Distinguishing Characteristics of Spring and Summer Onset El Niño Events

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ABSTRACT

El Niño events can be classified into two categories according to the onset time: the spring (SP) El Niño with onset time from April to June and the summer (SU) El Niño with onset time from July to October. The SP El Niño is a basin-scale phenomenon and is closer to the conventional ENSO. It goes through the earlier and stronger heat build-up process, and the earlier occurrence of westerlies in the equatorial Pacific, which can partly explain its earlier onset time. For SU El Niño, in contrast, the anomalous signals, such as SSTAs, zonal wind anomalies, and subsurface variations, are much weaker, which can be attributed to the weaker accumulation of warm water and shorter duration of positive Bjerknes feedback. During its peak phase, anomalous southeasterlies over the eastern Pacific enhance the wind–evaporation–SST (WES) feedback and impede the development of positive SSTAs there, and then lead to a west shift of SSTA center. Recharge/discharge processes exist in both types of events but are weaker in the SU type, which may be caused by the lack of meridional Sverdrup transports as a result of weak zonal wind anomalies. A heat budget analysis demonstrates that the relative importance of thermocline (TH) and zonal advective (ZA) feedbacks in SP and SU El Niño is different. In SP El Niño, the TH feedback is dominant compared to ZA feedback in both the GODAS and SODA datasets. In SU El Niño, however, these two terms are equally important in GODAS, but not in the SODA dataset.

1. Introduction

El Niño usually means a significant warming of the sea surface temperature in the central and eastern tropical Pacific Ocean. It is the strongest interannual climate variation signal in the coupled air–sea system and has profound impacts on global climate. Bjerknes (1969) first linked El Niño with the Southern Oscillation, and

pointed out that they are two different aspects of the same phenomenon, which is called ENSO now.

During the recent decades, a new type of ENSO event has occurred more frequently (Ashok et al. 2007; Kao and Yu 2009; Kug et al. 2009; Lee and McPhaden 2010). Differing from conventional El Niño, this flavor has its SSTA center shifted to the central Pacific. Based on different SSTA spatial patterns, various terminologies have been used to represent these two flavors of ENSO, such as date line El Niño (Larkin and Harrison 2005a,b), El Niño Modoki (Ashok et al. 2007), central Pacific (CP) and eastern Pacific (EP) El Niño (Kao and Yu 2009), and warm pool (WP) and cold tongue (CT) El Niño (Kug et al. 2009).

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Previous studies have shown that variations in tropical SST and surface wind fields during El Niño are well phase-locked with the annual cycle (Rasmusson and Carpenter 1982; Philander 1990). However, Neelin et al. (2000) pointed out that large deviations exist in observed El Niño onset, and they first suggested a possible link between El Niño onset and subsequent behavior. Xu and Chan (2001) identified two types of El Niño events, the spring (SP) type and the summer (SU) type, according to the onset time. Although they did not highlight the spatial patterns in their study, it is noteworthy that the composite SSTA for the SP type centered in eastern equatorial Pacific, but the SSTA center for the SU type is more west than that for SP El Niño. Cai et al. (2019) compared the definitions based upon SSTA spatial patterns and the onset time, and showed that SP (SU) El Niño is more likely to correspond with the CT (WP or mixed) type.

It seems that the contrasting SSTA pattern is a common feature among all these definitions. As the atmospheric response pattern to SSTAs is sensitive to their exact location (Barsugli and Sardeshmukh 2002; Hoerling and Kumar 2002), different types of El Niño events may have different impacts on the global climate (Larkin and Harrison 2005a,b; Ashok et al. 2007; Kao and Yu 2009; Kug et al. 2009). Therefore, the study of ENSO diversity is necessary.

It seems plausible to study ENSO diversity based on spatial SSTA structure. However, classification based on the SSTA pattern does not mean a clear dichotomy. For example, indistinct cases exist between EP and CP type: in Fig. 1 of Capotondi et al. (2015), the SSTA extrema occur over a broad range of longitudes and many of them commingle in the center. Qualitatively, Kug et al. (2009) defined a mixed El Niño type that has its SSTA center between the CT and WP type. Ashok et al. (2007) demonstrated that El Niño Modoki, which has its SSTA center in the central Pacific, is an important mode in climate variability and is independent of the conventional ENSO signal. However, none of the first eight leading EOF modes, which can explain 80% of the interannual SST variance during 1999 to 2017, is similar to Modoki (not shown). Note that the year 1998 is suggested as a climate regime shift (Minobe 2000; Lyon et al. 2014).

In this study, we classify El Niño events according to the onset time following Xu and Chan (2001). Thus, we can get two definite sample categories. Furthermore, El Niño events usually peak in wintertime (Rasmusson and Carpenter 1982). Different onset time of warm events may suggest different phase-locking and phase evolution under different dynamic processes. The key issue of this study is to reveal the different characteristics and

physical processes of spring and summer onset El Niño events. This way of classification and research can help to enhance our understanding of this phenomenon. Furthermore, it may offer some clue to improve the forecasting capabilities of ENSO diversity. The specific timing when some particular signals (such as warm water volume or zonal wind signals in the equatorial Pacific) occur can be a hint for what kind of ENSO it could be. In addition, one can immediately tell what type an event is when the timing of onset is known.

The rest of this paper is organized as following. Datasets are briefly described in section 2. The definition and classification of El Niño events based on the onset time are shown in section 3. Section 4 focuses on the differences in the characteristics of spring and summer onset El Niño events, including the spatiotemporal evolutions and precursor manifestations of SP and SU El Niño. The differences in physical processes of two types of events are revealed in section 5. A summary and discussion are provided in section 6.

2. Datasets

The Niño-3.4 index from the Climate Prediction Center (CPC) is used to define and classify El Niño events. It is the average SST anomalies in the region of 5°S–5°N, 170°–120°W. It shows the SST variation in the equatorial central-eastern Pacific and is a meaningful indicator for El Niño events because it is highly correlated with Southern Oscillation index. Further, the central equatorial Pacific has the largest east–west SST gradient and the anomalous warming there appears to be most influential to the shift of the rising branch of Walker circulation (Wang 1995; Bjerknes 1966; Xu and Chan 2001; Horii and Hanawa 2004). Using the Niño-3.4 index, we examine all El Niño events during the period from January 1950 to December 2017 in our study.

The SST data ($2.0^\circ \times 2.0^\circ$; 1854–present) are from NOAA (National Oceanic and Atmospheric Administration) ERSST v4 (Extended Reconstructed Sea Surface Temperature version 4) (Huang et al. 2015). Atmospheric wind components ($2.5^\circ \times 2.5^\circ$; 1948–present) are from the NCEP–NCAR (National Centers for Environmental Prediction and National Center for Atmospheric Research) reanalysis version 1 (Kalnay et al. 1996). Further, we compute the surface wind stress from the NCEP surface wind speed using a bulk formulation given by Trenberth et al. (1990) with estimated parameters from Harrison and Chiodi (2009). In addition, the HadISST ($1.0^\circ \times 1.0^\circ$; 1870–present) from the Hadley Centre (Rayner et al. 2003) and the ERA5 monthly mean surface wind components ($0.25^\circ \times 0.25^\circ$; 1979–present) from the European Centre for Medium-Range

Weather Forecasts (ECMWF 2017) are also used for comparison.

The subsurface temperature is taken from GODAS (Global Ocean Data Assimilation System) ($1^\circ \times 1/3^\circ$, 1980–present, 25 levels in upper 300 m) (Behringer and Xue 2004) and SODA (Simple Ocean Data Assimilation) version 2.2.4 ($0.5^\circ \times 0.5^\circ$, 1871–2010, 16 levels in upper 300 m) (Carton and Giese 2008). In this analysis, the subsurface temperature is from SODA over 1950–79 and from GODAS over 1980–2017. For verification, the EN 4.2.1 ocean data ($1^\circ \times 1^\circ$) covering 1900 to the present from the Hadley Centre (Good et al. 2013) are also employed. To ensure the proper usage, we have checked the consistency of these subsurface datasets by comparing warm water volume (figure not shown). The long-term sea surface height (SSH) and the oceanic circulation data are from SODA over 1950–79 and from GODAS over 1980–2017. We interpolate GODAS data into the SODA grids for temperature and SSH.

Monthly mean latent heat flux products and evaporation products ($1.0^\circ \times 1.0^\circ$; 1958 to the present) are from the Woods Hole Oceanographic Institution OAFlux project (Yu et al. 2008). The precipitation dataset is from JRA-55 Reanalysis (Harada et al. 2016).

All original data have been detrended before further analysis. A low-pass filter is applied to all time derivative series, to remove the variability with period less than 12 months and to reduce noise.

3. Definition and classification of El Niño events

In this study, El Niño is defined as a warm event when the Niño-3.4 index is greater than 0.5°C for 5 consecutive months or longer. However, due to the uncertainties in evolution of warm episodes or in data records, the Niño-3.4 index may not exceed the threshold for 5 consecutive months or longer. To pick out all the warm events reasonably, we modify the definition of El Niño event with two additional conditions: 1) When Niño-3.4 index falls under 0.5°C for 2 consecutive months, the warm episodes before and after the interruption are regarded as two episodes, such as the 1968/69 and the 1969/70 events. 2) When the Niño-3.4 index falls under the threshold for 1 month and the 3-month running mean of this month is greater than 0.5°C , the warm episodes before and after this month are considered as one consecutive episode, such as the 1991/92 event. Twenty El Niño events occurred during 1950–2017 according to the above definition (Fig. 1a). Specifically, the Niño-3.4 index of the 1986–88 event has double peaks and the mature phase occurs around September of the next year after onset (green dashed line in Fig. 1b). Wang (1995) also pointed out that the 1986 episode is not well phase-locked with

the annual cycle. Hence, the 1986–88 El Niño event will not be discussed in this study.

The first time when the Niño-3.4 index exceeds 0.5°C is defined as the onset month. Figure 1b and 1c show that the onset time of El Niño events is not stochastic. Most of them (18 of 20) distribute from April to October. There are two exceptions that will not be discussed in this study. They are the 1953/54 event with an onset time in January (brown dashed line in Fig. 1b) and the 1968/69 event with an onset time in November (black dashed line in Fig. 1b). Figure 1b and 1d show that most El Niño events (17 of 20) peak in wintertime from October to January.

Based on previous studies (Xu and Chan 2001; Horii and Hanawa 2004), El Niño events can be classified into different types according to the onset time. Since the onset months are mainly from April to October, all El Niño events can be classified as follows: 1) When the onset time is in April to June, the El Niño event is classified as spring (SP) type. 2) When the onset time is in July to October, the El Niño event is classified as summer (SU) type. According to the above classification, eight SP warm events were picked out, that is, the 1957/58, 1965/66, 1972/73, 1982/83, 1991/92, 1997/98, 2002/03, and 2015/16 El Niño events; nine SU warm events were picked out, that is, the 1951, 1958/59, 1963/64, 1969/70, 1976/77, 1994/95, 2004/05, 2006/07, and 2009/10 El Niño events. The list of El Niño events before 2000 is almost the same as that of Xu and Chan (2001) except for two events in 1958 and 1968. The types of warm episodes also coincide with Xu and Chan (2001).

4. Characteristics of spring and summer onset El Niño events

a. Composite spatiotemporal characteristics of SP and SU El Niño events

Composite temporal characteristics of the Niño-3.4 index of SP and SU El Niño are shown in Fig. 2. The average Niño-3.4 values (solid red circles) show that the onset of SP and SU El Niño occurs in May and August, respectively. However, both types of events peak in December. The SP El Niño lasts longer (13 months) and has a larger amplitude (1.82°C) than the SU El Niño (7 months, 0.89°C). The height of the box is the interquartile range (IQR) between the upper and lower quartiles, and is a measure of statistical dispersion (Upton and Cook 1996). The solid line inside each box is the median. The boxplots in Fig. 2 show a common feature for both types of events, that is, the spread of data is stronger in the end of the decaying year, implying that great uncertainties exist in the phase transition of both types of El Niño events. However, the SU El Niño shows a quicker transition into cold phase in terms of

FIG. 1. (a) Time series of the Niño-3.4 index during 1950–2017. Red (blue) bars indicate values greater (less) than the threshold of 0.5°C (-0.5°C). (b) Time evolution of the Niño-3.4 index of the 20 El Niño events. The solid circle marks the onset month and the solid diamond marks the peak month. The three events are explicitly labeled (see the text). Frequency distribution of the (c) onset and (d) peak month of the 20 El Niño events.

both mean and median. Note that the distributions of almost half of the data are skewed, which may be a result of insufficient sample size and some extreme El Niño events.

Composite spatiotemporal characteristics of SSTAs, zonal wind stress anomalies, and 20°C isotherm depth anomalies are shown in Fig. 3. The numbers -1 , 0 , and $+1$ represent the previous, onset, and decaying year of the El Niño event. The classifications of El Niño events based on the onset time make it possible to conduct these composites according to the calendar months, because the evolution of El Niño events which occur in adjacent time intervals could be phase-locked with similar annual cycle.

For SP El Niño, significant positive SSTAs around 0.2°C occur in the western equatorial Pacific during year (-1) (Fig. 3a). These positive anomalies strengthen and reach the threshold of 0.5°C in April (0) around the onset time. At the same time, significant positive SSTAs around 0.5°C appear in the eastern equatorial Pacific, which will be further discussed in Fig. 3c. The SP El Niño reaches its peak in December (0). During the whole warm episode, significant positive SSTAs dominate

over a wide range across the central to the eastern Pacific and persist for about 13 months. Notice that significant negative SSTAs dominate over western Pacific during the development and peak phase of SP El Niño. For the SU El Niño (Fig. 3d), significant positive SSTAs of 0.2°C occur in western equatorial Pacific around April (0). These positive anomalies reach the threshold of 0.5°C around the onset of the SU El Niño in August (0) to September (0), 4–5 months later than SP El Niño, consistent with the result of Fig. 2. The SU warm episode lasts for about 8 months. Its maximum of SSTAs is about 0.95°C and locates around the location 30° longitude west of the SP El Niño. Note that the development of the positive SSTAs in the eastern Pacific is relatively weak in SU El Niño (Fig. 3d).

For SP El Niño, significant westerly anomalies occur in the western equatorial Pacific around January (0) and then propagate eastward to central-eastern Pacific (Fig. 3b). These westerly anomalies last for almost the whole warm episode. The westerly wind forcing can excite a sequence of eastward propagating, downwelling

FIG. 2. Boxplots for composite time series of Niño-3.4 index of (a) SP and (b) SU El Niño events. The height of the box indicates the IQR, and the line inside each box shows the median. The ends of the whiskers represent the minimum and maximum of all data. Outliers are plotted as individual points beyond the whiskers. The blue dashed lines plot the criteria for 0.5°, 0°, and -0.5°C . The red solid circles show the average.

equatorial Kelvin waves that will deepen the thermocline in eastern equatorial Pacific and create positive SSTAs there (McPhaden 1999). These positive SSTAs will be enhanced further through the positive Bjerknes feedback (Bjerknes 1969). For SU El Niño (Fig. 3e), the intensity of westerly anomalies is much weaker, about half of SP El Niño. These significant westerly anomalies appear in the western equatorial Pacific around June (0) and last only for a short duration. Although westerly anomalies have an eastward propagation process, the values are not significant in the central Pacific in SU El Niño.

The 20°C isotherm depth, which is used as proxy for pycnocline (thermocline) depth (Kessler 1990), can be a good predictor of ENSO events (Meinen and McPhaden 2000). For SP El Niño, significant positive 20°C isotherm depth anomalies, which indicate the deepened thermocline, occur in western Pacific around July (-1) (Fig. 3c). This anomalous signal extends and propagates eastward along the equator through downwelling equatorial Kelvin waves in response to the surface anomalous westerlies. When the signal reaches the eastern Pacific, it can influence SST strongly due to the vertical advection of anomalous subsurface temperature by the mean upwelling there, which is called the “thermocline feedback” (Jin and An 1999). Then the SST becomes anomalously warm around spring there (which can be found in Fig. 3a). Around summer (0), significant

negative 20°C isotherm depth anomalies appear in the western Pacific. These negative anomalies extend and propagate eastward and could contribute to terminate the warm episode. For the SU El Niño (Fig. 3f), significant positive 20°C isotherm depth anomalies occur in central and eastern Pacific around July (0) and last for the SU episode. It should be noticed that the subsurface process of the SU type is similar to that of the SP type according to the contour lines (Fig. 3f vs Fig. 3c). Positive anomalies can also be found in western and central Pacific before the onset of the SU El Niño despite the weaker intensity and lower significance.

In conclusion, different spatiotemporal characteristics exist in these two flavors of El Niño events. Both types of warm events peak in December, but the onset of the SP El Niño occurs earlier (Fig. 2), implying a longer period of developing and strengthening. As a result, the SP type is stronger and has a longer duration than the SU type (Fig. 2). Manifestations of SSTAs, zonal wind stress anomalies, and 20°C isotherm depth anomalies between these two types of events are also different. For the SP El Niño, continuously significant SSTAs and significant positive westerly anomalies appear over western equatorial Pacific almost simultaneously (January 0), but the thermocline occurs several months earlier (July -1) (Figs. 3a–c), which may imply an important role of the deepened thermocline and its eastward propagation in SP El Niño. But for SU El Niño, positive SSTAs appear

FIG. 3. Composites of anomalies of (a) SST ($^{\circ}\text{C}$), (b) zonal wind stress (10^{-2} N m^{-2}), and (c) 20°C isotherm depth (m) over the equatorial area (2°S – 2°N) for SP El Niño. (d)–(f) As in (a)–(c), but for SU El Niño. The shaded areas in dark red and dark blue are statistically significant positive and negative values above 95% confidence level from a two-tailed Student's t test, respectively. Values between 90% and 95% confidence level are shaded in light red and light blue. The numbers -1, 0, and +1 represent the previous, onset, and decaying year of the El Niño event.

in western equatorial Pacific first (April 0). These SSTAs are favorable conditions for triggering the westerly anomalies that can be found in June (0) (Fig. 3e). The significant deepened thermocline occurs around July (0) in the central and eastern Pacific and seems a response to the surface wind driven to some extent (Figs. 3e,f).

b. Characteristics of the surface phase evolution of SP and SU El Niño events

Different onset times of SP and SU El Niño can lead to different surface phase evolution. Figure 4 shows the surface wind stress anomalies and SSTAs for the antecedent phase [SON (-1) to DJF (-1)], onset phase [MAM (0)], development phase [JJA (0) to SON (0)], and peak phase [DJF (0)] of the SP El Niño. Figure 5 is the same as Fig. 4, but for the antecedent

phase [MAM (0)], onset phase [JJA (0)], development phase [SON (0)], and peak phase [DJF (0)] of the SU El Niño.

A common feature in the antecedent period of SP and SU El Niño is the significant positive SSTAs over the southern subtropical Pacific extending northwestward to the western equatorial Pacific near 160°E (Figs. 4a and 5a). In the SP El Niño, these positive SSTAs in western equatorial Pacific could excite significant westerly anomalies west of the SSTAs in DJF (-1) (Fig. 4b). During MAM (0), the onset phase of the SP El Niño (Fig. 4c), the SSTAs and westerly anomalies develop and strengthen through the positive Bjerknes feedback (Bjerknes 1969) and extend to the Niño-4 and Niño-3.4 region. At the same time, positive SSTAs occur in eastern equatorial Pacific along the Peruvian

FIG. 4. Surface wind stress anomaly (vector; 10^{-2} N m^{-2}) and SSTA (contour; $^{\circ}\text{C}$) for the (a),(b) antecedent, (c) onset, (d),(e) development, and (f) peak phase of SP El Niño. Statistically significant positive and negative values of SSTAs above the 95% confidence level are shaded in dark red and dark blue. Values between 90% and 95% confidence level are shaded in light red and light blue. Only wind stress anomalies reaching a 90% confidence level are shown.

coast (Fig. 4c) because of the deepened thermocline and the effect of thermocline feedback in eastern Pacific around March (see discussion of Fig. 3c). During the development phase (Figs. 4d,e), the western and eastern part of the positive anomalies have developed and merged as one wide range of SSTAs extending from the central to eastern tropical Pacific. In the meantime, westerly anomalies prevail in a wide region over the tropical western to central Pacific (Figs. 4d,e). The warm event reaches its peak phase in DJF (0) (Fig. 4f). Significant positive SSTAs dominate

the entire central to eastern tropical Pacific with a maximum about 1.9°C located at 140°W and extend to extratropical areas along the North and South American coast. The off-equator cyclonic pair in the central Pacific leads a strong anomalous convergence and strong westerly anomalies in the equatorial area (Fig. 4f). Meanwhile, an anticyclone can be found in the far western Pacific with easterly anomalies lying in the equatorial area. These easterly anomalies can drive upwelling equatorial Kelvin waves and induce shoaling of the thermocline from the central to the eastern

FIG. 5. Surface wind stress anomaly (vector; 10^{-2} N m^{-2}) and SSTa (contour; $^{\circ}\text{C}$) for the (a) antecedent, (b) onset, (c) development, and (d) peak phase of SU El Niño. Statistically significant positive and negative values of SSTas above 95% confidence level are shaded in dark red and dark blue. Values between 90% and 95% confidence level are shaded in light red and light blue. Only wind stress anomalies reaching a 90% confidence level are shown.

Pacific, which will help to terminate the warm event (McPhaden and Yu 1999; Boulanger et al. 2003). The surface phase evolution of the SP El Niño is closer to the conventional ENSO depicted by Rasmusson and Carpenter (1982) and fits well with the evolution described by the western Pacific oscillator theory of ENSO (Weisberg and Wang 1997; Wang et al. 1999).

Two seasons later than the SP El Niño, a positive SSTa signal in SU El Niño (Fig. 5a) appears in the western equatorial Pacific in MAM (0). In JJA (0), the onset phase of SU El Niño (Fig. 5b), significant westerly anomalies occur west of the positive SSTas. Different from the onset phase of SP El Niño, no significant positive SSTas occur along the South American coast during the onset phase of the SU type (Fig. 4c vs Fig. 5b), which may be caused by the weaker intensity of subsurface variation (Fig. 3c vs Fig. 3f) and a weaker thermocline feedback. During the development phase (Fig. 5c), positive SSTas extend from the central to eastern Pacific with a weaker intensity than in SP El Niño, and westerly anomalies appear in some places in the western to central Pacific. In DJF (0) (Fig. 5d), SU El Niño reaches its peak phase. Positive SSTas, with a

maximum about 0.8°C located at 160°W , dominate in the tropical central Pacific where weak anomalous westerlies can be found.

With earlier antecedent signals over western equatorial Pacific (Figs. 4a,b vs Fig. 5a), and an earlier onset (Fig. 4c vs Fig. 5b) of SP El Niño, the SSTas and zonal wind anomalies at the peak phase of SP El Niño show a stronger amplitude and a wider range than the SU type (Fig. 4f vs Fig. 5d). Later onset time means a shorter duration for positive feedback, which can partly explain the weaker intensity of SSTas and westerly anomalies in the SU El Niño. The whole surface evolution of SP El Niño is similar to the conventional ENSO and fits well with the western Pacific oscillator theory of ENSO. However, the surface manifestation of SU El Niño seems more likely a CP type depicted by Kao and Yu (2009), with an SSTa center confined in the central equatorial Pacific during its peak phase. It is well known that climatological low sea surface temperatures exist in the southeastern Pacific Ocean. This is caused by the climatological cross-equatorial winds and strong meridional SST gradient extending from the southeastern to northeastern Pacific, which is maintained through

FIG. 6. Evolution of subsurface temperature anomalies ($^{\circ}\text{C}$) in the equatorial area (2°S – 2°N) for SP El Niño. Stippling shows the significant values above 95% confidence level. Black solid lines represent the climatological thermocline and dashed lines represent the thermocline of the composite.

the wind–evaporation–SST (WES) feedback (Xie and Philander 1994). During the development and peak phase of SU El Niño, significant anomalous southeasterlies can be found over the tropical eastern Pacific in the Southern Hemisphere (Figs. 5c,d). These southeasterly anomalies could enhance the cross-equatorial winds and strengthen the evaporation, which could lead to a suppression in the development of positive SSTAs there. In contrast, strong anomalous northeasterlies can be found over the tropical eastern Pacific in the Northern Hemisphere during the development phase of SP El Niño (Figs. 4d,e). The roles of these two branches of wind anomalies will be discussed in section 5b.

c. Characteristics of the subsurface phase evolution of SP and SU El Niño events

Previous works (Ramesh and Murtugudde 2013; Li and Mu 2000) have shown that positive subsurface temperature anomalies will propagate eastward along the thermocline and trigger positive SSTAs in the eastern tropical Pacific during El Niño. And the eastward propagation of subsurface anomalies can be considered as a fundamental driver of ENSO onset (Ramesh and Murtugudde 2013). However, the manifestations of subsurface variations in SP and SU El Niño are not clear yet.

Figures 6 and 7 show the evolution of subsurface temperature anomalies (depth from 5 to 300 m) for SP and SU El Niño. In the year prior to the SP El Niño, significant anomalous warm water accumulates beneath the surface of western Pacific from summer to fall [Fig. 6a; plot for JJA (–1) is not shown here, in which the subsurface manifestations are similar to Fig. 6a]. The anomalous warm signal then propagates eastward along the thermocline (Figs. 6a–c). These positive anomalies extend upward to the surface of the western and the eastern Pacific in MAM (0), that is, the onset time of SP El Niño (Fig. 6c). Note that the locations of significant signals near the surface (5 m) correspond with those of the SSTA signals (Fig. 6c vs Fig. 4c). In JJA (0), anomalous warm water dominates in the central to eastern Pacific from surface to subsurface and anomalous cold water accumulates in the western Pacific at the same time (Fig. 6d). Both the cold and warm anomalies strengthen in SON (0) and constitute a seesaw pattern, with the thermocline shoaling in western Pacific and deepening in eastern Pacific (Fig. 6e). In DJF (0), the seesaw pattern reaches its peak (Fig. 6f). After that, the anomalous cold signal propagates eastward along the thermocline and the SP El Niño gets into its decaying period (not shown).

FIG. 7. As in Fig. 6, but for SU El Niño.

During the SU El Niño, the eastward propagation process of the subsurface temperature anomalies along the thermocline is similar to that of the SP type (Fig. 7). However, it is not until JJA (0) that a relatively wide range of significant positive anomalies appear in the upper 100 m around the date line (Fig. 7d). That is when and where the SSTa signal appears in Fig. 5b. These positive anomalies are mainly confined in situ and slightly develop during SON (0) (Fig. 7e). Meanwhile, positive temperature anomalies along the thermocline also become significant and reach the surface of the eastern Pacific (Fig. 7e). However, these positive anomalies in the eastern Pacific get weaker in DJF (0) (Fig. 7f), which is likely to be caused by the southeasterly anomalies and the enhanced WES feedback (Fig. 5d). As a result, the seesaw pattern in the peak phase of SU El Niño is also weaker than SP El Niño (Fig. 6f vs Fig. 7f). The characteristics in subsurface evolution for both SP and SU El Niño are well in accordance with surface signals described in Figs. 4 and 5.

Overall, it can be deduced that the subsurface variation, mainly the thermocline variation, plays a fundamental role in the SP El Niño. But for the SU El Niño, the subsurface signals are weaker. The significant signals occur after its onset, and are mainly confined in the upper 100 m over the central Pacific (Figs. 7d–f). The subsurface signals in eastern Pacific strengthen and

become significant in JJA (0) and SON (0), which may be in response to the surface wind driven. Besides, we also conducted the same composites using subsurface temperature data (EN 4.2.1 ocean data) from the Hadley Centre (Good et al. 2013). The main conclusions are not changed.

d. Characteristics of the precursors of SP and SU El Niño events

It is well established that the warm water volume (WWV) is a major precursor of El Niño events (Meinen and McPhaden 2000; McPhaden 2012). We calculated the WWV (defined as the volume of water with temperature greater than 20°C) over the region 120°E–80°W, 5°S–5°N, and then removed the seasonal cycle to get anomalous time series. A low-pass filter is applied to these series to remove the signals with a period less than 12 months to emphasize interannual variability. Figure 8 shows the evolution of WWV anomaly basin-wide within 120°E–80°W and 5°S–5°N (V'), over the basin west of 155°W (V'_w) and east of 155°W (V'_e), and the WWV anomaly tendency (dV'/dt) during SP and SU El Niño.

The V' maintains positive before the peak month of December (0) in both SP and SU El Niño (solid lines in Fig. 8a). It implies that a relatively warm upper layer of equatorial Pacific from the previous year to the peak

FIG. 8. Composites of (a) warm water volume (WWV) anomaly basinwide within 120°E – 80°W and 5°S – 5°N (V'), (b) WWV anomaly over the basin west of 155°W (V'_w), (c) WWV anomaly over the basin east of 155°W (V'_e), and (d) WWV anomaly tendency (dV'/dt) for the SP and SU El Niño. The solid circles show the composite values statistically significant at 90% confidence level. Dashed lines are composite Niño-3.4 index. The triangles and squares in (b) show the onset and peak, respectively.

time exists in both events. The V' leads Niño-3.4 index by 6 (5) months in SP (SU) El Niño (solid lines vs dashed lines in Fig. 8a). The dV'/dt shows that the SP El Niño experiences a longer duration of the heat build-up from January (–1) to June (0) than the SU El Niño from November (–1) to July (0) (solid lines in Fig. 8d). Correspondingly, the intensity of V' is weaker in SU El Niño, implying less accumulation of warm water. Similarly, the V'_w for SP El Niño goes through an increasing period from May (–1) to November (–1); however, the variation of V'_w for the SU El Niño is not obvious (solid lines in Fig. 8b). The V'_e leads Niño-3.4 by two months for both types of events (solid lines vs

dashed lines in Fig. 8c). Note that the V'_e in SP El Niño event becomes positive phase one season earlier and grows faster than that of the SU type due to the earlier and stronger heat build-up process in the equatorial Pacific. That can partly explain the earlier onset of SP El Niño. Similar composites for the averaged zonal wind stress anomaly are shown in Fig. 9. During the previous year of both SP and SU El Niño, the U' , U'_w , and U'_e all sustain negative (solid lines in Figs. 9a–c), implying a strengthened trade wind in equatorial Pacific. However, the U' and U'_w turn to positive (i.e., anomalous westerlies) several months earlier in SP El Niño than the SU type (solid lines in

FIG. 9. Composites of averaged zonal wind stress anomaly (a) basinwide within 120°E – 80°W and 5°S – 5°N (U'), (b) over the basin west of 155°W (U'_w), and (c) over the basin east of 155°W (U'_e) for the SP and SU El Niño. The solid circles show the composite values statistically significant at 90% confidence level. Dashed lines are composite Niño-3.4 index. The triangles and squares in (b) show the onset and peak, respectively.

Figs. 9a,b), and could contribute to the earlier onset of SP El Niño.

Overall, a relatively warm upper layer exists in the equatorial Pacific before the peak of both types of events. The upper ocean exhibits an accumulation of heat prior to El Niño and a loss of heat during and after El Niño in the equatorial ocean for both SP and SU El Niño. This process is consistent with the “delayed oscillator” paradigm (Schopf and Suarez 1988; Suarez and Schopf 1988) and the “recharge oscillator” model (Jin 1997a,b). The earlier and stronger heat build-up process and the earlier occurrence of westerlies in equatorial Pacific can account for the earlier onset of SP El Niño to some extent.

5. Physical processes of SP and SU El Niño events

Previous studies have shown that heat exchange exists between the equator and higher latitude during ENSO events (Wyrski 1985; Cane et al. 1986; Miller and Cheney 1990; Springer et al. 1990). The paradigm is summarized as the recharge oscillator model by Jin (1997a,b). In a recent study of Cheng et al. (2019), the

picture of ocean heat change related to ENSO has been depicted more completely. They pointed out that the ocean builds up heat prior to El Niño in the southern and tropical ocean (20°S – 5°N) and loses heat during and after El Niño, with some of it discharged into the northern Pacific (5° – 30°N). However, the manifestation of heat variation in SP and SU El Niño is not clear yet.

a. Recharge/discharge processes in SP and SU El Niño

The left panel of Fig. 10 composites the zonally averaged sea surface height anomalies (SSHAs) over the Pacific basin (120°E – 80°W). In the first-order approximation, the SSHAs can well represent the thermocline variations (Ren and Jin 2013). We also composite the averaged SSHA and $d(\text{SSHA})/dt$ (time derivative of averaged SSHA) over the southern and equatorial tropical Pacific (SETP; 20°S – 5°N and 120°E – 80°W) region and the northern tropical Pacific (NTP; 5° – 30°N and 120°E – 80°W) region for SP and SU El Niño (middle and right panels of Fig. 10). The $d(\text{SSHA})/dt$ is derived by five-points differentiation (Davis and Polonsky

FIG. 10. (left) Composites of sea surface height anomalies (SSHA; cm) averaged over 120°E–80°W, (middle) temporal variations of SSHA, and (right) $d(SSHA)/dt$ averaged over the SETP and NTP region for (top) SP and (bottom) SU El Niño events. Statistically significant values of SSHAs above 90% confidence level are shaded (at left) or marked with solid circles (at middle and right). Green solid lines in left panel indicate 5°N.

1972), and positive (negative) values suggest a recharge (discharge) of ocean heat.

During the previous year of SP El Niño, weak positive (negative) SSHAs exist in the SETP (NTP) region (Figs. 10a,b). In January (0), significant SSHAs occur and gradually strengthen over the equatorial region, implying a recharge process. The warm pattern reaches its peak at October (0), then declines quickly and turns to a significant negative phase around February (+1) (Figs. 10a,b), implying a discharge process. In the North Pacific, the distribution of SSHAs is opposite. Note that the sign of the SSHAs is opposite north and south of 5°N (Figs. 10a,b), and this implies a recharge/discharge process between the SETP region and the NTP region.

The time evolution of $d(SSHA)/dt$ further confirms that the SETP region mainly goes through a recharge process before July (0) and a discharge process after that (solid line of Fig. 10c), and the recharge/discharge process in the NTP region is almost the opposite (dotted line in Fig. 10c). Note that the magnitude of positive SSHAs in the NTP region is weaker than the magnitude of negative SSHAs in the SETP region in the decaying year of the SP El Niño (Figs. 10a,b), suggesting some loss of heat during the discharge process in SETP, for example discharge into ocean at higher latitude or the atmosphere. The evolution of zonal mean SSHAs in SU El Niño is similar to that in the SP type but with a weaker magnitude (lower panel vs upper panel of Fig. 10). However,

FIG. 11. Composites of time-longitude section of SSTA ($^{\circ}\text{C}$) and mixed layer temperature tendency (TH and ZA; $0.01 \text{ K month}^{-1}$) for (top) SP and (bottom) SU El Niño. TH and ZA represent the thermocline feedback and the zonal advective feedback term in the temperature equation, respectively. All values are averaged over the 5°S – 5°N band. The positive values are shaded. TH and ZA for 1980–2017 (1950–79) are from the GODAS (SODA) dataset.

the significant SSHAs mainly happen in the equatorial Pacific (5°S – 5°N) and the recharge process in the NTP region is not in phase with the discharge process in SETP region (lower panel of Fig. 10). This implies a weaker recharge/discharge process in SU El Niño. It may be caused by the lack of meridional Sverdrup transports as a result of the weak zonal wind anomalies during SU episode (Fig. 9).

The recharge/discharge mechanism includes two key dynamical feedbacks (Jin and An 1999): that is, the thermocline feedback (the vertical advection of anomalous subsurface temperature by the mean upwelling) and the zonal advective feedback (the zonal advection of mean SST by anomalous current). To examine how these feedbacks contribute to the SP and SU El Niño events, we performed a heat budget analysis of the mixed layer following An et al. (1999), Kug et al. (2009), and Ren and Jin (2013) using the

reanalysis datasets. The thermocline (TH) feedback and zonal advective (ZA) feedback terms can be obtained from the temperature tendency equation (Ren and Jin 2013):

$$\text{TH} = \bar{w} \frac{T'_{\text{sub}}}{H}, \quad (1)$$

$$\text{ZA} = -u' \frac{\partial \bar{T}}{\partial x}, \quad (2)$$

where the overbar and prime indicate monthly climatology and anomaly, respectively. The terms T and u indicate oceanic temperature and zonal current averaged over the mixed layer (top 50 m); w is the vertical velocity at the bottom of the mixed layer, and H is a fixed mixed layer depth of 50 m. Subscript “sub” donates a subsurface layer averaged between 50 and 100 m.

FIG. 12. (top) Climatic precipitation (shaded; averaged over 1958–2017) and surface wind stress (vector; averaged over 1950–2017). (middle) Composites of the surface wind stress anomaly (vector) and SSTA (contour; $^{\circ}\text{C}$) for SU El Niño. (bottom) Composites of latent heat anomaly (shaded) for SU El Niño. (left) Boreal autumn (SON) for the climatology or SON (0) for the composites, and (right) boreal winter (DJF) for the climatology or DJF (0) for the composites. Statistically significant values of SSTAs above 90% confidence level are shaded. Only wind stress anomalies above 90% confidence level are shown. Statistically significant values of latent heat anomalies above 90% confidence level are stippled. The rectangular box (130° – 80°W , 10°S – 5°N) shows the location of anomalous southeasterlies.

Figure 11 shows the composites of time–longitude section of SSTA and TH and ZA terms for SP and SU El Niño. As large uncertainties exist in the ocean current estimation in reanalysis datasets, we examine the El Niño events during 1980–2017 using GODAS dataset, and El Niño events during 1950–79 using the SODA dataset. In both SP and SU El Niño, the TH term leads the SSTA peak by about 3 months, and contributes to both ENSO growth and phase transition (Figs. 11b,c,g,h). The ZA term exhibits a phase shift relative to the SSTA peak in both SP and SU El Niño (Figs. 11d,e,i,j), indicating that it contributes to the phase transition of both ENSO types. In SP El Niño, TH is a dominant term and is almost the double of ZA (Figs. 11b,c vs Figs. 11d,e). However, in SU El Niño, TH and ZA are of equal importance in GODAS dataset (Fig. 11h vs Fig. 11j). This phenomenon is absent in the SODA dataset (Fig. 11g vs Fig. 11i), which may be caused by the large uncertainties of ocean currents in different datasets and the lack of reliable subsurface observations for the equatorial Pacific. Another

reason for this difference is we used an earlier time period of SODA (1950–79) than the GODAS dataset (1980–2017). Sparse observations in early years could degrade the assimilation results. In addition, the ZA term is very weak in SODA (Fig. 11i). As ZA tends to be important in WP El Niño (Kug et al. 2009; Yeh et al. 2014), which has similar features with the SU type, we suspect that the SODA result for SU El Niño is less reliable than GODAS. However, the relative importance of TH and ZA in the SU El Niño needs further studies using more reliable datasets.

Overall, recharge/discharge processes exist between the 20°S – 5°N band and 5° – 30°N band in both SP and SU El Niño. However, it is weak in the SU El Niño, which may be caused by the lack of meridional Sverdrup transports as a result of the weak zonal wind anomalies during SU episode. The TH and ZA terms play similar roles between two ENSO types. In SP El Niño, TH is a dominant term compared to ZA. In SU El Niño, however, these two terms are equally important in GODAS dataset.

FIG. 13. As in Fig. 12, but for SP El Niño, for (left) JJA and (right) SON. The rectangular box (0° – 10° N, 140° – 80° W) shows the location of the anomalous northeasterlies.

b. Roles of anomalous southeasterlies and northeasterlies in the eastern Pacific

In section 4, we mentioned two branches of anomalous winds in two ENSO types. During the development and peak phase of SU El Niño, significant anomalous southeasterlies exist over the equatorial southeastern Pacific (Figs. 12c,d, also in Figs. 5c,d) and contribute to the strong positive latent heat anomalies there (Figs. 12e,f). Note that the SSTA center locates in the central Pacific during the peak phase of SU El Niño (Fig. 12d). The anomalous southeasterlies enhance the cross-equatorial winds in the eastern Pacific (Fig. 12b), strengthen the latent heat flux and evaporation (Fig. 12f, evaporation not shown), and lead to a suppression in the development of positive SSTAs there. For the SP El Niño, on the contrary, strong anomalous northeasterlies can be found over the tropical northeastern Pacific during the development phase (Figs. 13c,d; also in Figs. 4d,e). These northeasterly anomalies can weaken the cross-equatorial winds in the eastern Pacific (Figs. 13a,b), reduce the latent heat flux and evaporation (Figs. 13e,f; evaporation not shown), and lead to a further development of positive SSTAs there. Similar conclusions can be reached when the wind data of ERA5 and SST data from the Hadley Centre are employed (figure not shown), implying that the influence of these anomalous winds are robust.

It should be noted that anomalous southeasterlies can also be found during the SP El Niño (Figs. 13c,d). However, the southeasterlies in the SP El Niño are much weaker than the homochronous northeasterlies, and are weaker than the southeasterlies in the peak phase of SU El Niño. The link between the wind anomalies and the onset time needs further study.

6. Summary and discussion

Based on the onset time, El Niño events can be classified into two categories: the SP El Niño with onset time from April to June and the SU El Niño with onset time from July to October (Xu and Chan 2001). This study reveals the distinguishing characteristics of spatiotemporal evolutions and precursor manifestations of SP and SU El Niño, and further explores the differences in physical processes of two types of ENSO events.

Results show that the SP El Niño is stronger and has a longer duration than SU El Niño. Despite the large disparity of onset time, both SP and SU El Niño peak in December. Before both types of events, the upper layer in equatorial Pacific keeps a relatively warm status. However, the SP El Niño goes through an earlier and a stronger heat build-up process, and an earlier occurrence of westerlies in equatorial Pacific, which can partly explain the earlier onset time of SP El Niño. The surface and subsurface phase evolutions show that the SP El

Niño is a basin-scale phenomenon. It is closer to the conventional ENSO and fits well with the western Pacific oscillator theory. For SU El Niño, the magnitude of anomalous signals, such as SSTAs, zonal wind anomalies, and subsurface variations, are much weaker than that of the SP type. The weaker intensity could be due to the weaker warm water accumulation in the equatorial Pacific before the event and to the later onset time, which means a shorter duration for positive Bjerknes feedback. During the peak phase of the SU El Niño, the SSTA center locates in the central Pacific, which could be due to the anomalous southeasterlies in the eastern equatorial Pacific. These southeasterlies can strengthen the cross-equatorial winds and enhance the WES feedback, and then impede the development of positive SSTAs there.

The recharge/discharge theory can explain both SP and SU El Niño. In the SP El Niño, recharge/discharge processes exist between the southern and equatorial tropical Pacific (20°S–5°N) and the northern tropical Pacific (5°–30°N). However, the recharge/discharge processes are weak in the SU El Niño and the significant ocean heat signals mainly happen in the equatorial Pacific, which may be caused by the lack of meridional Sverdrup transports as a result of weak zonal wind anomalies. The thermocline feedback and zonal advective feedback play similar roles between the two types of events. The TH feedback contributes to the growth and phase transition, while the ZA feedback contributes mainly to their phase transition. However, the relative importance of these two feedbacks in SP and SU El Niño is different. In SP El Niño, the TH feedback is a dominant term compared to the ZA feedback. In the SU El Niño, however, these two terms are equally important in GODAS, but not in the SODA dataset. The relative importance of the TH and ZA feedbacks in the SU El Niño needs further studies using more reliable datasets.

Some of the contrasting characteristics of SP and SU El Niño are similar to those of EP/CP (Kao and Yu 2009) and CT/WP (Kug et al. 2009) El Niño events, which indicate some links between the time classification and the spatial classification. It is possible that the onset time determinates the spatial pattern. Similar conclusions were also reached by Kao and Yu (2009). However, the spatial classification is not a clear dichotomy. Moreover, the pattern of the SSTA of a specific event is not clear until the peak phase. However, based on the time classification, one can tell a definite type as soon as the onset time is known.

There are several issues that need further study. First, during the previous year of SP El Niño, significant accumulation of warm water exists in western Pacific, but

the source of the anomalous warm water is not clear yet. Composites give a hint that the SP El Niño may come from a La Niña-like SSTA pattern (with an anomalous warm subsurface in western tropical Pacific), and the SU El Niño is likely to come from a neutral pattern (not shown). Second, for both SP and SU type events, positive SSTAs occur in the western equatorial Pacific before the onset. It is not clear whether these SSTA signals are from higher latitudes or an outcome of stochastic disturbances by atmospheric forcing. Previous studies have shown that extratropical atmospheric variability can play an important role in triggering ENSO (Vimont et al. 2003; Chang et al. 2007; Zhang et al. 2014; Vimont et al. 2014). Besides, stochastic variability of the NPO in winter–spring could affect the evolution of El Niño events (Wu et al. 2019). The impact of the extratropical atmospheric variability on the onset time and the subsequent events needs further study.

An important feature of SU El Niño is the strengthened cross-equatorial winds over the eastern equatorial Pacific during the peak phase of SU El Niño. Hu and Fedorov (2018) showed that cross-equatorial winds may control El Niño diversity on multidecadal time scales. According to their results, strengthening of cross-equatorial winds could lead to a reduction in ENSO variability and a shift from EP to CP events within the El Niño continuum. Our composites in SU El Niño show that the enhanced cross-equatorial winds are accompanied by an SSTA pattern similar to CP-type El Niño, which can mutually verify with the conclusion of Hu and Fedorov (2018) to some extent. The decadal variability of SP and SU El Niño and its relationship with cross-equatorial winds need further studies.

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