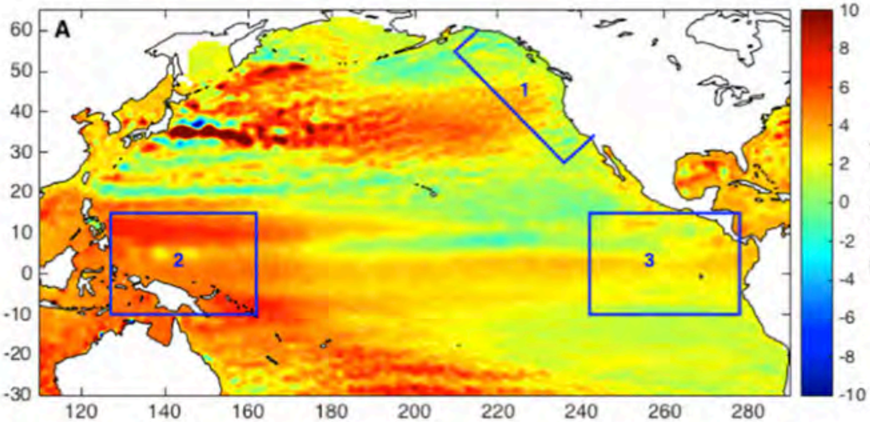
Ongoing Shift in Pacific Ocean Sea Level

Ben Hamlington
Old Dominion University
OSTST, November 2nd, 2016

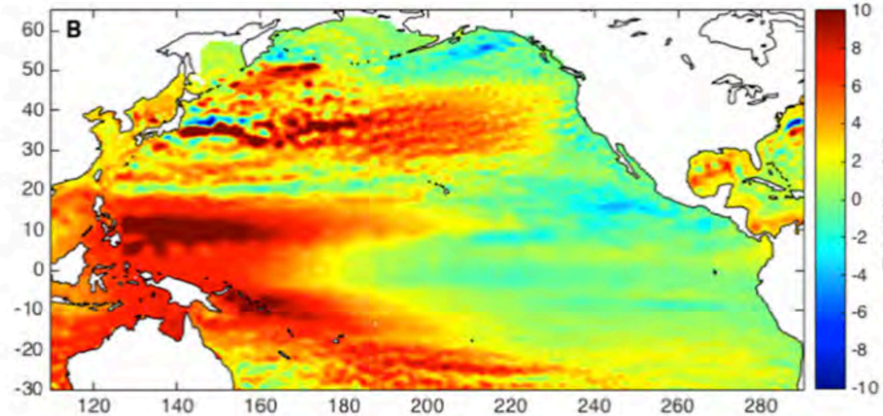
Se-Hyeon Cheon, Philip Thompson, Mark Merrifield, Steve Nerem, Robert Leben, J.T. Reager

Pacific Ocean Sea Level Trends

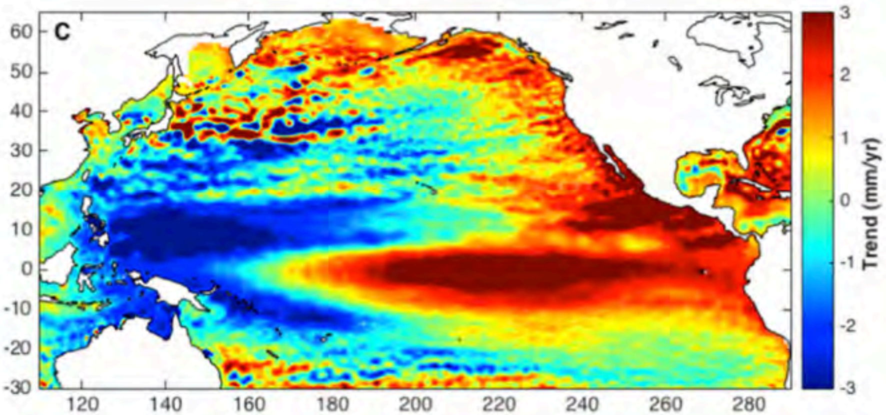
1993-2016



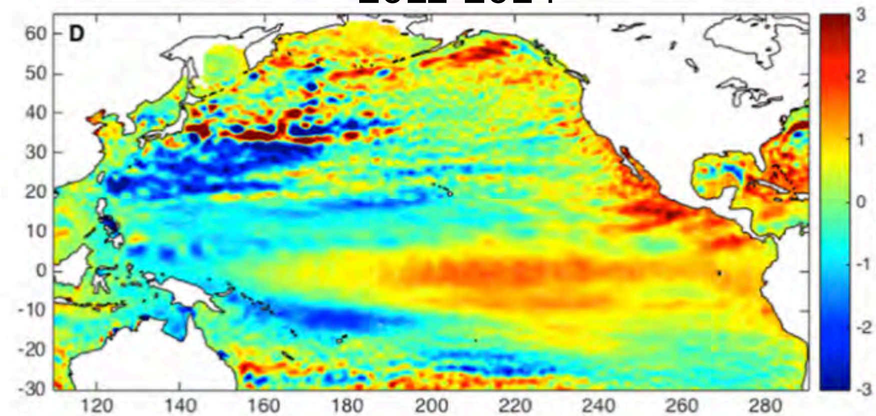
1993-2011



2011-2016



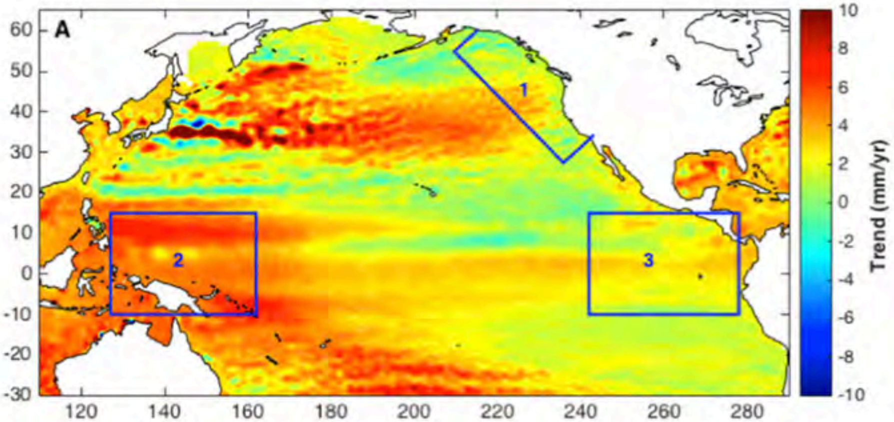
2011-2014



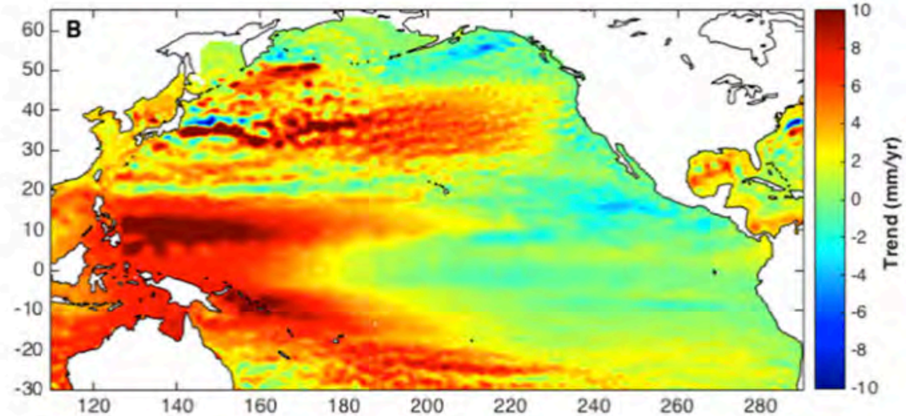
Sea level trends in the Pacific Ocean from the AVISO satellite altimetry data.

Pacific Ocean Sea Level Trends

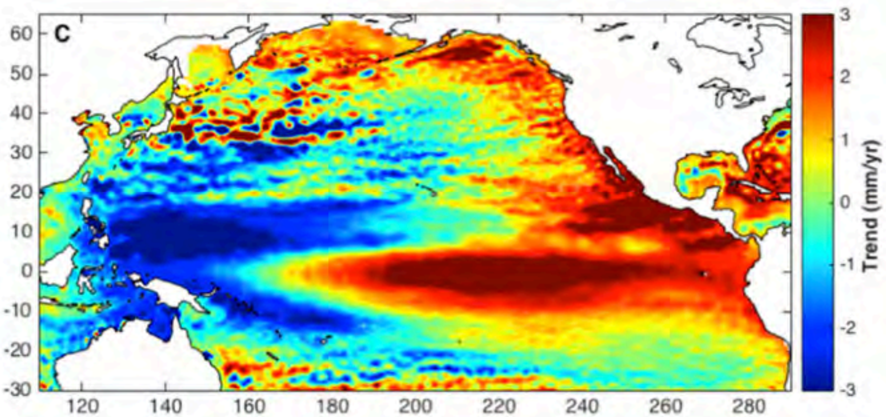
1993-2016



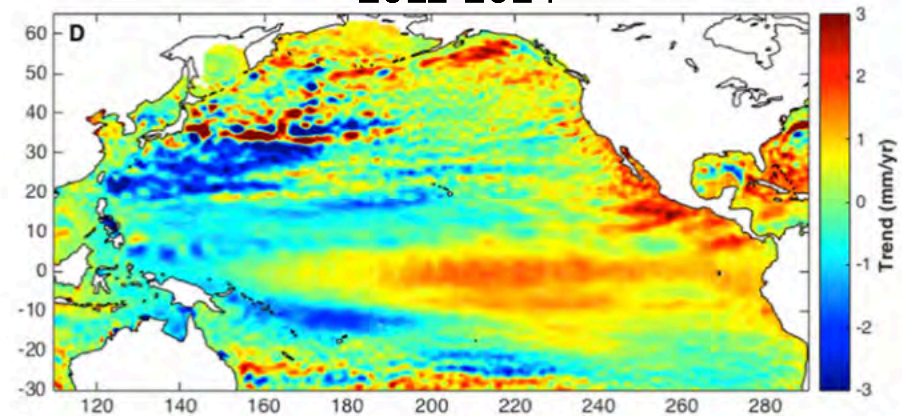
1993-2011



2011-2016



2011-2014



What is causing this shift? Is it a short term shift or longer term (decadal) shift?

Cyclostationary Empirical Orthogonal Functions

- As a starting point to investigate this trend variability, we are going to use CSEOFs.
- In contrast to EOFs, CSEOFs have time-dependent Loading Vectors (LV).

$$T(r,t) = \sum_n P_n(t) LV_n(r,t)$$

$$LV_n(r,t) = LV_n(r,t+d)$$

  - The temporal evolution of the spatial pattern of the CSEOF LVs is constrained to be periodic with a “nested period”.
  - The principal component time series (PCTS) represents the change in strength of this spatial pattern through time.
  - When studying the annual cycle, for example, the LVs would represent the one-year nested periodicity, while the PCTS would describe the change in amplitude of the annual cycle over time.
  - Each CSEOF mode is composed of 12 maps (comprising one LV) and one PCTS when using, for example, monthly data and a one-year nested period.
  - Increased information in the CSEOFs improves ability to physically interpret the modes.

CSEOF Decomposition of Satellite Altimetry Record

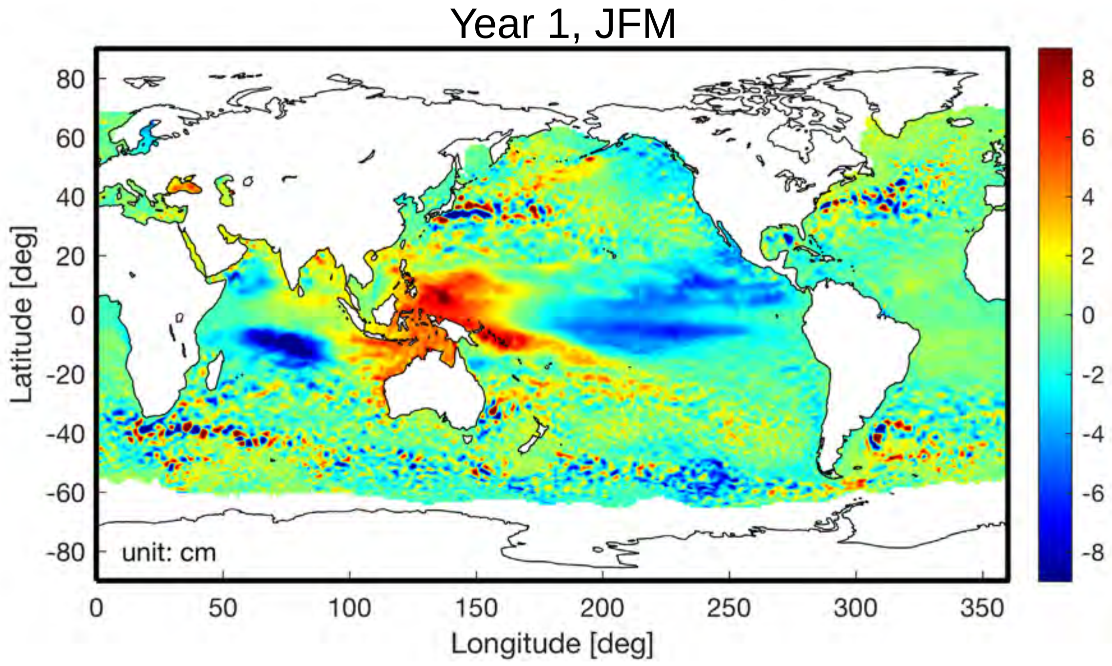
- To investigate the sea level variability in the Pacific Ocean, a CSEOF with a two-year nested period is performed on AVISO gridded satellite altimetry → 24 maps in each LV.

- The first mode is associated with the trend, and the second mode is associated with the annual cycle.

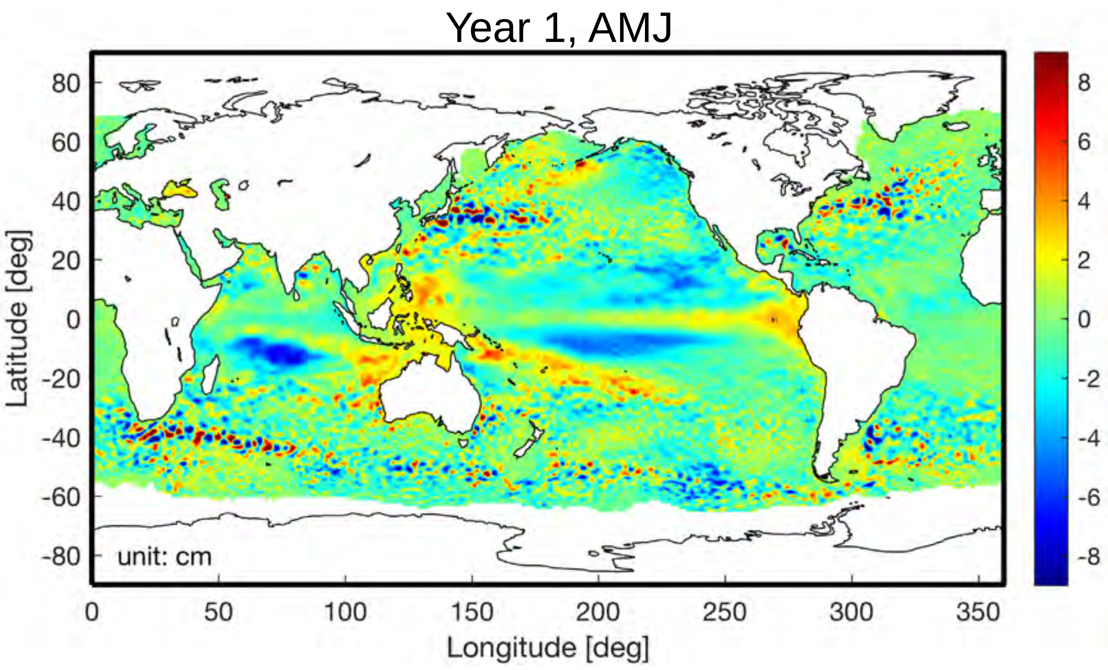
- The third mode is representative of the biennial oscillation associated with ENSO.

CSEOF Decomposition of Satellite Altimetry Record

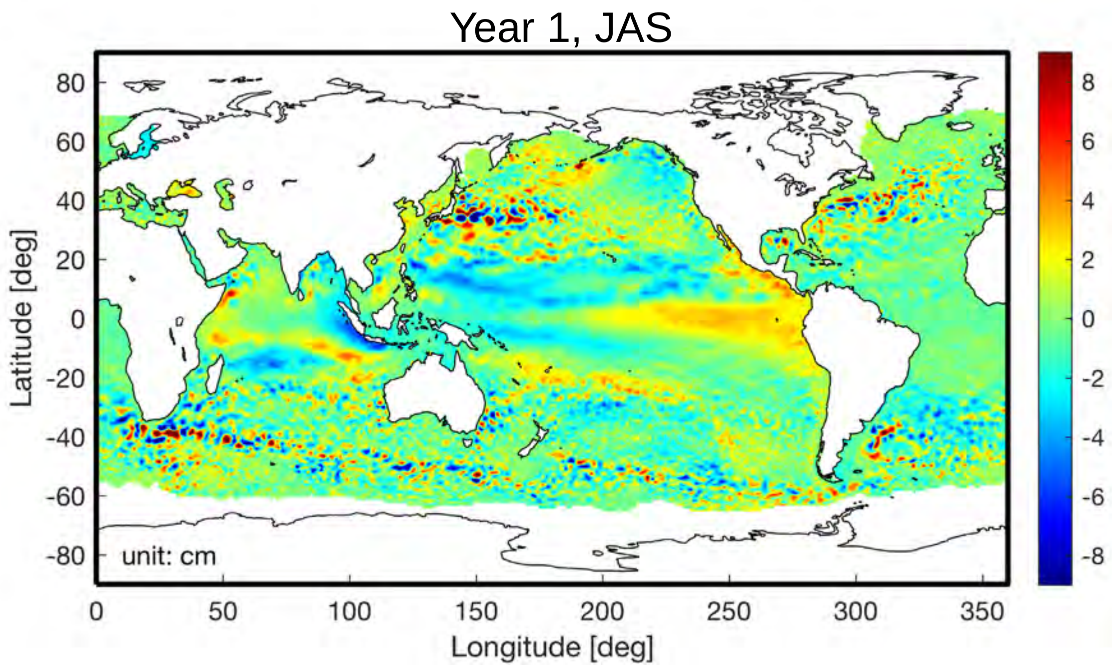
- The third mode is representative of the biennial oscillation associated with ENSO.



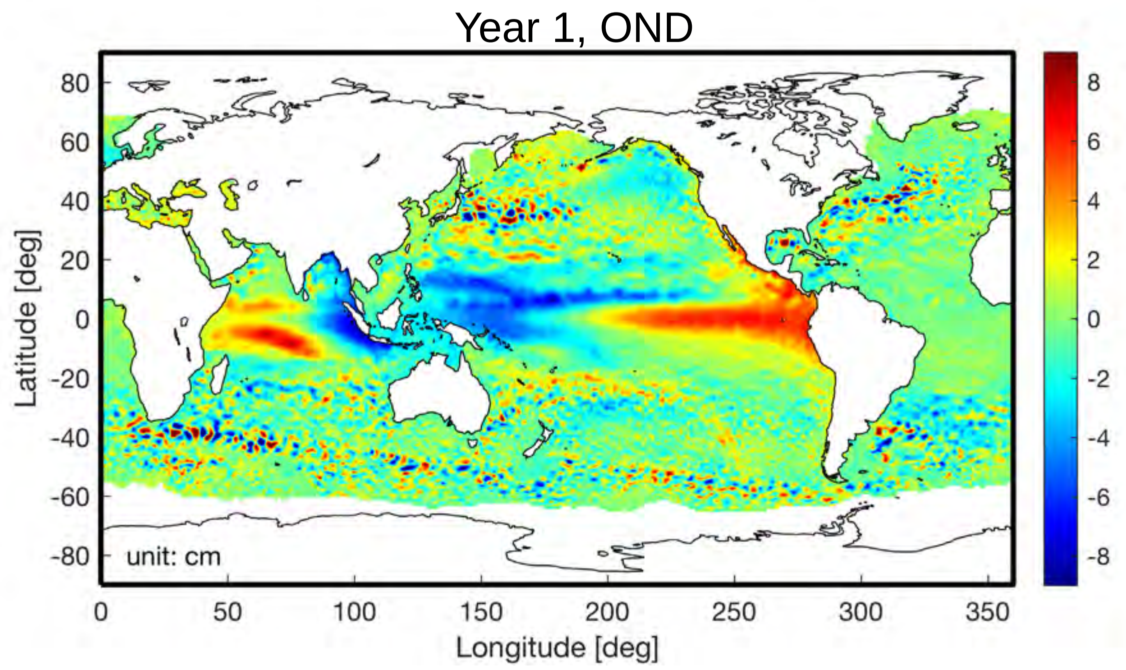
CSEOF Decomposition of Satellite Altimetry Record



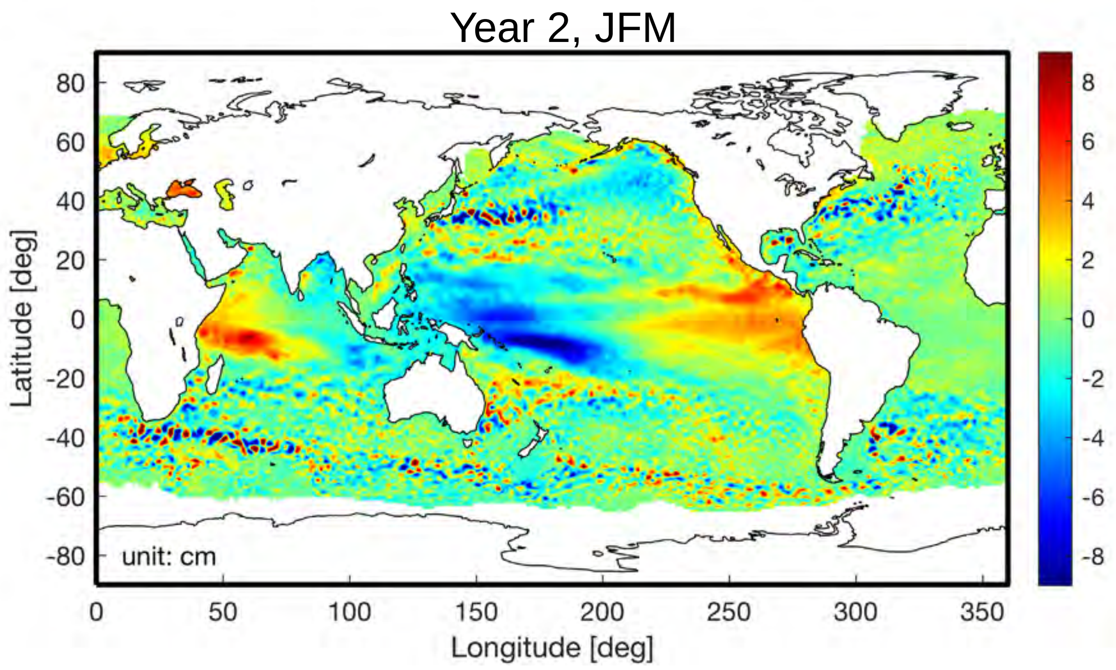
CSEOF Decomposition of Satellite Altimetry Record



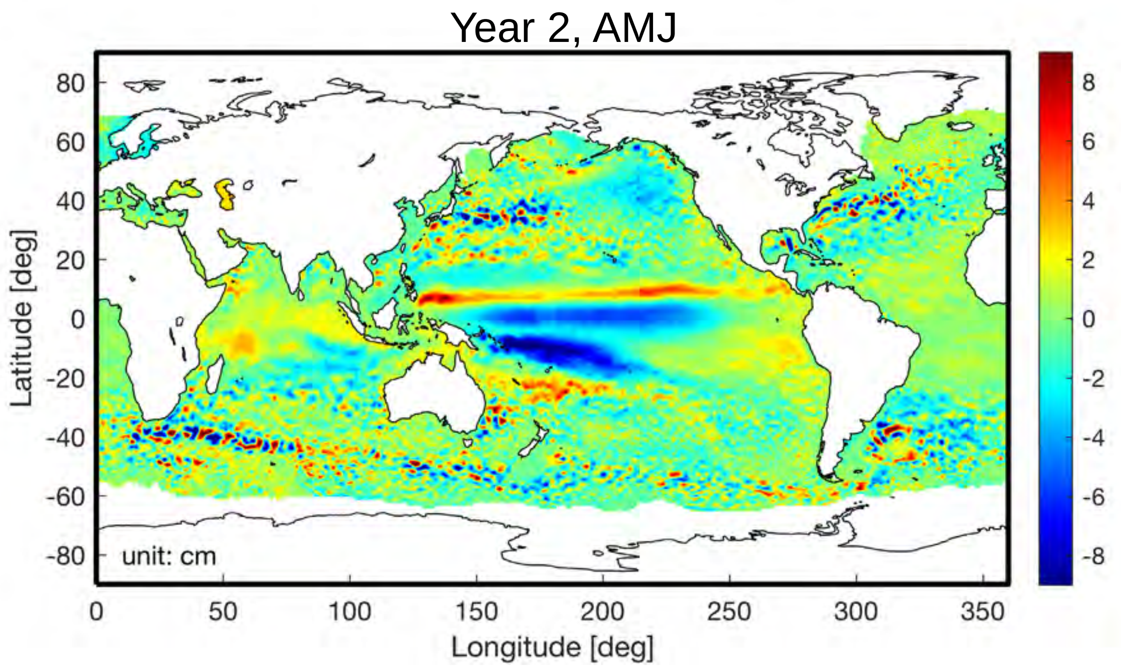
CSEOF Decomposition of Satellite Altimetry Record



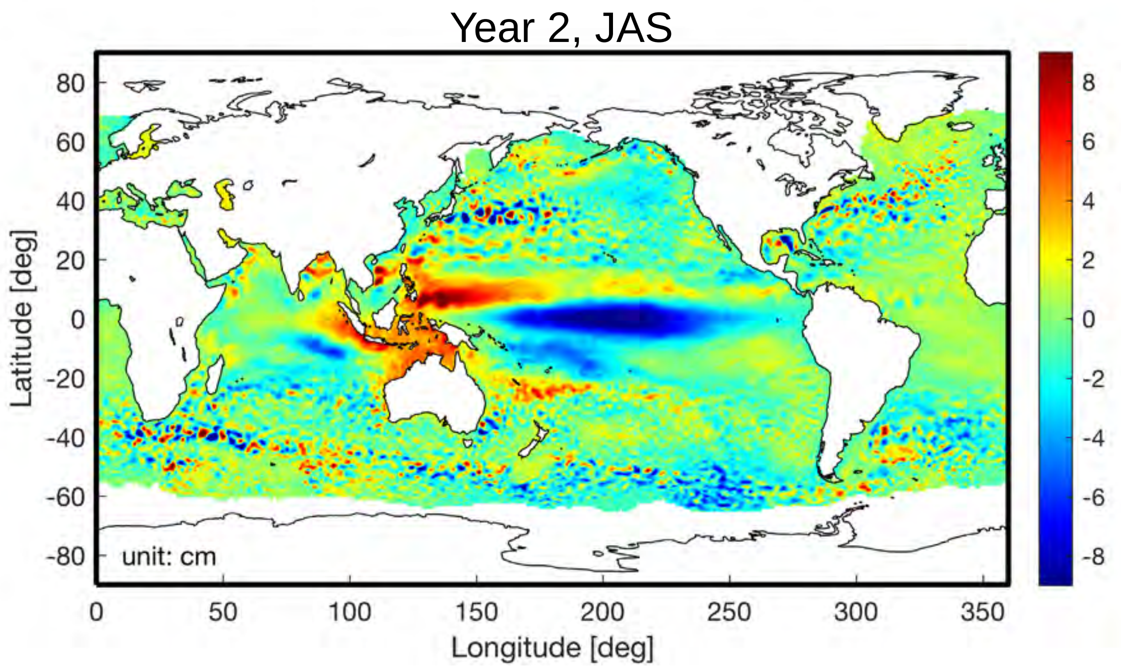
CSEOF Decomposition of Satellite Altimetry Record



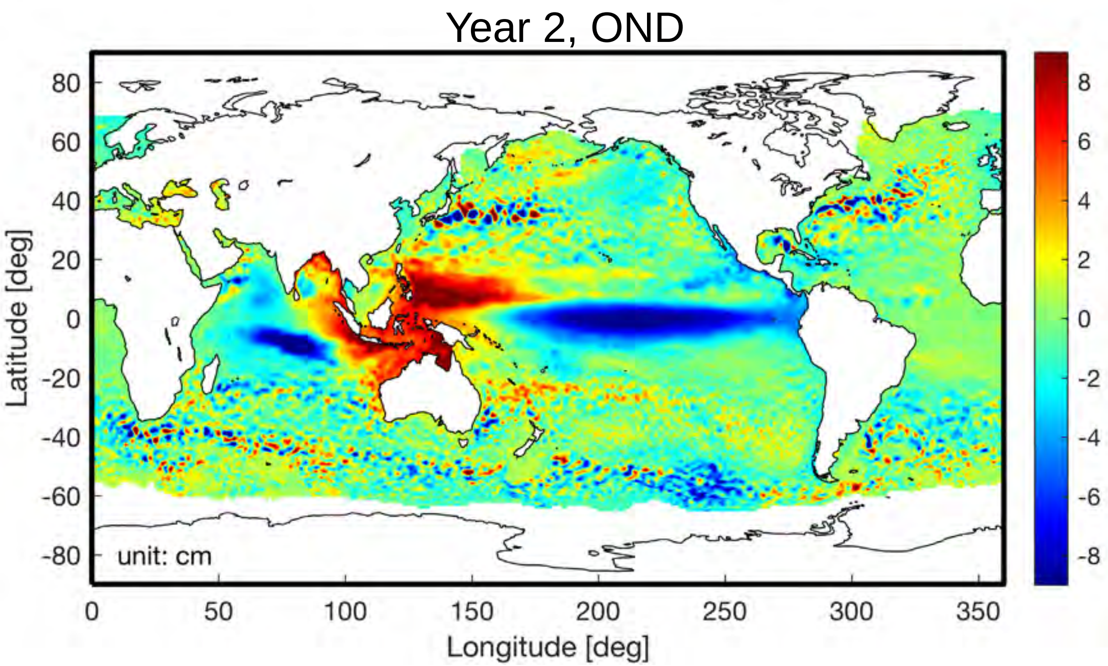
CSEOF Decomposition of Satellite Altimetry Record



CSEOF Decomposition of Satellite Altimetry Record

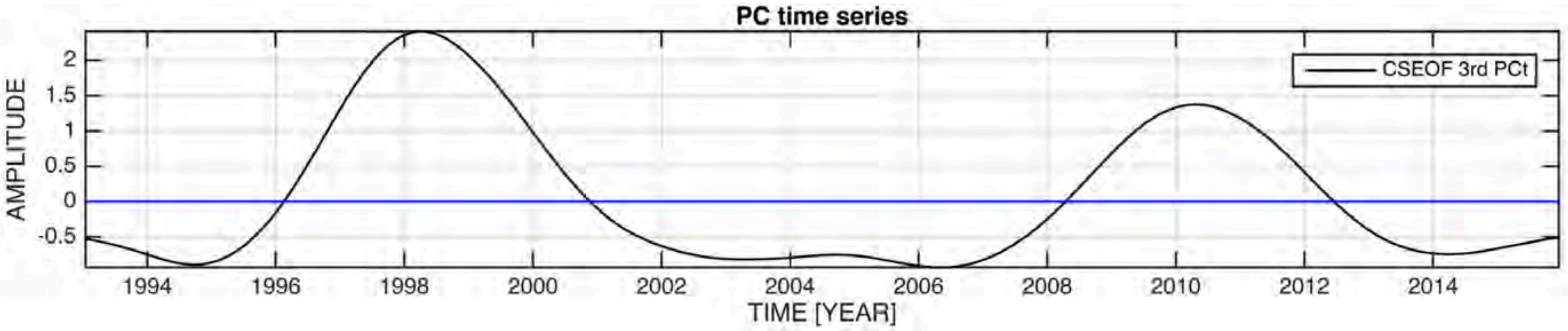


CSEOF Decomposition of Satellite Altimetry Record



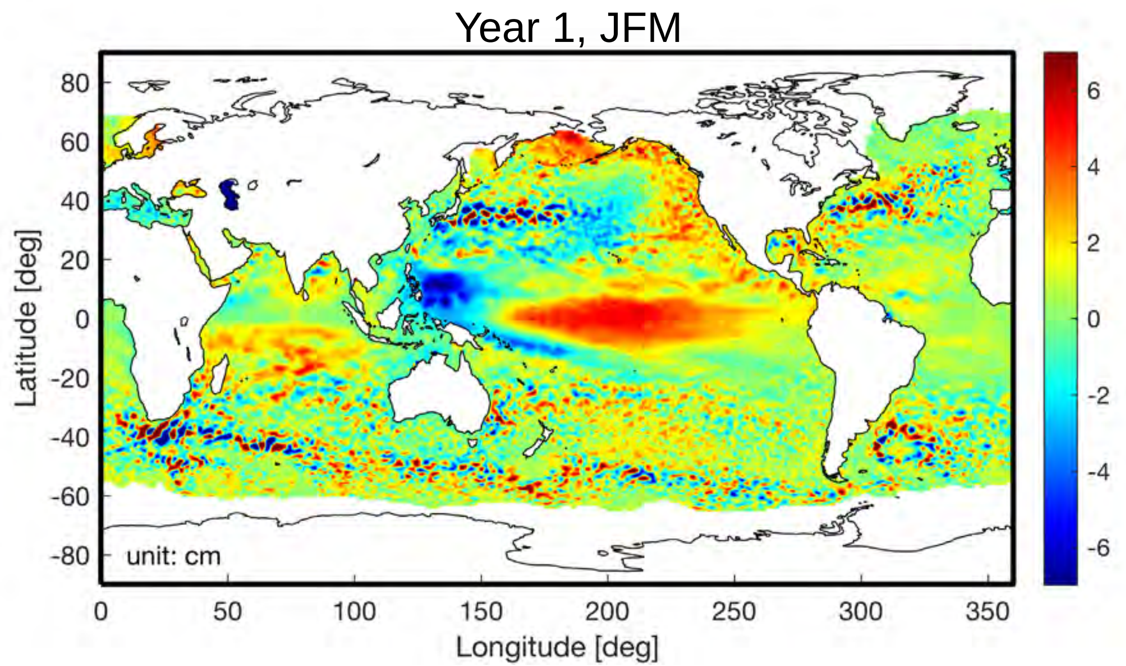
CSEOF Decomposition of Satellite Altimetry Record

- PCTS represents the strength of this pattern during the record.
- Largest values are found when there is an El Nino followed by a La Nina (or vice versa) → 1998/1999 and 2010/2011.
- Sign depends on the year an event occurs → 1993 corresponds to "Year 1".
  - 2001 to 2008 represents weak oscillations between positive and negative phase.
  - Extended El Nino conditions lasting more than a year will require a sign change in the PCTS during that time period.

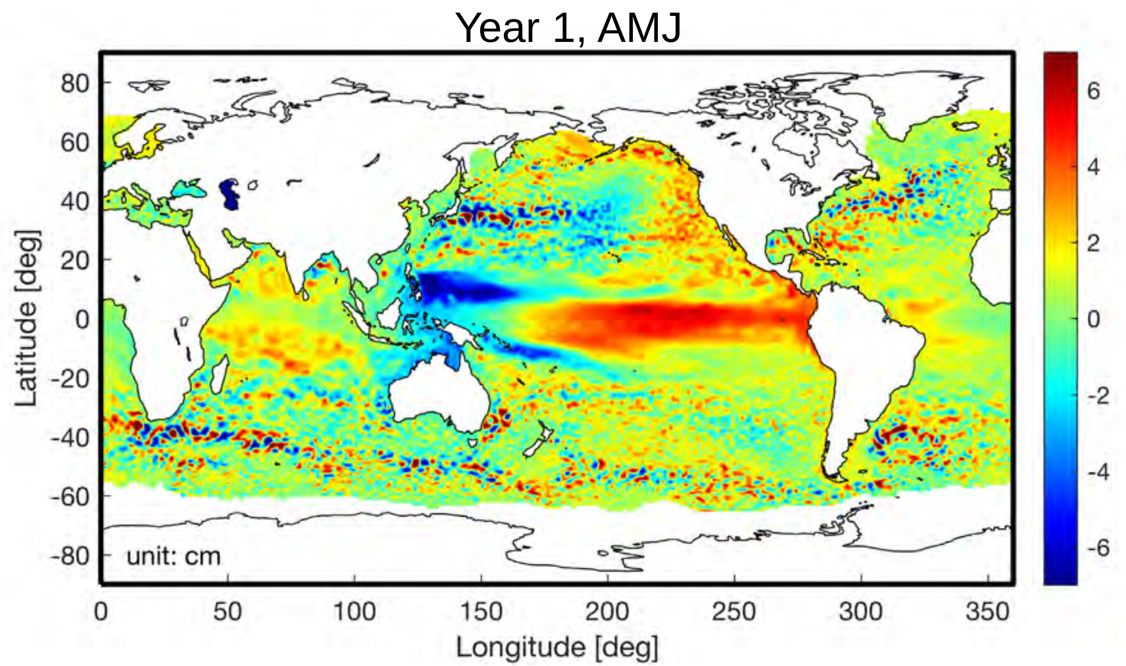


CSEOF Decomposition of Satellite Altimetry Record

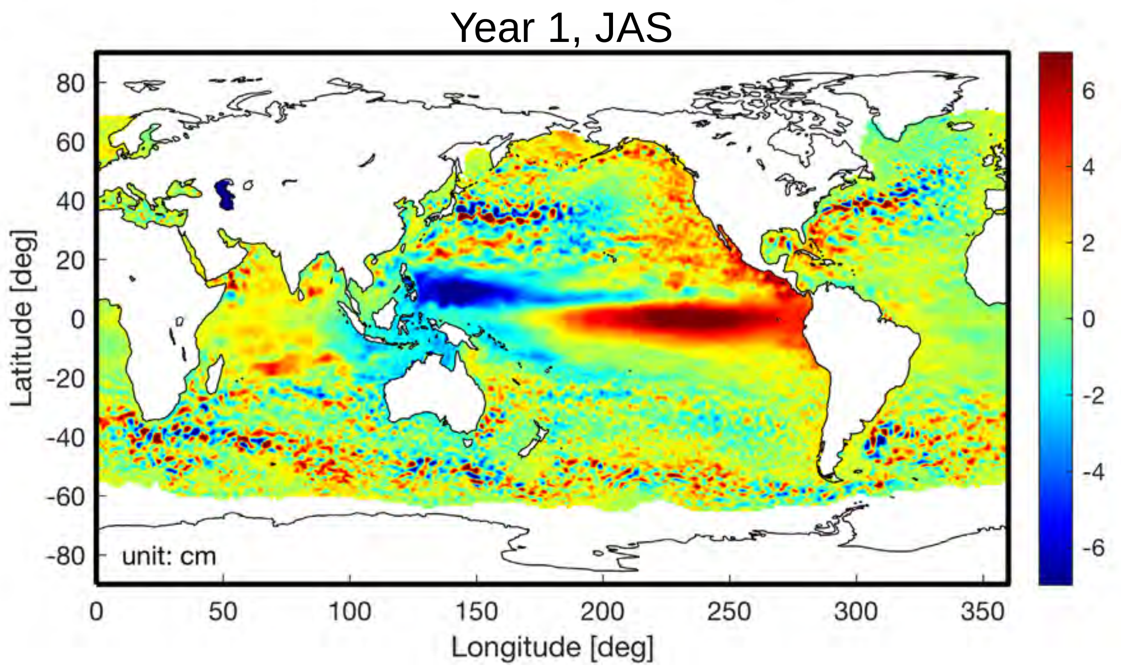
- The fourth mode is associated with lower frequency variability → How can we tell?



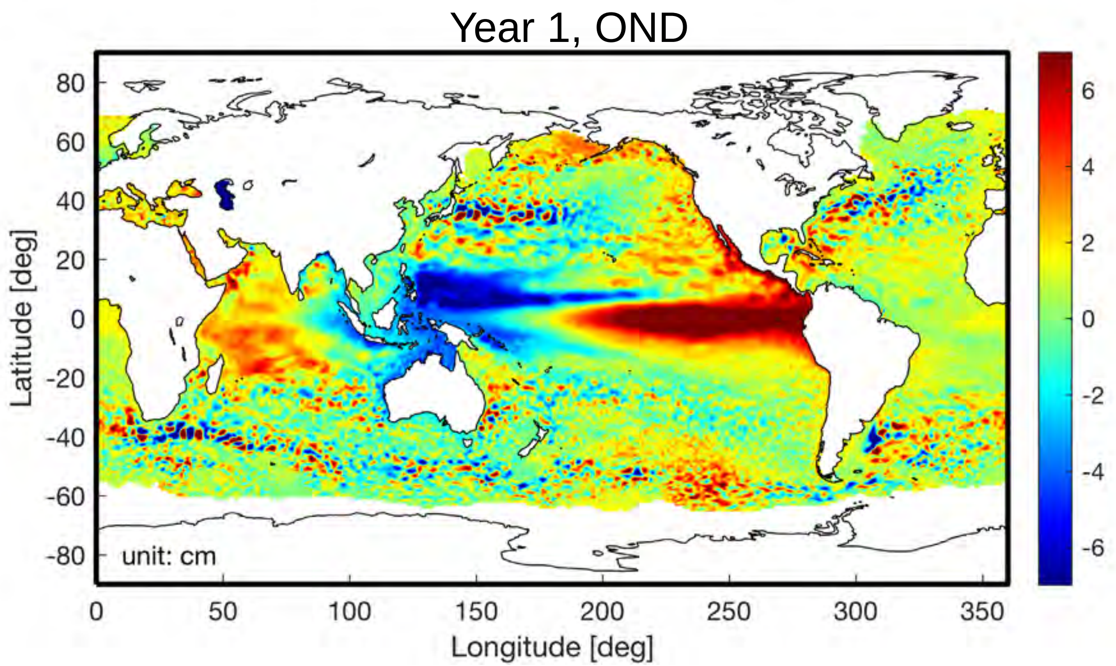
CSEOF Decomposition of Satellite Altimetry Record



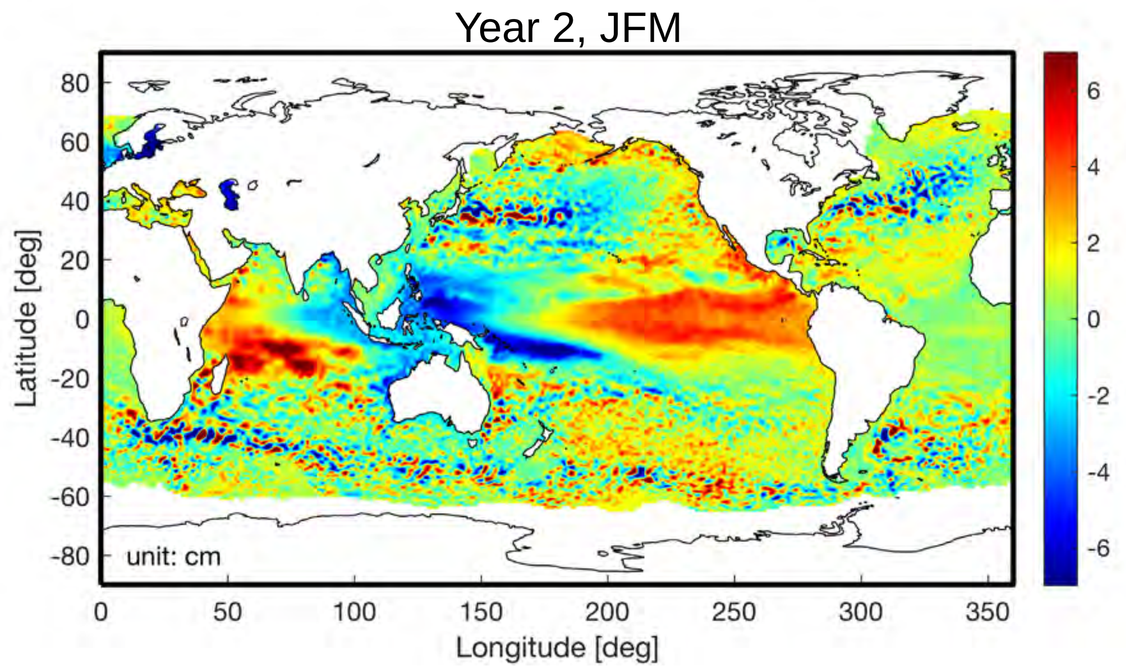
CSEOF Decomposition of Satellite Altimetry Record



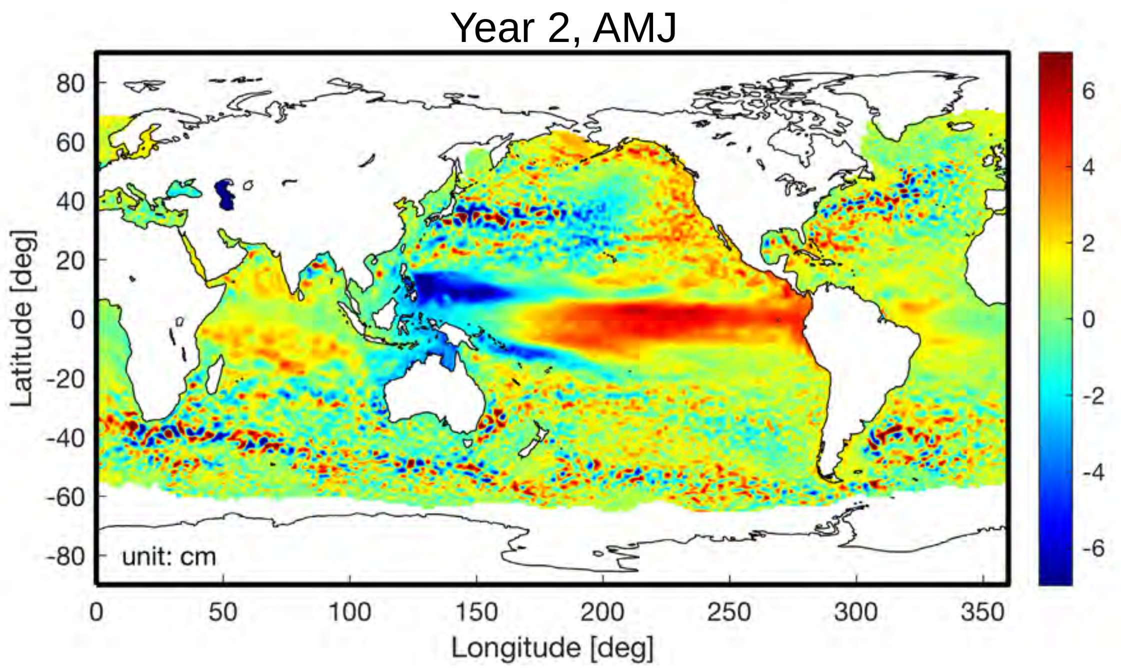
CSEOF Decomposition of Satellite Altimetry Record



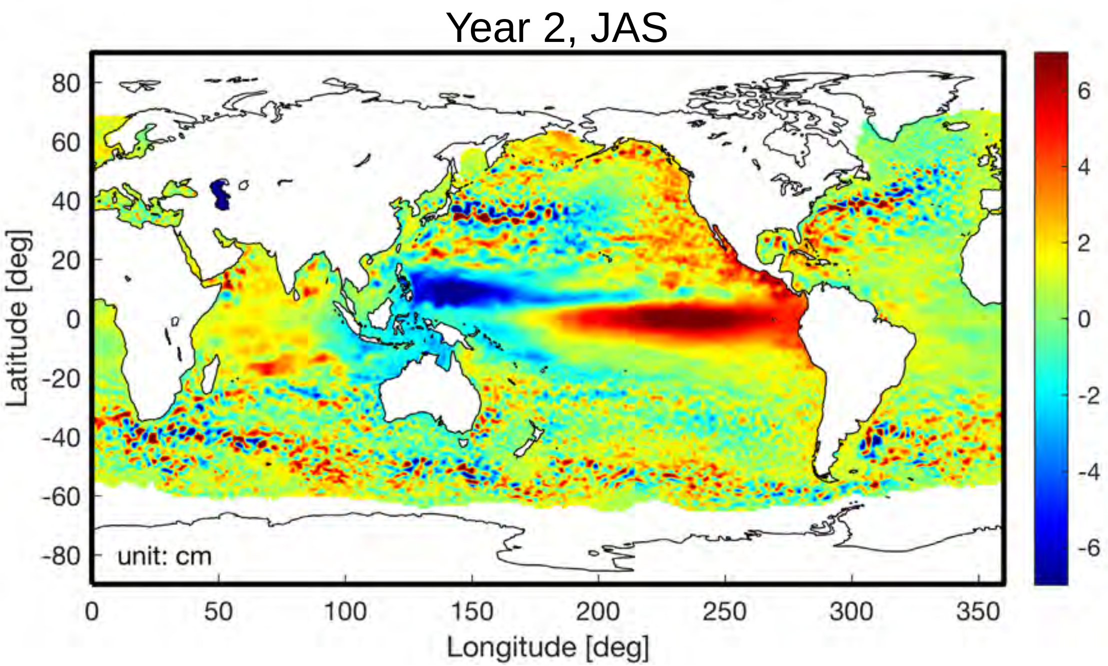
CSEOF Decomposition of Satellite Altimetry Record



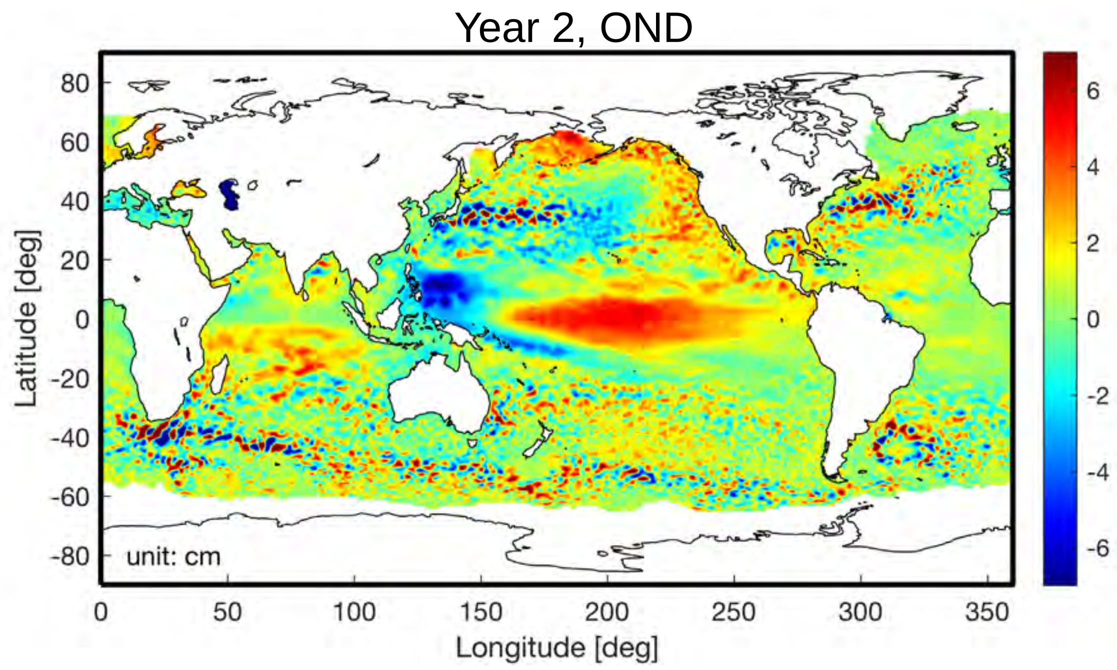
CSEOF Decomposition of Satellite Altimetry Record



CSEOF Decomposition of Satellite Altimetry Record

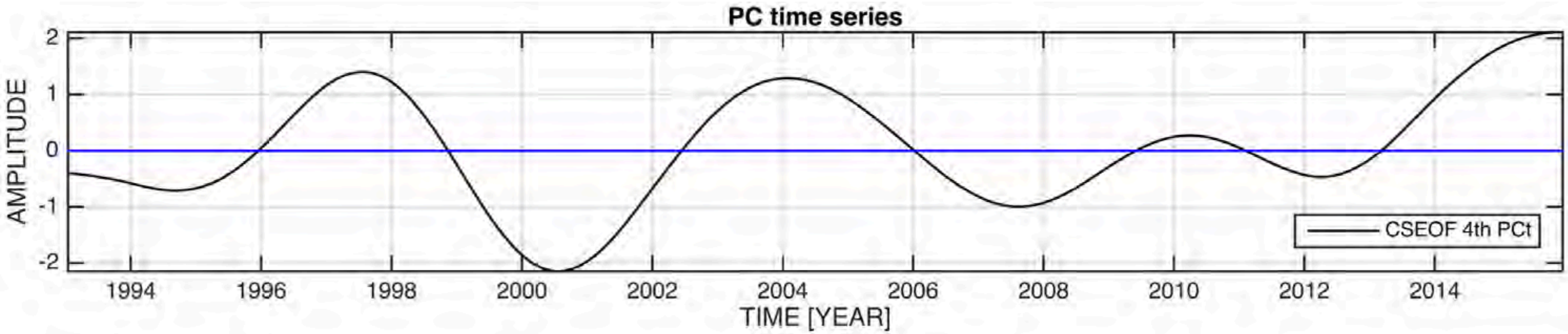


CSEOF Decomposition of Satellite Altimetry Record

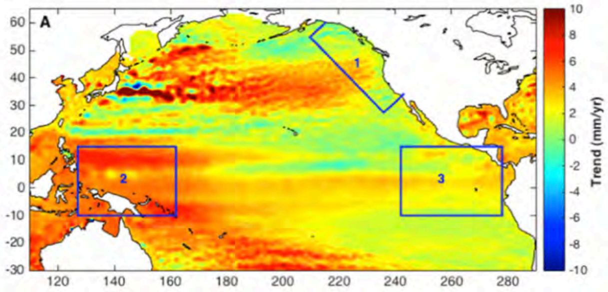


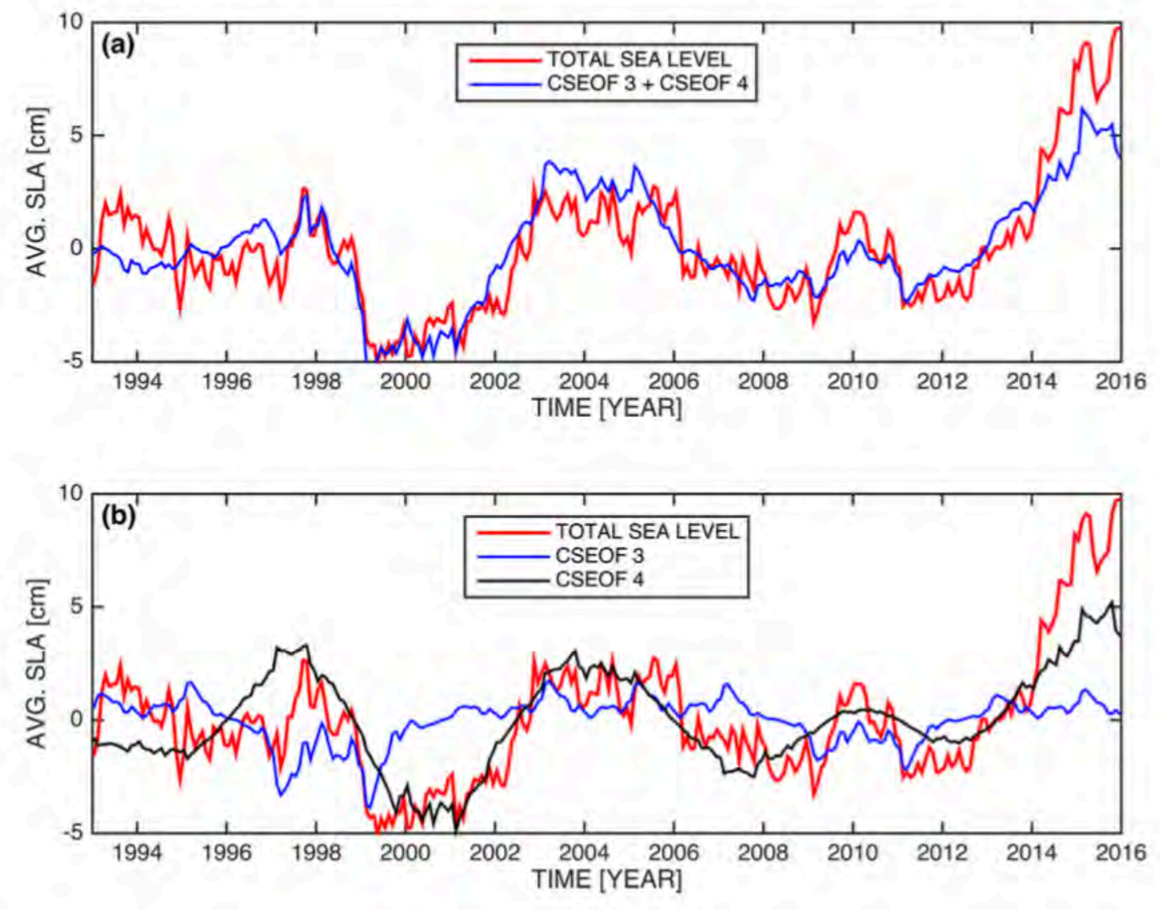
CSEOF Decomposition of Satellite Altimetry Record

- Consistent pattern in LVs (i.e. no sign change) indicates timescales longer than nested period of two years.
- Shows a similar pattern to the Pacific Decadal Oscillation (PDO) “horseshoe” in the northeastern Pacific (although we do not call this a “PDO” mode). Here, we just refer to it as a ‘low frequency mode’.
- PCTS shows some agreement with PDO index (correlation ~0.7).
  - PDO index is first EOF of SST in north Pacific – no attempt to separate variability from other signals.
  - Both time series show sharp increase since 2011.



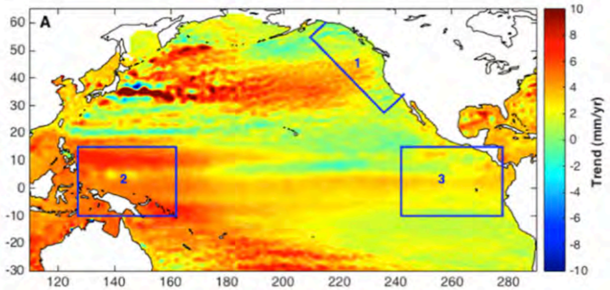
Contribution to Regional Sea Level

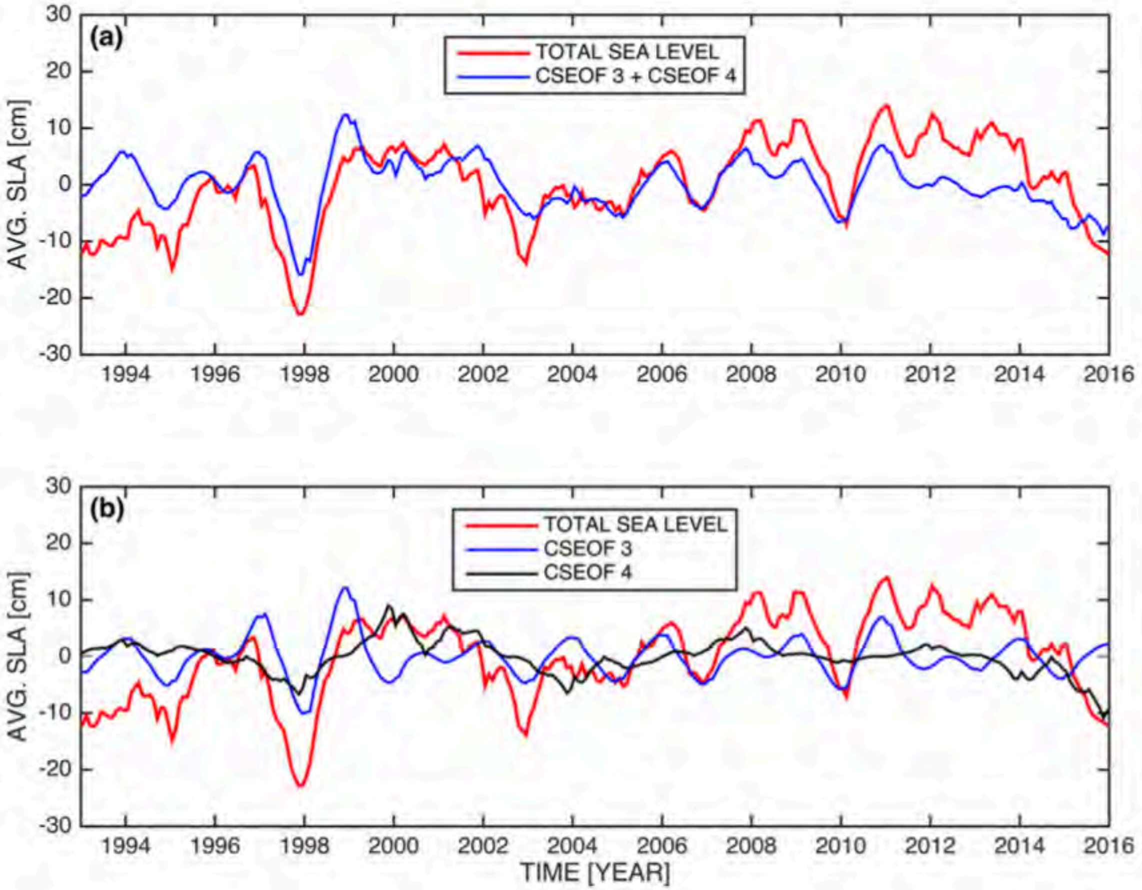




Variability dominated by low-frequency mode (mode 4).

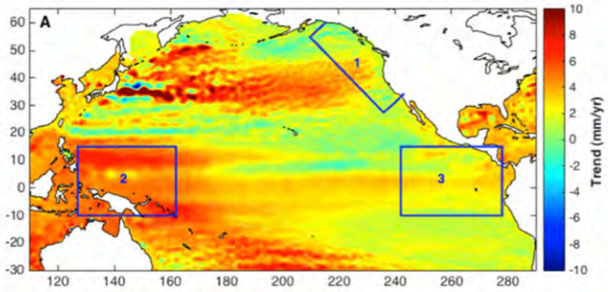
Contribution to Regional Sea Level



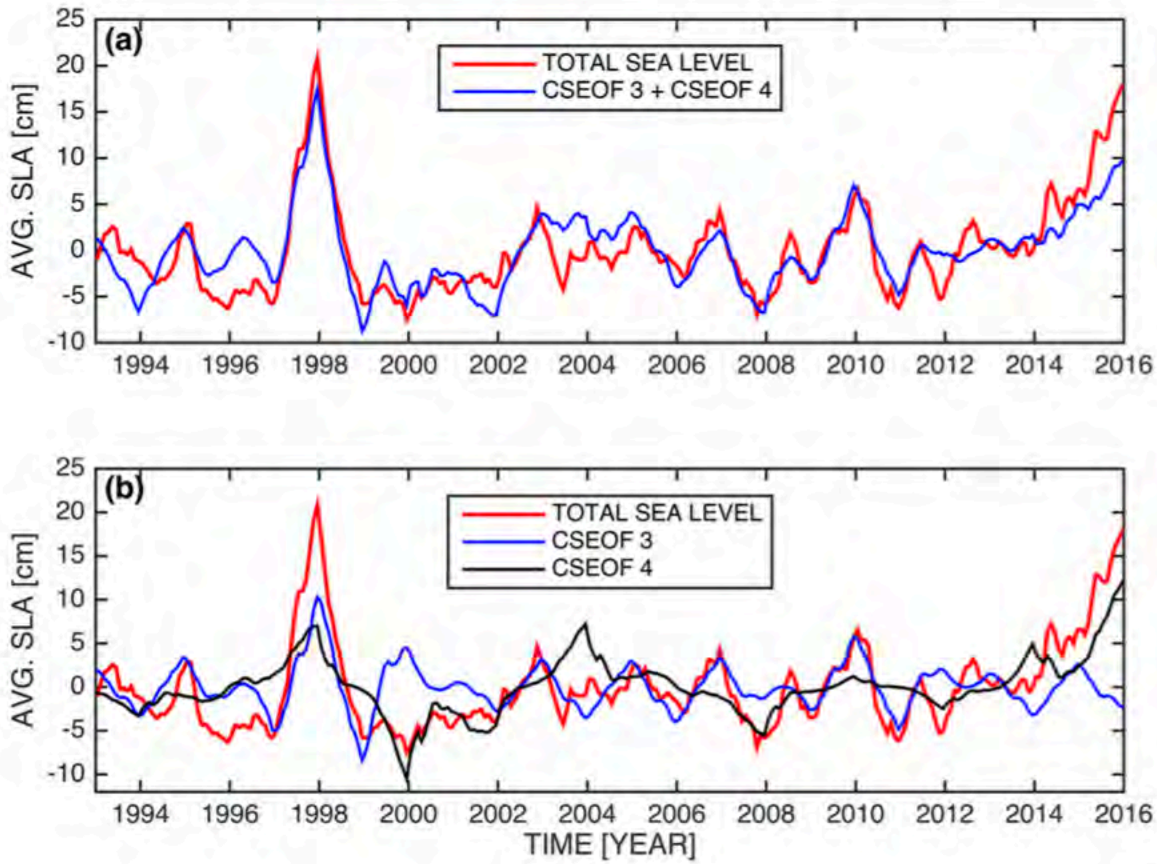


Both modes contribute, although recent dip explained by low frequency mode.

Contribution to Regional Sea Level



Again, low frequency mode explains recent increase in sea level.



Pre-altimeter Variability

- What did these modes look like before the altimeter time period?
- To answer this question and provide context for the variability during the altimeter time period, we can use a sea level reconstruction → need a reconstruction that represents internal variability well.

Aside: Reconstructing Sea Level

- In general, when creating a sea level reconstruction, you can either:

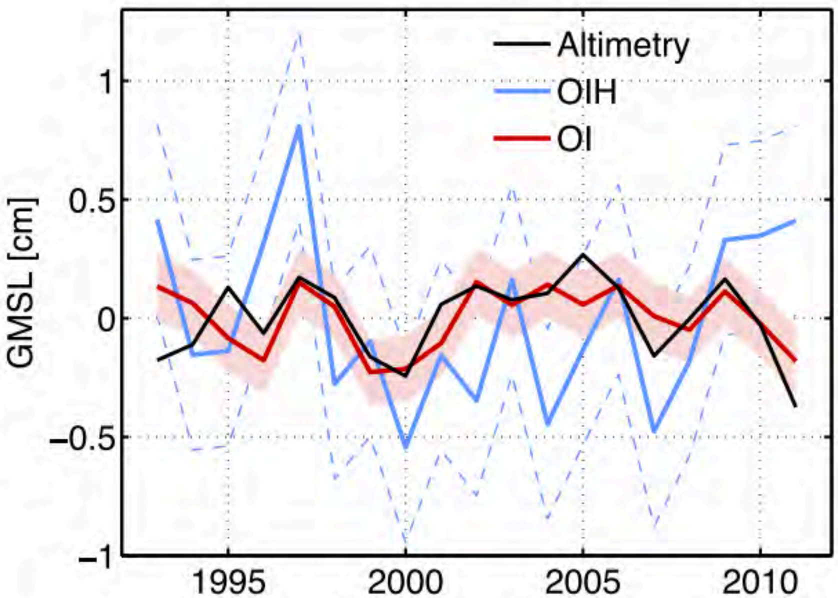
(A) Reconstruct the trend in GMSL

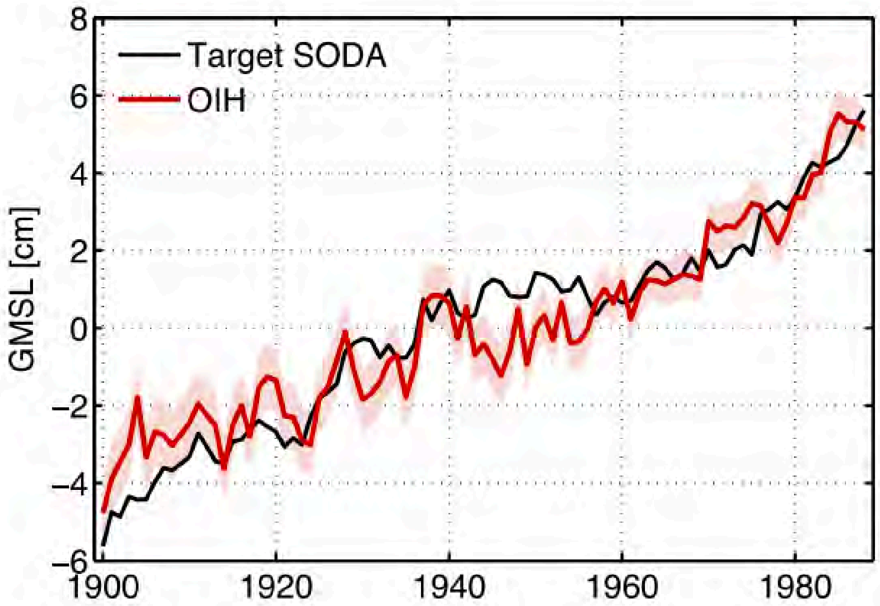
or

(B) Reconstruct the internal variability

- Why not do both?
  - When computing EOFs used in the reconstruction, the trend in GMSL is typically removed → There is then no basis function to capture the trend in GMSL.
  - Introduce "EOF0", and remove the GMSL contribution of the other EOFs.
  - The low number of available "high quality gauges" in past reduces the amount of variability you can fit.

The Problem with “EOF0”





(Calafat et al., 2014)

- If you don’t include EOF0, you will improve the representation of the internal variability in the reconstruction, but will lose the background trend.
- If you include EOF0, you will reconstruct the trend, but will not accurately represent internal variability.

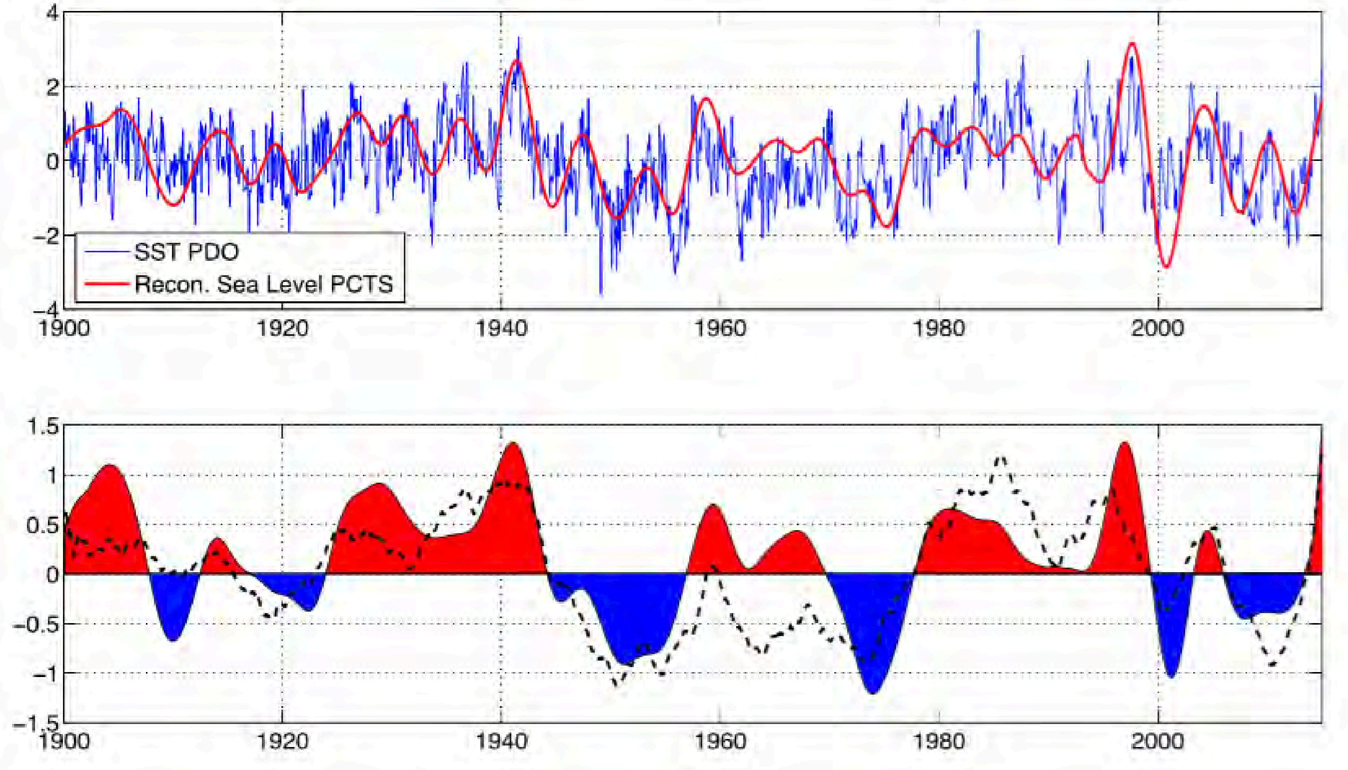
Pre-altimeter Variability

- Here we use a CSEOF-based reconstruction from 1900 to 2015.
  - A single CSEOF explains more variance than a single EOF → can fit more variability back through time.
  - Use SST measurements to improve reconstruction in past.
  - Reconstruct Indo-Pacific and Atlantic separately.
  - Do not account for long-term trend → no EOF0 or any other attempt to capture the trend.
  - All of these decisions should lead to improved representation of internal variability.

Reconstructing CSEOF Modes

Run a two-year CSEOF analysis on the full reconstruction → 2nd mode corresponds to low frequency mode obtained from altimetry (LVs not shown).

Good agreement with phase changes of smoothed PDO index (dashed line; bottom).

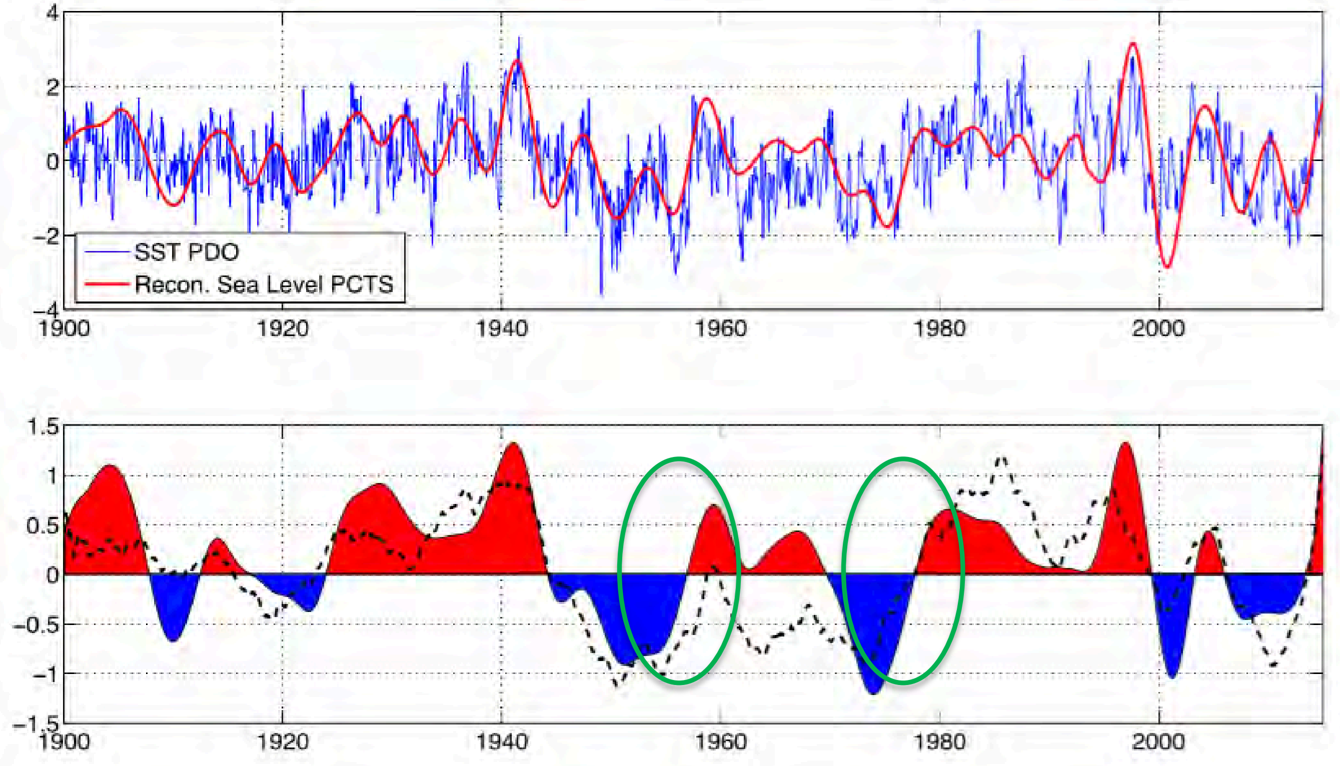


Note, the largest trends will occur during the transition between phases, not simply when the mode is in one phase or the other.

Reconstructing CSEOF Modes

Run a two-year CSEOF analysis on the full reconstruction → 2nd mode corresponds to low frequency mode obtained from altimetry (LVs not shown).

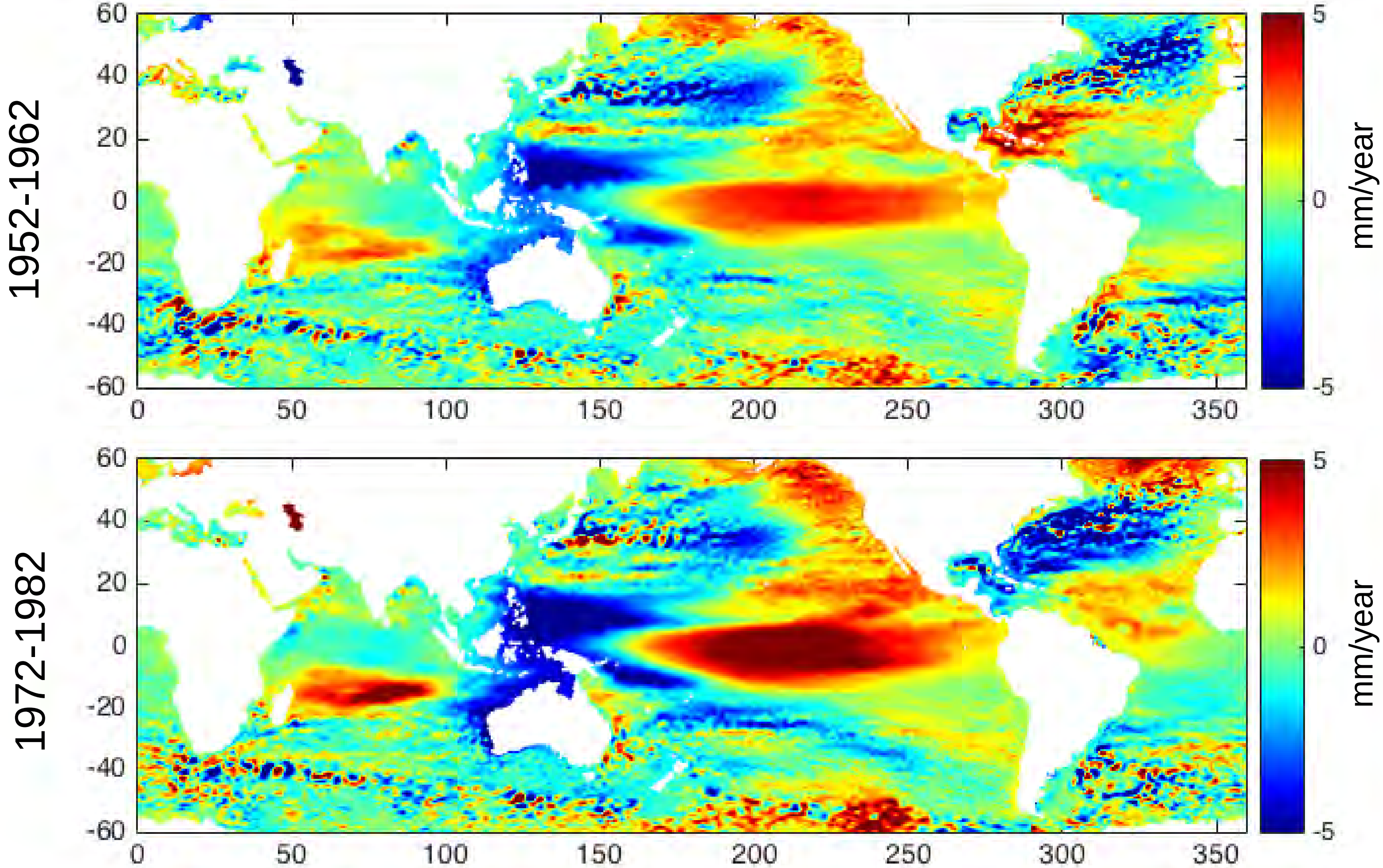
Good agreement with phase changes of smoothed PDO index (dashed line; bottom).



Note, the largest trends will occur during the transition between phases, not simply when the mode is in one phase or the other.

Reconstructing CSEOF Modes

Past shifts in in the decadal mode show a trend pattern very similar to what has bene observed in the satellite altimetry.

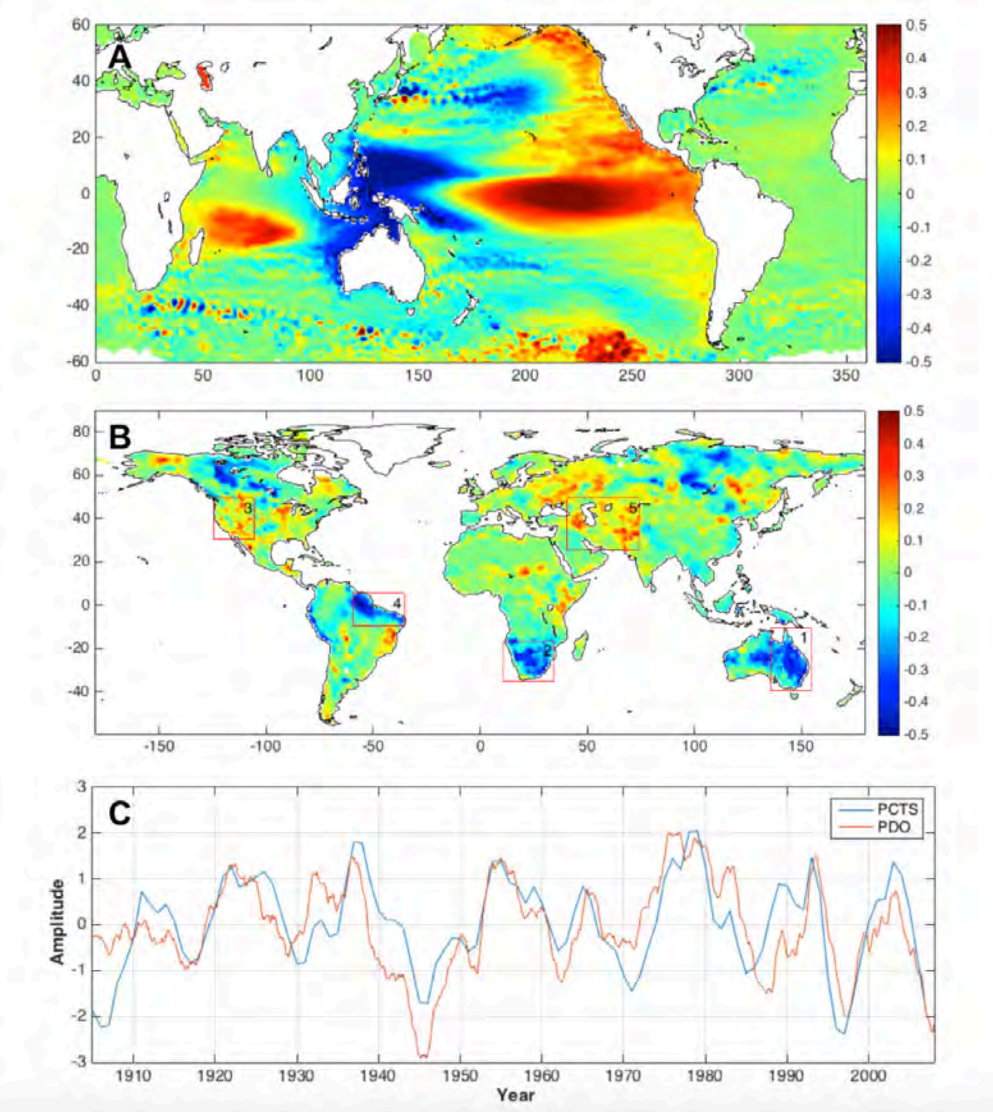


Impact on GMSL

- These comparisons suggest that the regional trends observed in the past few years will persist for several more years.
- Does this decadal variability have an impact on GMSL?
- Reager et al. [2016] found that decadal variability in climate-driven terrestrial water storage (TWS) has served to suppress GMSL rise from 2002-2014 (~0.3 mm/year).
- What are the climate signals driving the TWS trends? Is there a link to the signal just discussed?
- To answer this, we do a combined analysis of the CSEOF sea level reconstruction and the Global Land and Data Assimilation System Version 2 (GLDAS-2) terrestrial water storage data.

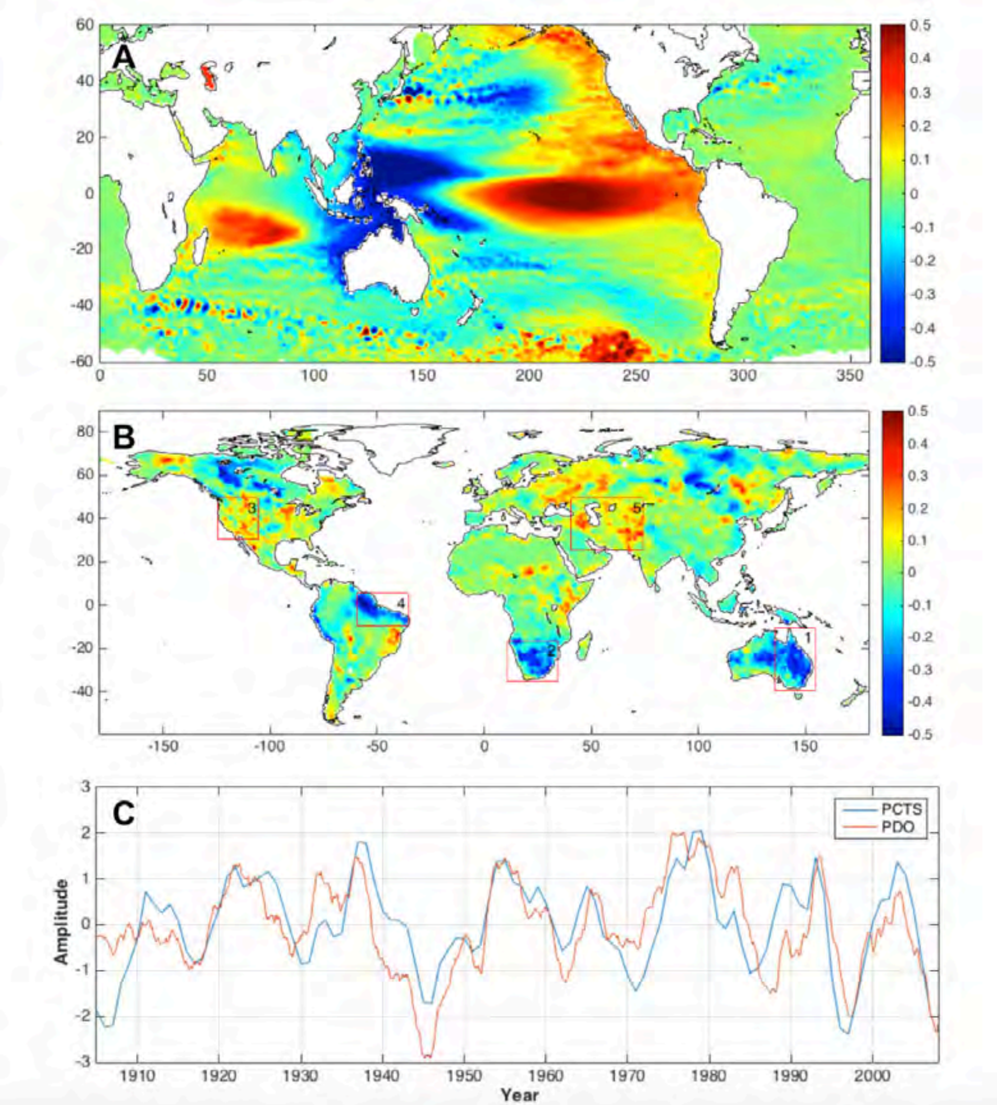
Decadal Variability in Sea Level and TWS

1. Compute 10-year trend patterns from the sea level reconstruction from 1900 to 2014 → 104 sea level trend patterns.
2. Perform an EOF decomposition of these trend patterns to determine the “dominant” 10-year trend pattern (A).
3. Project the PCTS associated with this mode onto the 10-year TWS trend patterns computed from GLDAS-2 (B).
4. Compute the contribution to GMSL from the two separate modes (sea level and TWS).

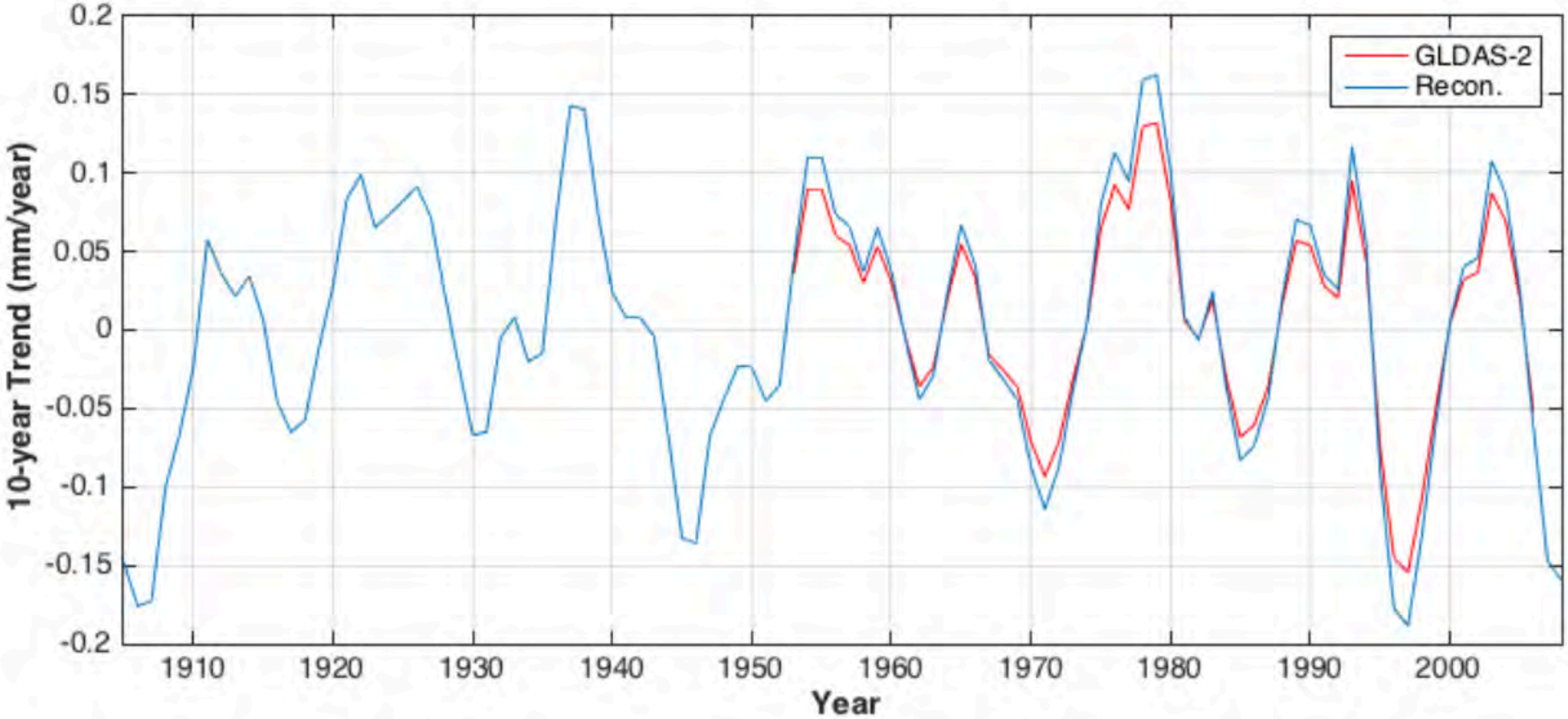


Decadal Variability in Sea Level and TWS

- PCTS has a 0.71 correlation with the 10-year trends in the PDO from 1900 to 2014 (bottom).
- During the altimeter time period, the PCTS shows that we have been in the negative phase of this mode → consistent with observed trends.
- Decadal sea level trends are dominantly driven by decadal variability in the Pacific.
- Spatial pattern of decadal TWS variability agrees with Reager et al. [2016] obtained from GRACE.



Decadal Variability in Sea Level and TWS



- Excellent agreement between GMSL 10-year trend contributions of GLDAS-2 and reconstruction on decadal timescales.
- Signal has suppressed global sea level rise from 2002-2012, consistent with Reager et al. [2016].

Putting it All Together…

- There is an apparent ongoing shift in sea level in the Pacific Ocean associated with a change in phase of decadal variability.
- This shift will lead to increased decadal trends off the coast of California and lower trends in the western tropical Pacific (already observing this).
- This same decadal sea level variability is associated with variability in TWS, which will likely lead to a positive contribution to GMSL in the coming decade.
- Australia, southern Africa, and the Amazon will likely see an extended reduction in TWS, while much of the United States and western Asia will see increased TWS.