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Key Points:

- Tide gauge sea level and the SOI highlight a prolonged equatorial trade wind relaxation after the 1970s
- Interdecadal trade wind variations were of weaker amplitude earlier in the 20th century
- In contrast, interdecadal climate variations in the midlatitude North Pacific are more consistent in amplitude over the century

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Interdecadal Sea Level Variations in the Pacific: Distinctions Between the Tropics and Extratropics

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Abstract Long tide gauge records from Fremantle and San Diego are used to examine interdecadal sea level fluctuations and their relationship to Pacific climate variability. The sea level difference between the tide gauges and the Southern Oscillation Index (SOI) provide a consistent depiction of trade wind variations along the equator over the past century. The sea level difference and SOI exhibit weak interdecadal variability prior to the late 1970s, followed by an extended 40-year period of high levels at San Diego and low at Fremantle, and low SOI levels signifying weakened equatorial trade winds. By referencing the tide gauge records to global mean sea level, we infer that Pacific trade winds exhibited weak departures from mean conditions on interdecadal time scales prior to the late 1970s and that a prolonged El Niño-like lull dominated the tropics at the end of the century. A recent shift suggests that the trades are reverting back to the El Niño-like state. These tropical interdecadal variations have counterparts in the extratropical North Pacific after the 1970s, as captured by the Pacific Decadal Oscillation, but the early twentieth century quiescent phase in the tropical Pacific is not reflected in the extratropics, which exhibits more energetic oscillatory behavior over the same time span.

Plain Language Summary Long tide gauge records from Fremantle and San Diego provide a measure of interdecadal variations in trade wind forcing that impacts both locations. The records indicate substantial interdecadal sea level variation after the 1970s caused by a prolonged relaxation of the Pacific trade winds. Sea level and trade wind variations of this sort were considerably weaker earlier in the century. Measures of interdecadal climate variations in the extratropical North Pacific covaried with the trade winds after the 1970s, but the correspondence breaks down early in the century when tropical winds were near normal and the extratropics exhibited energetic interdecadal variability. The findings support previous studies that emphasize that the tropical and extratropical Pacific are not always in sync at these time scales, which has ramifications for understanding the underlying drivers of these variations as well as for decadal climate prediction.

1. Introduction

Climate variations on interdecadal time scales occur prominently throughout the Pacific Ocean basin, particularly those associated with the Pacific Decadal Oscillation (PDO; Mantua et al., 1997). Sea surface temperature (SST) variations related to the PDO peak in the Aleutian low region, with a prominent anticorrelated signal in the eastern equatorial Pacific cold tongue region. This meridional dipole pattern suggests a dynamical linkage between the tropical and extratropical Pacific, in the manner of the higher-frequency El Niño Southern Oscillation (ENSO; Y. Zhang et al., 1997). In this study, we consider how consistent this linkage is over interdecadal time scales.

Y. Zhang et al. (1997) noted that the *ENSO-like* variability at interdecadal frequencies is symmetric about the equator, which also has been referred to as the Interdecadal Pacific Oscillation (IPO) pattern (Power et al., 1999). Newman et al. (2016) characterized the symmetric IPO as a reddened ENSO component driven by both interannual and decadal ENSO variability, whereas the asymmetric PDO includes internal North Pacific processes, primarily due to atmospheric noise at high latitudes.

A notable feature of Pacific interdecadal variability is the prominence of fluctuations on 50- to 70-year time scales. These interdecadal oscillations, evident in both the PDO and IPO, have been related to climatic regime shifts (Minobe, 1997). Notably, the regime shift in the 1970s marked a transition (among other indicators) of warming tropical Pacific SSTs and weakening trade winds (Graham, 1994; Nitta & Yamda, 1989; Trenberth, 1990; Trenberth & Hurrell, 2014). Earlier North Pacific regime shifts in the instrumental record have been identified in the 1890s, 1920s, and 1940s (Minobe, 1997). Here we emphasize that the oscillatory behavior and regime shifts identified in the extratropics may not necessarily involve the tropics, and as such the 1970s shift in the tropics stands out as a more singular event over the century.

To examine interdecadal variations of Pacific climate going back to the early part of the twentieth century, we take advantage of the distinctive sea level anomaly patterns associated with low-frequency trade winds fluctuations, which lead to sea level anomalies along the equatorial and coastal wave guides at similar time scales (Clarke & Lebedev, 1999; Feng et al., 2004; Merrifield, 2011; Thompson et al., 2014). For example, beginning with the 1970s regime shift, weakening trade winds led to rising sea levels to the east and falling sea levels to the west in the zonal dipole region, followed by a trend reversal in the early 1990s (Chen & Wallace, 2015; Feng et al., 2011; Merrifield et al., 2012). Interdecadal sea level variations in the western tropical Pacific (Feng et al., 2011; Merrifield et al., 2012) and along the Pacific coast of North America (Bromirski et al., 2011; Thompson et al., 2014) have been linked to the PDO, and X. Zhang and Church (2012) identified a PDO-related sea level pattern similar to the SST-based PDO mode, with an implied connection between the tropics and extratropics.

Although Pacific sea level variations have been related to PDO variability, it has been established that different forcing mechanisms, independent as well as coupled, drive changes in the PDO pattern (Newman et al., 2016), which raises questions about the interpretation of extratropical/tropical coupling associated with the PDO. Another concern for assessing interdecadal climate variations in the Pacific is the poor sampling of SST and other fields early in the twentieth century (Deser et al., 2010). Sea level represents one of the few in situ data sets available to infer basinwide patterns on these time scales.

To explore these issues, we use two representative tide gauges with long records, San Diego and Fremantle, to document interdecadal sea level variations driven in the tropics. The sea level time series provide a consistent view of tropical wind forcing on interdecadal time scales when compared to the Southern Oscillation Index (SOI) and provide corroborating evidence of conditions in the early twentieth century. Our analysis extends the studies of Clarke & Lebedev (1996, 1999) by taking into account 20 more years of data and by taking advantage of comparisons with global mean sea level (GMSL) estimates to assess how the regional sea level, and by inference wind anomalies, departs from a background mean state. This leveling of the records emphasizes the prolonged trade wind pause that dominated the post-1970s climate shift in the tropics, and points to a clear distinction with PDO-related variability on these time scales.

2. Data Sets

We focus on tide gauges positioned on either side of the dipole sea level response to equatorial trade wind forcing as described by Clarke and Lebedev (1996). To the west of the trade wind forcing region, the longest tide gauge record is from Fremantle, Australia (Figure 1a). Previous studies have documented the utility of the Fremantle record for diagnosing Pacific trade wind variability associated with ENSO and longer-time scale signals (Chen & Wallace, 2015; Feng et al., 2004, 2010; Thompson et al., 2014). The Fremantle time series is constructed using monthly sea level time series from the Permanent Service for Mean Sea Level (PSMSL) from 1897 to 2016. To the east, a number of tide gauges date back to the late 1800s (San Francisco) and early 1900s (Seattle and San Diego). We use the San Diego tide gauge based on the results of Thompson et al. (2014), who showed that San Diego exhibits weaker locally wind-forced sea level variability than stations to the north and hence is more representative of equatorial trade wind forcing. The PSMSL record for San Diego spans 1906 through 2016.

Similar to Feng et al. (2004), we compare the SOI, a well-established proxy for trade wind variability, to the sea level time series. We select the SOI over other ENSO indices derived from SST because the SOI represents a relatively self-consistent, in situ measurement that dates back as far as the tide gauge records. The SOI index from 1951 to 2016 was obtained from the National Oceanic and Atmospheric Administration National Center for Environmental Information (NCEI). To extend the record back to 1882, we used atmospheric pressure records obtained from the Australia Bureau of Meteorology. A small bias offset (0.16) was added to the pre-1951 SOI record for consistency with the NCEI record. The Equatorial Southern Oscillation Index was obtained from Lucia Bunge's website at Florida State University. To examine climate variability representative of the North Pacific, we use the PDO and IPO SST-based indices from the NCEI. We also compare the tide gauge results to SST patterns obtained from the gridded National Oceanic and Atmospheric Administration Extended

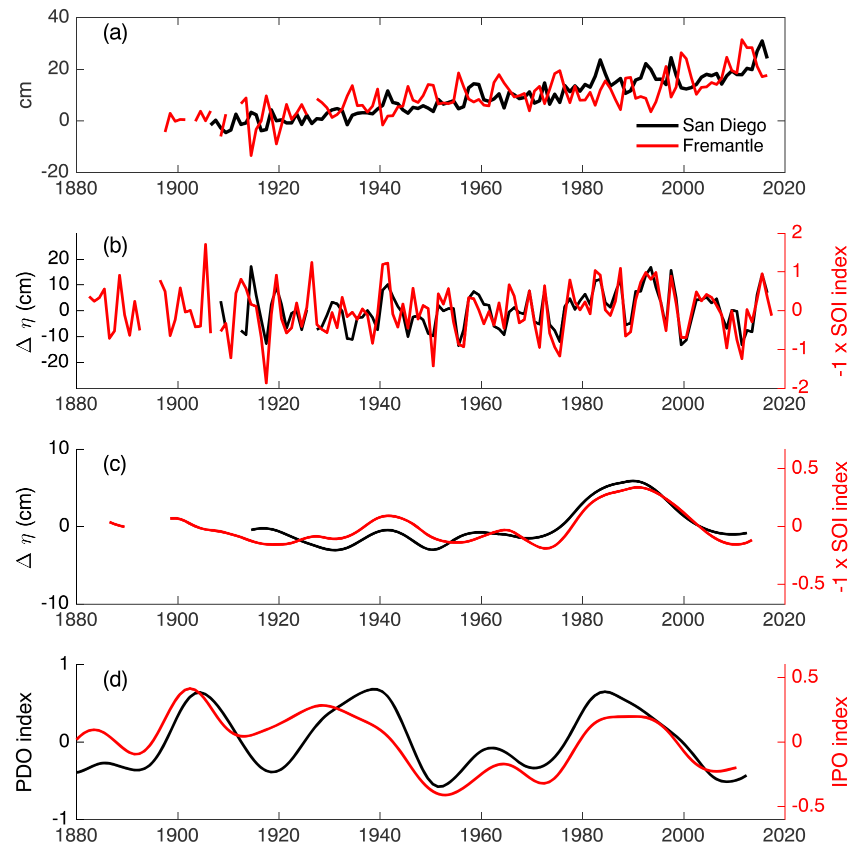

Figure 1. (a) Annual average sea level at Fremantle and San Diego. (b) $\Delta\eta$ = San Diego − Fremantle sea level versus the SOI multiplied by −1. The squared correlation is 0.69. (c) Low-pass-filtered versions of the time series in (b). (d) Low-pass-filtered time series of the PDO and IPO indices. SOI = Southern Oscillation Index; PDO = Pacific Decadal Oscillation; IPO = Interdecadal Pacific Oscillation.

Reconstructed Sea Surface Temperature data set (Smith et al., 2008; Xue et al., 2003). Wind stress fields (1948–2016) were obtained from the National Centers for Environmental Prediction (NCEP)/National Center for Atmospheric Research Reanalysis 1 (NCEP1) project (Kalnay et al., 1996). Interdecadal variations in all variables are obtained by convolving the time series with a 21-year Hanning filter.

3. Results

The Fremantle and San Diego sea level records contain a GMSL component, the dipole fluctuations associated with trade wind forcing in the equatorial Pacific, a response to forcing along the continental margins connecting each site to the equatorial region, and vertical land motion (VLM) at the tide gauges. The trade wind-forced response is featured by taking the difference of the annually averaged San Diego and Fremantle tide gauge records, $\Delta\eta$, which minimizes the common GMSL signal (Figure 1b) and emphasizes the zonal dipole. The relationship of $\Delta\eta$ to trade wind forcing has been considered by Li and Clarke (1994) and others and is illustrated by the significant correlation ($r = -0.83$) between $\Delta\eta$ and the SOI. The sea level difference captures the well-known ENSO signal with anomalously high sea level at San Diego and low at Fremantle when the trade winds weaken (negative SOI) and vice versa during periods of strong trades (positive SOI).

The average of Fremantle and San Diego sea levels, $\bar{\eta}$, tends to minimize the anticorrelated dipole signal. The linear trend of $\bar{\eta}$ for the 1905–2010 period, 1.81 mm/year, is slightly higher than the trend of GMSL, 1.72 mm/year, obtained from the estimate of Church and White (2011). Other GMSL estimates, summarized for example in Natarov et al. (2017), may yield larger trend differences with $\bar{\eta}$. Featherstone et al. (2015) reported a nonlinear VLM trend in the Fremantle sea level time series. We note that the difference of tide gauge and satellite altimeter data at Fremantle (http://ccar.colorado.edu/altimetry/) yields a residual with a linear trend, implying steady VLM, but with no indication of a significant nonlinear trend. We attribute the nonlinear trend

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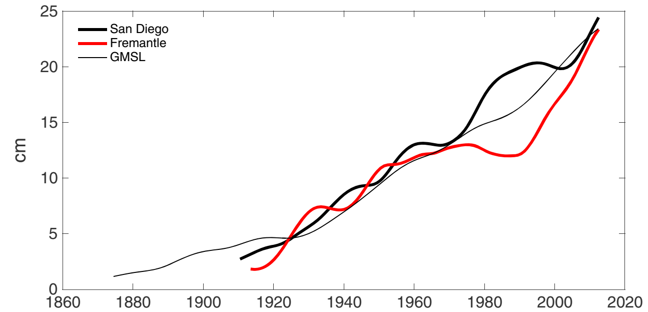

Figure 2. Low-pass-filtered San Diego and Fremantle sea levels and global mean sea level (GMSL) from Church and White (2011), extended to 2016 using GMSL estimated from Aviso sea surface height. The records are offset to have similar mean values during 1910–1940.

in relative sea level at Fremantle to absolute sea level changes and not local VLM. Given the correspondence between $\Delta\eta$ and the SOI, and the lack of obvious VLM contributions that might obscure the ocean signals, we proceed under the assumption that the two sea level records provide an adequate representation of wind forcing in the equatorial Pacific.

The main focus of this study concerns the interdecadal variability of Pacific trade wind forcing at the equator, as captured by $\Delta\eta$. Low-pass-filtered $\Delta\eta$ exhibits weak departures from steady conditions prior to the late 1970s (Figure 1c). Subsequently, $\Delta\eta$ increases and peaks near 1990 and returns back to the pre-1970s mean after 2000. A similar interdecadal variation occurs in the SOI index (Figure 1c), which corresponds to a trade wind weakening in the late 1970s, reaching a minimum near 1990, and rebounding since then. Together the variations characterize a prolonged period of El Niño-like conditions on interdecadal timescales, which began with the regime shift of the late 1970s. Clarke and Lebedev (1996) noted the trade wind weakening in the SOI index following the 1970s regime shift, and these more recent data emphasize the relaxation back to the mean. The Equatorial Southern Oscillation Index of Bunge and Clarke (2009) (not shown) exhibits a similar pattern as the SOI.

The sea level and SOI signals covary, but is sea level dynamically consistent with the implied wind forcing? The momentum balance relating the sea level difference and the zonal wind stress (τ^x) is

$$\Delta\eta = \frac{1}{\rho g H}\int_0^L \tau^x \mathrm{d}x, \tag{1}$$

where g is the acceleration due to gravity, ρ is water density, x is the distance along the equator, $L = 1.62\times10^7$ m is the estimated width of the equatorial Pacific, and H is a measure of the thermocline depth (Clarke & Lebedev, 1999; Li & Clarke, 1994). Following Bunge and Clarke (2009), we estimate the average zonal wind stress from the SOI. We use NCEP reanalysis zonal wind stress, annually averaged and spatially averaged between 1°N and 1°S and between 133°E and 280°E, and regress the averaged wind stress (from 1975 to 2016) on to the SOI, yielding a regression coefficient of $b = -6.4 \times 10^{-3}$ Pa. We then estimate H from

$$\mathrm{SOI} = \frac{\rho g H}{bL}\Delta\eta. \tag{2}$$

A least squares fit yields $H = 63 \pm 17$ m (95% confidence interval, assuming an independent point every 3 years), which is comparable to, although shallower than, recent estimates by Yang and Wang (2009) of the mean thermocline depth along the equatorial Pacific (~100 m, their Figure 1). A similar estimate of H is obtained using low-pass-filtered time series in (2). The sea level difference appears to scale reasonably well with equatorial wind forcing.

We next compare the interdecadal wind fluctuations in the tropical Pacific, inferred from the SOI and $\Delta\eta$, with indicators of interdecadal climate variations in the North Pacific in the form of the PDO index and the IPO (Figure 1d). Interdecadal fluctuations in the PDO and the IPO exhibit 50- to 70-year variations that have been noted in various studies (Minobe, 1997). $\Delta\eta$ and the SOI match the PDO and IPO after 1980 but do not exhibit similar amplitude fluctuations prior to this period. Thompson et al. (2014) noted the changing relationship between the SOI and PDO based on low-pass filtered time series with a higher-frequency cutoff than considered here. The difference between the SOI and PDO/IPO is particularly pronounced at interdecadal time scales. Tropical wind forcing in the Pacific appears to co-oscillate with proxies of extratropical climate variations in the North Pacific after the late 1970s regime shift but not during the earlier portion of the twentieth century.

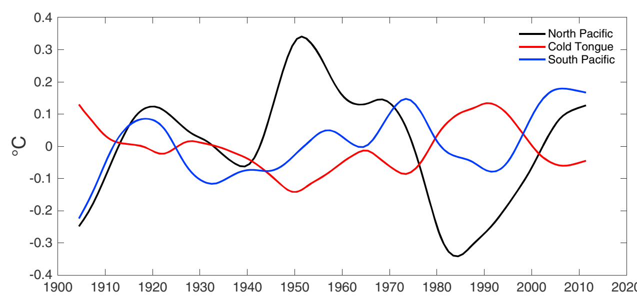

Figure 3. Low-pass-filtered time series of sea surface temperature averaged in the three tripole regions identified by Henley et al. (2015). The Tripole regions are identified in Figure 4).

The weak interdecadal variations in $\Delta\eta$ and the SOI prior to the 1970s suggest weak departures from mean equatorial Pacific wind forcing during

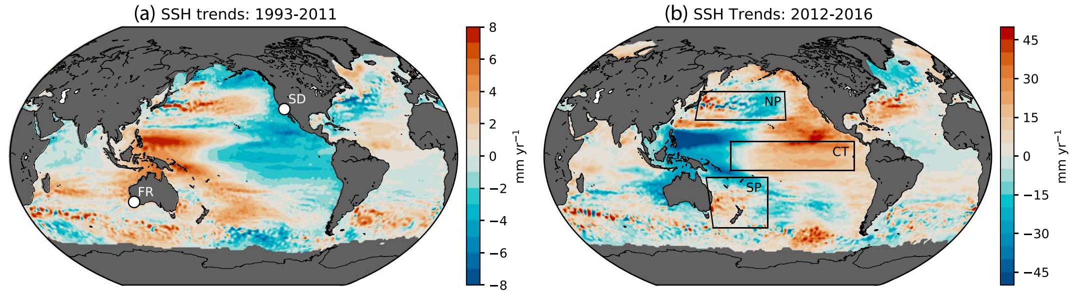

Figure 4. Sea surface height trends from (a) 1993–2011 and (b) 2012–2016 based on Aviso sea surface height gridded data. The locations of the San Diego (SD) and Fremantle (FR) tide gauges and tripole regions used in Figure 3 are identified.

this period. To further illustrate this point, we plot low-pass-filtered San Diego and Fremantle sea level versus GMSL (Figure 2). The absolute means of each of these records are not known; however, we can level the records approximately by assuming that the two sea level records tracked GMSL prior to the 1970s regime shift, as the equatorial wind fluctuations that would cause significant departures from GMSL were relatively weak as suggested by the SOI. The dominant interdecadal variability in the combined record occurs after the regime shift, at which point sea level rises and falls at San Diego, with a near-mirror image at Fremantle, due to the decrease in the trade wind forcing in the equatorial Pacific. Having independent atmospheric and oceanic indicators of the interdecadal trade wind variability increases our confidence in the result. Moreover, the leveled record also emphasizes that the last third of the twentieth century can be characterized as a prolonged trade wind lull in the tropics with associated El Niño-like background conditions.

Is the difference in interdecadal variability in the tropics and extratropics evident in SST? We explore this using SST in the tripole regions identified by Henley et al. (2015) (Figure 3). A large variation in SST occurs prior to the 1970s in the North Pacific (25°N–45°N, 140°E–145°W), the main center of action of the PDO, which is absent in the tropical Cold Tongue (10°S–10°N, 170°E–90°W) and South Pacific (50°S–15°S, 150°E–160°W). The North Pacific SST tracks the interdecadal fluctuations in the PDO (Figure 1d). The Cold Tongue temperatures exhibit a prolonged El Niño-like warm phase after the 1970s, similar to that seen in $\Delta\eta$ and the SOI. The warm SSTs during this period are not as pronounced from earlier interdecadal anomalies in SST, such as the slight cooling in the 1950s. We speculate that sparse data coverage of SST in the tropics prior to the 1970s makes the El Niño-like warm phase less pronounced in the cold tongue SSTs than it is in the long tide gauge and atmospheric records examined here.

The tide gauge records suggest a return to the mean in the early 21st century (Figure 2); however, Hamlington et al. (2016) describe a recent shift in the PDO index from a cold to a warm state. This is illustrated by comparing satellite sea surface height trends from 1993 to 2011 (Figure 4a), when trade winds were increasing toward a more normal state, and from 2012 to 2016 which depicts the flip in the dipole pattern (Figure 4b). Based on the San Diego and Fremantle comparisons, the recent change, at least for the tropics, represents a return to weak trade wind conditions following a brief period of normal, or perhaps slightly above normal, conditions when the respective sea level records reverted back to the GMSL (Figure 2). This implies that the tropics may be experiencing consecutive El Niño-like anomalies on interdecadal time scales rather than an oscillation from warm to cold to warm states.

4. Discussion

Sea level provides unique insights into wind patterns on interdecadal and shorter time scales as departures of sea level from a global average generally require sustained wind forcing to maintain the anomaly. Likewise, regional sea level trends that differ from the GMSL trend typically reflect trending wind patterns (Merrifield & Maltrud, 2011). We exploit this dynamical connection between sea level and winds to assess wind-forced sea level anomalies captured in the long San Diego and Fremantle tide gauge records. Although positioned nearly at antipodes, the two sea level stations are intrinsically linked by Pacific trade wind forcing which, because of a long, coherent fetch along the equatorial Pacific waveguide, dominates sea level anomalies along the downstream boundaries of the Indo-Pacific. Dipole or seasaw variations on either side of the main forcing region persist as long as the anomalous wind forcing is sustained. The San Diego-Fremantle sea level difference thus provides a direct measure of tropical trade wind strength, measured in a consistent fashion, dating back to the early 1900s.

At interdecadal time scales, the tropics does not necessarily covary with the extratropics, which may have implications for decadal forecasts. The lack of a consistently synced interdecadal response between the tropics and extratropics supports the notion that climate variations in the Pacific driven by trade winds can be a distinct phenomenon from the variations centered in the Aleutian Low region associated with the PDO. Significant interdecadal variations in the Aleutian Low region may occur without an obvious teleconnection to the tropics. We note that Deser et al. (2004) found a stronger connection between interdecadal climate variations in the tropics and extratropics than described here. Many of the tropical indicators that they describe, for example, SST anomalies in the tropical Indian Ocean and southeast Pacific Ocean and variations in the South Pacific convergence zone, may not necessarily reflect changes in trade wind strength. We emphasize that our conclusions are based solely on changes in equatorial trade winds and the resulting sea level response.

Indicators that measure trade wind strength, such as the SOI, are more useful for assessing tropical and connected coastal sea level anomalies at interdecadal time scales than the PDO index. In a related study, Chambers et al. (2012) found a lack of a 60-year PDO-like oscillation in North American tide gauge data, including San Diego, even though the gauges are adjacent to the PDO center of action in the Aleutian Low region. This is consistent with our findings, as well as those of Thompson et al. (2014), that the North American records reflect tropical wind forcing more than local forcing and the tropical forcing does not feature a 60-year oscillation. Along that same coastline, Bromirski et al. (2011) describe dynamical suppression of sea level trends associated with PDO regime shifts. We note, however, that the PDO regime shifts were not a feature of the Pacific coast tide gauge records earlier in the century. Thus, the long sea level records discussed here reinforce conclusions reached from the SOI that the prolonged trade wind lull in the tropics beginning around 1970 represents a departure from the character of tropical variability earlier in the century, not an ongoing multidecadal oscillation. By extension, coupling of tropical and extratropical Pacific climate may be a feature of recent decades only and not necessarily a stationary relationship.

Although the San Diego and Fremantle tide gauge time series are among the longest sea level records in the Pacific, or of any in situ ocean variable for that matter, they provide only a snapshot of interdecadal variability. Longer time series are needed to evaluate the drivers of the trade wind lull, as well as to assess the linkages, or lack thereof, of multidecadal climate fluctuations in the tropics and extratropics.

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References

Bromirski, P. D., Miller, A. J., Flick, R. E., & Auad, G. (2011). Dynamical suppression of sea level along the Pacific coast of North America: Indications for imminent acceleration. *Journal of Geophysical Research*, *116*, C07005. https://doi.org/10.1029/2010JC006759

Bunge, L., & Clarke, A. J. (2009). A verified estimation of the El Niño index Niño-3.4 since 1877. *Journal of Climate*, *22*, 3979–3992.

Chambers, D. P., Merrifield, M. A., & Nerem, R. S. (2012). Is there a 60-year oscillation in global mean sea level? *Geophysical Research Letters*, *39*, L18607. https://doi.org/10.1029/2012GL052885

Chen, X., & Wallace, J. M. (2015). ENSO-like variability: 1900–2013. *Journal of Climate*, *28*, 9623–9641.

Church, J. A., & White, N. J. (2011). Sea-level rise from the late 19th to the early 21st century. *Surveys in Geophysics*, *32*, 585–602.

Clarke, A. J., & Lebedev, A. (1996). Long-term changes in the equatorial Pacific trade winds. *Journal of Climate*, *9*, 1020–1029.

Clarke, A. J., & Lebedev, A. (1999). Remotely driven decadal and longer changes in the coastal Pacific waters of the Americas. *Journal of Physical Oceanography*, *29*, 828–835.

Deser, C., Alexander, M. A., Xie, S.-P., & Phillips, A. S. (2010). Sea surface temperature variability: Patterns and mechanisms. *Annual Review of Marine Science*, *2*, 115–143.

Deser, C., Philips, A. S., & Hurrell, J. W. (2004). Pacific interdecadal climate variability: Linkages between the tropics and the North Pacific during boreal winter since 1900. *Journal of Climate*, *17*, 3109–3124.

Featherstone, W. E., Penna, N. T., Filmer, M. S., & Williams, S. D. P. (2015). Nonlinear subsidence at Fremantle, a long-recording tide gauge in the Southern Hemisphere. *Journal of Geophysical Research: Oceans*, *120*, 7004–7014. https://doi.org/10.1002/2015JC011295

Feng, M., Boning, C., Biastoch, A., Behrens, E., Weller, E., & Masumoto, Y. (2011). The reversal of the multi-decadal trends of the equatorial Pacific easterly winds, and the Indonesian throughflow and Leeuwin current transports. *Geophysical Research Letters*, *38*, L11604. https://doi.org/10.1029/2011GL047291

Feng, M., Li, Y., & Meyers, G. (2004). Multidecadal variations of Fremantle sea level: Footprint of climate variability in the tropical Pacific. *Geophysical Research Letters*, *31*, L16302. https://doi.org/10.1029/2004GL019947

Feng, M., McPhaden, M. J., & Lee, T. (2010). Decadal variability of the Pacific subtropical cells and their influence on the southeast Indian Ocean. *Geophysical Research Letters*, *37*, L09606. https://doi.org/10.1029/2010GL042796

Graham, N. E. (1994). Decadal-scale climate variability in the 1970s and 1980s: Observations and model results. *Climate Dynamics*, *10*, 135–162.

Hamlington, B. D., Cheon, S. H., Thompson, P. R., Merrifield, M. A., Nerem, R. S., Leben, R. R., & Kim, K.-Y. (2016). An ongoing shift in Pacific Ocean sea level. *Journal of Geophysical Research: Oceans*, *121*, 5084–5097. https://doi.org/10.1002/2016JC011815

Henley, B. J., Gergis, J., Karoly, D. J., Power, S., Kennedy, J., & Folland, C. K. (2015). A tripole index for the Interdecadal Pacific Oscillation. *Climate Dynamics*, *45*, 3007. https://doi.org/10.1007s00382-015-2525-1

Kalnay, E., Kanamitsu, M., Kistler, R., Collins, W., Deaven, D., Gandin, L., et al. (1996). The NCEP/NCAR 40-year reanalysis project. *Bulletin of the American Meteorological Society*, *77*(3), 437–471. https://doi.org/10.1007s00382-015-2525-1

Li, B., & Clarke, A. J. (1994). An examination of some ENSO mechanisms using interannual sea level at the eastern and western equatorial boundaries and the zonally averaged equatorial wind. *Journal of Physical Oceanography*, *24*, 681–690.

Mantua, N. J., Hare, S. R., Zhang, Y., Wallace, J. M., & Francis, R. C. (1997). A Pacific interdecadal climate oscillation with impacts on salmon production. *Bulletin of the American Meteorological Society*, *78*, 1069–1079.

Merrifield, M. A. (2011). A shift in western tropical Pacific sea level trends during the 1990s. *Journal of Climate*, *24*, 4126–4138. https://doi.org/10.1175/2011JCLI3932.1

Merrifield, M. A., & Maltrud, M. E. (2011). Regional sea-level trends due to a Pacific trade wind intensification. *Geophysical Research Letters*, *38*, L21605. https://doi.org/10.1029/2011GL049576

Merrifield, M. A., Thompson, P. R., & Lander, M. (2012). Multidecadal sea level anomalies and trends in the western tropical Pacific. *Geophysical Research Letters*, *39*, L13602. https://doi.org/10.1029/2012GL052032

Minobe, S. (1997). A 50–70 year climatic oscillation over the North Pacific and North America. *Geophysical Research Letters*, *24*(6), 683–686.

Natarov, S. I., Merrifield, M. A., Becker, J. M., & Thompson, P. R. (2017). Regional influences on reconstructed global mean sea level. *Geophysical Research Letters*, *44*, 3274–3282. https://doi.org/10.1002/2016GL071523

Newman, M., Alexander, M. A., Ault, T. R., Cobb, K. M., Deser, C., Di Lorenzo, E., et al. (2016). The Pacific Decadal Oscillation, revisted. *Journal of Climate*, *29*, 4399–4427. https://doi.org/10.1175/JCLI-D-15-0508.1

Nitta, T., & Yamda, S. (1989). Recent warming of tropical sea surface temperature and its relationship to the Northern Hemisphere circulation. *Journal of the Meteorological Society of Japan*, *67*, 375–383.

Power, S., Casey, T., Folland, C., Colman, A., & Mehta, V. (1999). Inter-decadal modulation of the impact of ENSO on Australia. *Climate Dynamics*, *15*, 319–324.

Smith, T. M., Reynolds, R. W., Peterson, T. C., & Lawrimore, J. (2008). Improvements to NOAA's historical merged land-ocean surface temperature analysis (1880–2006). *Journal of Climate*, *21*, 2283–2296.

Thompson, P. R., Merrifield, M. A., Wells, J. R., & Chang, C. M. (2014). Wind-driven coastal sea level variability in the northeast Pacific. *Journal of Climate*, *27*, 4733–4751.

Trenberth, K. E. (1990). Recent observed interdecadal climate changes in the Northern Hemisphere. *Bulletin of the American Meteorological Society*, *71*, 988–993.

Trenberth, K. E., & Hurrell, J. W. (2014). Decadal atmosphere-ocean variations in the Pacific. *Climate Dynamics*, *9*, 303–319.

Xue, Y., Smith, T. M., & Reynolds, R. W. (2003). Interdecadal changes of 30-yr SST normals during 1871–2000. *Journal of Climate*, *16*, 1601–1612.

Yang, H., & Wang, F. (2009). Revisiting the thermocline depth in the equatorial Pacific. *Journal of Climate*, *22*, 3856–3863.

Zhang, X., & Church, J. A. (2012). Sea level trends, interannual and decadal variability in the Pacific Ocean. *Geophysical Research Letters*, *39*, L21701. https://doi.org/10.1029/2012GL053240

Zhang, Y., Wallace, J. M., & Battisti, D. S. (1997). ENSO-like interdecadal variability: 1900–93. *Journal of Climate*, *10*, 1004–1020.