

The role of Pacific subtropical high belts in the ENSO cycle

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ABSTRACT

This article conducted statistical analyses on the formation of El Niño and Southern Oscillation (ENSO) from several angles by using conventional data. We found that both El Niño and La Niña are closely associated with the preliminary activity of the Pacific subtropical high (PSH) belts on both sides of the equator if bringing an assumption of the influence of annual cycle on ENSO cycle into our calculations. The PSH belts, especially in their eastern sides, tended to have been continuous weakening for months before El Niño maturing. Oppositely, the continuous enhancing of the PSH belts might be regarded as a prelude of a La Niña. This signal the PSH belts send to omen ENSO's coming appeared about two months earlier than the one from the elements in tropical regions. We found that the strengthening or weakening of the PSH belts could act as a more original force for driving the ENSO cycle than the elements in tropics through controlling the variation of trade winds. Since the southern PSH belt appeared more powerful than the northern one in the situation, the phase lock of the ENSO cycle might be explained by this clue. Because the southern PSH belt that approaches the nearest area of the equator every June–August in a calendar year can exert a more powerful impact on equatorial elements, SST in Eastern Equatorial Pacific will be significantly affected 3–4 months later, i.e. the general ENSO mature phase happening around the end of a calendar year. We proposed a plausible mechanism for the ENSO formation based on the results and conducted a targeted discussion on this new mechanism that could explain the problems the current conceptual ENSO models left.

Keywords: ENSO cycle, pacific subtropical high, original force, new ENSO theory, phase lock reason

1. Introduction

The El Niño–Southern Oscillation (ENSO) has always been the focus of the public attention to the meteorological/climatological study since it is undoubtedly accounted as one of the most valuable signals in climate prediction (e.g. Wang et al., 2001, etc.). After the protracted and unremitting efforts, scientists have made many breakthroughs on the mechanism of formation and impact of ENSO (Bjerknes, 1966, 1969; Wytrki, 1975; Rasmusson and Carpenter, 1982; Philander et al., 1984; Gill, 1985; Wright et al., 1988). Particularly what be worth to mention is the birth of a numerical model (Zebiak and Cane, 1987) that made the ENSO prediction possible although the model did not include any anomalous external forcing. Based on this work, a more improved version namely delayed oscillator model was born (Battisti, 1988; Schopf and Suarez, 1988; Battisti and Hirst, 1989; Tziperman et al., 1994), which has become a widely recognised theory. The core content of

this model emphasised that the trade winds stress can afford a positive Bjerknes feedback on the East Pacific sea surface temperature (SST) anomalies so that a delayed restoring force is supplied by the propagation of equatorially trapped waves in the upper ocean. This east–west delayed oscillation of SST anomalies can also be explained by the heat content piling up or not in the Western Pacific, which coincides with another widely referenced ENSO theory: ‘the recharge-discharge oscillator model’ (Jin, 1997a, 1997b). Afterward, Wang (2001) has created a unified ENSO model that combines all the leading contemporary theories.

However, these conceptual models have some flaws: (1) current ENSO models still lack adequate explanation for the onset or termination of ENSO events (McPhaden, 1999); (2) the equatorial oceanic waves that index to measure ENSO in the delayed oscillator model evolve too fast compared with observed ENSO time scale (Deser et al., 2006), which would result in the ENSO prediction to fail. In fact, although the steep mountains on the eastern bank of Pacific Ocean can be approximated as a steel

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wall, the west side of the Pacific is a relatively open water area that cannot well reflect ocean waves, which is in conflict with the primary setting of the delayed model; (3) the recharging or discharging time in Jin (1997a, 1997b) may not precisely coincide with observations, which might lead to failure of the ENSO prediction; (4) current ENSO models also cannot explain why ENSO events tend to be matured by the end of a calendar year. For example, the El Niño matured time in Battisti's (1988) model occurred in spring, a season later than that in the development of an actual event.

On the other hand, current theories mainly focus on discussing the evolution of the ENSO related elements within tropical regions since the fluctuations of them (e.g. SST) are obviously larger than in other regions during the period. However, a fact that cannot be ignored is that the oceanic/atmospheric heat exchange between higher and lower latitudes exists forever. Thus, the impact from non-tropical regions on ENSO should be taken into account as well. A number of studies have pointed out that the extratropics would embody a source of skill for the longer lead ENSO forecast (White et al., 2002; Vimont et al., 2003; Anderson, 2004; Tasambay-Salazar et al., 2015). The evidence pointed out by them appears to be not enough to shake the dominance of current ENSO theory. Wang et al. (2013) found that there is a kind of response in the ENSO cycle to Rossby wave propagating from extratropical regions during the El Niño to La Niña transition in North Pacific. They, especially, identified that a strong anticyclone enhanced by Rossby wave propagation over northeast Pacific could play a role that cannot be ignored in generating La Niña phenomenon by the cold-water southward advection. Although this result suggests that extratropical factors could affect the ENSO cycle in a more direct way, it is obviously not the explanation of the mechanism of the whole ENSO cycle as well. The aim of this study is to propose a more reasonable mechanism that involves dynamical factors over Pacific extratropics in driving the ENSO cycle, which might be able to explain the questions remaining in current models.

2. Data

The National Centers for Environmental Prediction (NCEP)/National Center for Atmospheric Research global atmospheric reanalysis dataset is the primary dataset used in this study (Kalnay et al., 1996). Specifically, the monthly (1963–2015) sea level pressure (SLP) and surface wind on a 2.5° latitude/longitude grid were used here. The National Oceanic and Atmospheric Administration Extended Reconstructed monthly SST V4 on a 2° latitude/longitude grid from 1963 to 2015 is used. Here the

suffix 'a' is used to express anomaly or anomalies of an acronym of an element, e.g. SST anomaly to SSTa, and so on.

3. The evolution of elements with the occurrences of the ENSO events

Since air force, e.g. SLP can play a relatively major part in air–sea interaction over extratropical regions (Kushnir et al., 2002, etc.), we would investigate how the SLP can spread this role from middle latitudes to Tropical Ocean here.

For the sake of the clarity, we chose the SST averaged over Niño-3 region (5°N – 5°S , 150° – 90°W) from December to next February (SST3DJF) to measure if an ENSO event occurs. Although researchers believe that the key region for coupled ocean–atmosphere interactions for ENSO lies further west (e.g. Trenberth, 1997), SST in Niño-3 region is still a good index for diagnosing ENSO happening in current studies (e.g. Wang et al., 2013). Figures 1 and 2 show the time versus longitude or latitude sections of SSTa (a), surface zonal wind anomalies (b), SLPa (c, d, e, f). The analysis is based on the monthly averages between 2°N and 2°S (a, b, c), 25° – 30°N (d), 30° – 40°S (e), 150° – 160°W (f) for the years when the SST3DJFa was beyond 0.5 K and under -0.65 K respectively (refer to similar definition by Wang et al., 2001). Figures 3 and 4 show the same classification of the distributions of the SLPa and surface wind vector anomalies from January to December respectively. Both El Niño (warm) and La Niña (cold) composites included the respective 15 years' information. Note that these composites were based on an assumption, i.e. the ENSO cycle is strongly influenced by the annual cycle.

Showing a strong El Niño, the equatorial maximal SSTa reached 1.4 K in the longitude of 110° – 150°W in December when the minima of SLPa was below -0.8 hPa around 110°W longitudes in 0 years (Fig. 1a,c). This indicates that the response of air to SST in tropics was quick (Matsuno, 1966; Gill, 1980). However, the positive surface zonal wind (PSZW) anomalies reached the maxima 2.6 ms^{-1} was around 170°E in October (two months earlier than former elements, Fig. 1b). Similar but opposite signs appeared in Fig. 2, which shows the evolution of the elements for La Niña composite. The lowest SSTa (-1.3 K) around 140°W and highest SLPa (0.6 hPa) around 100° – 110°W appeared in December, and lowest negative surface zonal wind (NSZW) anomaly -1.8 ms^{-1} around 170°E and -1.4 ms^{-1} around 147.5°W occurred in October, respectively (Fig. 2a–c). Note that the PSZWa had a clear tendency that spread eastward with time in Fig. 1b whereas there was no apparent tendency

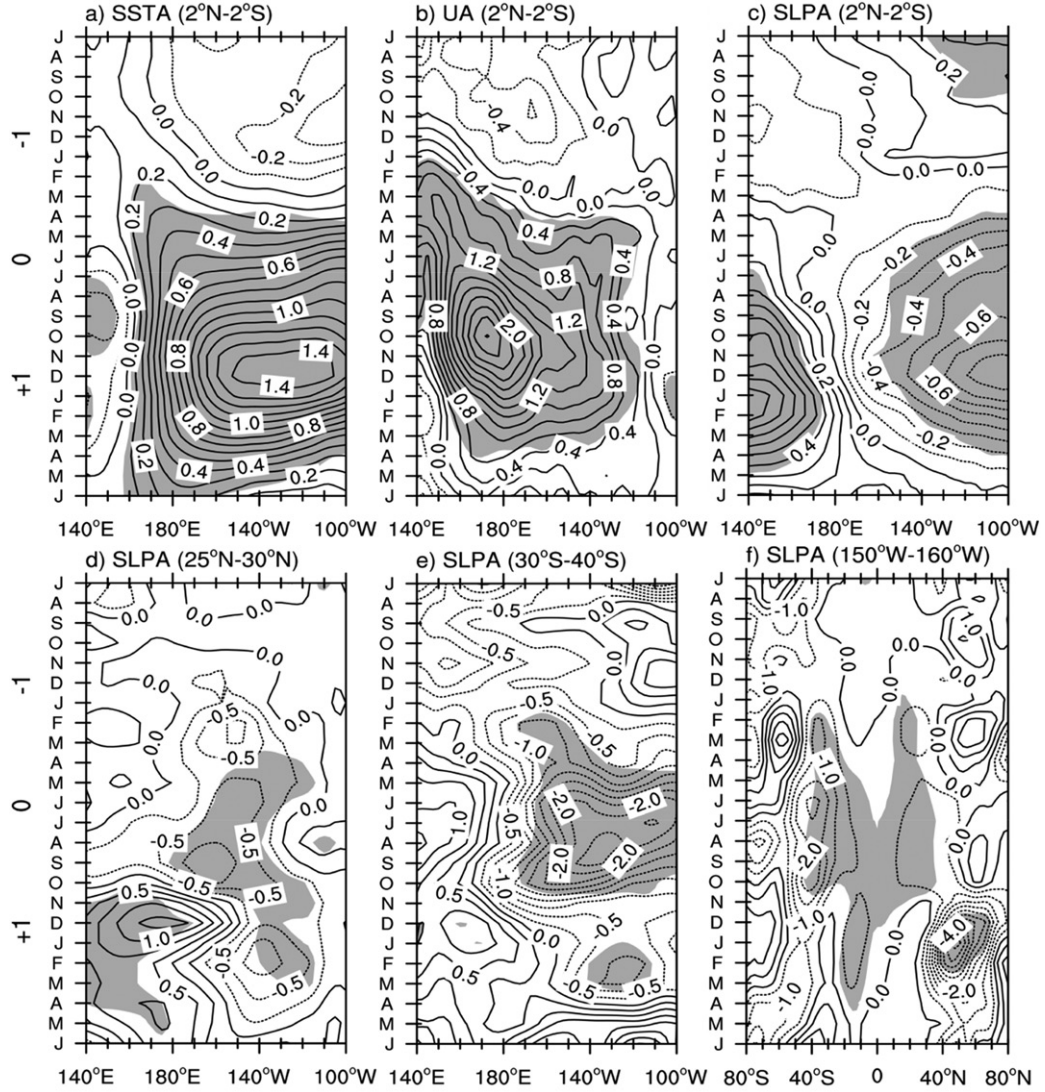


Fig. 1. The El Niño composite for SSTa (a, unit: K), surface zonal wind anomalies (b, unit: ms^{-1}), SLPa (c, unit: hPa) averaged between 2°N and 2°S; SLPa averaged between 25°N and 30°N (d), averaged between 30°S and 40°S (e), averaged between 150°W and 160°W (f) from July of -1 year to June of +1 year. The 0 years for the composite included 1965, 1972, 1976, 1982, 1986, 1987, 1991, 1994, 1997, 2002, 2003, 2006, 2009, 2014, 2015. Shaded areas indicate significance at 95%.

for eastward spreading NSZWa with time especially after October 0 year in Fig. 2b.

On the other hand, the negative (Fig. 3) and positive (Fig. 4) SLPa centres with isolated contour lines dominated over Eastern Extratropical Pacific (EEtP) in both Northern and Southern Hemispheres in the most of months especially from February to October whereas oppositely weaker SLPa appeared over Western Extratropical Pacific (WEtP). The subtropical SLPa was larger than that in tropics in Figs. 3 and 4. All of the evolutions could be explained by those in Figs. 1d-f and 2d-f. The stronger SLPa, especially in South Pacific, exhibits zonal-belt shape with its centres drifting over

EEtP in different months. The SLPa belts over EEtP in South Pacific appeared much stronger than those in the North Pacific, especially from August to October. The dipole pattern with opposite SLPa between WEtP and EEtP in Southern Hemisphere became clear since May (Figs. 3 and 4). The dipole pattern gradually expanded to tropical and North Pacific regions in the rest months. The dipole pattern appeared to be an enlarged version of the Southern Oscillation pattern because the subtropical areas largely covered. Note that the west part of the dipole became a split pattern extending eastward from tropics to extratropics separately between November and December (Figs. 3k,l and 4k,l), which might imply a peak

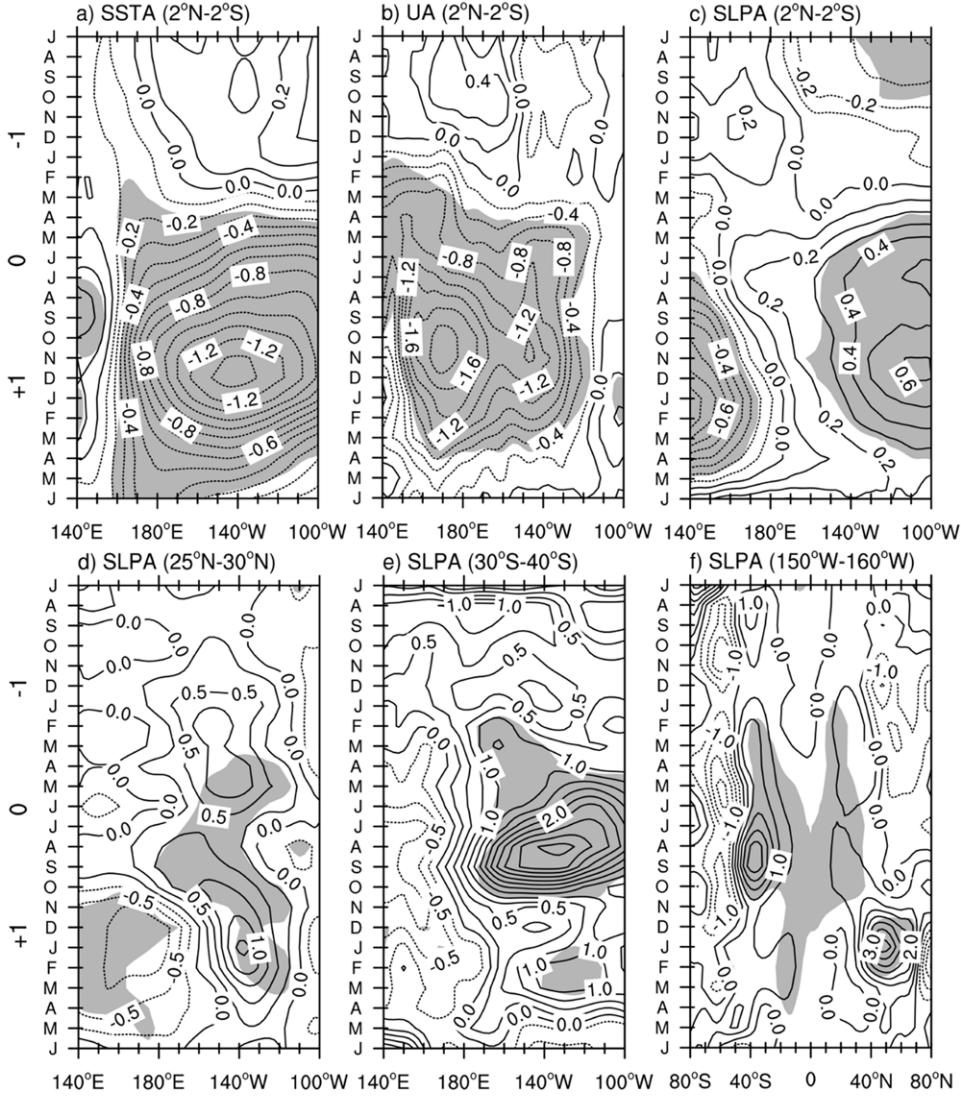


Fig. 2. Same as Fig. 1, except for the La Niña composite for the years of 1964, 1967, 1970, 1971, 1973, 1974, 1975, 1984, 1988, 1995, 1996, 1998, 1999, 2007, 2010.

of the matured phase or preparation of a start of the opposite event for a cycle. The SLPa belts in El Niño composite appeared to evolve a similar but opposite process to that in La Niña composites. However, there are three different points between them as follows: (1) the southern negative (positive) SLPa belt in El Niño (La Niña) cases tended to have a strong centre in western (eastern) EETP (e.g. Fig. 3b and Fig. 4b; Fig. 3e and Fig. 4e; Fig. 3g and Fig. 4g); (2) the northern negative SLPa belt from February to May in El Niño cases tended to occur in lower latitudes than the positive one in La Niña ones (Figs. 3b–e and 4b–e); (3) at the beginning of the El Niño composite (e.g. January, Fig. 3a), the negative SLPa covered a large area including tropical and southern WETP, which was against the positive SLPa over

southern EETP. This SLPa confrontation was another dipole pattern that was just opposite one occurring in May. However, a similar but opposite SLPa confrontation did not explicitly extend to tropical western Pacific during the initial stage of La Niña (Fig. 4a).

The positive or negative SLPa generally accompanies anticyclonic or cyclonic wind vector anomalies that could deeply extend to equatorial Pacific as shown in Figs. 3 and 4. This implies that the northern and southern SLPa belts should strongly affect the strength of the wind on both sides of the equator, i.e. the trade winds.

Then again, the extreme subtropical SLPa in Figs. 1e and 2e occurred around 130°W in August, about two months earlier than the extreme surface zonal wind in Figs. 1b and 2b. Also, the southern negative (positive)

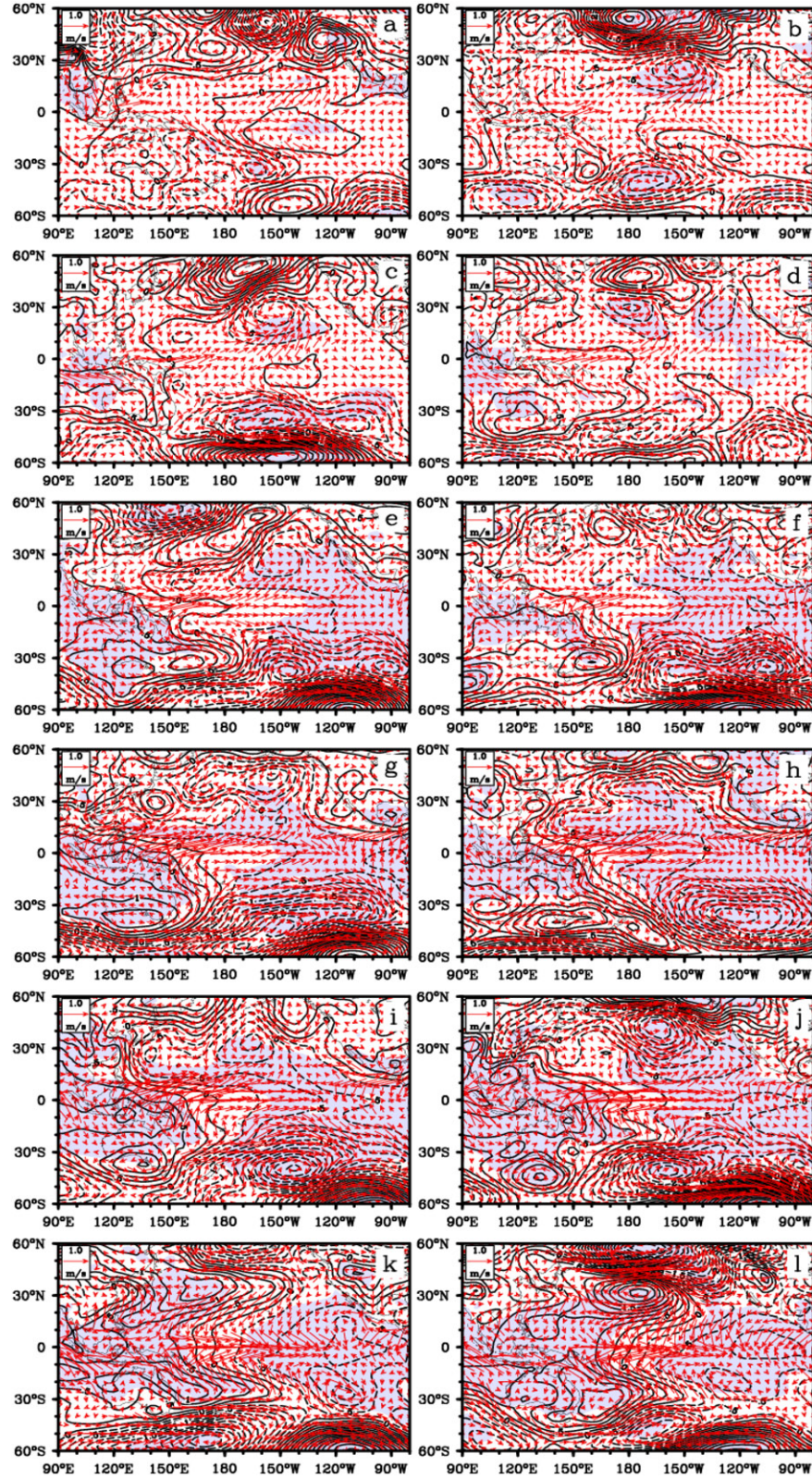


Fig. 3. Distributions of SLPa (unit: hPa) and surface wind vector (unit: ms^{-1}) anomalies for El Niño composite from January to December (a–l). Shaded areas indicate the significance at 95%.

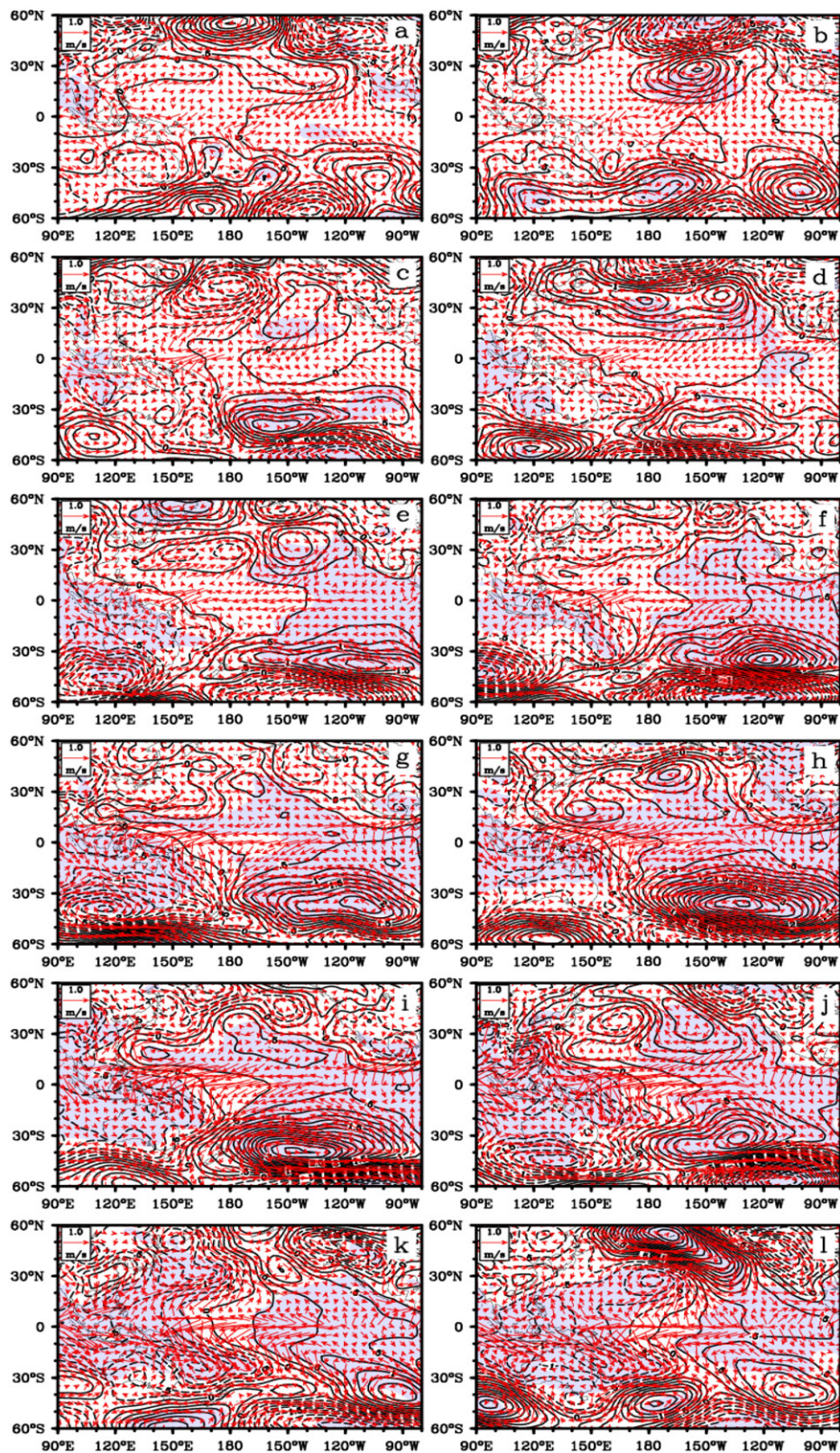


Fig. 4. Same as Fig. 3, except for the La Niña composite.

SLPa extended to northernmost places significantly in July–September as shown in Figs. 1f and 2f. All of these can be confirmed in Figs. 3 and 4. There should be more impact of the SLPa on corresponding equatorial SST during the months. This generates an assumption, i.e. the SLPa belt over southern EEP may need about two months to arrive in equator and affect equatorial surface wind without considering other factors since the southern SLPa was much stronger than the northern one, which may substantially affect the SST over Eastern Equatorial Pacific (EEP) in another 1–2 months. In other words, the impact of the southern SLPa may mainly make a significant change of equatorial SST by the end of a calendar year through affecting equatorial surface wind. Certainly, the role of the northern SLPa with the same symbol as the southern one could not be ignored although the northern one may not as strong as the southern one.

4. Correlation analysis

Figure 5 shows the monthly correlation between SLP from January to December and SST3DJF during 1963–2015, which aims to more deeply examine the relationship between SLP and ENSO. Significant negative correlation area (SNCA) was centred over northern and southern EEP from February to March (Fig. 5b,c) respectively, which coincides with significant SLPa centres in the composite maps (Figs. 3b,c and 4b,c). The two centres combined with two negatively narrow east–west correlation belts were generally symmetrical about the equator. However, there were two SNCAs in southern EEP in April (Fig. 5d) whereas less significant anomaly areas appeared there in Figs. 3d and 4d. And then, the two SNCAs gradually spread toward the equator in the rest months, which finally developed into a huge centre in the eastern Pacific. On the other hand, a significant positive correlation area (SPCA) occurred around tropical to south subtropical regions to the west of 120°E in March. It grew up into a vast SPCA just to the west of the big SNCA after May as well. Although the significant area in Fig. 5 obviously expressed different meaning from that in Figs. 3 and 4, similar significant areas appeared in all three figures. Note that strong anomalous SLPa centres over EEP accompanied with significant areas extending to tropical regions especially from May to October in Figs. 3 and 4 whereas in the meantime, no strong correlation centre appeared over EEP in Fig. 5, which was the big difference of the distribution images between the composite maps and correlation map. However, Fig. 5 also confirmed that the SLP over EEP had significant correlations with ENSO occurrences in most months. Similar to Figs. 3k,l and 4k,l, the split pattern also appeared in Fig. 5k,l.

Since the SNCA largely and dynamically existed over EEP, it is difficult to grasp the whole picture of the SLP belts. We actually made many tests to create indices of SLP in expressing the relationships with SST3DJF. Here, we have only selected representative examples. Three types of SLP indices were created: (1) The SLPa at 20°N, 155°W (I-N) (2) The SLPa at 30°S, 155°W (I-S), (3) The averages above two indices (I-All). These two points involved significant correlation areas over a relatively long period as shown in Fig. 5.

The increasing monthly indices from February to October for the three types were produced respectively. Every type has included derived indices. For example, I-N2-3 means the I-N averaged from February to March while the I-N2-10 means the I-N averaged from February to October, and so on, which was used to reflect the accumulative effect for SLP in respective increasing months. Tables 1–3 show the correlations between the three kinds of increasing SLP indices and SST3DJF respectively. The correlation values of -0.271 and -0.351 indicated the thresholds for the significance at 95% and 99%. The negative correlations exceeding 95% confidence level can be seen almost everywhere except for the ones involving I-S2-2 (-0.079) in Table 2 and I-N4-4 (-0.266) in Table 1 and most of the values in Tables 1–3 were beyond 99% confidence level. These imply that the SLP over both southern and northern EEP in most of the previous months was closely associated with EEP SST in winter. All of the three types of indices with the suffix 10 that was related to the accumulative effect with the months until October have a higher correlation with SST3DJF than those with other suffixes, which implies an accumulative impact of EEP SLP on ENSO. The accumulative growth rate of correlation for I-S is obviously higher than that for I-N, and most of the former ones could also reach higher values than later ones. The correlations between SST3DJF and I-All were the highest among the correlations for three types of indices. In particular, the value of the I-All5-10 reached -0.74601 that reached the highest level in fitting ENSO mature phase.

The correlations calculated until October is due to the SLPa dominating over EEP in those months (Figs. 3b–j and 4b–j). However, ENSO generally matures since September (Wang et al., 2001) when equatorial SST time series have stronger auto-correlations. Although we actually cannot exclude the response to the tropics in the correlations in September and October, the accumulation into boreal fall is also importantly included. The highest correlation until October in Table 1 did not deny the particular importance in August among other months as mentioned in Sections 3 and 5.

Figure 6 shows the evolution of the representative SLP indices, i.e. the anomalies of I-All5-10 and I-All3 and

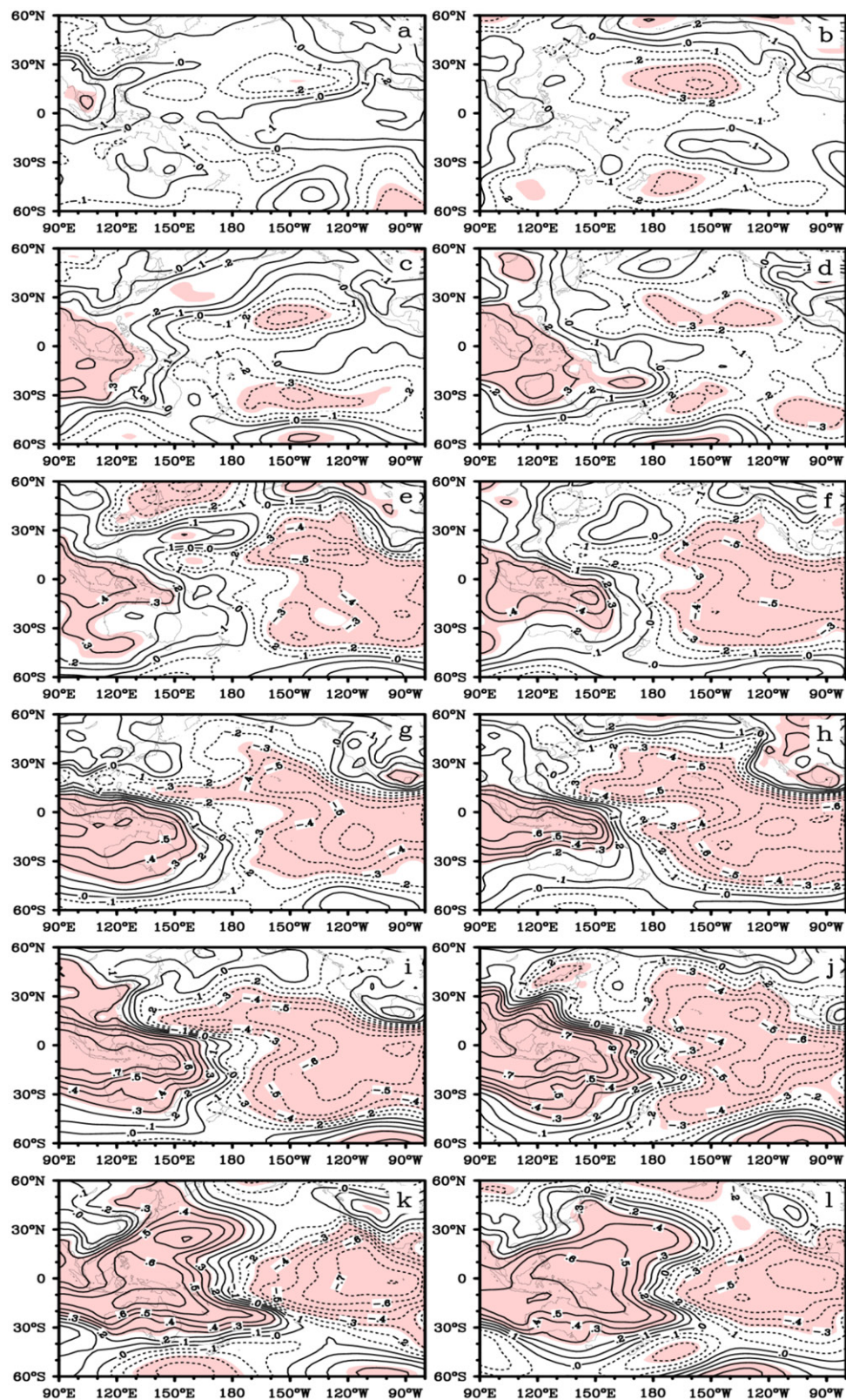


Fig. 5. The correlation between SLP and SST3DJF from January to December. Shaded areas indicate the significance at 95%.

Table 1. Correlation coefficients between I-N and SST3DJF.

	cor.2	cor.3	cor.4	cor.5	cor.6	cor.7	cor.8	cor.9	cor.10
cor.2	<i>-0.502</i>	<i>-0.537</i>	<i>-0.4957</i>	<i>-0.5355</i>	<i>-0.5625</i>	<i>-0.5837</i>	<i>-0.604</i>	<i>-0.61</i>	<i>-0.627</i>
cor.3		<i>-0.416</i>	<i>-0.3939</i>	<i>-0.4757</i>	<i>-0.519</i>	<i>-0.5554</i>	<i>-0.588</i>	<i>-0.598</i>	<i>-0.619</i>
cor.4			<i>-0.2663</i>	<i>-0.4206</i>	<i>-0.4929</i>	<i>-0.5362</i>	<i>-0.58</i>	<i>-0.591</i>	<i>-0.612</i>
cor.5				<i>-0.5305</i>	<i>-0.586</i>	<i>-0.6083</i>	<i>-0.635</i>	<i>-0.632</i>	<i>-0.648</i>
cor.6					<i>-0.4918</i>	<i>-0.5614</i>	<i>-0.607</i>	<i>-0.607</i>	<i>-0.63</i>
cor.7						<i>-0.5538</i>	<i>-0.618</i>	<i>-0.614</i>	<i>-0.638</i>
cor.8							<i>-0.603</i>	<i>-0.596</i>	<i>-0.629</i>
cor.9								<i>-0.531</i>	<i>-0.602</i>
cor.10									<i>-0.582</i>

The cor.2, cor.3... show coordinates for the accumulative months of I-N. For example, cor. 2 vs. cor. 5 means the correlation between I-N2-5 and SST3DJF and cor.3 vs. cor.10 means the correlation between I-N3-10 and SST3DJF, and so on. Italic values signify significance above 99% confidence level.

Table 2. Same as in Table 1 except for the correlations involving I-S.

	cor.2	cor.3	cor.4	cor.5	cor.6	cor.7	cor.8	cor.9	cor.10
cor.2	<i>-0.079</i>	-0.308	<i>-0.4116</i>	<i>-0.509</i>	<i>-0.5569</i>	<i>-0.581</i>	<i>-0.667</i>	<i>-0.696</i>	<i>-0.699</i>
cor.3		<i>-0.393</i>	<i>-0.4545</i>	<i>-0.5282</i>	<i>-0.588</i>	<i>-0.623</i>	<i>-0.708</i>	<i>-0.725</i>	<i>-0.726</i>
cor.4			-0.3062	<i>-0.4484</i>	<i>-0.5401</i>	<i>-0.5808</i>	<i>-0.672</i>	<i>-0.709</i>	<i>-0.713</i>
cor.5				<i>-0.3653</i>	<i>-0.5052</i>	<i>-0.5411</i>	<i>-0.663</i>	<i>-0.704</i>	<i>-0.705</i>
cor.6					<i>-0.417</i>	<i>-0.4724</i>	<i>-0.592</i>	<i>-0.643</i>	<i>-0.657</i>
cor.7						-0.3392	<i>-0.515</i>	<i>-0.594</i>	<i>-0.626</i>
cor.8							<i>-0.459</i>	<i>-0.572</i>	<i>-0.605</i>
cor.9								<i>-0.501</i>	<i>-0.547</i>
cor.10									<i>-0.412</i>

Italic or bold values signify significance above 99% or 95% confidence level.

Table 3. Same as in Table 1 except for the correlations involving I-All.

	cor.2	cor.3	cor.4	cor.5	cor.6	cor.7	cor.8	cor.9	cor.10
cor.2	-0.343	<i>-0.513</i>	<i>-0.5482</i>	<i>-0.6278</i>	<i>-0.6578</i>	<i>-0.6627</i>	<i>-0.716</i>	<i>-0.723</i>	<i>-0.73</i>
cor.3		<i>-0.512</i>	<i>-0.5196</i>	<i>-0.6029</i>	<i>-0.6517</i>	<i>-0.6713</i>	<i>-0.734</i>	<i>-0.739</i>	<i>-0.743</i>
cor.4			-0.34	<i>-0.5212</i>	<i>-0.6135</i>	<i>-0.6465</i>	<i>-0.721</i>	<i>-0.733</i>	<i>-0.739</i>
cor.5				<i>-0.4959</i>	<i>-0.6126</i>	<i>-0.6409</i>	<i>-0.741</i>	<i>-0.744</i>	<i>-0.746</i>
cor.6					<i>-0.4948</i>	<i>-0.5644</i>	<i>-0.678</i>	<i>-0.69</i>	<i>-0.705</i>
cor.7						<i>-0.4553</i>	<i>-0.626</i>	<i>-0.654</i>	<i>-0.684</i>
cor.8							<i>-0.579</i>	<i>-0.635</i>	<i>-0.669</i>
cor.9								<i>-0.547</i>	<i>-0.608</i>
cor.10									<i>-0.537</i>

Italic or bold values signify significance above 99% or 95% confidence level.

-SST3DJFa (a) n-I-All5-10 (b). The new SLP index (n-I-All5-10) was created by including averaged SLPa with the broad northern and southern areas, i.e. 30–40°N, 130–170°W and 30–40°S, 110–170°W, respectively. Note that for convenience, the SST3DJFa has been multiplied by -1 here. The SLP indices primarily evolved consistent trends with the negative SST3DJFa due to their significant correlations. Even I-All3 that had a lower correlation with SST3DJF (-0.51236) could display peak and valley values similar to the negative SST3DJFa, not

mention to I-All5-10. Thus, relative extrema of the SLP indices would be able to predict an El Niño or La Niña profoundly matured in the coming winter. Particularly, although I-All5-10 showed almost the same progression as the -SST3DJFa did, the index in the remarkable El Niño year of 1997 did not appear a more significant decrease than other El Niño years. However, the better match in 1997 can be found with n-I-All5-10. Its correlation coefficient with SST3DJF is -0.784 . The much better-predicting result would be obtained if involving more

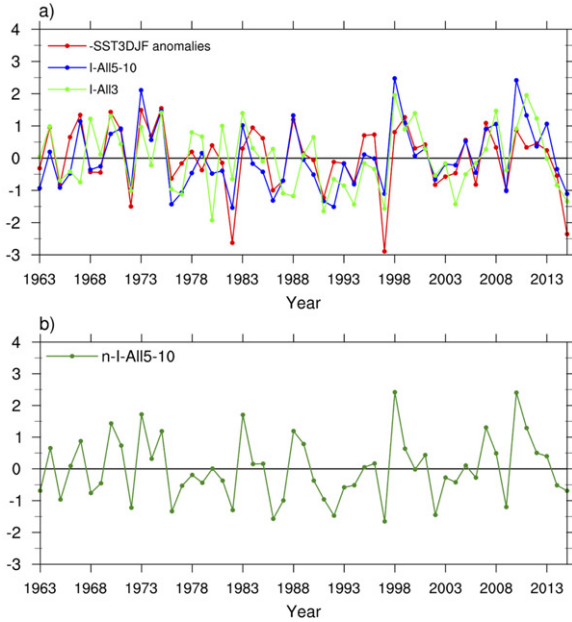


Fig. 6. The evolution of I-All3, I-All5-10, and SST3DJF multiplied by -1 (a) and n -I-All5-10 (b) from 1963 to 2015. The data were normalised by their own standard deviations.

points or more appropriate areas in the SLPa belts. The SLPa values in WEtP might also be considered for testing the ENSO prediction effect.

5. Seasonal climate conditions

It would be necessary to further understand the seasonal variations of the related meteorological elements climatologically since ENSO peak usually occurs in the boreal winter, which implies the importance of the annual cycle for ENSO development.

Figure 7 shows the climate mean of SLP with surface wind vector and SST areas over 27°C from boreal spring to winter (March to May, MAM; June to August, JJA; September to November, SON; December to February, DJF). There is a low SLP zonal-belt in the tropical Pacific with two high SLP zonal-belts on each side in every season. These two ‘high pressure’ belts over Pacific are certainly the parts of the subtropical ridge that mainly results from the descending flow of the Hadley Cell. Note that the two SLPa belts over EEP in Figs. 3 and 4 were within the scope of the two Pacific subtropical high (PSH) belts in Fig. 7 as well. The two PSH belts with centres shift southward from boreal summer to winter and come back from austral summer to winter while a low SLP zonal tongue in between strongly extends to the west of 160°W in boreal spring and winter. The north–south swing distance of the PSH belts with seasons is

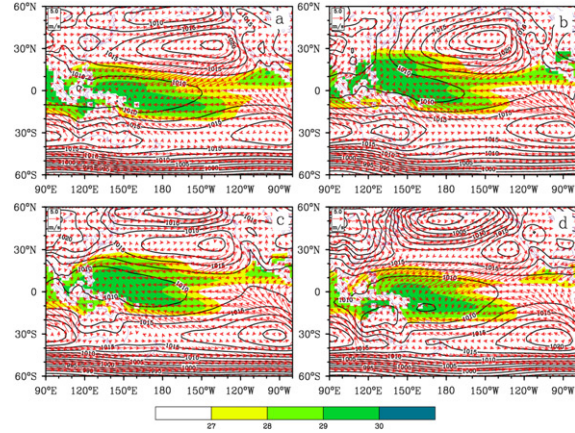


Fig. 7. Climatic distribution of monthly SLP, surface wind vector and SST over 27°C averaged from 1963 to 2015 for MAM (a), JJA (b), SON (c) and DJF (d).

about five latitudes or more. The northern PSH tends to cover North Pacific with a strong centre located about 32.5°N , $145^{\circ}\text{--}150^{\circ}\text{W}$ from MAM to JJA and behaves narrower belt across Pacific with a weaker centre to the east of 147.5°W from SON to DJF. The southern PSH tends to shape a narrow zonal-belt traversing extensive South Pacific, generally, with a centre located to the east of 100°W . In addition, the low SLP tongue shifts southward from the tropical region largely invading Australian continent in DJF, which cause the high SLP zonal-belt broken in situ. This can also be considered as the sign of the southern oscillation extending to higher latitudes in this season. The equatorial easterlies known as the trade winds dominate in the tropical region in all seasons, variations of which are obviously associated with the strength of the PSH belts on both sides of the equator. The easterlies over southeastern equatorial Pacific reached its maximum in JJA when the southern high belt is closest to the equator. On the other hand, SST over EEP becomes lowest in DJF since the area covered with the contour line of 27°C appears smaller than other seasons within the annual cycle. Note that La Niña also tends to occur in winter with the lower SST over EEP, which implies some connection of ENSO formation with the annual cycle. When normal southern PSH approaches equator in JJA, the trade winds near the equator will become stronger than other seasons after a time (perhaps two months later, e.g. Fig. 2b,e). Note that the correlations involving suffix 8 of I-S began to exceed those of I-N (see Tables 1 and 2). This means that accumulative effect of southern PSH belt on ENSO is more important than that of northern PSH belt after August when southern PSH belt moves nearest to equator although the selected points for producing I-S were fixed. The stronger trade winds can reduce equatorial SST more effectively

through stronger upwelling effect so that the lowest SST over EEP emerges in about three to four months (just by the end of a calendar year, Figs. 2 and 4). This mechanism could be applied to La Niña events too except for needing persistently stronger southeastern PSH. For the same reason, the persistently weaker southeastern PSH especially from July to September would result in an El Niño (Figs. 1 and 3). Thus, the two PSH belts especially the southern one might be a more original power source for driving ENSO cycle that is associated with the annual cycle inevitably.

6. A case from El Niño to La Niña

The El Niño occurring in 1997–98 was undoubtedly one of the strongest in the last century. A strong La Niña in 1998–99 followed the super-strong El Niño immediately. Here we would examine the evolution of the warm and cold events.

Figures 8 and 9 show the monthly SLPa distribution from January to December 1997 and 1998, respectively. Figure 10 shows the section map similar to them in Figs. 1 or 2 except for the period from July 1996 to June 1999.

The negative SLPa, especially the northern one, over WEtP began to spread eastward in January 1997 (Fig. 8). In fact, this spread can be traced back to November 1996 (figures omitted). Both sides of negative SLPa largely covered EEtP from March to October 1997, and the southern one appeared more significant in April, May, July and August 1997. Additionally, the southern negative SLPa centre over EEtP strongly shifted northward closest to the equator in August 1997 when the normal southern PSH belt reached position nearest the equator (Figs. 7b,d and 8h). Figure 10f did not catch the northward-moving for the negative SLPa in August 1997 because the major northward-moving part was to the east of 140°W. Note that the n-I-All5-10 that took account of broader related areas was able to display a significant decrease in 1997 in Fig. 6b. The sharp contrast of southern negative SLPa over EEtP and positive one over WEtP occurred between July and September 1997. Similar signs could be found in the middle months in Fig. 3 too. On the other hand, the positive SLPa began to split over western Pacific in November 1997 and this split extended to EEtP in February 1998 (Fig. 9), which was similar to the images in November and December of Fig. 3k,l. The southern SLPa belt over EEtP became significantly strong from June to October 1998. However, no opposite split pattern was found between November and December 1998, which might mean no preparation to start a warm event. In fact, the cold event occurred again in 1999 (Fig. 6).

The equatorial SSTa reached the highest value (over 3.5 K) around 105°W in December 1997 and lowest value (below -1.75 K) around 165°W in December 1998,

respectively (Fig. 10a), which indicated matured states of the strong El Niño and La Niña, respectively. Correspondingly, the highest PSZWa (over 8 ms⁻¹) was around 180° in October 1997, and lowest one (below -4 ms⁻¹) was around 175°E in January 1999 (Fig. 10b). The evolutions of SSTa and PSZWa in the El Niño in 1997–98 were similar to the composite ones (see also Fig. 1a,b). However, the situation in La Niña in 1998–99 was different from composite one (Fig. 2a,b) because the lowest NSZWa occurred about one month after the lowest negative SSTa, which was about two months delayed compared with the composite. The negative (positive) SLPa over EEtP has persisted for months until the El Niño (La Niña) in 1997 (1998) matured (Figs. 8, 9, and 10a,d,e). There were two negative centres (below -5 hPa, 145°W, May 1997 and below -6 hPa, 137.5°W, January 1998) in northern subtropical Pacific and one negative centre (below -5 hPa, 125°W, August 1997) in the southern side (Fig. 10d,e). On the other hand, there were two strong positive centres (over 5 hPa, 160°W, May 1998 and over 5 hPa, 155°W, February 1999) in northern side (Fig. 10d) and two strong ones (over 6 hPa, 170°W, February 1998 and over 7 hPa, 125°W, August 1998) in southern side (Fig. 10e). Strong positive SLPa over southern EEtP in August 1998 appeared to reach northernmost places as shown in Figs. 9 and 10f too. The phenomena occurring in August in Figs. 8 and 9 roughly coincided with those in Figs. 3 and 4.

The El Niño event appeared undergoing similar evolution as composite did since the extreme PSZWa was prior to the extreme SSTa about two months. This suggests that the strong equatorial westerly played a major role in maturing El Niño through transporting warm water to the east, which coincides with the delayed oscillator model theory. The eastward driving force of the westerlies was so strong that the positive SSTa centre had approached the Pacific east coast in the matured phase. However, the PSH would behave like the more original force sources because the negative SLPa in both PSH zones occurred earlier in the west and quickly spread to east broadly in the warm case of 1997–98. The persistent negative SLPa, which was much lower than the composite especially to the east of 180° in boreal summer, appeared to play an essential role in enhancing the equatorial PSZWa that led to the formation of the super-strong El Niño. The much more warm water piled in EEP appeared to cause a reverse event quickly since the Pacific east coast acting as a steel wall could fast reflect the warm water back to the west. This might be the reason why the negative SSTa centre occurred prior to the appearance of the NSZWa about one month (Fig. 10a,b) because the eastern Pacific boundary would reflect the warm water to the west and generate cold water in the east through the

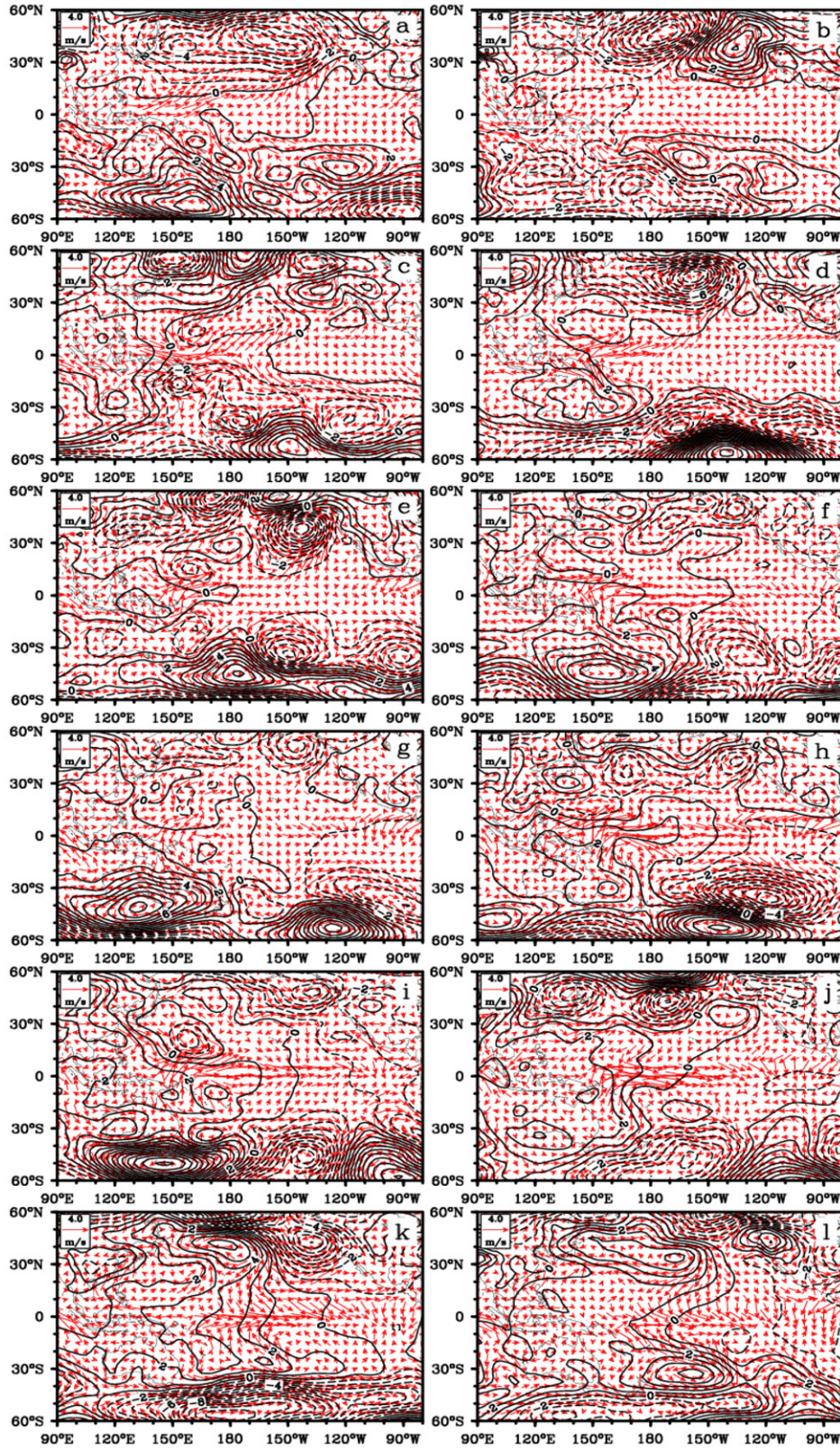


Fig. 8. Same as Fig. 3, except for the period in 1997.

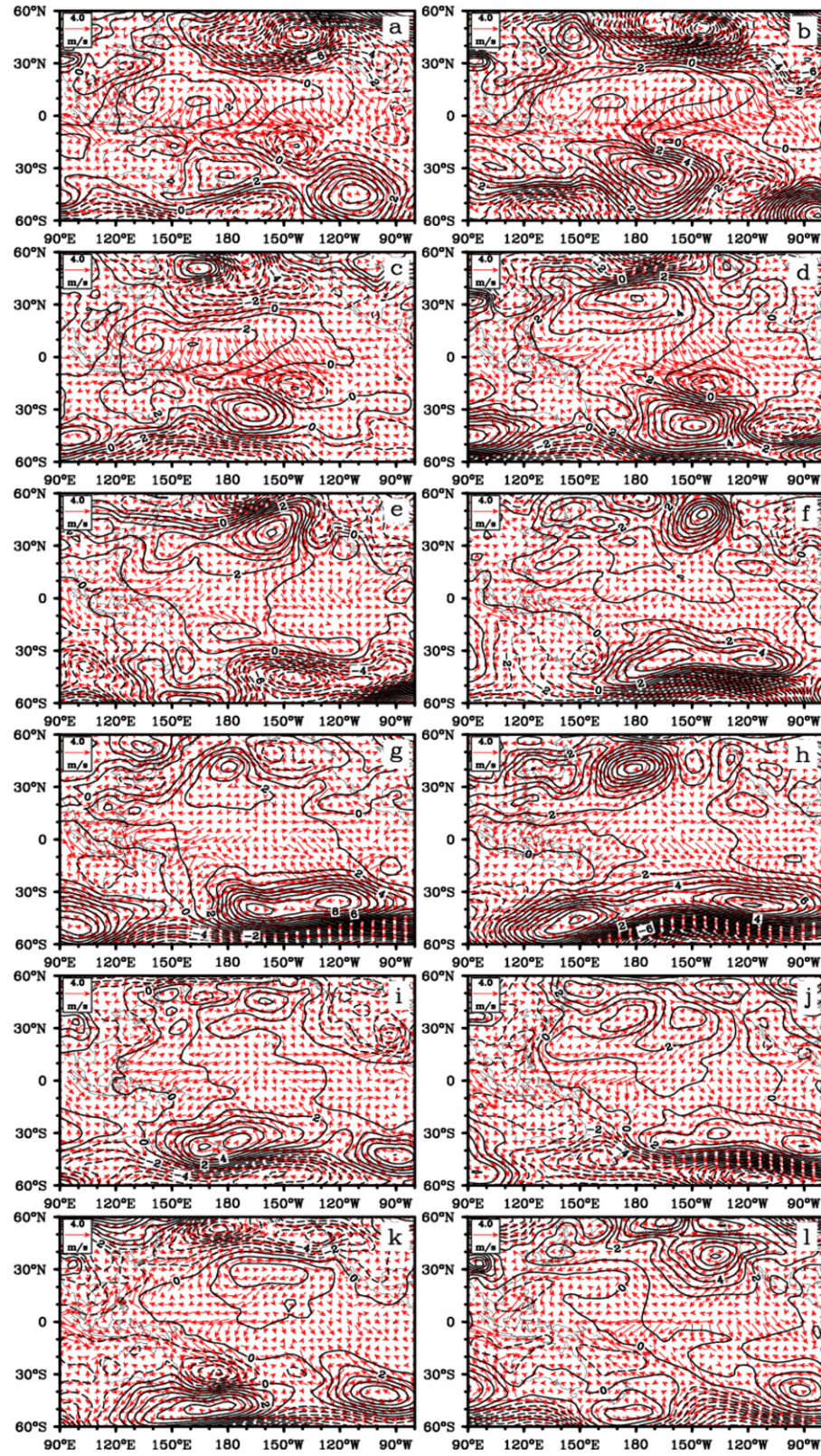


Fig. 9. Same as Fig. 8, except for the period in 1998.

significant than the North Pacific, which also suggests the stronger impact in situ as point (1) shows.

3. The SLPa was within the scope of subtropical high belts activity over both sides of EETP. In particular, the location of the southern SLPa was more close to the normal position of the southern PSH belt over EETP. These suggest that the extratropical SLPa's activity would just display the strength of the PSH belts.
4. The southern SLP over EETP in ENSO composites showed greatest anomalies in around August when the powerful southern PSH belt climatically moves closest to the equator with the seasonal progress. This may generate suspense, i.e. the strong SLPa plus subtropical high belt climatically approaching equator may have a greater impact on ENSO formation since the equatorial surface zonal wind anomalies, and SST3a reached greatest in the following 2 and 3–4 months, respectively. The lag time of the SSTa that might be the response to the impact of the SLPa was just around the end of a calendar year, which may be able to explain the phenomenon of phase-lock for ENSO. This is because all of the calculations were based on the assumption that the ENSO cycle varies on the basis of annual changes of elements.
5. The anomalous SLP over EETP could be an excellent index to predict ENSO mature phase in a very early time. The indices also show that the persistent strong or weak eastern PSH belts were crucial in forming a cold or warm event.
6. The trade wind's strength is a critical factor in forming a warm or cold event according to current ENSO theories. However, the strength of the PSH belts especially the eastern ones could control the variation of the trade winds. Thus, the PSH belts would be a more original force in driving the ENSO cycle, which suggests that a new ENSO theory is necessary.

8. Discussions and a proposed ENSO mechanism

8.1. The confusing role of PSH

The PSH could directly affect rainfall pattern in monsoon regions (Wang et al., 2001). However, our analyses strongly suggest that the variation of the PSH strength might be an original force¹ in driving the ENSO cycle, which impacts the rainfall pattern in ENSO regions as well. The sign of the variation in subtropical areas obviously occurred ahead of the variation of the elements in tropical regions before ENSO events emerged, which might be the evidence mentioned above. However, this

force was too vague to detect, which may be the reason why it has not been discovered by others so far. The reasons include (1) the anomalous force, i.e. SLPa centres drifted at different locations along both sides of subtropical high belts in different months before the occurrence of ENSO event; (2) the intensities of the PSH belts in both sides did not keep synchronised during the period of the formation of ENSO events; (3) hard to distinguish the role of the extratropical force when the southern oscillation appeared (e.g. Fig. 5). This would result in a misunderstanding, i.e. the process of ENSO formation is mainly limited within tropical regions.

Above problems can be explained here: No matter how the force drifted, SLPa would persistently and negatively occur within the scope of the two PSH belts especially over EETP before an El Niño maturing. Moreover, a similar process would happen in a La Niña case except for the positive SLPa existing. In addition, since the amplitude of variation of the extratropical SLPa is generally much larger than that of that in tropics, it has a potentially strong influence on the equatorial elements. This evidence indicates that PSH belts might be able to slowly exert equatorward or poleward force in the help of ENSO formation. The poleward force (negative SLPa) over EETP would play an essential role in cutting or reducing the supplement source of the trade winds so that the warm water over EWP can migrate eastward more easily. An El Niño may occur consequently if the negative force persists long enough. Note that the force reaching equator to change the in situ trade winds would take some time, i.e. about two months if estimating with southern PSH force's impact on trade winds as shown in Fig. 1b,e. Oppositely, the persistent equatorward force (positive SLPa) would result in a La Niña.

All of our analysis indicates that the larger and longer persistent SLPa over EETP would lead to ENSO events more easily. However, since both PSH belts are changed with different factors and even have the seasonal changes effect, the forces on both sides of the equator cannot be symmetrical. The topography of the North and South Pacific and various teleconnection patterns can also block the forces of the two sides synchronised. On the other hand, although the southern oscillation pattern was centred in the tropical region, it extended to mid-latitudes (e.g. Fig. 5h). In fact, the early sign of the pattern mainly existed over EETP before evolving into the Southern Oscillation (e.g. Fig. 5c). Note that the part of the pattern over mid-latitudes was formed initially by a response of SST to air whereas the Southern Oscillation is usually be considered as a result for the air response to SST. However, we cannot deny that air response to SST tends to occur in middle latitudes especially in the matured phase of La Niña. Very warm water can overflow to high

latitudes when heat content is excessively accumulated in the western equatorial Pacific by strong trade winds. Thus, the SST in mid-latitude would become abnormally high so that the high SST heating could reduce the overlying air pressure in this situation. The subtropical high over WEtP begins to weaken at this point, which may become a preparation for a warm event occurring within the ENSO cycle. However, the air response to SST is very limited in mid-latitudes, which will be further explained in subsection 8.3. On the other hand, SLPa over WEtP tended to be opposite to SLPa over EEtP, which might be due to the influence of the southern oscillation evolution or difference of surface character (e.g. the existence of Australian continent in the west) in between. The effect of the opposite sign of western PSH should also be inclusive although it might be less than the eastern one.

8.2. *The Pacific subtropical gyres*

There were two climatic subtropical high centres located over EEtP almost every season. Coincidentally, two permanent subtropical gyres (Fig. 8.1 in Peixoto and Oort, 1992 cited from Tolmazin, 1985) existed roughly underlying the two high-pressure centres. The low-latitude parts of the two gyres, i.e. the westward moving currents in Equatorial Pacific were transporting cold water from east to west, which plays an important role in keeping a normal state of lower SST in the east and higher SST in the west. The formation of the gyres would result from the Coriolis Effect on Pacific water and its terrain, and so on. In particular, the overlying high-pressure centres should act to modify gyres' surface strength and position through the wind stress that follows the Ekman transport principle (Tolmazin, 1985). In the case of other conditions remain unchanged, the SLP centres appeared to determine the climate presence of the subtropical gyres. In other words, the subtropical high belts could change the equatorial current by both modifying the subtropical gyres and equatorial easterlies (trade winds). The former modification that plays the same role in affecting SST over EEtP as the latter one does would be much slower because the anomalous current from subtropical gyres driven by overlying air pressure would take much more time to reach tropics due to its slow time scale. This slow effect of PSH needs to be more studied in the future.

8.3. *The respective characteristics of the formation of El Niño and La Niña regarding the behaviours of the PSH*

The formation process of El Niño with the variation of PSH belts appeared similar but opposite to the one of La

Niña as shown in composite and correlation analyses. The anomalous/persistent forces coming from the subtropical highs would lead to an ENSO event forming. However, the situation might not be as simple as it emerged on the surface. Wang et al. (2013) pointed out that the occurrence of a La Niña event following an El Niño one in the following year was far more common than the opposite case. This asymmetric occurrence implies that both opposite PSH forces that are exerted on the formation of El Niño and La Niña must be unequal. Similar results can also be found in the article of Clarke and Zhang (2019). The Pacific topography might mainly be responsible for this situation. The Pacific East Bank can roughly serve as a steel wall to reflect eastward current back in another direction, which is an extra force for cold water upwelling in EEP. From this perspective, not too strong eastern PSH might be able to help in forming La Niña as long as it can ensure the extra force direction westward by applying strong equatorward pressure. The situation could be seen in the mature phase of the La Niña case of 1998–99 when there were less NSZWa over EEP. However, the extra force from Pacific West Bank is much weaker due to its relatively open terrain in situ. Thus, it is not natural that an El Niño that follows a La Niña occurs immediately. The weakness of the PSH belts on both sides of equator might be majorly responsible for the formation of an El Niño.

The weakened sign of western PSH belts especially the southern one could be traced back to the late summer to winter one year ahead of the mature phase of an El Niño (Figs. 1d–f and 10d–f). The weakness propagated eastward to the eastern parts of the PSH accordingly. This might result from the air response to the warmer SST over WEtP because of the too much-piled heat content over the western equatorial Pacific. The warm water with extra heat content would spill over to the sea areas in both sides of higher latitudes, which will lead to weakening in situ subtropical highs through the air–sea interaction. This effect will continually erode the eastern part of the subtropical high belts within the Westerly area.² The split pattern in the mature phase of the cold event in Fig. 4k,l might be the explanation for this. Here we think that the negative SLPa split pattern over West Pacific is a preparation for the next warm event coming if together with other factors to cause complete weakness of the subtropical high belts over EEtP. The split pattern in Fig. 3k,l might also be the preparation for next cold event occurring but would have a more limited effect of air response to cold SST in mid-latitudes. However, an early sign of the strong subtropical high belts over EEtP appeared essential for the formation of a La Niña as well (Figs. 2, 4 and 5) because it can play an important role in intensifying the trade winds in correspondent longitudes

of tropics. The different points between the warm and cold composites, which were picked up in Section 3, could be explained in this subsection as well.

8.4. The influence of the annual cycle on the ENSO cycle

Since ENSO events tend to be matured by the end of a calendar year, we cannot ignore the seasonal change's influence on the ENSO formation. A clue might be obtained to reveal the mechanism since introducing the equatorward force from PSH belts at this point. As mentioned in former sections, the southern PSH that is more powerful than the northern one would move to the nearest equator every JJA especially August.³ In the case of La Niña, the strong southern PSH belt could exert the most considerable equatorward force during the period. However, the maximal force could not really work on largely changing SST over EEP until after 3–4 months that is just around the end of a calendar year. The evidence can be found in composite maps (e.g. Figs. 2 and 7b,d) if ignoring the northern equatorward force. For the same reason, the weak southern PSH belt in JJA would exert maximal poleward force. Moreover, significant SLPa (especially the southern one) in Figs. 1f and 2f displayed an apparently equatorward shift in JJA. Thus, the persistent strong/weak PSH force accumulated until JJA would be crucial to forming a La Niña/El Niño by the end of a calendar year, which might be an explanation for the phase-lock of ENSO cycle. Further study regarding this hypothesis is desired in the future.

8.5. New theory

We would like to propose a hypothesis about a new ENSO formation mechanism here:

The formation process of an El Niño: Assuming that the process starts with a normal state, the trade winds with a climatic speed keeps a balance of the SST difference between western and eastern tropical Pacific, i.e. higher SST in the west and lower SST in the east through the upwelling by the easterlies. The PSH belts with normal strength are at a normal position at this point. If the process lasts long enough, the over-piled warm water with great high heat content in WEP will spread to WEtP to weaken western part of PSH with a temporally baroclinic state. The unstable erosion would be able to slowly spread to the east part of PSH in succession when the conditions are ripe. If other factors, e.g. teleconnection effects, and so on also join such erosion, the eastern PSH would collapse essentially, which will break the normal balance of the equatorial SST distribution. The eastern PSH's weakness that exerts the poleward forces would

result in the collapse or even reverse of the trade winds, which would lead to the weakness of the upwelling over EEP and allow the warm water piled in the west moving eastward. Thus, the persistent poleward force that especially lasts until around August in the southern side would finally lead to an El Niño mature phase occurring by the end of a calendar year.

The formation process of a La Niña: (a) Also if starting with the normal conditions over tropical Pacific, the abnormally strong subtropical high over EEtP would be crucial for the formation of La Niña event. The stronger subtropical high persisting would result in the enhancement of trade wind that also makes the enhancement of upwelling over EEP. La Niña would finally occur due to the decrease of SST by the anomalously strong upwelling over EEP. The southern PSH belt would be quite strong enough in JJA and also majorly responsible for forming the mature phase of the cold event by the end of a calendar year. (b) Supposing a very strong El Niño occurring firstly, the eastward equatorial sea current would fast move to the eastern bank of Pacific Ocean with strong impact in the El Niño mature phase. If the eastern PSH keeps strong enough, the sea current would have to turn round moving westward because the Pacific East Bank would play a role in reflecting the eastward-moving current to other directions and both sides high pressure would act to make the reflecting direction toward the west to cause strong upwelling over EEP. Thus, the abnormally strong upwelling, which may lead to a La Niña as an early forcing, would also happen without initially stronger trade winds in this situation. Similarly, the conditions for the PSH belts in (a) would also be necessary to finally lead to a cold event maturing by the end of a calendar year.

This theory is obviously different from the conceptual ENSO models: (1) By introducing the force from PSH, the new mechanism has discarded the old form, i.e. the driving force of the ENSO cycle is mainly in the tropical region. This is actually expanding the horizon to a global scale because any significant impact of a factor in the world on PSH may cause the change of the ENSO cycle; (2) This proposed mechanism is designed based on the existing terrain of the Pacific Ocean. It assumes that the east boundary of Pacific is equivalent to a steel wall that could reverse the eastward flow of water to the westward to enhance the upwelling whereas the western boundary is a more open water area where the westward sea current driven by trade winds would hardly reverse. This can explain why a La Niña following an El Niño in the following year was far more common than the opposite (Wang et al., 2013). In addition, it emphasises the driving force in the southern side due to a more extensive Pacific area in Southern Hemisphere; (3) The new mechanism

pays more attention to the role of annual cycle with the seasonal progress of PSH, which could explain the rationality of ENSO cycle, i.e. why ENSO events tend to mature by the end of a calendar year. (4) Current ENSO theory pointed out that the warm pool in the tropical area of Western Pacific is particularly important because most signs that show ENSO's coming to appear in the warm pool firstly (Wang, 2001). For example, the westerlies or vigorous activity of Madden Julian Oscillation in the warm pool or further upstream area is considered as a crucial signal for the formation of El Niño. However, our study found that the complete weakness of the subtropical high over EETP might be more important in forming El Niño. This implies that an El Niño cannot be formed without previously longtime weakness of the subtropical highs over EETP even if there is a clear signal in the warm pool as mentioned in previous studies. This finding may provide better explanation for the formation mechanism of the El Niño Modoki (Ashok et al., 2007; Xu et al., 2017). Similarly, the persistent enhancement of the subtropical high over EETP is also crucial for the formation of the La Niña phenomenon.

On the other hand, this mechanism coincides with previous ENSO theory in the following important aspects: (1) It attaches importance to the role of the trade winds in the ENSO cycle too except for paying more attention to the more original force that could control the trade winds; (2) It partly agrees with the role of the reflection of sea current by the Pacific Banks. However, the new theory does not need to use equatorial wave reflection to explain the ENSO cycle; (3) It acknowledges that 'Bjerknes feedback' principle is significant in ENSO cycle except for applying it to the extratropical regions.

Our study has provided a new way to forecast ENSO event by creating PSH indices although the forecasting was not the purpose of this paper. The method of generating indices by selecting right SLPa at points or in averaged areas in PSH belts would have great potential for predicting ENSO event in a very early stage. The various characteristics appearing in the indices also confirm the above new ENSO mechanism correctly. This study, as a first step, hypothesises that extratropical climate variability may influence the ENSO cycle in a more direct way than what has been believed. It would be more interesting if we will convincingly be able to show that the interannual variability of the seasonal migrations of the Hadley Cell may partly be considered as the Southern Oscillation. Actually, as we pointed out, it is reasonably possible that the tropical SST and the subtropical highs form a coupled mode. Since ENSO could also affect PSH intensity through the Hadley Cell's ascending flow, the interaction between ENSO and PSH might be the core for the intensity changes of these two systems. If it is

true, ENSO cycle may evolve in the way, i.e. El Niño→enhancement of PSH→La Niña→weakness of PSH→(next round) El Niño, and so on. This also coincides with above new ENSO theory. We may further study how the combination of Walker Circulation and Hadley Cell over the Pacific plays a major part in driving the ENSO cycle in the future. Nevertheless, detailed ENSO simulations by an excellent global ocean-atmosphere coupled model⁴ that emphasises the role of the PSH belts are necessary for future since current observational data are not good enough to provide a complete picture for ENSO formation.

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Notes

1. Note that the trade wind is still a direct force as pointed out by previous studies.
2. Note that this does not mean that equatorial high SST shifting to extratropical regions could always be a forcing source to cause significant negative SLPa to western PSH belts because the atmospheric state over tropics (extratropics) tends to be baroclinic (barotropic), which is due to the different Coriolis effect and SST magnitude between two regions (Wang and Lupo, 2009). The very high equatorial SST migrating to WETP as shown in deep El Niño matured phase may cause shallow baroclinic atmospheric state with overlying negative pressure anomalies in situ. However, this effect is not big enough to cause long-lasting significant negative SLPa of western PSH belts. This is because this high SST migration to mid-latitudes would need to undergo a barotropic process through an interaction with overlying air flow inevitably, which

should weaken this baroclinicity from tropics and would finally evolve into positive SSTa with overlying positive SLPa (Fig. 10 in Wang et al., 2013).

3. The August importance means that the southern PSH belt, which is closest to the equator in August, continues to maintain an abnormality from the previous period to August. It might not be important whether this abnormality in August itself increases or not. This PSH could exert the most significant impact on the ENSO cycle as long as it keeps the long-lasting abnormality until approach equator nearest. This importance could also apply to June, July or even September secondarily because the southern PSH belt in the months is located to the north of the average position within one year.
4. However, data analysis is more reliable than a simple model experiment in this issue because settings subjectively embedded into the model may cause a wrong result. Data analysis appears responsible for an initial study stage in this situation.

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