A Statistical Comparison of the Westerly Wind Bursts between the Positive and Negative Phases of the PDO

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ABSTRACT

To understand the diversity of the El Niño–Southern Oscillation (ENSO) under the background of Pacific decadal oscillation (PDO) during recent decades, characteristics of westerly wind bursts (WWBs) during positive and negative phases of the PDO were analyzed. It is shown that, during the ENSO developing period, the El Niño evolution may be affected by stronger or more frequent WWBs in the positive PDO phase than in the negative PDO phase. The sustained effects of atmospheric dynamics on the equatorial ocean can be indicated by the accumulated WWB strength, which contains most WWB characteristics, including the accumulated days, occurrence frequency, strength, and spatial range of WWBs. The synoptic/climate systems that are directly related to WWBs show a wider spatial distribution in the positive PDO phase than in the negative PDO phase.

Key words: westerly wind bursts (WWBs), WWB strength, WWB accumulated day, Pacific decadal oscillation (PDO), El Niño–Southern Oscillation (ENSO)

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1. Introduction

As the most prominent interannual variability in the tropical Pacific, the El Niño–Southern Oscillation (ENSO) has a significant influence on regional climate around the world (Philander, 1990). It was widely accepted that El Niño/La Niña has a regular and self-sustaining oscillation, determined by the recharge and discharge of the equatorial upper-ocean heat content (Jin, 1997; Li, 1997). Another mechanism regards ENSO as a damped oscillation, with each event triggered by atmospheric noise, especially westerly wind bursts (WWBs) in the equatorial Pacific (Keen, 1982; Harrison and Giese, 1991; Chen et al., 2015). A recent modeling study (Chen et al., 2016) has demonstrated the critical role of high frequency variability such as westerly wind event (WWE) in the ENSO development. Significant improvements have been achieved in seasonal forecast models and assimilation systems (Balmaseda et al., 2013; Zhao et al., 2013, 2014; Saha et al., 2014), as well as in the ocean initial conditions, due to the advent of the Argo float profiling program after 2000 (Schmid et al., 2007). Unfortunately, the long-lead prediction skill of El Niño/La Niña declined in the early 21st century (Barnston et al., 2012).

The decadal shift in ENSO predictability in approximately year 2000 may be attributed to ENSO diversity changes (Zhao et al., 2016). After the late 1990s, the El Niño variability moved westward into the central Pacific, and its strengths were also weakened (Ashok et al., 2007; Hu et al., 2013). There are additional difficulties in the prediction of weaker and more irregular El Niño/La Niña events. At the same time, the accuracy of the equatorial upper-ocean heat content as an indicator for ENSO formations has been less accurate in recent decades than in previous decades (McPhaden, 2012). Several ENSO prototypes, with an adequate equatorial heat content, were hindered from smoothly developing into a mature event...
(Su et al., 2014, 2018; Min et al., 2015). The predictability of the El Niño has been weakened in the early 21st century (Zhao et al., 2016; Barnston et al., 2019), and the forecasting of ENSO events remains a challenge beyond the 2–3-season lead time.

The above decadal changes in ENSO variability and surface winds occurred just during the period of the negative phase of the Pacific decadal oscillation (PDO) (Grassi et al., 2012). Thus, many questions are posed, as follows. What is the cause of the characteristic evolution of El Niño in the negative phase of PDO? Could the evolution of El Niño be explained based on the decadal changes in WWBs? What is the cause of WWB characteristics difference between the positive PDO phase and the negative PDO phase? How can the statistical characteristics of the activity of synoptic systems/climatic systems that are related to WWBs be described? This study intends to investigate the different characteristics of WWBs during the positive PDO phase and the negative PDO phase. Furthermore, the relationship between the change in WWBs and the change in synoptic systems or climatic systems is explained.

An overview of the data and the criteria of WWBs are provided in Section 2. In Section 3, the spatial and temporal distributions of the WWB characteristics are identified during the positive/negative phase of the PDO. Section 4 offers a summary and discussion.

2. Data and methods

2.1 Data

The 10-m wind fields are from the ERA-Interim data-set provided by the ECMWF (Dee et al., 2011). The u component of the wind field is 4 times a day with a spatial resolution of 1° × 1°. The monthly sea surface temperature (SST) dataset with a resolution of 2° × 2° is from Extended Reconstructed Sea Surface Temperature, version 5 (ERSSTv5; Huang et al., 2017). The definition of PDO index is based on the NOAA’s extended reconstruction of SSTs (ERSST, version 4) (https://www.ncdc.noaa.gov/teleconnections/pdo/).

2.2 Identification of westerly wind bursts and easterly wind bursts

In the present study, westerly wind burst is defined according to the following criteria: 1) the zonal extension of significant westerly wind anomalies (WWAs; > 5 m s⁻¹) is larger than 1500 km, defined as a zonal fetch; 2) there are at least 4 zonal fetches in the equatorial Pacific (5°S–5°N, 110°E–120°W); and 3) the duration of these fetches is no less than 2 days. Similarly, easterly wind burst (EWB) is defined according to the following criteria: 1) the zonal extension of significant easterly wind anomalies (EWAs; < −4 m s⁻¹) is larger than 1500 km, defined as a zonal fetch; 2) there are at least 4 zonal fetches in the equatorial Pacific (5°S–5°N, 110°E–120°W); and 3) the duration of these fetches is no less than 2 days. A WWB/EWB should be at least 4 strong westerlies with each of them having 1500-km zonal fetch at the same time. To describe the WWB/EWB strength, the cumulant of the westerly wind anomaly (cumulantWWA) is defined as the time integral of the positive zonal wind anomaly, integrated within the region (5°S–5°N, 110°E–120°W) over the specified duration, following the definition of wind measure (Harrison and Vecchi, 1997). The cumulant of the easterly wind anomaly (cumulantEWA) is defined as the time integral of the negative zonal wind anomaly integrated over the same region as follows:

\[
\text{cumulant}_{\text{WWA}} = \int \int u' \, \text{d}x \, \text{d}t, \quad \text{(WWA: only for } u' > 0),
\]

\[
\text{cumulant}_{\text{EWA}} = \int \int u' \, \text{d}x \, \text{d}t, \quad \text{(EWA: only for } u' < 0). \tag{2}
\]

Before the cumulant calculation, the zonal wind anomalies are first meridionally averaged over the equatorial region (5°S–5°N), and the cumulant is calculated along the longitudinal direction and temporally integrated. Actually, the quantitative measurement of WWB strength has attracted much attention. Chen et al. (2017) introduced a new index that described the accumulated effect of WWEs and the result exhibits clearly that the overall intensity of the WWEs in January–March 2015 is the strongest from 1980 to 2015. The daily climatological mean in PDO positive (negative) phase is calculated based on the data over the period 1980–1998 (1999–2013). Similarly, the sea surface temperature anomalies (SSTAs) are obtained based on the climatological period 1981–2010. The anomaly \( u' \) is the departure from the climatological cycle. The developing period of ENSO is chosen as the period of February–June, covering the late winter, the spring, and the early summer seasons. In the following, the positive phase of PDO is defined as the period 1980–1998, and the negative phase of PDO is from 1999 to 2013 (Fig. 1).

3. Results

3.1 The temporal and zonal range distributions of WWBs

As shown by the temporal and spatial distributions of WWBs (Fig. 1), a significant change in the WWB characteristics occurred during a switch of the PDO from a positive phase to a negative phase in approximately
1999. Generally, the WWBs had a longer duration and a wider spatial range during the positive PDO phase (left panel) than the negative PDO phase (right panel). In El Niño years, the WWBs lasted longer and had wider spatial ranges than in the other years. A high frequency of WWBs occurred in strong El Niño years (e.g., 1982 and 1997). The WWB frequency decreased in neutral years, and WWB events seldom occurred in La Niña years. In total, the duration, spatial range, and occurrence number of WWBs were high in El Niño years, which indicates that WWBs preferentially occur in El Niño years (Vecchi and Harrison, 2000).

Furthermore, large decadal and interannual variabilities can be found in the time series of WWB frequency and strength (Fig. 2), referring to the definition of WWA/EWA cumulant. The interannual variability of the occurrence frequency of WWBs/EWBs was consistent with that of the cumulant of WWAs/EWAs in both the developing period and the whole year. There was a remarkable negative correlation \( r = -0.81 \) between the time series of the annual WWA cumulant and the absolute values of the annual EWA cumulant. For the cumulants during the ENSO developing period, a similar relationship \( r = -0.76 \) also existed between the WWA cumulant and the absolute values of the EWA cumulant. During the positive PDO phase, there were more WWBs than EWBs, which could provide favorable environmental conditions for extreme El Niño events. During the negative phase of PDO, the total cumulant depicted more EWAs than WWAs, indicating unfavorable conditions for an intense El Niño.

Moreover, the total occurrence frequency and the annual WWA cumulant during the positive PDO phase were both larger than those during the negative PDO phase. The number of WWBs was 182 during the positive PDO phase, while it was 144 during the negative PDO phase (Table 1). The mean annual WWA cumulant was \( 0.5 \times 10^{6} \) m during the positive PDO phase and \( 0.4 \times 10^{6} \) m during the negative PDO phase. During the ENSO developing period, the mean WWA cumulant reached 0.2

![Fig. 1](image-url)
× $10^6$ m (approximately 40% of the annual mean) in the positive PDO phase, which was larger than that in the negative PDO phase (0.15 × $10^6$ m; approximately 38% of the annual mean). Hence, the large cumulant of the WWA during the positive PDO period plays a predominant role in the wind anomaly distribution. Such strong WWAs prove favorable environmental conditions for the formation of El Niño, particularly approximately 40% of WWAs occurring during the ENSO developing period. The average duration of WWBs was shorter (7 days) in the negative PDO phase than that (9 days) in the positive PDO phase. Compared with the positive PDO phase, the annual WWA cumulant was reduced (0.4 × $10^6$ m) in the negative PDO phase. However, the appearances of the EWAs are obviously different from those of WWB. The absolute value of the annual EWA cumulant in the negative PDO phase (0.5 × $10^6$ m) was nearly equal to that (0.5 × $10^6$ m) in the positive PDO phase. During the ENSO developing period, the mean annual EWA cumulant reached −0.15 × $10^6$ m (approximately 30% of the annual mean) in the negative PDO phase, which was weaker than that (−0.2 × $10^6$ m) in the positive PDO phase. Hence, the stronger annual EWA cumulant could play a predominant role in the wind anomaly distribution in the negative PDO phase. In fact, both the number and intensity of El Niño events in the positive PDO phase exceeded those in the negative PDO phase (Timmermann et al., 2018).

### 3.2 The two-dimensional spatial distribution of WWB

Theoretically, the anomalous westerly winds that are dynamically related to oceanic Kelvin waves during ENSO formation are mainly centered near the equator, generally set in a meridional zone of 5°S–5°N. In an ENSO
prediction and predictability study, the WWBs were usually focused in the specific area of 5°S–5°N, 110°E–120°W (e.g., Chen et al., 2015). During each WWB event, the spatial pattern of the related WWA changes from day to day. The reason for this variability is that the WWBs are influenced by various synoptic systems or climatic systems, with sources from areas beyond the equator. To study the statistical relationship between outside synoptic systems and the WWBs near the equator, the spatial pattern of the characteristics related to WWBs must be investigated. Here, we focused on the accumulated days and strength of WWBs. In this way, the factors (accumulated days, occurrence frequency, and strength) affecting the WWA cumulant were collectively informed.

For each local grid, the local accumulated days related to WWBs were defined as the accumulated days directly related to all the WWB events during a certain period (one year or several months for the developing phase) (shading in Fig. 3). Similarly, the anomalous westerly strength (cm s⁻¹) related to the WWBs was defined as the mean of the positive westerly wind anomalies directly related to all the WWB events during a specified period (contour in Fig. 3). The mean WWB-related accumulated days had a distribution similar to the mean WWB-related strength (Fig. 3). In this way, the statistical spatial distribution of the outside synoptic systems directly related to WWBs can be conveniently displayed.

The centers of the statistical spatial distribution of the synoptic systems were along the equator (within 5°S–5°N), and their edges were mainly within

**Fig. 3.** Spatial distributions of the mean accumulated days (shading; day) of WWBs in each local grid for each year and the daily accumulated westerly anomalous strengths (contour; cm s⁻¹) during (a) the positive PDO phase, (b) the negative PDO phase, (c) the El Niño years (1982, 1986, 1991, 1994, and 1997) in the positive PDO phase, (d) the El Niño years (2002, 2004, 2006, and 2009) during the negative PDO phase, (e) the La Niña years (1983, 1984, 1988, 1995, and 1998) in the positive PDO phase, and (f) the La Niña years (2005, 2007, 2008, and 2010) during the negative PDO phase. Concerning the accumulated occurrence frequency of WWBs and the accumulated westerly anomalous strengths, all the values are first calculated for the whole year and then averaged over multiple years.
15°S–15°N. Generally, the spatial patterns of the mean WWB-related accumulated days (shading in Fig. 3) agreed with those of the WWB-related strength (contour in Fig. 3). The central location of the WWBs in the positive PDO phase was concentrated at approximately 174°E, while the easternmost edge was at the longitude of 126°W, and the meridional span covered approximately 747 km (7 degrees latitude). The central WWB location (163°E) in the negative PDO phase was to the west of the central WWB location (174°E) in the positive PDO phase, and the corresponding easternmost edge (125°W) in the negative PDO phase was located to the east of that (126°W) in the positive PDO phase (Table 1).

The area of the high WWB-related strength (> 30 cm s⁻¹) during the positive phase of the PDO (with a zonal range of 75°; Fig. 3a) was larger than that during the negative phase of the PDO (with a zonal range of 51°; Fig. 3b). Specifically, the strong area (> 30 cm s⁻¹) shrank zonally, while the eastern edge moved westward during the switch from the positive PDO phase to the negative PDO phase. During the positive PDO phase, large values of WWB-related strength (> 50 cm s⁻¹) appeared over 5°S–2°N, 155°E–172°W. However, during the negative PDO phase, the area with strong WWB-related strength (> 50 cm s⁻¹) only appeared over 2°S–0°, 160°–165°E. Furthermore, the spatial distribution of moderate WWB-related strengths (> 20 cm s⁻¹) shrank westward, indicating that the WWB-related synoptic/climatic system moved westward. Such a westward movement of WWBs could lead to more central-Pacific El Niño events, as observed after 2000 (Yang et al., 2018). The WWB-related strength became weak from the positive PDO phase to the negative PDO phase. As a result, the warm SST associated with ENSO events extended westward, and the intensity of El Niño events decreased during the negative PDO phase.

The spatial distribution of the mean WWB-related accumulated days was in accordance with the spatial distribution of the WWB-related strengths. The boundary of the 20-day accumulated-day had a distribution similar to the boundary of the 20-cm s⁻¹ strength (Figs. 3a–f). In the El Niño years during the positive PDO phase (Fig. 3c), the boundary of the 90-day accumulated-day distribution was consistent with the boundary of the 120-cm s⁻¹ strength distribution. The area of the long accumulated days (> 20 days) during the positive phase of the PDO (with a zonal range of 69°; Fig. 3a) was larger than that during the negative phase of the PDO (with a zonal range of 57°; Fig. 3b). Specifically, the area of the long WWB-related accumulated days (> 20 days) shrank zonally, while the eastern edge moved westward during the switch from the positive to negative PDO phases.

### 3.3 The spatial distribution of the WWA occurrence frequency

On the one hand, westerly wind anomalies can often be generated by synoptic activities within 15°S–15°N. On the other hand, not all westerly wind anomalies within 15°S–15°N can efficiently form a WWB event. To distinguish whether the westerly wind anomalies could form a WWB event, a new parameter was defined. For each local grid, the duration period (day) of WWAs was defined as the accumulated duration days with local positive westerly anomalies \[u'(i,j,t) > 0\].

The WWA duration period (shading in Fig. 4) covers a larger spatial range than the WWB-related duration period (shading in Fig. 3), almost filling all the region of 15°S–15°N. During both the positive PDO phase and the negative PDO phase, significant WWA durations (> 20 days) not only existed within the region of 5°S–5°N but also expanded to the region of 15°S–15°N, extending to the northeast of the main range (10 cm s⁻¹) of WWB-related strength. Furthermore, the amplitude of the WWA duration period was generally larger than that of the WWB-related duration period, even in the region of 5°S–5°N. It can be deduced that a large fraction of the WWAs failed to match the definition of a WWB. For example, the maximum WWA duration within 5°S–5°N was 60 days during the positive PDO phase (Fig. 4a), and the maximum WWB-related duration was 58 days (Fig. 3a). Only approximately 73% of WWAs within 5°S–5°N during the positive PDO phase matched the WWB definition.

In the negative PDO phase (Fig. 4b), the area with a significant WWA duration (> 20 days) shrank westward compared to that in the positive PDO phase (Fig. 4a). The WWA duration during the negative PDO phase was less than that during the positive PDO phase, regardless of whether it was an El Niño year (Figs. 4c, d) or La Niña year (Figs. 4e, f). In the El Niño years of the two PDO phases (Figs. 4c, d), the mean WWA duration was larger than the multi-year mean WWA duration (Figs. 4a, b) and the mean WWA duration in the La Niña years (Figs. 4e, f), indicating that more synoptic activities related to WWA tend to occur in El Niño years. In the La Niña years during the positive PDO phase (Fig. 4e), the synoptic systems related to WWA were active only along the east coast of
the Philippine Islands and over 10°–15°N. In general, synoptic systems related to WWA in the positive PDO phase were more active and covered a larger area than those in the negative PDO phase.

3.4 The relationship between the WWB strength and duration

Generally, the interannual variabilities of the WWBs match well the ENSO variabilities. But the two main factors of WWB, i.e., the number of WWB and the WWA cumulant, may have different characteristics in certain El Niño years which have similar strength. Taking the years 1982 and 1997 as examples in the positive PDO phase, the ratio of the WWB occurrence frequency (7) in developing period to that (12) in the whole year of 1997 was 58%, larger than that ratio in 1982 (6 : 12; 50%). For the cumulant of WWA, the ratio of the WWA cumulant in developing period to the total annual WWA cumulant in 1997 (38%) was larger than that (18%) in 1982. The WWA cumulant reached $0.5 \times 10^6$ m in developing period in the 1997 El Niño and it was $1.3 \times 10^6$ m in the whole year. But in the 1982 El Niño, the WWA cumulant in developing period reduced to $0.2 \times 10^6$ m, and it was $1.1 \times 10^6$ m in the whole year. The occurrence frequency of WWB in developing period in 1997 was larger than that in 1982, and the mean zonal wind anomaly of WWB strength during the developing period (2.9 m s$^{-1}$) in 1997 was larger than that (about 1.4 m s$^{-1}$) in 1982. Since the WWA cumulant in the developing period in 1997 was much higher than that in developing period in 1982, it can be deduced that the WWB strength is crucial to the value of WWA cumulant. The relationship between the WWB strength and the WWA cumulant manifests that the WWB strength is a significant factor of the El Niño formation.

In addition, the two El Niño years (2002 and 2009) are taken as examples during the developing period of ENSO in PDO negative phase. The WWB number in 2002 was more than that in 2009, not only during the developing period (6 : 4) but also during the whole year (16 : 12).
15). The WWA cumulant in developing period (0.26 × 10^6 m) in 2002 was larger than that (0.22 × 10^6 m) in 2009. The average duration of WWEs in 2002 was 11 days and the meridional span of WWBs covered 8 degrees latitude, while the average duration of WWEs in 2009 was 7 days and the meridional span of WWBs covered 7 degrees latitude. The average value of WWB strength in 2002 was larger than that in 2009. Therefore, the intensity of WWB in 2002 was apparently stronger than that in 2009.

According to the WWB duration, WWB events can be classified into two categories: brief events with a period of 5–25 days and sustained events with a period of 30–90 days (Kiladis et al., 1994). Here, we choose 20 days as the appropriate threshold to distinguish between the brief events and the sustained events. In addition, the WWB events were classified into another two categories based on their maximum strength: strong westerly wind events with a maximum strength larger than 15 m s⁻¹ and moderate westerly wind events with a maximum strength less than 15 m s⁻¹. Similarly, the events were classified into another two categories according to the mean zonal wind anomaly strength: positive wind events with a positive mean strength and negative wind events with a negative mean strength. The maximum/mean strength–duration distribution tended to have an inherent relationship with the brief/sustained categories (Fig. 5).

In the positive PDO phase, some (12; 46%) strong westerly wind events (> 15 m s⁻¹) lasted longer than 20 days. The strong WWB with a sustained duration (> 20 days) and large strength (> 15 m s⁻¹) occurred in the mature period (6; the first quadrant in Fig. 5a). The mean strength of westerly wind events in the negative PDO phase was less than that in the positive PDO phase.

![Fig. 5. Scatter plots of the WWB duration compared to the (a) maximum u-wind anomaly and (b) mean u-wind anomaly. The blue (red) dot represents a westerly wind event during the ENSO developing period of the positive (negative) phase of the PDO, and the values during the ENSO mature period are indicated by blue (red) circles. The events are separated into four groups according to their duration and strength. The numbers of WWBs in each group are shown at the corner of each quadrant, following the order listed by the legend.](image-url)
(the first and second quadrants in Fig. 5b), and there were fewer events with a sustained duration and large mean strength in the ENSO mature period in the negative PDO phase (7) than in the positive PDO phase (13; the first quadrant in Fig. 5b).

In Fig. 5b, the mean zonal strength of the wind anomaly may be positive or negative. The negative values indicate that the strength of the EWA is larger than the strength of the WWA over the specified area. The WWBs generally have a positive mean strength (305; 84%) and most (276; 76%) are brief WWBs (< 20 days) (the second quadrant in Fig. 5b). The mean wind anomaly strength and duration decreased during the negative PDO phase compared to the positive PDO phase. Meanwhile, the occurrence frequency of WWBs decreased during the switch from the positive PDO phase (220) to the negative PDO phase (144).

4. Summary and discussion

The predictability of El Niño has been degraded after 2000. The potential direct reason for this decrease is that the characteristics of ENSO in the positive PDO phase (1980–1998) are different from those in the negative PDO phase (1999–2013). To investigate the mechanism of ENSO diversity changes in recent decades, it is necessary to clarify the comparison of WWB differences between the positive PDO phase and the negative PDO phase.

Both the WWB numbers and the WWA cumulant are important for ENSO formation. During the El Niño years, the WWA cumulant reached high values, and the WWB number was relatively high, both during the developing period and the whole year. On the other hand, the WWB number and the WWA cumulant were relatively low both in the normal years and in the La Niña years.

Because equatorial WWB events are commonly caused by synoptic activities beyond the equatorial region, the spatial patterns of westerly anomalies related to WWB events were further investigated. The spatial distribution of the WWB-related duration in the positive PDO phase was wider than that in the negative PDO phase. This characteristic is consistent with the spatial pattern of WWB-related strength. Compared to the positive PDO phase, the WWB spatial range and WWB-related strength during the ENSO developing period in the negative PDO phase were decreased. Meanwhile, the spatial distribution of the WWB-related duration during the ENSO developing period in the positive PDO phase was also larger than that in the negative PDO phase.

The spatial and temporal distribution of WWBs reveals obvious interannual variability and apparent decadal change. The typical ENSO diversity during the two phases of the PDO can be well explained by the changes in the WWBs near the equatorial region. As the climatological mean state of the tropical Pacific during the different PDO phases has changed, such decadal changes in WWBs may be related to large-scale climate shifts. Considering the difficulties arising in ENSO prediction in recent years, a more thorough investigation of WWB variabilities could provide potential precursor signals for ENSO prediction.

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