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Reconstruction of Sea Level Change in Southeast Asia Waters Using Combined Coastal Sea Level Data and Satellite Altimetry Data

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ABSTRACT: Low-lying and densely populated coastal areas with thousands of small islands spreading across Southeast Asia are highly prone to sea level rise caused by global warming. Accurate sea level change maps in Southeast Asia are of great importance to scientists and decision makers in the region interested in past and present sea level change. Improving near-coast satellite altimetry data processing will extend the coastal sea level record back in time and allow accurate mapping of sea level change in the region as well as supporting various potential applications of sea level data in the coastal zone. Our initial comparisons of sea level trends show good agreement between global sea level reconstructions in areas and times of larger signal to noise associated with strong decadal sea level variability forced by low frequency wind forcing.

KEYWORDS: *sea level change, tide gauge, coastal altimetry, reconstruction, re-tracking, Cyclostationary Empirical Orthogonal Function (CSEOF)*

Introduction

Since 1993 satellite altimetry has provided accurate measurements of sea surface height (SSH) with near-global coverage. These measurements have led to the first definitive estimates of Global Mean Sea Level (GMSL) rise and have improved our understanding of how sea level is changing regionally at decadal timescales. The relatively short satellite record, however, does little to answer the question of how the current state of the ocean compares to previous states. Tide gauges, on the other hand, have measured sea level over the last 200 years, with some records extending back to 1807. While providing long records, the spatial resolution of tide gauges is poor, making studies of GMSL and the large-scale patterns of low-frequency ocean variability difficult. Reconstruction of sea level overcomes these respective shortcomings of tide gauge and satellite altimetry records by combining the shorter but essentially complete global coverage offered by satellite altimetry with the longer but sparsely distributed tide gauge data set. The work presented here focuses on sea level trends in the Southeast Asian Seas (SEAS) region as quantified by the satellite altimetry and sea level reconstructions.

The SEAS region spans the largest archipelago in the global ocean and is comprised of a total of 20 seas according to the Limits of the Ocean and Seas published by the International Hydrographic Organization (IHO) in 1953 (IHO, 1953). Figure 1 shows the regional seas, straits, and gulfs as defined by the IHO and delineated by a high-resolution coastline data set. The region has many low-lying and densely populated coastal areas, including large urban and rural river deltas and thousands of small-inhabited islands. The Indonesian archipelago alone consists of 17,508 islands (6,000 inhabited) and encompasses the only tropical interoceanic throughflow in the global ocean, providing a complex oceanic pathway connecting the Pacific and Indian Oceans. The Indonesian throughflow, and thus sea level, is driven primarily by free equatorial Kelvin and Rossby waves (Figure 2) originating along the Indian and Pacific equatorial waveguides (Wijffels & Meyers, 2004). The SEAS region is also one of the most biodiverse oceanographic regions on the planet. Southeast Asia's coral reefs have the highest degree of biodiversity of all of the world's coral reefs and it is estimated that only 10 percent of the marine species associated with coral reefs have been identified and described (Reaka-Kudia, 1997). As a result, this region is increasingly impacted by sea level rise and a warming climate.

HIGHLIGHTS

- Maps of global sea level change affected by global warming are reconstructed using CSEOFs by fitting the satellite-derived sea level variability to coastal tide gauge observations. This method is an improved reconstruction technique, in comparison to methods based on fitting EOFs to global coastal tide gauge data. Regional distribution of sea level trends over the last 60 years has been estimated.
- The CSEOF reconstruction method, applied to an improved satellite altimeter-data archive calibrated using coastal gauge stations in the region and incorporating the spatial data, can potentially improve mapping of sea level change in the Southeast Asia region.
- Coastal Altimetry is a developed method to utilise a relatively mature open ocean altimetry technology in coastal areas. However, a proper processing including re-tracking and/or new/improved corrections can improve the accuracy of satellite in coastal area and shallow waters.

Methodology

Satellite Altimetry: The satellite altimeter data set used in this study was produced and distributed by the Archiving, Validation, and Interpretation of Satellite Oceanographic (AVISO; http://www.aviso.oceanobs.com/) as part of the SSALTO ground-processing segment. The data set has a quarter-degree resolution and was created from measurements spanning 1992 through 2009 using the following satellites: TOPEX/Poseidon, ERS-1&2, Geosat Follow-On, Envisat, Jason-1, and OSTM. These sea level measurements were updated and reprocessed by applying homogeneous corrections and inter-calibrations and referenced to a consistent mean. Then, the along-track data were gridded through a global space-time objective mapping technique. These data are used as a baseline for comparison as well as in four of the five sea level reconstructions used in this study.

Attempts had been made to improve satellite altimetry data sets in low-lying coastal areas where the accuracy of satellite altimeter data is highly degraded because the altimeter measurement system was primarily designed to accurately measure sea surface height measurements in the open ocean, not near the coast. It should be recalled that coastal altimetry products in the archipelagic area such as Indonesia are still experimental and undergoing further refinement. Much has been learned on how to handle data and interpret outputs. A series of MATLAB scripts were made available to assess the improvement gained from the adoption of specialised retrackers and corrections in the coastal zone.

Tide Gauge Data: Each reconstruction uses tide gauge data from the Permanent Service for Mean Sea Level (PSMSL; http://www.psmsl.org). PSMSL supplies a wide range of tide gauge data, but availability depends highly on the region and timeframe in question. Each reconstruction uses different tide gauge editing and selection criteria depending on time-series length, data gaps, area weighting, etc. These will not be discussed in this report but can be found in the respective references for each of the reconstructions.

Sea Level Reconstruction Methods: Sea level reconstructions are created by decomposing the training data into basis functions to explain the original variance, in this case satellite data and/or ocean model data. These basis functions are then interpolated back in time using in situ measurements. Sea level measurements from tide gauges were used for the four univariate reconstructions. For the bivariate reconstruction, both sea level measurements from tide gauges and shipboard measurements of sea surface temperature were used.

The reconstructions compared here use two basis function decomposition methods: empirical orthogonal functions (EOFs) and cyclostationary empirical orthogonal functions (CSEOFs). Both methods decompose the training data set into loading vectors (LVs) and principal component time series (PCTS) for each individual mode. CSEOFs differ from EOFs, however, in that they include a time dependence in the LVs, allowing extraction of non-stationary cyclostationary signals. See Kim et al. (1996) or Kim & Wu (1999) for more details. A number of modes are selected, which explain a subset of variance in the original training data set, and are interpolated back in time to determine the PCTS to create the reconstructed sea level data set. The five different sea level reconstructions used in this analysis vary based on the training data and reconstruction method used. A summary of basic information concerning each reconstruction is given in Table 1. More details on some of the reconstruction are given in the following sections. If more information is desired about any reconstruction, please refer to the corresponding references.

Hamlington et al. (2012) Bivariate Reconstruction (HLK/BV): In addition to AVISO and PSMSL data, HLK/BV uses sea surface temperature (SST) to create a bivariate reconstruction. The SST training data are Optimal Interpolation SST (OISST; http://www.esrl.noaa.gov/psd/data/) data from NOAA, which are a combination of in situ and satellite measurements, as well as simulated SST values near sea ice. The historical in situ SST data come from the International Comprehensive Ocean-Atmosphere Data Set (ICOADS; http://icoads.noaa.gov/), averaged to a 2°x2° grid and known as superobservations (Smith et al., 1996).

To utilise SST measurements for an SSH reconstruction, basis functions of the SST training data are computed using CSEOFs. These basis functions are then transformed to have the same principal component time series as the SSH basis functions. The transformed SST basis functions and the SSH basis functions are then interpolated with the respective in situ measurements to form a bivariate reconstruction. See Hamlington et al. (2012) for more details.

Church and White (2011) Reconstruction (CW): CW utilises a custom satellite altimetry training data set, merging and filtering data from 3 different satellites, as described in Church et al. (2004).

Meyssignac et al. (2011) Mean Reconstruction (M/Mean): Meyssignac et al. (2011) created a mean sea level reconstruction data set by averaged a satellite altimetry reconstruction with two model data reconstructions made using the SODA 2.0 (Carton & Giese, 2008) and the Drakkar/NEMO (Dussin et al., 2009) ocean models.

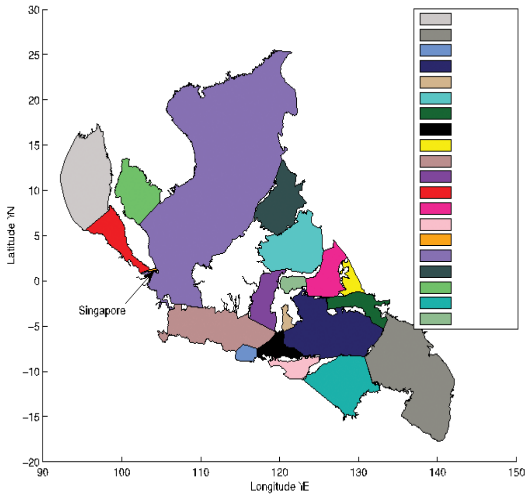

Figure 1. The 20 bodies of water (seas, straits, and gulfs) defined in the Limits of the Ocean and Seas (IHO,1953) for the SEAS region.

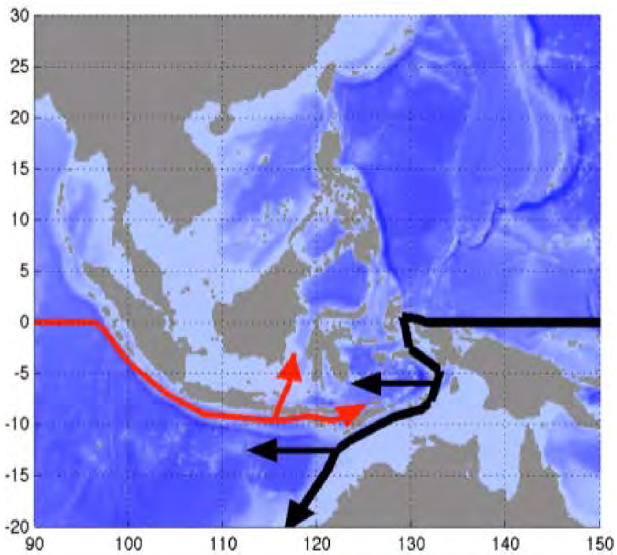

Figure 2. Schematic of remotely forced wave pathways into the Indonesian throughflow region (after Wijffels & Meyers, 2004).

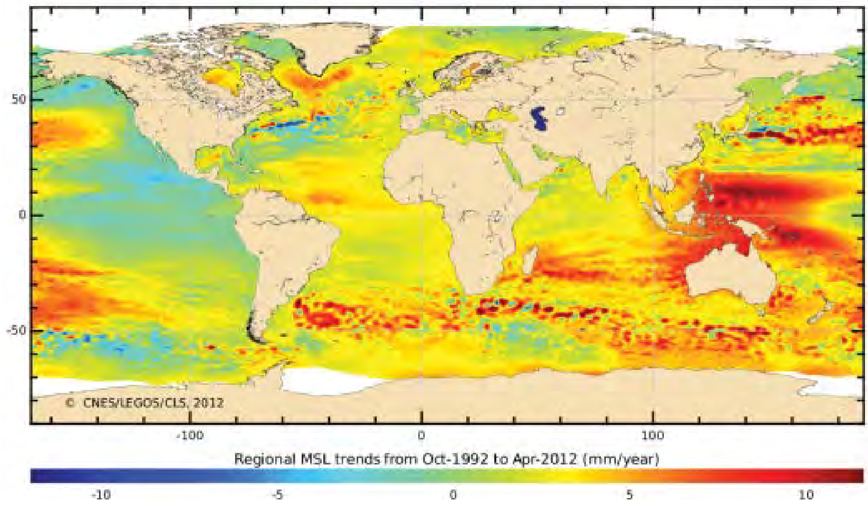

Figure 3. Regional sea level trends computed from October 1992 to April 2012 using AVISO SSH data.

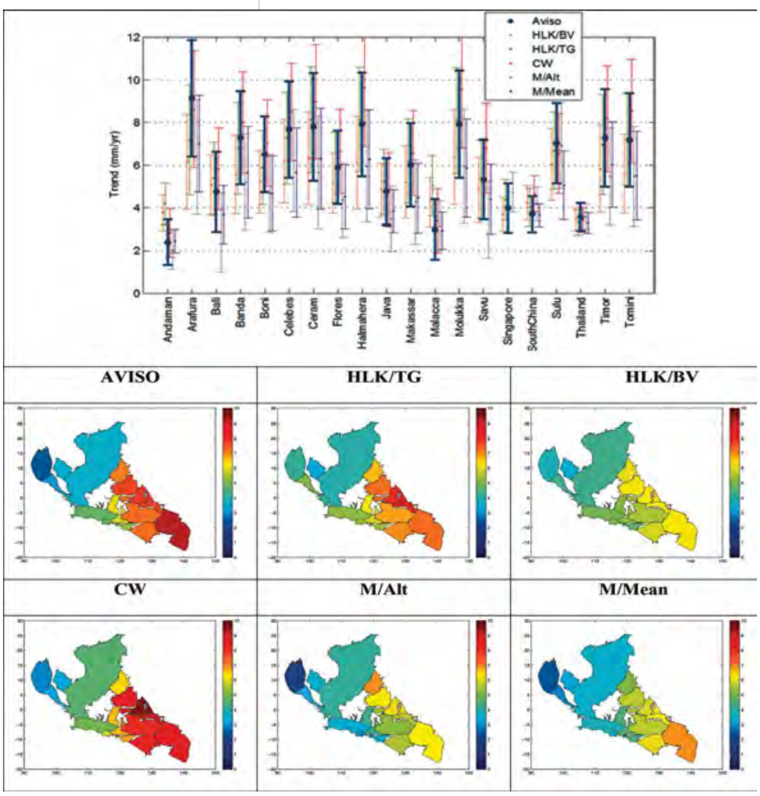

Figure 4. SEAS average sea level trends over the 17-year satellite altimeter record from 1993–2009 shown plotted as trend values with standard (upper plot) and as colour maps (bottom panels) for AVISO and each of the reconstructions.

Estimating Sea Level Trends: Prior to any comparison, each reconstruction was annually averaged for consistency. Linear trends were computed over a variety of time spans and the uncertainty of each trends was found using standard error estimates for the trend term determined from the least squares linear regression.

SEAS Region Definition and Analysis: For the SEAS regional analyses, the region was subdivided into 20 separate bodies of water defined according to the Limits of the Oceans and Seas (1953). For each data set, all points within a given boundary were averaged to determine an areal averaged mean time series for each body of water. If no points were present in a data set, the nearest point was used. Linear trends were found after the calculation of subregion averages.

Transfer of Knowledge: Two workshops, two training sessions, and continuous technical and scientific support were conducted during the project duration. An important effort was dedicated to information transfer, namely software to read, process and visualise altimeter data and sea level reconstructions. The retracking methodology was also seen as another key aspect to be focused upon. The Workshops were aimed at (1) transferring knowledge in terms of data and methods, and (2) assisting the local community in building autonomous capacity of developing and processing satellite and in situ measurements of sea level.

Results and Discussion

Sea level changes in the SEAS region are among the largest observed in modern satellite altimeter record (Figure 3). Regional sea level trends over the 17-year satellite altimeter record (1993 through 2009) are shown in Figure 4 for the AVISO data set and each of the sea level reconstructions during the training data set time period. Reconstructed sea level average trends in the SEAS agree with the AVISO values to within the estimated error.

To highlight the trend variability at the time scales observed over the current altimetric record we performed the following analysis:

- Averaged all reconstructed data sets to form annual averages over the 1950 through 2009 record.
- Calculated 17-year linear trends from the annual averaged data sets to produce 44 17-year trend maps from 1958 through 2001.
- Performed a lagged correlation analysis (present versus past) of the 17-year trend time series for each data set.

A sample of the lagged correlation analysis is shown for the HLK/BV reconstruction in Figure 6. There are roughly three extrema in the 17-year trend variability of the global sea level reconstructions associated with independent 17-year time periods in the 60-year record: 1959–1975 (centred on 1967); 1976–1992 (centred on 1984); and 1993–2009 (centred on 2001). The 1959–1975 time period was correlated with the 1993–2009 record, showing strong regional sea level trends in the western Pacific similar to those observed during the satellite record. On the other hand, anti-correlation is found between the 1976–1992 and 1993–2009 17-year trends, with the former time period exhibiting much smaller sea level

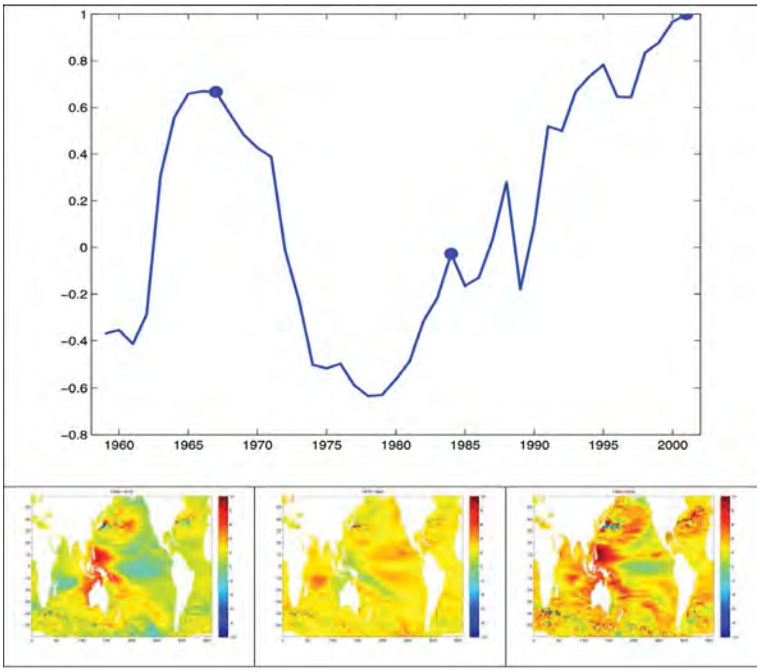

Figure 5. Lagged correlation coefficient (shown as the blue line in the upper plot) of the historical 17-year regional linear trend maps with the linear trend map from the satellite altimeter time period 1992–2009 centred on 2001 (leftmost blue dot). The bottom plots show the 17-year sea level trend map¬s in mm/year for the 1959–1976 (left), 1977–1992 (centre), and 1992–2009 (right) time periods. The blue dots shown on the upper plot are the centre points of the three 17-year windows.

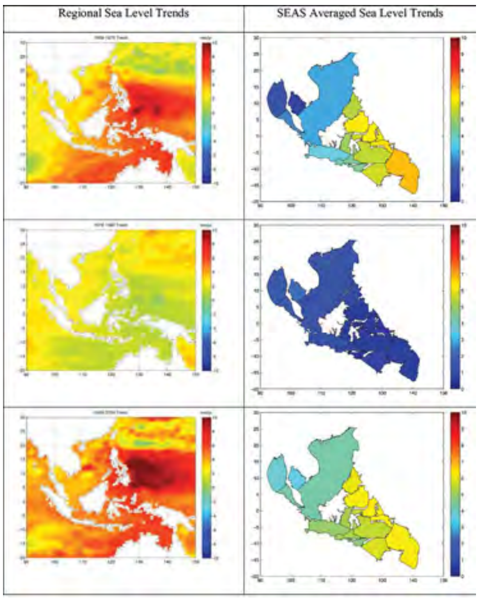

Figure 6. SEAS regional and averaged sea level trends for the (a) 1959–1975, (b) 1976–1992, and (c) 1993–2009 time periods from the bivariate sea level reconstruction (Hamlington et al., 2012).

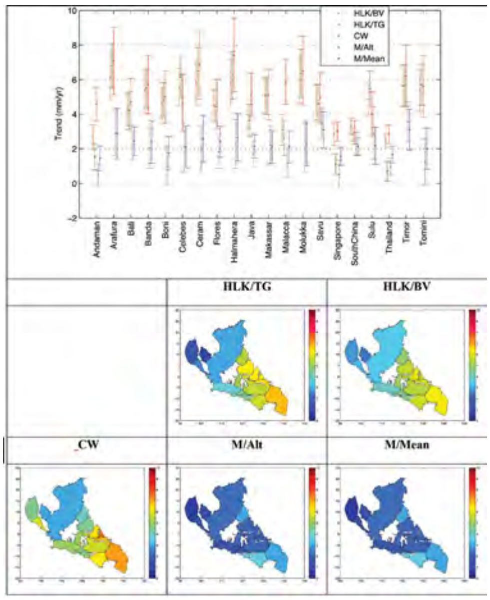

Figure 7. SEAS average sea level trends over the 17-year time period from 1959 through 1975 shown plotted as trend values with standard error (upper plot) and as color maps (bottom panels) for each of the reconstructions.

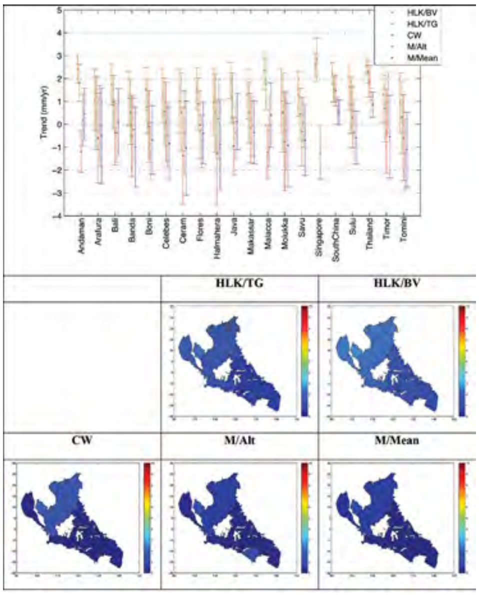

Figure 8. SEAS average sea level trends over the 17-year time period from 1976 through 1992 shown plotted as trend values with standard error (upper plot) and as color maps (bottom panels) for each of the reconstructions.

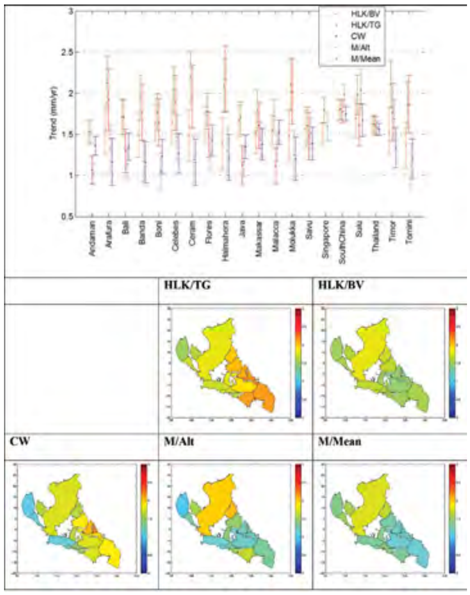

Figure 9. SEAS average sea level trends over the 60-year time period from 1950 through 2009 shown plotted as trend values with standard error (upper plot) and as color maps (bottom panels) for each of the reconstructions.

trends in the western Pacific than those observed during the satellite record.

What is driving these changes in the western Pacific sea level trends? Merrifield et al. (2012) showed that, when detrended by GMSL, the western Pacific sea level is correlated with the low-frequency variability of the Pacific Decadal Oscillation (PDO) and the Southern Oscillation Index (SOI). This sea level signal is driven by anomalous decadal wind variability over the equatorial Pacific and propagates along the Rossby waveguide through the SEAS archipelago, reaching as far south as Fremantle on the western Australian coast. Figure 6 shows the impact of the Pacific wind forcing induced sea level variability on the SEAS sea level trends determined from the bivariate reconstruction for each of the independent 17-year time periods. Figures 7, 8 and 9 show SEAS averaged sea level trends, error estimates, and SEAS averaged maps for each of the reconstructions over the two 17-year time periods, 1959–1975 and 1976–1992, and the 60-year time periods, 1950–2009, respectively.

Conclusions

Our initial comparisons of sea level trends show good agreement between global sea level reconstructions in areas and times of larger signal to noise associated with strong decadal sea level variability forced by low frequency wind forcing.

SEAS regions along the deepwater Rossby waveguide connecting the Pacific and Indian Oceans are most affected by this variability.

The good news for the SEAS region is the likelihood that recent strong sea level trends observed during the altimetry record will abate as trade winds fluctuate on decadal and multi-decadal time scales.

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