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Contribution of the Pacific Decadal Oscillation to global mean sea level trends

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[1] Understanding and explaining the trend in global mean sea level (GMSL) have important implications for future projections of sea level rise. While measurements from satellite altimetry have provided accurate estimates of GMSL, the modern altimetry record has only now reached 20 years in length, making it difficult to assess the contribution of decadal to multidecadal climate signals to the global trend. Here, we use a sea level reconstruction to study the 20 year trends in sea level since 1950. In particular, we show that the Pacific Decadal Oscillation (PDO) contributes significantly to the 20 year trends in GMSL. We estimate the PDO contribution to the GMSL trend over the past 20 years to be approximately 0.49 ± 0.25 mm/year and find that removing the PDO contribution reduces the acceleration in GMSL estimated over the past 60 years. **Citation:** Hamlington, B. D., R. R. Leben, M. W. Strassburg, R. S. Nerem, and K.-Y. Kim (2013), Contribution of the Pacific Decadal Oscillation to global mean sea level trends, *Geophys. Res. Lett.*, *40*, 5171–5175, doi:10.1002/grl.50950.

1. Introduction

[2] Since 1993, satellite altimetry has provided accurate measurements of ocean surface height. The near-global satellite coverage has improved the understanding of how sea level is changing on regional and global scales, leading to the first definitive estimates of global mean sea level (GMSL) rise [e.g., *Beckley et al*., 2007; *Mitchum et al*., 2010]. The modern satellite altimetry record, however, spans only 20 years, making it difficult to separate secular (used here to mean the long-term nonperiodic variation) trends including accelerations from natural climate variability. Sea level variations on decadal—and longer—time scales are known to contribute to the sea level [e.g., *Feng et al*., 2004; *Woodworth et al*., 2011; *Sturges and Douglas*, 2011; *Chambers et al*., 2012], but evaluating their impact is challenging using only the short satellite altimeter record. In particular, the "red" nature of the sea level spectrum makes it difficult to separate secular trends from longer (decadal to multidecadal) time scale variability without a long record of sea level [e.g., *Sturges*, 1987; *Hughes and Williams*, 2010; *Hamlington et al*., 2011a]. Sea level reconstructions provide a possible solution to this problem [*Chambers et al*., 2002; *Church et al*., 2004; *Hamlington et al*., 2011b, 2012; *Ray and Douglas*, 2011; *Meyssignac et al*., 2012]. Combining the dense spatial coverage of satellite altimetry with the long record length of the tide gauges provides the opportunity to examine longer time scale climate signals and to attempt assessing their contribution to sea level trends both regionally and globally.

[3] Identifying and explaining signals contributing to regional and global sea level trends, both during the satellite altimetry time period and over the past century, has been a frequently studied problem in recent years [e.g., *Meyssignac et al*., 2012; *Bromirski et al*., 2011; *Chambers et al*., 2012; *Feng et al*., 2004; *Kolker and Hameed*, 2007; *Hamlington et al*., 2011a; *Merrifield et al*., 2012; *Sturges and Douglas*, 2011; *Zhang and Church*, 2012]. Removing short-term (interannual to decadal) trends associated with known climate signals can allow for a better understanding of the underlying warming trend, serving to unmask the presence of acceleration in GMSL measured by satellite altimetry, for instance. In this paper, we analyze the 20 year trends from sea level reconstructions using a data-driven technique to assess the variability of the spatial pattern of sea level rise over the past 60 years and its relationship to GMSL during the same time period. Through this study, we find that the Pacific Decadal Oscillation (PDO) [*Cummins et al*., 2005; *Mantua et al*., 1997; *Mantua and Hare*, 2002] has a significant impact on decadal sea level trends not just regionally in the Pacific Ocean [*Meyssignac et al*., 2012; *Bromirski et al*., 2011; *Merrifield et al*., 2012; *Zhang and Church*, 2012] but also globally. The PDO is a decadal-scale pattern of predominantly North Pacific climate variability, with the associated variability commonly tracked by computing the first empirical orthogonal function of the North Pacific sea surface temperature [*Mantua et al*., 1997; *Mantua and Hare*, 2002]. Here, the PDO contribution to the trend in GMSL over the last 20 years is quantified, and by removing this contribution, a better estimate of the remaining secular trend in sea level during the satellite altimetry time period can be obtained. This has important implications for the estimates of both the trend and acceleration in GMSL, which provides an important indicator of climate change. Gaining a better understanding of the trend in GMSL will also serve to improve future projections of sea level rise.

2. Reconstructed Sea Level Data

[4] Two types of sea level data are analyzed in this paper—satellite altimeter-measured sea level (see supporting information for details) and reconstructed sea level. Sea level reconstructions are created by decomposing the satellite altimeter data into l functions and then subsequently using these basis functions to interpolate in situ tide gauge measurements back in time. The result is a data set with the

Additional supporting information may be found in the online version of this article.

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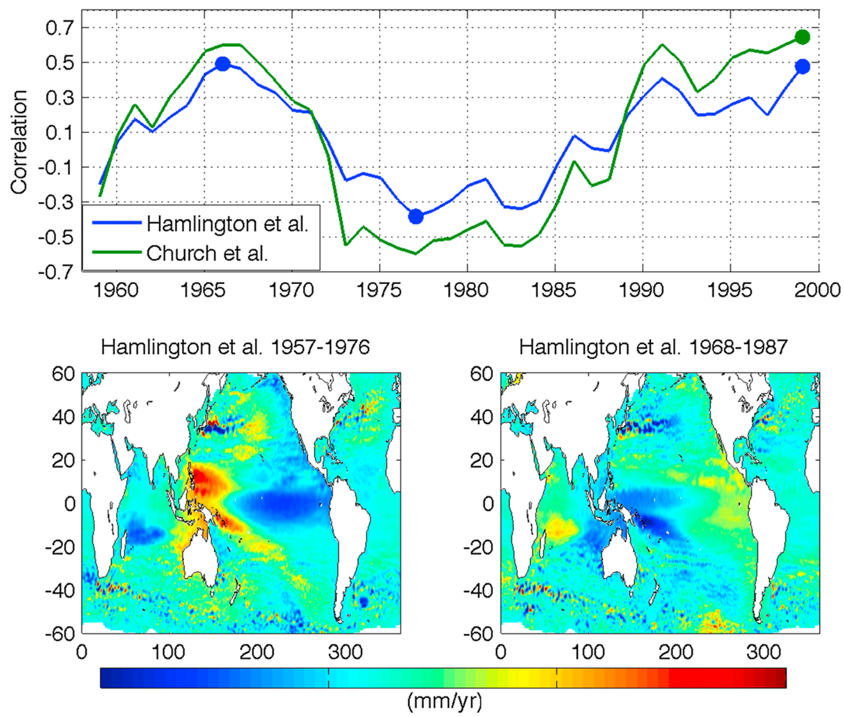

Figure 1. Correlation between the regional trend map from the Archiving, Validation, and Interpretation of Satellite Oceanographic data set and 20 year trend patterns from two sea level reconstructions, *Hamlington et al.* [2012] (blue) and *Church et al.* [2004] (green). Twenty year trend patterns from the HRSL data set are also shown for two different periods associated with extrema in the correlation time series.

spatial resolution of the satellite altimetry data and the record length of the tide gauge data. For the majority of the analysis in this paper, we use the cyclostationary empirical orthogonal function (CSEOF) reconstructed sea level from 1950 to 2010 [*Hamlington et al*., 2011b, 2012]. For comparison, we also use the empirical orthogonal function (EOF) reconstructed sea level from 1950 to 2010 [*Church et al*., 2004; *Church and White*, 2006]. Each of these data sets uses approximately 400 edited tide gauges, but rely on different techniques for performing the reconstruction, including the use of different basis functions. Both of these data sets are updates from the cited papers, but the reconstruction techniques described therein are applicable to the data sets used here. It should be noted that the CSEOF sea level reconstruction is also uniquely suited for the present study, since it provides the opportunity to estimate the contribution of climate variability to GMSL. Rather than introducing an “EOF0” basis function [as in *Church et al*., 2004] and adjusting the altimetry-derived basis functions, GMSL is estimated after reconstructing the variability associated with the basis functions, and then added back into the reconstructed data set. Further details of this approach are given in *Hamlington et al*. [2011b].

[5] To perform the analysis presented here, the satellite altimetry data and reconstructed sea level data sets were first annually averaged from 1950 onwards (i.e., a time series of yearly averages was computed for each grid point over the whole ocean). Twenty year regional trend maps were then computed using a least squares estimate of the trend over 20 year windows from both the satellite altimetry data and from the two reconstructed sea level data sets. For the reconstructed sea level data, trend maps were computed starting in 1959 (using annual trend maps from 1950 to 1969), and then advancing 1 year at a time to end up with 41 total trend maps, compared to one 20 year trend map available from the satellite altimetry data. After checking the agreement between the altimetry and reconstructed data sets (Figure S1 in the supporting information), a lagged correlation analysis was performed. To determine the variability of the trend pattern observed over the current altimetric record (the past 20 years), the altimetric trend pattern was correlated with the 20 year trends computed from the two sea level reconstructions. As seen in Figure 1, the correlations obtained from the CSEOF and EOF reconstructions agree well over the full 60 year record. There are approximately three extrema in the 20 year trend variability of the global sea level reconstructions when compared to the altimetric trends: 1957 to 1976, trend window centered on 1967/1968; 1968 to 1987, trend window centered on 1977/1978, and 1991 to 2010, trend centered on 2000/2001. This correlation time series provides two important pieces of information: (1) the trend map observed in the last 20 years from satellite altimetry has been similarly observed at different times in the past 60 years and (2) this trend pattern is modulated through time, reversing sign in the past and suggesting a relationship to decadal-scale variability. Additionally, the agreement between the CSEOF and EOF sea level reconstructions provides confidence in the robustness of the reconstructions and further motivates and strengthens the decision to use of the CSEOF sea level reconstruction for the analysis shown in this paper.

3. PDO Contribution to Sea Level Trends

[6] While the satellite altimetry record alone is too short, it is possible to assess the contribution of decadal and multidecadal-scale signals to GMSL using sea level reconstructions. As

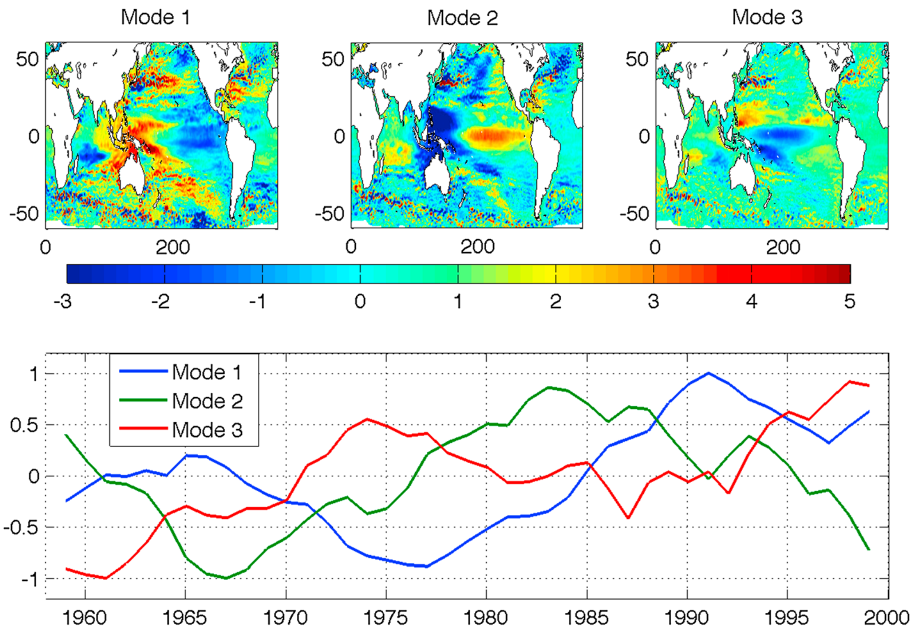

Figure 2. (top) Loading vectors and (bottom) Principal Component Time Series (PCTS) for the EOF decomposition of 20 year trends in the CSEOF reconstructed sea level data set. The first three modes are shown, explaining 84% of the variance in the 20 year trend patterns.

discussed in section 2, 20 year regional trend maps were computed using a least squares estimate of the trend from the sea level reconstruction data set created using cyclostationary empirical orthogonal function (CSEOF) bases [*Hamlington et al*., 2011b, 2012]. Empirical orthogonal functions (EOF) of the resulting 20 year trend maps from the sea level reconstruction were computed, and the contribution of the first three dominant (i.e., explaining the most variance) EOF modes to the 20 year trends in GMSL over the past 60 years was assessed by averaging the spatial component of the EOF (named the loading vector, following the terminology of *Hamlington et al*. [2011a]) and combining with the temporal component (the principal component time series, again following *Hamlington et al*. [2011a]). By averaging the loading vector globally and then combining this value with the principal component time series, a time series with units of mm/year was obtained that described the variation of the 20 year GMSL trends associated with each of the first three EOF modes. Prior to computing the EOFs, a trend of 1.54 mm/year was removed from the data (note that this has not been corrected for Global Isostatic Adjustment (GIA)). This trend is the average trend over the 60 year sea level reconstruction, and by removing it, the data are centered before computing the EOFs. Furthermore, since we are interested in the 20 year trends and their temporal variations, the 60 year trend will just appear as a mean in the results and can thus be removed without significantly impacting the analysis. Without knowledge of longer time scale (multidecadal and longer) variability that may be present, this removed trend is considered to be the secular trend in the reconstructed data set.

[7] To assess the error on the estimates of PDO trend contribution and acceleration, a randomization test on the EOF decomposition of the 20 year trend maps was performed. Before performing the EOF decomposition, two (~5%) of the 41 20 year trend maps were randomly removed and replaced by two other randomly selected trend maps. EOFs of the new set of trend maps were computed. This process was then completed 1000 times. The error estimates provided here represent ±2 standard deviations as computed from the results of this randomization procedure. It should be noted that there is also an error present in the reconstructed sea level data as a result of a combination of factors including tide gauge sampling and basis function truncation. Quantifying this error, particularly how it would contribute to the 20 year trends and accelerations, is a challenge and will not be dealt with explicitly here. It should be noted, however, that without

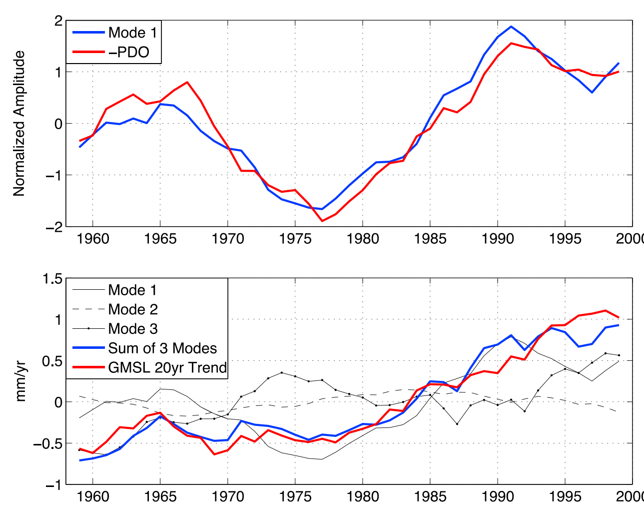

Figure 3. (top) Comparison between the mode 1 of the EOF decomposition of 20 year trends from the CSEOF reconstructed sea level data set and 20 year trends computed from the PDO index (shown with opposite sign for direct comparison). (bottom) Contribution of the first three EOF modes to the 20 year trends in GMSL. For comparison, the 20 year trends computed directly from the GMSL of reconstructed sea level data are shown with a mean value of 1.54 mm/year removed.

a complete treatment of the errors in the reconstructed data set, the included error estimates might be underestimated or even overestimated to some degree. A discussion of errors in sea level reconstructions can be found in *Church et al.* [2004] and *Hamlington et al.* [2011b, 2012], but the randomization tests described here should provide adequate error estimates for the statistics provided in this paper.

[8] The resulting first three modes from the EOF decomposition are shown in Figure 2. The variance explained by the trend patterns of the first three EOFs is 41%, 30%, and 13%, respectively, with a total of 84% variance in these first three modes. Having extracted the three dominant 20 year trend modes from the sea level reconstruction, the important question to be answered is whether any of these patterns (EOF modes) can be attributed to a specific climate process. To evaluate whether any of the modes are related to the PDO and by extension whether changes in the PDO affect the trends in global mean sea level, a 20 year running trend is calculated for the PDO index, which is derived from sea surface temperature patterns in the North Pacific [*Mantua et al.*, 1997; *Mantua and Hare*, 2002]. In Figure 3 (top), the resulting 20 year trends from the PDO index are compared to the first mode from the EOF decomposition. The negative of the PDO trends are shown, since the pattern of mode 1 in the North Pacific corresponds to the negative PDO phase in the PDO index. In addition to the agreement of the spatial patterns of mode 1 and the PDO in the North Pacific [see, for example, *Cummins et al.*, 2005], the strong relationship between the two is demonstrated by a correlation of 0.96 between the 20 year PDO trends and EOF mode 1 of the 20 year trends from the reconstructed sea level data set. In other words, the first EOF mode from the decomposition of the 20 year trends in the sea level reconstruction appears to be closely linked to the PDO, both in terms of its spatial pattern and temporal variability over the past 60 years. As an added check of the analysis, a test was conducted on the suitability of using a 20 year window as opposed to a shorter or longer window length. While primarily being motivated by the length of the current satellite altimeter record (~20 years) in the choice of window size, the results of the test show that 20 years is appropriate for extracting the PDO-related variability (see supporting information for further details).

[9] By multiplying the global average of each of the first three EOF loading vectors with the corresponding principal component time series, the contribution of each EOF mode to the 20 year trends in GMSL can be calculated. In Figure 3 (bottom), the contributions to the GMSL trends of the first three EOF modes are shown, in addition to the 20 year trends in GMSL from the reconstructed sea level data set. The average 20 year trend of 1.54 mm/year (described in detail above) was removed from GMSL in order to make a direct comparison to the EOF decomposition results, which were obtained after this same trend was removed from the data. Given the high correlation (0.96) shown in Figure 3 and the good agreement between the spatial patterns, the contribution of the PDO to 20 year trends in GMSL can be evaluated directly from mode 1. Over the last 60 years, mode 1, and by extension, the PDO has contributed significantly to the 20 year trends in GMSL during certain time periods. In the last 20 years, when the PDO went from generally positive to negative phase (as defined by *Mantua et al.* [1997] and *Mantua and Hare* [2002]), the PDO contributed 0.49 ± 0.25 mm/year to the trend in GMSL. From 1968 to 1987 when the PDO went from negative to positive phase, however, the PDO contribution lowered the trend in GMSL by 0.70 ± 0.26 mm/year. With an estimate of the actual contribution of the PDO to the trends in GMSL, the influence of the PDO can be removed to gain a better understanding of the underlying secular trend in GMSL that may be associated with anthropogenic climate change. For example, during the satellite altimeter time period, removing a trend of 0.49 mm/year would lead to an estimate of the trend in PDO-corrected GMSL closer to 2.7 mm/year as compared to the GIA-corrected estimate of 3.2 mm/year [e.g., *Mitchum et al.*, 2010] from the total GMSL. The acceleration in the 20 year trends in GMSL can also be calculated with and without the PDO. With the PDO contribution included, the acceleration of the 20 year trends in GMSL is found to be 0.04 mm/year^2 over the full record and an acceleration of approximately 0.08 mm/year^2 since the late 1970s. After removing the PDO contribution, the rate of increase of the 20 year trends, and hence, the acceleration in GMSL becomes 0.02 ± 0.005 mm/year^2 over the full record, and approximately 0.02 ± 0.0121 mm/year^2 since the late 1970s. While unlikely to have a significant impact on accelerations over a longer time period [*Church and White*, 2011; *Woodworth et al.*, 2011], the change in estimated acceleration has important implications for studying the secular trend in the satellite altimetry data as the record gets longer.

4. Discussion

[10] Several studies have looked at the relationship between the PDO and sea level in the Pacific [*Meyssignac et al.*, 2012; *Merrifield et al.*, 2012; *Zhang and Church*, 2012; *Cummins et al.*, 2005], but this paper is the first to attempt to quantify how much these signals contribute to trends on a global scale. Relying on the data and without making a priori assumptions about the climate signals driving sea level change, we have quantified the relationship between the PDO and GMSL trends at the 20 year time scale. Removing the influence of the PDO from GMSL lowers the trend over the past 20 years and reduces the estimated acceleration in GMSL over the past 60 years; suggesting the observed increase in the underlying secular trend in GMSL is more linear than previously thought. With the short satellite altimeter record alone, it is difficult to assess the contribution of signals like the PDO to decadal—and longer—trends. The short record length combined with the red spectrum of sea level makes it a challenge to separate secular trends observed by satellite altimetry from low-frequency decadal climate variability. Leveraging the tide gauge record to create the reconstructed sea level data sets provides the opportunity to extract these climate signals from the sea level record. While questions can be raised regarding how well a tide gauge-based data set captures GMSL variability, this study demonstrates the value of sea level reconstructions to provide a plausible estimate of the influence of decadal-scale climate signals on GMSL derived solely from the data, something that has not been done to date. As climate models mature, this first estimate of the PDO influence on GMSL will provide an important check and comparison for model-based estimates. Determining exactly how the PDO affects and contributes to changes in GMSL is the subject of future study, but it is likely to be a combination of thermosteric and mass changes, driven in some part by related precipitation pattern changes. This study focuses primarily on the contribution of the PDO to

GMSL, but the same results could be applied to the study of regional sea level trends. Combining the information from the loading vectors and principal component time series seen in Figure 2 provides an estimate of the regional contribution of the PDO to sea level trends. As seen by the loading vector of mode 1, this has important implications for the study of sea level rise of both the west coast of the United States and throughout the tropical Pacific.

[11] While identifying the climate signals and processes that contribute to observed regional and global sea level trends can provide insight into past and future sea level change, it is important to keep the magnitude of their contribution in context. The PDO contribution to the 20 year trends discussed here is a significant component of the 20 year trends in GMSL but does not reverse the recent positive trend observed during the satellite altimeter time period. The PDO causes acceleration and deceleration in GMSL on decadal time scales, and also appears to have a significant impact on the patterns of regional sea level change. Nevertheless, the underlying secular trend in sea level is larger than the PDO contribution, and over the last 60 years, the 20 year trends in GMSL have consistently been positive. With the results presented here, however, we can develop a better understanding of this underlying trend, particularly during the satellite altimeter era, and provide insight into how sea level may change in the coming decades.

[12] **Acknowledgments.** The Editor thanks two anonymous reviewers for their assistance in evaluating this manuscript.

References

Beckley, B. D., F. G. Lemoine, S. B. Lutchke, R. D. Ray, and N. P. Zelensky (2007), A reassessment of global and regional mean sea level trends from TOPEX and Jason-1 altimetry based on revised reference frame and orbits, *Geophys. Res. Lett.*, *34*, L14608, doi:10.1029/2007GL030002.

Bromirski, P. D., A. J. Miller, R. E. Flick, and G. Auad (2011), Dynamical suppression of sea level rise along the Pacific Coast of North America: Indications for imminent acceleration, *J. Geophys. Res.*, *116*, C07005, doi:10.1029/2010JC006759.

Chambers, D. P., C. A. Melhaff, T. J. Urban, D. Fuji, and R. S. Nerem (2002), Low-frequency variations in global mean sea level: 1950–2000, *J. Geophys. Res.*, *107*(C4), 3026, doi:10.1029/2001JC001089.

Chambers, D., M. Merrifield, and R. S. Nerem (2012), Is there a 60-year oscillation in global mean sea level?, *Geophys. Res. Lett.*, *39*, L18607, doi:10.1029/2012GL052885.

Church, J. A., and N. J. White (2006), A 20th century acceleration in global sea level rise, *Geophys. Res. Lett.*, *36*, L01602, doi:10.1029/2005GL024826.

Church, J. A., and N. J. White (2011), Sea-level rise from the late 19th to the early 21st century, *Surv. Geophys.*, *32–4*, 585–602.

Church, J. A., N. J. White, R. Coleman, K. Lambeck, and J. X. Mitrovica (2004), Estimates of the regional distribution of sea level rise over the 1950–2000 period, *J. Climate*, *17*, 2609–2625.

Cummins, P. F., G. S. E. Lagerloef, and G. Mitchum (2005), A regional index of northeast Pacific variability based on satellite altimeter data, *Geophys. Res. Lett.*, *32*, L17607, doi:10.1029/2005GL023642.

Feng, M., Y. Li, and G. Meyers (2004), Multidecadal variations of Fremantle sea level: Footprint of climate variability in the tropical Pacific, *Geophys. Res. Lett.*, *31*, L16302, doi:10.1029/2004GL019947.

Hamlington, B. D., R. R. Leben, R. S. Nerem, and K.-Y. Kim (2011a), The effect of signal-to-noise ratio on the study of sea level trends, *J. Climate*, *24*, 1396–1408.

Hamlington, B. D., R. R. Leben, R. S. Nerem, W. Han, and K.-Y. Kim (2011b), Reconstruction sea level using cyclostationary empirical orthogonal functions, *J. Geophys. Res.*, *116*, C12015, doi:10.1029/2011JC007529.

Hamlington, B. D., R. R. Leben, and K.-Y. Kim (2012), Improving sea level reconstructions using non-sea level measurements, *J. Geophys. Res.*, *117*, C10025, doi:10.1029/2012JC008277.

Hughes, C. W., and S. D. P. Williams (2010), The color of sea level: Importance of spatial variations in spectral shape for assessing the significance of trends, *J. Geophys. Res.*, *115*, C10048, doi:10.1029/2010JC006102.

Kolker, A. S., and S. Hameed (2007), Meteorologically driven trends in sea level rise, *Geophys. Res. Lett.*, *34*, L23616, doi:10.1029/2007GL031814.

Mantua, N. J., and S. R. Hare (2002), The Pacific Decadal Oscillation, *J. Oceanogr.*, *58*, 35–44.

Mantua, N. J., S. R. Hare, Y. Zhang, J. M. Wallace, and R. C. Francis (1997), A Pacific interdecadal climate oscillation with impacts on salmon production, *Bull. Am. Meteorol. Soc.*, *78*, 1069–1079.

Merrifield, M. A., P. 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.

Meyssignac, B., D. Salas y Melia, M. Becker, W. Llovel, and A. Cazenave (2012), Tropical pacific spatial trend patterns in observed sea level: Internal variability and/or anthropogenic signature?, *Clim. Past*, *8*, 787–802.

Mitchum, G. T., R. S. Nerem, M. A. Merrifield, and W. R. Gehrels (2010), Modern sea-level-change estimates, in *Understanding Sea-level Rise and Variability*, edited by J. A. Church et al., pp. 122–142, Wiley, Chichester, U. K.

Ray, R. D., and B. C. Douglas (2011), Experiments in reconstructing twentieth-century sea levels, *Prog. Oceanogr.*, *91*(4), 496–515.

Sturges, W. (1987), Large-scale coherence of sea level at very low frequencies, *J. Phys. Oceanogr.*, *17*, 2084–2094.

Sturges, W., and B. C. Douglas (2011), Wind effects on estimates of sea level rise, *J. Geophys. Res.*, *116*, C06008, doi:10.1029/2010JC006492.

Woodworth, P. L., M. Menendez, and W. R. Gehrels (2011), Evidence for century-timescale acceleration in mean sea levels and for recent changes in extreme sea level, *Surv. Geophys.*, *32*, 603–618.

Zhang, X., and J. A. Church (2012), Sea level trends, interannual and decadal variability in the Pacific Ocean, *Geophys. Res. Lett.*, *39*, L21701, doi:10.1029/2012GL053240.