Multidecadal sea level anomalies and trends in the western tropical Pacific

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[1] Tide gauge data are used to relate low frequency sea level changes over the past 60 years in the western tropical Pacific, including a significant positive trend over the past two decades, to Pacific climate indices. Five-year averages of western tropical Pacific sea level are well explained by global sea-level rise and a combination of slowly varying trade wind fluctuations captured by dominant climate indices for the tropical Pacific. Implications for multidecadal sea level variations in the region are considered using reconstructions based on the climate indices. **Citation:** Merrifield, M. A., P. R. Thompson, and M. Lander (2012), Multidecadal sea level anomalies and trends in the western tropical Pacific, *Geophys. Res. Lett.*, *39*, L13602, doi:10.1029/2012GL052032.

1. Introduction

[2] The highest rates of regional sea level rise over the past two decades have occurred in the western tropical Pacific (WTP) (Figure 1), with values that are nearly three times the global average [*Nerem et al.*, 2010]. The cause of high sea level trends is a concern in this region given the large number of inhabited coral atolls and low-lying islands that are vulnerable to rising sea levels. Numerous studies have linked recent high sea level trend patterns in the WTP (global mean removed) to trade wind forcing [e.g., *Carton et al.*, 2005; *Kohl et al.*, 2007; *Timmermann et al.*, 2010; *Becker et al.*, 2012]. *Merrifield* [2011] used tide gauge data to show that the regional sea-level rise rate increased abruptly in the early 1990s shortly before the start of the TOPEX/Poseidon altimeter record, and that the trend shift matched an enhancement in reanalysis trade wind speeds averaged across the tropical Pacific. Numerical model simulations [*Merrifield and Maltrud*, 2011; *McGregor et al.*, 2012] confirm that the steady intensification of the trade winds largely accounts for the amplitude and spatial pattern of WTP sea-level rise since the early 1990s (depicted in Figure 1).

[3] *Feng et al.* [2004] noted that sea level measured at Fremantle, Australia exhibits multi-decadal fluctuations related to the Southern Oscillation Index (SOI) and the Pacific Decadal Oscillation (PDO) index. The relationship was attributed to low frequency Pacific trade wind fluctuations that force sea level anomalies that pass from the WTP, through the Indonesian Throughflow region, and along the coastal waveguide of the west coast of Australia. The Fremantle sea level variations indicate a trade wind weakening from 1950 to 1990 and intensification since 1990. *Feng et al.* [2010] showed that sea level variations at Pohnpei in the WTP are consistent with the multidecadal changes observed at Fremantle. *Feng et al.* [2011] later showed that a trade wind intensification since the early 1990s is captured in all atmospheric reanalysis products. These multidecadal trade wind shifts have been related to changes in the strength of shallow meridional overturning circulation in the Pacific [*McPhaden and Zhang*, 2002], changes in the Indonesian Throughflow and Leeuwin Current transports [*Feng et al.*, 2011], upper-ocean heat content changes in the Indian Ocean [*Schwarzkopf and Boning*, 2011], and variations in the bifurcation of the North Equatorial Current [*Qiu and Chen*, 2010].

[4] *Merrifield* [2011] reported that five-year averages of WTP sea level and the PDO index are poorly correlated, whereas dominant EOFs of global sea surface temperature and outgoing longwave-radiation appear to track the WTP sea level trend change. He speculated that the trade wind intensification might be associated with recent warming trends distinct from the PDO. Here we reexamine the western tropical Pacific tide gauge data to show that the sea level changes in the WTP in fact are related to the PDO and to low frequency fluctuations in the Southern Oscillation Index (SOI), consistent with the results of *Feng et al.* [2004, 2010]. We use regional sea level reconstructions based on the PDO and SOI to emphasize that while multidecadal trade wind fluctuations have a strong influence on regional sea level trends, the impact on regional sea level anomalies amounts to modest variations (a few centimeters) about global sea-level.

2. Data and Methods

[5] WTP tide gauge time series from the University of Hawaii Sea Level Center Research Quality and Fast Delivery databases are examined from 12 island stations with relatively long records, at least back to the 1970s (Figure 2). A seasonal cycle is fit and removed from the monthly data and annual averages are formed if at least eight months of data are available. The time series are first-differenced in time, an average of all records is computed, and a five-year running mean is applied. A cumulative summation results in the average WTP sea level time series shown in Figure 2, which will be referred to as western Pacific sea level (WPSL).

[6] Trends associated with vertical ground motion at each tide gauge are assessed by considering the relative trends between tide gauge and satellite altimeter time series during 1993–2011. For the latter we use the AVISO product at the ocean grid point closest to each tide gauge location. The difference between tide gauge and altimeter trends is taken

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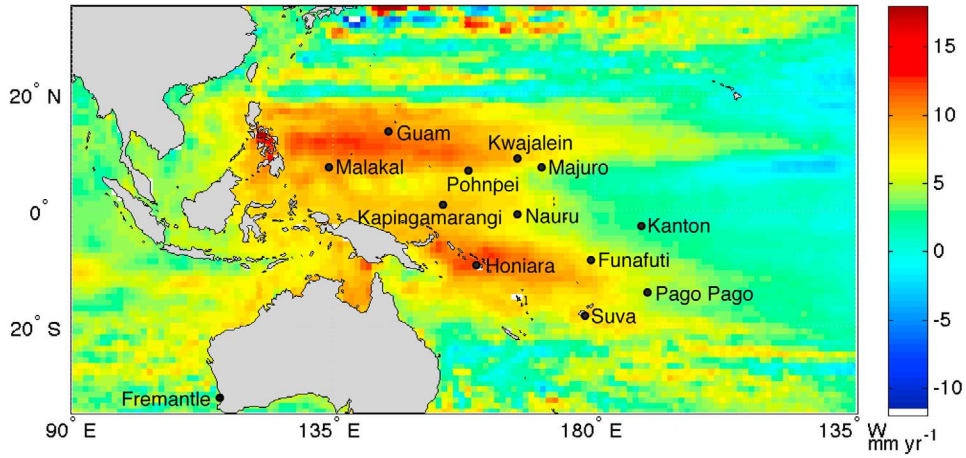

Figure 1. Sea surface height trends from 1993–2010 from the AVISO multimission gridded product. Tide gauge stations used in this analysis are indicated.

as a measure of vertical land motion at each tide gauge station [*Nerem and Mitchum*, 2002], which is assumed to be constant over the tide gauge records. The inferred land motion is indistinguishable from zero and hence a ground motion correction is not applied to the WPSL time series. The weak vertical land motion signals in this region generally are consistent with the assessment of continuous GPS records by *Becker et al.* [2012]. In particular, vertical land motion cannot account for the high WPSL rate after the early 1990s (Figure 2).

[7] The PDO index, obtained from the website of the Joint Institute for the Study of the Atmosphere and Ocean at the University of Washington, is the leading principal component of North Pacific sea surface temperatures poleward of 20°N [*Mantua et al.*, 1997; *Zhang et al.*, 1997]. The SOI, obtained from the Australian Bureau of Meteorology, National Climate Centre, is the sea surface atmospheric pressure difference between Papeete, Tahiti and Darwin, Australia.

3. Regional Sea Level Reconstructions

[8] The WPSL time series represents a sum of global mean sea level (GMSL) and regional sea level variations. We use the *Church and White* [2011] reconstruction as a model for GMSL, which is subtracted from the WPSL time series. The squared correlation between WPSL-GMSL and the PDO is $r^2 = 0.75$ (Figure 3a). The Church and White reconstruction and the PDO together account for 87% of the uncorrected WPSL record, which is higher than the WPSL variance explained by a linear trend and the PDO (81%). Correcting for GMSL, as was done in *Feng et al.* [2004], emphasizes the regional component in the WPSL, which is correlated with the PDO and SOI regional climate indices (Figure 3a). *Merrifield* [2011] reported low correlations between WPSL and the PDO without accounting for GMSL.

[9] The five-year running mean time series of the SOI and the PDO index are quite similar after 1950 (Figure 4). In particular, both show a trend change in the early 1990s that is associated with multidecadal variations in the indices throughout the 20th century. We obtain similar WPSL sea level regression results using the SOI instead of the PDO index (Figure 3a). The correlation of WPSL-GMSL is higher with the PDO index ($r^2 = 0.75$) than with the SOI ($r^2 = 0.69$), which is due in part to more energetic high frequency ENSO variability in the SOI than in either the PDO index or WPSL.

[10] We compare the Fremantle record studied by *Feng et al.* [2004] with the WPSL results (Figure 3b). Fremantle includes more high-frequency variability than the WPSL record, and as a result the SOI explains a higher fraction of Fremantle sea level variance (0.58) compared to the PDO (0.24). The regression coefficient of Fremantle sea level on the PDO (a = −2.2 cm/PDO units) is about 25% smaller than for WPSL, and the SOI coefficient (a = 0.66 cm/SOI units) is 25% larger. The lower correlation with the PDO index is due in part to a weaker correspondence between Fremantle sea level and the PDO prior to 1950 than after (Figure 3b). If we compute the correlations since 1950, similar to the computation for WPSL, the correlation with the PDO improves ($r^2 = 0.55$), and the regression coefficient for the PDO becomes larger (a = −3.3 cm/PDO units) than the coefficient for WPSL. The correspondence between Fremantle sea level and the SOI is more consistent before and after 1950 than it is for the PDO. The WPSL record is not long enough to distinguish between the SOI and PDO prior to 1950.

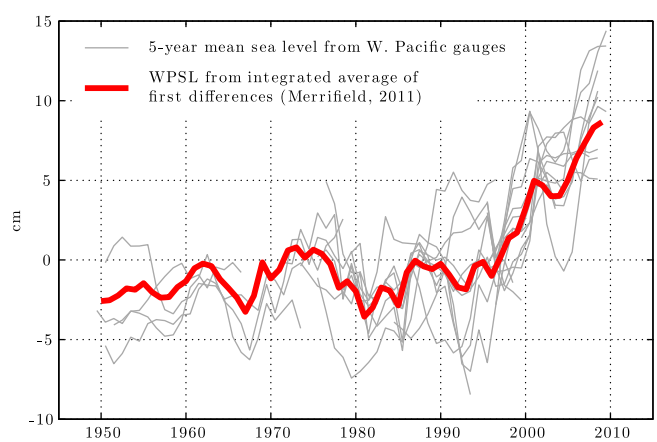

Figure 2. Five-year average sea level time series from tide gauge stations in the western tropical Pacific. The average of all stations (red curve) is referred to as western Pacific sea level (WPSL).

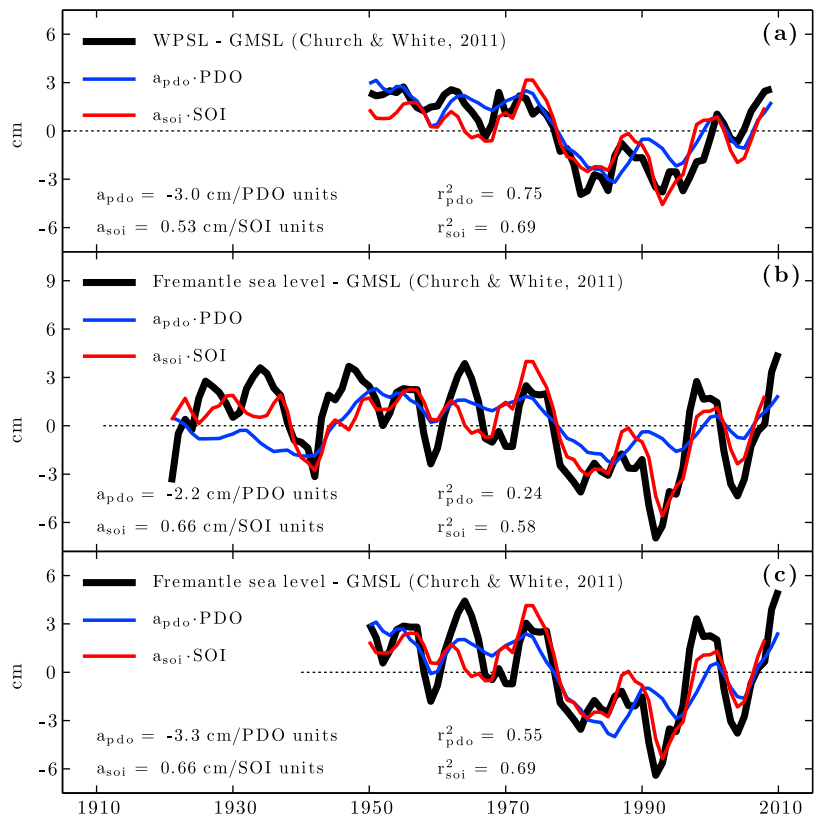

Figure 3. (a) WPSL sea level minus the *Church and White* [2011] reconstruction of GMSL (black) compared to the scaled PDO index (blue) and SOI (red). (b) Same as Figure 3a except for Fremantle sea level. (c) Same as Figure 3b for the time period since 1950.

[11] A hindcast reconstruction of WPSL is formed using the regression coefficients for the PDO and SOI indices with Church and White GMSL (Figure 4). In general, WPSL reconstructed from the PDO is higher than GMSL during positive phases of the PDO, such as the mid 1940s to the climate shift in the late 1970s, and lower during negative phases, such as the 20-year period that ended in the late 1990s. For the five-year running mean time series, WPSL variations scale as −3.0 cm times the PDO index. Using this scaling and the long PDO record, the standard deviation of low frequency WPSL is 1.7 cm about global mean sea level, with peak amplitudes of ±3.9 cm.

4. Trade Wind Forcing and the PDO

[12] *Merrifield* [2011] based his conclusions regarding a lack of PDO influence on wind-forced WTP sea levels in part on the weak projection of the PDO onto Pacific trade winds based on a multiple regression of ORA-S3 wind stress [*Balmaseda et al.*, 2008] with the PDO and the North Pacific Gyre Oscillation (NPGO) indices [*Merrifield*, 2011, Figure 12]. Given that the increasing trade wind forcing can account for WPSL trends [*Merrifield and Maltrud*, 2011; *Becker et al.*, 2012; *McGregor et al.*, 2012], and WPSL matches the PDO (Figure 3a), how do we reconcile the weak PDO projection previously noted by *Merrifield* [2011]?

[13] Differences in reanalysis wind products appear to account for the discrepancy. If we regress the NCEP-NCAR reanalysis (NCEP1 [*Kistler et al.*, 2001]) wind stress on to the PDO and NPGO indices and time, the regression coefficients for the PDO index are higher in the Pacific trade wind region (Figure 5a) than the previous result of *Merrifield* [2011] using ORA-S3 wind stress [see *Merrifield*, 2011, Figure 12a]. In addition, the NCEP1 regression coefficients for the NPGO in the trade wind region (not shown) are weak compared to those for the PDO. The different trends in the

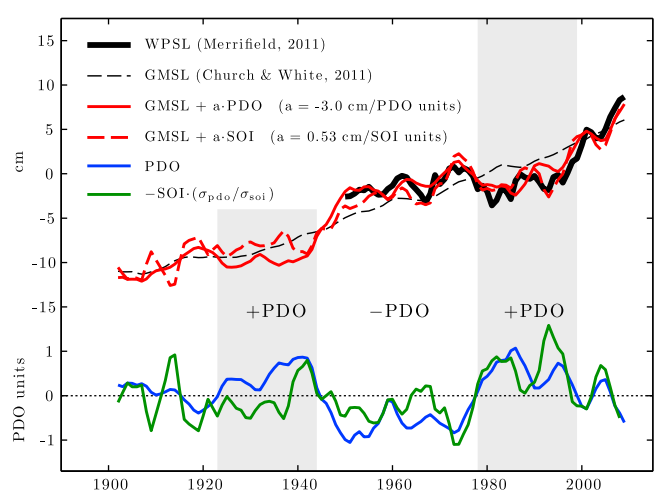

Figure 4. WPSL (black) compared to WPSL reconstructions based on the PDO (red) and the SOI (red dash) with the *Church and White* [2011] GMSL included (black dash). The PDO index (blue) and scaled SOI (green) are shown for comparison.

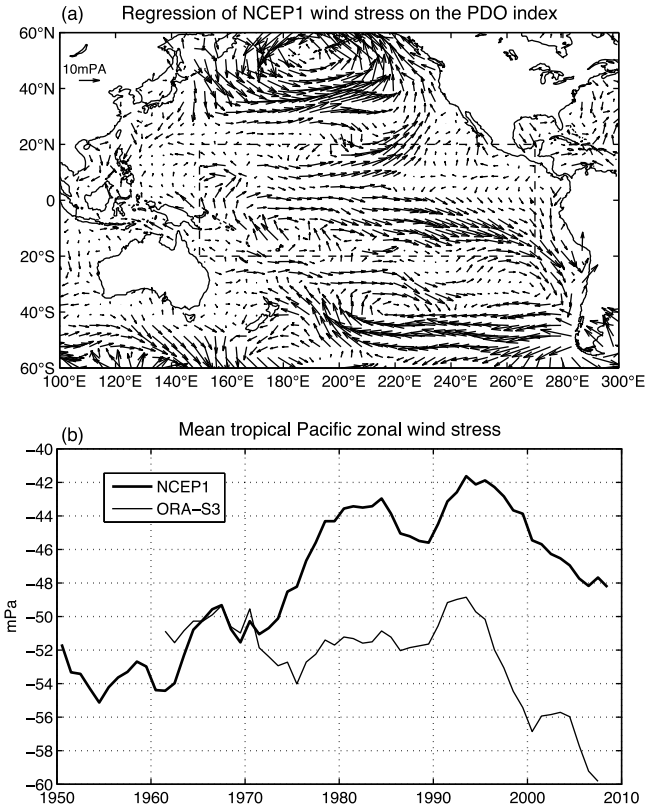

Figure 5. (a) Regression coefficient for the PDO index in a multiple linear regression of NCEP1 wind stress on the PDO and NPGO indices and time. The scale shows a 10 mPa change in wind stress for a unit change in the PDO index. (b) Mean zonal wind stress in the tropical Pacific (see boxed region in Figure 5a) from the NCEP1 reanalysis (dark curve) and the ORA-S3 wind stress product (Figure 5b).

wind products are particularly evident in time series of regionally averaged zonal wind stress in the tropical Pacific (boxed region in Figure 5a, 20°S to 20°N, 150°W to 270°W). The two wind products include the trade wind intensification after the 1990s; however, the ORA-S3 zonal wind stress is relatively steady from the early 1960s to the early 1990s whereas the NCEP1 wind stress decreases during this time period (Figure 5b). A wind stress decrease is consistent with the minimal WPSL rise during this period, i.e., a trade wind weakening accounts for the reduced WPSL trend during 1950–1990 relative to GMSL (discussed by *McGregor et al.* [2012]). We note, however, that *Merrifield and Maltrud* [2011] found that NCEP1 wind stress does not do as well as ORA-S3 in accounting for the spatial structure of the altimeter trend in the WTP since 1993.

[14] We use NCEP1 and ORA-S3 to illustrate how wind stress-PDO index regressions vary in the trade wind region depending on the reanalysis product. A thorough assessment of the skill of numerical model hindcasts of WPSL using different wind stress products has been considered recently by *McGregor et al.* [2012]. They emphasize the importance of including GMSL in the hindcasts and report a wide range of skill dependent on the wind product. Their results suggest that WASWind [*Tokinaga and Xie*, 2011] and ERA-interim [*Dee and Uppala*, 2009] winds yield the best representation of WPSL, although discrepancies prior to 1970 remain to be explained.

[15] *Merrifield* [2011] also argued that the recent WPSL trend could not be explained as an artifact of high frequency ENSO events using a multiple regression analysis with ENSO-related indices. That result appears to contradict the high correlations of WPSL with the SOI and PDO index presented here. To clarify, the ENSO indices based on eastern tropical Pacific SST, such as Nino3 and Nino3.4, do not have a strong influence on WTP SSH trend estimates as described by *Merrifield* [2011]. These indices also do not exhibit a noticeable trend after 1990. In contrast, the SOI and PDO index both exhibit a trend after 1990, and inclusion of these indices in a multiple regression does impact the SSH trend analysis in the WTP. So while we agree that high frequency ENSO variability, as represented in all the main ENSO indices, does not account for the recent high SSH trend pattern in the WTP, we find that certain indices with energetic low frequency variations, such as the SOI and PDO index, do account for a portion of the SSH trend pattern in the WTP.

5. Discussion

[16] Tide gauge observations in the western tropical Pacific provide a 60 year long record that strongly reflect trade wind forcing on multidecadal time scales. Similar variations are also exhibited by the dominant climate indices in the tropical Pacific. The recent high sea level rise rates in the WTP beyond the global mean rate are a result of increasing trades, which occur when the PDO (SOI) index exhibits a negative (positive) trend. These rates are expected to weaken and reverse when current trends in the indices reverse sign. A similar relationship between regional Pacific sea level trends and PDO wind forcing has been noted by *Bromirski et al.* [2011], who focused on the importance of PDO-related wind stress curl forcing off the Pacific coast of North America. The importance of internal climate variability and tropical Pacific sea level trends has been investigated by *Meyssignac et al.* [2012].

[17] Our results confirm the previous findings of *Feng et al.* [2004, 2010] regarding the importance of tropical Pacific decadal variability and regional sea level fluctuations. The WPSL changes are in better agreement with the PDO rather than the SOI, whereas the opposite is true for Fremantle sea level. We attribute this to more energetic high frequency wind fluctuations along the equatorial waveguide than off the equator, which are better represented by the SOI than the PDO index. The WPSL time series is formed using a number of tide gauge stations outside of the equatorial zone. We note, however, that a clear distinction between the relationship of the SOI and PDO to WPSL variability is not possible due to limited record length. This difficulty is illustrated by the improvement of the PDO fit to Fremantle sea level by shortening the Fremantle record to the length of the WPSL curve.

[18] The relationship of the SOI and PDO to WPSL lends credence to interpretations of the PDO as a "reddening" of ENSO [e.g., *Newman et al.*, 2003]. This interpretation appears particularly valid since 1950 when five-year averages of the SOI and PDO are highly correlated. This relationship is less apparent before 1950, however, as the PDO state transition in the 1940s is noticeably absent in the SOI. This earlier PDO

transition may reflect extratropical contributions to PDO variability such as those considered by *Schneider and Cornuelle* [2005]. Due to the lack of sea level data in the western tropical Pacific before 1950, it is not possible to assess whether trends in WPSL are sensitive to PDO variability not directly associated with low-frequency ENSO variations captured by the SOI.

[19] In terms of the impacts of regional sea level rise in the WTP, we note that low frequency trade wind changes contribute to order 1 cm variations in sea level in the WTP on decadal to multidecadal time scales. While multidecadal variations are weak, for example compared to WTP sea level variations associated with interannual ENSO events that are an order of magnitude larger [e.g., *Becker et al.*, 2012], they do influence regional sea level trend estimates. Multidecadal variations can lead to linear trend changes over 20 year time scales that are as large as the global sea level rise rate, and even higher at individual tide gauges (e.g., Guam [*Merrifield*, 2011]). Linear trend maps such as Figure 1 can give the impression that sea level rise is a particular concern for the WTP relative to other ocean regions. On the contrary, the map symbolizes sea level changes of centimeter scale that rise and fall with low frequency trade wind fluctuations.

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