Mechanism of interannual variability of ocean bottom pressure in the South Pacific

Jianhuang Qin1 · Xuhua Cheng1,2* · Chengcheng Yang1 · Niansen Ou3 · Xiaoqin Xiong1

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Abstract
The study of ocean bottom pressure (OBP) is useful for understanding the variability that contributes to sea level change. Previous studies have reported the strong OBP anomalies in the Southern Ocean on different timescales. In this study, the characteristic and mechanisms of the energetic interannual OBP variability in the southeastern Pacific are examined using 14 years of Gravity Recovery and Climate Experiment (GRACE) data. It is found that the OBP anomalies are positive (negative) related to the convergence (divergence) of Ekman transport forced by local winds variability. Such local winds are attributed to atmospheric teleconnections, particularly the second Pacific-South American (PSA2). The sea level pressure (SLP) anomalies associated with the positive phase of PSA2 shows a wavenumber-3 structure in the high latitude of South Pacific, which benefits a strong and persistent anticyclone over the southeastern Pacific, leading to the positive OBP anomalies there. Moreover, El Niño–Southern Oscillation (ENSO) plays an important role in the concurrent OBP variability during austral spring (August–November) and leads the austral autumn (March–June) OBP variability by 1 season. These results highlight the influence of atmospheric teleconnections on interannual OBP variability and are validated by a mass conservation (non-Boussinesq) ocean model, which is expected to not only better understanding of OBP mechanisms in a longer time, but also predict OBP variation in the global scale.

1 Introduction
Sea level variation is a key indicator of climate change. Sea level variability is mainly consisted of two factors: one is the steric component, considered as an indicator for how the ocean heat content changes the sea surface height over time. The other is the ocean bottom pressure (OBP) associated with the pressure exerted on the ocean floor by the water column and the overlying atmosphere. The OBP helps to understand the nature of a similar signal in sea level anomaly, which is related to water mass change (Cazenave and Nerem 2004; Chambers 2006a). For instance, the OBP trend accounts for 69% global mean sea level rise over 2005–2014 (Chambers et al. 2016). Thus, insights into OBP variability and its relation to sea level variability are expected to lead to better understanding the vertical structure of oceanic variability, meridional overturning circulation, deep water formation and global climate system.

OBP is the vertical integral of atmosphere and sea water mass. Its variability is mainly induced by local mass redistribution as a result of changes in ocean circulation driven by winds (Gill and Niller 1973), the global hydrological cycle including the loss of glaciers and runoffs (e.g., Chambers et al. 2004) and atmospheric pressure variability over the ocean (Ponte 1999). Generally, the former is the dominant factor for local OBP variability on synoptic-interannual timescales, such as in North Pacific and North Atlantic (e.g., Stepanov and Hughes 2006; Cheng et al. 2013).

Due to the paucity of observations, researches of OBP were dependent on theoretical diagnosis and numerical models in the last century (e.g., Gill and Niller 1973; Ponte 1999). Since 2002, the launch of the Gravity Recovery and Climate Experiment (GRACE) provides an entirely new tool for monitoring global ocean mass variability (Tapley et al. 2004; Chambers 2006b), including mass loss from the Greenland and Antarctic ice sheets (Velicogna 2009), and global scale sea level change (Willis et al. 2008). To date, the
accumulated GRACE record during 2003–2016 provides an unprecedented view of global scale OBP variability, which can advance our process understanding of global sea level height, steric height and Antarctic ice sheet (e.g., Piecuch et al. 2013; Ren et al. 2013; Simpson et al. 2014; Storto et al. 2015; Volkov et al. 2015; Srinivasu et al. 2017).

Using GRACE observations, the long-term trend and interannual variability of OBP have been examined in global ocean (e.g., Johnson and Chambers 2013), especially in the North Pacific (Song and Zlotnicki 2008; Chambers 2011; Cheng et al. 2013). In the Southern Ocean, a number of previous studies have used GRACE OBP gauges to infer gradients of pressure across major currents, such as the volume transport variations of the Antarctic Circumpolar Current (e.g., Zlotnicki et al. 2007; Makowski et al. 2015). The variation of OBP in South Atlantic is driven by basin-wide Sverdrup transport related to local wind stress and Rossby waves (Cabanes et al. 2006). Boening et al. (2011) reported a record-high OBP signal in the southeastern Pacific during 2009/2010, and investigated the mechanisms caused by wind stress curl associated with a strong and persistent anticyclone. Quinn and Ponte (2012) suggested that the observed intraseasonal sea level related to OBP are significantly coherent with total sea level at high latitudes in the Southern Ocean. Ponte and Piecuch (2014) revealed that the strong OBP variability in the Australian–Antarctic and Bellingshausen Basins are partly related to enhanced local wind curl forcing and weakened gradients in the ratio of ocean depth and the Coriolis parameter. These results are consistent with the classic theory of Gill and Niiler (1973), that is, the OBP variability can represent the response to changes in the wind stress, ultimately resulting in sea level height variability. Overall, the process of OBP variability in the Southern Ocean remains an interesting issue, and has not been fully investigated.

El Niño–Southern Oscillation (ENSO) teleconnection contains both atmospheric and oceanic variables, especially the sea surface temperature (SST; Horel and Wallance 1981) and sea level pressure (SLP; Bjerknes 1969). The signal of ENSO can transfer from tropics to extra-tropical South Pacific via atmospheric teleconnection [commonly known as the Pacific South American (PSA) patterns; Mo 2000], which provides a possible linkage between ENSO and OBP variability in the high latitudes. However, less attention of ENSO-related teleconnection studies has been given to OBP in Southern Ocean. Cazenave et al. (2012) found that the positive global mean sea level anomaly during ENSO is attributed to ocean mass rather than thermal expansion increase. Song and Zlotnicki (2008) found a strong dipole of OBP in North Pacific during the ENSO events. Such result is further confirmed by Chambers (2011) using longer–time span GRACE data, but ENSO explains only 50% of the low-frequency OBP variance. In the Southeastern Pacific, an OBP monitoring was carried out by Fujimoto et al. (2003) for 14 months from 1997 to 1998. It is observed that the local OBP increased in December 1997 in company with the 1997/1998 ENSO. Additionally, the high record of OBP in the southeastern Pacific during 2009/2010 also has association with ENSO (Lee et al. 2010; Boening et al. 2011). Since the time-span was too short to conclude the reason for OBP variation, it is not clear the connection and process between ENSO and low-frequency OBP variability in the South Pacific.

Although previous studies discovered the active OBP variability in the South Pacific during high and low frequency timescales (e.g., Boening et al. 2011, 2012; Piecuch et al. 2013; Ponte and Piecuch 2014), the impact of atmospheric teleconnections on local OBP variability has less been discussed, particularly in light of current efforts to understand what controls regional OBP fluctuations on interannual timescale and to simulate and predict such variability. This is the motivation of this paper. The remainder of this paper is organized as follows. Data and methods used in this study are introduced in Sect. 2. Section 3 describes the characteristic and possible mechanisms of the interannual variability of OBP in the southeastern Pacific. Finally, Sect. 4 concludes with a discussion.

2 Data and methods

Monthly OBP data with a resolution of 1°×1° are available for 2003–2016 from the GRACE Gravimetric Satellite RL06 (release 06) processed by the Center for Space Research (CSR) of the University of Texas (http://GRACE.jpl.nasa.gov). Linear interpolation was performed to reconstruct the values in months to avoid missing values. Atmospheric variables including SLP and surface winds are used from the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) atmospheric circulation reanalysis (Kalnay et al. 1996) for the period 2003–2016 on a 2.5°×2.5° grid. Chaudhuri et al. (2013) verified that the zonal winds in different reanalysis products display similar characteristics and they have similar uncertainties when compared against observations. The SST data used in this study are from the National Oceanic and Atmospheric Administration (NOAA) Extended Reconstructed Sea Surface Temperature (ERSST) V5 dataset for the period 2003–2016, which has a horizontal resolution of 2°×2° (Huang et al. 2017). The ENSO is indicated by Niño 3.4 index derived from SSTA estimates in the (5°N–5°S, 170°–120°W), downloaded from https://www.esrl.noaa.gov/psd/gcos_wgsp/Timeseries/Nino34/. We calculated the
monthly anomalies by subtracting the climatological mean annual cycle (defined by the period of 2003–2012), and the trend has been removed before doing analysis. The austral spring covers ASON (April–November), and the austral autumn is defined as MAMJ (March–June). The preceding year from December to February is referred to as D(−1)JF.

Partial correlation is a measure of the linear relationship between two continuous variables whilst controlling for the effect of one or more other continuous variables. The partial correlation is calculated as

\[ R_{12/3} = \frac{R_{12} - R_{13} \cdot R_{23}}{\sqrt{(1 - R_{13}^2) \cdot (1 - R_{23}^2)}} \]

where \( R_{12}, R_{13} \) and \( R_{23} \) are the linear correlation coefficients, respectively. \( R_{12/3} \) is the correlation coefficient between variable 1 and 2 with the variable 3 removed.

The statistical significance of the correlation and regression coefficients are tested with the Student \( t \)-test, which determines whether two populations express a significant difference between the population means.

### 3 Results

#### 3.1 Characteristics of OBP variability in the South Pacific

The standard deviation map of monthly OBP in the South Pacific from 2003 to 2016 is shown in Fig. 1a. It is obvious that the OBP variability is pronounced in the southeastern Pacific. Such result is consistent with Piecuch et al. (2013) and Ponte and Piecuch (2014), which reported the large OBP anomaly observed in the South Pacific. Then, a simple index (hereafter referred to as the OBP index, OBPI, Fig. 1b) that measures the variability of the OBP in the southeastern Pacific was constructed by the OBP averaged in the southeastern Pacific (60°–45°S, 120°–80°W; black box in Fig. 1a), where the OBP variability is relatively strong. The largest amplitude of the OBPI is higher than 6 cm in 2015.

Figure 2 shows the empirical orthogonal function (EOF) analysis of monthly OBP anomalies in the South Pacific.
The leading two EOF modes for the period of 2003–2016 explain 47.7% and 11.7% of the total squared covariance, respectively. As shown in Fig. 2a, the positive center of OBP anomalies in the southeastern Pacific (70° − 45°S, 140° − 80°W) is captured by the spatial structure of EOF1, which is similar with the standard deviation map of monthly OBP (Fig. 1a). The principal component (PC) of EOF1 has a close relationship with the OBPI during the period 2003–2016 ($R = 0.83$, significant at a 99% confidence level). Therefore, OBPI can also be used to represent the temporal variation of the EOF1 (i.e., PC1). In contrast, the EOF2 represents a “sea-saw” OBP anomalies in the meridional direction, and the correlation coefficient between the OBPI and PC2 is only 0.03.

Figure 1c shows the climatological seasonal variation of the OBPI. It can be seen that the OBPI is relative energetic from March to November, but is suppressed during austral summer (December to February). In comparison, the amplitudes of PC1 for both the positive and the negative phases are also enhanced from March to November (Fig. 2e), while the PC2 is active during austral summer and winter (Fig. 2f). Thus, the question that will be addressed in this study is—what facilitates energizing the OBP variability in the southeastern Pacific (Fig. 1a) during austral spring (ASON) and autumn (MAMJ)?

According to the classic theory of Gill and Niiler (1973), low frequency OBP variability is mainly driven by local redistribution of internal mass forced by winds.
Regression maps of the OBPI with OBP (colors) and Ekman transports (vectors) during spring (ASON) and autumn (MAMJ) in the South Pacific for the period of 2003–2016 are shown in Fig. 3a and b, respectively. One can see that OBP is significant positive in the southeastern Pacific consistent with convergence Ekman transports both during spring (ASON) and autumn (MAMJ), indicating the important role of surface winds in OBP variability. Figure 3c and d show the regression maps of the OBPI with SLP (colors) and winds at 10 m (vectors) during austral spring (ASON) and autumn (MAMJ) in the South Pacific for the period of 2003–2016, respectively. The positive OBP anomaly in the southeastern Pacific is associated with anomalous high pressure and anticyclone on the sea level, which benefit to ocean circulation convergence. However, the low pressures consistent with cyclones over the South Pacific are not coincident during two seasons. There is a significant low pressure in west-southern Pacific (60°–40°S, 180°–130°W; Fig. 3c) during austral autumn (Fig. 3c), but in central-southern Pacific (40°–20°S, 160°–110°W; Fig. 3d) during austral spring (Fig. 3d). This result suggests that OBP variabilities in the South Pacific during different seasons are likely due to different atmospheric variabilities.

3.2 Mechanisms of OBP variability during austral spring and autumn

To further explore the influence of atmosphere teleconnections on the OBP in the South Pacific, we compare with
the three leading modes of atmospheric variability in the Southern Hemisphere. Following Mo (2000), the canonical Southern Annular Mode (SAM) and PSA patterns are usually obtained from EOF analysis of the Southern Hemisphere monthly SLP anomalies (Qin et al. 2017, 2018). The first three leading EOF modes of the monthly SLP anomalies in the Southern Hemisphere poleward of 20°S (after removing the monthly mean global average sea level pressure anomalies). Results only over the South Pacific are shown. (Middle) Time series and (Bottom) climatological seasonal variation of PCs

Table 1  Correlation coefficients between the OBPI and PCs (obtained by SLP over Southern Hemisphere; Fig. 4) during MAM and ASON

| Correlation | The SAM index | The PSA1 index | The PSA2 index |
|-------------|---------------|----------------|----------------|
| MAM OBPI    | −0.21         | −0.02          | 0.74**         |
| ASON OBPI   | −0.22         | 0.46*          | 0.67**         |

* and ** represent the significant at 90% and 95% confident level, respectively

EOF1, EOF2, and EOF3 account for 22.4%, 11.8%, and 8.9% of the SLP variability, respectively. The EOF1 pattern (Fig. 4a) is the SAM, which is a dominant mode of atmospheric variability in the Southern Hemisphere. The EOF2 and EOF3 patterns are referred to as the first PSA (PSA1) and second PSA (PSA2), respectively. Moreover, both of PSA patterns display a zonal wavenumber-3 structure from the tropical Pacific to Argentina (Fig. 4b and c), and their phases are almost in quadrature. Correlation coefficients between the OBPI and the time series of the three leading modes (referred to as the SAM index, PSA1 index and PSA2 index, respectively) are listed in Table 1. The OBPI has a high correlation with the PSA2 index during austral spring and autumn (R = 0.74 and 0.67, respectively, significant at the 99% confidence level), which is slightly greater than the correlation between the OBPI and the PSA1 index during austral spring (R = 0.46, significant at the 90% confidence level). Similar to the OBPI, the PSA2 index is also energetic from March to November, while the PSA1 index is active during ASON (Fig. 4). Both PSA1 and PSA2 patterns show closed high pressure over
the Ocean (Fig. 4b and c), which benefits to persistent convergence of Ekman transports driven by associated winds. In contrast, the correlation coefficients between the OBPI and SAM index is below 0.25 (not significant even at the 90% confidence level). Previous studies have reported the relation between OBP and SAM in the medium and high latitudes of South Hemisphere, but their relation is based on certain specific spatio-temporal conditions (e.g., Zlotnicki et al. 2007; Bergmann and Dobslaw 2012; Makowski et al. 2015). As shown in Fig. 4a, the high pressure exists mainly to the south of 60°S related to SAM (Fig. 4a), leading to ocean circulations toward the Antarctica continent (not shown). As a result, the Ekman transports cannot accumulate in the study region, so that the SAM has little influence on the interannual OBP variability in the southeastern Pacific during austral spring and autumn.

To discover the linkage between PSAs and OBP variability, Fig. 5 shows partial regressions of the OBPI with OBP anomalies, Ekman transport, SLP and winds at 10 m over South Pacific during austral spring (ASON) and autumn (MAMJ) with the PSA2 index removed. Compared with Fig. 3, it is shown that partial regressions of positive OBP anomalies and Ekman transports are remarkably reduced in the southeastern Pacific and the triple pattern of SLP becomes indistinct after the PSA2 index removed from the OBPI. The OBP anomaly averaged in Southern Pacific (black box in Fig. 1a) declines from 1.24 cm to 0.65 cm during austral autumn (Fig. 5a), and decreases 44% during austral spring (Fig. 5b) with PSA2 removed. Thus, it can be concluded that the PSA2 (the spatial structure of PC3, Fig. 4c) plays an important action role in the interannual OBP variability in the southeastern Pacific. However, the PSA2 only explain approximately 45% of the OBP variability, and the residual regression of SLP during austral spring (ASON, Fig. 5d) is close to the spatial structure of PSA1 (Fig. 4b), which indicates other factors in affecting the OBP variability in the southeastern Pacific.

**Fig. 5** is the same as Fig. 3, but with PSA2 removed
Previous studies found that the energy of ENSO can be transmitted from the low latitudes to the mid and high latitudes of the Southern Hemisphere by PSA wave trains, allowing the influence of ENSO to extend from tropics to extra-tropics (e.g., Mo 2000; Yu et al. 2015; Luo et al. 2021). As shown in Fig. 6a, the Niño 3.4 index has highest correlation coefficient ($R = 0.67$, significant at the 95% confidence level) with the MAMJ-averaged PSA2 index.

![Fig. 6](image)

**Fig. 6** Lead correlation coefficients of (a) the MAMJ-averaged and (b) the ASON-averaged PSA1 (red line) and PSA2 (blue line) index with the 3 month averaged Niño 3.4 index. The horizontal dashed line shows the 95% significance level.

![Fig. 7](image)

**Fig. 7** Regression maps of the D(−1)JF-averaged SST anomalies ($^\circ$C) with the (a) MAMJ-averaged and (b) ASON-averaged OBPI in the tropical and South Pacific for the period of 2003–2016. Significant SST anomalies at a 95% confidence level are stippled. (c) and (d) are the same as (a) and (b), but for the SST anomalies ($^\circ$C) at the same time.
(blue line) when ENSO leads the PSA2 around 3 months, but the correlation between the Niño 3.4 index and PSA1 index is extremely low (red line). For the ASON-averaged PSA indices (Fig. 6b), the significant correlation coefficients occur when ENSO leads PSAs around 3 months, and reach highest during the corresponding period (R = 0.46 and 0.74, both of them are significant at 95% confidence level).

Figure 7 shows the regression maps of SST anomalies with the MAMJ-averaged and ASON-averaged OBPI in the tropical Pacific for the period of 2003–2016. The SST anomalies associated with the MAMJ-averaged OBPI are dominated by negative anomalies in the western tropical Pacific and positive anomalies in the central and eastern tropical Pacific during austral summer (Fig. 7a). Similar result can be seen in Fig. 7d, which represents the regression map of SST anomalies with the OBPI during austral spring (ASON). In contrast, the ENSO-like SST anomalies pattern is weak associated with the ASON-averaged OBPI (Fig. 7b) and is disappeared during austral autumn (Fig. 7c). It indicates that ENSO has a simultaneous impact with the OBP during austral spring (ASON), and leads the austral autumn OBP variability around 3 months.

To further illustrate the independent relationship of ENSO and PSAs with OBP variability, partial correlation is carried out. The partial correlation between the PSA indices and OBPI during austral spring (ASON) and autumn (MAMJ) are listed in Table 2 with the Niño 3.4 index removed. Compared with Table 1, the correlation coefficients of the OBPI with PSA1 and PSA2 indices almost unchanged with ENSO removed during austral autumn (MAMJ). In addition, it is evident that the partial correlation coefficient between the OBPI and PSA2 index remains significant at the 95% confidence level both during austral spring (ASON) and autumn (MAMJ). However, correlation coefficient between the PSA1 index and OBPI is declined and non-significant after the Niño 3.4 index removed during austral spring (ASON). Mo (2000) found that the signal of ENSO transfers from tropics to the high latitude of South Pacific via PSA patterns. Therefore, it can reasonably deduce that the PSA1 (the spatial structure of PC2, Fig. 4b) links ENSO to the OBP variability in the southeastern Pacific, although both PSA1 and PSA2 have significant correlations with ENSO.

To further confirm the processes related to ENSO, partial regression maps of the OBPI on OBP anomalies, Ekman transport, SLP and winds at 10 m during austral spring (MAMJ) are shown in Fig. 8a and c with ENSO removed. Compared with Fig. 3, the OBP and SLP anomalies (especially the positive centers) are weaker in the southeastern Pacific. Similar conclusions are yield out by comparing the OBPI during austral autumn (ASON) with the result that the coincident ENSO removed (Fig. 8b and d). Moreover, we have checked that the partial regressions on OBP anomalies, Ekman transport, SLP and winds are negligible after removing PSA2 and ENSO (not shown). Therefore, we can surmise that the energetic OBP variability in the southeastern Pacific is dominated by PSA2 and ENSO during austral spring (ASON) and autumn (MAMJ).

### 3.3 OBP variability in PCOM

Boening et al. (2011) estimated the OBP variability in the south Pacific (90°–140°W, 35°–55°S) using a barotropic vorticity equation. The diagnostic OBP anomaly is close to observations. However, the barotropic vorticity equation works no quite well in basin scale when close potential vorticity contours exist (caused by ocean topography, white lines in Fig. 1a), which prevent OBP signal propagating westward (Gill and Niller 1973; Cheng et al. 2021). Therefore, to further examine the processes of PSA2 and ENSO related to OBP variability, the Pressure Coordinate Ocean Model (PCOM) is used in this study. PCOM is a mass conservation (non-Boussinesq approximation) ocean model, which can be used to directly simulate the OBP [See Huang et al. (2001) and Zhang et al. (2014) for more detailed descriptions about the model]. In this study, a spin-up run in PCOM with 60 pressure layers and the horizontal resolution of 1° × 1°, was performed for 600 years from a static state under repeating climatological monthly mean atmospheric forcing, including fresh water flux, surface heat flux, surface wind and SLP. To examine the contributions of wind and sea level pressure forcing to the OBP variability, two experiments are carried out from 1990 to 2018 restarting from the spin-up run. The control run (Exp. 1) is forced by daily atmospheric forcing during 1990–2018. Exp. 2 is the same as the control run, except excluding wind forcing. As shown in Fig. 9a, the pattern of OBP standard deviation in the southeastern Pacific is quite similar to observations (Fig. 1a), especially in 60°–45°S, 120°–80°W (black box in Fig. 1a), which indicates that the control run in PCOM can reproduce interannual variability of OBP quite well. Without wind forcing, the standard deviation of OBP is quite weak, except along the coasts and Mid-Ridges (Fig. 9b), where the non-static

| Table 2 | The SAM index | The PSA1 index | The PSA2 index |
|---------|---------------|---------------|---------------|
| With D(− 1)JF ENSO removed | MAMJ OBPI | − 0.09 | 0.09 | 0.66** |
| | ASON OBPI | − 0.22 | 0.50** | 0.69** |
| With concurrent ENSO removed | MAMJ OBPI | − 0.07 | − 0.03 | 0.73** |
| | ASON OBPI | − 0.12 | − 0.20 | 0.50** |
response to sea level pressure forcing cannot be neglected. This result confirms that the OBP variability in southeastern Pacific is forced by winds, which highlights the importance of atmospheric teleconnections in OBP variability.

In the following study, only the control run in PCOM is used. The PCOM OBPI is calculated by the PCOM OBP averaged in the (60°–45°S, 120°–80°W; black box in Fig. 1a). The correlation coefficient between the monthly observed OBPI (red line, also shown in Fig. 1b) and PCOM OBPI (blue line) is 0.66 (significant at 99% confidence level, Fig. 10a). As shown in Fig. 10b, the OBPI in PCOM is also active during austral spring (ASON) and autumn (MAMJ). The EOF1 calculated by PCOM OBP in the South Pacific (Fig. 10c) is also similar with that in GRACE (Fig. 2a), which is captured by positive OBP anomalies in the southeastern Pacific. In addition, the PC1 (Fig. 10d) has a high correlation with that in observation (R = 0.93, significant at 99% confidence level).

Fig. 8 a and c are the same as Fig. 3a and c, but with D(− 1)JF ENSO removed. b and d are the same as Fig. 3b and d, but with concurrent ENSO removed.

Fig. 9 Standard deviation map of PCOM OBP a control run and b without winds in the South Pacific from 2003 to 2016.
Regression maps of the PCOM OBPI with OBP anomalies in PCOM, Ekman transports, SLP and winds at 10 m during austral spring (ASON) and autumn (MAMJ) in the South Pacific for the period of 2003–2016 are shown in Fig. 11. The convergence Ekman transports are forced by high pressure and anti-cyclone, leading to positive OBP anomalies in the southeastern Pacific. The significant values are disappeared with ENSO and PSA2 removed (not shown). The above results are the same with observations (Figs. 3, 5 and 8). Furthermore, PSA2 has close relationship with the PCOM OBPI (exceed 0.60, listed in Table 3), and the significant correlations decrease slightly after ENSO removed. Therefore, it is proved the mechanism of OBP variability associated with ENSO and PSA2 in the PCOM.

4 Conclusion and discussion

In this study, we examined the interannual characteristic and processes of OBP in the South Pacific during austral spring (ASON) and autumn (MAMJ). Consistent with previous studies, the interannual variability of OBP in the southeastern Pacific is mainly controlled by Ekman transport driven by wind stress. We conclude that the atmospheric teleconnections are the sources for local wind stress. During the positive OBP anomalies in the southeastern Pacific, a strong and persistent anticyclone is forced by wavenumber-3 structure of atmospheric circulation anomalies over the South Pacific (Fig. 12), and vice versa. Such atmospheric circulation anomalies are similar to a PSA2-type wave train over the South Pacific. Additionally, ENSO also plays an important role in the OBP variability in the southeastern Pacific. PSA1 wave train and atmospheric circulation variability link the influence of ENSO to extra-tropical South Pacific. The OBP anomalies during austral spring are influenced by concurrent ENSO, while the austral autumn OBP anomalies are affected by austral summer ENSO in the Southeastern Pacific.

The findings of this study emphasize the role played by PSA2 and ENSO in OBP variability in the southeastern Pacific. Atmospheric circulation anomalies can explain 64% (PSA2 ~ 44%, ENSO ~ 20%) of austral spring OBP variability, and 80% (PSA2 ~ 25%, ENSO ~ 55%) of OBP variability during austral autumn, respectively. This result emphasizes the significance of atmospheric teleconnections for OBP variation, which are the sources of local wind stress. It helps...
understand the reason for controlling regional OBP fluctuations on interannual timescale, and to qualify the effects of atmospheric teleconnections on OBP variability in the Southeastern Pacific.

The OBP variability contains both barotropic and baroclinic signals. Barotropic response dominates the OBP variability at high latitudes, while the baroclinic response is important at low latitudes (Gill and Niller 1973). For example, the root-mean-square value of barotropic component can reach 4 cm to the south of 40°S in Southern Ocean, but baroclinic component is generally under 0.5 cm (Piecuch et al. 2015). Therefore, the influence of baroclinic OBP variability is ignorable in the study region, but is worthy for further research.

The GRACE data processes have only 14 years, which are too short to give a long-term perspective of the correlation between the interannual OBP variability and ENSO events. It is evident that PCOM, a mass conservation model, can reproduce the spatio-temporal variation of OBP quite well in the South Pacific. Therefore, PCOM simulations provide not only a long-term solution for a better understanding of the OBP variability mechanisms, but also predicting sea level change in the future.

![Fig. 11](image-url) is the same as Fig. 3, but with PCOM OBPI

### Table 3 Correlation coefficients of the PCOM OBPI with ENSO and PSA2 during MAMJ and ASON

| Correlation | The PSA2 index | Niño 3.4 index | The PSA2 index with ENSO removed |
|-------------|----------------|----------------|----------------------------------|
| MAMJ OBPI   | 0.83**         | 0.56** D(− 1)JF | 0.72**                           |
| ASON OBPI   | 0.60**         | 0.82** ASON     | 0.45*                            |

* and ** represent the significant at 90% and 95% confident level, respectively
Fig. 12  Schematic of the mechanism for the positive OBP variability during austral spring (ASON) and autumn (MAMJ) in the southeastern Pacific

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Data availability Enquiries about data availability should be directed to the authors.

Declarations

Conflict of interest The authors have not disclosed any competing interests.

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