Sea level trends, interannual and decadal variability in the Pacific Ocean

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[1] Linear trend analysis is commonly applied to quantify sea level change, often over short periods because of limited data availability. However, the linear trend computed over short periods is complicated by large-scale climate variability which can affect regional sea level on interannual to inter-decadal time scales. As a result, the meaning of a local linear sea level trend over the short altimeter era (since 1993; less than 20 years) is unclear, and it is not straightforward to distinguish the regional sea level changes associated with climate change from those associated with natural climate variability. In this study, we use continuous near-global altimeter measurements since 1993 to attempt to separate interannual and decadal sea level variability in the Pacific from the sea level trend. We conclude that the rapid rates of sea level rise in the western tropical Pacific found from a single variable linear regression analysis are partially due to basin-scale decadal climate variability. The negligible sea level rise, or even falling sea level, in the eastern tropical Pacific and US west coast is a result of the combination of decreasing of sea level associated with decadal climate variability and a positive sea level trend. The single variable linear regression analysis only accounts for slightly more than 20% of the observed variance, whereas a multiple variable linear regression including filtered indices of the El Nino-Southern Oscillation and the Pacific Decadal Oscillation accounts for almost 60% of the observed variance.
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1. Introduction

[2] Sea level changes occur over a wide range of temporal and spatial scales. High-quality long-term tide gauge data indicate the global mean sea level (GMSL) has been rising for the past 100+ years [e.g., *Douglas*, 2001; *Church and White*, 2006, 2011]. Since the launch of the Topex/Poseidon altimeter, near-global altimeter measurements have been used to infer rising GMSL [e.g., *Mitchum et al.*, 2010; *Cazenave and Llovel*, 2010]. The temporal Linear Trend (LT) is a popular metric often used to quantify sea level change at both global and regional scales, despite the possible presence of nonlinear trends [e.g., *Church and White*, 2006, 2011; *Jevrejeva et al.*, 2006; *Woodworth*, 2006; *Merrifield et al.*, 2009; *Woodworth et al.*, 2009; *Merrifield*, 2011]. There are many studies examining the regional sea level LT from the available altimeter data over time spans ranging from 3 to 18 years [e.g., *Nerem*, 1995; *Cabanes et al.*, 2001; *Church et al.*, 2006; *Wunsch et al.*, 2007; *Cheng et al.*, 2008; *Cazenave and Llovel*, 2010; *Bromirski et al.*, 2011].

[3] As revealed by many of the above references, sea level changes are usually not spatially uniform. Many regions experience a higher or lower rate of sea level change than the global average. In some locations, the linear trend over 1993–2009 based on altimeter measurement can be five times the global average value [*Church et al.*, 2010]. Large-scale climate phenomena induce regional climate variability on interannual, decadal and inter-decadal time scales. Sea level, as a sensitive dynamical parameter integrating ocean variations from the surface to the bottom, is also affected by large-scale climate variability and consequently spatial and temporal variability of sea level should be expected [e.g., *Woodworth et al.*, 2009; *Bromirski et al.*, 2011].

[4] As the dominant source of interannual variability, the El Niño-Southern Oscillation (ENSO) can induce significant sea level changes, especially in the tropical Pacific [*Nerem et al.*, 1999; *Landerer et al.*, 2008]. More frequent or larger El Niño (La Niña) events during the period of study could result in an El Niño-like (La Niña-like) LT of sea level. There is also an ENSO-like climate variability pattern in the Pacific on decadal to interdecadal time scales, i.e., the Pacific Decadal Oscillation (PDO) or the Interdecadal Pacific Oscillation (IPO). The PDO is characterized by changes in large-scale atmospheric circulation and physical and biological changes in the North Pacific [*Mantua et al.*, 1997; *Mantua and Hare*, 2002; *Zhang et al.*, 1997]. The IPO [*Power et al.*, 1999] has similar sea surface temperature (SST) and sea level pressure patterns as the PDO in the North Pacific, and also has a comparable expression in the South Pacific. The IPO is often regarded as the Pacific-wide manifestation of the PDO [*Folland et al.*, 2002; *Trenberth et al.*, 2007].

[5] Many sea level studies have an underlying purpose of detecting and quantifying sea level change due to anthropogenic climate change. However, particularly on a regional scale, such a signal is mixed with that due to natural climate variability. As a result, it is extremely difficult to separate the natural and anthropogenic signals, especially when they have comparable amplitudes and the available time series is short relative to the period of the natural variability. This dilemma has been recognized in some historical studies [e.g., *Sturges and Hong*, 2001; *Feng et al.*, 2004], but the possible impacts

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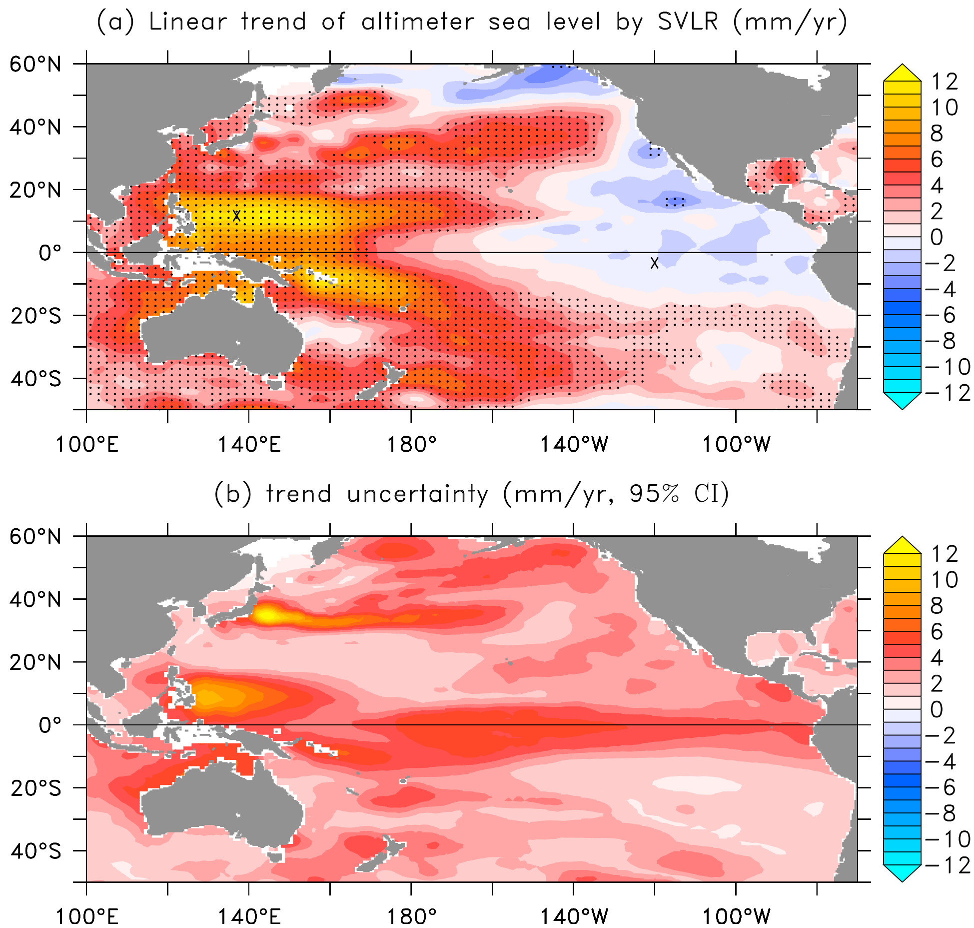

Figure 1. (a) Sea level linear trend (mm yr^{-1}) over 1993–2009 based on merged TOPEX/Poseidon and Jason altimeter measurement. Seasonal cycles have been removed from each grid point before the linear trend calculation. The sea level linear trend is derived by single variable linear regression of sea level with respect to time (Eq. (1)). (b) Sea level linear trend uncertainty at the 95% confidence interval. Dotted areas in Figure 1a indicate trends which are insignificantly different from zero at the 95% confidence interval. Statistical calculations were based on a two-sided student's t-test with the effective degrees of freedom estimated by considering serial autocorrelation of data [*Emery and Thomson*, 2001].

of background interannual to interdecadal oscillations on the LT definition were often discussed qualitatively and not quantitatively. For example, in the tropical Pacific, the western (eastern) basin experienced much higher (lower) LTs than the global average over the period of satellite altimeter observations from 1993 to 2009 (or similar period) (Figure 1). Similar maps of altimeter-derived sea level trends have been commonly discussed and analyzed, and sometimes it has been implicitly suggested that theses sea level trends are associated with climate change. However, it is likely that these spatial distributional patterns are a mixture of anthropogenic signals and natural variability.

[6] Here, we attempt to identify the interannual and decadal sea level fingerprints, as well as linear sea level trends using altimeter observations for the Pacific Ocean since 1993. Through this study, we want to emphasize that climate variability, with typical period comparable to or longer than the length of study period, can often obscure the underlying sea level trends. In other words, there is danger of aliasing the low-frequency sea level variability into the sea level trend.

2. Data and Processing

[7] Monthly merged TOPEX/Poseidon and Jason altimeter data on a 1° × 1° grid for the period 1993 to 2011 are provided by the sea-level group of the *Commonwealth Scientific and Industrial Research Organization* (http://www.cmar.csiro.au/sealevel/sl_data_cmar_alt.html). The inverse barometer correction has been applied to the altimeter data we use.

[8] The Multivariate ENSO Index (MEI, data source at: http://www.esrl.noaa.gov/psd/enso/mei/) is chosen to represent ENSO variability. The MEI is defined based on six main observed atmospheric and oceanic variables over the tropical Pacific that are closely related to ENSO events [*Wolter and Timlin*, 1998]. The MEI is preferred here rather than the conventional ENSO indices defined with single variable, e.g., the Southern Oscillation Index (SOI) based on sea level pressure difference between Tahiti and Darwin. Note similar conclusion can also be drawn if the SOI is used

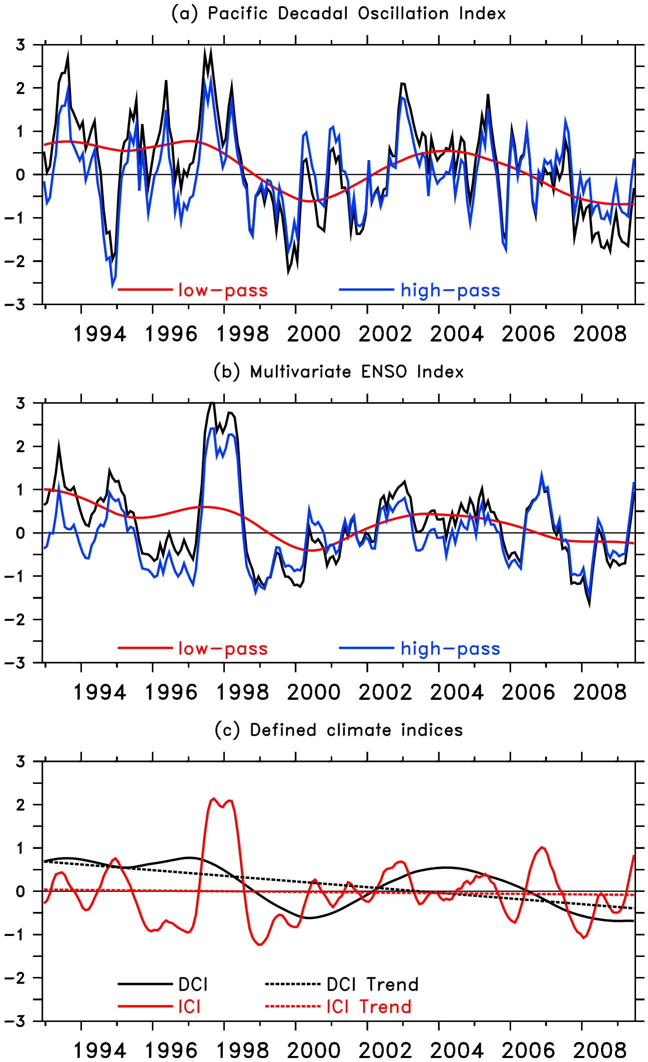

Figure 2. (a). The Pacific Decadal Oscillation (PDO) index (black) and its low-pass filtered (red) and high-pass filtered (blue) components. (b) Same as Figure 2a, but for the Multivariate ENSO Index (MEI). (c) Newly defined climate indices: the Decadal Climate Index (black) and Interannual Climate Index (red). The linear trends of both climate indices are also plotted as dashed curves. A version of this figure covering a longer period from 1950 to present can be found in the auxiliary material (Figure S1).

other than the MEI, since the two of them are highly correlated (correlation coefficient is 0.89 during the altimeter era between the two monthly time series smoothed with 5-month running-mean filter; the monthly SOI tends to be nosier than the MEI).

[9] The PDO (data source at: http://jisao.washington.edu/pdo/) is defined as the leading principal component of Empirical Orthogonal Function (EOF) analysis of monthly SST anomalies (with the global average removed) north of 20°N in North Pacific Ocean [*Mantua et al.*, 1997; *Mantua and Hare*, 2002]. The PDO shifted from a warm to a cold phase in the late 1990's, then went back to a short-lived warm phase in the early 2000's, before quickly swinging back to a cold phase in mid- to late-2000's (Figure 2). There is an obvious decreasing trend of the PDO index over the altimeter era (Figure 2c). The IPO time series is derived by the UK Meteorological Office from the EOF of SST over the Pacific north of 55°S (see online at http://www.iges.org/c20c/). Partially because of limited observational records, there is a debate whether the PDO (or equivalently the IPO) can be confidently treated as an independent mode of climate variability to ENSO [e.g., *Schneider and Cornuelle*, 2005; *Trenberth et al.*, 2007; *Deser et al.*, 2010]. For Instance, the PDO can be regarded as a reddened response to ENSO [*Newman et al.*, 2003] (also see Figure 2), or a response to ENSO and atmospheric noise [*Schneider and Cornuelle*, 2005]. The PDO and ENSO are highly correlated in the low (decadal period) frequency band [*Newman et al.*, 2003; *Power and Colman*, 2006] (also refer to Figure 2). *Deser et al.* [2010] hypothesized that the PDO is likely not a single physical mode but rather the sum of several phenomena. As a result, and following *Zhang et al.* [1997], we don't presume that the PDO or the IPO is a totally independent mode of climate variability from ENSO, or that the decadal-to-interdecadal variability of ENSO and the PDO/IPO can be easily separated. Rather, we derive new climate indices from the MEI and PDO/IPO to focus on the interannual and decadal-to-interdecadal climate variability, respectively.

[10] The low-pass filter used is successive application of a 25- and 37-month running mean to the climate indices. The low-pass filter has a good spectral response curve, with small side lobes [*Zhang et al.*, 1997; *Vimont*, 2005]. The amplitude response function of this low-pass filter has half power point at a period of 6.2 years, thus the low-pass filtered data contain mainly variability at decadal and longer time scales (see Figure 1 of *Vimont*, 2005). The corresponding high-pass-filtered data are derived by removing the low-pass-filtered data from the original data, and contain variability mainly at interannual and shorter time scales. The PDO index, by its name, is meant to represent decadal-to-interdecadal variability in the Pacific, nonetheless there is significant high-frequency variability (Figure 2a). The PDO index is therefore low-pass filtered to only retain the decadal to interdecadal climate variability in the Pacific. This low-pass filtered PDO index is referred to as the Decadal Climate Index (DCI) here (the low-pass filtered IPO index is very similar, and high correlation (0.96) can be found between the two of them, as it is in longer records [*Power et al.*, 1999]). The Interannual Climate Index (ICI) associated with ENSO events is defined by high-pass filtering of the MEI. The high-pass component closely matches the monthly MEI and explains the majority of MEI variance, but there is also a non-negligible low-pass component (Figure 2b). The ICI, representing ENSO influences on interannual time scales, is not significantly correlated with the DCI which describes large-scale climate system variations on decadal (to interdecadal) time scales (correlation coefficient 0.25). Note that the low-passed PDO is highly correlated with the low-passed MEI (correlation coefficient 0.95; Figure 2), which suggests a connection between the PDO and ENSO. This is consistent with the findings of *Power et al.* (2006), who found that the low pass-filtered ENSO time-series in their climate model bears a striking similarity to the model's IPO time-series. Such high correlation also means that pre-existing climate indices MEI and PDO are not totally independent of each other. We also wish to emphasize that although both climate indices are derived by filtering pre-existing indices, this is not the only way to define them. The main conclusions from this study,

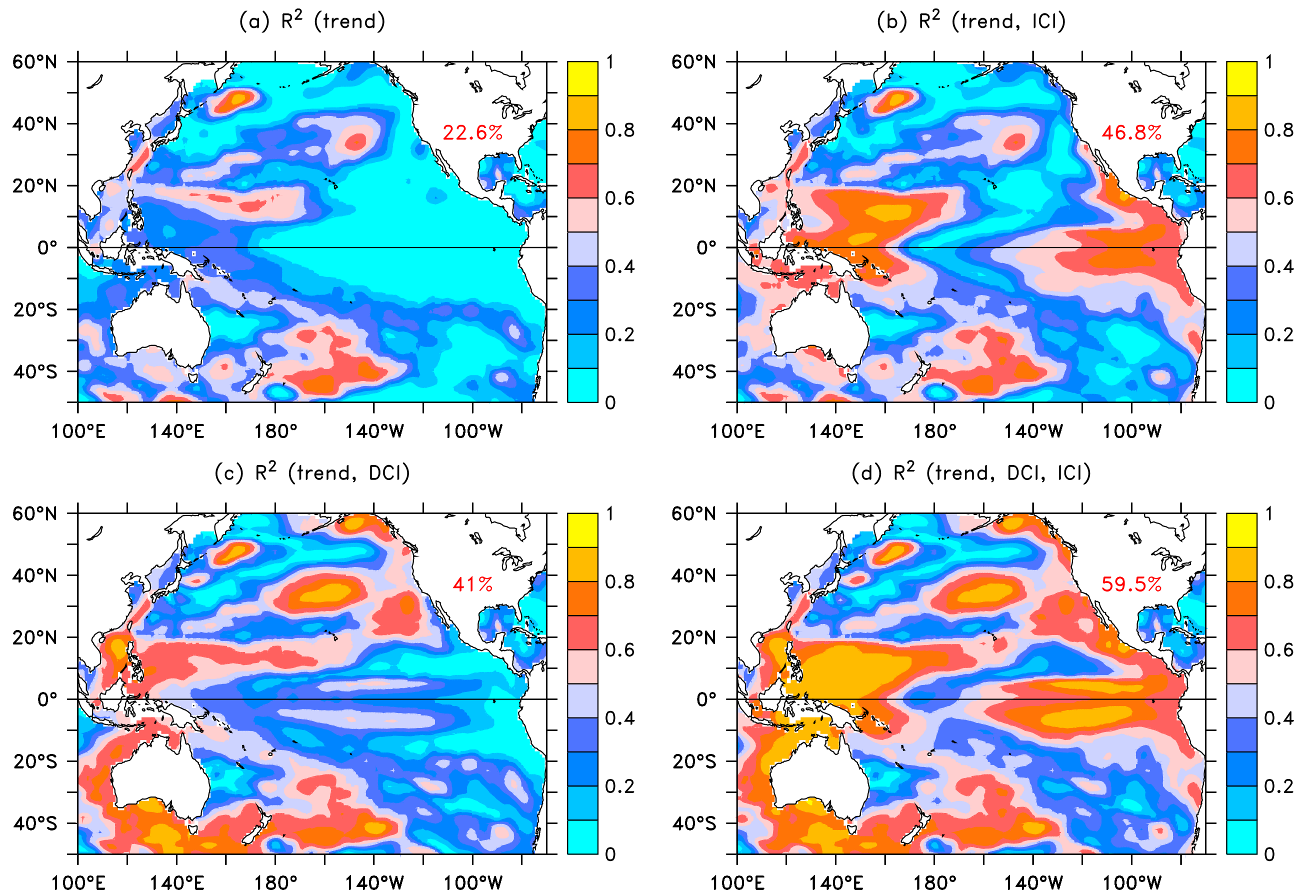

Figure 3. The fractional variance explained by the regression over total variance of sea level at each grid point for (a) single variable linear regression with respect to time (Eq. (1)), and multiple variable linear regression with respect to (b) both time and the Interannual Climate Index (Eq. (4)), (c) both time and the Decadal Climate Index (Eq. (3)), and (d) time, interannual and decadal climate indices over 1993–2009 (Eq. (2)). The percentage of total sea level variance over the whole Pacific basin (60°N–50°S, 100°E–70°W) explained by each regression model is shown in the upper right corner.

and decadal and interannual sea level fingerprints identified later do not critically depend on how the decadal and interannual climate indices are derived, as long as they can represent the dominant modes of climate variability in the Pacific at decadal and interannual time scales, respectively. For example, the DCI can be alternatively defined as the leading EOF principle component of decadal sea level in the Pacific (refer to Figure S2 in the auxiliary material).[1]

[11] Non-seasonal sea level anomalies are derived using monthly climatological cycles over the period 1993–2008. Sea level anomalies and the ICI are both smoothed with a 5-month running-mean filter before further analysis.

3. Linear Trend From Regression Analysis

[12] In its simplest form, the linear trend can be derived by single variable linear regression (SVLR) of the variable of interest (sea level in the current study) with respect to time using the method of least squares [*Emery and Thomson*, 2001]:

$$\hat{\eta} = a_0 + a_1 t + \varepsilon_a \tag{1}$$

where a_0 is the intercept, a_1 is the regression coefficient (trend), and ε_a is the error. Applying SVLR of sea level with respect to time implicitly assumes that linear temporal changes are dominant in sea level variations.

[13] However, as discussed in the Introduction, there is also large-scale climate variability which can affect the sea level variations in the Pacific. Thus a multiple variable linear regression (MVLR) can be designed to separately identify the interannual, decadal and longer term trend by linearly regressing sea level with respect to time, and interannual and decadal climate indices simultaneously:

$$\hat{\eta} = b_0 + b_1 t + b_2 DCI + b_3 ICI + \varepsilon_b \tag{2}$$

where b_1 is the sea level LT derived from the MVLR, b_2 is regression with respect to the DCI (i.e., the low-passed PDO index as discussed in Section 2), b_3 is regression with respect to the ICI (i.e., the high-passed MEI index).

[14] Two additional MVLR are also carried out by regression of sea level with respect to time and the DCI or ICI.

$$\hat{\eta} = c_0 + c_1 t + c_2 DCI + \varepsilon_c \tag{3}$$

$$\hat{\eta} = d_0 + d_1 t + d_2 ICI + \varepsilon_d \tag{4}$$

[1]Auxiliary materials are available in the HTML. doi:10.1029/2012GL053240.

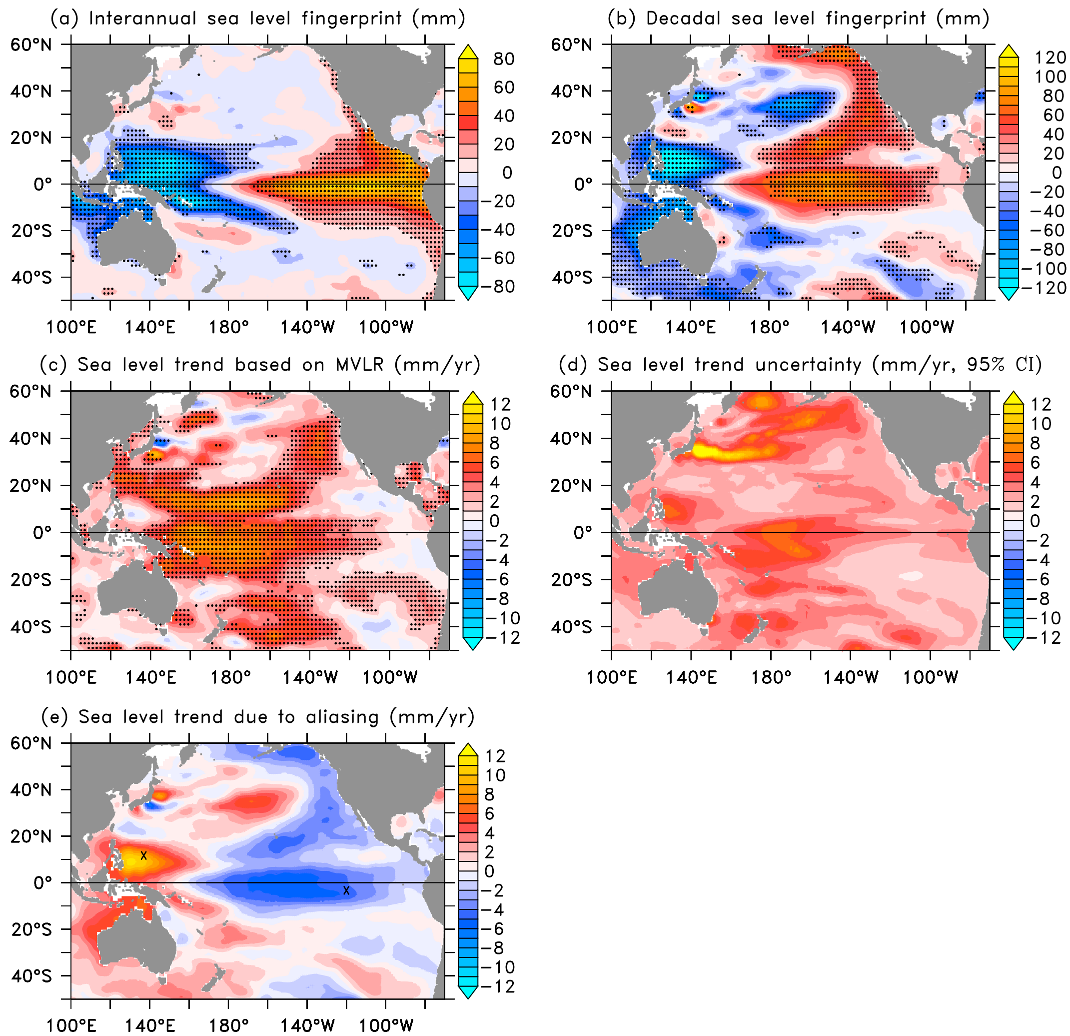

Figure 4. (a) Interannual sea level fingerprint (unit: mm), represented by the regression of the sea level with respect to the ICI (b_3 in Eq. (2)), (b) decadal sea level fingerprint (unit: mm), represented by the regression of the sea level with respect to the DCI (b_2 in Eq. (2)), and (c) sea level trend (unit: mm yr^{-1}; b_1 in Eq. (2)) derived from multiple variable linear regression of sea level with respect to time, interannual and decadal climate indices (Eq. (2)). (d) Sea level linear trend uncertainty (unit: mm yr^{-1}) for Figure 4c at the 95% confidence interval. (e) Sea level trend due to aliasing (mm yr^{-1}) which is defined as the difference between the linear trends derived from single variable linear regression (Eq. (1)) and multiple variable linear regression (Eq. (2)). Only significant values over the 95% confidence interval are shown in dotted areas in Figures 4a–4c. Statistical calculations in Figures 4a–4d were based on a two-sided student's t-test with the effective degrees of freedom estimated by considering serial autocorrelation of data [*Emery and Thomson*, 2001].

[15] The goodness of the above linear regression methods (Eqs. (1–4)) can be measured objectively by the ratio of variance explained by regression over total variance (R^2) of sea level at each location (Figure 3). The higher is the ratio R^2, the better is the regression performance. We applied all four models for the same period from January 1993 to June 2009 (some data points were lost due to filtering). For the SVLR (Eq. (1)), most regions in the Pacific have quite low values of R^2, 0~0.2, except the southwestern Pacific and the mid-latitude North Pacific. Adding interannual climate variability alone sharply increases R^2 in the tropical band between 20°N and 20°S except the central tropical Pacific around 160°W (Eq. (4)), but it has little impact outside this tropical band. Adding decadal variability alone also increase skill in many regions, especially in the extra-tropical North Pacific and the eastern Indian Ocean (Eq. (3)). Finally, the MVLR of sea level with respect to time, interannual and decadal climate variability shows much better skill almost everywhere than the SVLR of sea level with respect to time alone. The percentage of total sea level variance over the whole Pacific basin (60°N–50°S, 100°E–70°W) explained by the SVLR is slightly above 20%. Adding either decadal or interannual variability doubles the percentage to about 40%, while the MVLR including trend, decadal and interannual variability almost triples the percentage to 60% (Figure 3). Based on the above simple objective measures, the MVLR which considers trend, interannual and decadal variability simultaneously (Eq. (2)), is the preferred choice among the four regression methods (Eqs. (1–4)) to describe the sea level change in the Pacific. There are still some regions (e.g., east of Australia, southeast Pacific and east of Japan) where the MVLR model has little skill to explain the

observed sea level variance, possibly due to instability of boundary current systems, internal ocean variability, phase lags between sea level and modes of climate variability or other processes not included here.

4. The Sea Level Linear Trends and Interannual and Decadal Sea Level Fingerprints

[16] The interannual sea level fingerprint, represented by the regression of sea level with respect to the ICI from the MVLR (b_3 in Eq. (2)), shows close connection to ENSO events (Figure 4a). One attractive feature is that the significant regression is mainly confined in the narrow tropical band between 20°N and 20°S where interannual variability dominates. The interannual sea level fingerprint has a higher signal in the eastern and western extremities of the tropical Pacific, with maximum amplitudes of 70+ mm per unit ICI change in the east and −70 mm in the west. Such zonal distribution, sometimes referred to as the "tilting" or "sea-saw" mode [e.g., *Wang et al.*, 1999; *Meinen and McPhaden*, 2000], is what happens during the peak of a typical El Nino event [e.g., *Nerem et al.*, 1999; *Church et al.*, 2006]. This interannual sea level fingerprint is consistent with current understanding of ENSO dynamics. It can be explained well by the thermosteric sea level variability associated with the titling mode of the equatorial thermocline or equivalently heat content variability in the tropical Pacific during ENSO events [*Jin*, 1997; *Meinen and McPhaden*, 2000]. Large signals are present off the west coast of the Americas, with their magnitudes decreasing poleward. This pattern is likely related to poleward coastally-trapped wave propagation excited by tropical ENSO activities [e.g., *Enfield and Allen*, 1980].

[17] In contrast, the decadal sea level fingerprint, represented by the regression of sea level with respect to the DCI (b_2 in Eq. (2)), has a much broader meridional range, extending to high latitudes with a roughly symmetric distribution straddling the equator (Figure 4b). In the tropical Pacific, an El-Niño like (but distinct) distribution can be identified: positive sea level variations in the central and eastern tropical Pacific, with maximum amplitude of 80 mm per unit DCI change around 150°W on the equator; negative sea level changes in a narrow western tropical region with maximum amplitude of −150 mm per unit DCI change. Broad negative sea level changes can also be found in the northern central Pacific with a peak of −80 mm per unit DCI change at around 170°W, 35°N. There are also negative sea level variations with a broad spatial scale covering the western portion of the South Pacific though they are mostly not significant at the 95% confidence level. The fingerprint in the Southeast Pacific could be problematic as the hindcast skill is low there (Figure 3), which suggests other climatic processes such as the Southern Annual Mode [e.g., *Kwok and Comiso*, 2002] may play a role there. The decadal sea level fingerprint found here resembles the PDO pattern from EOF analysis of SST [e.g., *Zhang et al.*, 1997]. Such correspondence is consistent with *Cummins et al.* [2005] who found SST and sea level tend to vary coherently at large spatial scales and low frequencies in the North Pacific. It is also very similar to the IPO pattern in the upper ocean heat content identified by *Power and Colman* (2006) in their climate model.

[18] The spatial distribution of the decadal fingerprint is correlated with that of interannual fingerprint in the narrow tropical band, however the spatial correlation over the whole Pacific (60°N–50°S, 100°E–70°W) is not significant at 0.47 (less than 95% significance level). Therefore different underlying mechanisms may operate to cause different decadal and interannual sea level fingerprints (we plan to investigate these mechanisms in a follow-up study). This independence between interannual and decadal sea level fingerprints is, in turn, partially a consequence of distinct separation between the interannual and decal climate indices (Section 2). The robustness of both the interannual and decadal sea level fingerprints is supported by a separate EOF analysis. The first EOFs of interannual and decadal sea level are very similar to the corresponding fingerprints (compare Figure S2a with Figure S2c in the auxiliary material for interannual time scales, also Figure S2b with Figure S2d for decadal time scales). The associated principle components also closely follow the climate indices (Figures S2e and S2f). In other words, the sea level fingerprints derived from the MVLR model essentially are very similar to the dominant modes of sea level variability at corresponding time scales.

[19] The linear sea level trend from the MVLR (Figure 4c) over 1993–2009 is positive almost everywhere in the Pacific (except some small and isolated regions) even though quite large linear trend uncertainty values can be found as a consequence of short altimeter period and the small number of degrees of freedom (Figure 4d). The largest significant trends mainly appear in the western and central tropical Pacific, northeast Pacific and south Pacific. The strong zonal gradient of sea level trend based on the SVLR (Eq. (1)), i.e., positive (negative) sea level tend in the western (eastern) tropical Pacific is now barely present (compare Figures 1a and 4c). Moreover, the high sea level rise region is shifted eastward to the central tropical Pacific, with maximum rate 7+ mm yr^{-1} between 155°E and 165°W near the equator (compared with more than 12 mm yr^{-1} in the western Pacific in the SVLR). We should not assume this linear trend is the signal of anthropogenic climate change as some further decadal variability is likely to still be present and the current study period is short. As discussed in Section 3, considering the much better performance of the MVLR than the SVLR in representing sea level variance in the Pacific over the altimeter era, we can treat the regression coefficient difference a_1-b_1 as the sea level trend resulting from aliasing the interannual and decadal climate variability (Eqs. (1) and (2); Figure 4e). Further examination indicates this aliasing is almost solely due to the sea level associated with the decadal climate variability (b_2DCI in Eq. (2); compare Figures 4b and 4e), because the DCI has a decreasing trend over the study period (Figure 2c). In contrast, the sea level associated with interannual ENSO variability (b_3ICI in Eq. (2)) does not induce large linear trends, because there are multiple ENSO cycles and no significant trend in the ICI over the current study period of about two decades (Figure 2c). The regression residual (ε_b in Eq. (2)) should not induce noticeable trend either by definition. The high rate of sea-level rise in the western tropical Pacific and the negligible rate or even falling sea level in the eastern tropical Pacific and along the US west coast in the SVLR analysis is partially a result of the basin-scale decadal climate variability added to the global averaged rise (Figures 1a and 4). That is, the spatial pattern in Figure 1a can be approximated to the first order by a sea level trend as a result of aliasing of the decadal variability (Figure 4e) plus the global mean sea level rise rate of about 3.3 mmyr^{-1} over the

current study period [*Zhang and Church*, 2011]. Note the sea level rise rates associated with anthropogenic climate change are generally not expected to be geographically uniform [e.g., *Church et al.*, 2010].

5. Discussions and Summary

[20] By using a multiple linear regression model, we have simultaneously solved for the regional sea level changes in the Pacific in terms of a linear trend, and interannual and decadal climate variability using altimeter measurements since 1993. This multiple variable linear regression model explains three times the variance of the single variable linear regression model. Interannual and decadal climate indices defined here are independent of each other as a result of band-pass filtering, with the former representing the interannual climate variability associated with ENSO events only and the latter representing coherent decadal to interdecadal climate variability. Large-scale and low-frequency climate variability can induce regional variability of atmospheric and oceanic states, including sea level. As a result, the interpretation of regional sea level trends derived from altimeter measurement over only two decades is complicated by the existence of this climate variability. Especially important is the basin-scale decadal variability which can be erroneously aliased and mistreated as a longer term sea level trend. In contrast, the interannual sea level variability associated with ENSO events is less effectively aliased into the sea level trend because there are multiple ENSO cycles in the current study period of slightly less than two decades.

[21] The length of our current study period, constrained by the availability of altimeter measurement, is about two decades. Ideally, data over a much longer period are desired for identifying decadal sea level fingerprints and detection of sea level change. Unfortunately, long-term sea level measurements based on tide gauges are usually available only at a limited number of stations, mainly in the North Hemisphere, and mostly along continental coastlines. Analyses with a reconstructed historical sea level dataset [*Church and White*, 2011] over longer periods (as long as 1950–2009) indicates similar spatial structures of the decadal sea level fingerprint to that shown in Figure 4b, while the interannual fingerprint shown in Figure 4a is almost unchanged for various periods longer than two decades (not shown). By applying the multiple variable linear regression model (Eq. (2)) to atmosphere variables and subsurface ocean variables over the same altimeter era, we found a similar trend, and interannual and decadal fingerprints. We plan to investigate the underlying mechanisms in a follow-up study.

[22] Climate system modelling has made significant progress in the past two decades, which can provide complementary insights about sea level variability and change and alleviate the constraint of observational data. As an example, *Power and Colman* [2006] identified resembling interannual and decadal fingerprints in their climate model. Therefore similar climate models can be used to explore underlying processes for decadal variability in great detail and over much longer model periods.

[23] To study sea level changes related to climate change, ideally we need both good spatial resolution/coverage (like altimeters) and long time series (like tide gauges). It is tempting to use current-day altimeter-based regional sea level linear trends as a reference for future climate change projections. Such practice needs to be treated with caution as regional sea level linear trends derived over the short altimeter era can be greatly affected by low-frequency climate variability. For example, although the global mean sea level rose over the altimeter era, some regions experienced decreasing sea level. We showed that the decreasing regional sea levels in the eastern equatorial Pacific is mainly associated with the Pacific Decadal Oscillation (or the Interdecadal Pacific Oscillation). Not understanding this decadal variability can send a false message to nearby regions, including the U.S. West Coast, that sea level is not rising. However, such a message ignores the important decadal sea level variability that may mask the longer term trend (Figures 1 and 4e and Figure S3a in the auxiliary material). In contrast, for those island countries in the western tropical Pacific and especially low-lying atolls, the high rate of sea level rise over the altimeter era has a significant component associated with natural climate variability (Figures 1 and 4e and Figure S3b in the auxiliary material).

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