



Near Real-time and Historical Monitoring of the Earth's Climate System Using Satellite Altimetry and Reconstructed Sea Level

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Overview

- Monitoring of the Earth's climate system has taken on increasing importance as projections of climate change associated with global warming have been made → wide range of climate indices.
- Sea level is an integral component of climate monitoring since, as a dynamic ocean variable, changes in sea surface height (SSH) reflect the integrated volume changes due to both mass (salinity) and temperature variations over the entire ocean water column.
- Question: How is sea level being incorporated into climate monitoring efforts?

Google Search: Ocean Climate Indices

Of the top websites hosting climate indices, not a single climate index based on sea surface height (SSH) was found among the indices listed. In some cases, SSH wasn't even listed as a climate variable.

NOAA Earth System Laboratory: Physical Science Division

Climate Indices: Monthly Atmospheric and Ocean Time Series

- <http://www.esrl.noaa.gov/psd/data/climateindices/list/>

NOAA National Weather Service Climate Prediction Center

Monthly Atmospheric & SST Indices

- <http://www.cpc.ncep.noaa.gov/data/indices/index.shtml>

NCAR Climate and Global Dynamics Division Climate Indices

- <http://www.cgd.ucar.edu/cas/catalog/climind/>

Royal Netherlands Meteorological Institute (KNMI) Climate Explorer

- <http://climexp.knmi.nl/selectindex.cgi>

University of Hamburg Integrated Climate Data Center Climate Indices

- https://icdc.zmaw.de/climate_indices.html

University of Washington Climate Impacts Group Climate Time Series

- <http://www.cses.washington.edu/data/timeseries.shtml>

Sources of SSH-based Climate Indices

We know of three sources of SSH-based climate indices on the web with both historical and NRT time series:

- **AVISO's Ocean Indicator Products**
- **Earth & Space Research's PDO Index**
- **Georgia Tech (Di Lorenzo's) NPGO Index**

Are there any others?

AVISO Ocean Indicator Products

Indicators of ocean health and dynamics:

- El Niño Bulletin
- Mean Sea Level
- Kuroshio
- Ionian Sea Circulation

Reference:

Bessières, L., Rio, M. H., Dufau, C., Boone, C., and Pujol, M. I.: Ocean state indicators from MyOcean altimeter products, Ocean Sci., 9, 545-560, doi:10.5194/os-9-545-2013, 2013.

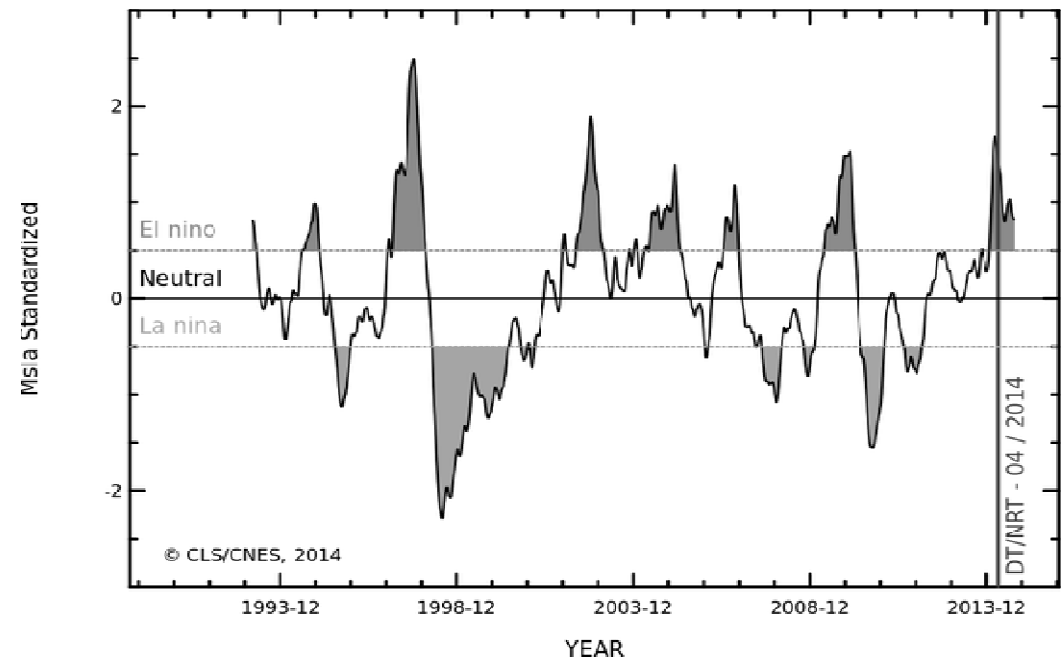
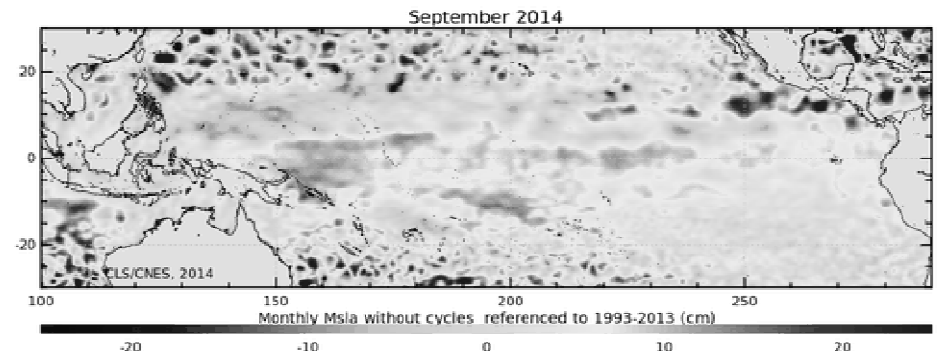


<http://www.aviso.altimetry.fr/en/data/products/ocean-indicators-products.html>

AVISO El Niño Bulletin

Altimetric ENSO Index

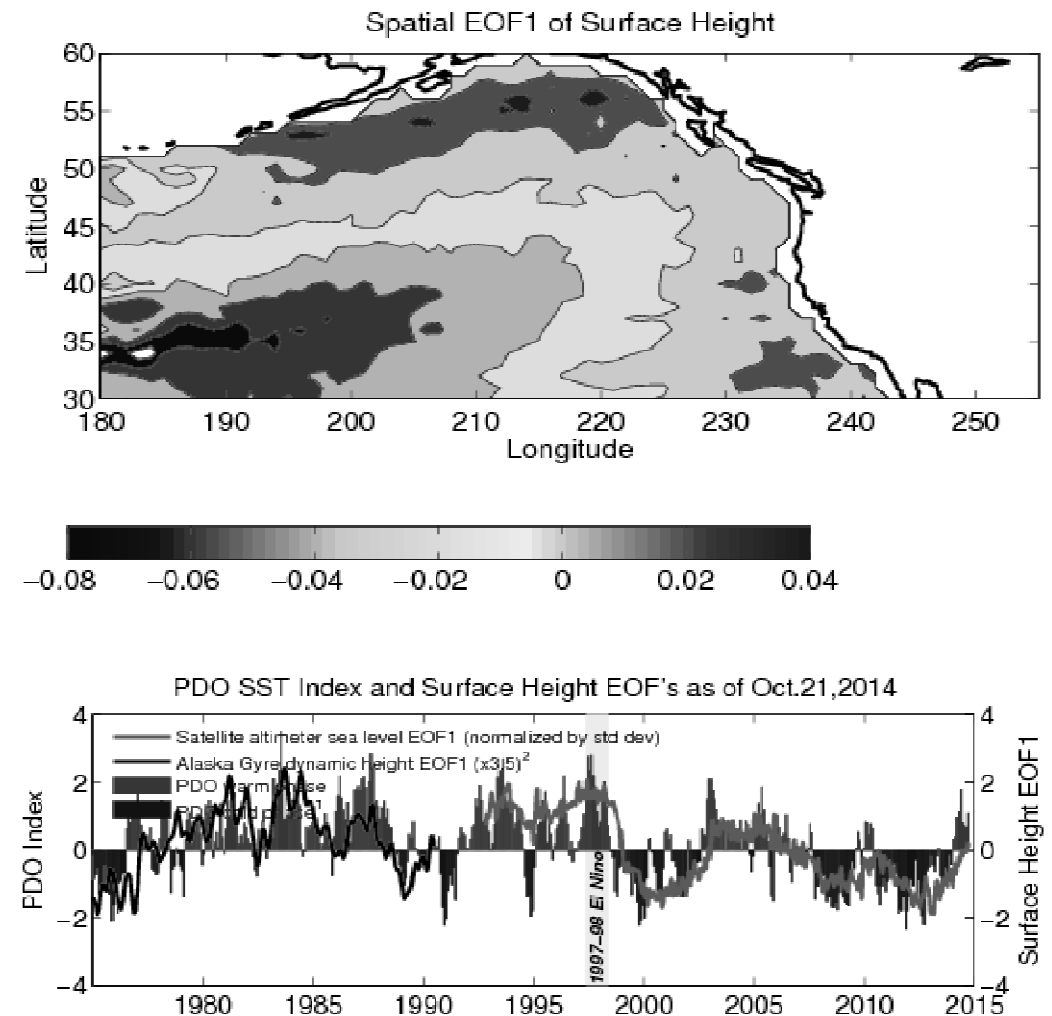
- Based on monthly AVISO Merged Sea Level Anomaly (MSLA) maps over the tropical Pacific.
- MSLA is averaged over the Niño 3.4 region (bounded by 120°W to 170°W and 5°S to 5°N) and normalized to unit standard deviation.



Earth & Space Research: Pacific Decadal Oscillation

Altimetric PDO Index

- Based on the AVISO Merged Sea Level Anomaly (MSLA) at 10-day intervals. Anomaly is computed w.r.t. seasonal cycle.
- Index is the EOF1 principal component time series calculated from SSH in the NE Pacific (bounded by the dateline and 30°N) and normalized to unit standard deviation.



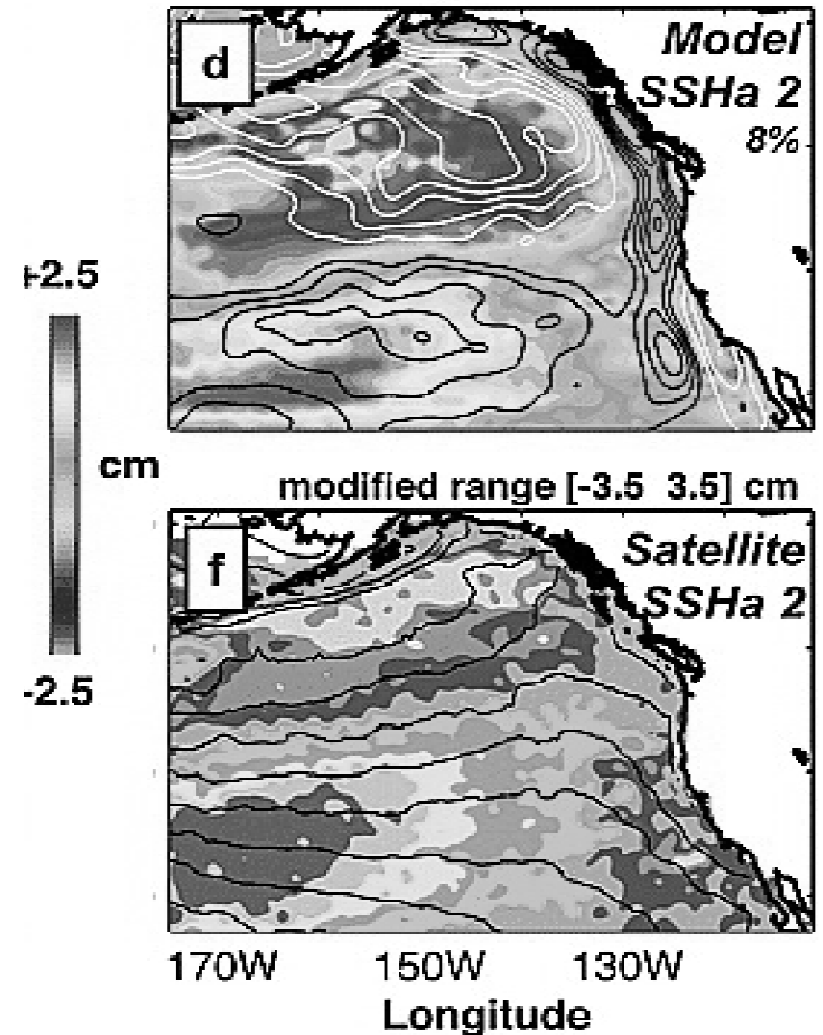
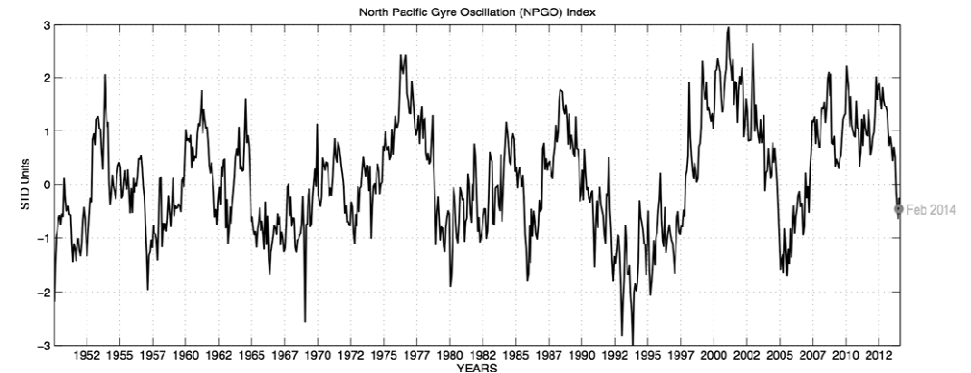
¹Mantua et al. (1997)

²Lagerloef (1995)

Georgia Tech(Di Lorenzo): North Pacific Gyre Oscillation Index

NPGO Index

- Based on monthly AVISO Merged Sea Level Anomaly (MSLA).
- SSH anomaly is computed w.r.t. the seasonal cycle(?) in the region from $180^{\circ}\text{W} - 110^{\circ}\text{W}$ and $25^{\circ}\text{N} - 62^{\circ}\text{N}$.
- Index is computed by projecting the AVISO MSLA onto the NPGO spatial pattern (SSHA EOF2) derived from the Di Lorenzo et al. (2008) North Pacific Ocean reanalysis.
- Combined model and altimeter record is from 1950 thru February 2014.



Issues

- Some time series are monthly (ENSO, NPGO) others are every 10 days (PDO).
- Some indices are based on patterns from ocean reanalysis not altimetry (NPGO).
- Timeliness of the NRT updates varies.
- Time span of the historical indices varies.
- Few of the climate signals in the ocean are represented by SSH-based indices.

(More) Issues

- Both near real-time (NRT) and historical time series are needed.
 - Understanding the past can help inform our understanding of the present and future.
- Long-duration, accurate sea level mapping is needed prior to satellite altimetry to differentiate between natural and anthropogenic variations in SSH associated with climate change.
 - Long record provides opportunity to separate decadal-scale variability.
- Estimating climate signals from sea level reconstructions before 1950 is very difficult; however, multivariate techniques show significantly improved performance as far back as 1900.
- In general, it is hard to get a clear and consistent idea of the state of the climate in the present with indices using different variables and different sampling, updating on different schedules.

Proposal

Produce a consistent set of near real-time (NRT) and historical ocean climate indices based on satellite altimetry and sea level reconstructions.

- Monthly time series.
- Observation based.
 - Altimetry based from January 1993 onward.
 - Pre-altimetry record is based on sea level reconstructions.
- Posted monthly (although more frequent updates could be made).

Example: El Niño Indices

There are a large number of El Niño Indices, based on SST:

NINO1+2, NINO3, NINO3.4, NINO4, ONI (oceanic Niño index), **EMI** (El Niño Modoki index), **IEMI** (improved El Niño Modoki index), **Trans-Niño Index** (TNI);

or upper-ocean temperature

WWV (integrated warm water volume);

or multivariate analyses including SST but not SSH:

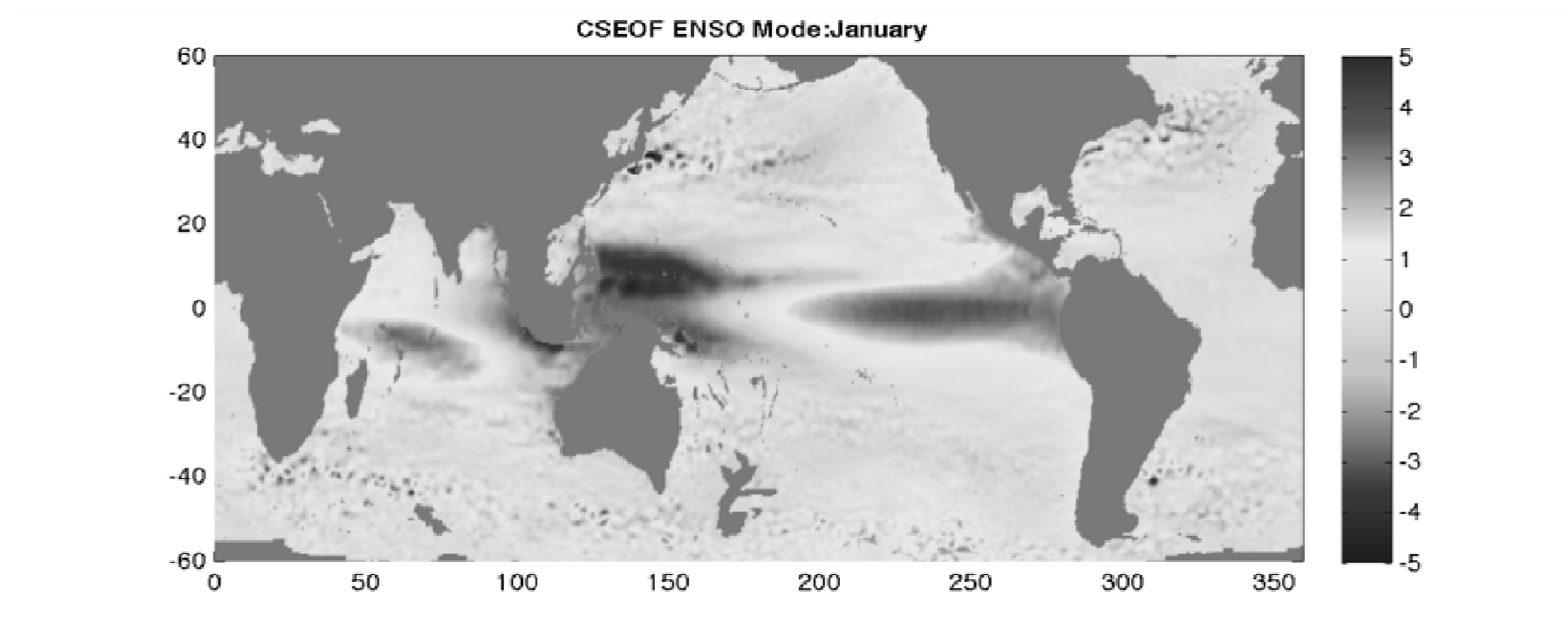
MEI (multivariate ENSO index), **BEST** (bivariate ENSO time series);

in the Tropical Pacific Ocean.

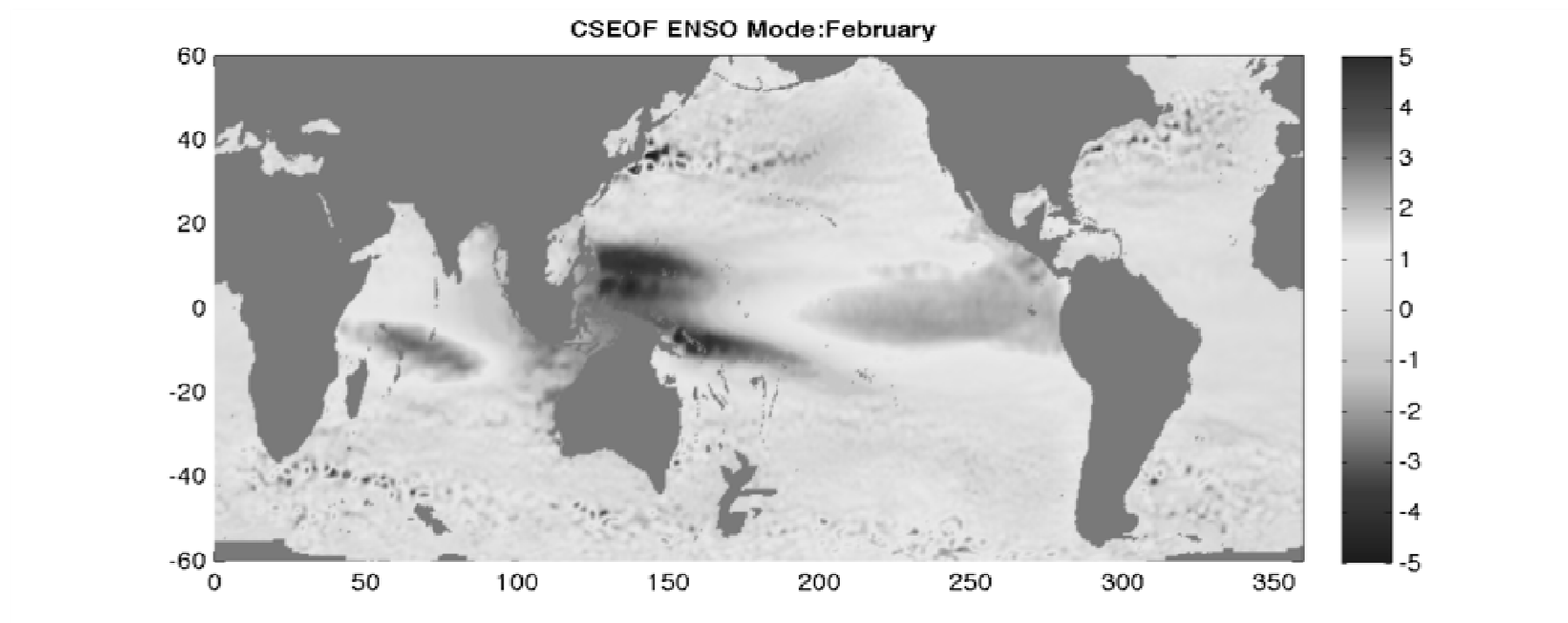
Proposed EP-ENSO Index

- By relying on cyclostationary empirical orthogonal function analysis and sea level reconstructions, a SSH-based ENSO index can be created.
- Second mode of a CSEOF decomposition of the AVISO satellite altimetry data represents the Eastern-Pacific ENSO signal (e.g. Hamlington et al., 2012).
 - First mode contains the modulated annual cycle.
- The CSEOF analysis provides a global spatial pattern (basis function) related to ENSO in addition to a time series that can serve as an SSH-based ENSO index.
- By fitting the basis function to the tide gauge data, this index can be reconstructed back in time.
- Additionally, fitting the basis function to NRT altimetry data provides a NRT SSH-based ENSO index.

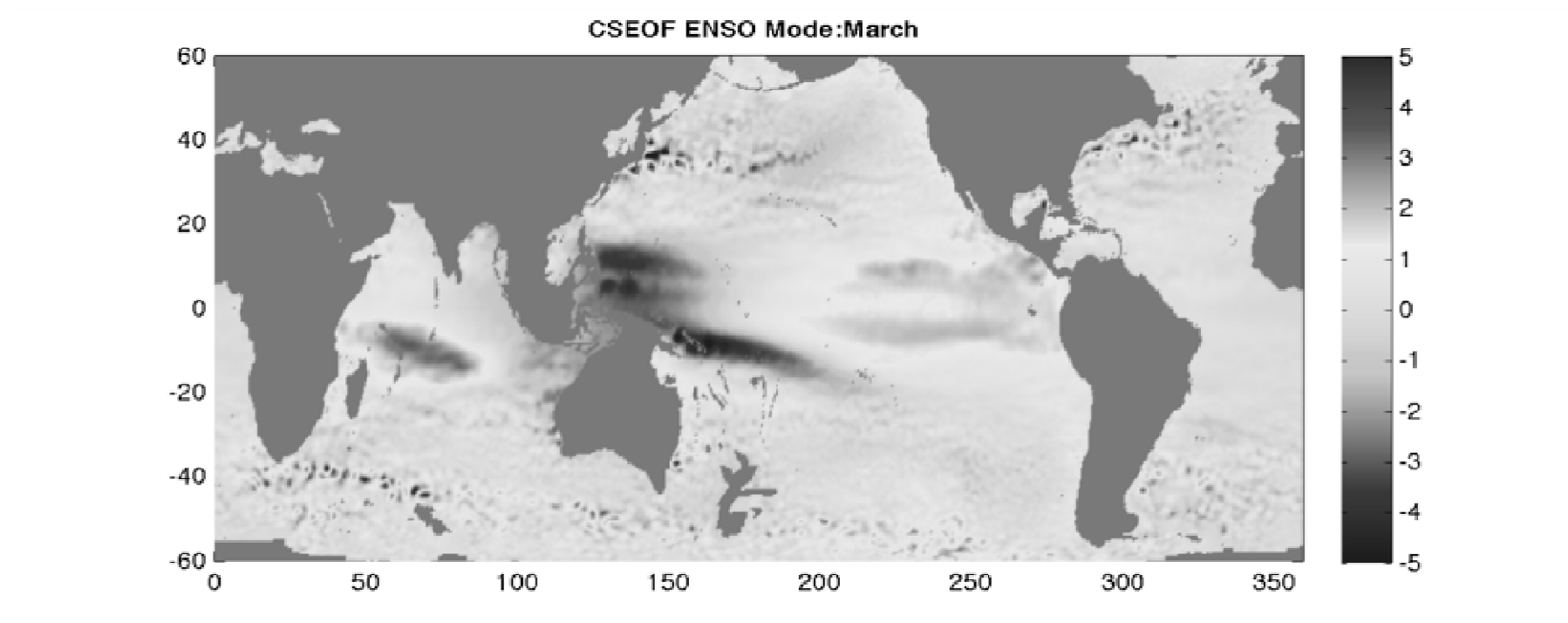
CSEOF EP-ENSO Basis Function



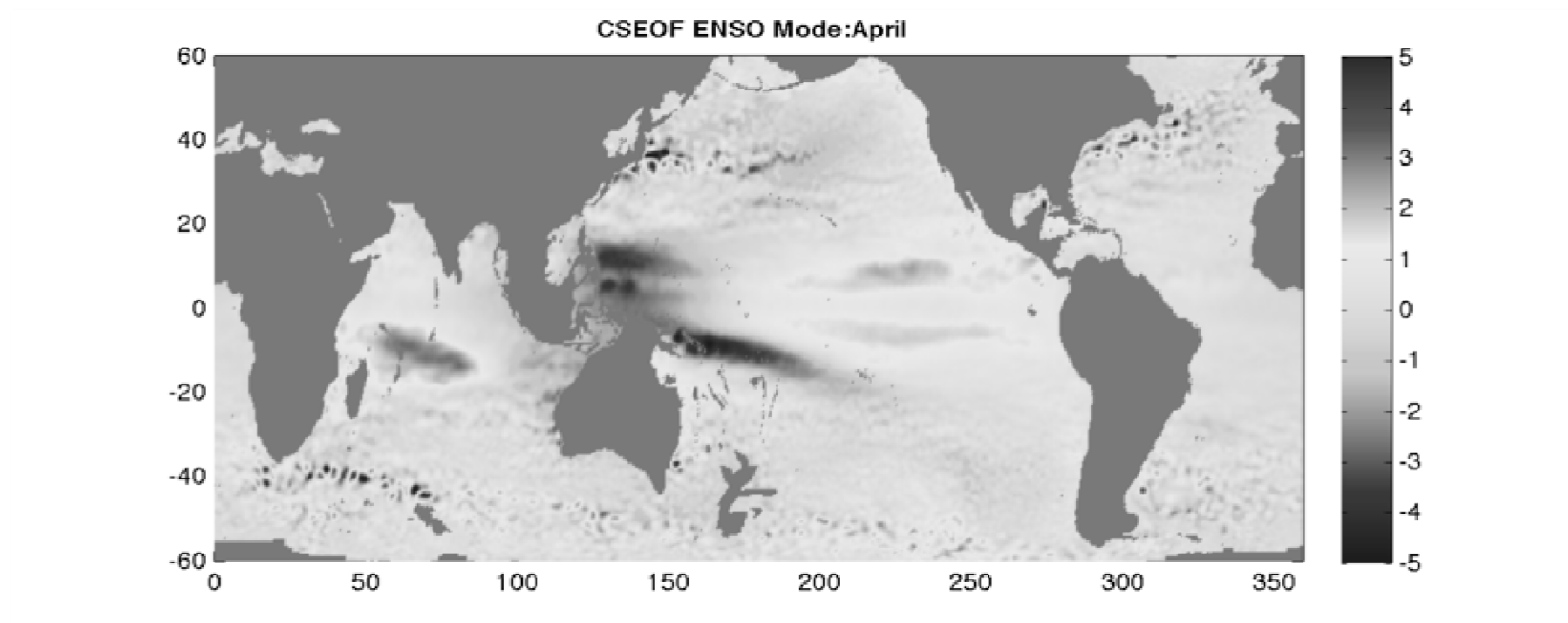
CSEOF EP-ENSO Basis Function



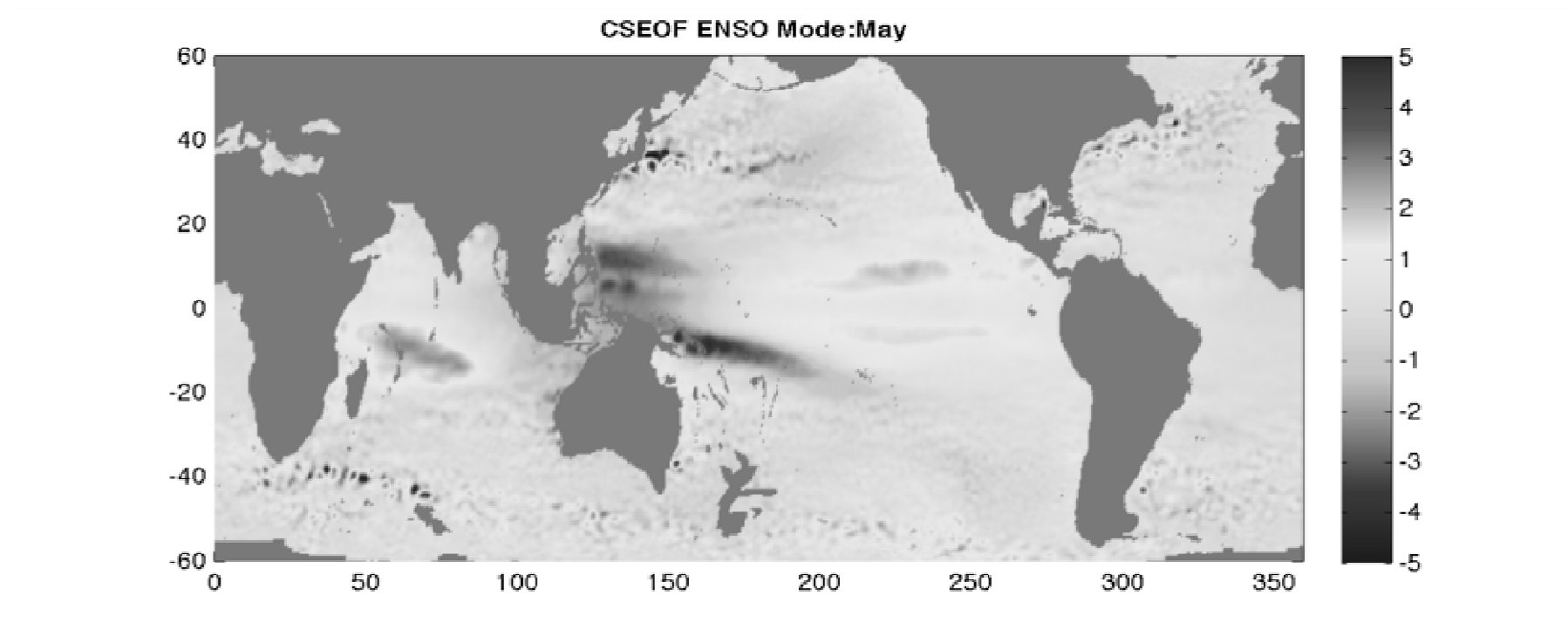
CSEOF EP-ENSO Basis Function



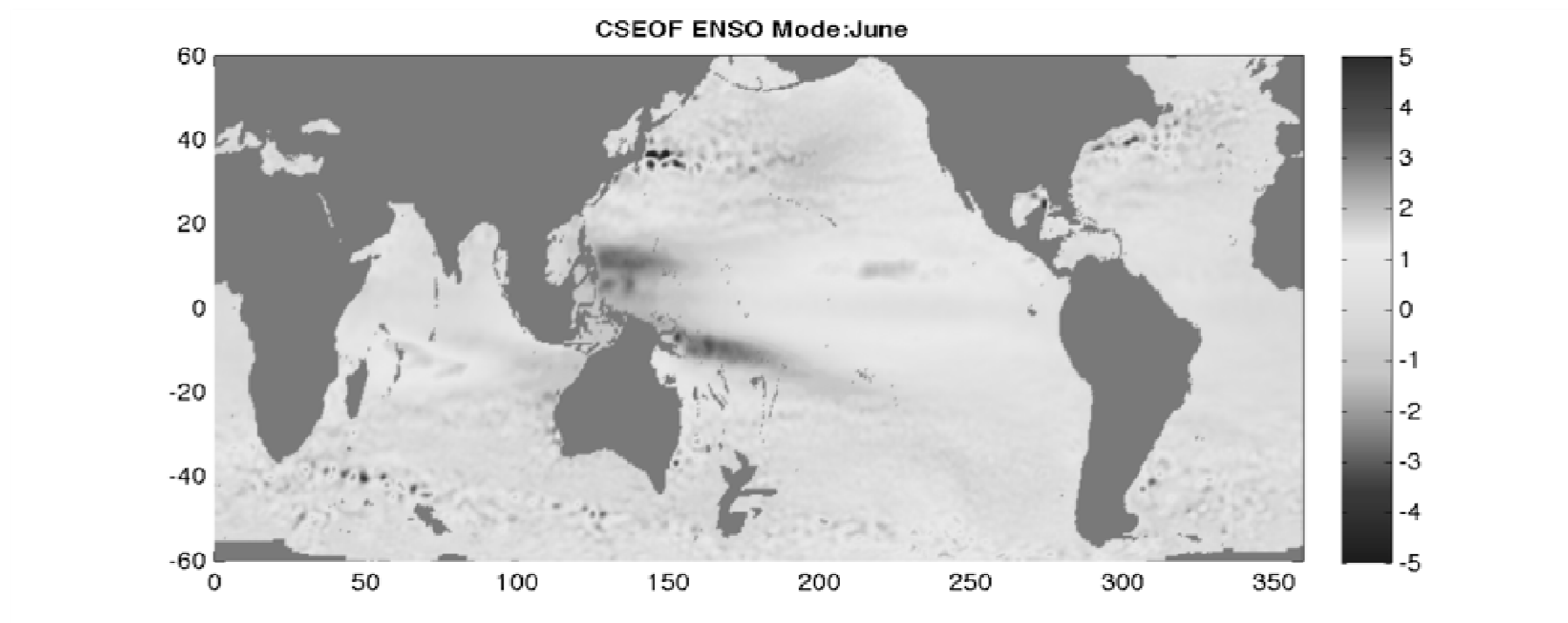
CSEOF EP-ENSO Basis Function



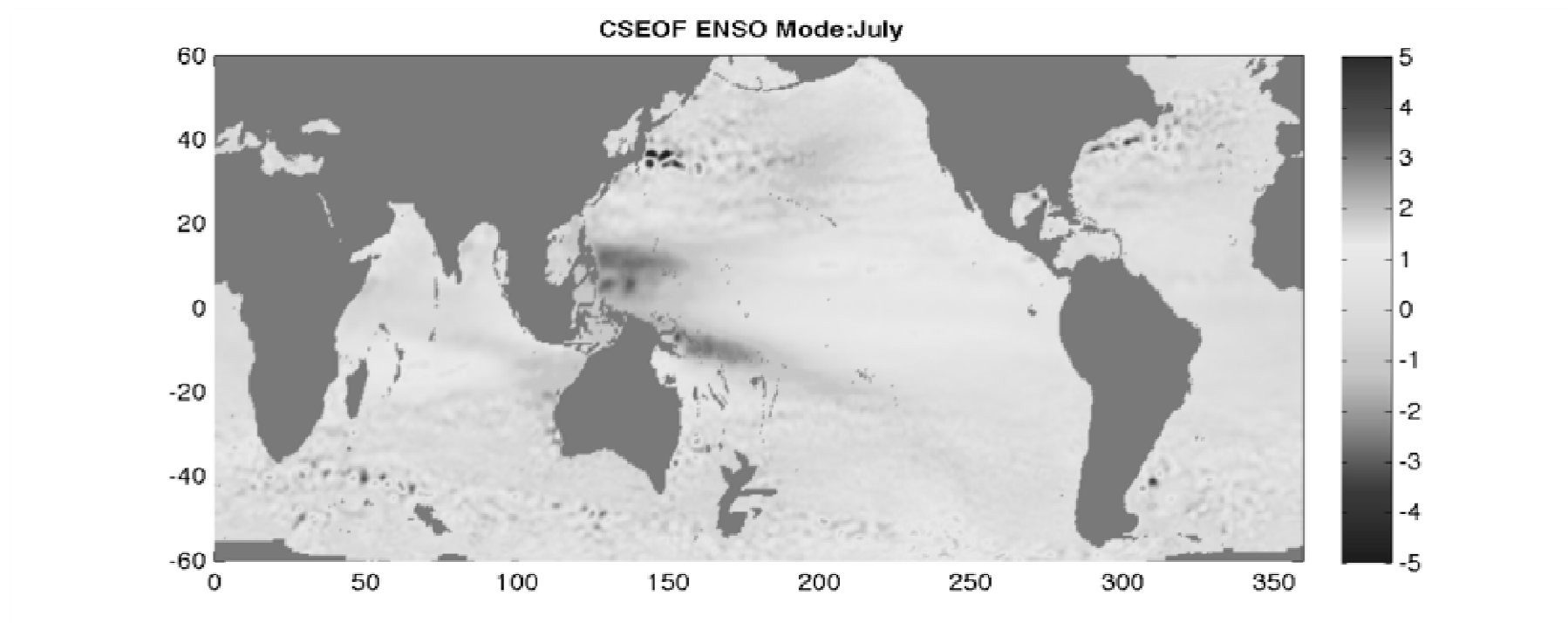
CSEOF EP-ENSO Basis Function



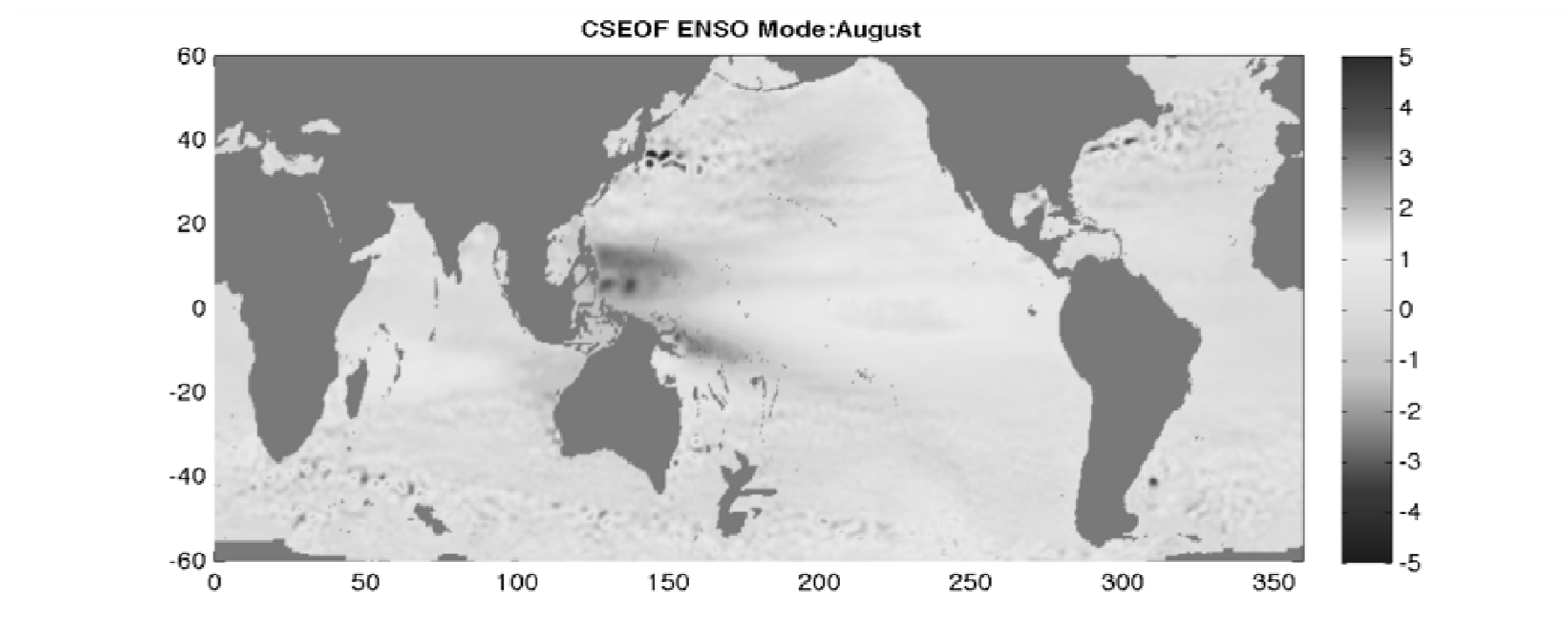
CSEOF EP-ENSO Basis Function



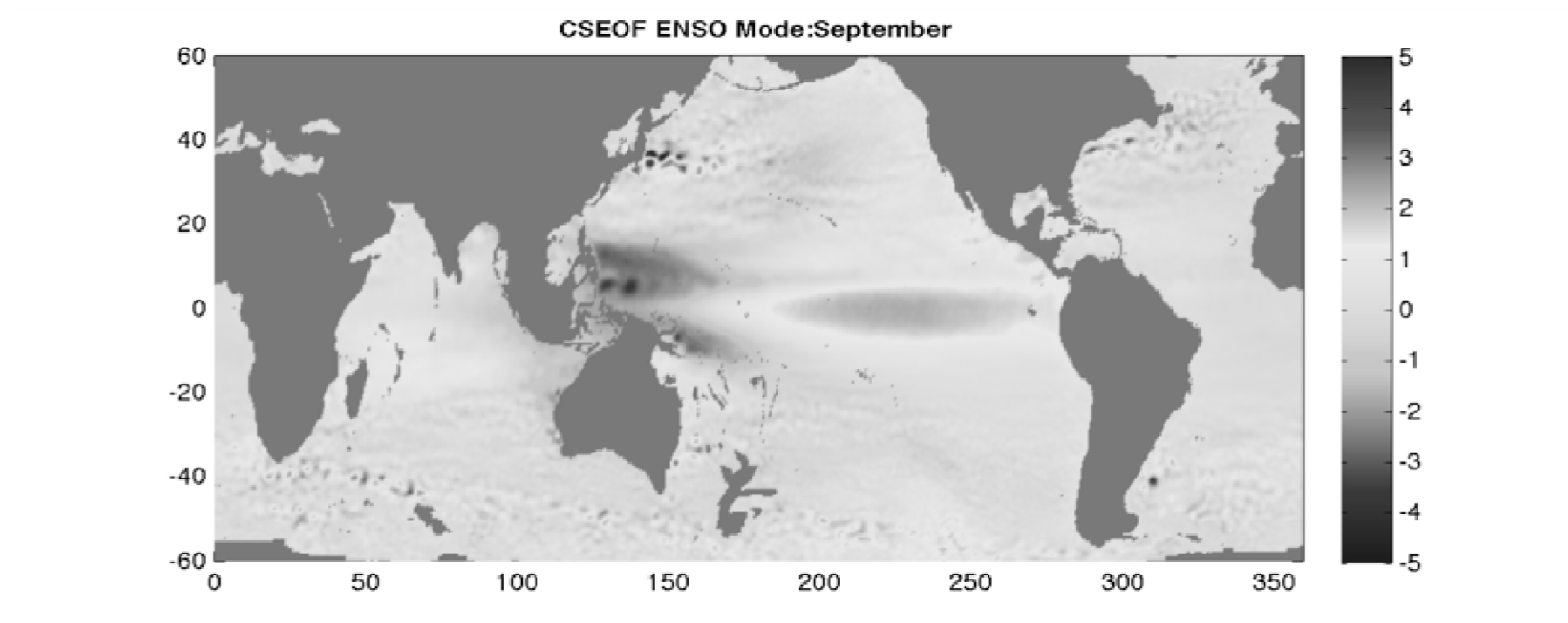
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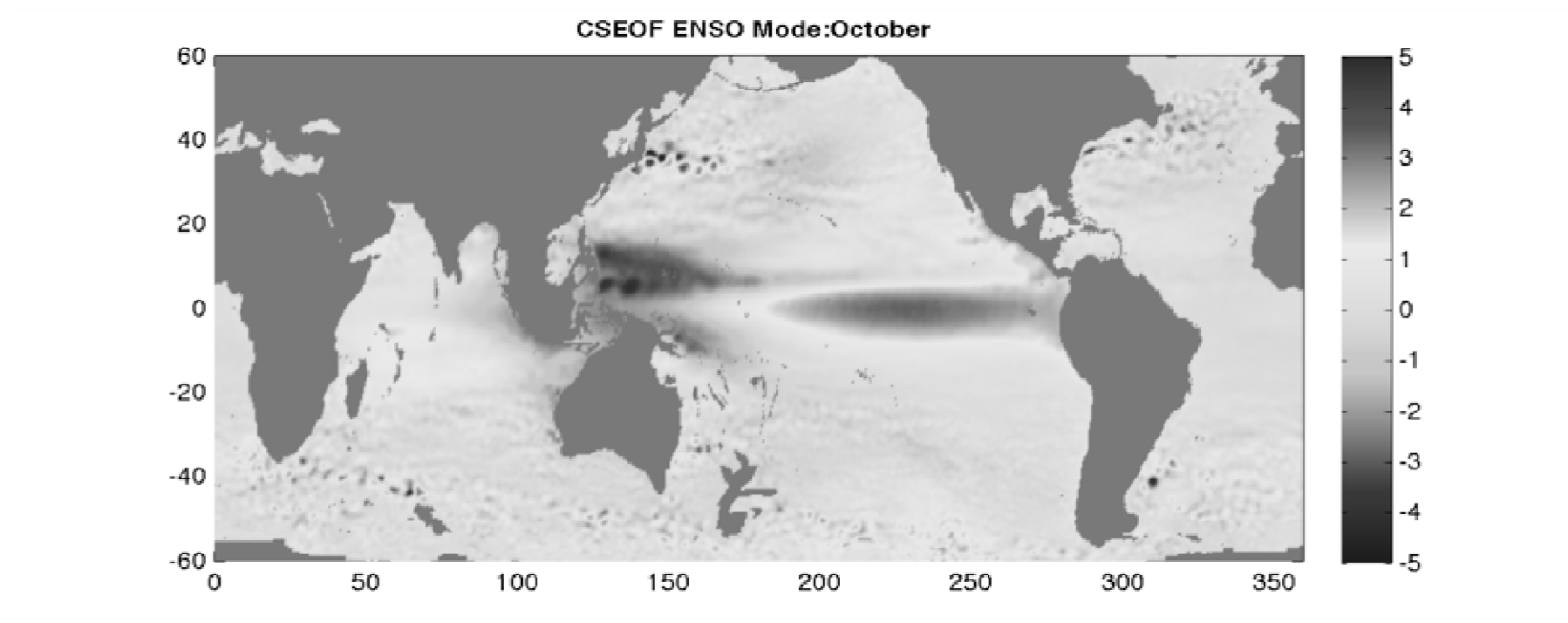
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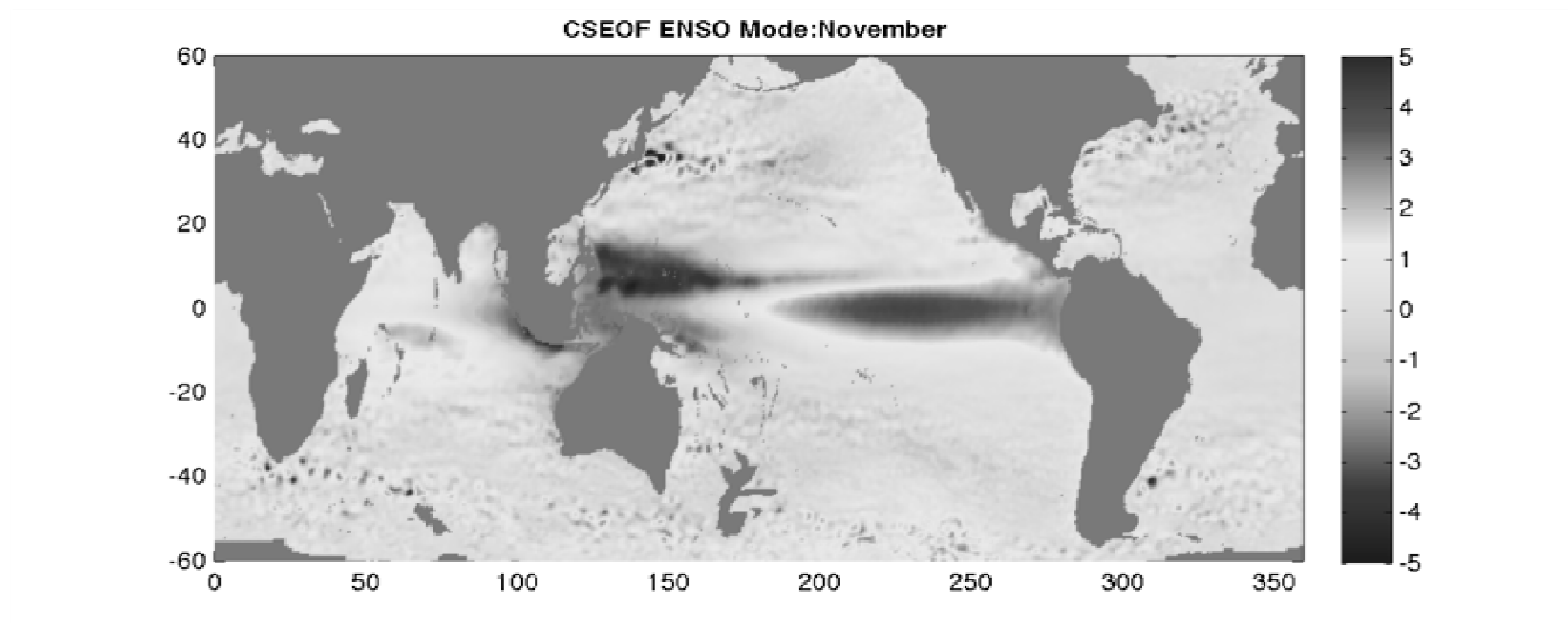
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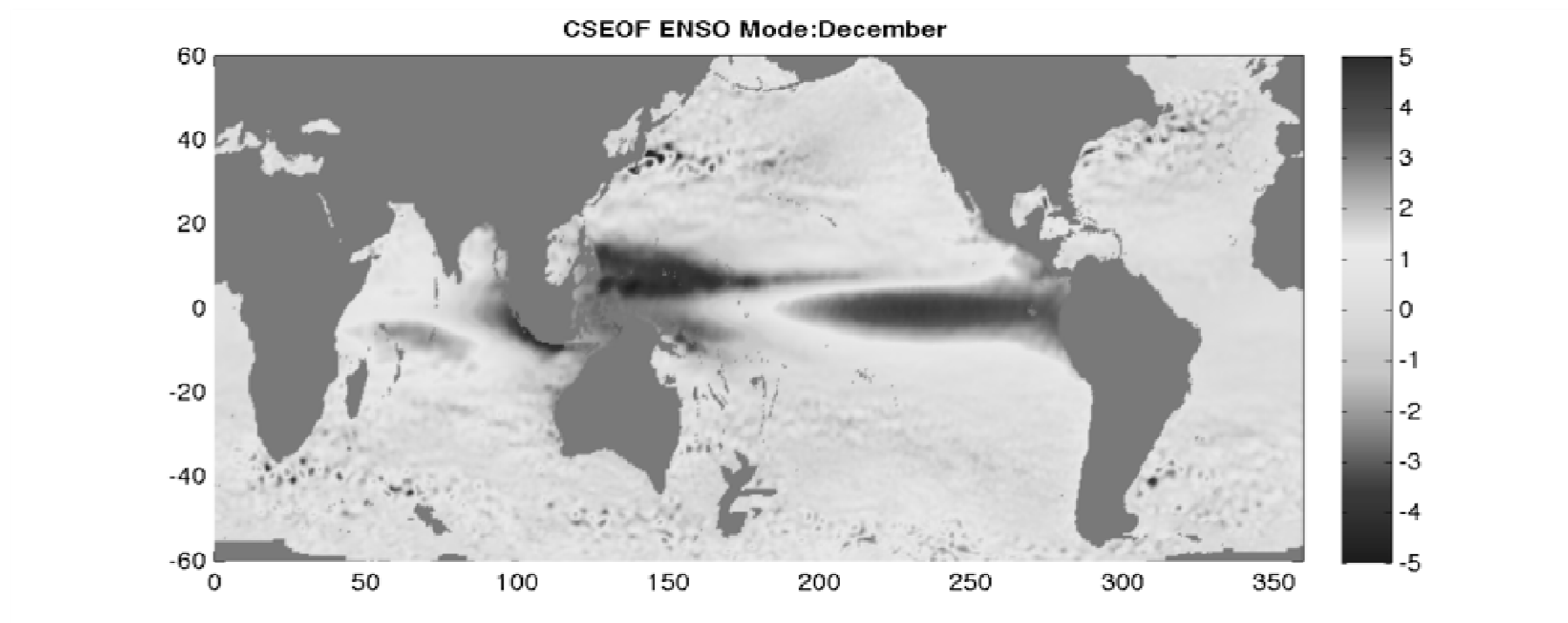
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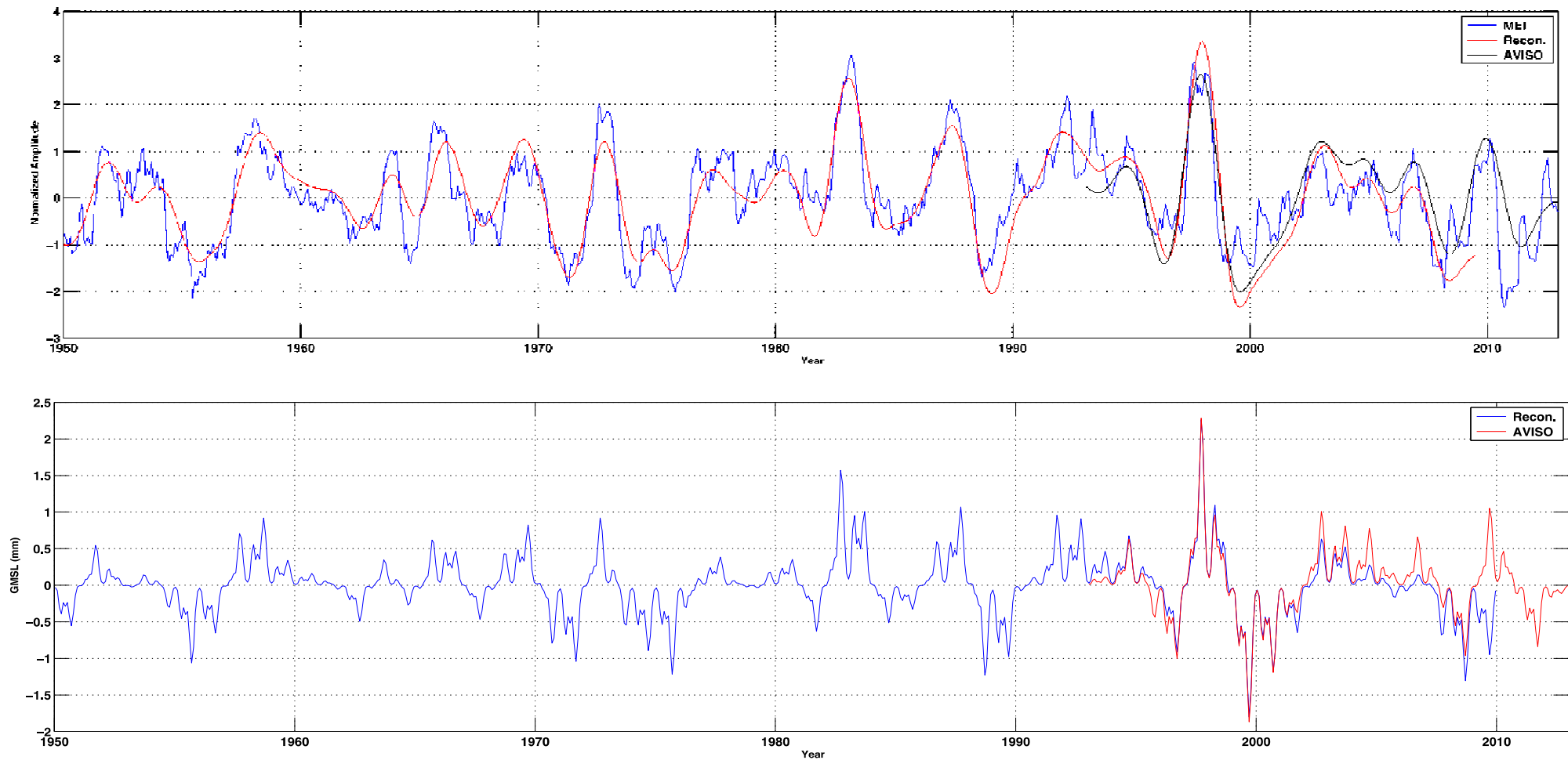
CSEOF EP-ENSO Basis Function



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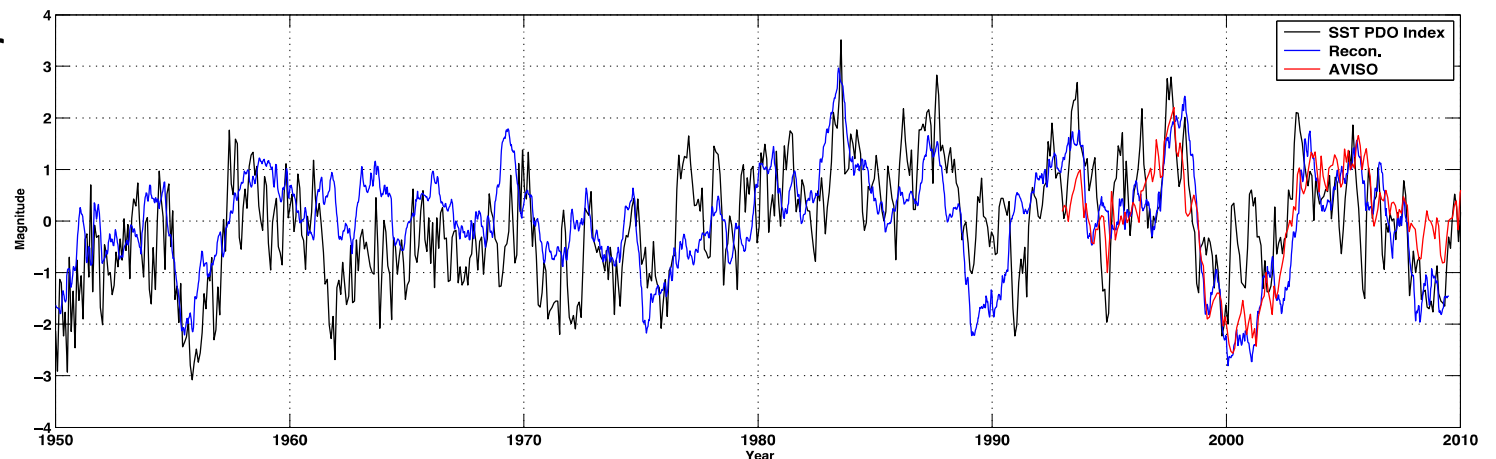
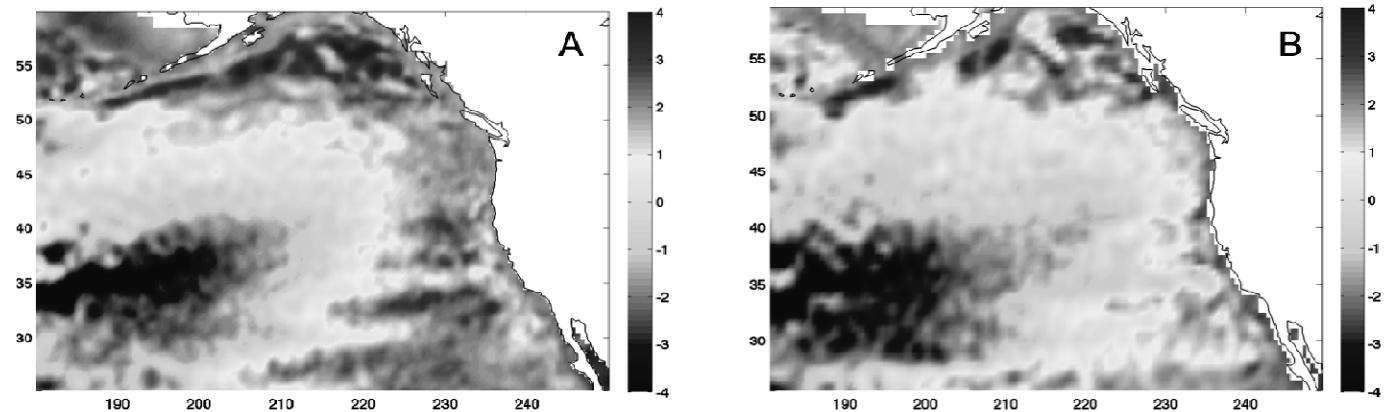


EP-ENSO Index



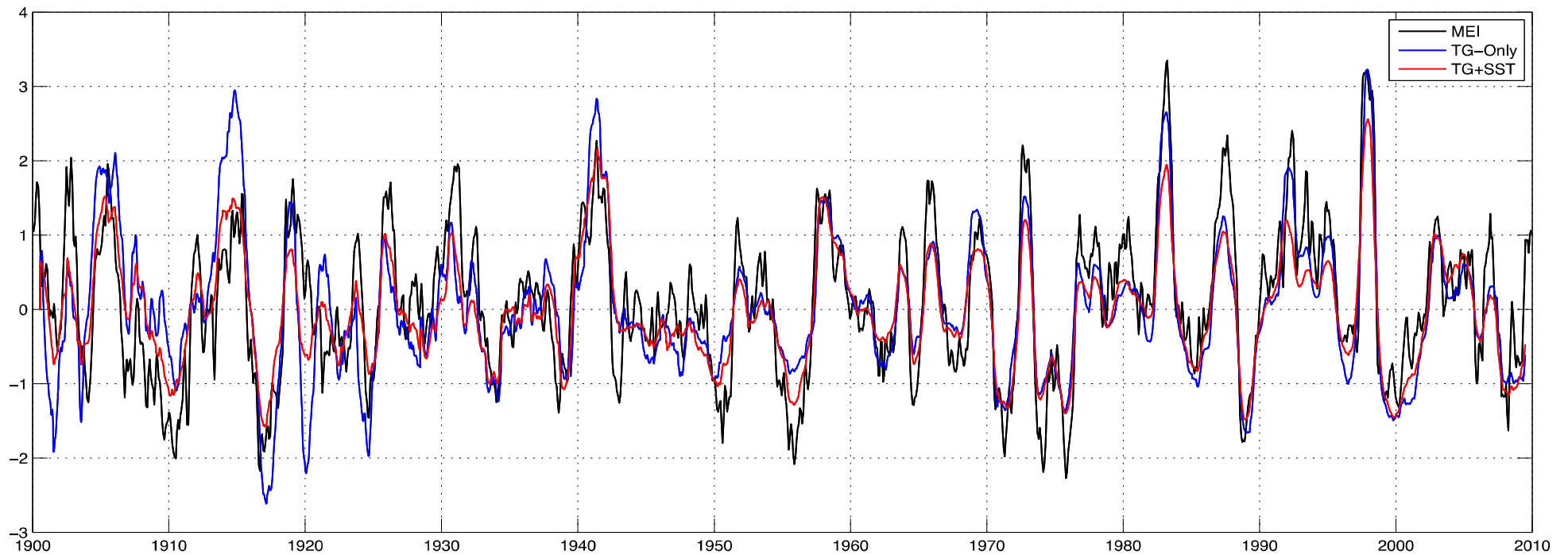
Example: Pacific Decadal Oscillation

- 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 from SST data is also shown for comparison.
- Also possible to create a global PDO mode for monitoring.



Extension back to 1900

- With the bivariate technique that incorporates SST into the reconstruction of sea level, it is also possible to extend these indices back to 1900 (Hamlington et al. 2012).



Correlation with Climate Indices

Reconstruction	TG-only	SST-only	TG+SST
MEI 1950-2010	0.92 (0.95)	0.92 (0.94)	0.95 (0.97)
MEI 1900-2010	0.77 (0.80)	0.84 (0.89)	0.86 (0.91)
EMI 1950-2010	0.72 (0.84)	0.75 (0.87)	0.82 (0.91)
EMI 1900-2010	0.34 (0.48)	0.58 (0.75)	0.64 (0.80)
PDO 1950-2010	0.62 (0.73)	0.54 (0.66)	0.67 (0.77)
PDO 1900-2010	0.49 (0.60)	0.55 (0.60)	0.59 (0.68)

(*Numbers in parentheses represent correlations after 1 year smoothing is applied)

Proposed Ocean Climate Indices

- Modulated Annual Cycle (MAC)
- Eastern Pacific ENSO (EP-ENSO)
- Central Pacific ENSO (CP-ENSO)
- Pacific Decadal Oscillation (PDO)
- North Pacific Gyre Oscillation (NPGO)
- Interdecadal Pacific Oscillation (IPO)
- Indian Ocean Dipole (IOD)
- Atlantic Multidecadal Oscillation (AMO)
- Western Hemisphere Warm Pool (WHWP)

Summary

- By relying on a combination of satellite altimetry data and sea level reconstructions, a wide variety of SSH-based climate indices can be computed.
 - Fills the gap created by other climate indices that do not incorporate sea level.
 - By creating them from the same datasets, the indices will be consistent with the same temporal resolution.
 - The CSEOF-based sea level reconstruction is ideal for this application due to its improved representation of climate variability into the past.
- Many of the climate indices can/will be updated in NRT.
 - For the EP-ENSO index, for example, the CSEOF analysis provides a map representing the EP-ENSO variability for each week of the year (when using weekly data).
 - These maps can be fit to the NRT altimetry data to provide weekly updates of the state of ENSO.
 - Since this index is based on global patterns as opposed to an area-average, the contribution of ENSO to changes in GMSL can also be computed in NRT.
- The first set of SSH-based climate indices will be released and made publicly available by the beginning of 2015.