Role of low-frequency wind variability in inducing WWBs during the onset of super El Niños

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Abstract
In this study, the effect of multiple timescale wind fields on the westerly wind burst (WWB) was investigated during the onset of super (1982, 1997, and 2015) and regular El Niño events. The results revealed that extreme WWBs during the onset of the super El Niño group were attributed to low-frequency westerly (≥ 90 days, LFW), medium-frequency westerly (20–90 days, MFW, or intraseasonal) and high-frequency westerly (≤ 20 days, HFW) components, accounting for approximately 56, 22 and 22%, respectively. Thus, the extreme WWBs during the onset of super El Niños were primarily contributed by LFWs. By contrast, the WWBs during the onset of regular El Niños were determined primarily by MFWs (37%) and HFWs (35%), whereas the LFW contribution is relatively small (28%). Further analysis indicated that LFWs during the onset of the super El Niños were primarily a response to a positive SST anomaly in the tropical to eastern North Pacific resembling the Pacific Meridional Mode (PMM), which had persisted during the preceding 9–12 months in the extratropical eastern North Pacific. A significant lagged correlation between the tropical and extratropical North Pacific SST was identified, and their correlation has become stronger since the late 1980s. MFWs during the onset of the super El Niños were primarily associated with the Madden–Julian Oscillation.

Keywords Westerly wind burst (WWB) · Super El Niño · Low frequency westerly · Medium frequency westerly · High-frequency westerly

1 Introduction
The El Niño–Southern Oscillation (ENSO) is the leading air–sea coupled mode in the tropical Pacific (Bjerknes 1969; Rasmusson and Carpenter 1982; Philander 1990; McPhaden et al. 2006a) and has a substantial effect on global weather patterns and climate (Fraedrich 1994; Chiew et al. 1998; Hansen et al. 1998; Chou et al. 2009; Ding and Li 2012; Ward et al. 2014). Although El Niños exhibits similar characteristics, such as a warm SST in the eastern Pacific and seasonal phase locking feature (initiates in boreal spring and matures in winter, An and Wang 2001; Spencer 2004; Chen and Jin 2020), it also exhibits a complicated diversity, including the amplitude (Stephens et al. 2007; Zheng et al. 2014a, b; Fang et al. 2015; Chen et al. 2016; Takahashi and Dewitte 2016), spatial pattern (Ashok et al. 2007; Kao and Yu 2009; Kug et al. 2009; Weng et al. 2009), and the duration (Ohba and Ueda 2009; Okumura and Deser 2010; Okumura et al. 2011; Fang and Zheng 2021).

Previous studies have revealed that large-scale oceanic conditions, including warm water volume (Meinen and McPhaden 2000; Bosc and Delcroix 2008; McPhaden 2012), zonal SST gradient, and tilted thermocline (Collins et al. 2010), are favorable for the onset of El Niño events. Furthermore, the atmospheric conditions of a sequence of near surface westerly were suggested to be the crucial factor triggering El Niño (Vecchi and Harrison 2000; Legaigne et al. 2003; Hu et al. 2014; Chen et al. 2017). The near surface strong westerlies in the equatorial western Pacific,
generally referred to as westerly wind events (WWEs) or westerly wind bursts (WWBs), may force a sequence eastward propagating downwelling Kelvin waves that create a positive SST anomaly in the eastern Pacific and accounts for triggering El Niño onset. Whereas the time scale of WWEs (~ several days) was relatively shorter than the lifecycle of El Niño (1 ~ 2 years), it was suggested as a random forcing crucial for ENSO onset. The initiation of WWBs has been reported to be associated with several processes, including (1) cold surge breaks (Li 1990; Hong et al. 2009); (2) tropical deep convections, such as the MJO (Lau and Chan 1986; Nitta and Motok 1987; Nitta 1989; Nitta et al. 1992; Kindle and Phoebus 1995; McPhaden 1999) and tropical cyclones (Keen 1982; Hartten 1996; Vecchi 2000; Lian et al. 2018); and (3) extratropical large-scale phenomena, such as, Arctic Oscillation and induced atmospheric circulation (Nakamura et al. 2006, 2007; Chen et al. 2014). Although WWBs may trigger the onset of El Niños, the El Niños also exert positive feedback modulating the magnitude of WWBs (Eisenman et al. 2005; Gebbie and Tziperman 2009; Chen et al. 2015; Levine et al. 2017).

The WWBs are generally assumed to constitute high frequency variation and a random noise relative to the slow temporal evolution of El Niños (Hartten 1996; Harrison and Vecchi 1997; Seiki and Takayabu 2007a, b). However, the observation yields that the WWB’s occurrences are not purely random, but are interactive with ENSO: The occurrence of WWBs significantly increased when the warm pool extended eastward, and the ENSO has positive feedback to result in an enhancement of the low frequency component of the WWBs (e.g., Eisenman et al. 2005; McPhaden et al. 2006b; Jin et al. 2007; Seiki and Takayabu 2007a, b; Gebbie et al. 2007; Kug et al. 2008; Gebbie and Tziperman 2009; Levine et al. 2017). It was reported that the magnitude of ENSOs forced by modulated WWBs to be twice as large as that of ENSOs forced by stochastic WWBs with the same amplitude and frequency (e.g., Eisenman et al. 2005). These studies indicate that the WWBs are treated as being partially stochastic and partially modified by the large-scale ENSO dynamics, and the feedback of WWB-ENSO was essential to result in a strong ENSO. Additionally, the WWBs were associated with eastward-propagating Madden–Julian oscillation (MJO). A strong MJO tended to enhance the WWB (Seiki and Takayabu 2007a, b; Hong et al. 2017). The aforementioned studies reveal that the WWBs were substantially modified by the ENSO and MJO.

Recently, Sullivan et al. (2021) demonstrated that the magnitude of high frequency WWBs was substantially modified by not-ENSO related low frequency variability, which was strongly connected with the Asian and Australian. Their study suggests that quantifiable physical processes rather than atmospheric stochastic signals determine the WWBs especially during the initiation of El Niño. Studies also indicate that the low frequency component of WWB is also substantially modified by extratropical circulation (e.g., Yu et al. 2003; Zheng et al. 2014a, b; Hong et al. 2017; Sullivan et al. 2021). That suggests the tropical-extratropical interaction might play a role on the establishment of unusually strong WWB. In reviewing the literatures, we found that whereas the effect of WWBs on the onset of El Niños had been widely discussed, the possible effect beyond ENSO, such as the extratropical systems, on the magnitude of WWB and the slow frequency component of WWB was less investigated. The observation yields that WWBs feature multiple timescales (Fig. 1) and its duration and magnitude exhibits highly diversity case by case. In this study, we decomposed the WWBs into different timescales based on a spectrum analysis. The relative contribution of distinct timescales fluctuations on the WWBs during the onset of El Niños was investigated. Especially, a comparison of the effect of the distinct frequency of WWBs on the onset of super El Niños and regular Niños was discussed. We reported that not-ENSO associated low frequency (≥ 90 days) WWBs play a crucial role on the magnitude and duration of extreme WWBs during the onset of super El Niño events, and this effect is not clearly seen in the regular El Niños. The remainder of this paper is organized as follows. The data and methods are documented in Sect. 2. In Sect. 3, we present the characteristics of WWBs by focusing on different timescales.

Fig. 1 a the variance and b power spectrum of near surface daily mean zonal wind (u10m, unit: m/s) from 1981 to 2016. Red noise was applied as the background for the significant test.
during the onset of three super El Niño events. The possible sources (processes) of the distinct timescales of WWBs, especially those which are interannual and intraseasonal, are addressed in Sect. 4. A summary and discussion of the findings is then presented in Sect. 5.

2 Data and methods

The datasets employed in this study comprised: (1) daily SSTs obtained from optimum interpolation sea surface temperature (OISST) version 2 (Reynolds et al. 2007); (2) monthly SSTs from the Met Office Hadley Centre sea ice and SST datasets (Rayner et al. 2003); (3) daily and monthly atmospheric fields of ERA-Interim and ERA-40 reanalysis (Uppala et al. 2005; Dee et al. 2011); (4) daily and monthly reanalysis of an outgoing longwave radiation dataset from the National Centers for Environmental Prediction (NCEP)/National Center for Atmospheric Research (NCAR) (Liebmann and Smith 1996); and (5) monthly ocean reanalysis data from the National Centers for Environmental Prediction (NCEP) global ocean data assimilation system (GODAS) (Behringer and Xue 2004). The study period is 1981–2016. The climatology was defined as the 36-year annual daily or monthly mean of atmospheric and oceanic variables from 1981 to 2016. For special long-term statistics, such as the 241 months (20 years) sliding correlation coefficient, a longer period during 1958–2016 was used.

The definition of El Niño basically followed that provided by Trenberth and Hoar (1997). Specifically, an El Niño event occurs when the corresponding oceanic Niño Index (ONI) is > 0.5 °C for at least 5 consecutive overlapping seasons; such ONI data were obtained from the climate prediction center of the US National Oceanic and Atmospheric Administration (available from https://origin.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ONI_v5.php). Based on the ONI data, 11 El Niño events were identified, comprising those in 1982, 1986, 1987, 1991, 1994, 1997, 2002, 2004, 2006, 2009, and 2015. Among these 11 events, the 1982, 1997, and 2015 events were considered super El Niño events because their ONI were larger than 1.5 standard deviations from the El Niño peak phase.

The WWBs were usually defined as the near surface zonal wind at 10 m (referred as u10m) larger then 4–6 m/s and persist 2–5 days (Hartten 1996; Yu et al. 2003; Gebbie and Tziperman 2009). The WWB event (or referred to westerly wind event, Harrison and Vecchi 1997; Sullivan et al. 2021) was defined as the box averaged of anomalous daily u10m in the equatorial western Pacific (150°E–170°E, 5°S–5°N) exceeds 5 m/s and persists at least for one day. A shorter duration used here to define WWB event was because that the magnitude of box averaged u10m was generally smaller than the grid’s wind.

Table 1 The initiation and ending date of the 17 WWBs for the super El Niños (1982, 1997 and 2015). Only the WWB occurs during January to June was selected

| Case | Date         | Case | Date         |
|------|--------------|------|--------------|
| S1   | 3/29–4/2     | S11  | 6/1–6/3      |
| S2   | 5/9–5/13     | S12  | 6/8–6/11     |
| S3   | 3/1          | S13  | 2/2–2/4      |
| S4   | 3/3–3/19     | S14  | 3/6–3/14     |
| S5   | 3/28         | S15  | 3/20–3/22    |
| S6   | 4/8          | S16  | 5/4–5/12     |
| S7   | 4/11–4/21    | S17  | 6/26–7/4     |
| S8   | 4/27–4/28    | S9   | 5/2–5/7      |
| S10  | 5/23–5/28    |      |              |

Table 2 Same as in Table 1 except for the 16 WWBs for regular El Niños (1986, 1987, 1991, 1994, 2002, 2004, 2006, 2009). Notably, no WWBs were identified in 2006 and 2009 because the WWBs occurred after July

| Case | Date   | Case | Date   |
|------|--------|------|--------|
| R1   | 5/10   | R11  | 6/29   |
| R2   | 5/13–5/19 | R12  | 1/6    |
| R3   | 5/11–5/12 | R13  | 3/26–4/4 |
| R4   | 5/19   | R14  | 4/14   |
| R5   | 3/16   | R15  | 6/21   |
| R6   | 3/19–3/20 | R16  | 6/24–6/26 |
| R7   | 5/11–5/12 |      |        |
| R8   | 3/25–2/28 |      |        |
| R9   | 1/31   |      |        |
| R10  | 2/25–2/28 |      |        |
The results yield the statistics were almost unchanged. A total of 17 and 16 WWBs during the onset of super and regular El Niño, respectively, were selected. The WWBs are detailed in Tables 1, 2. Averagely, 6 and 2.7 times of WWB occur for each of super El Niño and regular El Niño. It is evident more frequent WWBs occurred during the onset of super El Niño. Notably, no WWBs were identified in 2006 and 2009 because that the WWBs occurs after June 30 (not shown). Thus, the composite of regular El Niño only includes six El Niños.

The WWBs were further decomposed into three different frequencies based on the power spectrum (Fig. 1b), which were the low frequency westerly ($\geq$ 90 days, hereafter referred to as LFW), the medium frequency westerly (20–90 days, MFW), and the high frequency westerly ($\leq$ 20 days, HFW). The Lanczos filter (Duchon 1979) was used to separate distinct frequencies.
3 Characteristic of WWBs in three super El Niño events

3.1 Relative contribution of distinct timescale zonal wind fields on WWBs

Figure 2 presents a Hovmöller diagram (averaged over 5°S–5°N) of u10m anomalies (Fig. 2a–c), 20° isotherm depth anomalies (Fig. 2d–f), and SST anomalies (Fig. 2g–i) during the developing years of the three super El Niños (1982, 1997, and 2015). The diagram indicates that the WWBs were clearly identified in the western Pacific (150°E–170°E) during the initial stage of their corresponding El Niño event. For example, in 1997, strong WWBs occurred sequentially in the equatorial western Pacific during the onset stage (Fig. 2b). Following these, oceanic downwelling Kelvin waves propagating eastward from the western Pacific to the eastern Pacific were observed (Fig. 2d–f). When these waves reached the equatorial eastern Pacific, a significant positive SST anomaly occurred (Fig. 2g–i) because the downwelling Kelvin substantially decreased climatological upwelling in the equatorial eastern Pacific.

Figure 3a–c depicts the time series of box-averaged (150°–170°E, 5°S–5°N) anomalous u10m. A sequence of WWBs with amplitudes exceeding 5 m/s were clearly identified (marked with a vertical green highlight) during the onset of three super El Niños. The zonal winds were further decomposed into three distinct frequencies: the LFW (≥ 90 days), MFW (20–90 days), and HFW (≤ 20 days). The bottom panel of Fig. 3 indicates that the HFW exhibits a local peak for each of WWB. Most notably, the HFW was synchronized with a large MFW, which was accompanied with an evident positive LFW. Thus, the LFW in conjunction with the MFW and HFW can lead to an extreme WWB. Although the time series of WWBs (upper panels of Fig. 3) exhibited a high frequency, their magnitudes were substantially modulated by the MFW and LFW. To investigate the possible effect of ENSO on the LFW (i.e., El Niño induced equatorial zonal wind), the WWB index was recalculated by removing the component of ENSO-related WWB (i.e., the WWB regressed onto the Niño3.4 index). A comparison between the original WWB and non-ENSO WWB (black and blue lines in the upper panels of Fig. 3) revealed that the major difference between both indices occurs in the boreal winter (approximately in peak phase of El Niño), and their magnitude are approximately the same during the initiation stage. That indicates the LFW during the onset stage of super El Niño was not determined by the Niño3.4 SST. Figure 4 (left panels) reveals the relative contribution of each frequency on the total WWBs for all the 17 cases. Except for case 1 and 2, the magnitude of WWBs was primarily determined by the LFW and the contribution of MFW and HFW was relatively smaller. On average, the LFW contributed approximately 56% to the WWBs and the MFW and HFW, with similar contributions (22%), accounted for the residual portion (44%). The LFW and MFW thus accounted for approximately 80% of the magnitude of WWBs. The LFW clearly played a dominant role in extreme WWBs during the onset of the super El Niños. Notably, whereas the contribution of non-ENSO LFW slightly decrease (unfilled bar in right panel), it also accounts for 49% of the total WWBs and is the dominant term.
3.2 Comparison of WWBs between regular El Niño and super El Niño events

Figure 4 reveals that the majority of extreme WWBs during the onset of super El Niños primarily resulted from LFW. This raises the question as to whether the LFW and MFW also contributed substantially to WWBs during the onset of regular El Niños. To answer this question, 16 WWBs were selected from the regular El Niños that occurred during 1980–2016. Table 2 details these WWBs; the data indicated that the MFW and HFW contributed 37 and 35%, respectively, to the total WWBs and that the contribution of LFW was relatively small (28%) (Fig. 4). In contrast to the super El Niños, the MFW and HFW, both accounting for approximately 75% of total WWBs, dominated the WWBs during the onset of the regular El Niños.

A further comparison between super El Niños and regular El Niños by using the box plot (Fig. 5) reveals that the LFW of super El Niños was significantly (exceeding 95% confidence level) larger than that of regular El Niños. The magnitude of MFW of regular El Niños was larger than that of super El Niños, but the difference was not significant at 95% confidence level. In contrast to LFW, the magnitude of HFW for super El Niños was significantly (at 95% confidence level) smaller than for regular El Niños. The box plot also applied to neutral years.

Figure 4 The relative contribution (percentage) of LFW (red bar), MFW (blue bar), and HFW (gray bar) to the total WWBs for a super El Niños (17 cases) and b regular El Niños (16 cases). From left to right represents each cases of WWB (filled bar), the mean (filled bar), and the mean without ENSO effect (unfilled bar). The numbers next to each component represents the percentage (%) and magnitude (unit: m/s) of mean u10m.
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Overall, the HFW became smaller compared with the regular El Niños, besides the occurrence frequency of WWBs decrease substantially compared with super El Niño yeas (not shown). The detail comparison among different time scale of WWBs was summarized in Table 3. It comes out that the major difference between both groups of El Niño was the LFW plays a crucial role on the total WWBs for super El Niños, which was not identified in the regular El Niños. Additionally, the extreme WWBs during the onset of super El Niños were dominated by the LFW and further enhanced by MFW and the HFW. Conversely, the magnitude of the MFW and HFW was evidently larger than that of the LFW for regular El Niños. Thus, the WWBs were determined by the MFW and HFW, with the LFW playing a secondary role for regular El Niños. Figure 5 and Table 3 clearly indicate that the LFW was crucial in the onset of super El Niños. The slowly varying zonal wind in the equatorial western Pacific appeared to provide a favorable large-scale condition for the onset of super El Niños.

4 Possible physical processes-associated low frequency WWBs

Since lots of studies (McPhaden et al. 2006b; Hendon et al. 2007) mentioned the MJO-associated westerlies are important to the WWBs, our result is consistent to previous studies. Figure 6 depicts the Hovmöller diagrams of anomalous u10m (shaded) and 20–90 days OLR (contour, referred as MJO) during the development of the super El Niños. The OLR was filtered using a space–time filtering method developed by Wheeler and Kiladis (Wheeler and Kiladis 1999; Kiladis et al. 2006) with a cut-off period of 20–90 days. The eastward and westward waves were defined as zonal wavenumbers 1–4 and −1 to −15, respectively. The right panels in Fig. 6a–c indicate the time series of the box average (5°S–5°N, 150°E–170°E) of the non-filter zonal wind for the strong El Niños. It revealed that the WWBs were associated with eastward propagating MJO for 20–90 days. The OLR fields also indicate that the MJO propagated eastward from the Indian Ocean to the central Pacific. Following the arrival of the MJO at the equatorial western Pacific, an evident WWB was identified (shaded and red curves in Fig. 6a–c). The same approach was applied to the regular El Niños (Fig. 6d–h). Overall, the WWBs were followed by an eastward propagating MJO from the Indian Ocean to central Pacific. Figure 6 indicates that the MFW-associated WWBs were also associated with the eastward propagation of MJO. The role of MJO-associated westerlies in triggering the onset of El Niños is consistent with the findings of previous studies (McPhaden 1999; McPhaden et al. 2006b; Hendon et al. 2007; Seiki and Takayabu 2007a, b; Hong et al. 2017).

4.1 LFW associated SST and low-level wind

Figure 7a–b depicts a comparison of low-pass-filtered (≥ 90 days) u10m and SSTA during the onset stage for super El Niños and regular El Niños, respectively. A cyclonic circulation anomaly in the tropical western Pacific, accompanied by a southwest–northeast titled positive SSTA in the tropical central–eastern Pacific, was clearly identified for super El Niños (Fig. 7a). The anomalous cyclone yielded a Matsuno–Gill response (Matsuno, 1966; Gill, 1980) to the positive SSTA in the equatorial central Pacific. Evidently, the LFW in the equatorial western Pacific that contributed substantially to WWBs (Fig. 4) was associated with the positive SSTA distributing form the equatorial central to the subtropical eastern North Pacific. In contrast to super El Niños, the low frequency signals of SST and wind were relatively

Table 3 The student t test among different time scale of WWBs. The number out (in) bracket indicates the super (regular) El Niño. The bold number indicates the mean difference of student t exceeding the 99% confidence level

|                  | HFW (≤ 20 days) | MFW (20–90 days) | LFW (≥ 90 days) |
|------------------|-----------------|------------------|-----------------|
| HFW (≤ 20 days)  | 0.14 (0.36)     | 6.09 (−1.84)     |                 |
| MFW (20–90 days) |                 | 4.87 (−1.98)     |                 |
| LFW (≥ 90 days)  |                 |                  |                 |

Super El Niño cases: 17; Regular El Niño cases: 16

Overall, the HFW became smaller compared with the regular El Niños, besides the occurrence frequency of WWBs decrease substantially compared with super El Niño yeas (not shown). The detail comparison among different time scale of WWBs was summarized in Table 3. It comes out that the major difference between both groups of El Niño was the LFW plays a crucial role on the total WWBs for super El Niños, which was not identified in the regular El Niños. Additionally, the extreme WWBs during the onset of super El Niños were dominated by the LFW and further enhanced by MFW and the HFW. Conversely, the magnitude of the MFW and HFW was evidently larger than that of the LFW for regular El Niños. Thus, the WWBs were determined by the MFW and HFW, with the LFW playing a secondary role for regular El Niños. Figure 5 and Table 3 clearly indicate that the LFW was crucial in the onset of super El Niños. The slowly varying zonal wind in the equatorial western Pacific appeared to provide a favorable large-scale condition for the onset of super El Niños.
small for regular El Niños (Fig. 7b). Consistent with Fig. 3, this indicates that LFW was not the crucial factor in the onset of regular El Niños.

To investigate the relationship between the LFW and SSTA, we conducted a regression of SST and u10m on the LFW index; the LFW index was defined as the average LFW over the box shown in Fig. 7a. The regression map yielded a result similar to the composite of super El Niños (comparing Fig. 7a, c, the anomaly pattern correlation coefficient was 0.76), that is, a large-scale cyclonic circulation anomaly in the tropical western Pacific accompanied a positive SSTA in the equatorial central Pacific. Notably, the LFW index in MAM is used for indicating the ENSO onset stage. We used the LFW index in the other season, such as JFM (January, February, March) and JFMAM (January to May), to instead of MAM. It yields that the results are almost the same if the season falls in the onset stage (January–June). Figure 7d was recalculated by removing the ENSO effect (i.e., removing the regression of SSTA and wind onto the peak phase of Niño 3.4). It yields that except the magnitude decreases

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**Fig. 6** (Left panel) The Hovmöller diagram (averaged over 5°S–5°N) of u10m anomalies (shaded) and 20–90 days filtered OLR (contour), and (right panel) the time series of corresponding WWB index for super El Niño year in a 1982, b 1997, and, e 2015 and regular El Niño year in d 1986, e 1987, f 1991, g 1994, h 2002, and i 2004. The black dashed lines represent the WWBs. The space–time filter (Wheeler and Kiladis 1999; Kiladis and et al. 2006) was used for filtering OLR.
slightly, the spatial pattern nearly unchanged (comparing Fig. 7c, d). That indicates the major source of LFW in the western Pacific during the onset of super El Niños was not determined by the ENSO. Figure 7d yields that the LFW in the western Pacific was associated with a positive SSTA in the central Pacific. This linkage was further demonstrated by the scatter diagram of the LFW index against the SSTA in the equatorial central Pacific (170°E–170°W, 5°S–5°N) following Lindzen and Nigam (1987). It yields that both indices have a significant linear correlation coefficient (cr = 0.73, Fig. 8a) and this relationship still remains when effect of ENSO was removed off (cr = 0.53, Fig. 8b). In particular, the LFW index and the SSTA in the equatorial central Pacific reached a high value in 1982, 1997, and 2015 (marked with black circles in Fig. 8). Notably, the El Niño in 1987 had a high LFW index in MAM. However, it did not develop into a super El Niño because the magnitude of the MFW was weaker than that of the super El Niño during the onset stage. It indicates that a high LFW was a necessary but insufficient condition for the onset of a super El Niño. Only a high LFW in conjunction with an extreme MFW and HFW can lead to the extreme WWBs necessary for triggering a super El Niño.

4.2 Linkage between tropical–extratropical SSTs

Figure 7c shows that the LFW index was significantly correlated with SSTs, distributing from equatorial central Pacific to the subtropical eastern North Pacific. The possible linkage between tropical and extratropical SSTs was investigated through a lead–lag regression of SST and u10m wind on the LFW index. The results clearly revealed a horseshoe-shaped warm SST in the eastern North Pacific (≈150°W, 40°N) in the previous MAM prior to the initiation of a positive SSTA in the equatorial western Pacific (Fig. 9a). The warm SST gradually moved from being extratropical to tropical and arrived at the equatorial central Pacific in DJF (−1) (Fig. 9c–d). Notably, a westerly wind extending eastward from the equatorial western Pacific (≈150°E) and a southwesterly in the subtropical eastern North Pacific (≈150°W) were well established, associated with the horseshoe-shaped warm SST prior to the initiation of a positive SSTA in the equatorial central Pacific (comparing Fig. 9a–b with c). This suggested that the LFW was probably triggered by the subtropical positive SST anomalies. Figure 9c–d reveals that the southwesterly anomaly was against the prevailing northeasterly trade wind.
The anomaly decreased the prevailing wind substantially and thus provided positive feedback to the horseshoe-shaped warm SST through the wind–evaporation–SST feedback (Xie and Philander 1994; Xie 1996) (Fig. 9c, d). Accompanied by the warm SST extending to the equator, a stronger westerly occurred west of the center of the warm SST (150°E–180°E). The westerly and SST then continued to grow and finally developed into a super El Niño (Fig. 9e–h).

The lead–lag correlation coefficients among the three boxes, with major positive SSTAs in the equator (referred to as ST1), subtropical (referred to as ST2), and extratropical (referred to as ST3) (boxes in Fig. 9a) were calculated to investigate the linkage between tropical SST and extratropical SST. The results revealed that ST3 led ST1 (blue curve) by approximately 9 months and ST2 led ST1 (red curve) by 0–2 months (Fig. 10a). Evidently, the warm SST in the equatorial central Pacific had a significant lagged correlation with the subtropical–extratropical SST in the eastern North Pacific, a result similar to that reported in other recent studies (Bond et al. 2015; Di Lorenzo and Mantua 2016; Joh and Di Lorenzo 2017). We found that the aforementioned lead–lag relationship had become stronger since the late 1980s (Fig. 10b).

The enhancement of the interaction of tropical–extratropical Pacific SST since that time (the late 1980s) is concurrent with the active period of the central Pacific El Niño, which the tropical–extratropical interaction indicates is the crucial process that triggered its onset (Xie et al. 2013; Yu et al. 2015). Figure 10b presents the correlation of extratropical SST (ST3) and tropical SST (ST1) became higher since 1980. Additionally, The regression of 500 hPa geopotential height on LFW revealed that a meridional dipole-like structure in the North Pacific was clearly identified in SON(-1) (Fig. 11e) during 1980–2000, which was not observed in 1960–1980 (Fig. 11b). This dipole developed to a North Pacific Oscillation (NPO)-like structure in DJF (−1) (Fig. 11f), which persisted until the following spring. Whereas a similar dipole structure was seen in DJF (−1) during1960–1980 (Fig. 11c), the center of dipole structure associated cyclone anomaly in the south shifted westward approximately 15° longitude (∼180°E) compared with that in 1980–2000 (∼165°E) (comparing Fig. 11c with f). This westward shift leads to the cyclone anomaly associated southeasterly wind anomaly was not well coupled with the PMM-like positive SSTA as seen in 1980–2000. That is the LFW index that was associated with NPO-like atmospheric circulation played a critical role in bridging the tropical–extratropical SST interaction. A similar result was mentioned by Di Lorenzo et al. (2010). Notably, whereas the NPO-like associated cyclonic anomaly centered in north 20°N, the cyclone associated southwesterly extends approximately to 5°N. The southwesterly anomaly was against the prevailing northeasterly wind in situ to create a favorable environment for a positive SST anomaly in extratropical eastern North Pacific to develop to tropical eastern-central Pacific through the WES feedback (Di Lorenzo et al. 2010; Yu et al. 2015; Ding et al. 2015). Briefly, the south pole of the NPO-like pattern induced a lower-level cyclonic circulation anomaly in the eastern North Pacific that may have weakened the prevailing northeasterly trade wind in previous autumn to winter (Fig. 11b, d). This contributed to the Pacific Meridional Mode (PMM)-like (south part of horseshoe-shaped) SST warming through wind–evaporation–SST
Fig. 9 The lead–lag regression of seasonal mean SSTA and u10m anomalies onto the monthly LFW index (MAM0) during 1981–2016. The negative (positive) number in the bracket represents the seasons of SSTA and wind anomalies lead (lag) LFW index. The shaded and vector indicate the signal exceeding 95% confidence level. The purple vector in (e) represents the climatological wind at 850 hPa.
feedback (Chiang et al. 2004; Chang et al. 2007). The role of NPO in the initiation of El Niño was also reported by Ding et al. (2017).

To further diagnose the warm SST, Fig. 12a depicts the regression of SST tendency in DJF (−1) onto the LFW index in MAM (0). A southwest–northeast tilted positive SST tendency anomaly in the extratropical eastern North Pacific was identified in the preceding winter. The SST tendency is determined by the atmospheric process (i.e., surface flux) and oceanic dynamic (i.e., temperature advection) (Li et al. 2002; Hong et al. 2008). A calculation reveals that the positive SST tendency in the extratropical eastern North Pacific was primarily resulted from the surface flux (Fig. 12b) and the contribution of oceanic temperature advection was relatively small (not shown). Because the SST tendency leads the SST approximately 1–2 months, the southwest–northeast tilted positive SST anomaly in the extratropical eastern North Pacific as shown in Fig. 9d–e is evidently caused by the surface flux, which is dominated by the latent heat flux (Fig. 12c). Figure 12d further reveals that the positive SST tendency (blue box in Fig. 12a) initiates approximately in the previous summer, peaks in winter, and changes to negative in the next spring. The SST warming in the eastern North Pacific was primarily resulted from the latent heat flux and partially contributed by the sensible heat and shortwave radiation. Figures 11, 12 reveal that the tropical–extratropical SSTs interaction in the eastern North Pacific is primarily through the atmospheric process, the wind–evaporation–SST feedback.

5 Summary and discussion

This study investigated the relative contribution of distinct timescales, namely HFW (≤20 days), MFW (20–90 days), and LFW (≥90 days), of zonal wind on the WWBs during the initiation of super El Niño during the onset of super and regular El Niño events. The main results were as follows:

(1) Our observations revealed that extreme WWBs during the onset of the super El Niño group were resulted from a combination of LFW, MFW, and HFW, accounted for approximately 56, 22, and 22%, respectively. This indicates the LFW plays the dominant term, which was further enhanced by the MFW and HFW, on contributing to the extreme WWBs during the onset of super El Niños. It is evident the high frequency WWBs were substantially modified by the low frequency and intra-seasonal variability.

(2) In contrast to super El Niños, the WWBs were primarily determined by the MFW (38%) and HFW (35%) during the onset of regular El Niños. The contribution of the LFW to the WWBs was smaller than that of the MFW and HFW. The major distinction between super and regular El Niños lies in the crucial role played by the LFW during the onset of super El Niños.

(3) Our observations revealed that the MFW during the onset of super El Niños primarily resulted from the MJO. The onset of regular El Niños exhibited similar results, although the magnitude of the MJO was smaller. The MJO-associated WWBs played an essential role in triggering the onset of super El Niños and regular El Niños.

(4) The regression analysis indicated that the super El Niño–related LFW occurred in response to the positive SSTA in the tropical central Pacific to subtropical eastern North Pacific resembling the PMM, which had persisted during the preceding 9–12 months in the extratropical eastern North Pacific. A further analysis by removing the ENSO effect yields that the positive SSTA in the tropical central Pacific was not initiated by SST in the Niño3 or Niño3.4. A significant lagged
correlation between the tropical and extratropical North Pacific SST was identified, and their correlation has become stronger since the late 1980s. The LFW associated with NPO-like atmospheric circulation was suggested to play a critical role in enhancing this relationship.

This study reported that extreme WWBs triggering the onset of super El Niños were primarily determined by the LFW and MFW, both accounting averagely for approximately 80% of the total WWBs. Although WWBs exhibit a high frequency, the high frequency zonal wind alone was not sufficient to generate an extreme WWB. It is the LFW combined with the MJO-associated MFW and the HFW that created the extreme WWBs necessary for triggering super El Niños (Vecchi and Harrison 2000; Lengaigne et al. 2003; Hu et al. 2014; Chen et al. 2017). By contrast, the LFW was relatively small compared with the MFW and HFW during the onset of regular El Niños. Evidently, the LFW played a critical role in triggering super El Niños: the non-Niño3.4 associated with LFW and warm SST in the tropical central Pacific provided favorable atmospheric and oceanic preconditions for the onset of super El Niños.

The regression revealed that the LFW primarily occurred in response to the warm SST in the tropical central Pacific, which had a significant lagged correlation with the extratropical SST. This indicates that the extratropical SST could have been a precursor of El Niño (Chen et al. 2020), and may have been so since the late 1980s. The role of extratropical SST in the prediction of super El Niños merits further attention. The conclusions drawn in this study are limited by the small sample of super El Niños. The role of LFW and tropical–extratropical SST interaction in the onset of super El Niños will be investigated in future research by diagnosing long-term air–sea coupled simulations.
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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.

References

An S-I, Wang B (2001) Mechanisms of locking of the El Niño and La Niña mature phases to boreal winter. J Clim 14:2164–2176. https://doi.org/10.1175/1520-0442(2001)0142.0.0.CO;2

Ashok K, Behera SK, Rao SA, Weng H, Yamagata T (2007) El Niño Modoki and its possible teleconnection. J Geophys Res 112:C11007. https://doi.org/10.1029/2006JC003798

Behringer DW, Xue Y. (2004) Evaluation of the global ocean data assimilation system at NCEP: The Pacific Ocean. eighth symposium on integrated observing and assimilation systems for atmosphere, Oceans, and land surface, Seattle, WA. Amer Meteor Soc 2.3. [Available online at https://ams.confex.com/ams/84Annual/techprogram/paper_70720.htm.]

Bjerkenes J (1969) Atmospheric Teleconnections from the equatorial Pacific1. Mon Weather Rev 97:163–172. https://doi.org/10.1175/1520-0493(1969)072.3.CO;2

Bond NA, Cronin MF, Freeland H, Mantua N (2015) Causes and impacts of the 2014 warm anomaly in the NE PACIFIC. Geophys Res Lett 42:3414–3420. https://doi.org/10.1002/2015GL063306

Bosc C, Delcroix T (2008) Observed equatorial Rossby waves and ENSO-related warm water volume changes in the equatorial
Role of low-frequency wind variability in inducing WWBs during the onset of super El Niños

Vecchi GA, Harrison DE (2000) Tropical Pacific sea surface temperature anomalies, El Niño, and equatorial westerly wind events. J Clim 13:1814–1830. https://doi.org/10.1175/1520-0442(2000)0132.0.co;2
Vecchi GA (2000) Sub-seasonal wind variability and El Niño. Dissertation, University of Washington, pp 184
Ward PJ, Jongman B, Kummu M, Detttinger MD, Weiland FCS, Winsenius HC (2014) Strong influence of El Niño Southern oscillation on flood risk around the world. Proc Natl Acad Sci 111:15659–15664. https://doi.org/10.1073/pnas.1409822111
Weng H, Behera SK, Yamagata T (2009) Anomalous winter climate conditions in the pacific RIM during recent El Niño Modoki and El Niño events. Clim Dyn 32:663–674. https://doi.org/10.1007/s00382-008-0394-6
Wheeler M, Kiladis GN (1999) Convectively coupled equatorial waves: analysis of clouds and temperature in the wavenumber-frequency domain. J Atmos Sci 56:374–399. https://doi.org/10.1175/1520-0469(1999)0562.0.co;2
Xie S-P (1996) Westward propagation of latitudinal asymmetry in a coupled ocean-atmosphere model. J Atmos Sci 53:3236–3250. https://doi.org/10.1175/1520-0469(1996)0532.0.co;2
Xie S-P, Philander SGH (1994) A coupled ocean-atmosphere model of relevance to the ITCZ in the eastern Pacific. Tellus a: Dyn Meteorol Oceanogr 46:340–350. https://doi.org/10.3402/tellusa.v46i4.15484
Xie R, Huang F, Ren H (2013) Subtropical air-sea interaction and development of central Pacific El Niño. J Ocean Univ China 12:260–271. https://doi.org/10.1007/s11802-013-2143-7
Yu L, Waller RA, Liu WT (2003) Case analysis of a role of ENSO in regulating the generation of westerly wind bursts in the western equatorial Pacific. J Geophys Res Oceans 108:3128. https://doi.org/10.1029/2002jc001498
Yu J-Y, Kao P-k, Paek H et al (2015) Linking emergence of the Central Pacific El Niño to the Atlantic multidecadal oscillation. J Clim 28:651–662. https://doi.org/10.1175/jcli-d-14-0034.1
Zheng Y, Zhang R, Bourassa MA (2014a) Impact of East Asian winter and Australian summer monsoons on the enhanced surface westerlies over the western tropical Pacific Ocean preceding the El Niño Onset. J Clim 27:1928–1944. https://doi.org/10.1175/JCLI-D-13-00369.1
Zheng F, Fang X-H, Yu J-Y, Zhu J (2014b) Asymmetry of the Bjerknes positive feedback between the two types of El Niño. Geophys Res Lett 41:7651–7657. https://doi.org/10.1002/2014gl062125

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