NEW METHOD FOR RECONSTRUCTING SEA LEVEL FROM TIDE GAUGES USING SATELLITE ALTIMETRY

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1. INTRODUCTION

Sea level is a measurement of considerable interest for the study of climate because it reflects the mass and heat storage changes in the global ocean. Secular changes in sea level have significant societal, economic, environmental and scientific consequences. An emphasis in recent years has been placed on quantifying sea level variations in the past, present and future [1]. Over the last century, tide gauges have been the primary source of sea level measurements. While providing relatively long records, the spatial resolution of tide gauges is poor, thus making accurate estimates of global mean sea level (GMSL) difficult and studies of regional changes in sea level unfeasible [2].

In the past couple of decades, satellite altimetry has also provided measurements of sea level. The near-global coverage and accurate measurements provided by satellite altimeters allow changes in both GMSL and regional sea level to be determined more accurately and quickly than is possible from the sparsely distributed in situ gauges. Despite this improved spatial sampling, the satellite altimetry data record spans only 17 years. Nevertheless, the quality and coverage of satellite altimetry has allowed for a wide range of studies that were unfeasible using only tide gauges.

Combining the shorter but essentially complete global coverage offered by satellite altimetry with the longer but sparsely distributed in situ tide gauge dataset is an active research area. Using a technique known as empirical orthogonal function (EOF) reconstruction [3], Church et al. (CW, hereafter) offer the most complete and widely available reconstruction of sea level over the period from 1950-2000 [4]. Their reconstructed dataset has the spatial coverage of the altimeter data and the temporal span of the tide gauge data. With this reconstruction, they are able to provide estimates of GMSL change and identify patterns of regional sea level change over the period from 1950-2000.

2. CYCLOSTATIONARY EMPIRICAL ORTHOGONAL FUNCTIONS

There have been no published attempts to find a method to combine satellite altimetry data and tide gauge data that improves on the widely accepted reconstruction of CW based on EOFs. By using a more sophisticated set of basis functions, specifically cyclostationary empirical orthogonal functions (CSEOFs) [5], for the reconstruction, we attempt to improve upon the CW reconstruction. While similar in formulation to traditional EOFs, the CSEOF loading vectors (LVs) have a temporal dependence in addition to the spatial patterns that they represent. The temporal evolution of the CSEOF LVs is constrained to be periodic with a certain “nested period”. CSEOFs are based on the idea that spatial patterns in many geophysical processes fluctuate at longer timescales in addition to their well-defined periods. Recent studies demonstrate the capability of CSEOFs to extract modes representing the modulated annual cycle (MAC) and El Nino-Southern Oscillation (ENSO) variability from the altimetric record [5,6]. The motivation for suing CSEOFs in place of traditional EOFs for the reconstruction is threefold: 1) EOFs are not an optimal basis for nonstationary signals with nested oscillations that are undergoing lower frequency oscillation [5]; 2) CSEOFs account for both high and low frequency components of the annual cycle and do not require the removal of annual signals from the tide gauge records before reconstruction; and 3) specific signals such as those relating to the MAC and ENSO can be reconstructed individually with little mixing of variability between modes. Therefore, the variability associated with either the MAC or ENSO can be removed after the reconstruction procedure.

3. RECONSTRUCTION PROCEDURE

Our reconstruction methodology follows CW with the significant difference being that we use CSEOFs instead of EOFs. The process of solving for the amplitudes on each CSEOF mode amounts to solving a weighted least squares problem. In EOF decompositions, each LV is orthogonal to every other LV. However, in a CSEOF decomposition, LVs are not orthogonal at each point in time, but rather this orthogonality spans the entire nested period. Each of the CSEOF modes has 12 spatially varying LVs (one for each month in the year). To form an adequate orthogonal basis for the reconstruction procedure, all 12 LVs must be fit simultaneously. The computed amplitude is then assigned to the center of the nested period, and the entire computation is shifted one month.

We use the quarter-degree resolution multiple altimeter AVISO dataset derived from sea level measurements spanning 1993-2008 to estimate CSEOF basis functions for our reconstruction. A nested period of 12 months was used to distinguish the variability associated with the annual cycle. The MAC and ENSO signals captured in CSEOF modes 1 and 2 [6]. The tide gauge data we used are monthly mean sea levels for the period 1950-2000, gathered from the data archive at the Permanent Service for Mean Sea Level (PSMSL). We followed the tide gauge editing process described in CW, with the exception of not removing the annual cycle from the tide gauge signal prior to the reconstruction procedure.

4. RESULTS AND DISCUSSION

The amplitudes of the first five CSEOF modes computed in the reconstruction process are shown in blue in Fig. 1. The amplitude corresponding to the low-frequency variation in the tide gauges is also shown, designated as Mode 0. For comparison, the PC time series (red) computed from the original CSEOF analysis of the satellite altimetry data is overlaid on the amplitudes. The high correlation between the amplitudes from the reconstruction and the

CSEOF PC time series demonstrates that the agreement between the reconstructed data and the satellite altimetry data between 1993 and 2000 is excellent.

Of particular significance are the computed amplitudes of the first two modes. The amplitude of the first mode represents the modulation of the annual cycle. CSEOF analysis of the satellite altimetry data extracts the annual cycle as the first mode, which explains the most variability in the data. The one-year periodicity associated with the annual cycle is contained in the 12 monthly loading vectors, while the lower-frequency modulation of the annual cycle is separated and described by the amplitudes shown in the upper plot of Fig. 1A. It is clear, then, that if one were to remove a simple harmonic annual fit from the tide gauges prior to the reconstruction process, the low-frequency variability associated with the modulation of the annual cycle would remain in the data. Furthermore, unlike fitting a single EOF, fitting twelve CSEOF LVs simultaneously reduces the sensitivity to sparse tide gauge data at a given point in time. The ability of the CSEOF reconstruction technique to robustly handle the modulated annual cycle is a significant advantage over the simple EOF reconstruction.

The second CSEOF mode from the satellite altimetry was shown by Hamlington et al. [6] to describe the ENSO variability. One would expect, then, that the reconstructed mode would show a similar relation to ENSO. Indeed, the amplitude of the second CSEOF mode has a correlation of 0.87 with the SOI (the negative of the SOI was used so that positive values represented El Nino events). This is a significant improvement from the 0.78 correlation with a reconstructed mode computed by CW.

Comparison of the GMSL computed from the reconstruction and from the satellite observations provides a rigorous check on the fidelity of the reconstruction. Fig. 1B shows the GMSL change for the CSEOF reconstruction (blue), the EOF reconstruction of CW (red), and the AVISO merged satellite altimeter dataset (cyan). The global mean rate of sea level change from 1950-2000 for the CSEOF reconstruction is 1.5 mm/yr. CW published a rate of 1.8 mm/yr over the period from 1950-2000. Before 1985, the two reconstructions showed good agreement. The CSEOF reconstruction appears to agree better with the AVISO GMSL over the period from 1993-2000 than does the EOF reconstruction. We also compared the spatial maps of sea level for the CSEOF reconstruction and AVISO dataset at a given point in time. We found correlations upwards of 0.9 at some points in time and correlations generally above 0.5 over the entire period from 1993-2000.

As an additional check of the reconstruction we estimated the regional distribution of the sea level trends. This distribution of the sea level change agrees well qualitatively with the spatial distribution presented in CW for the period from 1993-2000. Furthermore, the area-weighted correlation between the spatial distributions of sea level trends for the CSEOF reconstructed data and for the AVISO data is remarkably high at 0.88. For the distribution of trends computed from 1950-2000, however, the agreement between our reconstruction and the CW reconstruction is not strong. While the magnitude of the trend is similar and the spatial variation exhibits a weak correlation, some of the larger scale features in the trend map for the CSEOF reconstruction do not appear clearly in the EOF reconstruction map.

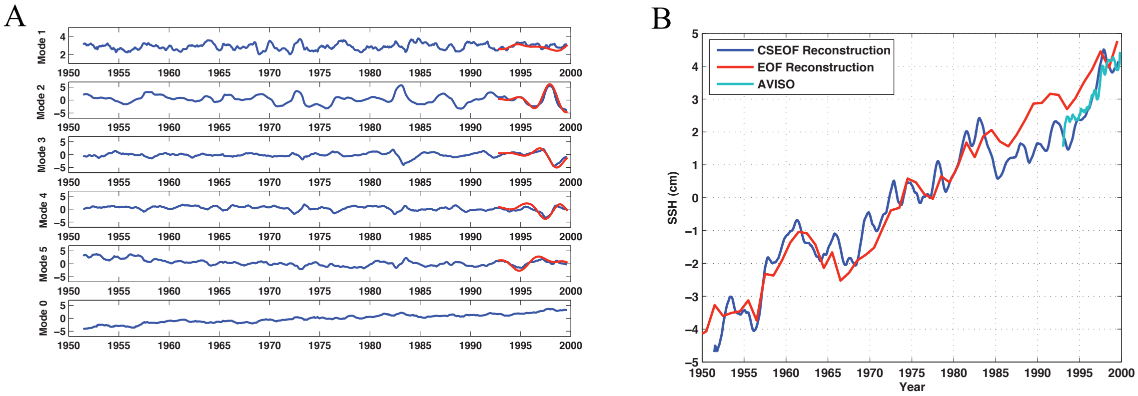

Figure 1. A) Reconstructed amplitudes (blue) computed for first five CSEOF modes, in addition to constant CSEOF mode. The PC time series from the CSEOF analysis are also shown (red). B) Global-averaged sea level between 1950 and 2000 from the CSEOF reconstruction (blue), and from the EOF reconstruction of CW (red). The GMSL from the AVISO dataset is also shown for the period between 1993 and 2000 (cyan).

The CSEOF reconstruction method is shown to represent a significant improvement over EOF reconstruction in accounting for the modulated annual cycle in the tide gauge data. Additionally, a mode relating to the ENSO variability in the tide gauge data is extracted with a higher correlation with the SOI than that stated for the corresponding EOF mode in CW. While it is difficult to definitively determine which method produces reconstructed data that most accurately reflects reality, performing reconstructions with more sophisticated techniques is clearly worth exploring.

5. REFERENCES

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