
# Uncovering an Anthropogenic Sea Level Rise Signal in the Pacific Ocean

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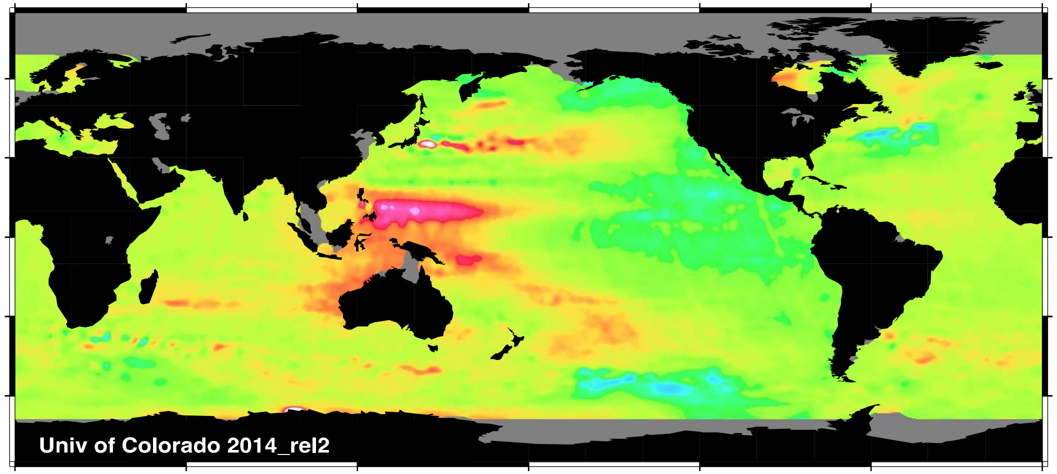
# Overview

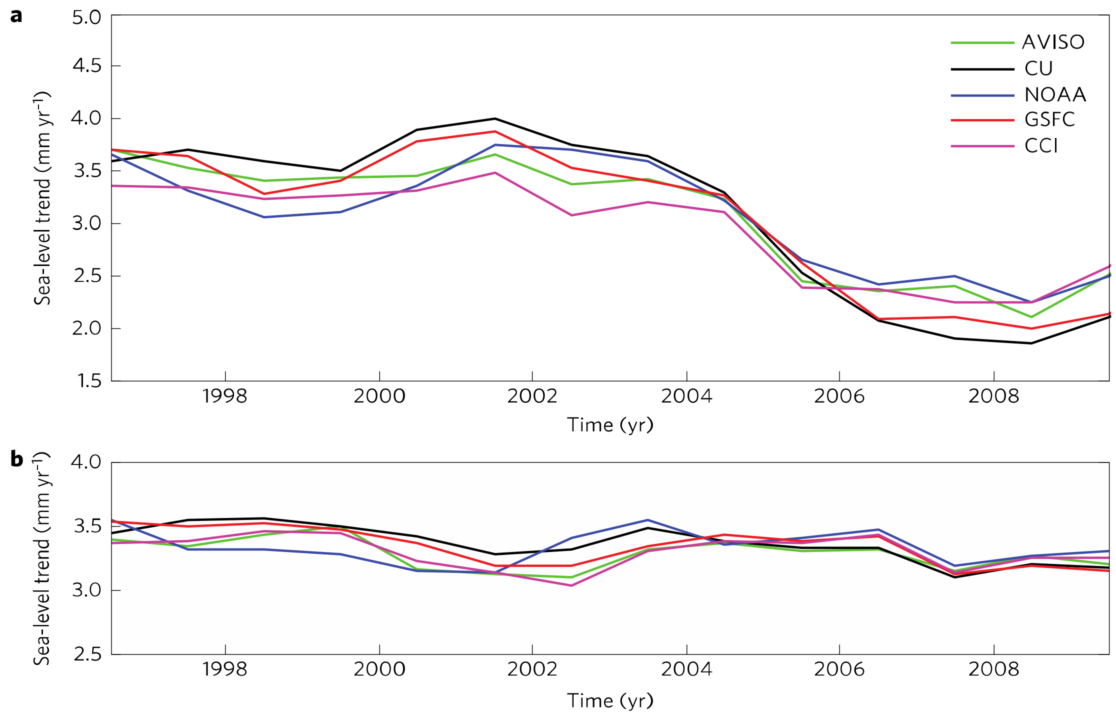
- **Why do we care about internal climate variability on interannual to decadal timescales when studying sea level trends?**

- **Satellite records have only recently reached two decades in length.**
- Internal climate variability is likely a significant contributor to the satellite-altimetry observed trend pattern.
  - Understanding this climate variability can improve our understanding of sea level trends.
- Climate signals like ENSO and the PDO can serve to heighten the impact of secular sea level rise depending on strength and phase.



# Overview

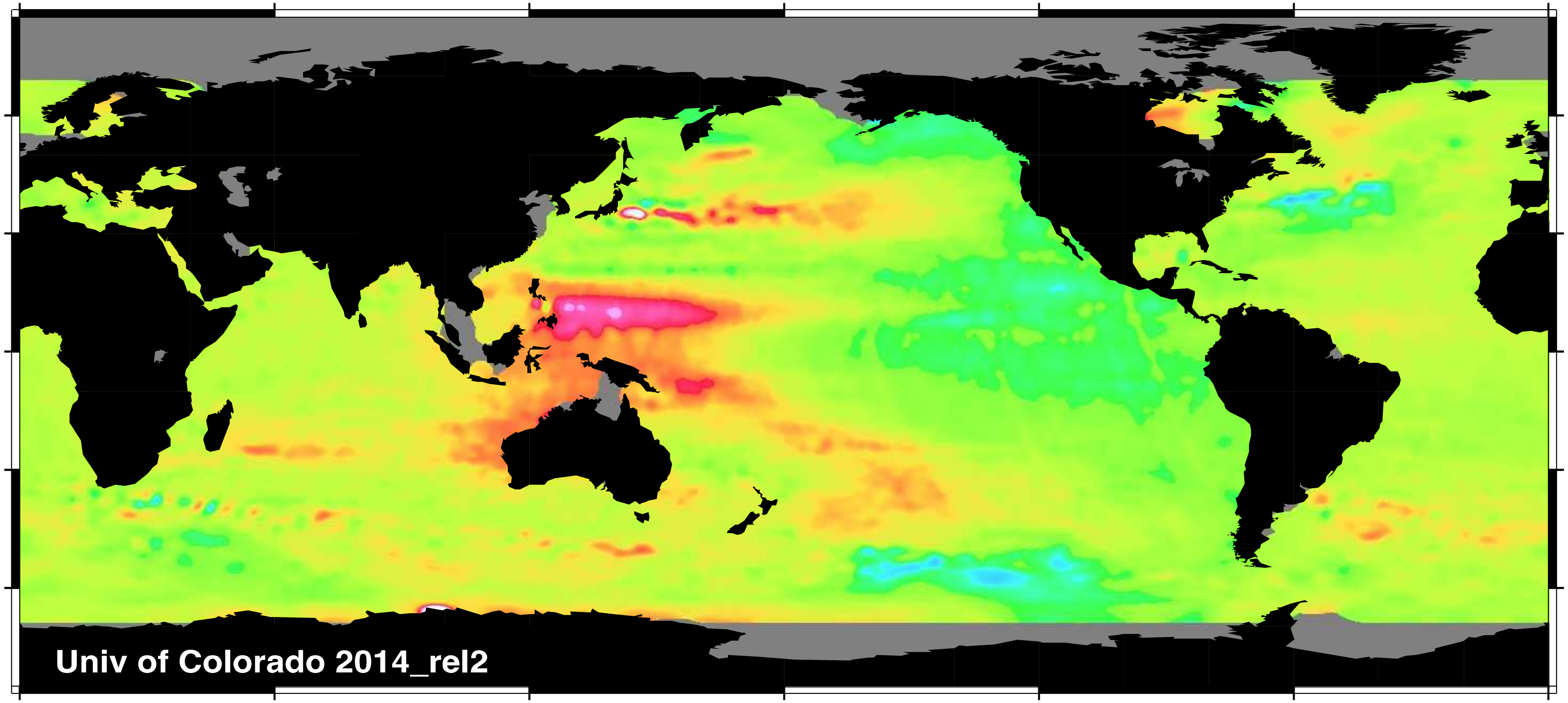
- Internal variability on interannual to decadal timescales can also obscure the underlying trends in sea level.
  - Cazenave et al (2014) demonstrated how removing this variability can change our understanding of the altimeter-measured trends.
  - Extracting and removing sea level trends related to internal variability can potentially help uncover the anthropogenic trends in sea level, both regionally and globally.




a) GMSL rate computed over five-year long moving window. b) Five-year GMSL trends after correcting for interannual variability (Cazenave et al., 2014).

# Pacific Sea Level Trend Variability

- **In recent years, there has been a focus on the regional trends in the Pacific Ocean and more specifically the Pacific Decadal Oscillation.**



# Pacific Sea Level Trend Variability

- **Recent Papers (to list just a few, apologies to those I missed):**
  - **Multidecadal sea level anomalies and trends in the western tropical Pacific**, Merrifield et al. 2012
  - **Sea level trends, interannual and decadal variability in the Pacific Ocean**, Zhang and Church, 2012
  - **Sea level: a review of present-day and recent-past changes and variability**, Meyssignac et al. 2012
  - **Understanding North Pacific sea level trends**, Bromirski et al., 2012
  - **Tropical Pacific spatial trend patterns in observed sea level: internal variability and/or anthropogenic signature?**, Meyssignac et al., 2012
  - **Contribution of the Pacific Decadal Oscillation to global mean sea level trends**, Hamlington et al., 2013
  - **Intensification of decadal and multi-decadal sea level variability in the western tropical Pacific during recent decades**, Han et al. 2013
  - **Quantifying recent acceleration in sea level unrelated to internal climate variability**, Calafat et al., 2013
  - **Wind-driven coastal sea level variability in the Northeast Pacific**, Thompson et al., 2014
  - **Uncovering an anthropogenic sea-level rise signal in the Pacific Ocean**, Hamlington et al. 2014

# Pacific Sea Level Trend Variability

- Many of these studies have been driven by the following three questions:

  1) How have regional sea level trend patterns changed during the past few decades?

  2) What are the characteristic timescales of changes in the sea level trend pattern?

  3) What are the factors driving the changes in the trend pattern?

- Here, we focus on the same three questions by analyzing the trends in the CSEOF sea level reconstruction.

# CSEOF Sea Level Reconstruction

- CSEOF-based sea level reconstruction from 1950 to 2010 is publicly available through NASA JPL PO.DAAC.
- Based on a recent study (Strassburg et al., 2014), in an idealized setting, the CSEOF-based reconstruction better represents climate variability when compared to a similarly computed EOF-reconstruction (primary difference is set of basis functions).

CSEOF Reconstruction

| | GMSL | PDO | AMO | Nino3 | Nino4 |
|---|---|---|---|---|---|
| 1900s (61 tide gauges) | 0.773 | 0.656 | 0.850 | 0.927 | 0.907 |
| 1920s (76 tide gauges) | 0.812 | 0.654 | 0.868 | 0.936 | 0.923 |
| 1940s (108 tide gauges) | 0.872 | 0.685 | 0.902 | 0.975 | 0.954 |
| 1960s (243 tide gauges) | 0.878 | 0.678 | 0.907 | 0.982 | 0.962 |
| 1980s (292 tide gauges) | 0.877 | 0.660 | 0.912 | 0.977 | 0.967 |
| 2000s (277 tide gauges) | 0.888 | 0.644 | 0.911 | 0.970 | 0.965 |
| All gauges (412 tide gauges, 70% variance explained with 11 modes) | 0.886 | 0.651 | 0.911 | 0.979 | 0.967 |
| Ideal Grid (410 tide gauges) | 0.909 | 0.628 | 0.926 | 0.983 | 0.977 |
| Basin Edges (342 tide gauges) | 0.883 | 0.655 | 0.906 | 0.975 | 0.957 |
| Northern Hemisphere Grid (411 tide gauges) | 0.906 | 0.635 | 0.924 | 0.981 | 0.971 |
| Southern Hemisphere Grid (393 tide gauges) | 0.910 | 0.657 | 0.928 | 0.975 | 0.979 |
| All gauges with noise | 0.886 | 0.658 | 0.910 | 0.977 | 0.967 |
| All gauges (90% variance explained with 16 modes) | 0.953 | 0.655 | 0.958 | 0.984 | 0.980 |
| All gauges (90% variance) with noise | 0.953 | 0.666 | 0.957 | 0.982 | 0.980 |
| Atlantic Reconstruction | 0.905 | | 0.927 | | |
| Pacific Reconstruction | 0.931 | 0.621 | | 0.976 | 0.971 |

EOF Reconstruction

| | GMSL | PDO | AMO | Nino3 | Nino4 |
|---|---|---|---|---|---|
| 1900s (61 tide gauges) | 0.112 | 0.018 | 0.095 | 0.226 | 0.042 |
| 1920s (76 tide gauges) | 0.077 | 0.131 | 0.172 | 0.150 | 0.036 |
| 1940s (108 tide gauges) | 0.059 | 0.019 | 0.138 | 0.115 | 0.045 |
| 1960s (243 tide gauges) | 0.642 | 0.449 | 0.663 | 0.925 | 0.896 |
| 1980s (292 tide gauges) | 0.710 | 0.498 | 0.729 | 0.947 | 0.958 |
| 2000s (277 tide gauges) | 0.666 | 0.480 | 0.722 | 0.898 | 0.909 |
| All gauges (412 tide gauges, 70% variance explained with 108 modes) | 0.716 | 0.519 | 0.765 | 0.950 | 0.970 |
| Ideal Grid (410 tide gauges) | 0.883 | 0.578 | 0.886 | 0.991 | 0.981 |
| Basin Edges (342 tide gauges) | 0.635 | 0.451 | 0.686 | 0.851 | 0.656 |
| Northern Hemisphere Grid (411 tide gauges) | 0.874 | 0.595 | 0.906 | 0.992 | 0.990 |
| Southern Hemisphere Grid (393 tide gauges) | 0.853 | 0.554 | 0.856 | 0.953 | 0.914 |
| All gauges with noise | 0.689 | 0.467 | 0.701 | 0.935 | 0.953 |
| All gauges (90% variance explained with 237 modes) | 0.811 | 0.534 | 0.817 | 0.953 | 0.973 |
| All gauges (90% variance) with noise | 0.684 | 0.418 | 0.556 | 0.887 | 0.943 |
| Atlantic Reconstruction | 0.550 | | 0.624 | | |
| Pacific Reconstruction | 0.682 | 0.406 | | 0.928 | 0.959 |

# Overview

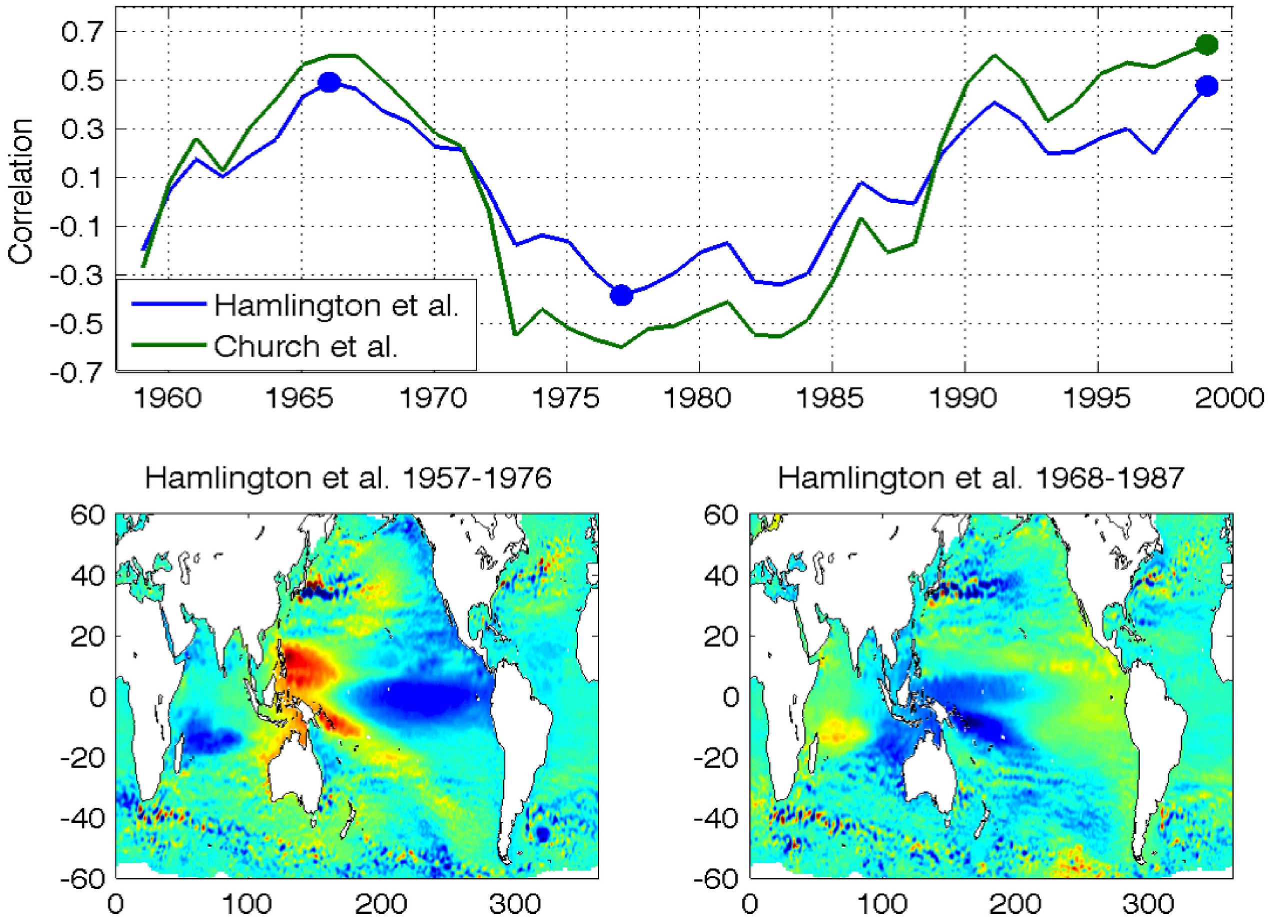
- As a first test, two different sea level reconstructions were used:

  1. **Hamlington et al. [2011] Cyclostationary Empirical Orthogonal Function (CSEOF) reconstruction.**
  2. **Church and White et al. [2004; 2011] EOF Reconstruction.**

- Twenty-year trend maps were computed from the two reconstructed datasets (CSEOF and EOF reconstructions).
- Resulted in 41 trend maps from 1950 to present for each reconstruction.

# Reconstructed Regional Sea Level Trends

- Correlation between the regional trend map from the AVISO dataset and twenty-year trend patterns from two sea level reconstructions, Hamlington et al. (blue) and Church and White et al. (green).
- Twenty-year trend patterns from the HRSL dataset are also shown for two different periods associated with extrema in the correlation time series.
- Question: What is the dominant 20-year spatial pattern of trends?

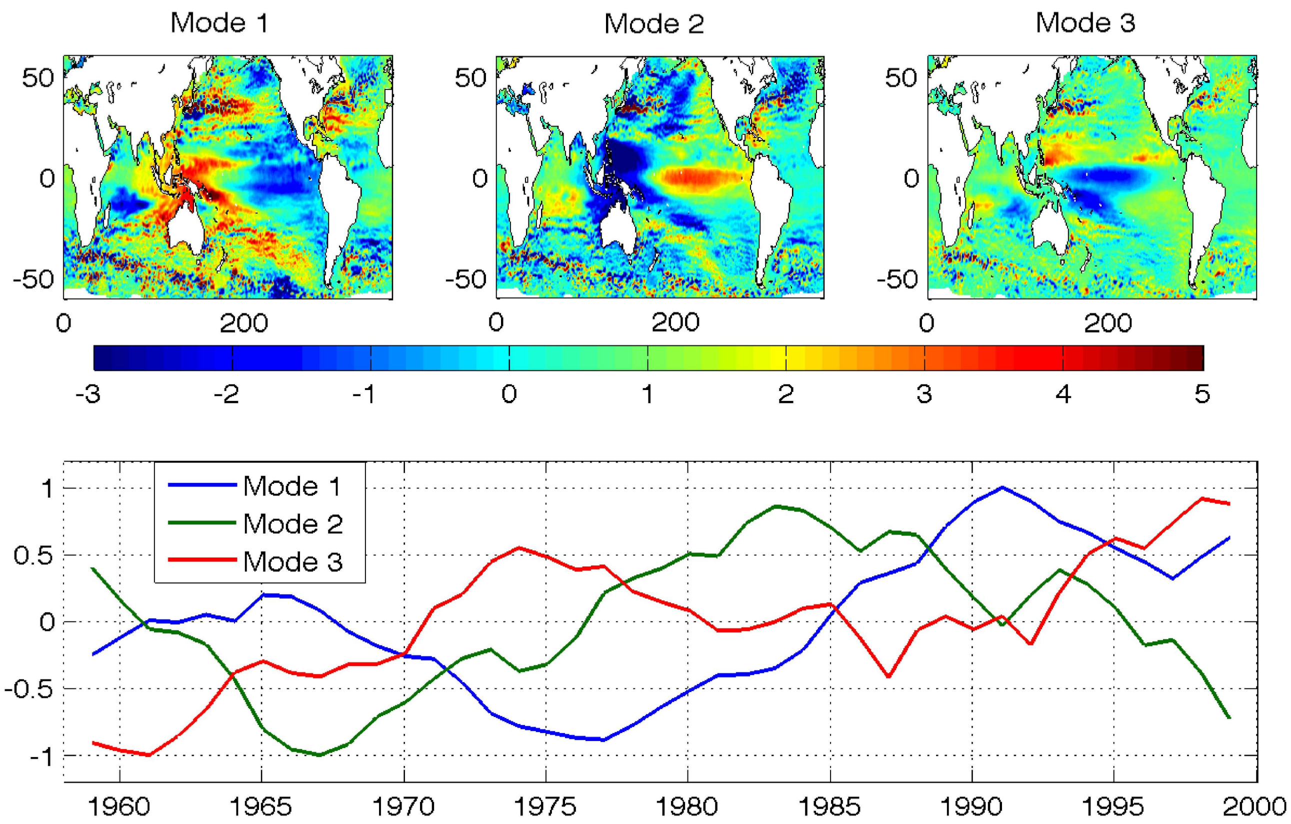


# Overview

- To determine the dominant twenty-year trend pattern over the past 60 years, we performed the following test:
    1. Create twenty-year trend maps from the reconstructed dataset → 41 trend maps from 1950 to present.
    2. Perform an EOF decomposition of the resulting twenty-year trend maps.
- This approach was motivated by Meyssignac et al. (2012) who looked at 17-year sea level trend patterns from 1950 to 2009 for the tropical Pacific Ocean.

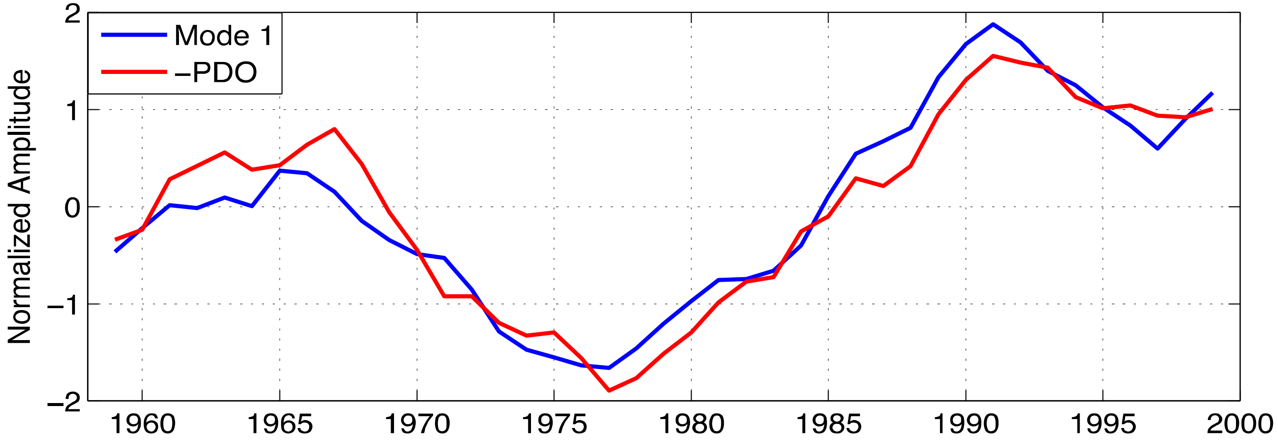
# EOF Analysis of 20-year Trends

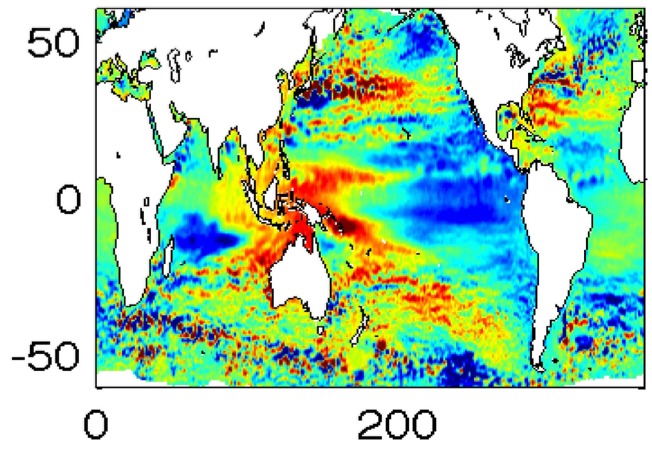
- Resulting principal component time series (PCTS) and loading vectors (LV) for first three modes are shown.
  - Explain 40%, 31% and 13%, respectively, of the total variance.
- Can we attribute these modes to natural climate variability?



# Relationship to the PDO

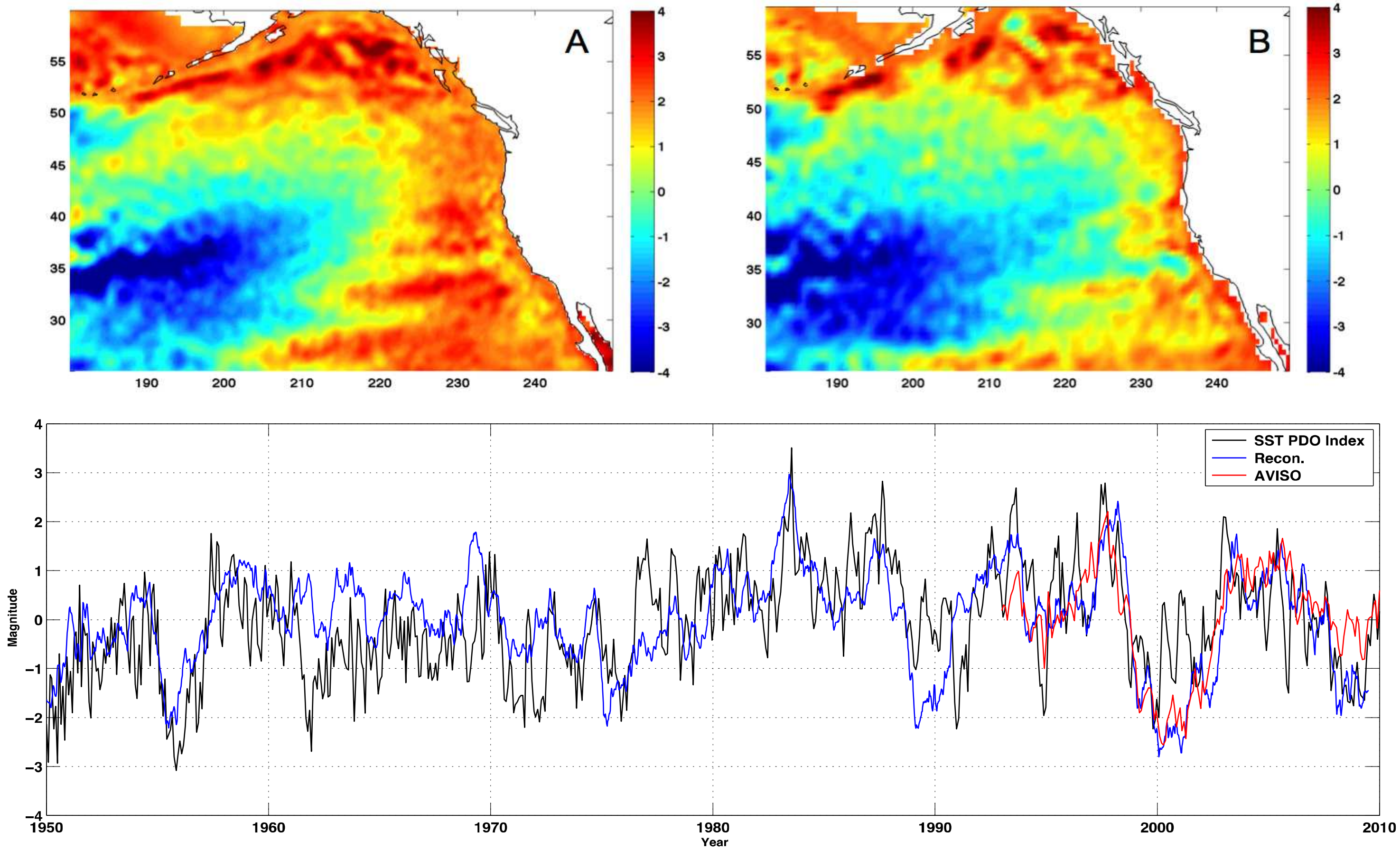
- Comparing the first mode PCTS with the twenty-year trends in the PDO index yields a correlation over the past 60-years of 0.96.
- Qualitatively, the spatial pattern of the first mode agrees well with the PDO in the North Pacific.



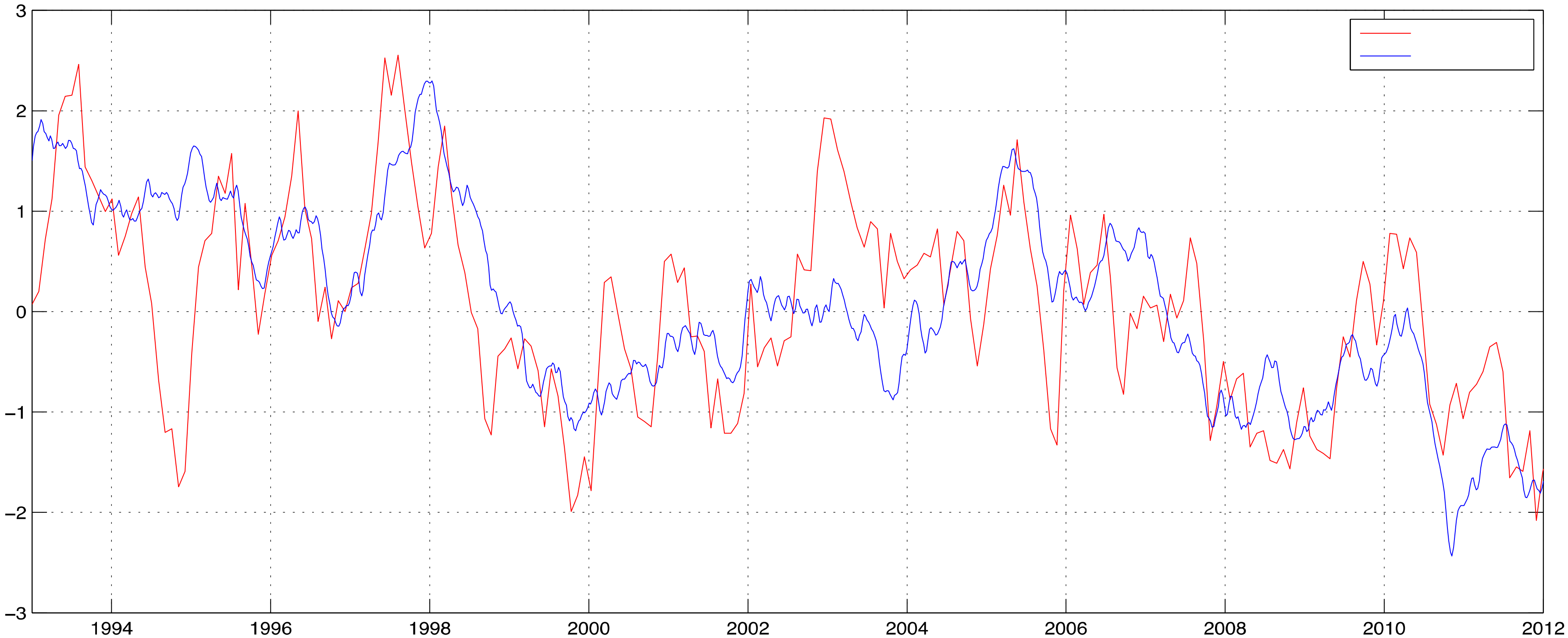
# PDO: AVISO vs. Reconstruction

- As an additional check, we computed the PDO from both the AVISO data and the reconstruction.
- SSH PDO index is created by computing the first EOF of the NE Pacific for (A) AVISO data, (B) CSEOF sea level reconstruction.
- PDO index computed from SST data is also shown for comparison



# PDO and Regional Sea Level Trends

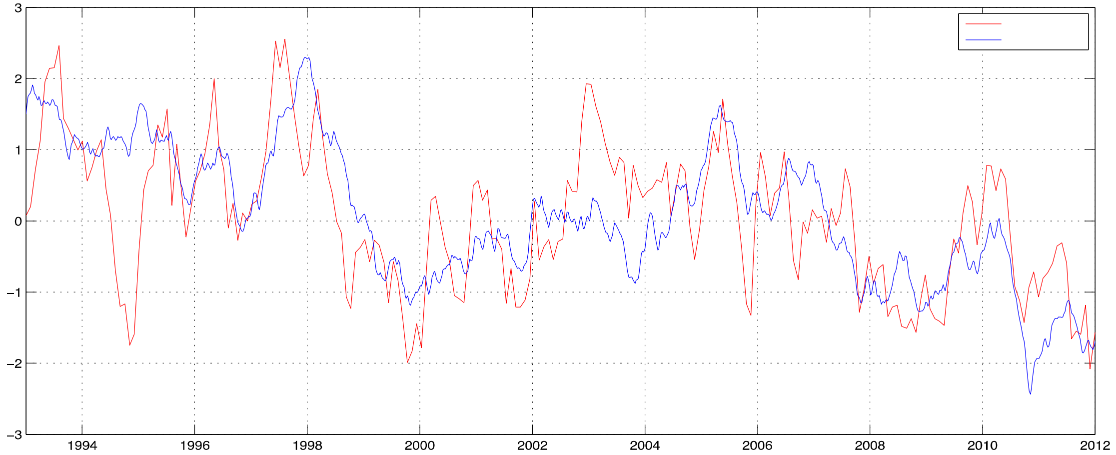
- To evaluate the contribution of the PDO to regional trends in the past 20 years, we project the leading trend EOF LV (time independent and dimensionless) on to the AVISO satellite altimetry data.



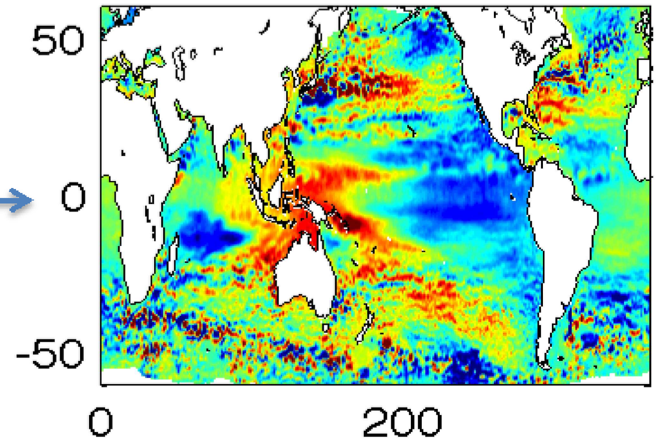
# PDO and Regional Sea Level Trends

- The projected PCTS is combined with the first trend EOF and the linear trend is computed at each point across the globe.

Projected PCTS



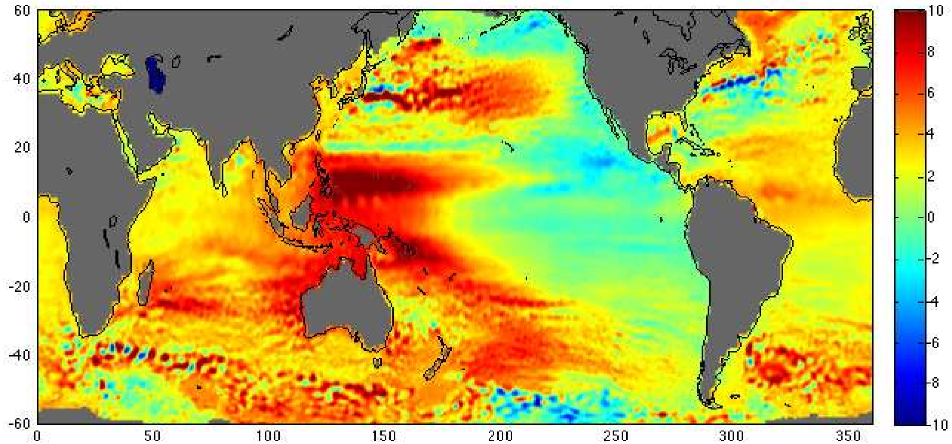

Trend EOF

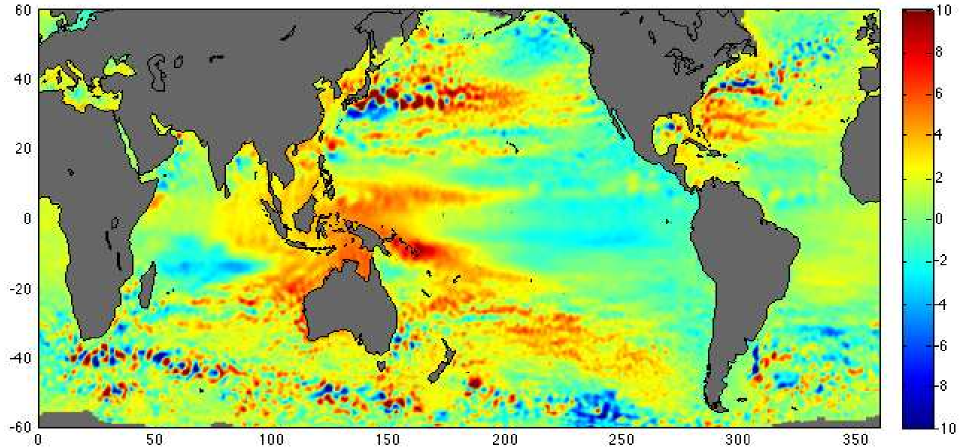


# PDO and Regional Sea Level Trends

- Combining PCTS from the projection with spatial pattern of PDO trend EOF LV, we can estimate the 20-year regional trend pattern (units of mm/yr) associated with the PDO (bottom).

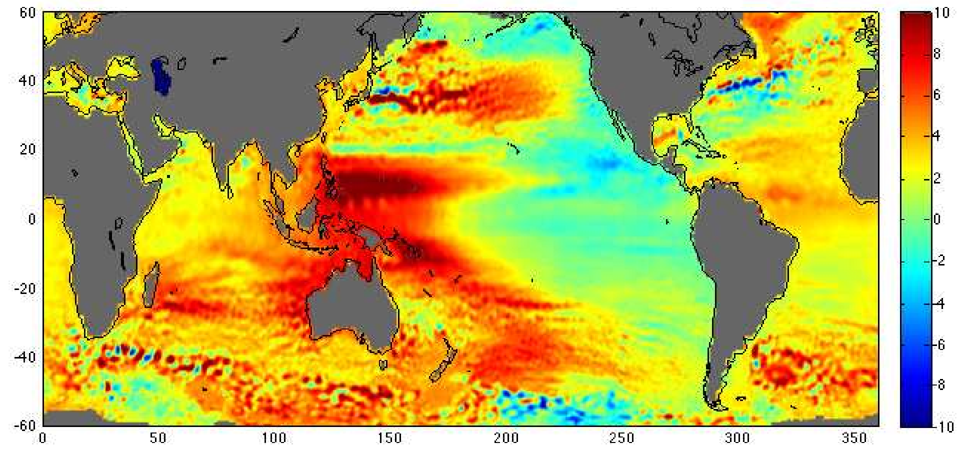
- Trends from the AVISO data from 1993 to 2013 are shown for comparison (top).

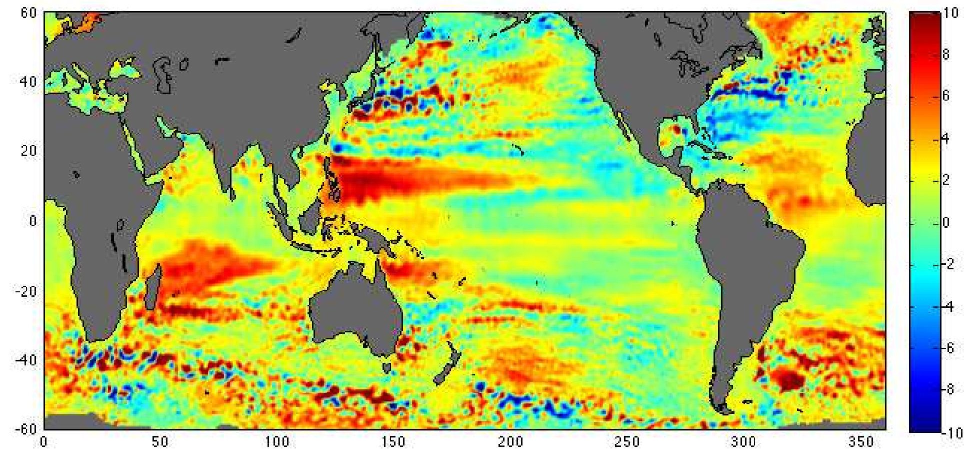


# PDO and Regional Sea Level Trends

- Finally, we can subtract the trend map from the previous slide from the AVISO trend map (top), to obtain the regional trends during the last twenty years with the contribution of the PDO removed (bottom).
  - Removing the contribution of natural variability helps isolate the secular (non-periodic) trends in sea level.
- Can we attribute the residual trend pattern to anthropogenic warming (or anything)?



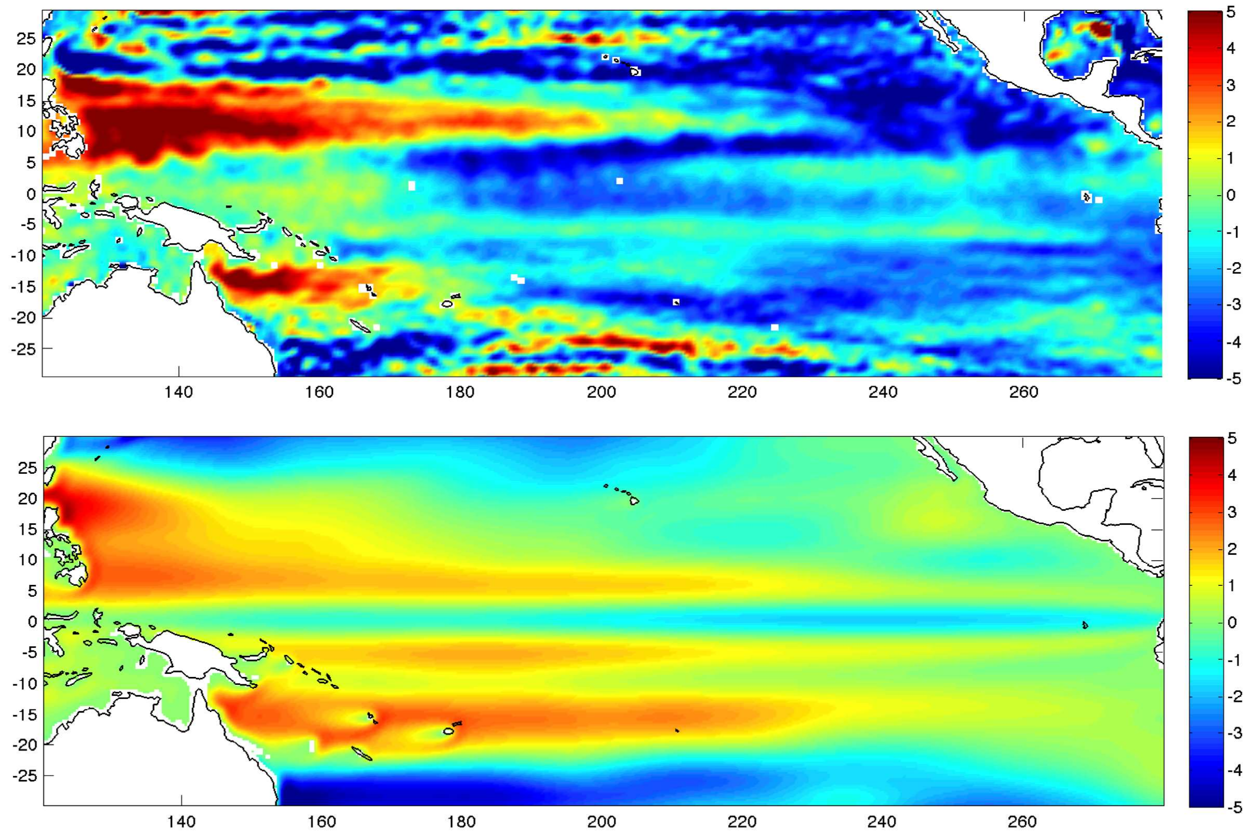



# PDO and Regional Sea Level Trends

- Han et al. (2013) demonstrates that tropical Indian Ocean (TIO) warming acts in concert with the warm western tropical Pacific (WTP) and cold central-eastern tropical Pacific to enhance the easterly trades in the central WTP, which subsequently increases the WTP sea level.
  - Also showed that in the past two decades, the in-phase relationship between the PDO and TIO has changed, with the PDO entering a negative phase and the TIO continuing to warm.
  - This change in the relationship between the TIO and PDO suggests the presence of a persistent warming trend in the TIO beyond that contributed by internal variability.
  - Previous studies (e.g. Du and Xie, 2008) have attributed the steady Indian Ocean warming since the middle of the twentieth century (~0.5◦C) to anthropogenic greenhouse gases.

# Attribution of Residual Trend Pattern

- Performed two idealized experiments with only difference of additional 0.5◦C warming in the TIO → differenced the two to isolate anthropogenic effect.
- Sea level trends (mm/year) in western tropical Pacific from (A) AVISO data minus PDO contribution (as in previous slide), and (B) linear model result obtained from 0.5°C tropical Indian Ocean warming.
- Agreement between observation result and mode result suggest attribution of (A) to anthropogenic warming.



# Summary and Conclusion

- Using the longer record provided by the sea level reconstructions, it is possible to isolate and remove internal climate variability on decadal and longer timescales.
  - Removing this variability can improve our understanding of sea level trends measured by the satellite altimeters.
- Here, we have removed the influence of the PDO from the satellite altimetry measurements and established a link between the residual pattern and anthropogenic forcing.
  - While a shift in the phase of the PDO may lead to lower rates of sea level change for Indonesia, the same may not be true for areas near the Philippines and northeastern Australia.
- With the number of studies on sea level trends in the Pacific and the sometimes differing results and conclusions of these papers, it is a topic that needs further examination and additional efforts to reach a consensus among the different approaches (and associated data/models).