AGU PUBLICATIONS

JGR

Journal of Geophysical Research: Oceans

RESEARCH ARTICLE

10.1002/2016JC011815

Key Points:

- Sea level in the Pacific has undergone a shift in the past 5 years, with sea level in the eastern (western) Pacific rising (falling)
- Sea level variability in the Pacific Ocean has been separated into a biennial oscillation mode and a decadal mode
- This shift appears to result from a change of phase of a low-frequency climate signal, that could continue on for the next several years

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Citation:
Hamlington, B. D., S. H. Cheon, P. R. Thompson, M. A. Merrifield, R. S. Nerem, R. R. Leben, and K.-Y. Kim (2016), An ongoing shift in Pacific Ocean sea level, *J. Geophys. Res. Oceans*, *121*, 5084–5097, doi:10.1002/2016JC011815.

Received 21 MAR 2016
Accepted 4 MAY 2016
Accepted article online 9 MAY 2016
Published online 30 JUL 2016

An ongoing shift in Pacific Ocean sea level

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Abstract Based on the satellite altimeter data, sea level off the west coast of the United States has increased over the past 5 years, while sea level in the western tropical Pacific has declined. Understanding whether this is a short-term shift or the beginning of a longer-term change in sea level has important implications for coastal planning efforts in the coming decades. Here, we identify and quantify the recent shift in Pacific Ocean sea level, and also seek to describe the variability in a manner consistent with recent descriptions of El Nino-Southern Oscillation (ENSO) and particularly the Pacific Decadal Oscillation (PDO). More specifically, we extract two dominant modes of sea level variability, one related to the biennial oscillation associated with ENSO and the other representative of lower-frequency variability with a strong signal in the northern Pacific. We rely on cyclostationary empirical orthogonal function (CSEOF) analysis along with sea level reconstructions to describe these modes and provide historical context for the recent sea level changes observed in the Pacific. As a result, we find that a shift in sea level has occurred in the Pacific Ocean over the past few years that will likely persist in the coming years, leading to substantially higher sea level off the west coast of the United States and lower sea level in the western tropical Pacific.

1. Introduction

Since 1993, satellite altimeters have provided continuous, near-global (± 66°N) measurements of sea surface height. These measurements provide definitive estimates of global mean sea level (GMSL) rise during recent decades, indicating an increase at a rate of 3.3 ±0.4 mm/yr from 1993 to present [*Mitchum et al.*, 2010]. While the trend in GMSL has been positive and relatively linear, regional deviations from the global mean trend often reach 50-100% along the world's coastlines. This regional variability is particularly notable in the Pacific Ocean (Figure 1a) where trends in the western tropical Pacific have exceeded 1 cm/yr and trends along the United States west coast have been near zero over the past two decades. Much attention has been devoted to this trend pattern, with several studies examining the historical record provided by tide gauges and sea level reconstructions to understand this apparent dipole pattern in Pacific Ocean decadal sea level variability [e.g., *Enfield and Allen*, 1980; *Chelton and Davis*, 1982; *Merrifield et al.*, 2012; *Moon et al.*, 2013, 2015; *Bromirski et al.*, 2011; *Zhang and Church*, 2012; *Thompson et al.*, 2014; *Hamlington et al.*, 2014]. These studies have indicated an enhancement (suppression) in the western (eastern) Pacific Ocean sea level over the past two decades resulting from decadal-to-multidecadal shifts in wind patterns associated with the Pacific Decadal Oscillation (PDO). *Bromirski et al.* [2011] further suggested an imminent phase shift in the PDO indicated by recent changes in winds that would lead to a sharp increase in U.S. west coast sea level and a similar magnitude drop in sea level in the western tropical Pacific in the coming years.

Although a shift in Pacific Ocean sea level has been anticipated, detecting such a change in sea level is a challenge. The broad spectrum of variability in the ocean makes it difficult to separate and distinguish different climate signals. This problem is further exacerbated by the relatively short satellite altimeter record length, which has only recently extended beyond 20 years. Given this limitation, extracting decadal scale variability directly from the altimeter record is difficult. With specific regard to the Pacific Ocean, the recent occurrence of a strong La Niña (2010/2011) followed shortly after by a strong El Niño (2015/2016) has potentially obscured an underlying long-term (decadal) shift in sea level. Separating the PDO from the El Niño-Southern Oscillation (ENSO) would appear to be a necessary first step in assessing the impact of the PDO on sea level.

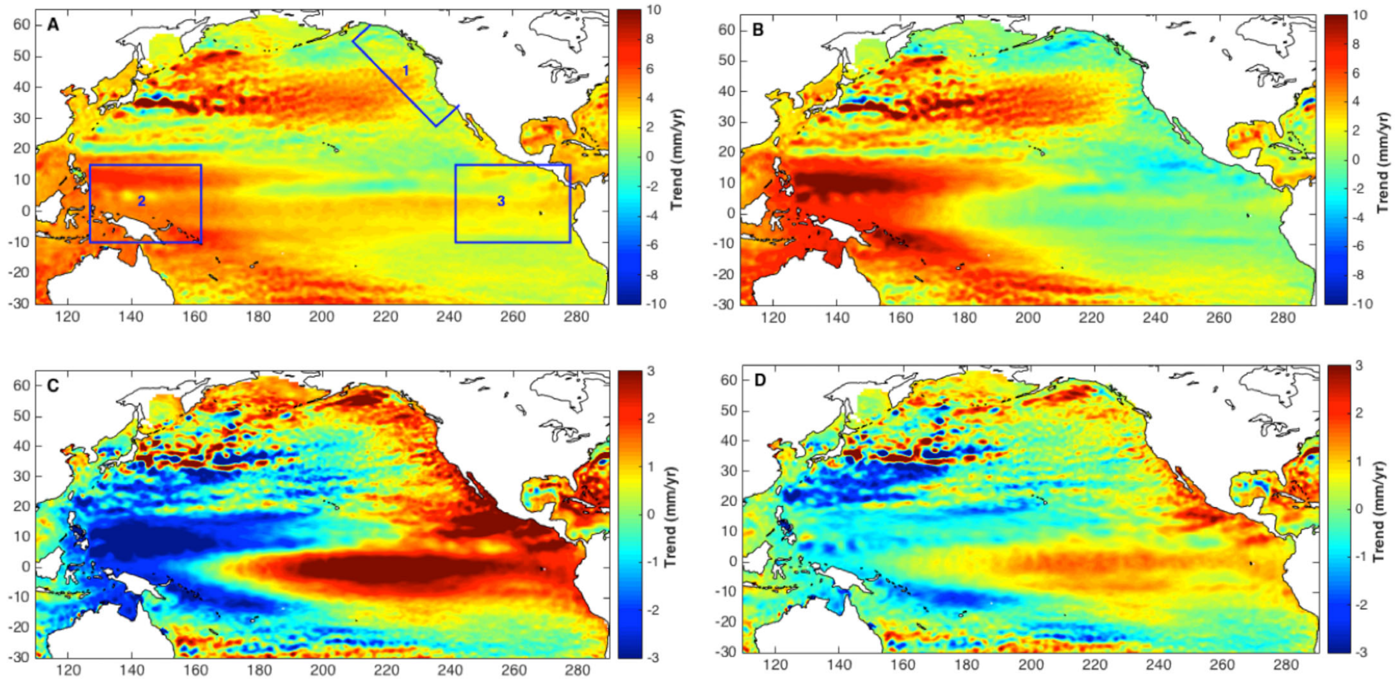

Figure 1. Regional sea level trends for the Pacific Ocean estimated from the satellite altimetry for (a) 1993 through 2015, and (b) 1993 through 2011. (c) The difference of Figure 1a and Figure 1b. (d) The difference between the trend pattern from 1993 through 2014 and the trend pattern from 1993 through 2011.

The PDO, however, is described in a largely statistical sense, originally defined as the first empirical orthogonal function (EOF) of sea surface temperature in the northeast Pacific [*Mantua et al*., 1997; *Mantua and Hare*, 2002; *Cummins et al*., 2005] (sea level definition). Defined in this way, the PDO is highly correlated with ENSO indices, particularly on interannual timescales, which leads to ambiguity concerning where ENSO ends and where the PDO begins. It is unclear if these two modes should even be defined independently [e.g., *Newman et al*., 2011]. Recent studies have re-examined the PDO [e.g., *Schneider and Cornuelle*, 2005; *Di Lorenzo et al*., 2015; *Newman et al*., 2016], describing the PDO not as a single climate signal, but as the result of a combination of different tropical and polar physical processes. As such, correlation between ocean variability (like sea level, in the case of the present study) and the PDO (as defined in *Mantua et al*. [1997]) is likely due to common forcing rather than an indication of a dynamical relationship between the variability and PDO itself. Based on this description, it is then questionable to define the PDO as a stationary and coherent climate mode as opposed to simply a statistical description of the combination of other physical processes acting in the Pacific. These issues again arise largely from the primarily statistical definition of the PDO. While a statistical mode may describe the bulk of the variability in a particular region, it need not directly correspond to a physical mode.

Based on the satellite altimeter data, sea level off the west coast of the United States has increased over the past 5 years (since roughly 2012), while sea level in the western tropical Pacific has declined. In this paper, we provide a statistical description of the sea level variability in the Pacific Ocean that diverges from a simple distinction of ENSO and/or PDO, which is consistent with recent papers on the subject [e.g., *Di Lorenzo et al*., 2015; *Newman et al*., 2016]. This statistical description suggests that the recent shift in Pacific sea level trends is likely attributable to long-term Pacific variability at time-scales longer than interannual and indicative of sea level tendencies that may continue into coming decades.

2. Data and Methods

2.1. Satellite Altimetry Data

To study the sea level variability of the past two decades, we relied on the quarter-degree multiple altimeter data product produced by Archiving, Validation, and Interpretation of Satellite Oceanographic (AVISO) covering the time period from 1993 to 2016. At the time of this writing, the monthly delayed-time product was only available through March of 2015. The ending point of the data set, however, coincides with the build-up towards a significant El Niño without including the peak of the event. To extend the record as near to present as possible, we computed monthly averages of the daily, near-real time quarter-degree gridded sea level anomalies also provided by AVISO. The resulting monthly grids from April 2015 to January 2016 were then appended to the delayed-time monthly data set. As a result of this procedure, it is possible that the sea level anomalies analyzed in this paper may not be consistent across the full length of the time series, particularly when considering the differences in processing to create the delayed-time product versus to the near-real time product. We do find agreement in comparisons to the global means of the along-track data produced by both the University of Colorado (sealevel.colorado.edu) and AVISO, indicating no offset or jump at the time the data products are merged.

2.2. Sea Level Reconstruction

The modern altimeter record as described above has only recently extended beyond two decades in length making it difficult to separate longer-scale internal climate variability from secular trends and acceleration [e.g., *Church et al.*, 2004; *Church and White*, 2006, 2011; *Hamlington et al.*, 2011a; *Woodworth et al.*, 2009]. To study past sea level and provide context for recent sea level variability, it is necessary to extend the record of sea level further into the past. Historical measurements of sea level from tide gauges extend back as far as the beginning of the 19th century [*Holgate et al.*, 2013]. While providing long records, the measurements from tide gauges are generally sparse, particularly before 1950. Tide gauges are also necessarily located on islands and along coastlines, leaving vast stretches of the open ocean unmeasured. However, by combining the dense spatial coverage of satellite altimetry with the long record length of the tide gauges, it is possible to reconstruct sea level on global scales to examine longer timescale climate signals and assess their contribution to sea level both regionally and globally [e.g., *Chambers et al.*, 2002; *Church et al.*, 2004; *Hamlington et al.*, 2011b, 2015; *Meyssignac et al.*, 2012]. Sea level reconstructions interpolate in situ tide gauge measurements back in time using basis functions (i.e. spatial patterns) derived from satellite altimetry data or, in some cases, model data. The result is a data set with the spatial resolution of the satellite altimetry data, and the record length of the tide gauge data.

A recent study examined the reconstruction of sea level prior to 1950, finding that the decline in tide gauge availability negatively impacts the ability to realistically represent sea level variability [*Hamlington et al.*, 2012]. As a result, a reconstruction technique that incorporates measurements of sea surface temperature (SST) was developed and applied with good success with regards to the reconstruction of the largest scale climate variability back to 1900. Specifically, we compute cyclostationary empirical orthogonal functions (CSEOFs; detailed description below) of both the satellite altimetry data described in section 2.1 and the Extended Reconstruction SST v3 (ERSST) [*Smith et al.*, 2008] data from 1900 to present. The SST CSEOFs are regressed on to the specific modes of interest from sea level over the common time period (1993 to present) to produce spatial patterns in both variables with similar temporal evolutions. The goal of the reconstruction is to reconstruct the time series associated with these modes into the past. Since the sea level and regressed SST modes have the same (similar) temporal evolution, the two variables can be used simultaneously to reproduce the time series back to 1900. We fit to the tide gauge data and in situ sea surface temperature, changing the weighting of the sea level relative to the SST according to tide gauge availability in the past. Further details of this procedure are found in *Hamlington et al.* [2012]. In this paper, we use the resulting data set to compute climate modes covering the time period from 1900 to present. This provides important context for a similar analysis performed on the satellite altimetry data alone.

2.3. Cyclostationary Empirical Orthogonal Function (CSEOF) Analysis

To extract the large-scale sea level variability in the Pacific, a cyclostationary empirical orthogonal function (CSEOF) analysis [*Kim et al.*, 1996; *Kim and North*, 1997] is applied to the satellite altimetry and sea level reconstruction data. Following the description provided in *Hamlington et al.* [2015b], the CSEOF method decomposes space-time data into a series of modes composed of a spatial component (known hereafter as the loading vector (LV)), and a corresponding temporal component (known hereafter as the principal component time series (PCTS)). The main difference between CSEOFs and the more widely-used empirical orthogonal function (EOF) analysis is that CSEOF spatial patterns (LVs) are allowed to vary in time with a "nested period" that is selected *a priori*. In other words, each LV is a set of spatial patterns that repeat with the nested period over the length of the data set, and the amplitude of the periodic LV is modulated by the PCTS. For monthly data and a 1 year nested period, each mode is composed of twelve sequential spatial patterns (the LV) and one PCTS. This allows the CSEOF decomposition to capture the temporal evolution of a physical process in the LV, while the corresponding PCTS explains the amplitude of this physical process through time. The nested period of the CSEOF analysis is generally selected based on some physical understanding or intuition regarding the data to be studied. When studying the annual cycle known to be present in many geophysical data sets, for instance, a nested period of 1 year is chosen. The resulting LV would contain a spatial pattern for each month and would describe the physical evolution of the annual cycle through the year. The PCTS then describes the amplitude change – or strength - of the annual cycle from year to year.

Here, we use a 2 year nested period to extract the dominant modes of sea level variability from the satellite altimetry and reconstruction data. As shown in recent studies, a 2 year nested period allows for the separation of variability in the Pacific Ocean into two primary modes [*Yeo and Kim*, 2013; *Hamlington et al*., 2015a]. One of these modes is associated with the biennial oscillation of ENSO, representing the shift from an El Niño to a La Niña (and back) over the course of a 2 year time period. The PCTS represents the occurrence of these events, typically on 2–6 year timescales. Periods in which a strong El Niño precedes a strong La Niña (or vice versa) will be particularly strongly represented by this mode. The second mode of interest is associated with lower-frequency variability in the Pacific Ocean and includes a strong northern Pacific signal that is not present in the biennial mode. As will be shown below, this mode is correlated with the PDO at interannual to decadal time-scales, but we refrain from calling this mode the "PDO" and instead refer to it simply as a low-frequency mode of variability.

3. Results

3.1. Pacific Ocean Sea Level Trends

As a starting point, we have computed the regional sea level trends for the Pacific Ocean for two separate time periods: 1993 through 2015 (Figure 1a), and 1993 through 2011 (Figure 1b). When comparing these two trend maps, there is a noticeable weakening of the sea level trends in the western tropical Pacific and a similar strengthening of the sea level trends in the northeast Pacific. To see this more clearly, we difference the two trend maps (Figure 1c), finding changes in the estimated trends of greater than 3 mm/yr (both positive and negative). Some of these changes – particularly in the tropical Pacific – are likely associated with the significant 2015/2016 El Niño, suggesting that the change in trends is simply due to the end-point of the time period being analyzed. To test this, the trends from 1993 through 2014 are estimated and compared to the trends from 1993 through 2011 (Figure 1d), thus removing the impact of the 2015/2016 El Niño on the trend pattern. Changes in the trend still approach 3 mm/yr, with the differences particularly strong off the U.S. west coast and further into the northeast Pacific. Although not a definitive test of shifting trends in the region as the end-point issue cannot be removed entirely, these comparisons do point towards increasing sea level trends in the eastern Pacific and decreasing sea level trends in the western Pacific.

3.2. CSEOF Analysis of Satellite Altimetry Data

To investigate the cause of this shift in Pacific Ocean sea level, we have conducted a CSEOF analysis of the satellite altimetry data from 1993 through 2015 using a 2 year nested period. In *Hamlington et al*. [2015a], a CSEOF analysis was performed on the sea level reconstruction data to extract the sea level signal associated with the biennial oscillation and low-frequency variability in the Pacific Ocean. Here the satellite altimetry data are directly decomposed using CSEOF analysis, with the results indicating that the satellite altimeter record is now approaching the length at which such signals can be separated. The first two CSEOF modes correspond to the modulated annual signal and global mean trend and will not be discussed at length in this section (for further discussion of these modes, see *Hamlington et al*. [2011a]). The third mode, however, represents the biennial oscillation of ENSO. The LVs in Figure 2 show the transition from La Niña at the beginning of the first year to El Niño conditions at the end/beginning of year 1/year 2. To ensure the periodicity of the LV, the patterns then show a transition from El Niño to La Niña in the remainder of the second year. This mode is representative of the delayed oscillator [*Suarez and Schopf*, 1988] or recharge-discharge oscillator [*Jin*, 1997] descriptions that have previously been used to describe the shifts between phases of

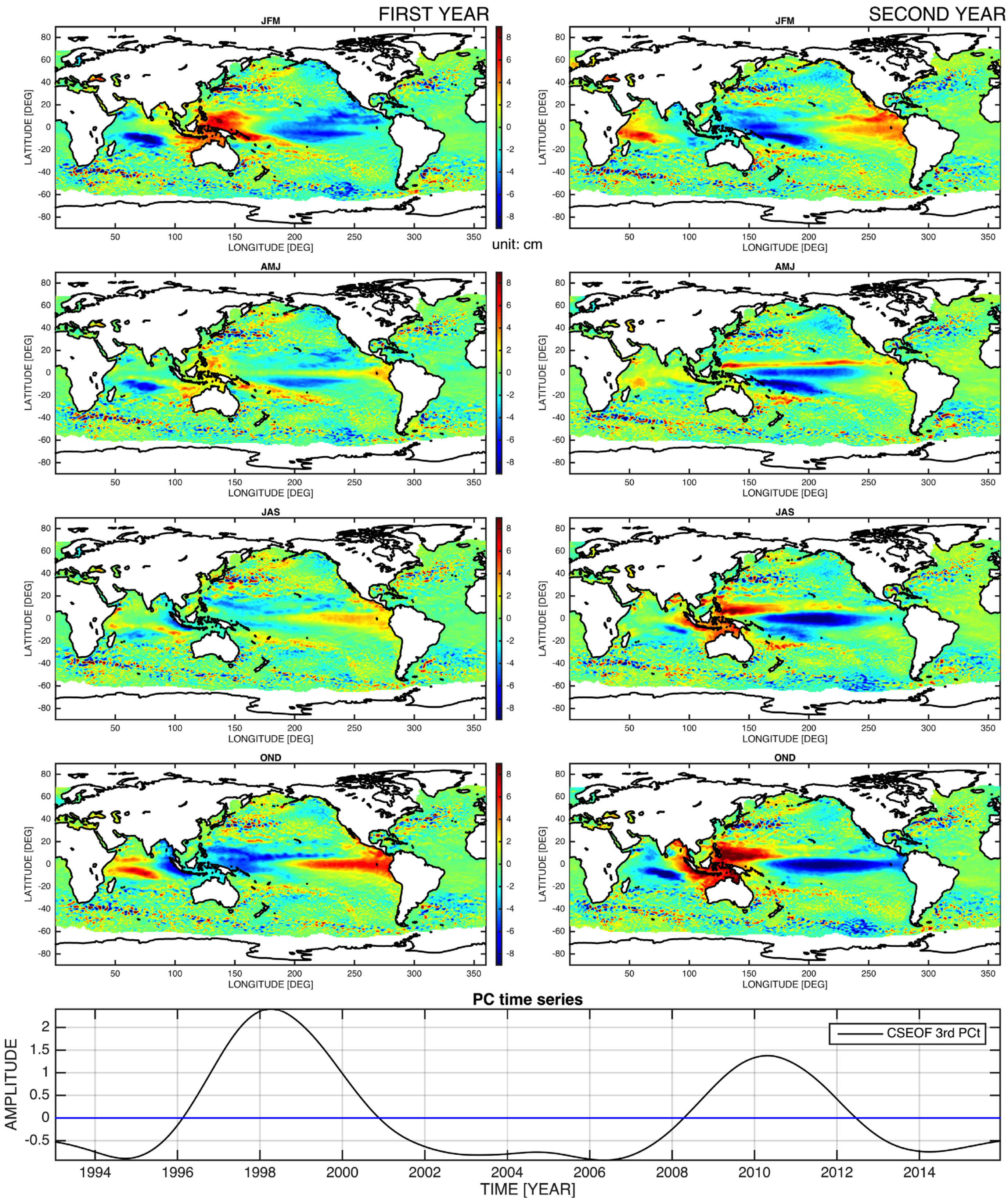

Figure 2. Third CSEOF mode from the decomposition of the satellite altimetry data from 1993 through 2015, representing the biennial oscillation of ENSO. Seasonally averaged maps for the LV are shown along with the associated PCTS (bottom).

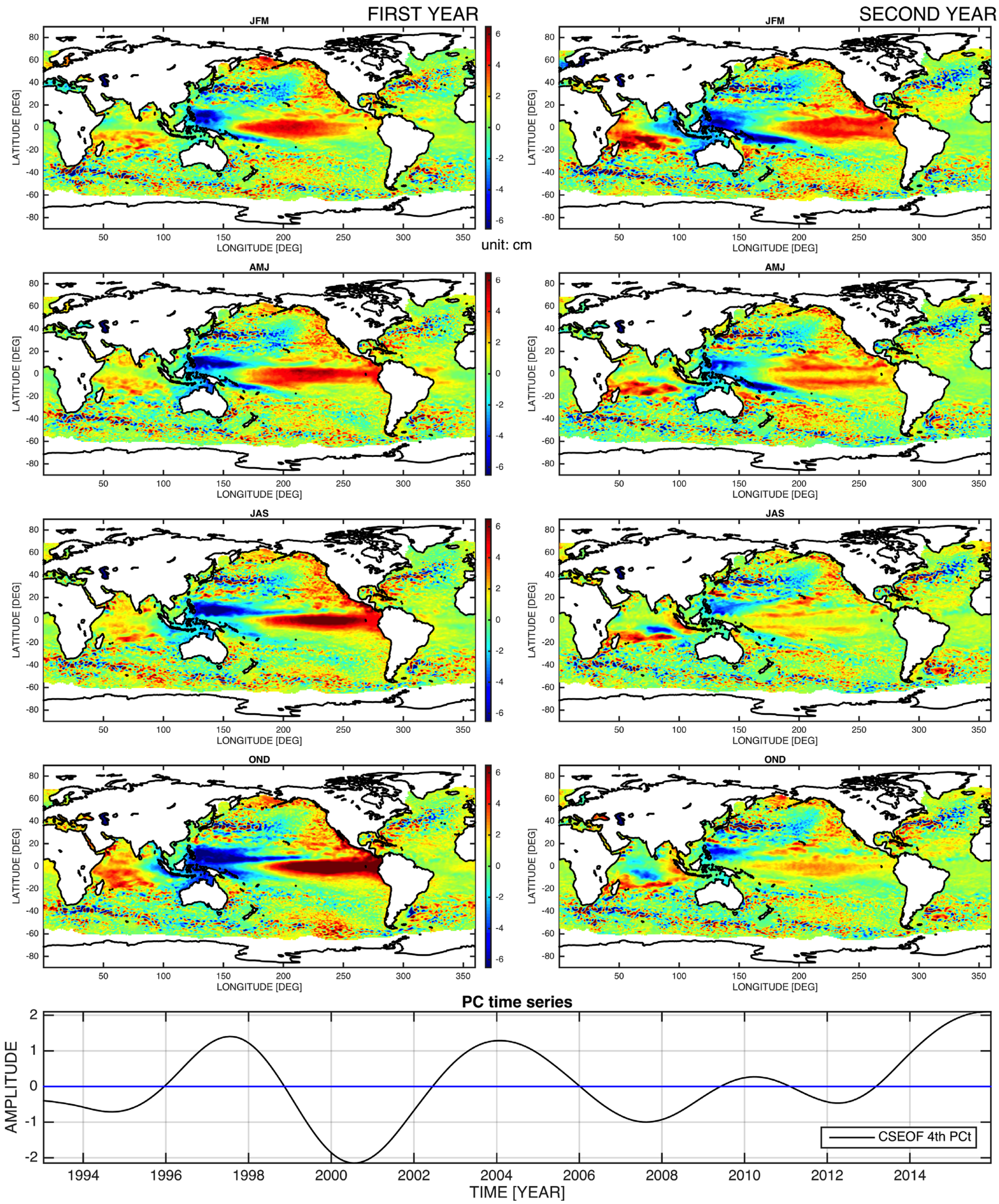

Figure 3. Fourth CSEOF mode from the decomposition of the satellite altimetry data from 1993 through 2015, representing the low frequency variability in the Pacific Ocean. Seasonally averaged maps for the LV are shown along with the associated PCTS (bottom).

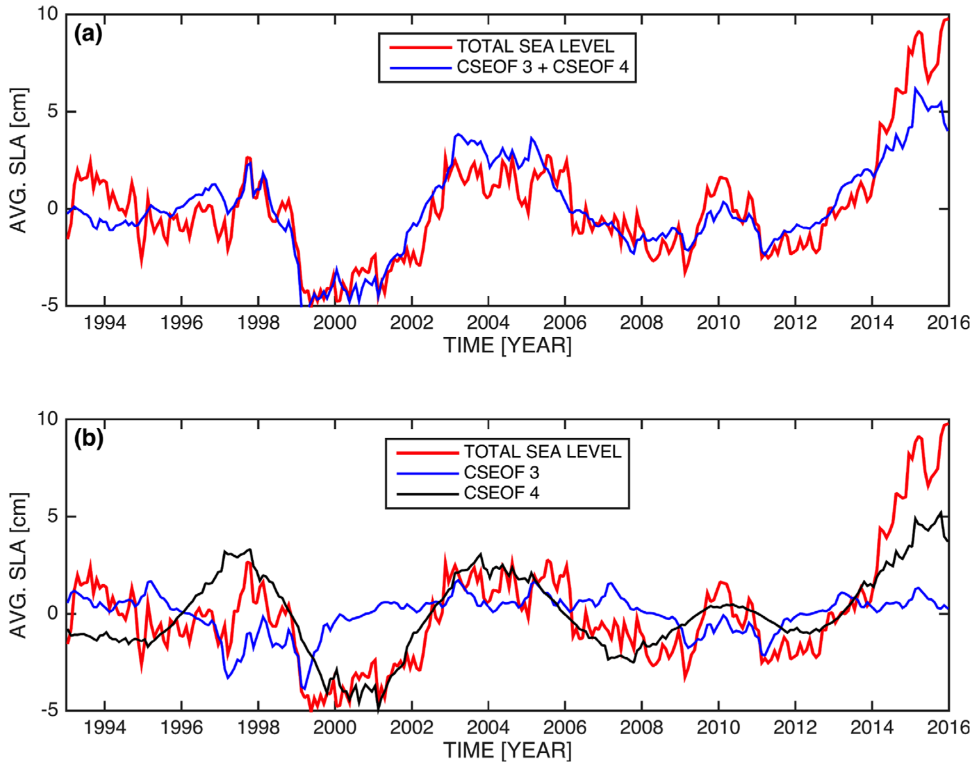

Figure 4. Sea level averages for Box 1 (seen in Figure 1a). The average sea level is associated with the (a) combined biennial and low frequency CSEOFs mode (blue) and (b) separate contributions for each mode (biennial mode in blue and low frequency mode in black). The average of the total sea level signal is shown in red.

ENSO. The PCTS provides an indication of the significant ENSO events in the past two decades, although care must be taken when interpreting the time series. Two distinctive ridges spanning 2–3 years are shown in the PCTS, centered at the end of 1997 and the middle of 2010. The end of 1997 and into the beginning of 1998 featured a strong El Niño event that was quickly followed by La Niña like conditions towards the end of 1998 and into 1999. Based on the start date of our analysis (1993 is year 1, designating all other odd years as year 1), 1997 into 1998 is shown by the transition from the end of year 1 into the beginning of year 2 (El Niño conditions indicated by the LV), explaining the positive sign in the PCTS in describing this event. A similar representation is provided for the 2009/2010 El Niño followed by the 2010/2011 La Niña. If, for example, an El Niño developed at the end of an even year, the sign of the PCTS would be negative even when describing a positive ENSO phase. Looking in more detail at the LV for this mode, little variability is seen in the northern Pacific that would normally be associated with the PDO. As a result of the character of this CSEOF mode, time periods with a two-year transition between El Niño and La Niña events (or the reverse) will be most strongly represented, with northern Pacific variability not strongly reflected in the PCTS of this mode. Importantly for the present study, the 2015/2016 El Niño is not represented by this mode, with the PCTS near zero at the end of the study time period. One explanation for this could be the lack of a transition from El Niño back to neutral or La Niña conditions that is apparent in this mode, suggesting that the value of the PCTS would increase with more years of data and a shift in phase. An additional explanation, as will be discussed more below, is the presence of a strong signal in the north Pacific that is not represented well by the variability in this mode.

Unlike the third CSEOF mode, the fourth mode of our CSEOF analysis (Figure 3) has a strong signal in the northern Pacific, demonstrating the noticeable horseshoe shape indicative of the PDO [*Mantua et al.*, 1997; *Mantua and Hare*, 2002; *Cummins et al.*, 2005]. The LVs of this mode vary little over the course of the 2 year nested period, particularly in the north Pacific, indicating the representation of variability with an inherent timescale greater than 2 years. When examining the PCTS, the time series is low in amplitude in 1998 and 2011, indicating little contribution to the ENSO events at those times. The PCTS does, however, increase

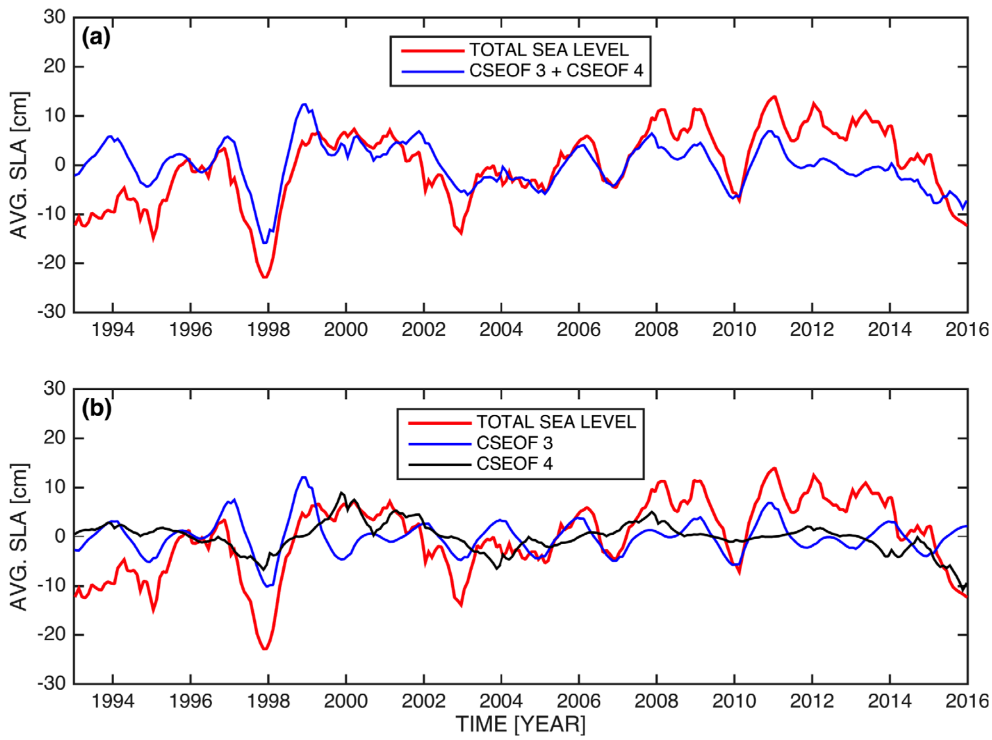

Figure 5. Sea level averages for Box 2 (seen in Figure 1a). The average sea level is associated with the (a) combined biennial and low frequency CSEOFs mode (blue) and (b) separate contributions for each mode (biennial mode in blue and low frequency mode in black). The average of the total sea level signal is shown in red.

significantly from 2012 onward. This, for example, represents a dramatic increase in U.S. west coast sea level indicated by the large, positive slope of the PCTS and positive value of the LV in this region. The correlation between the PCTS and the PDO index [*Mantua et al*., 1997] over this time period is 0.75 (significant at the 99% confidence level). Note, the PDO index was first smoothed using a 2 year window to provide a direct comparison to the PCTS that reflects periods longer than the 2 year nested period. Due to the spatial pattern in the north Pacific and based on this correlation, it can be said that this CSEOF mode is associated with the PDO mode in its statistical definition. As discussed above, however, this is likely an inadequate description of this mode, particularly given the strong signal in the equatorial Pacific. Following the discussions in *Newman et al*. [2016] and *Di Lorenzo et al.* [2015] this mode is likely a combination of forcing contributions and represents a "memory" mode, reflecting the re-emergence dynamics in the subtropics and their feedback on the tropics, which in turn accounts for the equatorial amplitude in the LVs. Subsequently, as opposed to simply calling this a PDO mode, we refer to it as the low-frequency mode in the remainder of the paper.

The modes in Figures 2 and 3 describe how sea level is varying in the Pacific Ocean at two different timescales, but we take the analysis one step further to quantify the contribution of these two modes to sea level variability in particular regions. Using the three areas from *Moon et al*. [2013], we compute box-averages for the northeast Pacific (Box 1; Figure 4), western tropical Pacific (Box 2; Figure 5), and eastern tropical Pacific (Box 3; Figure 6). For each box, we calculate the regional mean sea level variability associated with the two modes in Figures 2 and 3 and also for the de-seasoned sea level signal from the satellite altimetry. Figure 4a shows the results for the average of Box 1 for the combination of the biennial mode (CSEOF 3) and the low-frequency mode (CSEOF 4) with the average of the total sea level from the satellite altimetry also shown for comparison. These two modes combined explain the vast majority (76% of the variance) of the total sea level variability in this region. The shift in sea level in the region is also clearly visible from both the total sea level signal and combined contribution from the CSEOF modes, with sea level increasing by almost 10 cm from 2012 to 2016. When separating the contributions from the two modes, it is immediately seen that most of the sea level variability (63% of the variance) in this region - including the recent increase - is associated with the low-frequency mode (Figure 4b). The biennial mode, on the other hand, has almost

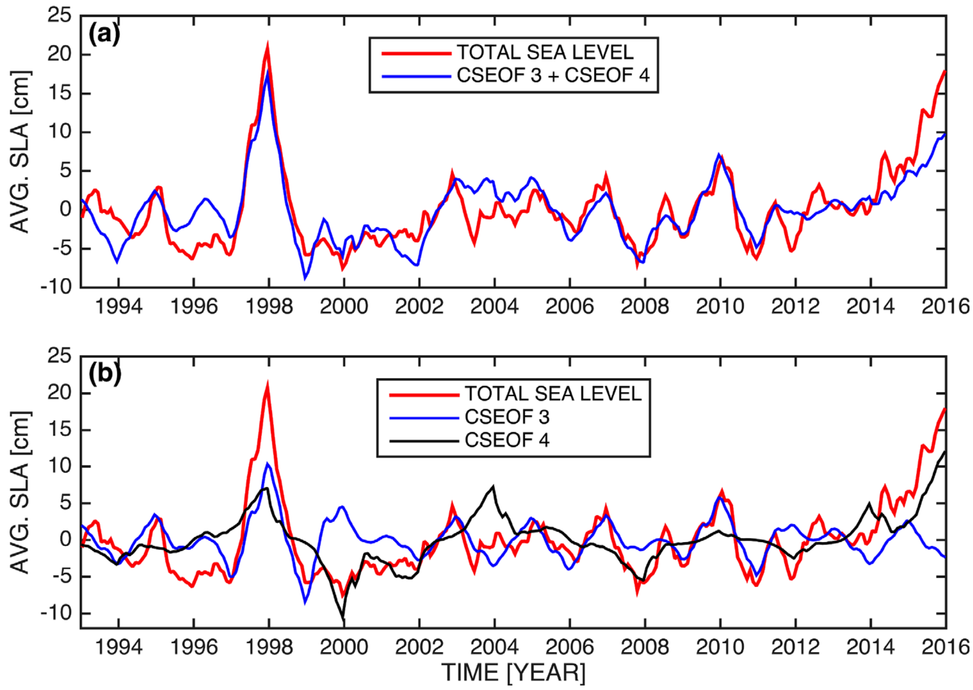

Figure 6. Sea level averages for Box 3 (seen in Figure 1a). The average sea level is associated with the (a) combined biennial and low frequency CSEOFs mode (blue) and (b) separate contributions for each mode (biennial mode in blue and low frequency mode in black). The average of the total sea level signal is shown in red.

no contribution (13% of the variance) to the sea level rise of the past 5 years. This is not surprising given the relatively small signal observed in the northeast Pacific for the biennial mode (Figure 2). When analyzing the sea level variability in Box 2 (Figure 5b) and Box 3 (Figure 6b), however, the biennial mode plays a larger role, explaining 19% and 50% of the variance respectively. The bulk of the 1997/1998 El Niño and 2010/2011 La Niña sea level signals are captured in the biennial mode. In both tropical boxes, the combined contribution of the two modes again explains much of the total sea level signal (Figures 5a and 6a), although more so for Box 3 (73% of the variance) than Box 2 (37% of the variance). Importantly for the recent record, the sea level increase (decrease) in the eastern (western) Pacific Ocean is again described primarily by the low frequency mode. Although the two modes discussed here are orthogonal (required by the CSEOF analysis), both modes have a strong signal in tropical Pacific. Coupled with the large positive value of the PCTS for the low frequency mode and the near-zero value of the PCTS for the biennial mode in 2015/2016, it is clear that the bulk of the 2015/2016 event is captured in the low frequency mode rather than the biennial mode.

At first glance, there would appear to be inconsistencies in the variability captured in these two modes. The biennial mode has a strong signal for two of the largest ENSO events in the satellite altimeter record but has little contribution to the recent El Niño. The low frequency mode, on the other hand, has a small contribution to the 1997/1998 El Niño and 2010/2011 La Niña, but appears to explain the sea level signal of the 2015/2016 El Niño. To investigate this further, we compare the November-December-January-averaged sea level signal from the 1997/1998 El Niño to the 2015/2016 El Niño (Figure 7). Both maps show strong tropical Pacific sea level signals, approaching 50 cm near their peak. Two main differences are seen between the two time periods: 1) in the northeastern Pacific where the 2015/2016 region is nearly 20 cm higher in much of the region, and 2) in the tropical Pacific where the 2015/2016 warm tongue extends further west than the 1997/1998. Looking at the LVs in Figures 2 and 3 (focusing on year 1 to coincide with 2015), there is a notable agreement between the 2015/2016 sea level pattern and the pattern at the end of second year of the LV of the low frequency mode. Another notable difference occurred in the time period leading up to the two events. Prior to the 2015/2016 El Niño, there was a weak El Niño that developed in 2014. Coupled with the strong event the following year, the time period

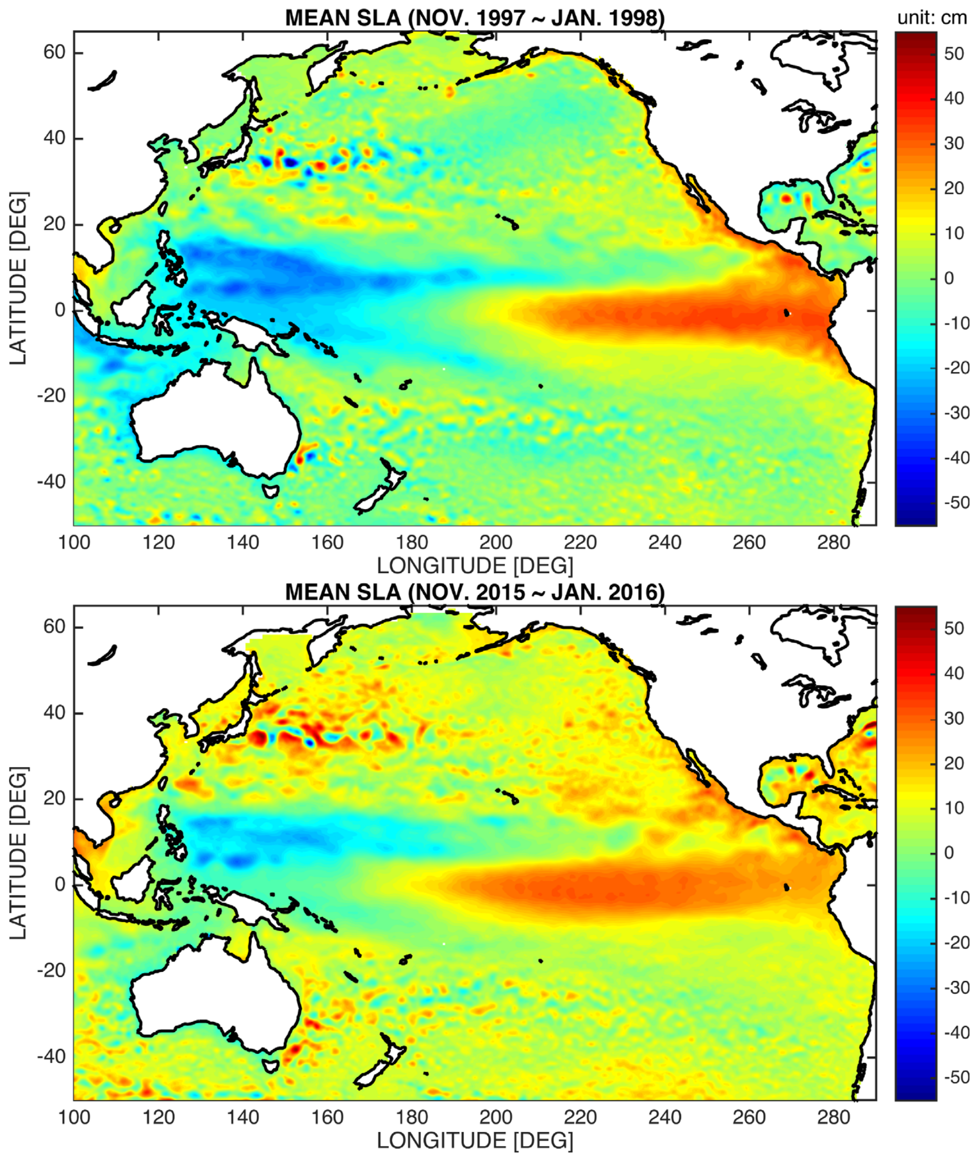

Figure 7. Comparison of the sea level anomaly from the 1997/1998 El Niño to the 2015/2016 El Niño. Maps are produced by averaging November, December, and January for the respective events.

from 2014 to 2016 had relatively persistent El Niño like conditions, which again appears to be represented in the low frequency mode. Although the 2015/2016 El Niño is largely captured in what we have described as the low frequency mode, the implication is not that an El Niño did not occur and instead was just a result of low-frequency variability. One possibility is that it is an artifact of the CSEOF analysis, either through mode-mixing or through an end-effect. As discussed above, with additional years of data and a subsequent shift away from El Niño conditions, it is possible that this event will be better represented by the biennial mode. Another possibility is that the 2015/2016 El Niño occurred in a time of transition in the Pacific Ocean, coinciding with a shift in the low frequency mode that results in an ENSO event of a different character and representation in sea level. To address these two possibilities, we examine the historical record.

3.3. Reconstruction of CSEOF Modes

Using the reconstructed data set from 1900 to present described in section 2.2, the PCTS time series associated with the biennial mode and low frequency mode are produced back to 1900 through CSEOF

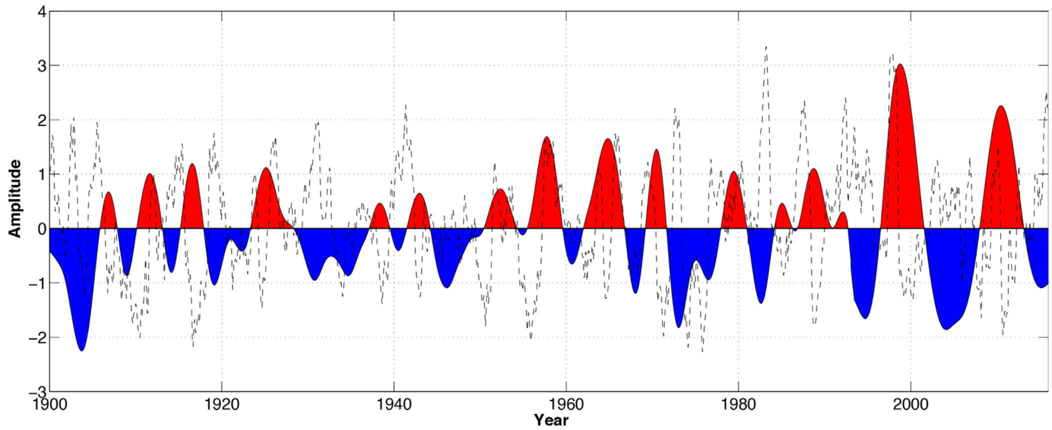

Figure 8. Biennial CSEOF mode PCTS from 1900 to present obtained from decomposition of the reconstruction. The Multivariate ENSO Index (black line) is shown for comparison.

analysis. Figure 8 shows the long-term PCTS for the biennial mode. The 1997/1998 and 2010/2011 El Niño/La Niña events provide clear representations of the 2 year period of the LVs. Both the El Niño and following La Niña events are contained within the time period of the peaks in the PCTS. Similar instances

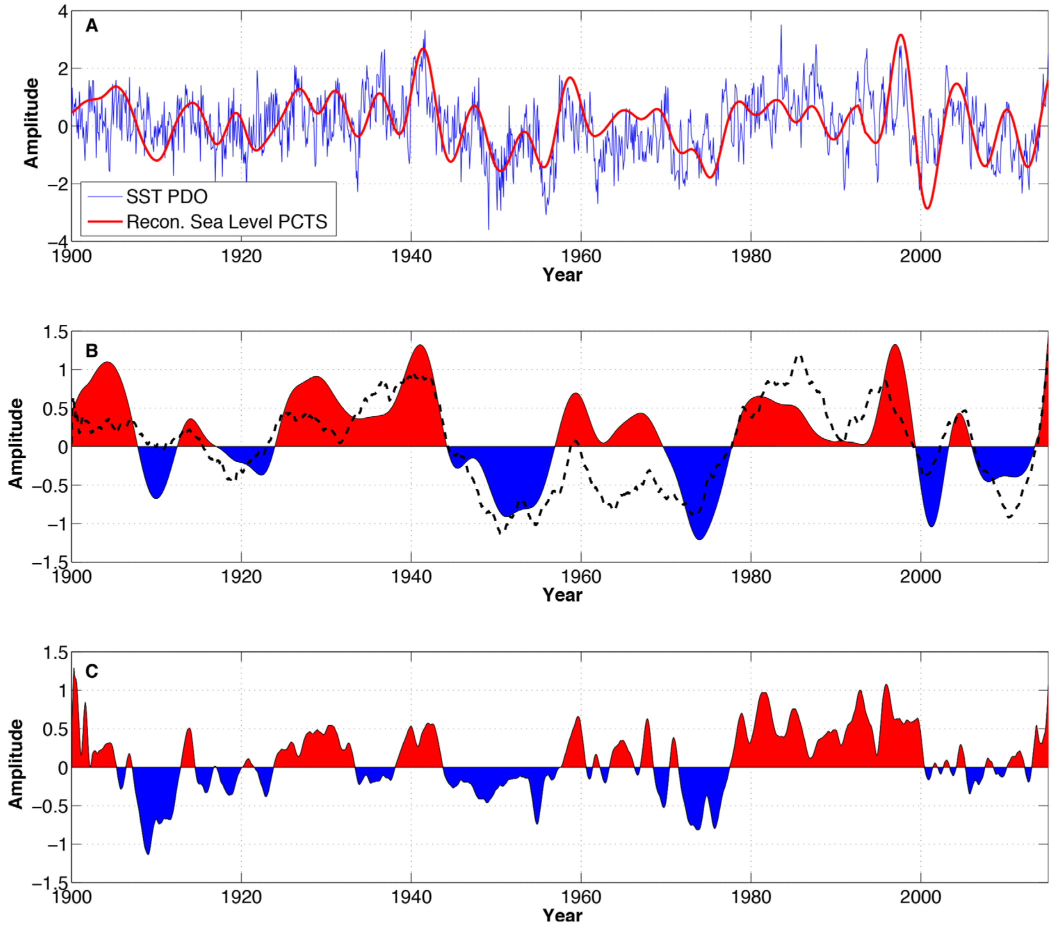

Figure 9. Low frequency CSEOF mode from 1900 to present obtained from the sea level reconstruction. (a) The reconstructed sea level PCTS (red) is compared to an index tracking the PDO [REF]. (b) The same time series (reconstructed sea level PCTS shown as the filled plot, PDO index shown as black dashed line) with a 5 year moving average window applied to highlight the low-frequency variability. (c) The difference between the MEI and Niño-3 index estimated from biennial mode.

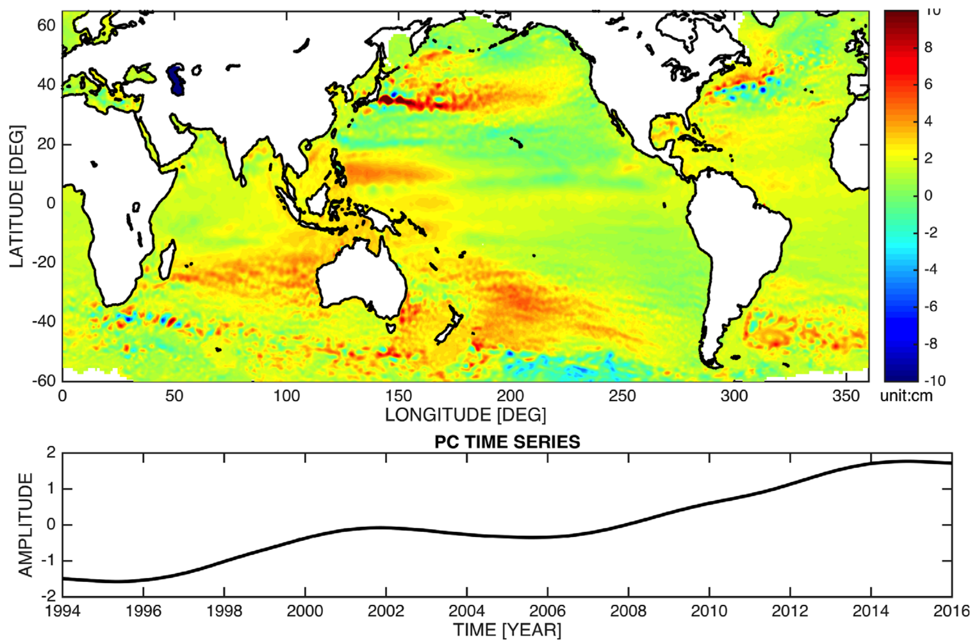

Figure 10. Second CSEOF mode from the decomposition of the satellite altimetry data from 1993 through 2015 representing the trend in the satellite altimetry data. All 24 LV maps are averaged together due to the small change in the pattern over the nested period.

are seen in the early 1970s, late 1950s, and even in the early 1900s. For a case when a significant La Niña does not follow a strong El Niño, the 1982/1983 El Niño provides an example, showing a reduced amplitude in the PCTS versus what is seen in the Multivariate ENSO Index (MEI) [*Wolter and Timlin*, 2011]. This is somewhat analogous to the 2015/2016 El Niño when a shift towards La Niña conditions has not yet occurred. When examining the full record, there is generally excellent agreement, albeit with a few notable differences between the MEI and the PCTS: 1910–1920, early-to-mid 1940s, late 1970s, early 2000s, and 2015/2016. In each case, the MEI indicates an ENSO event (either El Niño or La Niña) that was not similarly seen in the PCTS.

To examine these time periods more closely, we analyze the PCTS for the low frequency CSEOF mode obtained from the reconstruction. In Figure 9, the PCTS is shown in comparison to an SST-derived PDO index both in their unfiltered state (A) and after running a 5 year running average filter on both time series (B). The correlation between the two time series in Figure 9a is 0.62 over the 115 year record, although again, the PDO index correlates reasonably well with the MEI on interannual timescales, making interpreting such a correlation challenging. After filtering the two time series, however, an indication regarding the agreement on decadal timescales is obtained. While some differences between the two are seen, the transition times of the decadal signal agree between the two time series. In particular, both time series show clear transitions in the mid-1940s, late 1970s, and early 2000s, agreeing with the periods of disagreement found in the PCTS shown in Figure 7. To make this clearer, a scaled Niño-3 index was computed from the biennial mode in Figures 2 and 8, and then subtracted from the similarly scaled MEI (Figure 9c), confirming the time periods of disagreement and underscoring the difference between the modal description of biennial ENSO oscillation presented here and the description of ENSO by indices like the MEI. Similar transition points are suggested in the mid-to-late 1910s and in 2012 when both the PCTS and PDO index undergo a rapid increase. Given the apparent quick phase shift between the early 2000s and mid-2010s, it is also possible that the phase shifts in the mid-1950s and late-1960s indicated by the PCTS should not be immediately discounted. In support of this, *Baines and Folland* [2007] described a rapid global climate shift in the 1960s through the analysis of a several different climate variables, consistent with what we see in the sea level reconstruction. Although the low frequency CSEOF mode correlates highly with the PDO index, it is not immediately suggested that the PDO is causing these shifts in sea level. As discussed in *Deser et al*. [2004], *Schneider and Cornuelle* [2005], *Newman* [2007], and *Newman et al*. [2011, 2016], each phase of the PDO and any associated shift in the PDO could just be a result of different combinations of specific processes with variations in these processes causing shifts in phase. It is important, however, to make a distinction with regard to the relationship between sea level and the low frequency mode described here. The low frequency mode describes a significant portion of the sea level variability in the Pacific (particularly Box 1, as discussed above). With the high correlation between the low-frequency mode and PDO, it is apparent that some of the same processes that lead to the sea surface temperature variability captured by the PDO are also likely impacting sea level variability in the region. In this regard, the PDO index does provide a proxy for sea level change on intermediate timescales (interannual to decadal) in the extratropical Pacific.

4. Summary and Discussion

Since 2011, sea level has undergone a dramatic shift in the Pacific Ocean, as seen by the trend maps shown in Figure 1 and the box-averaged time series shown in Figures 4–6. Sea level in the western tropical Pacific has fallen and sea level in the eastern tropical and northeastern Pacific has risen. While this is clear from the satellite altimetry, attributing these sea level changes to a particular source is a challenge given the range of variability in the ocean. Determining if these sea level changes are part of a longer term shift has important societal and economic implications, as such a shift would alleviate many of the problems experienced in the past two decades in the western tropical Pacific and would likely change the discourse regarding sea level concern along the U.S. west coast. Here, we provide analysis that suggests the sea level variability of the last 5 years is—at least in part—a result of a shift in the phase of low frequency variability in the Pacific Ocean. It is important to note that the peak in the sea level trend signal we describe here with the low frequency mode occurs during times of transition. Over the course of the altimeter time period, the low frequency mode has been shifting from positive to negative phase, resulting in higher sea level trends in the western Pacific and lower trends in the eastern Pacific. The results presented here suggest an ongoing shift from negative to positive phase of the same mode, indicating a possible reversal in the trend pattern. The accompanying analysis also shows a relationship between ENSO and low frequency variability in the region that needs further exploration. At times of transition in the low frequency mode, the character of the ENSO signal appears to be altered, at least in the sense of the modal description provided here. Although it is possible to attribute the results for the 2015/2016 to mode mixing or end-effects in the CSEOF analysis, similar results are seen for other transition times over the previous 115 year record. On a more basic level, these results indicate it is necessary to analyze these two modes in tandem and hint at difficulties when trying to interpret the different modes of Pacific sea level variability in isolation. Further analysis is needed to establish a more comprehensive link between the descriptions of *Di Lorenzo et al*. [2015] and *Newman et al*. [2016] and the sea level modes presented here, which could lead to a better understanding of how climate variability impacts sea level in the region.

As a final note, the satellite altimeter record is now extending to a length where it appears to be possible to extract some portion of the decadal scale variability without the use of sea level reconstructions incorporating tide gauge data (as seen in the results here). This has important implications when trying to interpret the regional sea level trends estimated from the satellite altimetry data. Figure 10 shows mode 2 of the CSEOF decomposition of the satellite altimetry data. Since the LV maps do not vary significantly over the course of the nested period, we show only the average LV across the full nested period. The resulting PCTS shows little variability about the linear trend, and the trend map does not include the influence of the biennial or low frequency modes. Unlike the trend patterns in Figures 1a and 1b, this trend maps shows significantly lower trends in the western tropical Pacific and around Indonesia in particular. Furthermore, the trends off the U.S. west coast are closer to the global average of 3.3 mm/yr when the influence of the two modes is removed. To both ensure the separation of decadal scale variability from the regional trends and definitively assess long-term climate shift, a longer time series from the satellite altimetry is still required. However, ongoing monitoring of sea level and subsequent attempts in improving our understanding of associated variability are important for near-term planning efforts. Based on the satellite altimetry data, a shift in sea level in the Pacific Ocean has occurred in the past few years, and this study represents a first effort in both identifying and diagnosing this shift.

Acknowledgments
The CSEOF reconstructed sea level data set used is available at the NASA JPL PO.DAAC (http://podaac.jpl.nasa.gov/dataset/RECON_SEA_LEVEL_OST_L4_V1). Dataset name: RECON_SEA_LEVEL_OST_L4_V1. The satellite altimetry data is publicly available through the Archiving, Validation and Interpretation of Satellite Oceanographic (AVISO) website (http://www.aviso.oceanobs.com/en/data/products/sea-surface-height-products/). B.D.H. and R.R.L. acknowledge support from NASA Ocean Surface Topography Mission Science Team grant NNX13AH05G, and B.D.H., R.S.N, and R.R.L acknowledge support from NASA Sea Level Change Team grant NNX14AJ98G. B.D.H also acknowledges support from NASA New Investigator Program NNX16AH56G. K. Y. K. acknowledges support from SNU-Yonsei Research Cooperation Program through Seoul National University (SNU) in 2014. P.R.T and M.A.M. acknowledge support from the NOAA Climate Program Office in support of the University of Hawaii Sea Level Center.

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