A New Equatorial Oscillation Index for Better Describing ENSO and Westerly Wind Bursts

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ABSTRACT

An Equatorial Oscillation Index (EOI) is defined, based on the zonal gradient of sea surface pressure between the western Pacific and eastern Pacific along the equator, to describe the distribution of wind and pressure within the equatorial Pacific. The EOI has a stronger correlation with the Niño3.4 sea surface temperature anomaly (SSTA), as well as with westerly/easterly wind bursts (WWBs/EWBs), showing a superiority over the Southern Oscillation Index (SOI). In general, the EOI is consistent with the SOI, both of which reflect large-scale sea level pressure oscillations. However, when there are inconsistent SSTAs between the equator and subtropical regions, the SOI may contrast with the EOI due to the reverse changes in sea level pressure in the subtropical regions. As a result, the SOI fails to match the pattern of El Niño, while the EOI can still match it well. Hence, the EOI can better describe the variability of the Niño3.4 SSTA and WWBs/EWBs. The correlation between the SOI and Niño3.4 SSTA falls to its minimum in May, due to the large one-month changes of sea level pressure from April to May in the subtropical southern Pacific, which may be related to the spring predictability barrier (SPB). The newly defined EOI may be helpful for monitoring El Niño–Southern Oscillation (ENSO) and predicting ENSO.

Key words: Equatorial Oscillation (EO), Southern Oscillation (SO), westerly wind bursts (WWBs), EOF, ENSO prediction, spring predictability barrier (SPB)

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1. Introduction

When El Niño events occur, the sea surface temperature (SST) in the eastern equatorial Pacific can be several degrees Celsius higher than normal. These rising temperatures in the vast waters of the Pacific Ocean are associated with changes in the trade winds. The phenomenon most directly responsible for this is the inverse relationship of the sea level pressure between the eastern Pacific and the western Pacific, namely, the Southern Oscillation (SO; Julian and Chervin, 1978; Wright, 1989; Walker, 1933). During El Niño, the pressure in the southeastern Pacific decreases significantly, while the pressure near Indonesia and Australia increases; this pressure distribution follows the opposite trend during La Niña. The interaction between the ocean and atmosphere is collectively referred to as El Niño–Southern Oscillation (ENSO) in meteorology (Bjerknes, 1969; Timmermann et al., 2018).

ENSO shows many regularities, which may be explained by high-frequency atmospheric forcing along the equator; the forcing manifests as westerly wind bursts (WWBs). The high-frequency wind is one of the precursory factors that would influence the onset and evolution of a certain ENSO event (Chen et al., 2016a). Some recent modeling studies (Chen et al., 2016b, 2019) have also documented the critical role of the high frequency variability, such as westerly wind events (WWEs), in the ENSO development. WWBs prevail across the surface near the equator on a synoptic scale. WWBs can force seawater to flow eastward, propelling warm surface water from the western Pacific to the central Pacific. In addition, WWBs can also stimulate downwelling Kelvin waves that travel eastward along the equator and shallow

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the thermocline, resulting in a positive SST anomaly (SSTA) in the eastern Pacific Ocean (McPhaden and Taft, 1988; Kessler, 1990; Lengaigne et al., 2002). The generation of WWBs is associated with the atmospheric pressure gradient along the equator. Considering that WWBs that affect ENSO are mainly concentrated near the equator, whether the SO located in the Southern Hemisphere can be used as an effective indicator for the WWB characteristics needs to be verified. Thus, it is necessary to define a new index for describing WWBs along the equator.

The phenomenon that ENSO predictability plunges in spring in the Northern Hemisphere is called the “spring predictability barrier (SPB)” (Webster and Yang, 1992; Lau and Yang, 1996). The SPB exists as an obstacle in both dynamical and statistical prediction models (van Oldenborgh et al., 2005; Jin et al., 2008). Whether the relationship between the SO and the El Niño carries the SPB character? If so, how about the atmospheric variability concerned to the SO during the boreal spring season? Hence, some new investigations of the relationship between the SO and El Niño with a focus on the formation of WWBs are needed.

In order to answer the above questions, we intend to choose a high-pressure center and a low-pressure center along the equator and then define an Equatorial Oscillation (EOI) as an alternative for the SO. The new EO index (EOI) shows apparent advantage over the classic index of SO, e.g., a better correlation with Niño3.4 SSTA during the whole year. Furthermore, the EOI has a better correlation with WWB variability than all the previous related indices.

The data and method are described in Section 2. In Section 3, the EOI is defined, the relationship between the EOI and the Niño3.4 SSTA, as well as the EOI and WWB relationship, is shown, and a physical explanation of the EOI and SPB relationship is given. A summary is provided in Section 4.

2. Data and methods

2.1 Data

The 10-m zonal wind ($U_{10m}$) and sea level pressure (SLP) from 1980 to 2017 employed in this study are from the ECMWF interim reanalysis (ERA-Interim) data (Dee et al., 2011) with a $1^\circ \times 1^\circ$ spatial resolution and a 6-h temporal resolution, at http://apps.ecmwf.int/datasets/data/interim-full-daily/. The climatology is the 30-yr average from 1981 to 2010, and the $U_{10m}$ anomaly and the SLP anomaly are obtained as the departure.

The monthly Southern Oscillation Index (SOI) from 1980 to 2017 is obtained from NOAA at https://www.ncdc.noaa.gov/teleconnections/enso/indicators/soi/. The Equatorial SO Index (EQ-SOI) in the same period is from http://iridl.ldeo.columbia.edu/maproom/ENSO/Timeseries/Equatorial_SOI.html. The EQ-SOI represents the difference in air pressure measured over the equatorial eastern and western Pacific. It is calculated as the difference of standardized mean SLP over the equatorial eastern Pacific Ocean ($5^\circ$N–$5^\circ$S, $80^\circ$–$130^\circ$W) and the region near Indonesia ($5^\circ$N–$5^\circ$S, $90^\circ$–$140^\circ$E).

Historical records of El Niño and La Niña events are acquired from the NOAA National Weather Service Climate Prediction Center Niño3.4 SST seasonal monitoring data. The SSTA in the Niño3.4 area is the 3-month average SSTA of the Oceanic Niño Index (ONI). The SSTA field is obtained from NOAA extended reconstructed sea surface temperature version 5 (ERSSTv5) data (Huang et al., 2017), which are accessible at https://psl.noaa.gov/data/gridded/data.noaa.ersst.v5.html.

2.2 Definition of WWBs/EWBs

WWBs in this paper are defined as continuous positive westerly wind anomalies larger than 5 m s$^{-1}$, crossing 1500 km in the zonal direction and at least 4 latitudinal degrees in the meridional direction, with a duration of at least 2 days, over the equatorial eastern Pacific (5$^\circ$S–5$^\circ$N, 120$^\circ$E–170$^\circ$W). Easterly wind bursts (EWBs) are similarly defined, except for the continuous easterly wind anomalies above −4 m s$^{-1}$. To describe the WWB/EWB strength, following the definition of the accumulated wind measure (Harrison and Vecchi, 1997; Chen et al., 2015, 2017; Lian et al., 2017), the cumulant of the westerly wind anomaly (WWA cumulant, i.e., $WWA_{cu}$) is defined as the time integral of the positive zonal wind anomaly integrated within the region (5$^\circ$S–5$^\circ$N, 110$^\circ$E–120$^\circ$W) over a specified duration. The cumulant of the easterly wind anomaly (EWA cumulant, i.e., $EWA_{cu}$) is defined as the time integral of the negative zonal wind anomaly integrated within the same region.

$$WWA_{cu} = \int u' ds dt, \quad \text{for } u' > 0, \quad (1)$$

$$EWA_{cu} = \int u' ds dt, \quad \text{for } u' < 0. \quad (2)$$

Before calculating the cumulant, the zonal wind anomalies are first meridionally averaged over the equatorial region (5$^\circ$S–5$^\circ$N), and then the cumulant is calculated along the zonal direction and temporally integrated. For convenience, the calendar months are classified into the ENSO developing period (February–June) and the ENSO mature period (July–next January).
2.3 Methods

WWBs caused by atmospheric noise act as highly damped oscillations that can potentially explain the irregularities of El Niño (Gebbie et al., 2007; Chen et al., 2015). Usually, WWBs occur during the developing phase of El Niño; and thus, the corresponding sea level pressure anomaly field is accompanied by changes in the high-pressure center and low-pressure center. The present study starts with examining the characteristics of the high-pressure center and low-pressure center in the SLP anomaly field corresponding to a WWB, and consequently determines the positions of the high-pressure center and the low-pressure center.

The combined empirical orthogonal function (CEOF) decomposition method is used to obtain the main spatial modes and time varying characteristics of the $U_{10m}$ anomaly and SLP anomaly in the equatorial Pacific from 1980 to 2017. The locations of the high-pressure center and low-pressure center can also be determined according to the spatial distribution of the WWB.

The Fisher’s $r$–$z$ transformation (Fisher, 1921; Chen et al., 2018a) is used to estimate the significance of the difference between two correlation coefficients. First, the two involved correlation coefficients ($r_1$ and $r_2$) are subject to a Fisher transform as follows:

$$z_1 = 0.5 \ln \left[ \frac{1 + r_1}{1 - r_1} \right],$$

$$z_2 = 0.5 \ln \left[ \frac{1 + r_2}{1 - r_2} \right].$$

(3)

Then, the standard parametric test is employed to examine the null hypothesis of the equality of $z_1$ and $z_2$. The test statistic $u = (z_1 - z_2)/[1/(N_1 - 3) + 1/(N_2 - 3)]^{1/2}$ satisfies the normal distribution. Both $N_1$ and $N_2$ are the sample sizes corresponding to $r_1$ and $r_2$. Finally, the statistical significance is estimated based on the two-tailed Student’s $t$ test with the confidence level of 95%.

3. Results

3.1 Definition of the EOI

Through CEOF analysis of the monthly mean $U_{10m}$ anomaly and SLP anomaly averaged along the equatorial Pacific (5°S–5°N) from 1980 to 2017, the first leading mode (EOF1) of the maximum variance contributes 40.2% of the total variance. The correlation coefficient between the time series of the first principle component (PC1) and Niño3.4 SSTA reaches 0.8. The spatial distribution of EOF1 of the SLP anomaly (Fig. 1b) shows that the EOF1 reflects the seesaw pattern of the SLP anomaly field in the equatorial Pacific. When the pressure anomaly decreases from west to east, westerly wind anomalies appear in the eastern equatorial Pacific.

The spatial distribution of EOF1 of the $U_{10m}$ (Fig. 1b) anomaly field reflects the $U_{10m}$ anomaly in the equatorial Pacific, mainly within 120°E–140°W. The PC1 time series of the SLP and $U_{10m}$ anomaly field is dominated by interannual variation (Fig. 1a). The coefficient of correlation between the PC1 of the monthly mean SLP and $U_{10m}$ anomaly field and the Niño3.4 SSTA reaches its maximum of 0.80 at months from lag−1 to lead−1 (Fig. 1c). It is worth noting that the center of the maximum WWA appears to the east of the international dateline, which approximately coincides with the WWBs that frequently occur in the equatorial Pacific during the developing phase of El Niño. Therefore, this pattern mainly reflects the interannual variation characteristics of WWBs in the equatorial Pacific. The high-pressure center is positioned at approximately 120°E, and the low-pressure center is located at approximately 140°W. The spatial EOF patterns of the SLP/wind are not sensitive to the prescribed region for the EOF analyses (figure omitted).

Several recent studies have reported that spatial patterns of the ocean–atmospheric systems in the Pacific have experienced a significant interdecadal change around the mid-to-late 1990s (e.g., Chen et al., 2019; Guo et al., 2020). Have the intensity and location of the two pressure centers in the EOF results changed with time? To answer this question, EOF analyses are performed over the period of 1980–1999 and the period of 1998–2017, respectively (Fig. 2). The maximum values of SLP anomaly and $U_{10m}$ anomaly in different periods are close to each other. However, the maximum center of 10-m wind moves westward by about 10 degrees as a whole. This westward movement of EOF patterns after the 1990s is consistent with the decadal change in the ENSO variability. There is a higher frequency of central Pacific El Niño after the 1990s.

Based on the above information, the positions of the high-pressure center and low-pressure center in the first mode are identified. The high-pressure center is located within the region 5°N–5°S, 110°E–130°E, and the low-pressure center is located within (5°N–5°S, 150°–130°W). The area-averaged values over these two regions are used for the following calculations. Following the SOI calculation method (https://www.ncdc.noaa.gov/teleconnections/enso/indicators/soi/), the air pressure difference between the east and west regions is normalized. The standard deviation of the air pressure on the east and west regions and the monthly standard deviation of the air pressure on both regions are calculated. In this way, the new EOI is derived, which can directly re-
flect the “seesaw” pattern of the SLP variation along the equator. Similarly, a new index, SOIs, is defined by using ERA gridded data near the point (12.23°S, 130.44°E; corresponding to Darwin station) and the point (17.32°S, 149.37°W; corresponding to Tahiti station). Furthermore, an area-mean index, SOIm, is defined based on the values over the centers of the region (11°–21°S, 170°–130°W) and the region (7°S–17°S, 110°–150°E), which cover the Darwin and Tahiti stations, respectively. Thus, a comparison between the SOIm and the SOIs can explain the impact of the grid area mean.

3.2 Relationship between the EOI and ENSO

The relationship between the EOI/SOI and ENSO is illustrated by the time series of the EOI/SOI and Niño3.4 SST anomaly field (SSTA; Fig. 3). A significant correlation between the EOI and Niño3.4 SST can be observed from their time series ($r = -0.88$; Fig. 3b), and their correlation is better than that between the SOI and Niño3.4 SST ($r = -0.74$; Fig. 3a). Furthermore, the correlations between the EOI/SOI and Niño3.4 SST during different ENSO phases are compared (Table 1). The EOI has a more obvious negative relationship with the Niño3.4 SST during the developing period of ENSO ($r = -0.84$) and the mature period of ENSO ($r = -0.91$) than the SOI ($r = -0.70$ and $r = -0.79$, respectively).

The EOI and Niño3.4 SST show a good lead–lag correlation, even when the lead–lag timescale is more than six months (Fig. 4a). For example, the EOI in spring has correlativity ($-0.27$) with the Niño3.4 SST in following winter, reaching the significance level. This is consistent with the previous studies (Yu and Rienecker, 1998; Lengaigne et al., 2004; Chen et al., 2014, 2016c, 2018b), which suggested that preceding winter–spring
WWBs over the equatorial western Pacific can exert large impacts on the ENSO occurrence in the following winter. The lead–lag correlation coefficient between the EOI and Niño3.4 SSTA reaches the strongest value ($r = -0.88$) when the leading month is approximately zero. Similarly, the synchronous correlation between the SOI/ EQ-SOI, as well the SOIm/SOIs, and Niño3.4 SSTA displays a strongest value. Moreover, all the correlations between the EOI and Niño3.4 SSTA are stronger than those calculated by the SOI at any lead/lag time. In particular, the coefficient of correlation between the EOI and Niño3.4 SSTA is persistently strong in all 12 calendar months, with the largest value ($r = -0.94$) in September and the smallest value ($r = -0.80$) in March. However, the coefficient of correlation between the SOI and Niño3.4 SSTA reaches a minimum in May ($r = -0.40$; Fig. 4b). Such a low correlation between the SOI and Niño3.4 SSTA in May may be related to the SPB, as to be discussed in Section 3.5.

It is worth noting that the correlations between the EOI and the SOIm/SOIs ($r = 0.83/0.86$) are better than
that between the EOI and the SOI ($r = 0.82$). The correlation between the SOIm and Niño3.4 SSTA ($r = -0.77$) is better than the correlations calculated by the SOIs ($r = -0.76$) and SOI ($r = -0.74$). According to the Fisher’s $r\rightarrow z$ transformation, the difference of the correlation coefficient calculated by the SOIs and the SOIm is significant at the 99% confidence level. Such relationships indicate that the area-averaged SOIm can eliminate the random signals of in situ observations and single station observations of reanalysis data. In addition, the SOIs, calculated based on reanalysis data, has a better correlation with the Niño3.4 SSTA than the original SOI. The reason for this superiority is that the gridded data of the ERA-Interim reanalysis dataset already contain a smoothing effect, which can also eliminate the random signals of in situ observations.

### 3.3 Relationship between the EOI and the WWB

Another advantage of the EOI is its ability to effectively capture the variability of WWBs (Fig. 3c), which is more superior than the SOI. A significant correlation between the EOI and the days/cumulant of the WWB can be observed from their time series ($r = -0.73/-0.76$), and their correlation is significantly better than that between the SOI and the days/cumulant of the WWB ($r = -0.69/-0.67$). In addition, the correlations between the EOI and SOI and the days of WWBs during different ENSO phases are compared (Table 1). The EOI has a more obvious negative relationship with the days of WWB during the mature period of ENSO ($r = -0.79$) than the SOI ($-0.72$). Similarly, the correlations between the EOI/SOI and the cumulant of WWBs during different ENSO phases are also compared (Table 1). The EOI has a more obvious negative relationship with the cumulant of WWB during the developing period of ENSO ($r = -0.71$) and the mature period of ENSO ($r = -0.79$) than SOI ($r = -0.59$ and $-0.73$, respectively).

Therefore, these relationships indicate that the characteristics of the duration/intensity of the WWB can be better reflected by the EOI than by the SOI. As WWBs play an important role in the ENSO formation, it can be deduced that the EOI may be a better indicator than the classic SOI to forecast ENSO formation.

Furthermore, the results of linear fitting between the EOI/SOI and the days of WWBs during different ENSO phases are compared (Table 1). A tight-fitting relationship between the EOI and the days/cumulant of WWBs can be found from their linear fitting [root mean square error (RMSE) = 6.1/7.1], which is better than the relationship with the SOI (RMSE = 6.5/8.2). Similarly, the results of linear fitting between the EOI/SOI and the cumulant of WWBs during different ENSO phases are compared (Table 1). The EOI has a closer relationship with the cumulant of WWBs during the developing period (RMSE = 6.5) and the mature period (RMSE = 7.5) of ENSO than the SOI (RMSE = 7.4 and 8.4, respectively). In short, all the linear fitting results mentioned above indicate that the EOI is strongly related to WWBs with smaller RMSEs than the RMSEs of the SOI.

The advantage of the EOI in representing the WWE changes can be further displayed in all the ENSO years. The residual distribution in the linear regression analysis

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**Table 1.** Coefficients of correlations between the EOI/SOI and the WWB days and cumulant (m), the EWB days and cumulant (m), and Niño3.4 SSTA (°C) during the developing, mature, and whole periods of ENSO. The root mean square errors (RMSEs) for the WWB days and cumulant and EWB days and cumulant fitted with EOI/SOI are shown in the brackets.

| EOI/SOI     | WWB Days | Cumulant | EWB Days | Cumulant | Niño3.4 SSTA |
|-------------|----------|----------|----------|----------|--------------|
| Developing  | -0.63/-0.64 (6.2/6.1) | -0.71/-0.59 (6.5/7.4) | 0.67/0.49 (5.4/6.3) | -0.73/-0.57 (5.3/6.3) | -0.84/-0.7  |
| Mature      | -0.79/-0.72 (5.9/6.6) | -0.79/-0.73 (7.5/8.4) | 0.65/0.59 (6.6/6.9) | -0.77/-0.73 (6.7/7.2) | -0.91/-0.79  |
| Whole       | -0.73/-0.69 (6.1/6.5) | -0.76/-0.67 (7.1/8.2) | 0.65/0.54 (6.2/6.8) | -0.76/-0.66 (6.2/7.2) | -0.88/-0.74  |
between the large WWE cumulant (> 5 × 10^6 m) and the EOI/EQ-SOI/SOI are compared for different ENSO years (Figs. 5a–c). The upper quartile and the lower quartile in the linear fitting residual between the WWE cumulant and the EOI are more centralized than those between the WWE cumulant and the EQ-SOI/SOI. The correlation between EOI and the WWE cumulant in El Niño years (r = −0.71) and in normal years (r = −0.69) is better than calculated by the EQ-SOI (r = −0.69/−0.62) or SOI (r = −0.62/−0.66). This indicates that the EOI is closely related to the large WWE cumulant.

### 3.4 Relationship between the EOI and the EWB

Similarly, the EOI also has a better correlation than the SOI with the variabilities of the EWB (Fig. 3d; Table 1). The EOI has a more obvious positive relationship with the EWB days during the developing period of ENSO (r = 0.67) and the mature period of ENSO (r = 0.65) than the SOI (r = 0.49 and 0.59, respectively). In addition, the EOI has a more obvious relationship with the EWB cumulant during the developing period of ENSO (r = −0.73) and the mature period of ENSO (r = −0.77) than the SOI (r = −0.57 and −0.73, respectively).

Furthermore, the results of linear fitting between the EOI/SOI and the EWB days/cumulant during different ENSO phases are compared (Table 1). A tight-fitting relationship between the EOI and the EWB days/cumulant can be found from their linear fitting (RMSE = 6.2/6.2), as their RMSEs are smaller than those calculated by the SOI (RMSE = 6.8/7.2). The EOI has a closer relationship with the EWB days during the developing period of ENSO (RMSE = 5.4) and the mature period of ENSO (RMSE = 6.6) than the SOI (RMSE = 6.3 and 7.2, respectively). The EOI also has a closer relationship with the EWB cumulant during the developing period of ENSO (RMSE = 5.3) and the mature period of ENSO (RMSE = 6.7) than the SOI (RMSE = 6.3 and 7.2, respectively). The EWB cumulant, which is weakly related to the SOI, mainly occurs during the developing period of La Niña and in normal years. In contrast, the correlation between the EOI and the EWB days is more persistent in all the ENSO years.

![Fig. 5](https://example.com/figure5.png) The linear fitting residual boxplots of (a–c) the WWA cumulant (> 5 × 10^6 m) and (d–f) the EWA cumulant (< −5 × 10^6 m) versus the EOI, EQ-SOI, and SOI in (a, d) La Niña, (b, e) El Niño, and (c, f) normal years. The number below each index is the respective correlation coefficient. The red crosses indicate outliers.
In the residual distribution boxplots of the linear fitting between the large EWA cumulant ($< -5 \times 10^6$ m) and the EOI/EQ-SOI/SOI (Figs. 5d–f), the upper quartile and the lower quartile of the boxplots of the EOI and EWA$_{eu}$ are more centralized than those calculated by the EQ-SOI/SOI, no matter in La Niña years, El Niño years, or normal years. The correlation between the EOI and EWA$_{eu}$ in La Niña years ($r = -0.64$), El Niño years ($r = -0.53$), and normal years ($r = -0.5$) are better than those calculated by the EQ-SOI/SOI. This indicates that the EOI is closely related to EWA$_{eu}$.

3.5 Physical explanation of the EOI

To explain the similarities/differences between the SOI and EOI in the physical sense, the $U_{10m}$ anomaly and SLP anomaly fields are composited for different EOI/EOI phases. First, 26 cases are selected to show the similarities between the SOI and EOI (April 1993, May 1997, December 1986, November 1986, September 2002, May 1987, September 2015, August 2015, October 2015, October 2009, November 1997, August 1982, May 2015, July 1987, July 1982, March 1997, November 1991, July 2015, September 1997, September 1982, October 1982, August 1997, October 1997, January 1992, November 1982, and October 1997), which are depicted in rectangle a in Figs. 6c, g. In those cases, the WWB prevails throughout the entire equatorial Pacific when the phase of the SOI/EOI is negative. In the case of negative SOI and negative EOI phases (Fig. 7a), the high-pressure center is located in the western Pacific, and the low-pressure center is located in the eastern Pacific. The pressure gradient from the west to the east corresponds to a WWA in the $U_{10m}$ anomaly field. At the same time, the distribution of the corresponding SSTA field also shows negative SSTAs in the western Pacific and positive SSTAs in the eastern Pacific, reflecting a pattern resembling El Niño. The opposite pattern with positive SOI/EOI phases is also tenable (figure omitted), in which positive SLP anomaly exists in the east and negative SLP anomaly exists in the west.

However, there are still cases in which the EOI phase is opposite that of the SOI. Here, six cases with a negative SOI and nonnegative EOI are composited. Based on scatter plots of the SOI and the EWB cumulant (Fig. 6a), most large EWB cumulants ($< 1 \times 10^6$ m) occur when the SOI is positive. However, there are still some erratic cases when the SOI is negative but the EWB cumulant is strong, which seldom occurs in the relationship between the EOI and the EWB cumulant (Fig. 6e). Hence, the erratic cases with a strong EWB cumulant and a negative SOI (Fig. 6a), excluding the cases with a negative EOI (Fig. 6e), are selected here. The selected cases are shown as green dots in Fig. 3a (August 1989, September 1999, May 2003, February 2013, October 2016, and December 2012). In the southern Pacific subtropical region ($10^\circ$–$20^\circ$S) (including the Darwin station and Tahiti station), the high-pressure center is in the western Pacific, while the low-pressure center is in the eastern Pacific, indicating a negative SOI (Fig. 7b). However, in the equatorial/North Pacific region ($10^\circ$S–$20^\circ$N; including the two centers of EO), the high-pressure center is in the eastern Pacific, while the low-pressure center is in the western Pacific, indicating a positive EOI. On the whole, a significant EWA prevails in the equatorial Pacific, which is consistent with the La Niña-like SSTA distribution near the equator. On the other hand, the zonal SSTA gradient in the southern Pacific subtropical region is different from that near the equator. Positive SSTAs occupy the southeastern subtropical Pacific region, forming the pattern of a positive South Pacific meridional mode (SPMM; Zhang et al., 2014; Min et al., 2017). Such a positive SPMM is accompanied by a negative SOI and weakened trade winds, but the wind anomalies are limited to only the subtropical region ($10^\circ$–$20^\circ$S, $170^\circ$–$120^\circ$W). As a result, the negative SOI is confined to only the southern Pacific subtropical region, which contrasts with the overwhelming pattern of a positive EOI and a La Niña-like SSTA distribution.

To illustrate the potential relationship between the SOI and the SPB (Fig. 4b), we focus on the one-month changes of SLP/wind from April to May. The 10 years (1981, 1994, 1983, 1992, 1998, 1980, 2017, 1997, 2004, and 1993) are selected from the 10 largest residual errors (with maximum changes) in linear fitting between monthly increment of SOI from April to May and those of Niño3.4 SSTA. Similarly, 10 years (1984, 1989, 1991, 2001, 2005, 2009, 2013, 2014, 2015, and 2016) are selected from the 10 smallest residual errors (with minimum changes) in linear fitting in the 10 years of the largest residual error, the difference of SLP anomaly distribution between April and May is obvious (Fig. 8). The SLP increments from April to May in the maximum-changed 10 years (Fig. 9a) depict that intense change in the subtropical region of Southern Hemisphere, which is larger than that in the minimum-changed 10 years (Fig. 9b). In the $U_{10m}$ anomaly distribution, there is an obvious anomaly area across the equatorial and subtropical region in the Southern Hemisphere in the maximum-changed 10 years (Fig. 9c). However, such wind anomalies in the same area weaken in the minimum-changed 10 years (Fig. 9d). The amplitude of SSTA in maximum-changed 10 years (Fig. 9e) is larger than that in the minimum-changed 10
years (Fig. 9f). In addition, all the centers of variation of SLP/wind in the subtropics of the Southern Hemisphere is more intense in the maximum-changed 10 years than those in the minimum-changed 10 years. These discrep-

Fig. 6. Scatter plots of the EWB (a, e) cumulant ($10^5$ m) and (b, f) days and the WWB (c, g) cumulant ($10^5$ m) and (d, h) days versus the (a–d) SOI and (e–h) EOI in La Niña (blue dots), El Niño (red dots), and normal (black dots) years. The boxes marked by a and b indicate the selected cases applied to the calculations in Figs. 7a and b, respectively.
ancies illustrate that the SLP anomaly, $U_{10m}$ anomaly, and SSTA asynchronously change from April to May at the two stations of Darwin and Tahiti. The difference between the two stations is considered to be related to the SPB.

4. Summary

Considering the limitations of the SOI in the Southern Hemisphere to represent El Niño near the equator, a new index, the EOI, is defined to describe the wind–pressure distribution along the equator. Compared with the classic SOI, the EOI shows some advantages in representing the variability of El Niño.

The EOI is defined in order to better describe the WWB. The EOI is strongly related to the WWB with smaller RMSEs than that calculated by the SOI, no matter in the whole ENSO period or in the ENSO developing/mature period. Furthermore, the linear fitting residual between the EOI and the WWA cumulant in ENSO years is more centralized than that calculated by the SOI/EQ-SOI. Hence, the EOI shows its advantage in describing WWBs along the equator.

The EOI has a stronger correlation with the Niño3.4 SSTA than that calculated by the SOI. In particular, the EOI overcomes some shortcomings of the SOI, which has an extremely low correlation with the Niño3.4 SSTA during May. The EOI can also capture the WWBs/EWBs along the equator with significantly higher correlations than the SOI. Mostly, the SOI is consistent with the EOI, as the SLP oscillation covers a wide spatial range, covering both the equatorial region and the subtropical regions. However, when the equatorial SSTAs are inconsistent with those in the subtropical region, significant differences can also be found in the equatorial SLP and the subtropical SLP, forming a Pacific meridional mode. As a result, the SOI may contrast with the EOI due to the reverse changes in the SLP in the subtropical regions that are different from those along the equator. In this way, the SOI fails to match the SSTA pattern associated with El Niño, while the EOI can still match it well. When the SLP anomaly change at Darwin station is different from that at Tahiti station from April to May, the SOI fails to match the Niño3.4 SSTA well, which may be related to the SPB.

In summary, the relationship between the EOI and the Niño3.4 SSTA, as well as the relationships between the EOI and the WWBs/EWBs, is superior to that of the SOI. Hence, the EOI can better describe the variability of the Niño3.4 SSTA distribution and the WWBs/EWBs. The new EOI may be helpful in monitoring ENSO and predicting ENSO events.

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Fig. 8. Spatial distributions of the differences in the sea level pressure anomaly (shading; Pa), 10-m wind anomaly (vector; m s$^{-1}$), and SSTA (contour; °C; interval 0.4°C) between April and May in the selected 10 years: (a) 1981, (b) 1994, (c) 1983, (d) 1992, (e) 1998, (f) 1980, (g) 2017, (h) 1997, (i) 2004, and (j) 1993. The red rectangles in each panel indicate the Darwin station (the left one) and the Tahiti station (the right one).
Fig. 9. The mean absolute values of the one-month increments from April to May of the (a, b) sea level pressure (SLP; Pa); (c, d) 10-m zonal wind ($U_{10m}$; m s$^{-1}$); and (e, f) sea surface temperature (SST; °C) in (left panels) the selected 10 years (1981, 1994, 1983, 1992, 1998, 1980, 2017, 1997, 2004, and 1993) with maximum changes, and (right panels) the selected 10 years (1984, 1989, 1991, 2001, 2005, 2009, 2013, 2014, 2015, and 2016) with minimum changes.

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