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 bursts (WWBs) was investigated during the onset of super (1982, 1997, and 2015) and moderate 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 (≤ 10 days, HFW) components, accounting for approximately 51%, 33% and 16%, respectively. Thus, the extreme WWBs during the onset of super El Niños were primarily contributed by LFWs and MFWs. By contrast, the WWBs during the onset of moderate El Niños were determined primarily by MFWs (38%) and HFWs (35%), whereas the LFW contribution is relatively small (27%). A 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.

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; 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).

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 is suggested to be the crucial factor triggering El Niño (Vecchi and Harrison 2000; Lengaigne 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 ($\sim$ several days) was relatively shorter than the lifecycle of El Niño (1 $\sim$ 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; Chen et al. 2015).

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 2007). Recently, Sullivan et al. (2021) demonstrated that the magnitude of high frequency WWBs were substantially modified by not-ENSO related low frequency variability, which was strongly connected with the Asian and Australian. His study suggests that quantifiable physical processes rather than atmospheric stochastic signals determine the WWBs especially during the initiation of El Nino. In reviewing the literatures, we found that whereas the effect of WWBs on the onset of El Niños had been widely discussed, the effect of low frequency variation on the WWBs, especially the duration, was less investigated. However, 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 moderate (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 moderate 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 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 Method

The datasets employed in this study comprised: (1) daily SSTs obtained from optimum interpolation sea surface temperature (OISST) version 2 (Reynolds et al. 2007) for the period of September 1981–September 2016; (2) monthly SSTs from the Met Office Hadley Centre sea ice and SST datasets (Rayner et al. 2003) for the period of 1958–2016; (3) atmospheric fields of ERA-Interim and ERA-40 reanalysis (Uppala et al. 2005; Dee et al. 2011); (4) 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) ocean reanalysis data from the National Centers for Environmental Prediction (NCEP) global ocean data assimilation system (GODAS) (Behringer and Xue 2004) for the period of 1979–2016. Climatology was defined as the 36-year mean of atmospheric and oceanic variables from 1981 to 2016.

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 $> 0.5^{\circ}\text{C}$ 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 of WWBs usually defined as the near surface zonal wind (u_{10m}) larger than $4\text{--}6\text{ m/s}$ and persist $2\text{--}5$ days (Hartten 1996; Yu et al. 2003; Gebbie and Tzipermam 2009). The WWB event was defined as the box averaged of u_{10m} in the equatorial western Pacific ($150^{\circ}\text{E}\text{--}170^{\circ}\text{E}$, $5^{\circ}\text{S}\text{--}5^{\circ}\text{N}$) exceeds 5 m/s and persists at least for one day. The box is select based on the variance of u_{10m} that exhibits local maximum (Fig. 1). Here, we use a shorter duration than the typical definition was because the box averaged u_{10m} was used instead of the grid's wind. A sensitivity test reveals that the statistics of WWBs was not sensitive to the definition of the duration of WWB. In considering the duration of WWBs was generally prolonged in super El Niño, two WWBs with break less than one day was considered as a joint event. Because the onset of El Niños was generally initiated in the borer spring–summer, only WWBs occurring before August were analyzed. A total of 9 and 10 WWBs during the onset of super and moderate El Niño, respectively, were selected. The WWBs are detailed in Table 1 and Table 2. Averagely, 3.3 and 1.3 times of WWB occur for each of super El Niño and moderate 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 (Table 2), the composite of moderate El Niño only includes six El Niños.

Table 1
The initiation and ending date of the 9 WWBs for the super El Ninos (1982, 1997 and 2015).

Case	Date	Peak Phase
S1 (1982)	3/29–4/2	4/1
S2 (1982)	5/9–5/13	5/12
S3 (1997)	3/1–3/19	3/14
S4 (1997)	4/8–4/21	4/14
S5 (1997)	5/2–5/7	5/6
S6 (1997)	5/23–6/11	5/24
S7 (2015)	3/6–3/14	3/13
S8 (2015)	5/4–5/12	5/9
S9 (2015)	6/26–7/5	7/2

Table 2
Same as in Table 1 except for the 10 WWBs for moderate El Ninos (1986, 1987, 1991, 1994, 2002, 2004, 2006, 2009). Notably, no WWBs were identified in 2006 and 2009.

Case	Date	Peak Phase
R1 (1986)	5/10–5/19	5/17
R2 (1987)	5/11–5/12	5/11
R3 (1987)	5/19	5/19
R4 (1991)	3/19–3/20	3/19
R5 (1991)	5/11–5/12	5/11
R6 (1994)	3/21	3/21
R7 (2002)	1/31	1/31
R8 (2002)	2/25–2/28	2/27
R9 (2004)	3/26–4/4	3/30
R10(2004)	6/21–6/26	6/25

The WWBs were further decomposed into three different frequencies based on the power spectrum (Fig. 1b), which were the low frequency westerly (≥ 90 days, hereafter referred to as LFW), the medium

frequency westerly (20–90 days, MFW), and the high frequency westerly (≤ 10 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 850 hPa zonal wind anomalies (Fig. 2a–c), 20° isotherm depth anomalies (Fig. 2d–f), and SST anomalies (Fig. 2g–i) during the years in which three super El Niños (1982, 1997, and 2015) developed. 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, three 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 SSTA 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 $u_{10\text{m}}$ winds. 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 (≤ 10 days). The bottom panel of Fig. 2 indicates that the HFW reached a high value in each WWB for all 9 cases. Most notably, the HFW was synchronized with a large MFW, which occurred during the positive phase of the LFW. Thus, the MFW and LFW in conjunction with the 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 LFW 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 El Niño was not determined by the ENSO. Figure 4 (left panels) reveals the relative contribution of each frequency on the total WWBs for all the 9 cases. Except for case 1, the magnitude of WWBs was primarily determined by the LFW or MFW and the contribution of HFW was relatively smaller. On average, the LFW and MFW contributed approximately 51% and 33%, respectively, to the WWBs, with the HFW contributing to the residual portion (16%). The LFW and MFW thus accounted for more than 80% of the WWBs. The LFW and MFW clearly played a dominant role in extreme WWBs during the onset of the three super El Niños. Notably, whereas the contribution of non-ENSO LFW slightly decrease (hollow bar in right panel), it also accounts for 42% of the total WWBs and is the dominant term.

3.2 Comparison of WWBs between Moderate El Niño and Super El Niño Events

Figure 4 reveals that the majority of extreme WWBs during the onset of super El Niños resulted from LFW and MFW. This raises the question as to whether the LFW and MFW also contributed substantially to WWBs during the onset of moderate El Niños. To answer this question, 10 WWBs were selected from the moderate El Niños that occurred during 1980–2016. Table 2 details these 10 WWBs; the data indicated that the MFW and HFW contributed 38% and 35%, respectively, to the total WWBs and that the contribution of LFW was relatively small (27%) (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 moderate El Niños.

A further comparison between super El Niños and moderate El Niños by using the box plot (Fig. 5) reveals that the LFW of super El Niños was significantly ($p \leq 0.01$) larger than that of moderate El Niños. The MFW of super El Niños was nearly the same magnitude compared with of the moderate El Niños and both do not exhibit significant difference. In contrast to LFW and MFW, the magnitude of HFW for super El Niños was smaller than for moderate El Niños. 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 moderate El Niños. Additionally, the extreme WWBs during the onset of super El Niños were dominated by the LFW and MFW and further enhanced by the HFW. Conversely, the magnitude of the MFW and HFW was evidently larger than that of the LFW for moderate El Niños. Thus, the WWBs were determined by the MFW and HFW, with the LFW playing a secondary role for moderate El Niños. Figure 5 and Table 3 clearly indicate that the LFW and MFW were 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. In the next section, we discuss the possible physical processes associated with LFW and MFW.

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

HFW	MFW	LFW
HFW	2.11(0.46)	4.20 (-1.11)
MFW		2.17 (-1.62)
LFW		

4. Possible Physical Processes-associated Low Frequency Wwbs

Since lots of studies (McPhaden et al. 2006; Hendon et al. 2007) mentioned the MJO-associated westerlies are important to the WWBs, our result is consistent to previous studies. Figure 6 depicts presents the Hovmöller diagrams of anomalous u_{10m} (shaded) and 20–90 days OLR (contour) 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 to 4 and – 1 to – 15, respectively. The right panels in Fig. 6a–c indicate the time series of the box average ($5^{\circ}\text{S}–5^{\circ}\text{N}$, $150^{\circ}\text{E}–170^{\circ}\text{E}$) of the non-filter zonal wind for the three 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 moderate El Niños (Fig. 6d–h). Overall, the WWBs were followed by an eastward propagating MJO from the Indian Ocean Fig. 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; 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) low-level wind and SSTA during the onset stage for super El Niños and moderate El Niños, respectively. A cyclonic circulation anomaly in the WNP, accompanied by a southwest–northeast tilted 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 in the equatorial central to eastern North Pacific. In contrast to super El Niños, the low frequency signals of SST and wind were relatively small for moderate El Niños (Fig. 7b). Consistent with Fig. 3, this indicates that LFW was not the crucial factor in the onset of moderate El Niños.

To investigate the relationship between the LFW and SSTA, we conducted a regression of SSTA and u_{10m} 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 and c, the anomaly pattern correlation coefficient was 0.76), that is, a large-scale cyclonic circulation anomaly in the western North Pacific accompanied a warm SSTA in the equatorial central Pacific. The Fig. 7c was probably induced from the El Niños. Figure 7c 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 expect the magnitude decrease slightly, the spatial pattern nearly unchanged (comparing Fig. 7c and 7d). 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 a response to the

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). 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.

b. 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 ($\approx 150^\circ\text{W}$, 40°N) in the previous MAM prior to the initiation of a LFW 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 southwesterly extending from the equator ($\approx 150^\circ\text{E}$) to the subtropical Pacific was well established in response to 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 indicated that the LFW was not initiated by the tropical SST but by the subtropical warm SST. 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 east of the center of the warm SST (150°E – 180°E). The westerly and SSTA 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). The regression of 500 hPa geopotential height on the LFW index indicated that the tropic and extratropical interaction became stronger since 1980s (comparing Fig. 11a, c; Fig b, d). That is the LFW index that was associated with North Pacific Oscillation (NPO)-like atmospheric circulation played a critical role in bridging the tropical–extratropical SST interaction. Specifically, 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 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 MAN (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). The time series of box averaged (blue box in a) lead–lag regression further indicates that the positive SST tendency 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 and 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 moderate 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 51%, 33%, and 16%, 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 moderate 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 moderate 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 moderate 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 moderate 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 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 ENSO. 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 be 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 more 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. By contrast, the LFW was relatively small compared with the MFW and HFW during the onset of moderate El Niños. Evidently, the LFW played a critical role in triggering super El Niños: the LFW and associated 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 correlated 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.

Declarations

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Figures

Figure 1

(a) the variance and (b) power spectrum of near surface daily mean zonal wind (u10m) from 1979 to 2018.

Figure 2

The Hovmöller diagram (averaged over 5°S–5°N) of (a–c) 850 hPa zonal wind anomalies, (d–f) 20° isotherm depth anomalies, and (g–i) SST anomalies for the three super El Niños (1982, 1997, and 2015).

Figure 3

(upper panels) The time series of WWBs index (averaged u10m over 150°E–170°E, 5°S–5°N, box in fig.1a; black line) for (a) 1982, (b) 1997, and (c) 2015. The dot blue line is same as black line except for the ENSO associated WWB was removed off. (bottom panels) Decomposition of WWB index into the low frequency westerly (≥ 90 days, referred as LFW, red line), the medium frequency westerly (20–90 days, referred as MFW, blue line), and the high frequency westerly (≤ 10 days, referred as HFW, gray line) by Lanczos filter (Duchon, 1979). The vertical green shading indicates WWBs during the onset of the super El Niños.

Figure 4

(left panel): The relative contribution (percentage) of LFW (red bar), MFW (blue bar), and HFW (gray bar) to the total WWBs of each of WWBs (Table 1) for the super El Niños. (right panel): Same as in left panel except for the comparison between the composite WWBs of “super El Niños” and “moderate Niños”. The

filled and hollow bar indicates with and without ENSO (remove the regression of WWBs onto Niño 3.4 index) respectively.

Figure 5

The comparison of box plot of multiple timescales of WWBs (i.e., HFWs, MFWs, and LFWs) between super El Niño (red box) and moderate El Niño (gray box). The black horizontal line shown in each box plot (from top to bottom) represent the maximum, 75th, medium (50th), 25th percentiles, and minimum respectively. The red horizontal line shown in each box plot denotes the mean. The number represents the p-value of mean difference between super El Niños and moderate El Niños.

Figure 6

(left panel) The Hovmöller diagram (averaged over 5°S – 5°N) of $u_{10\text{m}}$ 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, (c) 2015 and moderate 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.

Figure 7

A comparison of composite anomalous SST and u10m during duration of the WWBs (listed in Table 1 and Table 2) between the (a) super El Niños, and (b) moderate El Niños. (c) The regression of box-averaged LFW over 150°E–170°E, 5°S–5°N (the blue box in panel a) onto the anomalous SST and u10m in boreal spring (from March to May). (d) is same as (c) but without ENSO effect (remove the regressions onto Niño 3.4 index). The shaded and black vector in (c) and (d) indicates the signals exceeding 95% confidence level.

Figure 8

(a) The scatter diagram of the box-averaged (170°E – 170°W , 5°S – 5°N) SSTA and box-averaged (150°E – 170°E , 5°S – 5°N) $u_{10\text{m}}$ anomalies in MAM during 1958 to 2016. The boxes are selected based on Fig. 7c, in where the tropical LFW and SSTA yield local maximum, respectively. The black line represents the linear regression line. The red, blue, and gray dots represent El Niño, La Niña, and normal year. The open

(close) circles indicate the year before (after) 1980. A 3 months running mean was applied to the SST and wind fields in the plotting. (b) is same as (a) but the ENSO effect was removed off

Figure 9

The lead-lag regression of seasonal mean SSTA and 850 hPa wind anomalies onto the LFW index. 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.

Figure 10

The lead-lag correlation coefficient between tropical SST (averaged SST over 170°E–170°W, 5°S–5°N, referred to as ST1) and subtropical SST (averaged over 115°W–155°W, 15°–28°N, referred to as ST2) (red line); tropical SST (ST1) and extratropical SST (averaged over 130°W–150°W, 30°–50°N, referred to as ST3) (blue line). The positive (negative) value in x-axis depicts the month ST1 lagging (leading) ST2

and ST3. (b) 21-year sliding lead-lag correlation coefficient between ST1 and ST3. The black line denotes the signals exceeding 95% confidence level of student-t test.

Figure 11

Same as in Figure 9 except for the regression of SSTA (shaded), 500 hPa geopotential height (contour) and 850 hPa wind fields in the previous autumn (SON -1) onto the LFW index in the followed spring (MAM 0) during the different episodes of (a) 1960–1980, and (b) 1980–2000. The black thick vector indicates the climatological northeasterly trade wind. (c) and (d) are the same as (a) and (b) but in previous winter (DJF -1).

Figure 12

The lead-lag regression of (a) SST tendency, (b) surface heat flux, and (c) latent heat in DJF (-1) onto the LFW index in MAM (0). The surface flux (referred to as HFLX) includes four terms, the sensible heat flux (referred to as SH), latent heat flux (referred to as LH), shortwave radiation (referred to as SW), and longwave radiation (referred to as LW). A positive surface flux anomaly denotes the atmosphere heats the ocean. The LFW index is same as in Fig. 7a. Blue boxes in (a)–(c) depict the region with local maximum positive SST tendency and positive surface heat flux anomalies. (d) Same as in (a) except for the time series of box (blue box in a) averaged SST tendency, total surface flux, the individual surface flux and oceanic 3-D temperature advection terms.