RECONSTRUCTING GLOBAL MEAN SEA LEVEL FROM TIDE GAUGES USING SATELLITE ALTIMETRY

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Why reconstruct sea level?

- Tide gauges have provided sea level measurements for 200 years.
  - Tide gauges have a long record, but the spatial distribution is poor.
  - Most tide gauges are located around heavily populated areas in North America, Europe and Eastern Asia (northern hemisphere).
- Satellite altimetry has provided accurate measurements of sea level with near-global coverage and led to the first definitive estimates of global mean sea level (GMSL).
  - Modern satellite altimetry records extends back only two decades.
- As a result of the shortcomings of the tide gauge and satellite altimetry records, combining the two datasets is an active research area.
  - Near global coverage of satellite altimetry data with the long record length of the tide gauge data → 'sea level reconstruction'.

Previous Reconstructions (cont.)

- Church and White et al. (2004) provide the only publicly available reconstructed sea level dataset covering the period from 1950 to 2001.
  - Used empirical orthogonal functions to form the basis of their reconstruction with annual cycle removed.
- Parameters in the reconstruction procedure have varying levels of impact on the resulting reconstruction:
  - **Choice of basis functions,**
  - **Selection of weighting scheme,**
  - **Method of accounting for GMSL,**
  - **Selection of tide gauge editing criteria.**
- In an attempt to improve current sea level reconstructions, we address the four points above and propose a new reconstruction method for combining satellite altimetry data and in situ tide gauge data.

Basis Functions: CSEOF vs. EOFs

- Previous attempts at reconstructing sea level have used EOFs as basis functions.
  - Techniques like EOF analysis do not accommodate time-dependent spatial patterns and, therefore, enforce stationarity.
  - EOFs are prone to mode mixing, particularly with regards to the annual signal.
- To address this problem, Kim et al. (1996; 2001) introduced the concept of cyclostationary empirical orthogonal function (CSEOF) analysis.
  - CSEOF analysis has been shown to extract the annual and ENSO signals from the satellite altimetry data (Hamlington et al., 2010).
  - By using CSEOFs in place of EOFs, an alternative and improved reconstruction could be computed.

Basis Functions: CSEOF vs. EOFs

- In traditional EOF analysis, space-time data are represented in terms of **loading vectors** (LVs) and their **principal components** (PC).

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

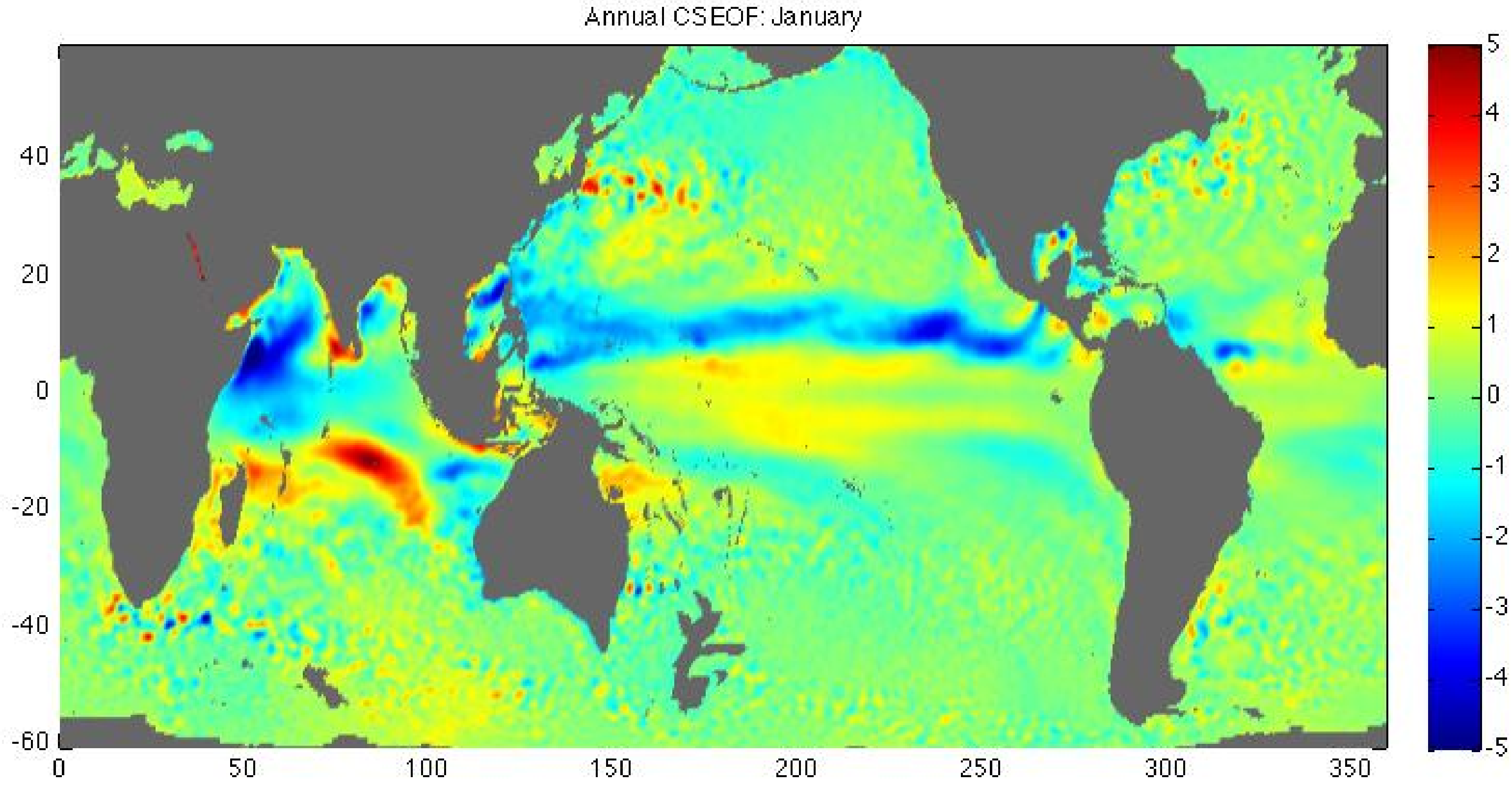
  - LVs represent spatial patterns of variability, PC time series represents temporal evolution of these patterns.
- CSEOFs, however, have time-dependent LVs.
  - The temporal evolution of the spatial pattern of CSEOF LVs is constrained to be periodic with a **"nested period"**.

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

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

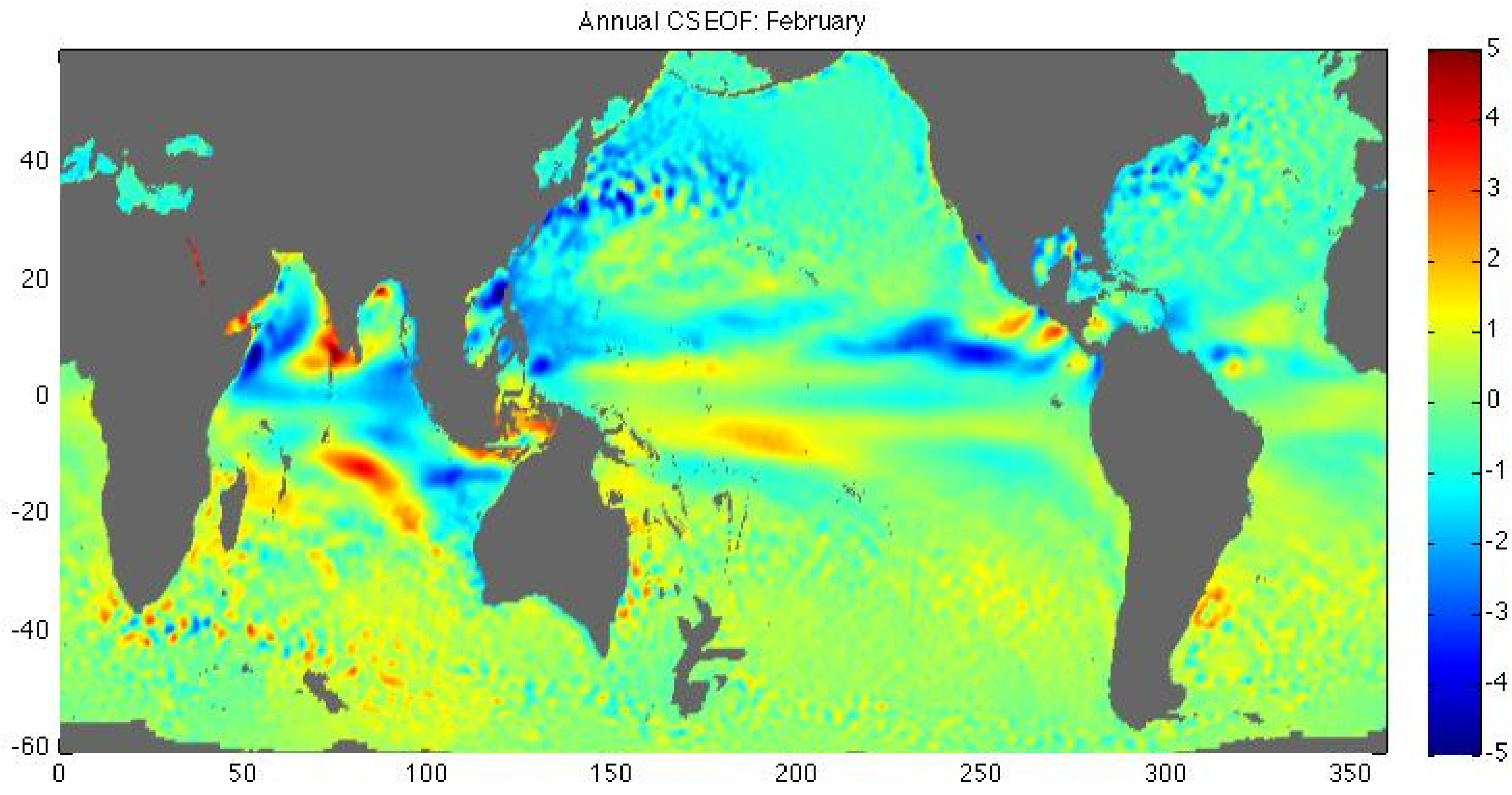
  - When studying the annual cycle, for example, the LVs would contain the one-year nested periodicity, while the PC times series would describe the change in amplitude of the annual cycle over time.

CSEOF Basis Function: Annual Signal

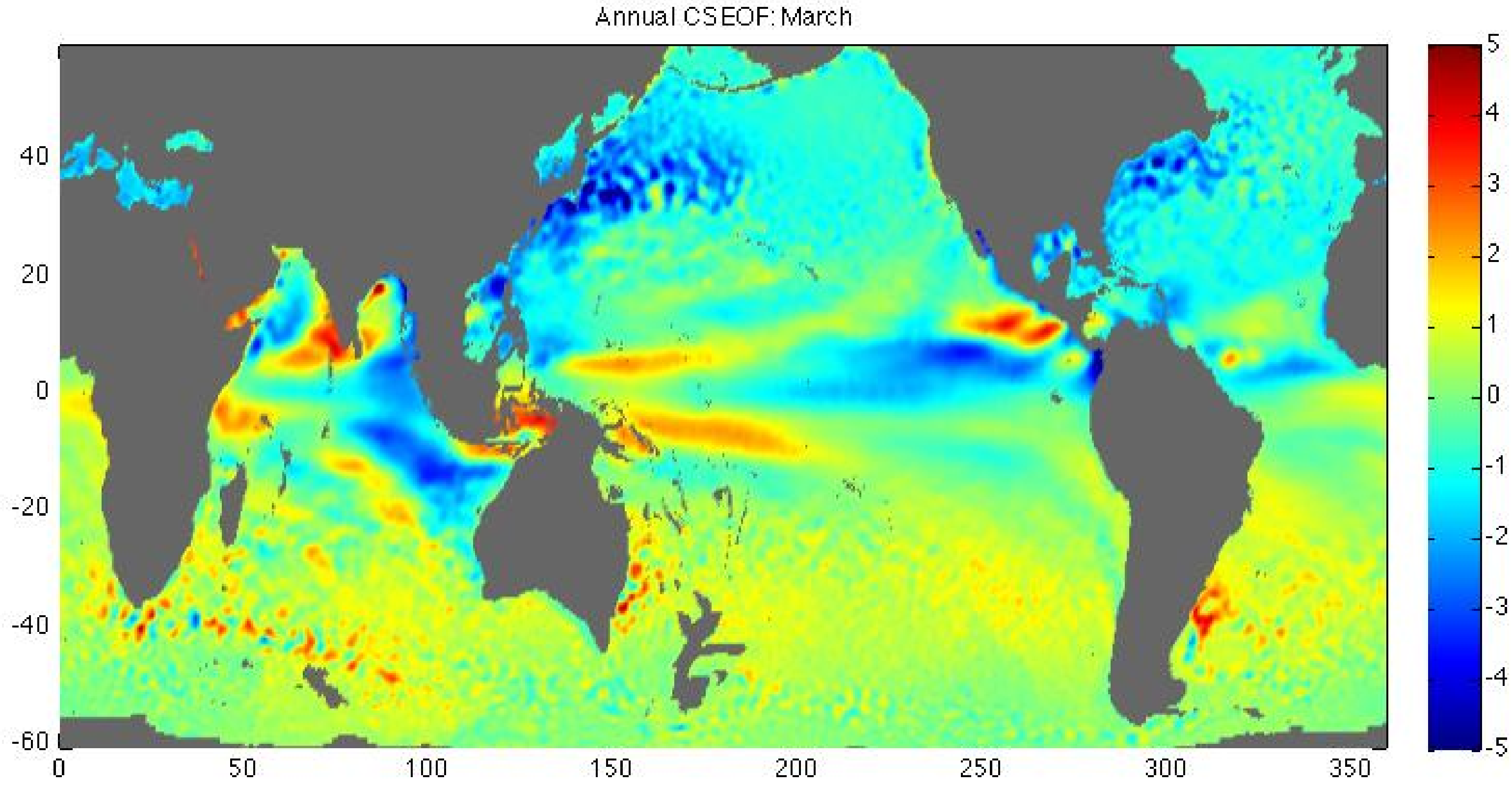


- Performing a CSEOF decomposition of AVISO satellite altimetry data with a nested period of one year gives the annual cycle as the first mode and ENSO as the second mode.

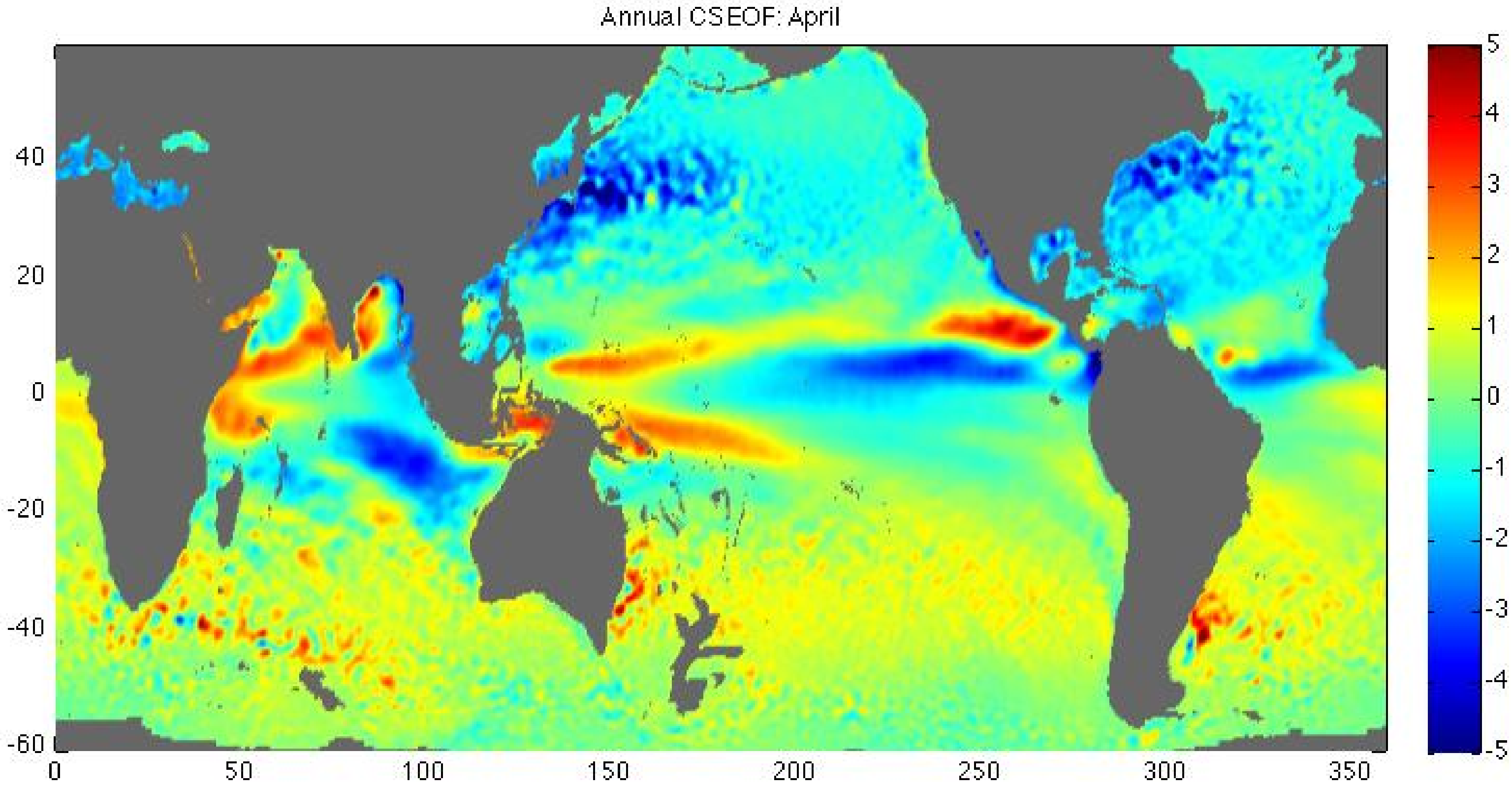
CSEOF Basis Function: Annual Signal



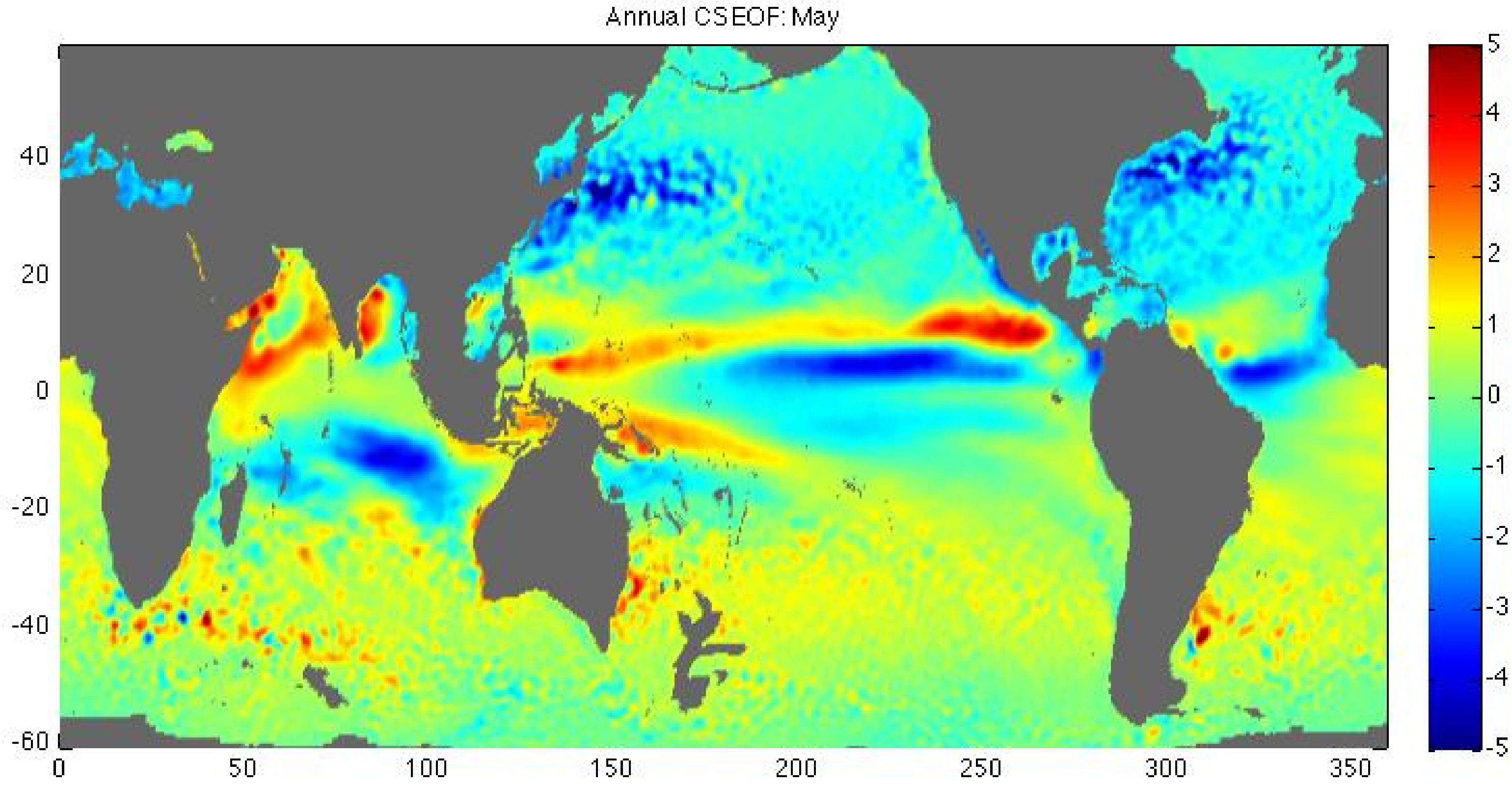
CSEOF Basis Function: Annual Signal



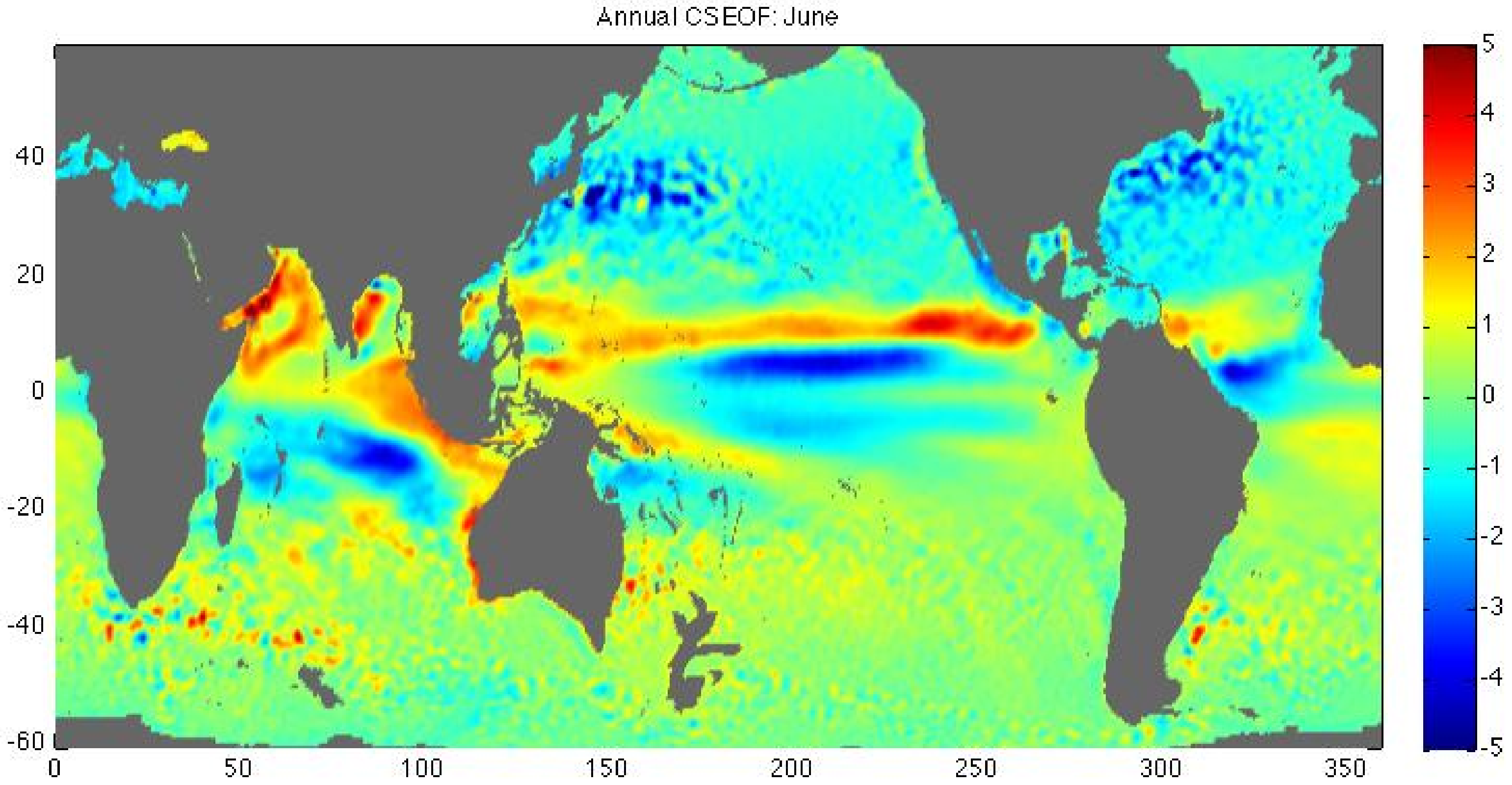
CSEOF Basis Function: Annual Signal



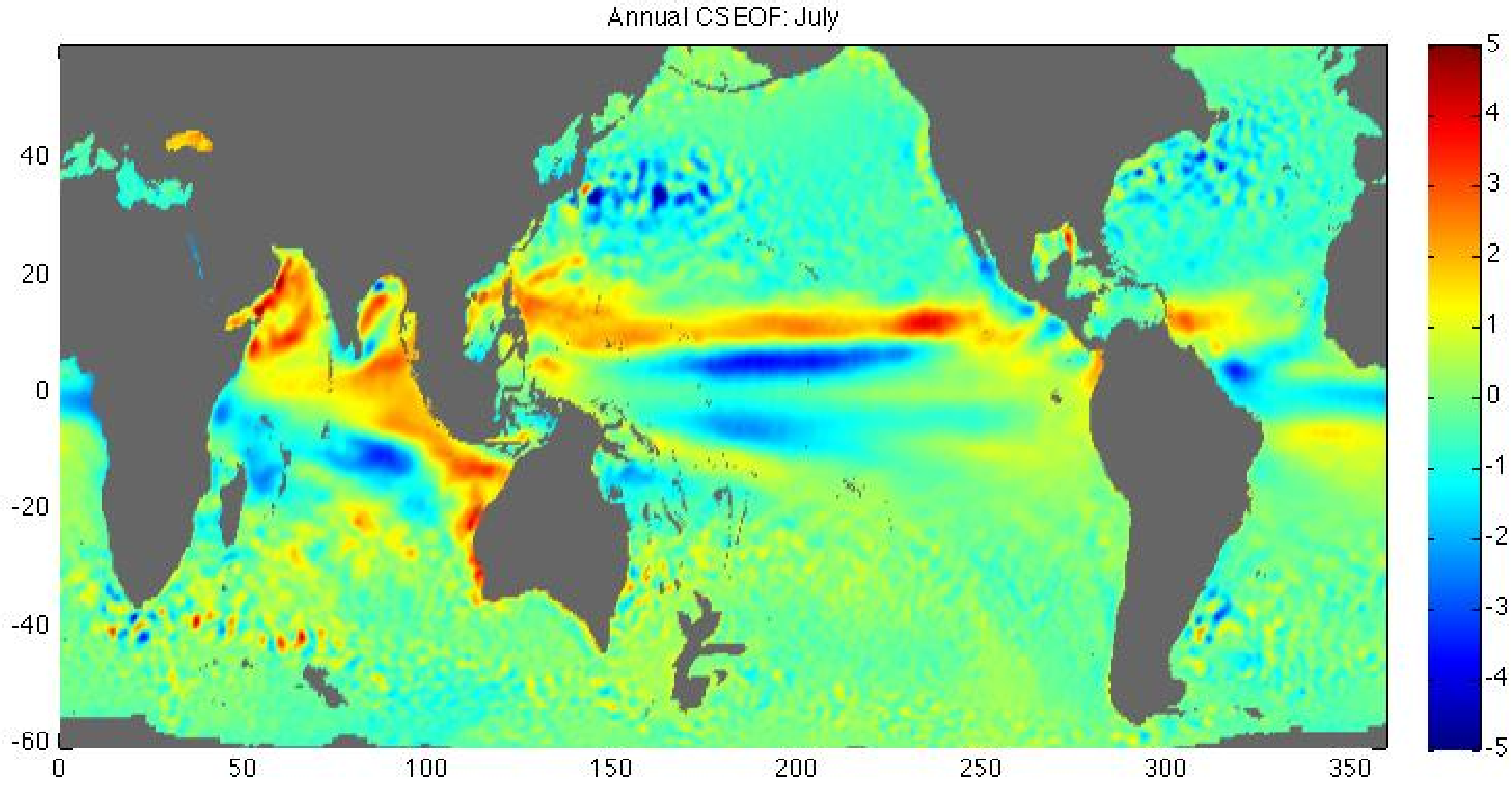
CSEOF Basis Function: Annual Signal



CSEOF Basis Function: Annual Signal



CSEOF Basis Function: Annual Signal



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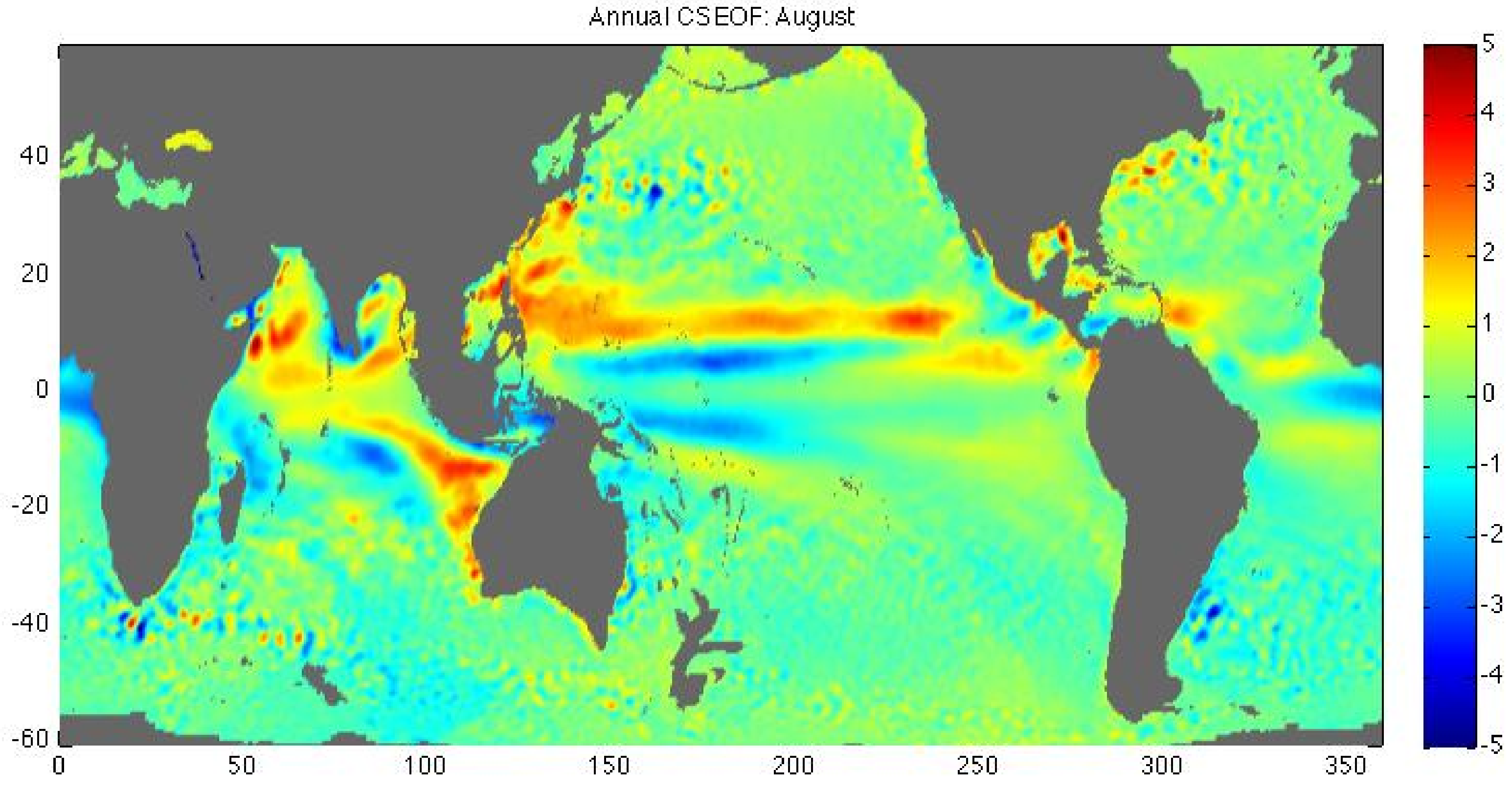
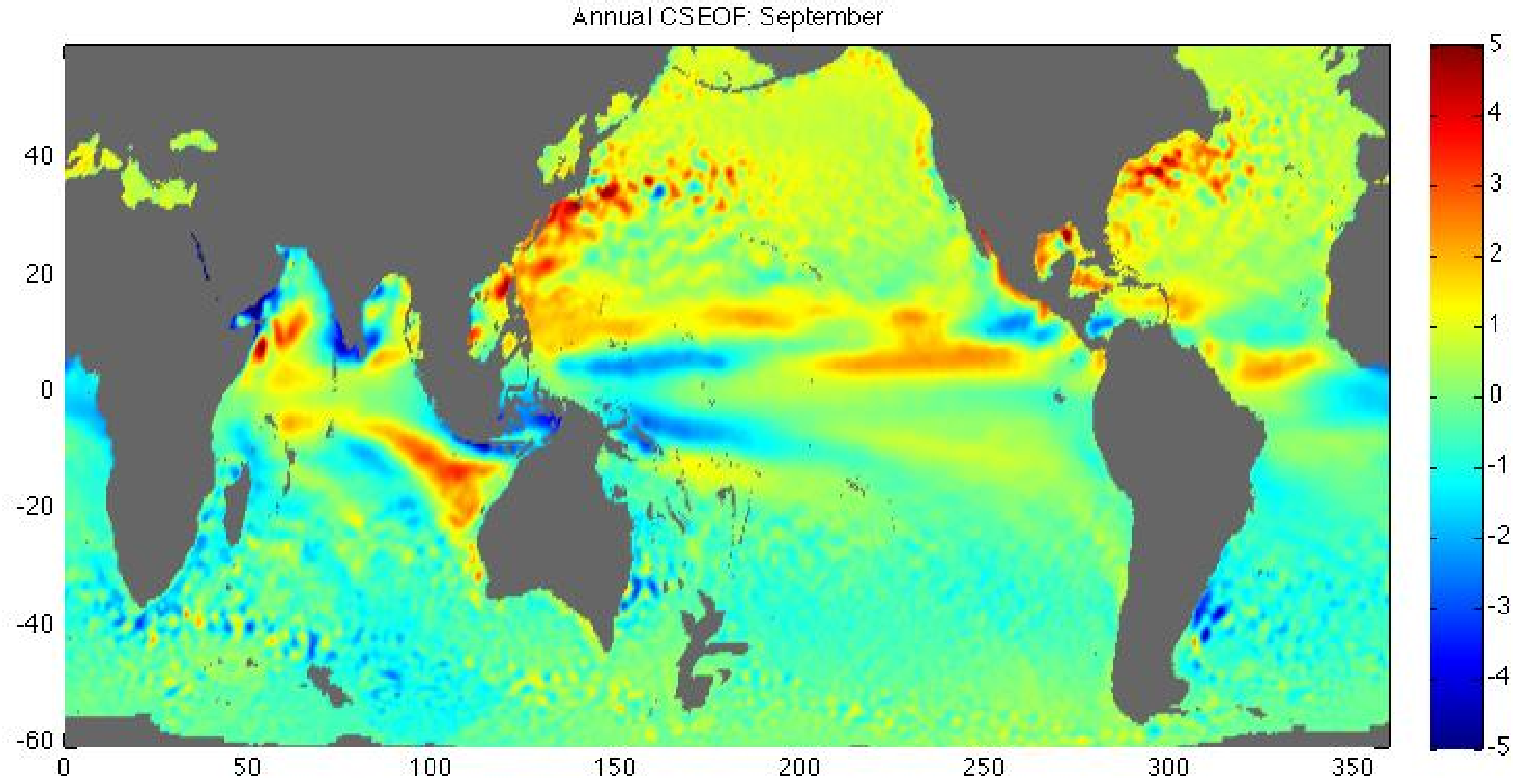


CSEOF Basis Function: Annual Signal



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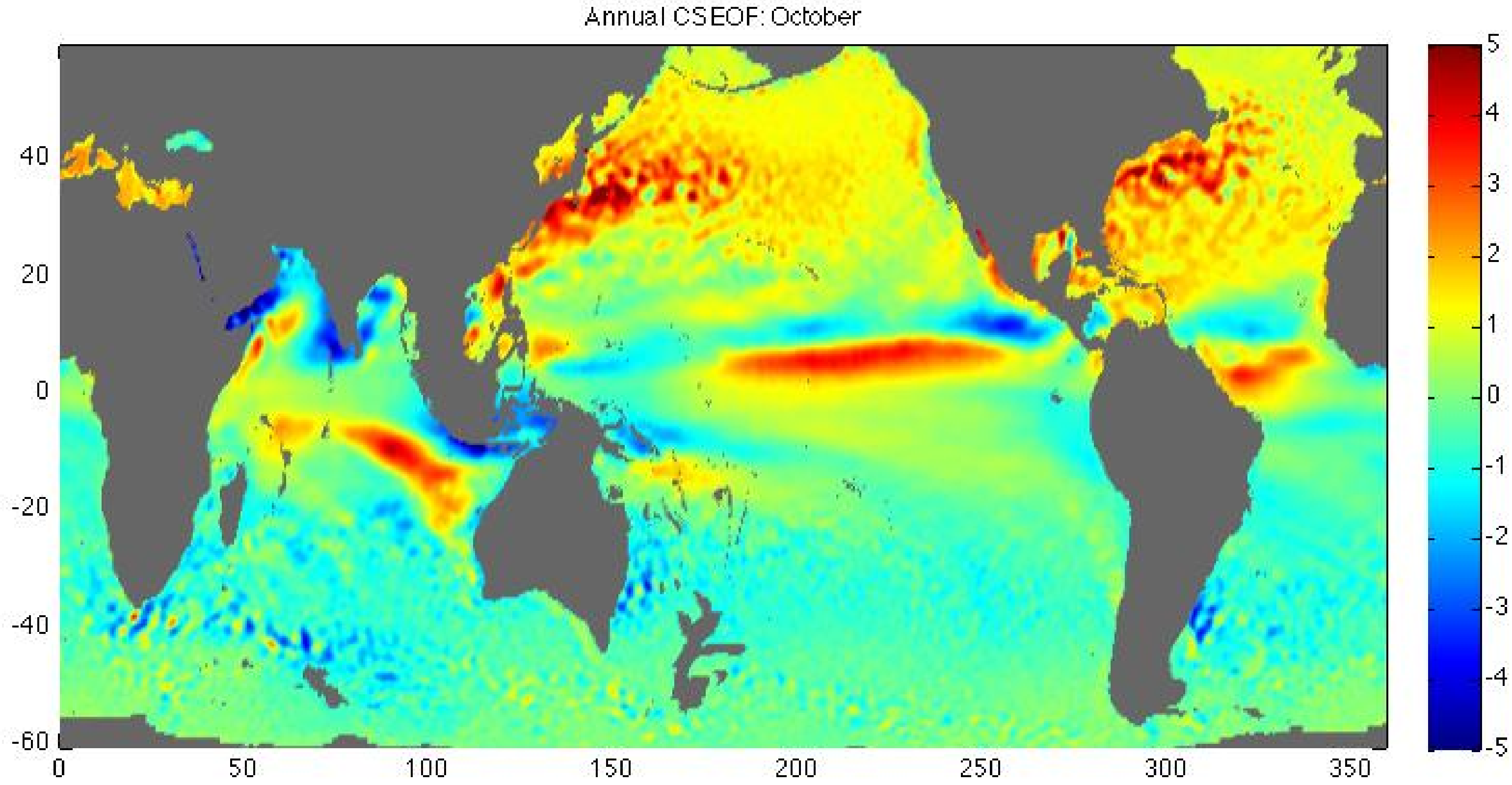

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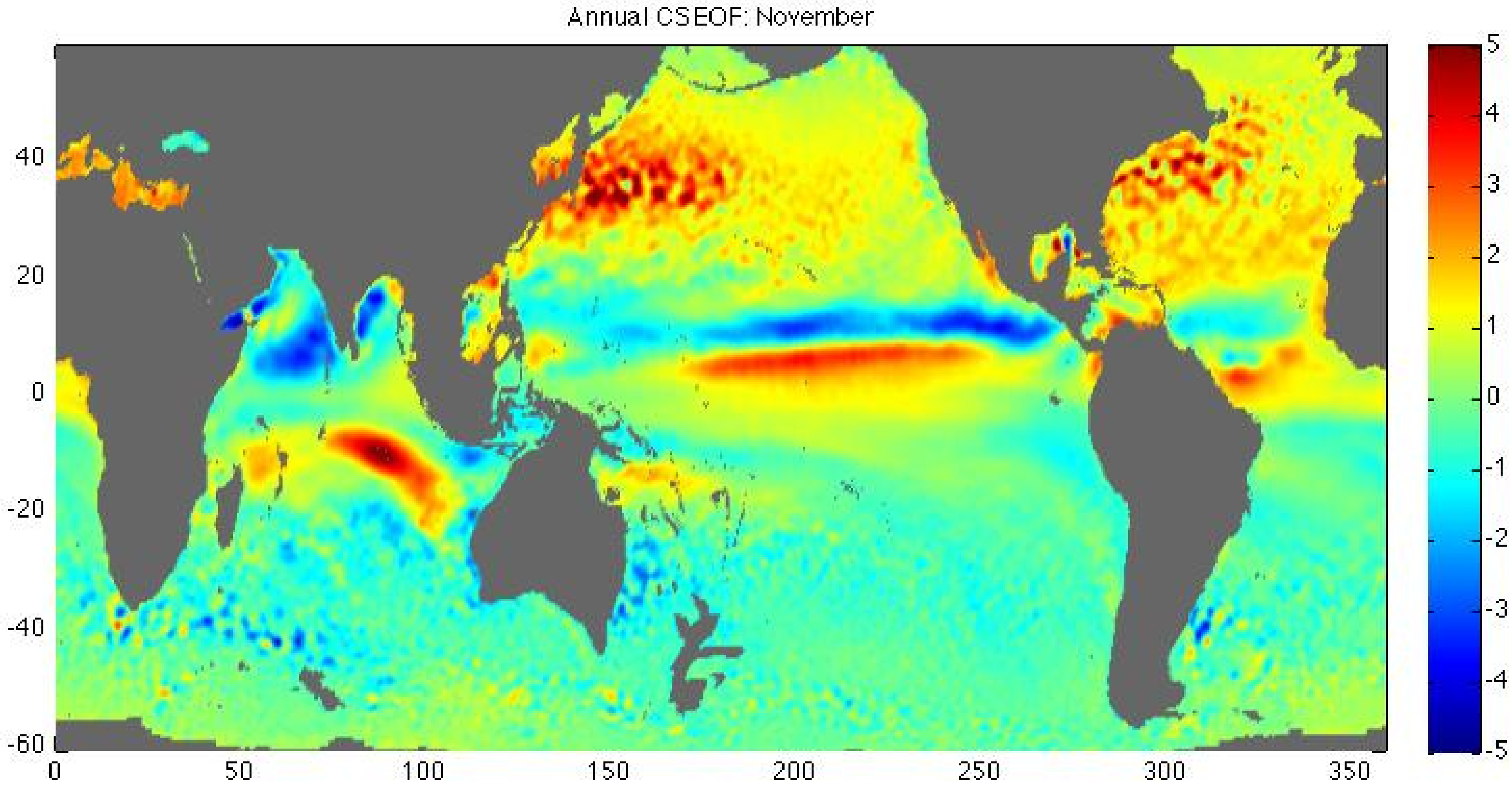

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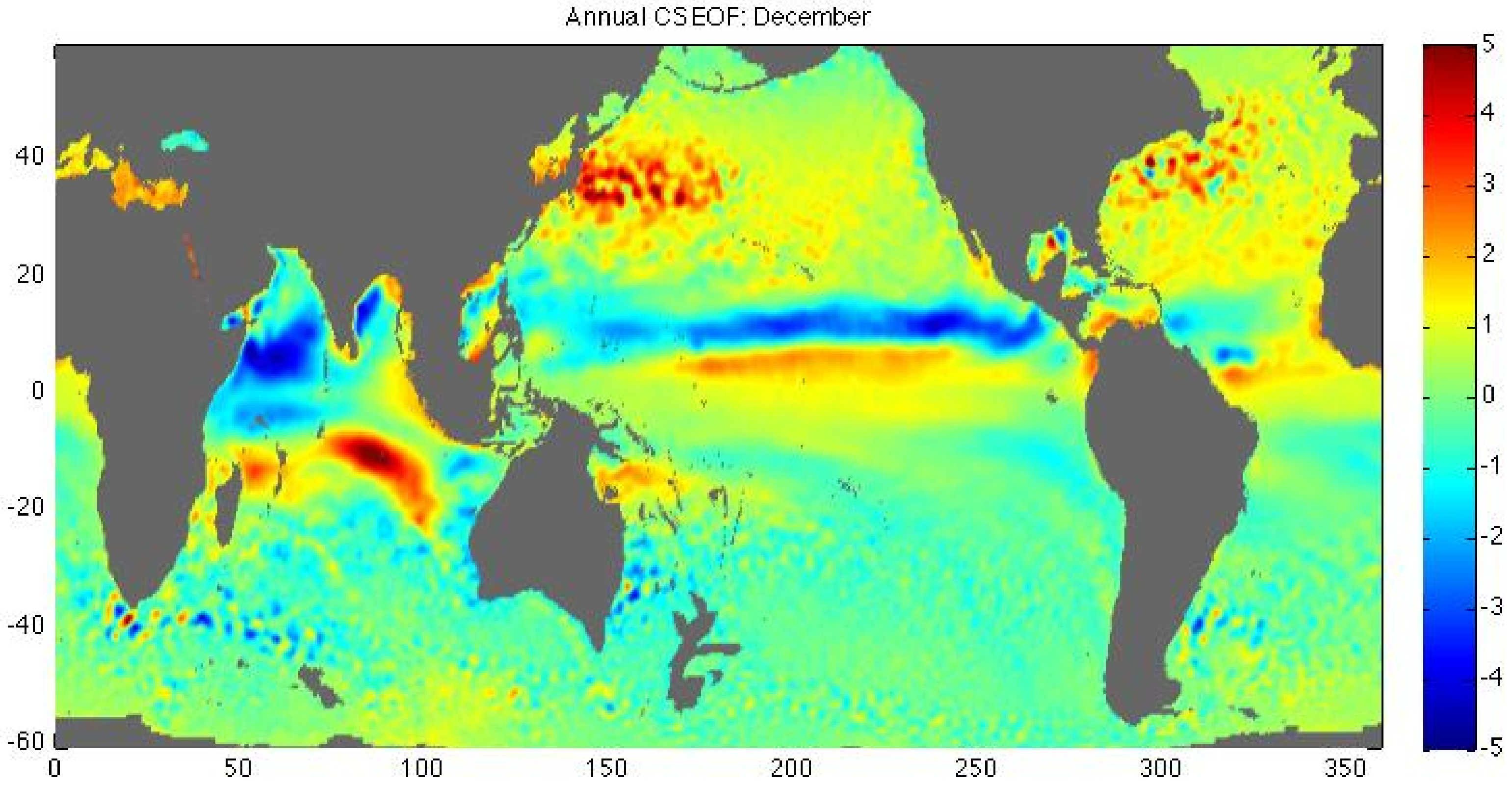
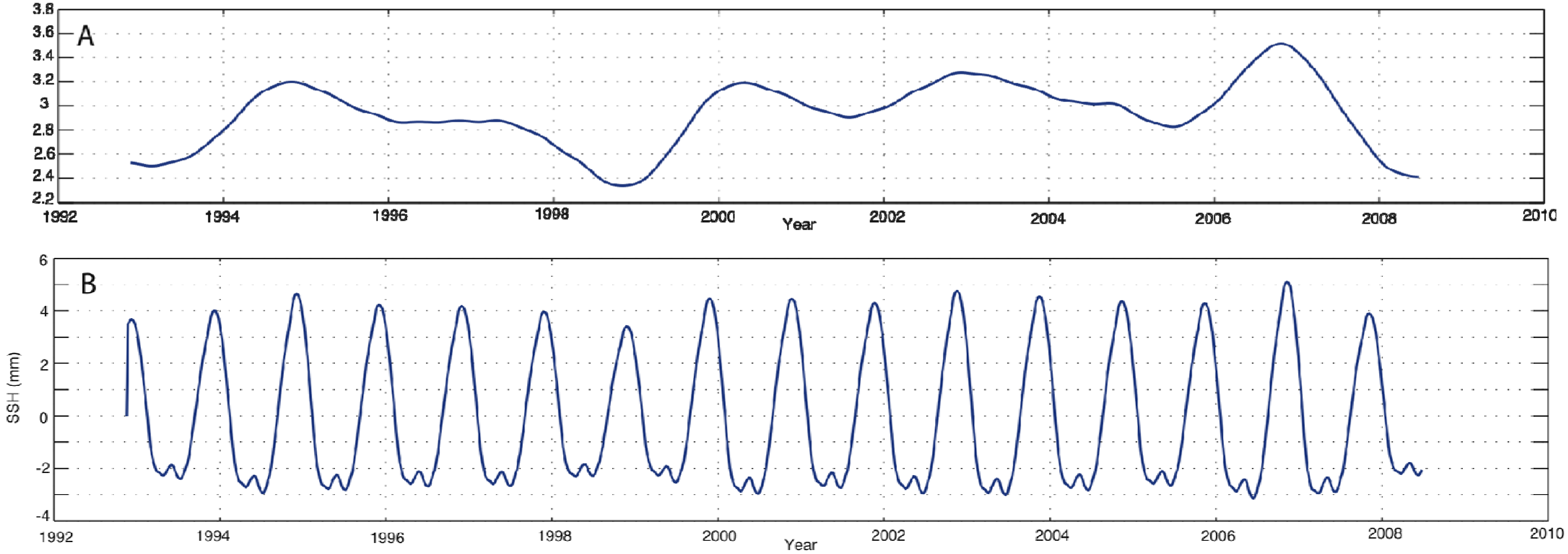


CSEOF Basis Function: Annual Signal

- The amplitude modulation of the annual cycle is represented by the PC time series (Fig. A). By combining the LVs and PC time series, we can compute the contribution of the annual cycle to GMSL (Fig. B).



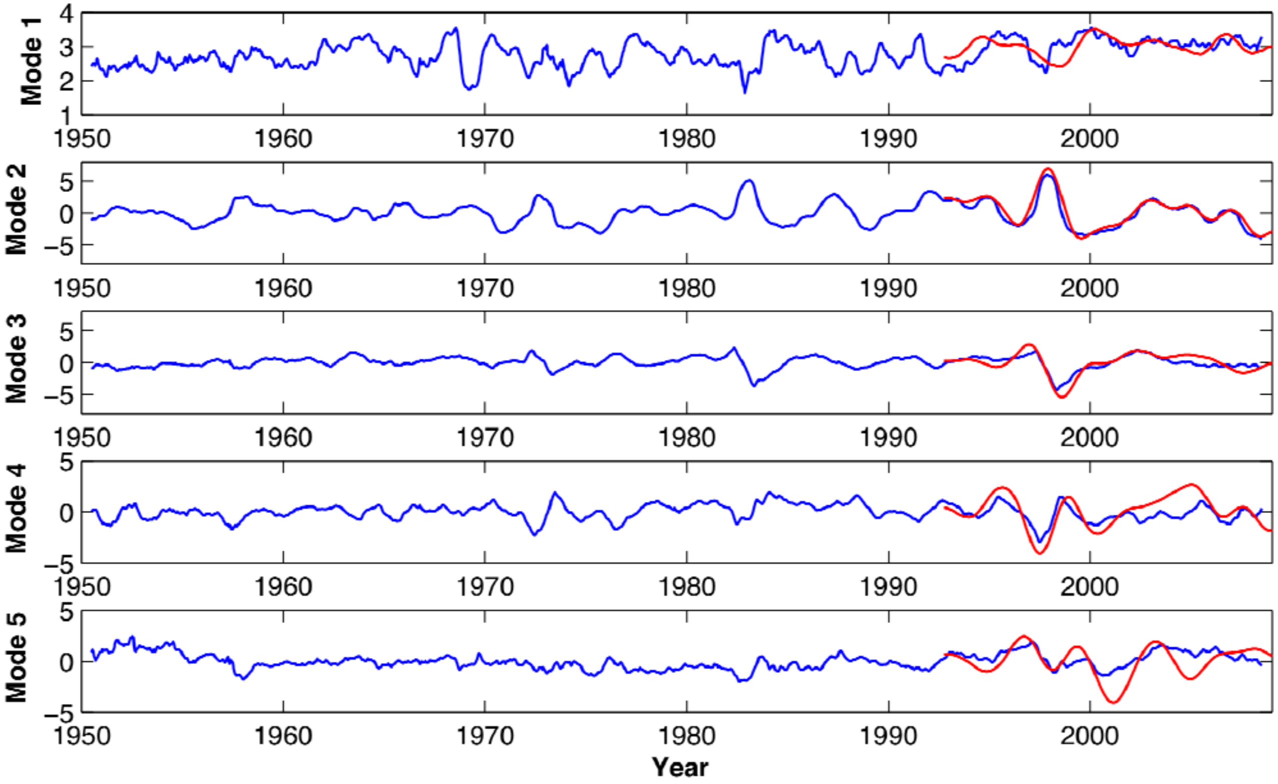
Basis Functions: CSEOFs vs. EOFs

- The motivation for using CSEOFs in place of traditional EOFs as the basis functions for the reconstruction is fourfold:
  1. EOFs are not a good basis for signals in the ocean and are unable to explain the temporal evolution of spatial variability.
  2. CSEOFs account for both the high and low frequency components of the annual cycle in a single mode and do not require the removal of the annual signals from both the altimetry and tide gauge records prior to reconstruction.
  3. Specific signals, such as those relating to the modulated annual cycle and ENSO, can be reconstructed individually with little mixing of variability between modes.
  4. The reconstruction procedure using CSEOFs inherently smoothes the reconstruction, allowing for the use of fewer tide gauges to obtain a meaningful result.

CSEOF Reconstruction Procedure

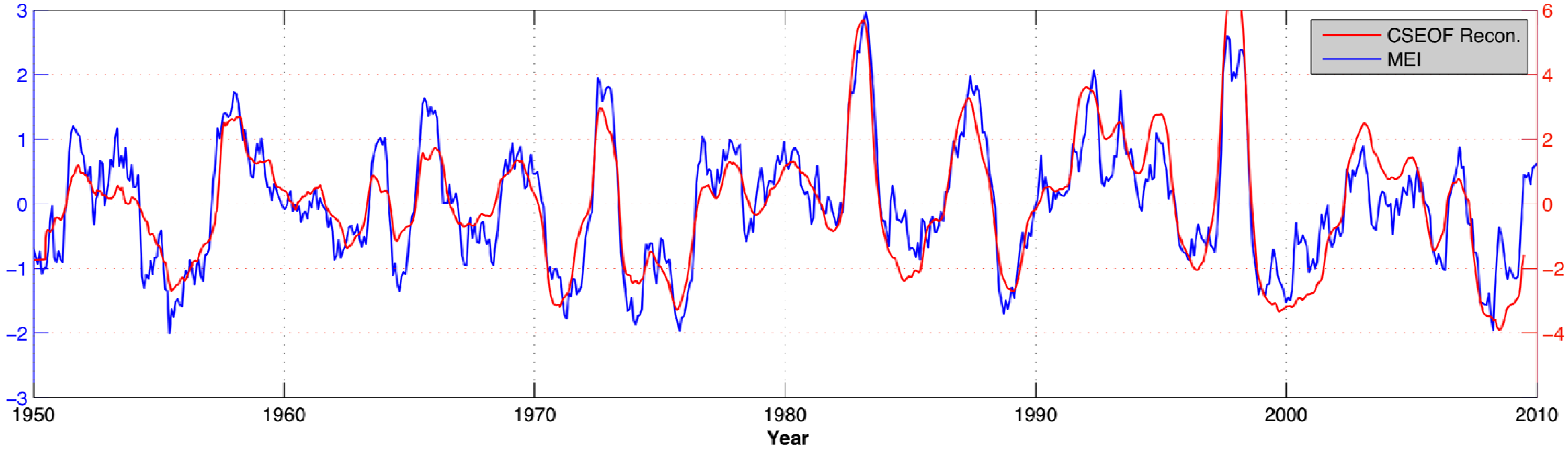
- Process of solving for the amplitudes of each basis function amounts to a weighted least squares problem (fitting satellite altimetry basis functions to tide gauge data).
  - Church and White et al. (2004) utilizes truncation and measurement errors for weighting.
  - As discussed in Merrifield et al. (2009), however, the sparse spatial distribution and regional clustering of the tide gauges should be taken into account.
  - For this reason, we adopt a latitude-band weighting scheme.
- 435 tide gauges are used from the PSMSL RLR dataset with editing criteria similar to that discussed in Church and White et al. (2004).
  - Tide gauges cover period from 1950 to 2010.
  - Annual, semi-annual and trend are not removed from the data.
- Basis functions are computed from the quarter-degree, merged satellite AVISO dataset with a one year nested period in the CSEOF decomposition.
  - Trend is removed from data prior to computing the CSEOFs.

CSEOF Reconstruction Results



- The tide gauge reconstructed PC time series for the first 5 CSEOF modes are shown overlaid with the original altimeter-derived PC time series. The quality of the reconstruction is shown by the agreement between the two.

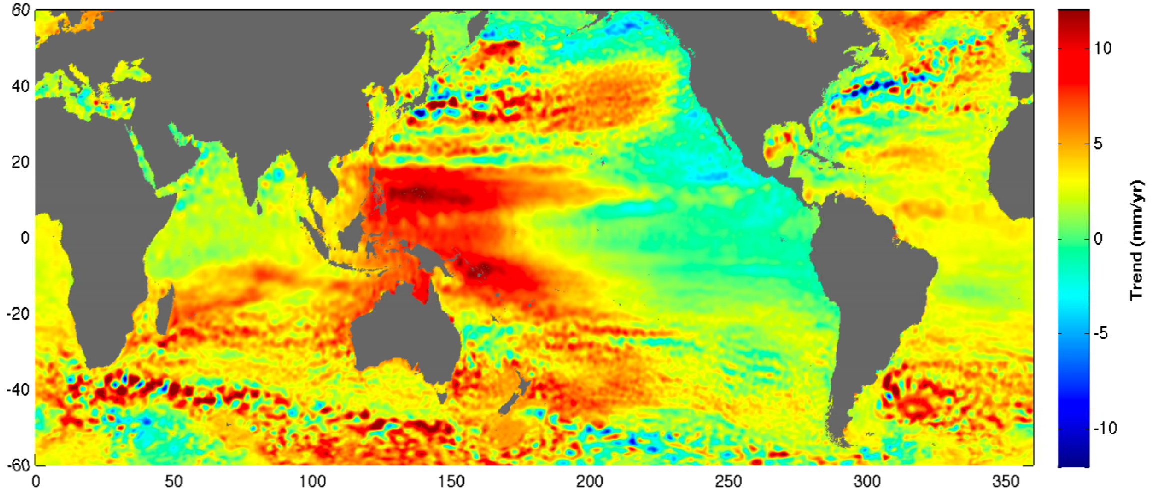
CSEOF Reconstruction Results: ENSO



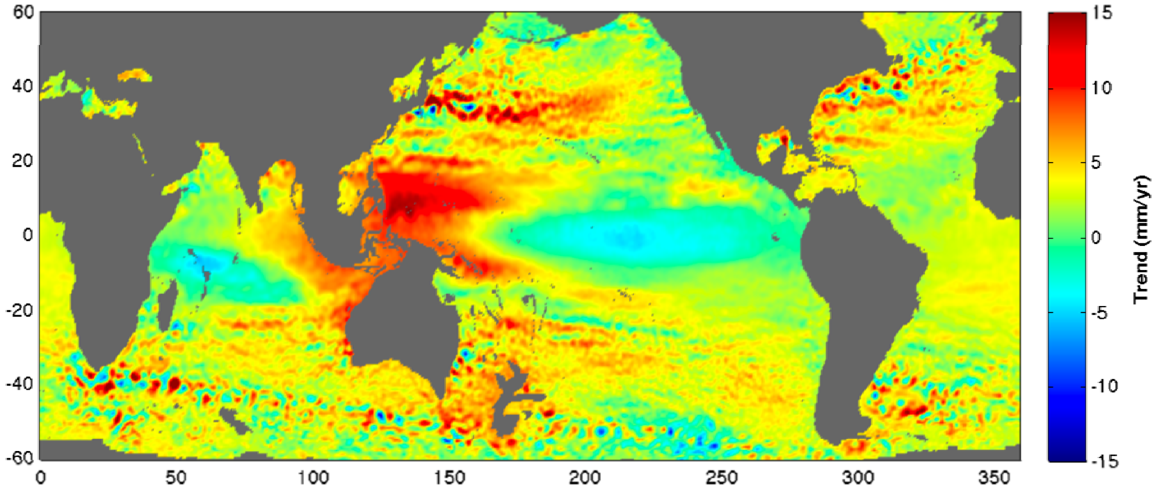
- **ENSO is described by CSEOF mode 2** in both the satellite altimetry and reconstructed sea level.
- The correlation between the Multivariate ENSO Index (MEI; Wolter and Timlin, 1998) and the reconstructed ENSO amplitude is **0.91** over the period from 1950 to 2010.

AVISO vs. CSEOF Reconstruction: Regional Trends 1993-2009

- Trend over the time period from 1993-2009 computed from **AVISO satellite altimetry data.**

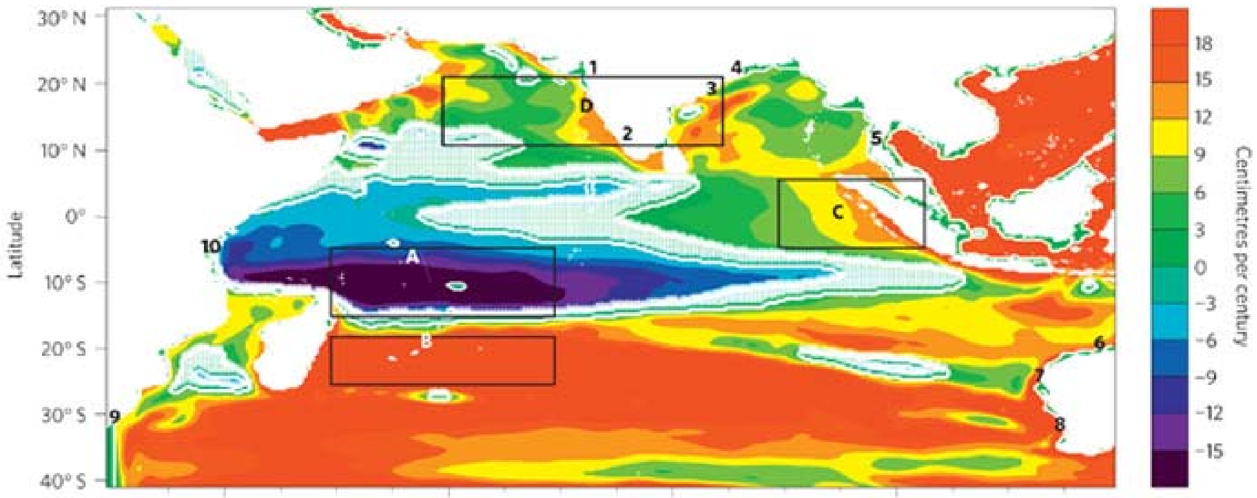


- Trends over the time period from 1993-2009 computed from **CSEOF reconstruction.**

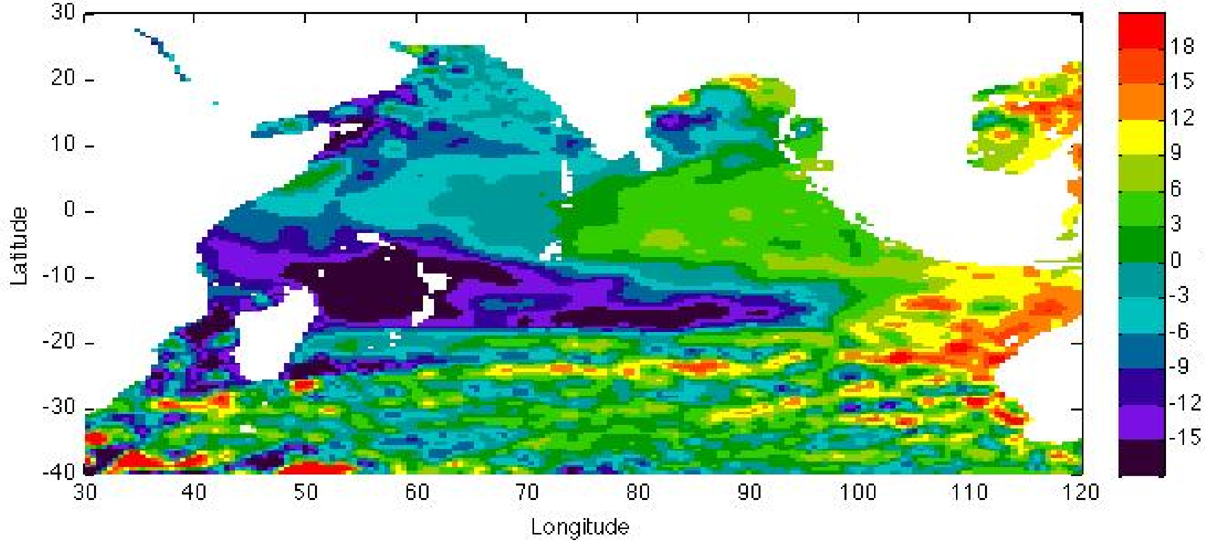


HYCOM Model vs. CSEOF Reconstruction: Regional Trends 1961-2008

- Spatial variation of trend for the Indian Ocean from 1961-2008 for **HYCOM SLA (Han et al, 2010).**

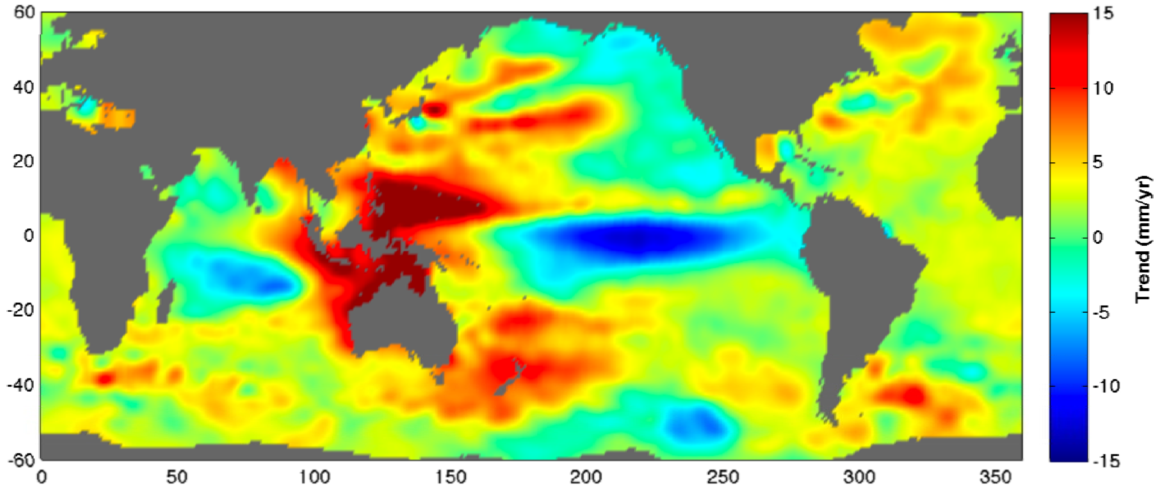


- Spatial variation of trend from 1961-2008 for the Indian Ocean computed from **CSEOF reconstruction.**

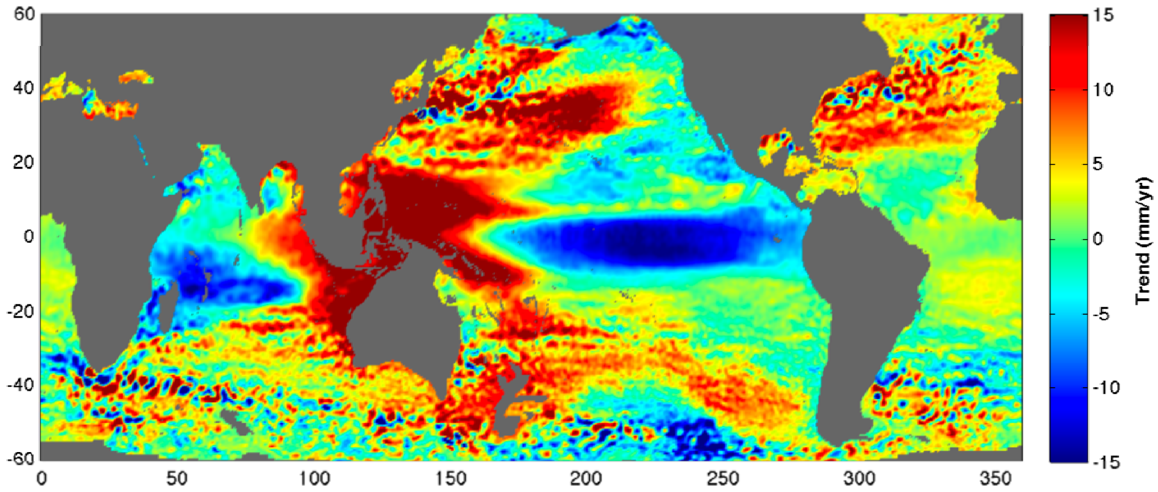


CW vs. CSEOF Reconstruction: Regional Trends 1993-2001

- Spatial variation of trend from 1993-2001 computed from **Church and White et al (2004)** (mm/yr).

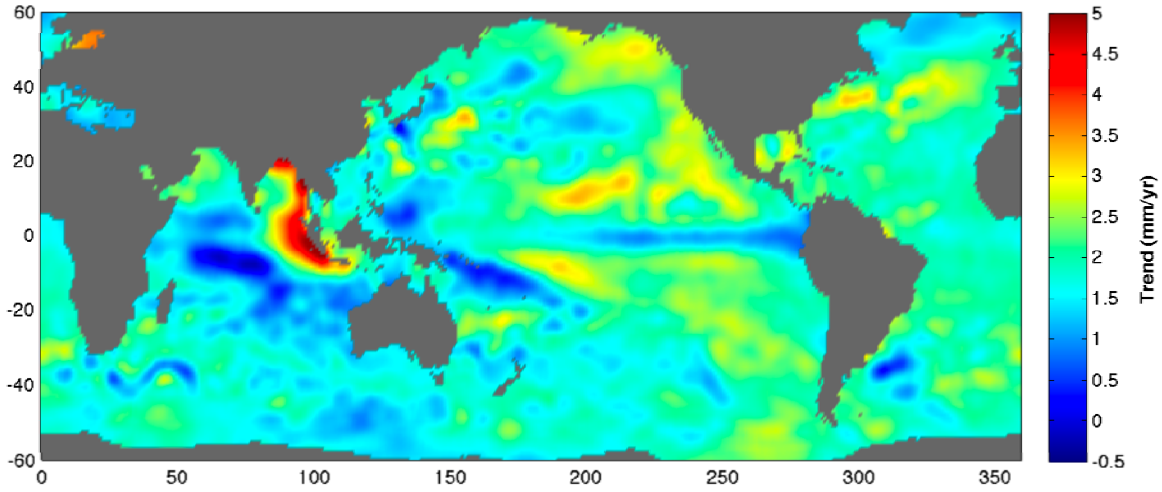


- Spatial variation of trend from 1993-2001 computed from **CSEOF reconstruction** (mm/yr).

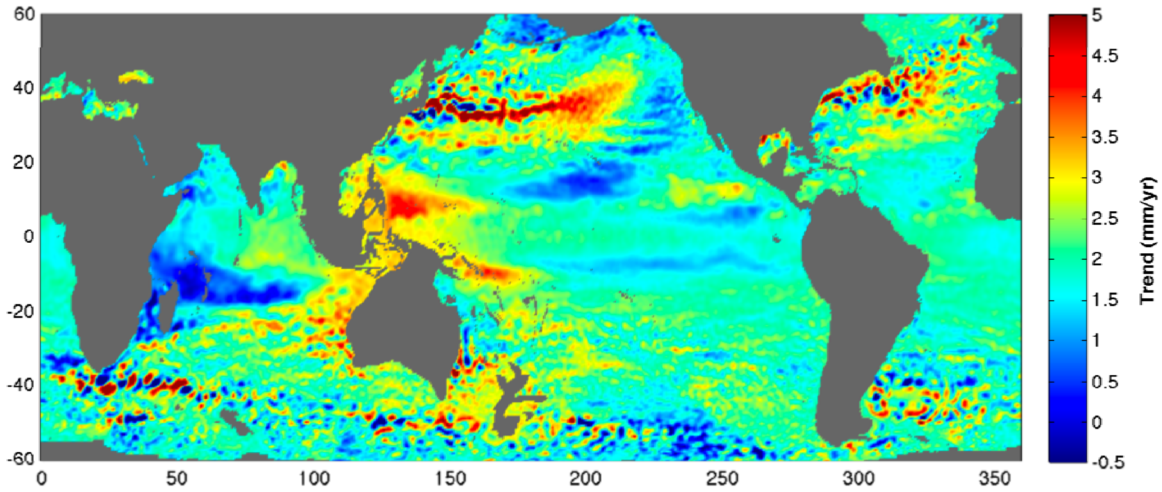


CW vs. CSEOF Reconstruction: Regional Trends 1950-2001

- Spatial variation of trend from 1950-2001 computed from **Church and White et al (2004)** (mm/yr).



- Spatial variation of trend from 1950-2001 computed from **CSEOF reconstruction** (mm/yr).

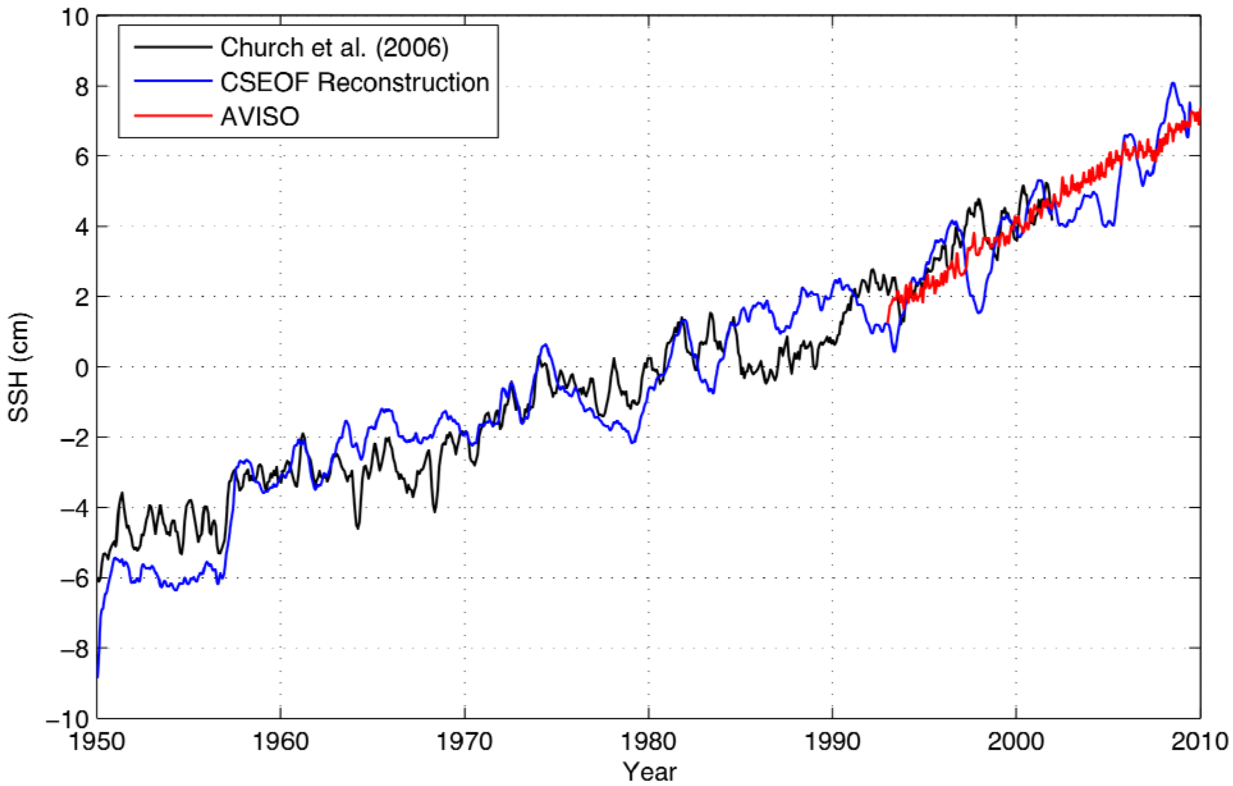


CSEOF Reconstruction: GMSL

- To account for GMSL in their reconstruction, Church and White et al. (2004) introduce a spatially uniform basis function, essentially computing a weighted (using the instrument and truncation errors) mean of the tide gauges.
  - Rather than introduce another basis function, we first compute our reconstruction with secular trends present in the tide gauge measurements.
  - The CSEOF reconstruction is then subsampled at each of the tide gauge locations and removed from the tide gauge data. This will attempt to correct of any sampling bias arising from the tide gauge distribution → will be referred to as the "**reconstruction correction**".
  - The tide gauge data is then differenced, average using latitude-band weighting, and re-integrated to produce a GMSL time series associated with the tide gauges.

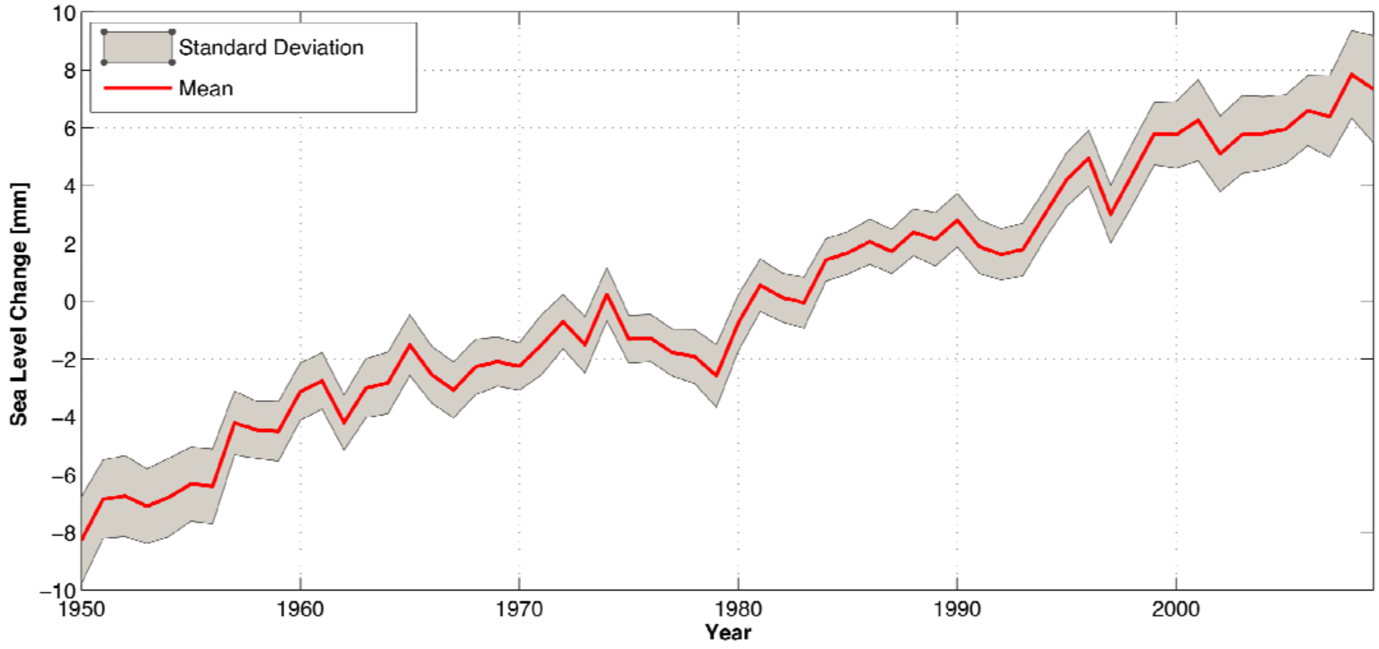
CSEOF Reconstruction: GMSL

- GMSL 1993-2010: Without Reconstruction Correction – **3.60 mm/yr**.
  With Reconstruction Correction – **3.19 mm/yr**.
- GMSL 1950-2010: Without Reconstruction Correction – **2.20 mm/yr**.
  With Reconstruction Correction – **1.91 mm/yr**.

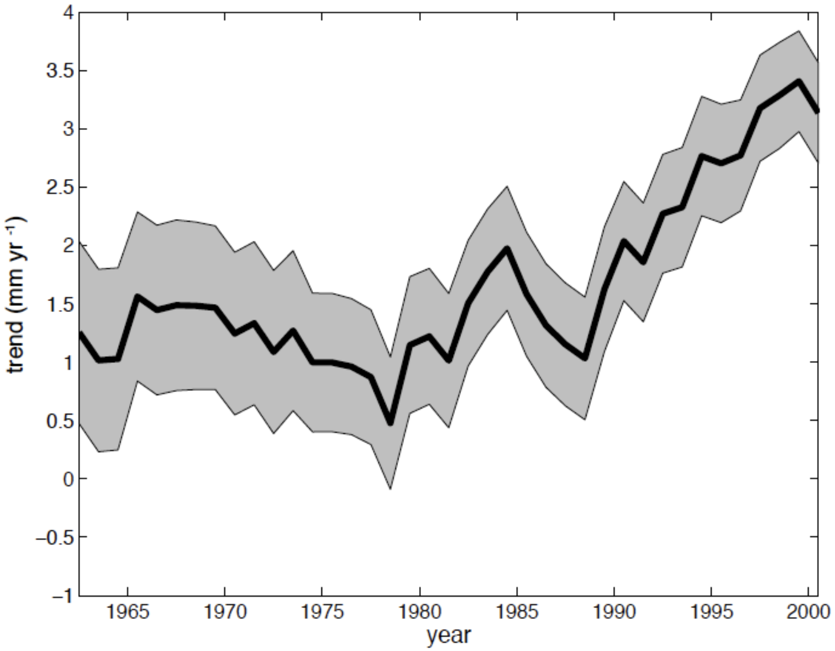


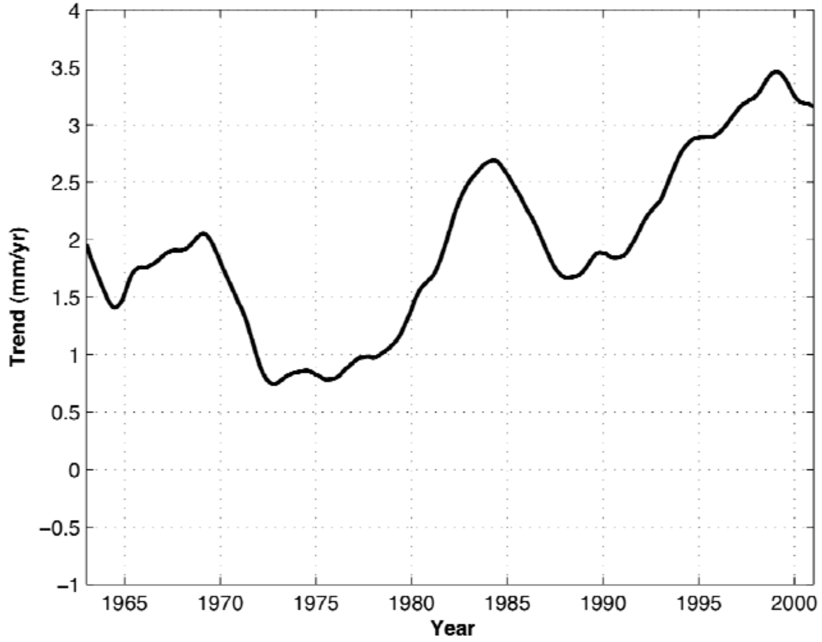
CSEOF Reconstruction: GMSL

- We can test the sensitivity of the reconstruction to the tide gauge sampling by randomly selecting 25% of the tide gauges to leave out.
  - 100 trials were performed and the standard deviation for GMSL was computed.
  - GMSL 1993 – 2010: **3.09 $\pm$ 0.6 mm/yr.**
  - GMSL 1950 – 2010: **2.05 $\pm$ 0.4 mm/yr.**
  - Reconstruction itself does not appear sensitive – ENSO mode correlation with MEI found to be **0.90 $\pm$ 0.04** across 100 trials.



CSEOF Reconstruction: 15-year trends





- As a check of the reconstruction, we can compare 15-year trends computed from the reconstructed GMSL (right) to the 15-year trends computed by Merrifield et al. (2009) (left).
  - Relatively **good agreement after 1980**, however generally **trends are higher before 1980** in the reconstructed GMSL.
  - Differences result from a combination of tide gauge dataset (**430+ vs. 120+ tide gauges**) used for the computation and the reconstruction correction for sampling bias.

Summary and Conclusions

- Using CSEOFs as basis functions, a new and perhaps improved reconstruction can be computed.
  - CSEOF reconstruction agrees well with AVISO satellite altimetry data and model data, and also extracts the variability related to ENSO over the period from 1950-2010.
  - Reconstructed signals (MAC, ENSO, etc.) are not very sensitive to tide gauge selection and weighting.
- Accounting for GMSL in the reconstruction is not a trivial matter.
  - There is no basis function that can account for GMSL in an EOF or CSEOF reconstruction.
  - Either an additional basis function needs to be introduced (Church and White et al. 2004), or GMSL must be estimated separately from the actual procedure of computing basis function amplitudes.
  - GMSL is sensitive to both tide gauge selection and weighting.
  - Estimates of GMSL can be improved by correcting for bias arising from tide gauge sampling of non-secular signals in the sea level data.

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