Title: Sea Level Trends in South East Asian Seas (SEAS)

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Abstract

Southeast Asian Seas (SEAS) span the largest archipelago in the global ocean and provide a complex oceanic pathway connecting the Pacific and Indian Oceans. The SEAS regional sea level trends are some of the highest observed in the modern satellite altimeter record that now spans almost two decades. Initial comparisons of global sea level reconstructions find that 17-year sea level trends over the past 60 years exhibit good agreement with decadal variability associated with the Pacific Decadal Oscillation and related fluctuations of trade winds in the region. The SEAS region exhibits sea level trends that vary dramatically over the studied time period. This historical variation suggests that the strong regional sea level trends observed during the modern satellite altimeter record will abate as trade winds fluctuate on decadal and longer time scales. Furthermore, after removing the contribution of the PDO to sea level trends in the past twenty years, the rate of sea level rise is greatly reduced in the SEAS region. As a result of the influence of the PDO, the SEAS regional sea level trends during 2010s and 2020s are likely to be less than the global mean sea level (GMSL) trend if the observed oscillations in wind forcing and sea level persist. Nevertheless, long-term sea level trends in the SEAS will continue to be affected by GMSL rise occurring now and in the future.

1. Introduction

Sea level is a measurement of considerable interest and importance for the study of climate because it reflects both mass and heat storage changes in the global ocean. Variations in sea level over long time periods provide an important "lens" into the current state of the climate. Over the last century, sea level has been rising at an increasing rate due to the thermal expansion of water associated with the warming ocean and the melting of land ice [e.g. *Church et al.,* 2011]. While the trend in global mean sea level (GMSL) is positive (estimated from satellite altimetry to be 3.2 mm/yr.), the rise of sea level is far from uniform across the globe. Regional sea level changes in most areas of the ocean are strongly affected by spatially varying factors such as ocean warming, ocean dynamic responses, and gravitational and solid earth effects from changing surface mass [e.g. *Slangen et al.*, 2012; *Perrette et al.,* 2013].

Attributing the trends in both regional and global sea level to specific processes has important implications for projecting sea level rise in the future. Removing short-term trends, for instance, associated with known climate variability can allow for a better understanding of the underlying warming trend [*Hamlington et al.,* 2011a; 2013; 2014b; *Chambers et al.*, 2012; *Frankcombe, et al.,* 2014]. In some regions, internal climate variability on decadal (or longer) timescales can lead to trends that are significantly larger than the background secular trend. Identifying and explaining signals contributing to regional and global sea level variability and trends has been a frequently studied problem in recent years [e.g. *Bromirski et al.,* 2011*; Chambers et al,* 2012; *Hamlington et al.,* 2011a; 2013; 2014b; *Merrifield et al.*, 2012; *Zhang et al.*, 2012; *Fasullo et al.*, 2013; *Moon et al. 2013, Frankcombe, et al.*, 2014].

Understanding how low frequency climate variability affects sea level trends (both globally and regionally) is in part hampered by the available observations. 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 GMSL rise and have improved our understanding of how sea level is changing regionally on 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. Furthermore, the short altimeter record is not long enough to separate decadal scale variability from the trend [*Frankcombe et al.*, 2014]. Tide gauges, on the other hand, have measured sea level over the last several hundred years, with some records extending back into the 17th century. 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. To overcome these challenges and to make accurate comparisons between climate variations over different time periods, a long and consistent data record is necessary. Through the incorporation of historical measurements, reconstruction techniques have been developed and used to overcome the challenges posed by short modern observational records [*Smith et al.,* 1996; *Smith and Reynolds,* 2004; *Chambers et al.,* 2002; *Church et al.,* 2004*; Hamlington et al.,* 2011b; 2012; 2014a; *Meyssignac et al.,* 2012]. By combining the dense spatial coverage of satellite altimetry with the long record length of the tide gauges in a sea level reconstruction, it is possible to create a dataset with the temporal length of the tide gauge record and the spatial coverage of the satellite altimetry. This allows for an examination of longer timescale climate signals and the chance to assess their contribution to sea level trends both regionally and globally. Furthermore, it is possible to determine whether the current rate and spatial pattern of sea level change are exceptional or instead are simply a recurrence of multi-decadal climate oscillations [*e.g. Meyssignac et al.,* 2012; *Hamlington et al.*, 2014b].

Here, we focus on an area of the ocean particularly affected by rising sea level in the past two decades. The Southeast Asian Seas (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 [*Fourcy and Lorvelec*, 2013]. 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 through flow 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 originating along the Indian and Pacific equatorial waveguides [*Wijffels and Meyers*, 2004].

In the past two decades the SEAS region has experienced rising sea levels at rates more than double the global mean. Given the low-lying and densely populated coastal areas, there is great concern regarding whether the trends observed in the past two decades will persist into the coming decades. In this study, we examine the sea level trends in the SEAS region over the past sixty years, and extend recent studies on sea level in the Pacific Ocean [e.g. *Meyssignac et al.*, 2012; *Merrifield et al.*, 2012; *Hamlington et* *al.*, 2013; 2014b] to assess the direction of sea level variability in the near future. Our goal is to understand if the trends observed in the SEAS region by satellite altimeters are exceptional or have similarly occurred in the past, and if the trend pattern in the region is driven by decadal variability, what should be expected with regards to sea level rise in the future. To do this, we will use two different sea level reconstructions coupled with the satellite altimetry data. Using the definition of the SEAS provided by the IHO, we also estimate the trend in each individual sea and discuss the effect of decadal climate variability on trends in the SEAS region. This study has important implications for the coastal populations in the SEAS region, providing the opportunity to gain a better understanding of future sea levels in perhaps the area on Earth most gravely affected by recent sea level rise.

2. Data and Methods

To study the historical sea level trends in the SEAS region, two different reconstructions are used. Sea level reconstructions are created by decomposing training data (provided by satellite altimeters in this case) into basis functions. These basis functions are then fit to *in situ* tide gauge measurements back through time to create a dataset with the spatial coverage of the satellite altimetry and record length of the tide gauges. The two reconstructions used here differ primarily in the selection of basis function decomposition methods. The first reconstruction of *Church and White et al.* [2004; 2006; 2011; referred to as the reconstruction of CW, hereafter] uses empirical orthogonal functions (EOFs). EOF basis functions were first used in reconstructions of sea surface temperature [*e.g. Smith et al.* 1996] and sea level pressure [e.g. *Kaplan et al.*

2000], and have been extended for use in sea level reconstructions [e.g. *Chambers et al.,* 2002]. The second sea level reconstruction considered here uses cyclostationary empirical orthogonal functions (CSEOFs) as basis functions [*Hamlington et al.,* 2011; 2012; referred to as the reconstruction of HLK (*Hamlington, Leben, Kim),* hereafter]. Like EOFs, CSEOF analysis decomposes the training data set (provided in this case by satellite altimetry measurements) into loading vectors (LVs) and principal component time series (PCTS) for each individual mode. CSEOFs differ from EOFs, however, in that they include time dependence in the LVs, allowing extraction of periodic or cyclostationary signals [see for example, *Kim et al.,* 1996; 1997]. A recent study examined the reconstruction of sea level using EOFs and CSEOFs in an idealized setting, and found the CSEOF reconstruction provided many advantages when attempting to capture the effect of internal climate variability on sea level [*Strassburg et al.,* 2014]. By using the satellite altimetry dataset as "truth", the ability to reconstruct regional variability given the distribution of tide gauges at different times in the past was tested. In each of the 17 cases tested, the CSEOF-based reconstruction outperformed the EOF-based reconstruction in the ability to accurately represent regional sea level. Based on the results of this prior study and for the purposes of this paper, the HLK reconstruction is considered to be the primary dataset for the historical trend analysis, with the CW reconstruction serving as a comparison.

Once the training data is decomposed using either EOF or CSEOF analysis, a number of modes are selected, explaining a subset of variance in the original training dataset, and fit to the tide gauge measurements back through time to create the reconstructed sea level dataset. The CW reconstruction uses 1°x1° monthly sea surface height anomaly (SSHA) maps derived from TOPEX/Poseidon, Jason-1 and Jason-2 10-day repeat altimetry data. The HLK reconstruction uses the satellite altimeter data product 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 quarter-degree resolution and was created from measurements spanning 1992 through present 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. In this paper, the AVISO data are also used as a direct comparison to the reconstructions during the past two decades.

The two reconstructions also differ in how global mean sea level (GMSL) is accounted for. The CW reconstruction introduces an "EOF0", a spatially constant mode that captures the mean of the tide gauges through time. *Calafat et al.* [2014] studied the use of this constant EOF mode and its effect on the GMSL in the resultant reconstruction. Although the inclusion of EOF0 was found to have a negative effect on the ability to explain the impact of internal climate variability on GMSL, the regional trends are not necessarily similarly negatively affected, making the use of the CW reconstruction suitable for the purposes of this study. Regardless, this computational difference should be kept in mind when comparing trends from the two datasets. The HLK reconstruction does not use a constant basis function, instead relying on a weighted average of the tide gauges that is added after the fitting of the CSEOF modes to the historical tide gauge measurements. Through this procedure, information regarding the contribution of internal climate variability to GMSL is preserved in the reconstruction.

For historical data, both of the two reconstructions considered here use 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. To establish a common time period for comparison, only the reconstruction data available from 1950 to 2009 is used in this analysis. For any additional details on the generation of the two reconstructed sea level datasets, the reader is directed to the references [EOF reconstruction – *Church and White et al.* 2004; 2006; CSEOF reconstruction – *Hamlington et al.* 2011; 2012], which provide a more complete description of the computational methods and selection choices that were involved.

3. Results

Before analyzing the trend variability in the SEAS region, the ability of the HLK reconstruction to accurately represent sea level variability in the SEAS region is evaluated. Fig. 2 shows the correlation between the AVISO satellite altimetry data (trend and seasonal signal removed) and HLK reconstruction (trend removed) averaged over each of the individual SEAS. In general, the correlations are high with statistical significance at the 90% or higher confidence level for all but three SEAS. The northwestern SEAS have lower correlations suggesting lower confidence should be given to the trend results in the relevant SEAS. To investigate this further and as an additional test, the HLK reconstruction is compared to the tide gauge records in the region (Fig. 3). Correlations between the tide gauge records and reconstruction are shown by the color of each marker, while the available record length of the tide gauge is provided by the size of the marker (largest markers represent tide gauges with most complete records over the time period from 1950 to 2009). Similar to the comparison with the altimetry, the agreement is good outside of the northwestern portion of the SEAS region. Examining the tide gauge records in this region, the tide gauge at Ko Lak, Thailand exhibits a sharp increase in trend after 2000. From 1950 to 2000, the sea level trend at this record has a negative trend. Without having a physical explanation of the sharp increase, it is likely that this gauge should have been left out of the reconstruction procedure, as it appears to have negatively impacted the results in this region. This highlights the care that must be taken when reconstructing sea level in regions with few tide gauge records – a single record has the potential to negatively affect the reconstruction in such regions. As will be shown below, however, the 20-year trends in these regions show good agreement with satellite altimetry, and poor agreement with regards to the internal variability in these northwestern regions do not detract from the discussion in this paper regarding the wider SEAS area. In short, from these two tests (Figs. 2 and 3), the HLK reconstruction appears to be sufficiently accurate to study the trend variability from 1950 to 2009 in the SEAS region.

While the sea level trends in the SEAS region have been large in the past two decades, a more pressing topic is whether the regional sea level trends will be similarly high in the coming decades. Projecting future regional sea level rise is a challenging task that requires expertise across a wide range of disciplines, and a broad understanding of the Earth system. One way to gain an understanding of possible future directions and ranges of sea level is to study changes on similar timescales in the past. As discussed above, sea level reconstructions extend the satellite altimetry record of sea level back in time, providing the opportunity to study the influence of low frequency variability on sea level trends. To highlight the trend variability at the time scales observed over the current altimetric record, both reconstructed sea level datasets (CW and HLK) were first annually averaged over the 1950 to 2009 record. 17-year regional trend maps were computed with a least-square estimate of the trend from the sea level reconstruction dataset. While recent studies have shown that serial correlation can affect the trend analysis of sea level [*e.g. Dangendorf et al.*, 2014], accounting for such correlation is beyond the scope of the present study and will not be considered. In *Meyssignac et* al. [2012], the question was asked whether the pattern of sea level trends observed during the satellite altimeter era had similarly occurred in the past 60 years. This was further explored in *Hamlington et al.* [2013] by correlating the AVISO trend map with roughly 20-year trend maps from the sea level reconstructions extending back to 1950. Both studies – *Meyssignac et al.* [2012] and *Hamlington et al.* [2013] - showed extrema centered in roughly 1967, 1977 and 1999, implying a trend pattern like that observed by satellite altimetry has existed in the past. These previous studies have important implications for the understanding of the sea level trends in the SEAS, highlighting the decadal variability that affects sea level in the region. Motivated by these results to explore the topic further, here we focus on the three independent 17-year sea level trend patterns from the sea level reconstructions centered on the years of 1967, 1984, and 2001.

Sea level trends in the SEAS region are some of the largest observed in the modern satellite altimeter record covering the past two decades. 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, with the two reconstructions also showing good agreement over the entire region. Trends in the region over this time period are strictly positive and approach values greater than 1 cm/year in some areas. Trend values in the southeastern part of the SEAS region have been particularly high in the past two decades. To determine how the recent sea level trends compare to the past, sea level trends from 1959 to 1975 are computed (Fig. 5). As in the past two decades, the sea level trend in each of the seas in the region is positive, with the highest trends found in the southeastern part of the SEAS region. In general, the two reconstructions agree although some discrepancy is seen in the northwestern region of the SEAS, possibly a result of differing tide gauge selection between the two reconstructions. As seen in Fig. 2, the agreement between the HLK sea level reconstruction and the satellite altimetry data in these same northwestern SEAS is not strong. Coupled with the disagreeing trend analysis here, there is an indication that reconstructing sea level in the northwestern region is difficult given the available tide gauges. Finally, the sea level trend pattern in the SEAS from 1976 to 1992 is computed from both reconstructions (Fig. 6). In contrast to the other two time periods, the sea level trends are much lower throughout the region, with the range of sea level trends in some areas becoming negative. Again, the two reconstructions agree to within the estimated error.

By comparing the 17-year sea level trend patterns from the past 50 years, the decadal-scale variability of sea level change in the SEAS region becomes evident. In Figure 7, using only the HLK reconstruction, the trends for each sea over the three independent time periods are presented to highlight this variability. The similarity between trends for the time periods centered on 1967 and 2001 is clear, as are the significantly lower trends estimated for the 17-year window centered on 1984. The question remains, what is driving these changes in the SEAS sea level trends and, more generally, 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.

Similarly, *Hamlington et al.* [2013; 2014b] discussed the influence of the PDO on both global and regional sea level trends, demonstrating that changes in the PDO have a significant impact on sea level trends in the tropical Pacific. Computing 17-year trends of the PDO index [*Mantua et al*, 2002], extrema are found centered roughly on the years of 1965, 1980, and 1997, corresponding closely to the centers of the three windows considered here. In light of the aforementioned previous studies and the analysis shown here, it is clear that there is a strong relationship between sea level trends in the SEAS region and decadal scale climate variability. *Hamlington et al.* [2014b] extended the study of *Hamlington et al.* [2013] and estimated the contribution of the PDO to regional sea level trends measured over the past twenty-years in the Pacific Ocean. Using a similar technique, here we estimate and subsequently remove the trends associated with the PDO in the SEAS region. First, twenty-year regional trend maps were computed with a least-square estimate of the trend from the sea level reconstruction dataset. Trend maps were computed starting in 1960 (using data from 1950 to 1970), and then advancing one year at a time to end up with 41 total trend maps. Empirical orthogonal functions (EOF) of the twenty-year trend maps from the sea level reconstruction were then computed. The variance explained by the trend patterns of the first three EOFs was found to be 41%, 30%, and 13%, respectively, with a total of 84% variance in these first three modes.

The question was then asked whether any of these EOF modes could be attributed to specific climate signals? To evaluate whether any of the modes are related to the PDO and by extension whether changes in the PDO affect the trends in global mean sea level, a twenty-year running trend is calculated for the PDO index, which is derived from sea surface temperature patterns in the north Pacific. In addition to the agreement of the spatial patterns of the first mode and the PDO in the north Pacific, the strong relationship between the two is demonstrated by a correlation of 0.96 between the twenty-year PDO trends and EOF mode 1 of the twenty-year trends from the reconstructed sea level dataset. In other words, the first EOF mode from the decomposition of the twenty-year trends in the sea level reconstruction appears to be closely linked to the PDO, both in terms of its spatial pattern and temporal variability over the past sixty years. The contribution of this first EOF mode to regional trends during the satellite altimetry time period (the last twenty years) was evaluated and used in this study.

Fig. 9A shows the AVISO measured sea level trends, while Fig. 9B shows an estimate of the portion of these trends that are attributable to the PDO, obtained from the procedure outlined above. The trends associated with the PDO are positive across the entire region, and removing the PDO contribution from the AVISO trends results in significantly reduced sea level trends in the SEAS region (Fig. 9C). While the presence of other internal climate variability can not be ruled out, the difference between the AVISO trends and the PDO-related trends provides an improved understanding of the long-term sea level trends that may persist into the future independent of fluctuations caused by natural occurring cycles.

4. Discussion and Conclusion

This study focuses on a region of the globe that has been significantly impacted by rising sea levels in the past two decades. Whether sea level trends will be similarly high in the coming decades is an important question with significant societal and economic implications for the SEAS region. While projecting future sea level is an expansive problem involving a wide range of disciplines, an understanding of future sea level can be gained by looking at the past. Sea level reconstructions provide a useful tool for understanding sea level changes in the past, present and future by extending the short satellite altimetry record back in time with the help of tide gauges.

Here, we have used two sea level reconstructions created using two different techniques to study the sea level trends in the SEAS. The two reconstructions agree reasonably well with the satellite altimetry and tide gauge data in the region, although some disagreement is found in the northwestern part of the region, likely resulting from poor tide gauge coverage and quality upon which to base the reconstruction. The reconstructions also agree well for the three 17-year windows considered (centered on 1967, 1984 and 2001), and exhibit decadal-scale fluctuations in the sea level trends in the

SEAS region over the past 60 years. In light of this study and other recent studies [*e.g. Merrifield et al*., 2012; *Hamlington et al.*, 2013], it is likely that the recent strong sea level trends observed during the altimetry record will abate as trade winds fluctuate on decadal timescales as the PDO undergoes a shift in phase. This suggests that SEAS regional sea level trends during the 2010s and 2020s are likely to be significantly lower than trends observed in the past 20 years, similar to the smaller sea level trends observed during the 1976 to 1992 time period relative to GMSL. While the trends can be expected to be lower in the coming decades the long-term sea level trends in the SEAS region will continue to be affected by GMSL rise occurring now and in the future. The sea level trends from both reconstructions over the full time period from 1950 to 2009 are positive for the entire SEAS region (Fig. 8). This underlying trend will be expected to persist (Fig. 9), increasing the impact of decadal-scale fluctuations of sea level trends. In other words, in the future when the large positive sea level trends in the SEAS observed during the satellite altimeter era return to the region, the impact can be expected to be much more severe due to the higher seas upon which the decadal variability is occurring. Studies such as this one serve to highlight the importance of understanding and estimating the contribution of naturally occurring periodic variability to sea level trends while maintaining the context of underlying long-term sea level rise that will persist now and in the future.

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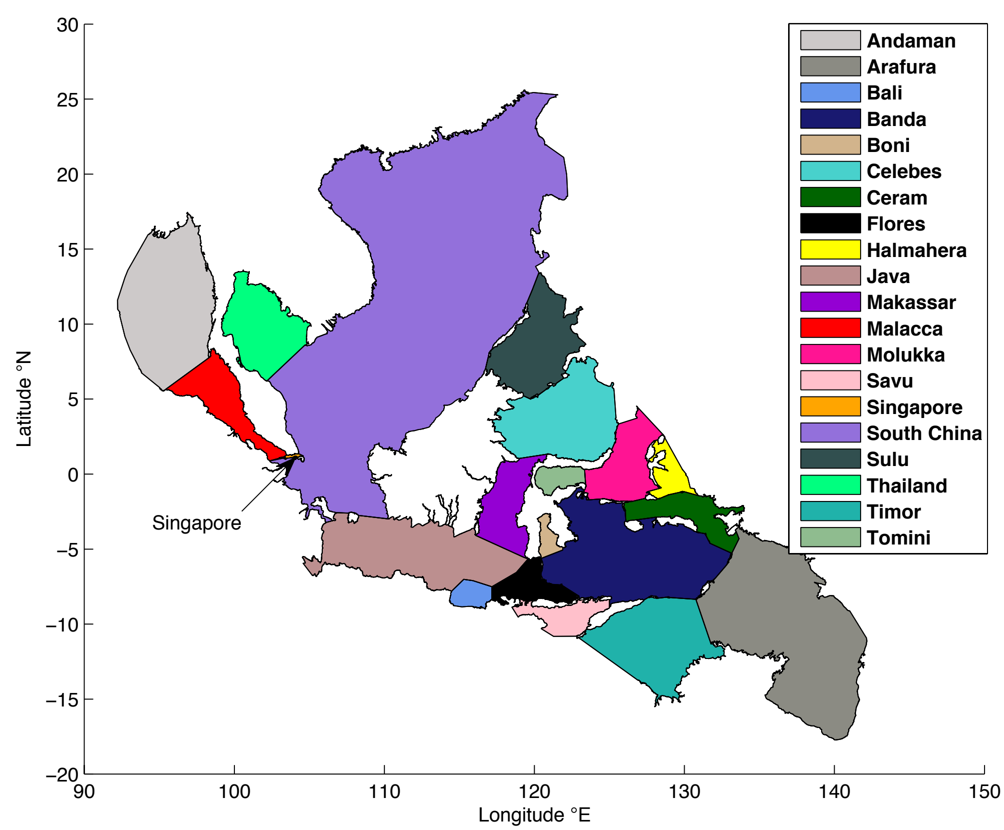

Figure 1. The 20 bodies of water (seas, straits, and gulfs) defined in the *Limits of the Ocean and Seas* (IHO,1953) for the SEAS region.

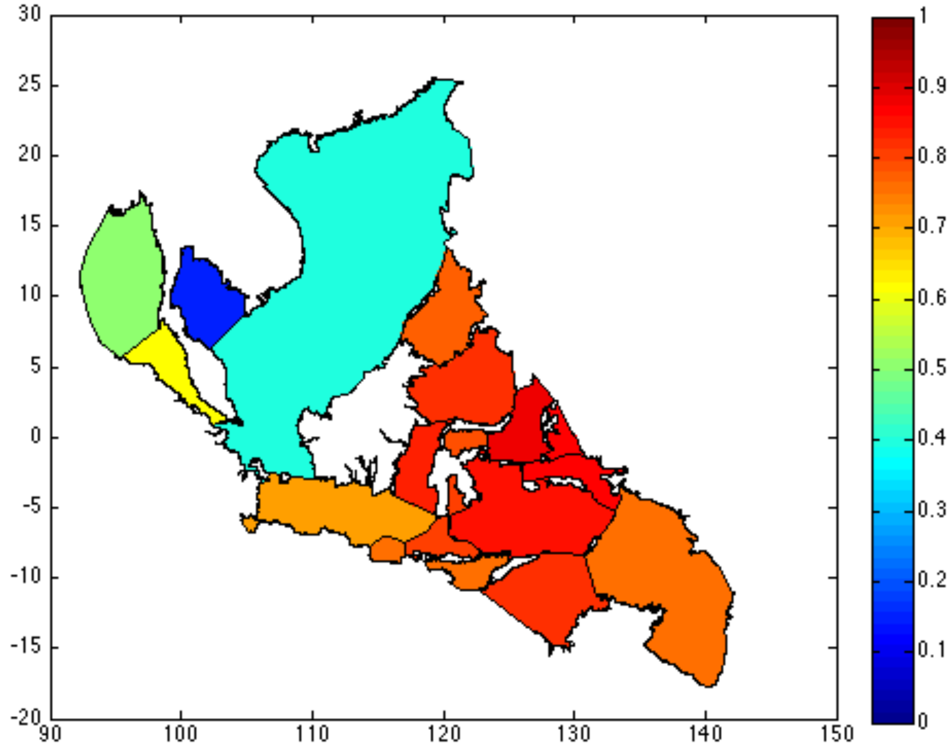

Figure 2. Correlation (averaged over each SEAS) between the HLK reconstruction and AVISO satellite altimetry data from 1993 to 2010.

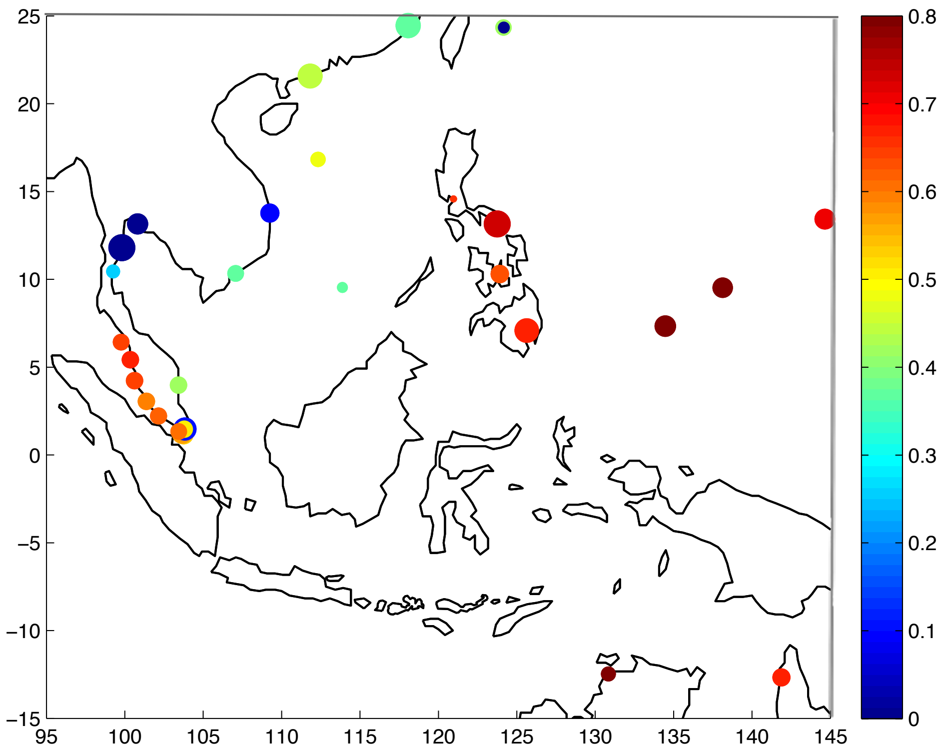

Figure 3. Comparison between the HLK reconstruction and the tide gauge data. Each circle represents a tide gauge used in the reconstruction. The color of each point represents the correlation between the reconstruction and tide gauge, while the size of the circle represents the length of the record available for comparison (largest circles relate to records that span the full time period from 1950 to 2010.

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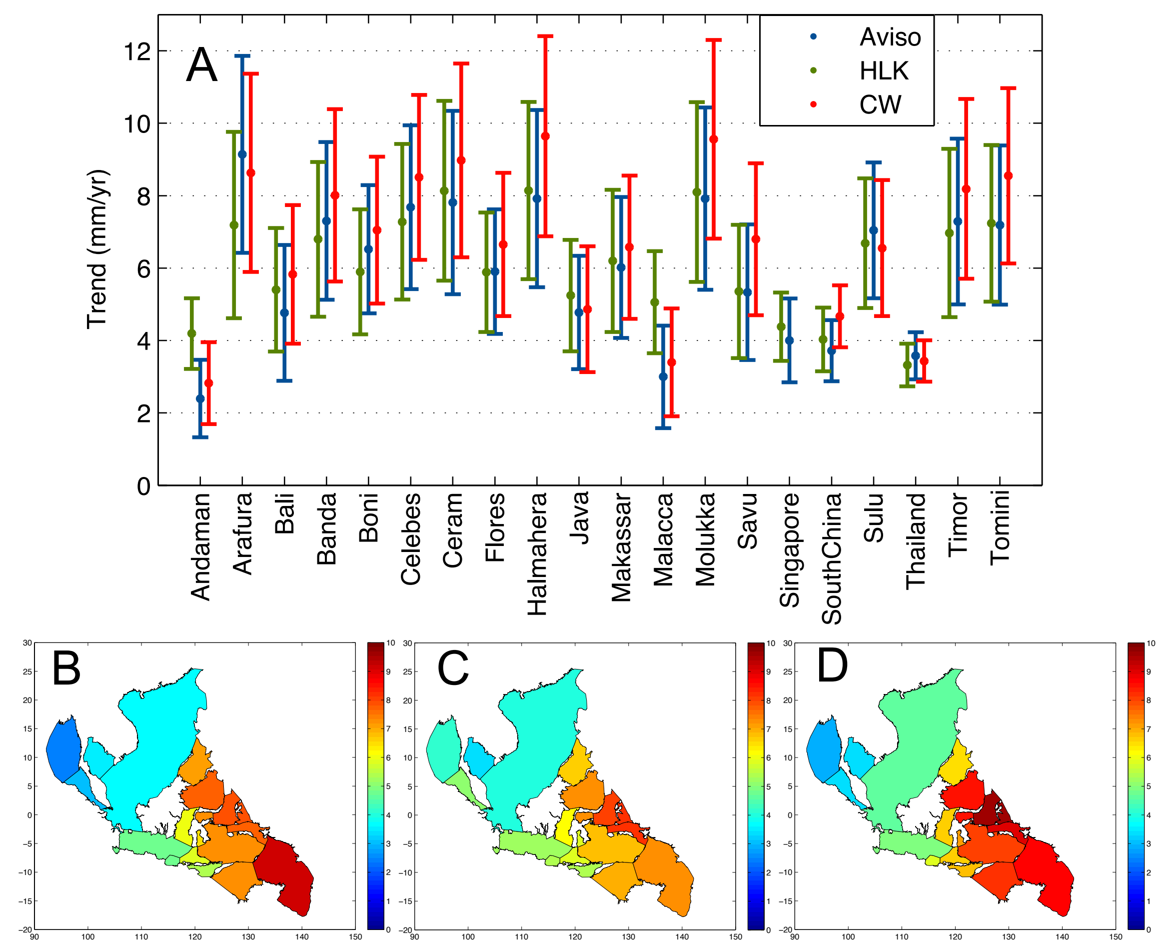

Figure 4. SEAS average sea level trends over the 17-year satellite altimeter record from 1993-2009 shown plotted as trend values with standard error estimates (A) and as color maps for AVISO (B), the HLK reconstruction (C), and the CW reconstruction (D). Reconstructed average trends agree with the AVISO values to within the estimated error.

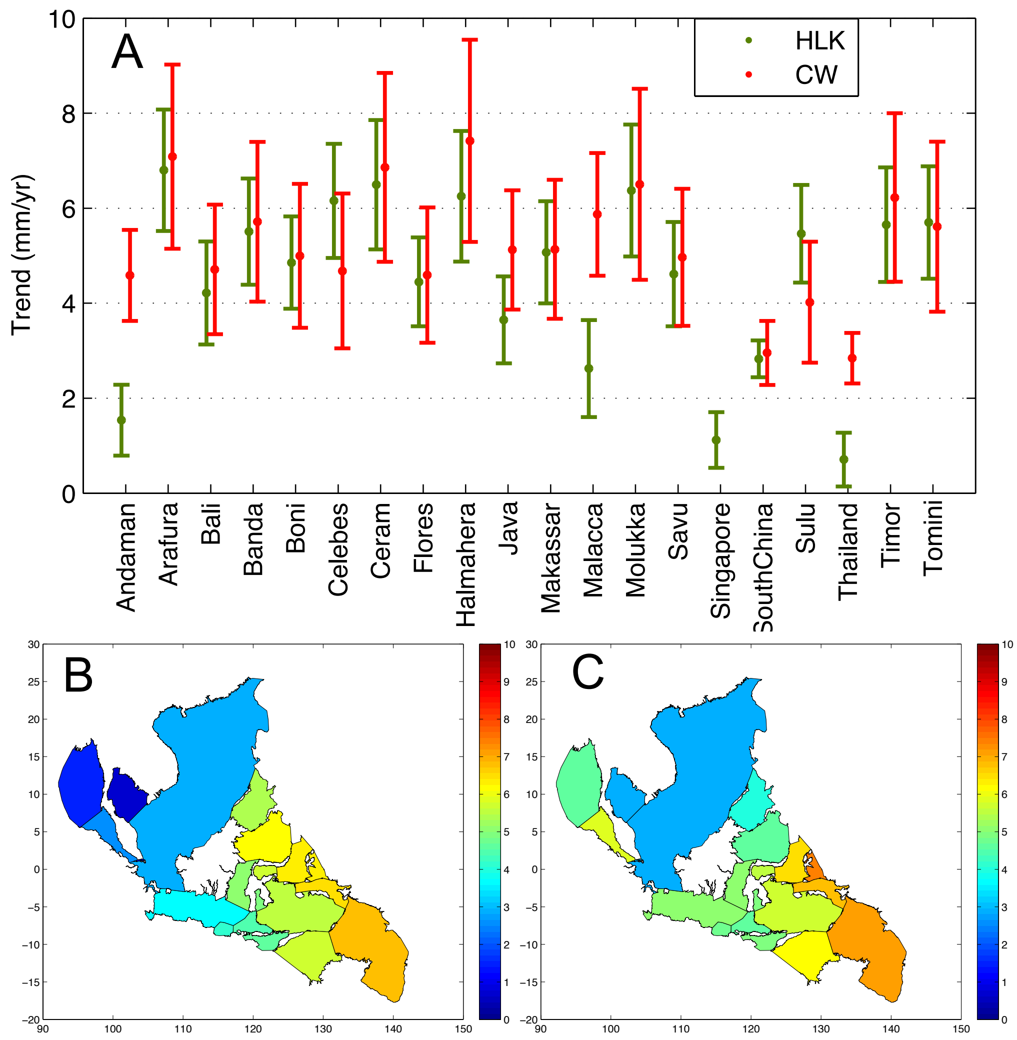

Figure 5. SEAS average sea level trends over the 17-year time period from 1959 through 1975 shown plotted as trend values with standard error (A) and as color maps for the HLK reconstruction (B) and the CW reconstruction (C).

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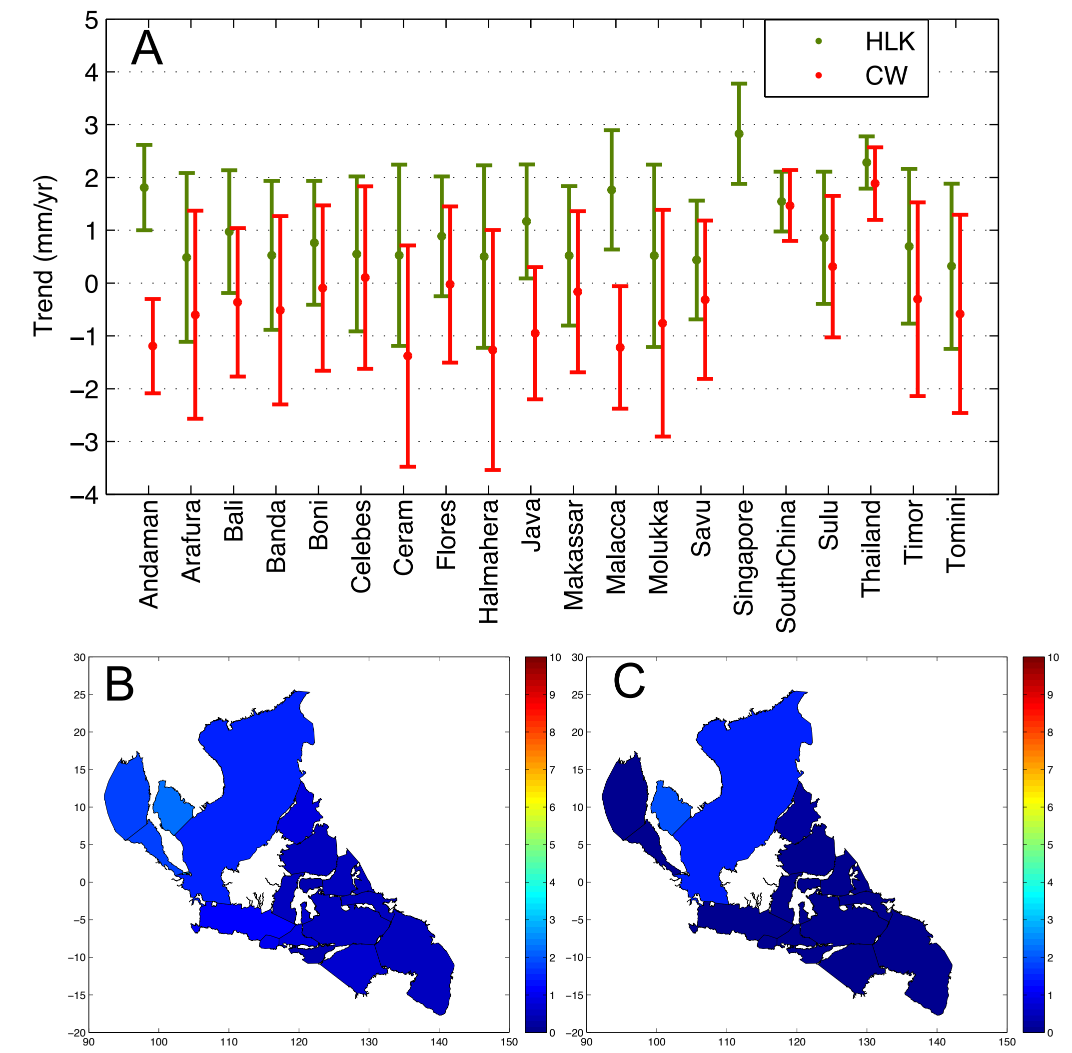

Figure 6. SEAS average sea level trends over the 17-year time period from 1976 through 1992 shown plotted as trend values with standard error (A) and as color maps for the HLK reconstruction (B) and the CW reconstruction (C).

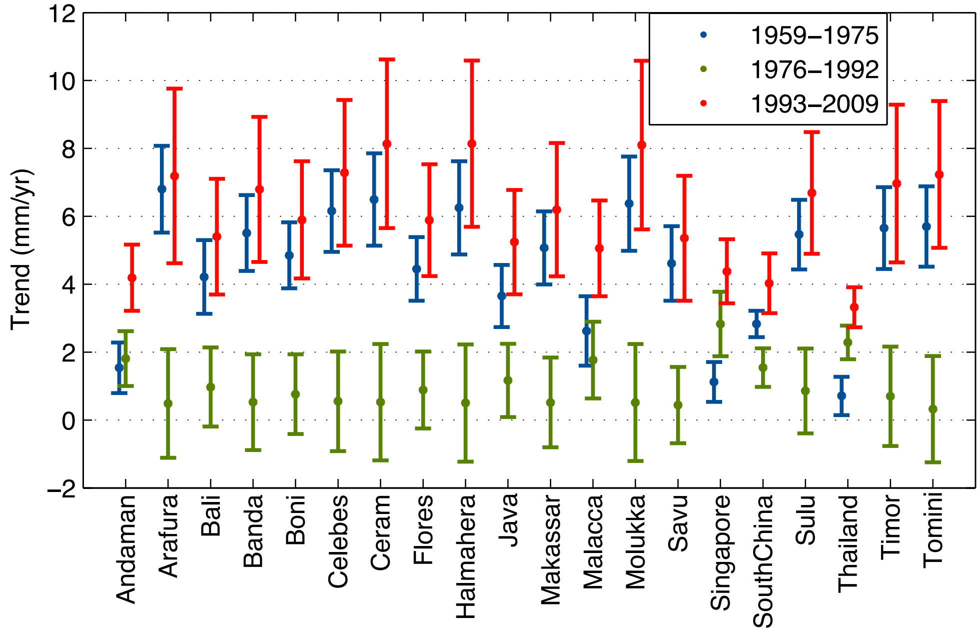

Figure 7. SEAS average sea level trends from the HLK reconstruction for the three 17-year time periods centered on 1967, 1984 and 2001.

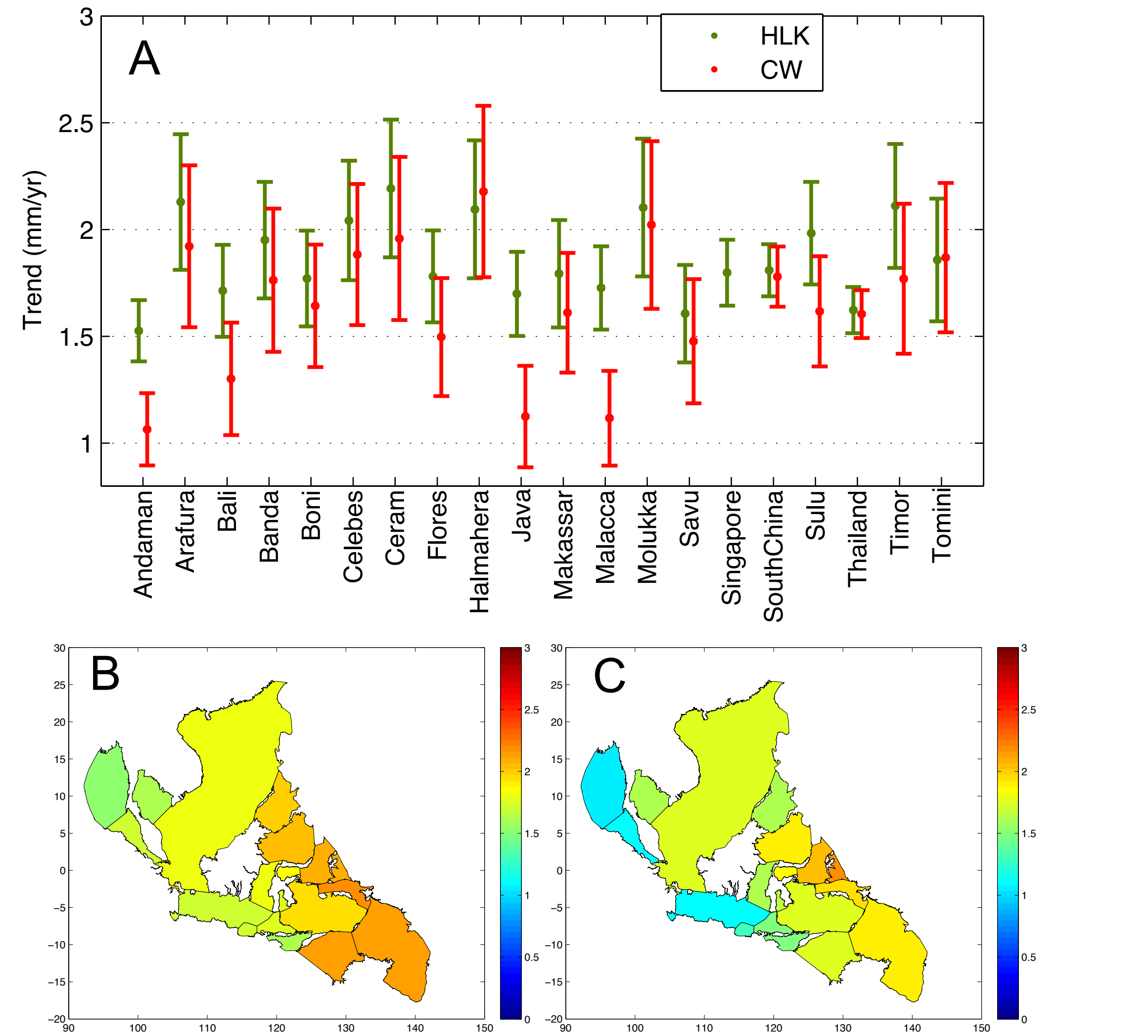

Figure 8. SEAS average sea level trends over the 60-year time period from 1950 through 2009 shown plotted as trend values with standard error (A) and as color maps for the HLK reconstruction (B) and the CW reconstruction (C).

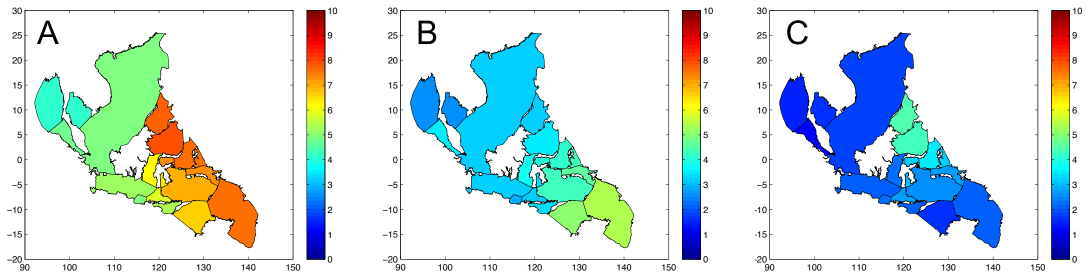

Figure 9. SEAS average sea level trends (mm/yr.) for the past 20 years from (A) the AVISO dataset (B) the PDO contribution estimated from the reconstruction (C) the difference between A and B.