimating of variability in the energy budget and water cycle over the 'historical' period.
- **The 2010-2011 sea level drop** arose largely due to anomalous TWS and was exceptional in both strength and duration due to unique circumstances over Australia, and secondarily, S. America.
- **Observations during the GRACE era** thus suggest an influential role for ENSO in TWS variability but also large inter-event variability. The Large Ensemble provides key insight into the asymmetric nature of this variability. It also suggests a revision of the common wisdom (OHC contributes).
- **Forced CLM4.5+ runs** accurately reproduce GRACE TWS and provide a means for extending TWS estimates over the altimeter era, and perhaps, the past several decades. One early suggestion is that OHC increases, and by extension the planetary imbalance, have not changed significantly during the recent hiatus in Ts, in agreement with direct OHC estimates.
- **Understanding the gauge record** since 1900 remains a work in progress. Various reconstructions lie outside of each other's error bounds in many instances. What is the sensitivity of these reconstructions to internal variability and how can they be improved?

END

The Altimeter Record: Seeking closure with TOA/TWS Estimates

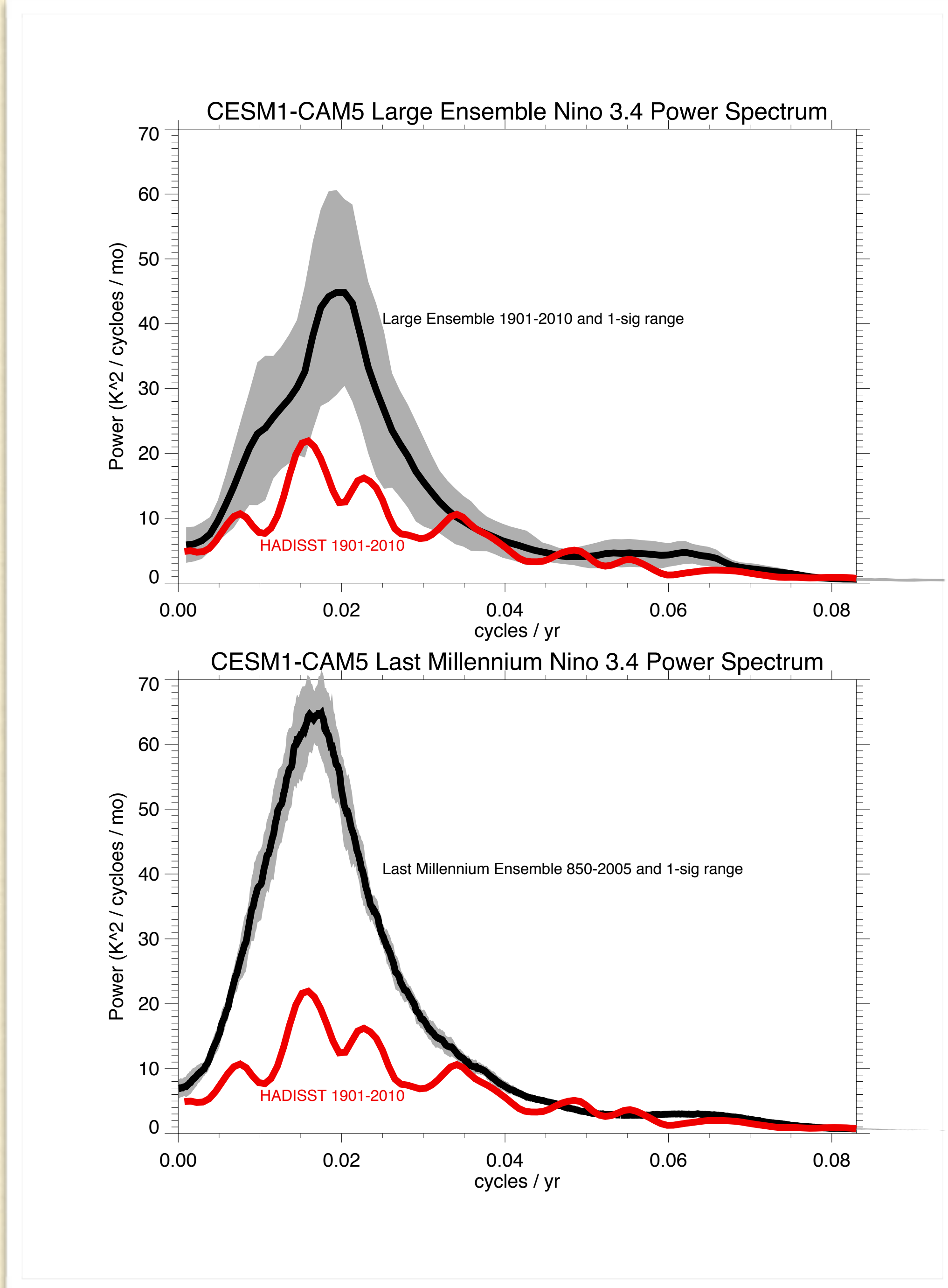
The Altimeter Record: 1997-98

Methods and Caveats

Niño 3.4 Spectra

Both the CESM1-CAM5 Large Ensemble (top) and Last Millennium simulations (bottom) exhibit excessive power in Niño 3.4 SST

Concerns also exist for validating teleconnections - ongoing work.



The Altimeter Record: Estimating Decadal Variability