Decadal Sea Level Variability in the Pacific Ocean: Origins and Climate Mode Contributions

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ABSTRACT

Sea level changes within wide temporal–spatial scales have great influence on oceanic and atmospheric circulations. Efforts have been made to identify long-term sea level trend and regional sea level variations on different time scales. A nonuniform sea level rise in the tropical Pacific and the strengthening of the easterly trade winds from 1993 to 2012 have been widely reported. It is well documented that sea level in the tropical Pacific is associated with the typical climate modes. However, sea level change on interannual and decadal time scales still requires more research. In this study, the Pacific sea level anomaly (SLA) was decomposed into interannual and decadal time scales via an ensemble empirical mode decomposition (EEMD) method. The temporal–spatial features of the SLA variability in the Pacific were examined and were closely associated with climate variability modes. Moreover, decadal SLA oscillations in the Pacific Ocean were identified during 1993–2016, with the phase reversals around 2000, 2004, and 2012. In the tropical Pacific, large sea level variations in the western and central basin were a result of changes in the equatorial wind stress. Moreover, coherent decadal changes could also be seen in wind stress, sea surface temperature (SST), subtropical cells (STCs), and thermocline depth. Our work provided a new way to illustrate the interannual and decadal sea level variations in the Pacific Ocean and suggested a coupled atmosphere–ocean variability on a decadal time scale in the tropical region with two cycles from 1993 to 2016.

1. Introduction

Sea level is an important indicator of climate change and it changes in broad spatial and temporal scales. The global mean sea level has been rising at a rate over 3 mm yr^{-1} since 1993 based on observation data from satellite altimeter. But the sea level changes are not spatially uniform, and regional sea level changes are on wide time

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scales, from monthly to interdecadal (Cazenave and Llovel 2010; Cazenave and Remy 2011; Merrifield 2011). Although challenging, many efforts have been made to quantify the long-term sea level trend and the part due to anthropogenic contributions (Merrifield and Maltrud 2011; Hamlington et al. 2013, 2014). Nevertheless, sea level variations on interannual and decadal time scales have larger magnitudes than long-term trends and thus have an essential influence on the oceanic and atmospheric circulations and climate change (Qiu and Chen 2012; Feng et al. 2010, 2011; Merrifield and Maltrud 2011). Lee and McPhaden (2008) found decadal sea level and wind stress changes around 2000 in the Indo-Pacific region. While the multidecadal regional sea level shifts in the Pacific during 1958–2008 were found by Moon et al. (2013), Hamlington et al. (2016) uncovered an ongoing shift in Pacific Ocean sea level over the past few years. Han et al. (2014) found the western tropical Pacific decadal and multidecadal sea level variability intensified during recent decades.

Many previous studies have associated sea level variability in the Pacific with climate variability (Cazenave and Remy 2011; Zhang and Church 2012; Chen and Wallace 2015; Liu 2012). Zhang and Church (2012) explained 60% of sea level variance, during the altimetry era, through a multivariate linear regression model by utilizing ENSO and interdecadal Pacific oscillation (IPO) index. Moon et al. (2015) found the intensification of decadal sea level variability in the tropical Pacific was due to PDO and ENSO modulations. Efforts have also been made to identify the contributions of climate variability to the sea level trends. Merrifield (2011) used a multiple regression to single out the ENSO-associated trend, while Hamlington et al. (2013, 2014) identified and removed the PDO-related sea level trend to uncover the anthropogenic sea level rise. Lyu et al. (2017) detected and explained an ENSO-like low-frequency (on quasi-decadal and multidecadal time scales) variability in the Pacific. Nevertheless, the specified contributions of climate modes to the Pacific sea level variation on different time scales requires more examination.

Efforts have also been made to interpret the causes of these sea level changes. Wind stress is suggested to be the primary forcing of sea level changes in the Pacific (Carton et al. 2005; Lee and McPhaden 2008; Qiu and Chen 2012; Zhang et al. 2012, 2014; Nidheesh et al. 2013). Lee and McPhaden (2008) pointed out the decadal sea level changes driven by wind stress and wind stress curl; Nidheesh et al. (2013) showed that decadal and long-term sea level variability was mainly driven by wind stress in the Indo-Pacific Ocean. Moreover, the wind stress and the sea surface temperature are coupled

in the tropical Pacific through, for example, the Bjerknes feedback (Bjerknes 1969) and wind–evaporation–SST (WES) feedback (Xie and Philander 1994). In the air–sea system, especially in the tropical Pacific, the changes in the sea level, sea surface temperature, and sea surface wind are associated with each period. Further research is needed to clarify their performance on different time scales.

Studying sea level changes on different time scales provides insight on oceanic circulations (Grodsky and Carton 2001; Lee and McPhaden 2008; Qiu and Chen 2012; Zhang et al. 2012, 2014; Nidheesh et al. 2013). This is beneficial and critical for determining sea level changes due to anthropogenic climate change (Zhang and Church 2012; Hamlington et al. 2014). Since 1992, altimeter satellites have been providing high-accuracy, high-resolution sea level data with global coverage. A comprehensive study of long-term sea level trend and sea level variability on different time scales is needed, which in return provides information for current and future oceanic and atmospheric circulations and climate changes predictions. In this study, we identified Pacific sea level variability and its long-term trend through a new method, and analyzed their temporal–spatial characteristics. In addition, the associated variations of wind, SST, subtropical cells (STCs), and thermocline depth were also discussed in a coupled ocean–atmosphere dynamic framework, to explore the potential formation mechanisms for the sea level changes.

This paper is organized as follows. The next section introduces the data and methods used, followed by the presentation of the main results in section 3. A discussion of the results and our conclusions are in section 4.

2. Data and methods

Monthly sea level anomaly (SLA) data from 1993 to 2016 on 0.25°-resolution grids measured by altimeters, were provided by Archiving, Validation, and Interpretation of Satellite Oceanographic Data (AVISO; Ducet et al. 2000).

Monthly wind data from the Cross-Calibrated Multi-Platform (CCMP; Atlas et al. 2011) were provided by Remote Sensing Systems (RSS). The CCMP wind data are a consistent, gap-free dataset available from July 1987 to the present, with a 0.25° resolution, and produced using satellite, moored buoy, and model wind data with a variational analysis method (VAM). NCEP–NCAR reanalysis wind data (Kalnay et al. 1996) were also used and are available from 1948 to the present with 2.5° horizontal resolution.

SST data were provided by the Optimum Interpolation Sea Surface Temperature (OISST) dataset from NOAA (Reynolds et al. 2007). The OISST product is an analysis

constructed by combining observations from different platforms (satellites, ships, buoys) on a regular global grid. The data derived from AVHRR-only were used and are available from November 1981 to the present.

ENSO indices are the time series of area-averaged SST (e.g., Niño-3.4: from 5°N to 5°S and from 170° to 120°W) used to identify El Niño and La Niña events. The data were provided by NOAA/ESRL (data source: https://www.esrl.noaa.gov/psd/gcos_wgsp/Timeseries/Nino34/), calculated from the HadISST, version 1 (HadISST1), data. The PDO (data source: <http://research.jisao.washington.edu/pdo/>) is a low-frequency (decadal to multidecadal) climate variability, predominantly in the North Pacific, and its variation is normally calculated based on the leading mode of empirical orthogonal functions (EOFs) of SST (Mantua et al. 1997; Cummins and Lagerloef 2002; Newman et al. 2016). The PDO index and ENSO index were highly correlated on decadal and longer time scales (Zhang and Church 2012), and we used the PDO index to represent Pacific climate variability on a decadal or longer time scale.

To study three-dimensional oceanic variations, Ocean Reanalysis Pilot 5 (ORAP5) data and SODA, version 3.4.2, 3D were used. ORAP5 is a new eddy-permitting ocean reanalysis dataset, provided by ECMWF (Zuo et al. 2017). The data contain high-horizontal-resolution and high-vertical-resolution fields of temperature, salinity, and horizontal velocity over 1979–2013. Monthly SODA 3.4.2 data contain oceanic variables of temperature, practical salinity, density, sea level, mixed layer depth, current velocities, and wind stress.

The SLA time series of each grid was decomposed into variations on different time scales [intrinsic mode functions (IMFs)] and a nonlinear trend through the ensemble empirical mode decomposition (EEMD) method (noise standard error = 0.2, iterations = 50). We discarded seasonal and higher-frequency IMFs and then arranged low-frequency IMFs into two groups. One group includes variations with a period of 1–7 years and was regarded as the interannual mode; the other group has a period of 6–20 years and was regarded as the decadal mode. In the Pacific, the dominant spatial pattern of SLA variability on different time scales was identified by the EOF method, and we associated SLA and climate variability by comparing EOFs patterns and principal components (PCs) time series. To investigate changes on interannual and longer time scales, monthly data of SLA, wind stress, and SST were smoothed with a 13-month centered running-box filter to remove the signals with periods shorter than 1 year. We also examined the relation between SLA and climate variability in the Pacific by calculating the linear correlation between the SLA and ENSO index on an interannual time scale, as well as

the linear correlation between the SLA and PDO index on decadal time scales.

3. Results

a. Decadal variability of the SLA in the Indo-Pacific Oceans

SLA in much of the Indo-Pacific region exhibited nearly coherent variations on decadal time scales based on satellite altimeter data, with the phase changes in 2000, 2004, and 2012 (Figs. 1a–d). Time series of box-averaged SLA in places that exhibited large-variation amplitudes also presented the near-coherent phase reversals in 2000, 2004, and 2012 (Fig. 1e). These places of large variability include the central equatorial Pacific (Fig. 1a, box a), western tropical Pacific (Fig. 1a, box b), southeast Indian Ocean (Fig. 1a, box c), north-central subtropical Pacific (Fig. 1a, box d), Alaska Gyre (Fig. 1a, box e), northeastern subtropical Pacific (Fig. 1a, box f), south-central subtropical Pacific (Fig. 1a, box g), southeast subtropical Pacific (Fig. 1a, box h), and the Southern Ocean (Fig. 1a, box i). The turning points display a near 6–12-month lag in the midlatitudes (Fig. 1e). The magnitudes of the linear tendencies of SLA during these periods were significantly larger than the global-mean sea level trend from 1993 to 2016, around 3.2 mm yr^{−1} (Fig. S1a in the online supplemental material; Cazenave and Llovel 2010; Cazenave and Remy 2011). SLA in other places like the Atlantic Ocean and north Indian Ocean did not show significant variations during these periods (Figs. 1a–d; Lee and McPhaden 2008).

These sea level changes in the Pacific exhibited an ENSO-like seesaw spatial pattern in the whole ocean basin and oscillated on a decadal time scale (Figs. 1a–d). Such ENSO-like seesaw patterns of SLA tendencies separated near 160°E in the tropical Pacific and extended northeast and southeast through the whole ocean basin during 1993–2000, 2000–04, and 2004–12 (Figs. 1a–c). However, the separation point was near 180° in the tropical Pacific during 2012–16 (Fig. 1d). In the tropical Pacific, large SLA variations are seen in the western and central areas, while SLA in the eastern tropical Pacific kept relatively steady during 1993–2000, 2000–04, and 2004–12, but increased significantly during 2012–16 (Figs. 1a–d). In addition, the amplitudes of the sea level tendencies are larger during 2000–04 and 2012–16 than that during 1993–2000 and 2004–12 (Figs. 1a–d). Overall, the basin mean SLA trend in the Pacific was the same as the global-mean sea level trend of 3.2 mm yr^{−1} from 1993 to 2016 (Figs. S1a,b).

As pointed out by previous studies (McPhaden and Zhang 2002, 2004; Feng et al. 2010), the changes in the

FIG. 1. Linear tendencies of SLA (mm yr^{-1}) during (a) 1993–2000, (b) 2000–06, (c) 2006–12, and (d) 2012–16 for altimeter monthly mean SLA. The linear tendencies are calculated after seasonal adjustment by a 13-point rectangular filter. Values not significantly different from zero at the 95% confidence level are masked out. (e) Time series of box-averaged SLA on interannual and longer time scales (solid curves) and on decadal and longer time scales (dash curves), derived through EEMD method.

tropical sea level indicates the changes of the Pacific STCs. Pacific STCs, connecting the tropical and subtropical region, are driven by the Ekman divergence and pycnocline convergence. A positive trend of sea level differences Δh between the western and eastern tropical Pacific, along approximately 9°N and 9°S (McPhaden and Zhang 2002, 2004), implies an enhancing convergence of pycnocline waters, indicating a strengthening of the STCs in both sides of equatorial Pacific (McPhaden and Zhang 2002, 2004). Therefore, Pacific STCs experienced decadal oscillations for two cycles from 1993 to 2016 (Figs. 1a–d,e), which increased during

1993–2000 and 2004–12, and decreased during 2000–04 and 2012–16. There was no significant trend of the STCs from 1993 to 2016 (Figs. S1c,d).

Moreover, the thermocline depth had a direct inverse relationship with the sea level in the tropical Pacific. During 1993–2000, for example, the thermocline largely deepened in the western tropical Pacific and it shoaled in the central tropical Pacific (Fig. S3). Such an inverse relationship between the sea level and the depth of the thermocline in the tropical Pacific can be well explained by a 1.5-layer gravity-reduced model (Zhuang et al. 2013; Huang 2015).

Sea level change in the eastern south Indian Ocean (SIO) was closely related to that in the tropical Pacific during the whole period (Figs. 1a–d; Feng et al. 2010, 2011). Sea level in the central and western SIO had opposite tendencies compared to the sea level in the eastern SIO during 1993–2000 and 2000–04, but its changes during 2004–16 were not obvious.

b. Variations of the wind stress and SST in the Indo-Pacific Oceans

In the equatorial areas, the Sverdrup balance requires the depth-integrated time-mean zonal pressure gradient to balance the equatorial wind stress. Therefore, the SLA variations could be mostly related to changes in the wind stress. During 1993–2016, sea level changes in the western (Fig. 1a, box b) and central tropical Pacific (Fig. 1a, box a) were well correlated with the equatorial zonal wind stress, with correlation coefficients R of 0.61 and -0.92 respectively. Linear tendencies of the wind stress in the tropical Pacific also exhibited a west–east seesaw pattern during 1993–2000, 2000–04, 2004–12, and 2012–16 (Fig. 2). Wind stress tendencies in the “west” half of equatorial Pacific hold a much larger amplitude than that in the “east” half, and the “separation” points were located near 150°W during 1993–2000, 2000–04, and 2004–12 (Figs. 2a–c). Such wind stress changes explained the large SLA tendencies in the western and central tropical Pacific and weak SLA changes in the eastern tropical Pacific. During 2012–16, the separating point was at 120°W , leading to large sea level rise in the eastern tropical Pacific (Figs. 2d and 1d). Therefore, sea level changes in the western and central tropical Pacific were mainly inhibited by the equatorial wind stress changes in the “western” half of the equatorial Pacific. The correlation coefficient between the equatorial zonal winds west of 150°W and the SLA in central equatorial Pacific (Fig. 1a, box a) and in west equatorial Pacific (Fig. 1a, box b) were 0.78 and -0.90 respectively during 1993–2016.

Changes in the extratropical SLA were mostly associated with the wind stress curl changes. A positive wind stress curl trend in the Northern (Southern) Hemisphere would lead to a negative (positive) trend of SLA. In much of the Indo-Pacific, the wind stress curl trends are centered to the east of the SSH pattern during 1993–2000, 2000–06, and 2006–12 (Fig. S2; Lee and McPhaden 2008; Zhuang et al. 2013), indicating the contribution of westward-propagating Rossby waves in wind forcing on the ocean. These places included the extratropical regions and the south-central Indian Ocean.

The wind stress was coupled with the SST in the tropical Pacific air–sea system. The changes in the strength of the easterly trades affect the SST in the equatorial Pacific.

A strengthening of easterlies increases equatorial Ekman divergence and strengthens the STCs, and the increasing equatorial upwelling brought more cold water to the surface and cooled the SST, and vice versa. This happens mostly in the central and eastern Pacific where the shallow thermocline favors the cooling of SST by upwelling (Fig. S3; England et al. 2014). Besides, there is also WES feedback (Xie and Philander 1994), a positive feedback over the equatorial region. The strengthening of the equatorial easterly piled more water in the western tropical Pacific, resulting in a positive anomaly of SST in the western tropical Pacific, and this SST anomaly extends to the midlatitudes (Fig. 2). The Pacific equatorial easterlies, as well as the STCs, experienced a strengthening–weakening oscillation during 1993–2000, 2000–04, 2004–12, and 2012–16 (Fig. 2). However, the magnitude of the wind stress tendency changed at the different periods as well. The wind stress tendency in the Pacific, especially in the tropical Pacific, displayed the largest magnitude during 2012–16, followed by that during 2000–04, and both were larger than the wind stress tendency during 1993–2000 and 2004–12 (Fig. 2).

The coherent wind–SST variability suggests that the Bjerknes feedback is at work on a decadal time scale. In the Pacific Ocean, linear trends of the SST also displayed the ENSO-like pattern and the pattern oscillated during 1993–2000, 2000–04, 2004–12, and 2012–16 (Fig. 2). The seesaw pattern of the SST tendency separated near 150°E . SST in the central equatorial Pacific had the largest tendency during each period, while SST at the east equatorial Pacific kept steady during 1993–2012. However, during 2012–16 the linear trend of the SST had a larger magnitude than that during 2000–04, and the positive SST tendency extended into the eastern tropical Pacific. SST in the southeast Indian Ocean held a similar variation with that in the western tropical Pacific.

c. Climate modes of Pacific SLA variability

Pacific SLA data during the altimetry era were decomposed into interannual and decadal components and a nonlinear residual via EEMD. The residual was the intrinsic trend of the SLA in the Pacific with the periodic signals removed. The pattern of linear trend SLA residual exhibited sea level rise in the Pacific Ocean during both 1993–2012 and 1993–2016; the sea level rise trends during 1993–2012 and 1993–2016 were similar but were not spatially even (Figs. S1b,d). Interestingly, the pattern of the linear trend of SLA was almost the same as the pattern of the linear trend of the SLA residual from EEMD during 1993–2016 (Figs. S1c,d). However, the linear trend of SLA during 1993–2012 was clearly different from that of the SLA residual

FIG. 2. Linear tendencies of wind stress (vectors; $\text{N m}^{-2} \text{yr}^{-1}$) and linear tendencies of SST (color shading; $^{\circ}\text{C yr}^{-1}$) during periods of (a) 1993–2000, (b) 2000–06, (c) 2006–12, and (d) 2012–16, as estimated from CCMP monthly wind data and OISST monthly data. The tendencies are calculated after seasonal adjustment with a 13-point rectangular filter. Values not significantly different from zero at the 95% confidence level are masked out.

during the same period (Figs. S1a,b). The mean sea level residual trend in the Pacific Ocean was also 3.2 mm yr^{-1} during this period.

EOF1 (51.3%) of the interannual SLA was an ENSO-like pattern with strong signals in the tropical Pacific area and weak signals in the midlatitudes (Fig. 3a). PC1 was highly correlated ($R = 0.95$) with the Niño-3.4 index on interannual time scale during 1993–2016 (Fig. 3b). EOF1 (44.5%) of the decadal component of SLA presented an ENSO-like pattern with signals extended into

the whole ocean basin (Fig. 3b); the PC1 was highly correlated ($R = 0.92$) with PDO index on decadal time scale. Such time series displayed a nearly 10-yr-period oscillation for two cycles from 1993 to 2016 (Fig. 3b). The dominating (EOF1) mode of interannual SLA held strong signals in the tropical Pacific and weak signals in the midlatitudes while the dominating mode of decadal SLA exhibited strong signals extending into the whole ocean basin (Figs. 3a,b). In the eastern tropical Pacific, however, strong signals could be found in the

FIG. 3. EOF1 of on (a) interannual and (b) decadal SLA variability from 1993 to 2016 for altimeter sea level data, decomposed via EEMD. (c) Principle component (PC) time series of EOF1 of interannual SLA (blue) and interannual Niño-3.4 index (red). (d) Times series of PC1 of decadal SLA (blue solid) and decadal PDO index (red dashed). Notice that EOF1 of decadal SLA in (b) was a negative ENSO-like pattern and PC-1 of decadal SLA in (d) was inverse. Interannual component of ENSO index and decadal component of PDO index were derived via EEMD method (noise standard error = 0.2, iteration times = 50).

dominating mode of interannual SLA but not in the dominating mode of decadal SLA (Figs. 3a,b). Furthermore, the time series of the dominating modes of interannual and decadal SLA exhibited very weak correlations. While extreme values were found in 1997/98, 2002/03, 2009/10, and 2015/16 on PC1 of interannual SLA variability, reflecting the influence of ENSO events (Fig. 3c), the turning points of PC1 of decadal variability can be seen at 2000, 2004, and 2012 (Fig. 3d). Such results indicated poor correlation between the interannual and decadal SLA variability.

FIG. 4. Correlation coefficient (a) between interannual sea level and Niño-3.4 on an interannual time scale and (b) between decadal sea level and PDO index on a decadal time scale from 1993 to 2016. The interannual and decadal components of SLA, Niño index, and PDO index were derived through EEMD.

In addition, the relation between the Pacific SLA and climate variability can be determined by linear correlation. The pattern of the correlation coefficient between the interannual SLA and ENSO index (interannual component) displayed an ENSO-like pattern and was highly similar to the EOF1 pattern of the interannual SLA during 1993–2016 (Fig. 4a). Whereas the pattern of the correlation coefficient between the decadal SLA and PDO index (decadal component) was an ENSO-like pattern and thus was highly similar to EOF1 of the decadal SLA (Fig. 4b). The high values of the correlation coefficient (Figs. 4a,b) implied a close relationship between ENSO and interannual SLA variability in the tropical Pacific, as well as a close relationship between PDO and the decadal SLA variability in the Pacific Ocean. The spatial pattern of EOF1 of the decadal SLA was similar to the patterns of the SLA tendencies (Figs. 3b and 1a–d) during 1993–2016. PC1 of the decadal SLA exhibited decadal variations with phase reversals in 2000, 2004, and 2012, coinciding with the turning time of the SLA tendencies (Fig. 3d).

SLA tendency during 2012–16 held larger amplitude, with a strong signal in the eastern tropical Pacific, compared to those during previous periods (Fig. 1d). Although the interannual component of ENSO hardly contributed to the SLA tendency during 2012–16, as

mentioned above, the type of El Niño most likely did. The El Niño events of 2002/03 and 2004/05 were of the central Pacific (CP) type, while the strong El Niño event of 2015/16 was of an eastern Pacific (EP) type (Yu and Kao 2007; Lee and McPhaden 2010). SST in the eastern tropical Pacific significantly changed during the EP El Niño but barely changed during the CP El Niño. There were obvious changes in SLA, wind stress, and SST in the eastern tropical Pacific during 2012–16 compared to those during 2000–04, which could be safely ascribed to differences in the type of El Niño.

4. Discussion and conclusions

Regional SLA changes, measured by satellite altimeters since 1993, were decomposed into different time scales and a nonlinear trend through the EEMD method. This method has the advantages of automatically getting a nonlinear trend and obtaining low-frequency signals without losing endpoints or prescribing the frequency range from using band filters. We identified the temporal–spatial features of interannual and decadal SLA variability in the Pacific Ocean and our results highlighted dominance of the ENSO and PDO over these interannual and decadal SLA variabilities (Merrifield and Maltrud 2011; Zhang and Church 2012; Hamlington et al. 2014). The Pacific SLA also exhibits multidecadal variability (Liu 2012; Lyu et al. 2017) and it has not been well understood due to the insufficiency of measured data with long temporal and large spatial coverage. Alternatively, model data and constructed data based on tide gauge records are used (Liu 2012; Chen and Wallace 2015; Lyu et al. 2017). In addition, sea level can also be decomposed into different components, such as steric sea level and mass sea level (Gill and Niller 1973; Wu et al. 2017); however, it will not be discussed in this study.

Near-coherent decadal SLA variations in the Indo-Pacific regions were found, with phase changes in 2000, 2004, and 2012, which were dominated by the decadal SLA variability mode. During 1993–2012, strengthening of equatorial wind stress was widely reported (England et al. 2014; Feng et al. 2011; Merrifield and Maltrud 2011), which was suggested to contribute to the tropical Pacific cooling during the global warming hiatus period from 1998 to 2013 (England et al. 2014; Yan et al. 2016). Also, during 1993–2012, the tropical Pacific experienced a high sea level rise rate in the western part and a low sea level rise rate in the eastern part (Merrifield and Maltrud 2011; Feng et al. 2010, 2011; Hamlington et al. 2016). However, our results indicated that such a 20-yr trend was probably a result of truncation on decadal variability, and

this trend of easterly trades was reversed by an intensive change during 2012–16. In addition, tendencies of sea level, wind stress, and SST exhibited different spatial patterns than those during previous periods, which can be ascribed to the difference in El Niño types. The increasing intensity of El Niño may be a result of the shoaling of the thermocline at the central equatorial Pacific (Lee and McPhaden 2010). Nevertheless, the sea level tendency on interannual or quasi-decadal time scales can also be largely impacted by the interannual sea level variability (Fig. 1e; Widlansky et al. 2015). For example, the SLA tendency on an interannual time scale starting or ending in 1998 will greatly affect the interannual variability due to the strong El Niño event during 1997/98.

Wind stress is the primary forcing of sea level changes in the Pacific (Lee and McPhaden 2008; Qiu and Chen 2012; Nidheesh et al. 2013; Zhuang et al. 2013). While sea level in the tropical Pacific was dominated by the changes in the Pacific trade winds (Lee and McPhaden 2008; Feng et al. 2010; Merrifield and Maltrud 2011), sea level in the mid- and high-latitude areas were greatly affected by the wind stress curl and sea level pressure (Lee and McPhaden 2008; Lyu et al. 2017). In the tropical Pacific, changes in the SLA were closely related to the changes in STCs and changes in the thermocline depth, and our results of STCs variations were consistent with previous studies (Lee and McPhaden 2008; Schott et al. 2008; Feng et al. 2010, 2011). Moreover, the wind stress was coupled with the SST as an air–sea system in the tropical Pacific due to the Bjerknes feedback mechanism.

The Pacific and the southeast Indian Oceans are dynamically connected through equatorial and coastal waveguides and thus stronger STCs are consistent with a stronger Indonesian Throughflow (ITF) and a stronger Leeuwin Current (LC) in the southeast Indian Ocean (Figs. 1a–d; Lee and McPhaden 2008; Feng et al. 2010, 2011). In addition, the Indo-Pacific region is also bridged through the atmospheric teleconnections (e.g., the Walker and Hadley circulations) (Klein et al. 1999; Lee and McPhaden 2008; Han et al. 2017). Therefore, the eastern SIO was closely linked to the western tropical Pacific and they had similar sea level and SST variations. Sea level in the central and western SIO could be impacted by the changes in the Walker circulation but also by local factors (Han et al. 2010; Zhuang et al. 2013; Trenary and Han 2013). Therefore, its variations in sea level and SST exhibited incongruous variations with the sea level changes in the eastern SIO and Pacific Ocean during 2004–16 (Figs. 1c,d and 2c,d).

Overall, the methods we used and described in this paper introduce new techniques with important geophysical implications. The findings presented on the Pacific sea level variability, as well as other physical mechanisms, provide

new insights in geophysical research, especially on interannual to decadal time scales, that may be important to future studies.

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REFERENCES

- Atlas, R., R. N. Hoffman, J. Ardizzone, S. M. Leidner, J. C. Jusem, D. K. Smith, and D. Gombos, 2011: A cross-calibrated, multiplatform ocean surface wind velocity product for meteorological and oceanographic applications. *Bull. Amer. Meteor. Soc.*, **92**, 157–174, <https://doi.org/10.1175/2010BAMS2946.1>.
- Bjerknes, J., 1969: Atmospheric teleconnections from the equatorial Pacific. *Mon. Wea. Rev.*, **97**, 163–172, [https://doi.org/10.1175/1520-0493\(1969\)097<0163:ATFTEP>2.3.CO;2](https://doi.org/10.1175/1520-0493(1969)097<0163:ATFTEP>2.3.CO;2).
- Carton, J. A., B. S. Giese, and S. A. Grodsky, 2005: Sea level rise and the warming of the oceans in the Simple Ocean Data Assimilation (SODA) ocean reanalysis. *J. Geophys. Res.*, **110**, C09006, <https://doi.org/10.1029/2004JC002817>.
- Cazenave, A., and W. Llovel, 2010: Contemporary sea level rise. *Annu. Rev. Mar. Sci.*, **2**, 145–173, <https://doi.org/10.1146/annurev-marine-120308-081105>.
- , and F. Remy, 2011: Sea level and climate: Measurements and causes of changes. *Wiley Interdiscip. Rev.: Climate Change*, **2**, 647–662, <https://doi.org/10.1002/wcc.139>.
- Chen, X., and J. Wallace, 2015: ENSO-like variability: 1900–2013. *J. Climate*, **28**, 9623–9641, <https://doi.org/10.1175/JCLI-D-15-0322.1>.
- Cummins, P., and G. Lagerloef, 2002: Low-frequency pycnocline depth variability at ocean weather station P in the northeast Pacific. *J. Phys. Oceanogr.*, **32**, 3207–3215, [https://doi.org/10.1175/1520-0485\(2002\)032<3207:LFPDVA>2.0.CO;2](https://doi.org/10.1175/1520-0485(2002)032<3207:LFPDVA>2.0.CO;2).
- Ducet, N., P. Y. Le Traon, and G. Reverdin, 2000: Global high-resolution mapping of ocean circulation from TOPEX/Poseidon and ERS-1 and -2. *J. Geophys. Res.*, **105**, 19 477–19 498, <https://doi.org/10.1029/2000JC900063>.
- England, M., and Coauthors, 2014: Recent intensification of wind-driven circulation in the Pacific and the ongoing warming hiatus. *Nat. Climate Change*, **4**, 222–227, <https://doi.org/10.1038/nclimate2106>.
- Feng, M., M. J. McPhaden, and T. Lee, 2010: Decadal variability of the Pacific subtropical cells and their influence on the southeast Indian Ocean. *Geophys. Res. Lett.*, **37**, L09606, <https://doi.org/10.1029/2010GL042796>.
- , C. Böning, A. Biastoch, E. Behrens, E. Weller, and Y. Masumoto, 2011: The reversal of the multi-decadal trends of the equatorial Pacific easterly winds, and the Indonesian Throughflow and Leeuwin Current transports. *Geophys. Res. Lett.*, **38**, L11604, <https://doi.org/10.1029/2011GL047291>.
- Gill, A., and P. Niller, 1973: The theory of the seasonal variability in the ocean. *Deep-Sea Res. Oceanogr. Abstr.*, **20**, 141–177, [https://doi.org/10.1016/0011-7471\(73\)90049-1](https://doi.org/10.1016/0011-7471(73)90049-1).
- Grodsky, S., and J. Carton, 2001: Intense surface currents in the tropical Pacific during 1996–1998. *J. Geophys. Res.*, **106**, 16 673–16 684, <https://doi.org/10.1029/2000JC000481>.
- 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, <https://doi.org/10.1002/grl.50950>.
- , M. W. Strassburg, R. R. Leben, W. Han, R. S. Nerem, and K.-Y. Kim, 2014: Uncovering an anthropogenic sea-level rise signal in the Pacific Ocean. *Nat. Climate Change*, **4**, 782–785, <https://doi.org/10.1038/nclimate2307>.
- , S. H. Cheon, P. R. Thompson, M. A. Merrifield, R. S. Nerem, R. R. Leben, and K.-Y. Kim, 2016: An ongoing shift in Pacific Ocean sea level. *J. Geophys. Res.*, **121**, 5084–5097, <https://doi.org/10.1002/2016JC011815>.
- Han, W., and Coauthors, 2010: Patterns of Indian Ocean sea-level change in a warming climate. *Nat. Geosci.*, **3**, 546–550, <https://doi.org/10.1038/ngeo901>.
- , and Coauthors, 2014: Intensification of decadal and multi-decadal sea level variability in the western tropical Pacific during recent decades. *Climate Dyn.*, **43**, 1357–1379, <https://doi.org/10.1007/s00382-013-1951-1>.
- , and Coauthors, 2017: Decadal variability of the Indian and Pacific Walker cell since the 1960s: Do they covary on decadal time scales? *J. Climate*, **30**, 8447–8468, <https://doi.org/10.1175/JCLI-D-16-0783.1>.
- Huang, R. X., 2015: Heaving modes in the world oceans. *Climate Dyn.*, **45**, 3563–3591, <https://doi.org/10.1007/s00382-015-2557-6>.
- Kalnay, E., and Coauthors, 1996: The NCEP/NCAR 40-Year Reanalysis Project. *Bull. Amer. Meteor. Soc.*, **77**, 437–471, [https://doi.org/10.1175/1520-0477\(1996\)077<0437:TNYRP>2.0.CO;2](https://doi.org/10.1175/1520-0477(1996)077<0437:TNYRP>2.0.CO;2).
- Klein, S. A., B. J. Soden, and N. Lau, 1999: Remote sea surface temperature variations during ENSO: Evidence for a tropical atmospheric bridge. *J. Climate*, **12**, 917–932, [https://doi.org/10.1175/1520-0442\(1999\)012<0917:RSSTVD>2.0.CO;2](https://doi.org/10.1175/1520-0442(1999)012<0917:RSSTVD>2.0.CO;2).
- Lee, T., and M. J. McPhaden, 2008: Decadal phase change in large-scale sea level and winds in the Indo-Pacific region at the end of the 20th century. *Geophys. Res. Lett.*, **35**, L01605, <https://doi.org/10.1029/2007GL032419>.
- , and —, 2010: Increasing intensity of El Niño in the central-equatorial Pacific. *Geophys. Res. Lett.*, **37**, L14603, <https://doi.org/10.1029/2010GL044007>.
- Liu, Z., 2012: Dynamics of interdecadal climate variability: A historical perspective. *J. Climate*, **25**, 1963–1995, <https://doi.org/10.1175/2011JCLI3980.1>.
- Lyu, K., X. Zhang, J. A. Church, J. Hu, and J. Yu, 2017: Distinguishing the quasi-decadal and multidecadal sea level and climate variations in the Pacific: Implications for the ENSO-like low-frequency variability. *J. Climate*, **30**, 5097–5117, <https://doi.org/10.1175/JCLI-D-17-0004.1>.
- Mantua, N., S. Hare, Y. Zhang, J. Wallace, and R. Francis, 1997: A Pacific interdecadal climate oscillation with impacts on salmon production. *Bull. Amer. Meteor. Soc.*, **78**, 1069–1080, [https://doi.org/10.1175/1520-0477\(1997\)078<1069:APICOW>2.0.CO;2](https://doi.org/10.1175/1520-0477(1997)078<1069:APICOW>2.0.CO;2).
- McPhaden, M. J., and D. Zhang, 2002: Slowdown of the meridional overturning circulation in the upper Pacific Ocean. *Nature*, **415**, 603–608, <https://doi.org/10.1038/415603a>.

- , and —, 2004: Pacific Ocean circulation rebounds. *Geophys. Res. Lett.*, **31**, L18301, <https://doi.org/10.1029/2004GL020727>.
- Merrifield, M., 2011: A shift in western tropical Pacific sea level trends during the 1990s. *J. Climate*, **24**, 4126–4138, <https://doi.org/10.1175/2011JCLI3932.1>.
- , and M. Maltrud, 2011: Regional sea level trends due to a Pacific trade wind intensification. *Geophys. Res. Lett.*, **38**, L21605, <https://doi.org/10.1029/2011GL049576>.
- Moon, J. H., Y. T. Song, P. D. Bromirski, and A. J. Miller, 2013: Multidecadal regional sea level shifts in the Pacific over 1958–2008. *J. Geophys. Res. Oceans*, **118**, 7024–7035, <https://doi.org/10.1002/2013JC009297>.
- , —, and H. Lee, 2015: PDO and ENSO modulations intensified decadal sea level variability in the tropical Pacific. *J. Geophys. Res. Oceans*, **120**, 8229–8237, <https://doi.org/10.1002/2015JC011139>.
- Newman, M., and Coauthors, 2016: The Pacific decadal oscillation, revisited. *J. Climate*, **29**, 4399–4427, <https://doi.org/10.1175/JCLI-D-15-0508.1>.
- Nidheesh, A., M. Lengaigine, J. Vialard, A. S. Unnikrishnan, and H. Dayan, 2013: Decadal and long-term sea level variability in the tropical Indo-Pacific Ocean. *Climate Dyn.*, **41**, 381–402, <https://doi.org/10.1007/s00382-012-1463-4>.
- Qiu, B., and S. Chen, 2012: Multidecadal sea level and gyre circulation variability in the northwestern tropical Pacific Ocean. *J. Phys. Oceanogr.*, **42**, 193–206, <https://doi.org/10.1175/JPO-D-11-061.1>.
- Reynolds, R. W., T. M. Smith, C. Liu, D. B. Chelton, K. S. Casey, and M. G. Schlax, 2007: Daily high-resolution-blended analyses for sea surface temperature. *J. Climate*, **20**, 5473–5496, <https://doi.org/10.1175/2007JCLI1824.1>.
- Schott, F. A., L. Stramma, W. Wang, B. S. Giese, and R. Zantopp, 2008: Pacific subtropical cell variability in the SODA 2.0.2/3 assimilation. *Geophys. Res. Lett.*, **35**, L10607, <https://doi.org/10.1029/2008GL033757>.
- Trenary, L., and W. Han, 2013: Local and remote forcing of decadal sea level and thermocline depth variability in the south Indian Ocean. *J. Geophys. Res. Oceans*, **118**, 381–398, <https://doi.org/10.1029/2012JC008317>.
- Widlansky, M., A. Timmermann, and W. Cai, 2015: Future extreme sea level seesaws in the tropical Pacific. *Sci. Adv.*, **1**, e1500560, <https://doi.org/10.1126/sciadv.1500560>.
- Wu, Q., X. Zhang, J. Church, and J. Hu, 2017: Variability and change of sea level and its components in the Indo-Pacific region during the altimetry era. *J. Geophys. Res. Oceans*, **122**, 1862–1881, <https://doi.org/10.1002/2016JC012345>.
- Xie, S.-P., and S. Philander, 1994: A coupled ocean-atmosphere model of relevance to the ITCZ in the eastern Pacific. *Tellus*, **46A**, 340–350, <https://doi.org/10.3402/tellusa.v46i4.15484>.
- Yan, X.-H., T. Boyer, K. Trenberth, T. R. Karl, S.-P. Xie, V. Nieves, K.-K. Tung, and D. Roemmich, 2016: The global warming hiatus: Slowdown or redistribution? *Earth's Future*, **4**, 472–482, <https://doi.org/10.1002/2016EF000417>.
- Yu, J.-Y., and H.-Y. Kao, 2007: Decadal changes of ENSO persistence barrier in SST and ocean heat content indices: 1958–2001. *J. Geophys. Res.*, **112**, D13106, <https://doi.org/10.1029/2006JD007654>.
- Zhang, X., and J. Church, 2012: Sea level trends, interannual and decadal variability in the Pacific Ocean. *Geophys. Res. Lett.*, **39**, L21701, <https://doi.org/10.1029/2012GL053240>.
- , B. Cornuelle, and D. Roemmich, 2012: Sensitivity of western boundary transport at the mean north equatorial current bifurcation latitude to wind forcing. *J. Phys. Oceanogr.*, **42**, 2056–2072, <https://doi.org/10.1175/JPO-D-11-0229.1>.
- , J. Church, S. Platten, and D. Monselesan, 2014: Projection of subtropical gyre circulation and associated sea level changes in the Pacific based on CMIP3 climate models. *Climate Dyn.*, **43**, 131–144, <https://doi.org/10.1007/s00382-013-1902-x>.
- Zhuang, W., M. Feng, Y. Du, A. Schiller, and D. Wang, 2013: Low-frequency sea level variability in the southern Indian Ocean and its impacts on the oceanic meridional transports. *J. Geophys. Res. Oceans*, **118**, 1302–1315, <https://doi.org/10.1002/jgrc.20129>.
- Zuo, H., M. A. Balmaseda, and K. Mogensen, 2017: The new eddy-permitting ORAP5 ocean reanalysis: Description, evaluation and uncertainties in climate signals. *Climate Dyn.*, **49**, 791–811, <https://doi.org/10.1007/s00382-015-2675-1>.