Why 1986 El Niño and 2005 La Niña evolved different from a typical El Niño and La Niña

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Abstract 1986 El Niño (EN) and 2005 La Niña (LN) experienced distinctive evolution features compared to the typical EN and LN events. The 1986 EN persisted for more than 2 years, whereas the 2005 LN transitioned into a warm episode in the following winter. The physical mechanisms that caused the distinctive evolution features are investigated through an oceanic mixed-layer heat budget (MLHB) analysis. For both cases, major differences with typical EN and LN lie in wind induced anomalous zonal advection and thermocline feedback terms. An anomalous cyclone appeared over the western North Pacific (WNPC) in late 1986, in contract to an anomalous anticyclone (WNPAC) during the mature winter of the typical EN. The eastward propagation of anomalous convective heating from tropical Indian Ocean in late 1986 holds a key for generating the anomalous WNPC in the mature winter of 1986/87 EN. The

equatorial westerly anomaly south of the WNPC triggered downwelling Kelvin waves, prolonging the positive SSTA throughout 1987. The negative SSTA center of the 2005 LN shifted eastward by at least 20° in longitude compared to the typical LN. As a result, an anomalous WNPC, with pronounced westerly anomalies at the equator, developed in the 2005 LN mature phase. This led to a rapid decay of the 2005 LN, and by the following boreal summer a positive SSTA formed. The season-dependent air-sea feedback further strengthens the warming in northern fall, leading to a transition from LN to EN in the succeed winter.

Keywords ENSO · Evolution asymmetry · Western-North Pacific circulation · Interannual variability

1 Introduction

As the most prominent interannual mode in the tropics, the El Niño–Southern Oscillation (ENSO) has a profound impact on global climate (e.g., Philander 1990; Trenberth et al. 1998; Wallace et al. 1998; Latif et al. 1998; Alexander et al. 2002). The fundamental cause of EN development is rooted on unstable atmosphere–ocean interactions (e.g., Bjerknes 1969; Philander et al. 1984; Cane and Zebiak 1985; Hirst 1986, 1988). The oscillatory feature of ENSO is caused by either a delayed oscillator mode that emphasizes the delayed ocean wave effect (Suarez and Schopf 1988; Battisti and Hirst 1989) or a discharge–recharge oscillator mode that emphasizes a phase difference between the eastern Pacific (EP) SSTA and zonal mean thermocline depth anomaly (TDA; Jin 1997; Li 1997).

An important scientific question on the ENSO dynamics is what causes the evolution asymmetry between EN and LN (EA-ENSO for short; Kessler 2002; Larkin and Harrison

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be answered. Compared to a rapid decaying of the typical EN in early of year + 1, what maintained the positive SSTA after peak phase of the 1986 EN? Compared to a slow decay of the typical LN in early of year + 1, what contributed to the fast decaying and quick transition into EN after the peak phase of 2005 LN?

We organize the remaining part as below. Section 2 presents datasets and analysis approach. Mechanisms responsible for special evolution of 1986 EN and 2005 LN are discussed in Sects. 3 and 4. Finally, it is a conclusion.

2 Data and methods

The ocean reanalysis datasets are derived from Simple Ocean Data Assimilation (SODA v2.1.6; Carton and Giese 2008), and ECMWF Ocean Reanalysis System 4 (ORAS4; Balmaseda et al. 2013). The SODA has a $0.4^\circ \times 0.25^\circ$ resolution and 40 vertical levels. While the ORAS4 product, in the horizontal direction, has a $1^\circ \times 1^\circ$ resolution, and 42 levels in the vertical direction. The primary surface heat flux and atmospheric field datasets are both from WHOI OAFlux (Yu et al. 2008), and NCEP reanalysis 2 (NCEP R2; Kanamitsu et al. 2002). The SST and OLR datasets are from the Extended Reconstructed SST version 3b (ERSST v3b; Smith et al. 2008) and NOAA (Liebmann and Smith 1996), respectively. The low-level wind field and sea level pressure datasets are from NCEP reanalysis 1 (NCEP R1; Kalnay et al. 1996). And zonal wind stress data are from the ECMWF ERA-Interim dataset (Dee et al. 2011).

To understand the fundamental processes in causing the special evolution features of 1986 EN and 2005 LN, we analyze the oceanic MLHB analysis. The tendency equation is:

$$\begin{aligned} \frac{\partial T'}{\partial t} = & - \left(\mathbf{u}' \frac{\partial \bar{T}}{\partial x} + \bar{\mathbf{u}} \frac{\partial T'}{\partial x} + \mathbf{u}' \frac{\partial T'}{\partial x} \right) \\ & - \left(\mathbf{v}' \frac{\partial \bar{T}}{\partial y} + \bar{\mathbf{v}} \frac{\partial T'}{\partial y} + \mathbf{v}' \frac{\partial T'}{\partial y} \right) \\ & - \left(\mathbf{w}' \frac{\partial \bar{T}}{\partial z} + \bar{\mathbf{w}} \frac{\partial T'}{\partial z} + \mathbf{w}' \frac{\partial T'}{\partial z} \right) \\ & + \frac{(\mathbf{sw}' + \mathbf{lw}' + \mathbf{sh}' + \mathbf{lh}')}{\rho C_p H} + \mathbf{R}, \end{aligned}$$

where $\mathbf{T}$ and $(\mathbf{u}, \mathbf{v}, \mathbf{w})$ represent oceanic mixed-layer temperature (MLT) and 3D ocean currents, ρ and C_p are the density and specific heat of water, H is MLT depth (derived by ORAS4 ocean reanalysis data), and $\mathbf{R}$ represents residual term (Li et al. 2002; Hong et al. 2008, Su et al. 2010, 2014; Chen et al. 2015).

Because heat flux products usually contain to a certain degree uncertainty, taking ensemble mean of various datasets can smooth out random errors and highlight the

effect of forcing. In this study, to eliminate uncertainty, the results of MLTA tendencies and ocean advection terms in MLHB analysis are calculated based on the ensemble average of SODA v2.1.6 and ORAS4 datasets, while the thermodynamic heat flux terms are calculated based on the ensemble average of OAFlux and NCEP R2 datasets averaged over EP region (180° – 80° W, 5° S– 5° N). The typical and special ENSO events are selected based on the period of 1980–2013. In this period, an EN (LN) event is defined as the 3-month running-mean of Niño-3.4 index that exceeds the threshold of $+0.5^\circ\text{C}$ (-0.5°C) for at least 5 consecutive months (the peak value needs to exceed one standard deviation). For the purpose of studying ENSO evolution asymmetry, only developing year of ENSO event should be considered in the composite analysis. According to this definition, there are eight ENs (1982/83, 1986/87, 1991/92, 1994/95, 1997/98, 2002/03, 2006/07, and 2009/10) and six LNs (1983/84, 1995/96, 1998/99, 2005/06, 2007/08, and 2010/11). Because 1986/87 EN and 2005/06 LN have the special evolution features, the composites of the rest of the ENSO events are defined as a “typical” EN and LN event. To illustrate how different the SSTA evolutions of the “typical” and “special” ENSO groups are, we calculate the difference of SSTA in the northern summer and fall of the second year (i.e., year + 1) between the two groups and compare the values against the standard deviation of the SSTA among the “typical” group (Table 1). The result shows clearly that the difference between the two groups is much greater than the spreading among the “typical” group. This points out that there are clear differences not only between the composite mean and the special event, but also between each individual event in the composite group and the “special” event.

3 Mechanisms responsible for the special evolution of 1986 EN

Both the typical and special 1986/87 EN experience a developing stage in the first year, but the onset time of

Table 1 Composite standard deviation of SSTA among the typical ENSO events, and the root mean square difference of SSTA between the typical and special ENSO events in the northern summer (JJA) and fall (SON) of the second year (i.e., year + 1)

	JJA + 1		SON + 1	
	STD	RMS	STD	RMS
El Niño	0.51	1.22	0.54	1.88
La Niña	0.30	0.75	0.36	1.54

The results are averaged in the eastern equatorial Pacific region (180° – 80° W, 5° S– 5° N)

the special 1986/87 EN is later than the other ENs in the typical group (Fig. 1a). In northern spring of the developing year, the typical EN has a warm SSTA in equatorial central Pacific (CP), and to the west of the SSTA, anomalous westerly wind has established (Fig. 2a). This air-sea coupled structure favors the development of EN events. In contrast, in the same period of special 1986/87 EN, there is still a negative SSTA retaining in equatorial EP region, and easterly anomalies are pronounced along the equator (Fig. 2b). In the following summer and autumn seasons, the positive SSTA and anomalous westerly are strengthened at the equator for both typical and special

EN (Fig. 2c, d). But such a wind field pattern changed in the following mature winter. For the typical EN, there is an anomalous WNPAC occurred (Wang et al. 1999, 2000, 2003; Weisberg and Wang 1997), and to south of WNPAC, it is dominated by anomalous easterly wind along the equatorial WP (Wu et al. 2010; Fig. 2e). In contrast, pronounced anomalous WNPC and anomalous westerly are found in the winter of the special 1986/87 EN (Fig. 2f). To illustrate the circulation differences is robust between the “typical” and “special” EN events, we did a comparison of circulation anomalies in tropical WNP and equatorial WP from all individual EN cases. The result shows clearly

Fig. 2 SSTA (shading; °C) and 850 hPa wind anomalies (vectors; m/s) for (left) composite typical and (right) special 1986/87 EN during **a, b** developing spring (MAM), **c, d** summer and autumn (JJASON), and **e, f** mature winter (DJF). The stream function anomalies (solid bars) area averaged in the western North Pacific region

($10^6 \text{ m}^2/\text{s}$; $120^\circ\text{--}150^\circ\text{E}$, $5^\circ\text{--}15^\circ\text{N}$) and anomalous zonal wind (diagonal bars) along the equatorial western Pacific (m/s; $120^\circ\text{--}150^\circ\text{E}$, $5^\circ\text{S--}5^\circ\text{N}$) for each EN events during mature winter are also shown (i.e., red solid bars represent anomalous anticyclone, whereas blue solid bar represents anomalous cyclone; bottom panel)

that only 1986/87 EN attained an anomalous cyclone (i.e., a negative stream function anomaly) in the WNP associated with westerly wind anomaly along the equatorial WP during its peak phase, whereas all other EN events in the typical group had an anomalous easterly wind and anticyclonic circulation (Fig. 2g).

Through a careful examination of each of individual EN events since 1980, we notice that the cause of the distinctive wind pattern in late 1986 arose from the slow eastward movement of a convective system from the equatorial central IO in October to the equatorial WP in December. In the late fall of composite EP-type EN (Fig. 3), there were clear zonal dipole modes of SSTAs and OLR anomalies in the tropical IO. As a result, anomalous easterly wind and anticyclonic circulation formed in the central IO. Because the anomalous anticyclone is cold and dry in nature, its anomalous anticyclonic flows advect mean cold and dry air to its east, but warm and wet air to its west, setting an eastward-moving tendency for the anomalous anticyclone (Chen et al. 2007). In the end, it was dominated by anomalous anticyclone over the WNP (Fig. 3f), and easterly anomalies south of the anticyclone can stimulate eastward propagating upwelling Kelvin waves that led to a fast decay of traditional EN (Wang and Weisberg 2000; Boulanger and Menkes 2001; Picaut et al. 2002; Boulanger et al. 2003; Chen et al. 2016). As easterly anomalies

and cold SSTa appeared in the equatorial EP in later of year + 1, EN transitioned into a LN episode. Further examination result showed that the CP-type EN had a similar process, thus it also had a fast decay (Fig. 4).

In contrast, in the late fall of 1986, the SSTa in the tropical IO had a uniform pattern, and anomalous ascending motion appeared in the eastern IO and Marine Continent region (Fig. 5b). As a result, there was clear eastward propagation of anomalous convective heating from tropical IO in late 1986 (October–December). The related twin cyclonic anomalies (i.e., Rossby wave response) propagated eastward all the way to the tropical WP, merging with the local anomalous convection forced by warm SSTa in the equatorial CP (Fig. 5f). As a result, there were large-scale westerly anomalies over the WP. The westerly anomalies induced downwelling Kelvin waves, which helped maintain the warm SSTa in the equatorial EP.

In addition, one possible process that might contribute to the slow decay of 1986/87 EN is the weak southward shift of westerly anomalies (SWS) in CP during mature phase. This SWS was noted previously by Harrison and Vecchi (1999), who found a transition of zonal wind anomaly from an equatorially symmetric state during earlier developing stage to an asymmetric state during EN mature phase. It was hypothesized that the SWS in CP may hasten the EN to LN transition through enhanced delayed oscillator oceanic wave

Fig. 3 SSTAs (shading; °C; left), OLR anomalies (shading; W/m^2 ; right), and 850 hPa wind anomalies (vectors; m/s) for composite EP-type EN (including 1982, 1997 and 2006 ENs) in late developing year (October–December in year 0). The green circles denote anticyclonic anomalies

Fig. 4 The same as in Fig. 3, but for composite CP-type EN (including 1991, 1994, 2002, and 2009 ENs)

Fig. 5 The same as in Fig. 3, but for the special 1986 EN. The red circles denote twin cyclonic anomalies

effect (McGregor et al. 2013; Abellan et al. 2017). The cause of the SWS was possibly related to the seasonal change of the mean state (Harrison and Vecchi 1999) or zonal wind

acceleration due to reduced boundary layer friction coefficients (McGregor et al. 2012). After carefully examining the strength of SWS in CP for each of individual EN cases,

the result illustrates that, indeed, the special 1986/87 El Niño had one of the weakest SWS for about 3 latitude degrees (Fig. 6b). But given that 1991/92 EN in the typical EN group

also had a similarly weak southward shift, this factor is not a sufficient and necessary condition for generating special 1986/87 El Niño event.

Fig. 6 The low-level 850 hPa zonal wind anomalies (*shading; m/s*) in the central Pacific for each individual EN events in mature winter (DJF). For comparison, the centers of maximum zonal wind anoma-

lies for each individual EN events are also shown in the *bottom panel* (i.e., *red solid points* for each individual EN events in the typical group, whereas *blue solid point* for special 1986/87 EN)

Another possible process that slows down the decay of the special 1986/87 EN during the second year is the occurrence of westerly wind events (WWEs). Following Chen et al. (2017), we calculate an index of zonal wind stress anomaly ($Taux'$) to quantitatively measure the strength of the WWEs. This index (named as E-HF- $Taux'$) is defined as the integration of the high frequency (HF) component (through 90 days HF filter) of $Taux'$ that exceeds its climatological standard deviation. Figure 7 gives us the evolution of E-HF- $Taux'$ for the typical and special 1986/87 EN along the equator. The result shows that there are no significant WWEs during the second year of the typical EN (Fig. 7a), but two strong WWEs did happen in earlier (from February to July) 1987 (Fig. 7b). It is likely that these two WWEs were responsible for reversing the SSTA decaying trend and helping re-intensify the warm episode in 1987. After carefully examining HF WWEs for each of individual EN cases, we note that the intensity of WWE in 1987 is the strongest among all the individual EN events in recent years (Fig. 7c). On other hand, the intensity of WWE in 2002/03 EN is also quite large. This indicates that the occurrence of strong WWE is not a sufficient and necessary condition for generating 1986-like EN event. However, strong WWE might help re-intensify the warm episode in 1987.

For the distinctive wind forcing, TDAs exhibited different evolution features between the typical and special 1986/87 EN in year + 1. For typical EN, the negative TDA was larger and its eastern edge reached to 150°W in the late winter (Fig. 8a). Since the anomalous easterly forcing in equatorial WP, this negative TDA was strengthened and propagated eastward in the following spring. As the consequence of the upwelling Kelvin wave propagation, the previous positive TDA in the EP was split into two centers off the equator (Fig. 8c). In the early summer, the equatorial Pacific is dominated by a shallower thermocline depth (Fig. 8e). The negative thermocline signal continued moving eastward throughout the year. As a result, the typical EN translates into a LN episode in later of year + 1 (Fig. 8g, i). However, the thermocline evolution feature of the special 1986/87 EN was quite different (right panel of Fig. 8). In the beginning of the second year, a similar TDA pattern appeared (Fig. 8b). Due to both the seasonal mean westerly anomaly (Figs. 2f, 5f) and continuous HF WWE forcing (Fig. 7b), negative TDA remained in equatorial WP (Fig. 8d–j).

The wind induced negative TDA in typical EN shown in Fig. 8 had two effects on the termination of the ENs. One is through induced westward geostrophic currents (Picaut et al. 1997; Wang and Picaut 2004; Su et al. 2014; Wang et al. 2016). The other is through the decrease of the subsurface ocean temperature, because the mean upwelling could advect colder subsurface temperature upward, which could further cool the SST (Li 1997; Chen et al. 2016). The

different evolution features of the TDA between the typical and special 1986/87 EN (shown in Fig. 8) implies that distinctive MLTA tendencies in the decaying phase. Table 2 gives MLHB analysis result in equatorial EP region during February–June in year + 1. The decaying rate of the typical EN is much larger than special 1986/87 EN. Further examination of dynamic and thermodynamic processes indicates it is dynamic term that contributes to the distinctive decaying tendencies. In fact, the thermodynamic damping is even larger in the special 1986/87 EN than in the typical EN. Following Su et al. (2010), the ocean advection term was further decomposed into nine terms, and the major contributors to the SSTA tendency difference are these three terms: $-u'\partial\bar{T}/\partial x$, $-\bar{v}\partial T'/\partial y$, and $-\bar{w}\partial T'/\partial z$. All of these three advective processes contribute to a rapid decaying of the SSTA in typical EN, but the maintenance of warm episode in special 1986/87 EN. To reflect how the special 1986/87 EN event budgets differ significantly from those of the typical EN events, we added the standard deviations for each budget term. As one can see, there are significant gaps in major dynamic (i.e., oceanic advection) budget terms and in the total mixed-layer temperature tendency terms between the typical and special EN events.

To understand how these dynamic terms caused the distinctive decaying rates between the typical and special 1986/87 EN, we plotted the composite TDA, current and temperature anomalies in the decaying phase (Fig. 9). Note that negative TDAs appeared in equatorial EP and positive anomalies appeared off the equator in the typical EN (Fig. 9a), and this meridional structure induced westward geostrophic currents at the equator. This westward ocean current anomaly led to a cold anomalous zonal advection. Meanwhile, mean upwelling in EP could advects colder subsurface water upward, leading to the surface cooling in the equatorial EP (Fig. 9c). In contrast, in earlier 1987, the negative TDA remained in the WP whereas the positive anomaly was located in the EP (Fig. 9b). As a result, westward geostrophic currents in the far EP were much weaker compared to that in the typical EN. This led to a much weaker cold anomalous zonal advection in the region. Meanwhile, because cold subsurface water was locked into the equatorial WP, positive ocean subsurface temperature anomalies were dominant in the EP (Fig. 9d).

In the tropical Pacific region, the mean subtropical cell circulation transported anomalous cold subsurface water upward and poleward in decaying phase of typical EN, promoting a negative tendency in the equatorial EP (Fig. 9e; Table 2). However, in special 1986/87 EN decaying phase, because the subsurface water was warmer than the surface, the mean meridional and vertical advection terms tended to maintain the warm SSTA (Fig. 9f; Table 2). Therefore, the typical EN decayed quickly, and translated into a LN by winter of year + 1. In contrast,

Fig. 7 Evolutions of equatorial westerly wind events (shading; N/m^2) for **a** typical and **b** special 1986/87 EN in year +1. **c** The strength of westerly wind events area averaged in the equatorial western Pacific

region (120°E–180°, 5°S–5°N) for each EN events in the decaying phase (February–July in year +1) are also shown

the special 1986/87 EN decayed slowly and remained the positive SSTA in earlier 1987. Due to the continuous WWE forcing and the strengthening of air-sea feedbacks (Li 1997) in later of the year, the special 1986/87 EN re-developed into another EN.

4 Mechanism responsible for the special evolution of 2005 LN

In the decaying year, typical LN decays slowly and re-intensifies in boreal fall. In contrast, special 2005/06 LN decays

Fig. 8 Evolutions of thermocline depth anomaly (shading; m) for (left) composite typical and (right) special 1986/87 EN in year + 1

Table 2 The mixed-layer heat budget analysis for typical and special 1986/87 EN decaying phase (February–June in year + 1; °C/month)

El Niño	dT'/dt	Adv	Hflx	Sum	$-u'\partial\bar{T}/\partial x$	$-\bar{v}\partial T'/\partial y$	$-\bar{w}\partial T'/\partial z$
Typical	-0.32 ± 0.18	-0.19 ± 0.18	-0.15 ± 0.22	-0.34 ± 0.16	-0.15 ± 0.07	0.04 ± 0.12	-0.11 ± 0.14
1986/87	-0.02	0.21	-0.24	-0.03	-0.06	0.15	0.14

The standard deviations for the typical event are in italics

fast and translates into an EN by winter of year + 1 (Chen et al. 2016, also see Fig. 1b). Such a distinctive evolution feature may arise from the difference of low-level wind in the WNP in the LN mature winter between the typical LN composite and the special 2005/06 LN. In October of the LN developing year (top panel of Fig. 10), anomalous WNPAC appeared in both the typical and special 2005/06 LN. Easterly anomalies south of the anticyclone induced upwelling Kelvin waves that may favor the continuous development of the LN. But such a wind field pattern changed in the following boreal winter. For the typical LN, the anticyclonic circulation was maintained and strengthened (Fig. 10c, e). In contrast, in December 2005, there is an anomalous WNPC occurred (Fig. 10d). The anomalous cyclone was

strengthened and shift to 150°E in February 2006. Because of the occurrence of the anomalous cyclone, the equatorial WP was dominated by anomalous westerly winds, which might promote a fast decaying of the LN (Fig. 10f). The circulation anomalies over the tropical WNP for each LN events further indicate that only 2005/06 LN has anomalous westerly wind and cyclonic circulation in the WP, whereas there is anomalous easterly wind south of WNPAC for the rest of typical LN events (Fig. 10g).

To get to the bottom of the distinctive circulations in the WNP between the special 2005/06 LN and the typical LN, we examine the evolutions of SSTA and OLR anomalies. For the typical LN, the SSTA center was located at 150°W in the mature winter (contours of Fig. 11a), and

Fig. 9 **a, b** The thermocline depth anomalies (shading; m); **c, d** equatorial (2°S–2°N) ocean anomalous zonal currents (vectors; m/s) and subsurface temperature (shading; °C); and **e, f** mean STC cur-

rents and anomalous subsurface temperature in eastern Pacific (180°–80°W) for (left) typical and (right) special 1986/87 EN decaying phase (February–June in year +1)

the corresponding anomalous suppressed convection was located mainly west of the date line (shading of Fig. 11a). As a result, the easterly anomaly extended all the way to 130°E (purple vectors of Fig. 11a). In contrast, the SSTA center of the special 2005/06 LN was located in 120°W, with an eastward shift of 30 longitude degrees compared to the typical LN (contours of Fig. 11b). The corresponding positive OLR anomaly center was shifted to the east of 180° (shading of Fig. 11b). As a Rossby wave response to the suppressed convection in the equatorial CP, two anomalous anticyclones were generated. Southerly anomalies to the west edge of anticyclone advect high MSE air northward, leading to enhanced convection in WNP,

which further favor the development of a cyclonic flow over Philippine Sea.

Furthermore, to illustrate the differences of SSTA and OLR anomaly is robust between the “typical” and “special” LN events, we did a comparison from all individual LN cases (Fig. 12). It is clearly seen that the negative SSTA center, compared to the individual LN events in the typical group, had an eastward shift by at least 20 longitude degrees in the special 2005/06 LN (Fig. 12g). In response to this eastward shift of SSTA center, only special 2005/06 LN had a positive OLR anomaly center east of the date line (green point in Fig. 12d), whereas all other LN events tended to shift west of 180° in the typical group.

Fig. 10 SSTA (shading; °C) and 700 hPa wind anomalies (vectors; m/s) for (left) composite typical and (right) special 2005/06 LN during **a, b** October, **c, d** December in the developing year, and **e, f** February in year +1. The stream function anomalies (solid bars) area averaged in the western North Pacific region (10^6 m²/s; 140–170°E,

5–15°N) and anomalous zonal wind (diagonal bars) along the equatorial western Pacific (m/s; 140–170°E, 5°S–5°N) for each LN events during mature winter are also shown (i.e., red solid bars represent anomalous anticyclone, whereas blue solid bar represents anomalous cyclone; bottom panel)

Figure 13 illustrates the evolution of the TDA during decaying phase of typical LN (left panel of Fig. 13) and year 2006 (right panel of Fig. 13). Due to the persistent easterly anomaly (Fig. 10e), the TDA remained negative throughout the year for the typical LN (left panel of Fig. 13). However, in the special 2005/06 LN, as the anomalous westerly in the equatorial WP could induce downwelling Kelvin waves that propagated eastward, a positive TDA can gradually penetrate in the equatorial EP (right panel of Fig. 13). By the summer 2006, the TDA in the equatorial EP has changed its sign (Fig. 13f). This positive TDA continued strengthening, helping transition the special LN event into an EN in December 2006.

The MLHB analysis result further supports the discussion above. Table 3 illustrates that in the decaying phase (February–June in year + 1), the special 2005/06 LN had a larger positive MLT tendency than that of the typical LN. Because the heat flux terms are nearly equal (0.1 and 0.07 °C/month for the typical and special 2005/06 LN, respectively), the difference is mainly attributed to the ocean temperature advection term, which is much larger in the 2005/06 LN than in the typical LN. In the ocean advection terms, the major contributors are the anomalous zonal advective and the thermocline feedback processes.

In typical LN decaying phase, there was negative TDA in EP (Fig. 14a). Because maximum amplitude of negative

Fig. 11 Longitude-time sections of equatorial (5°S–5°N) surface zonal wind stress anomalies (vectors; N/m^2), SSTa (contours; $^{\circ}\text{C}$), and OLR anomalies (shading; W/m^2) for **a** typical and **b** special 2005/06 LN

signal is off the equator, it caused eastward geostrophic current anomalies in the upper ocean. The anomalous warm zonal advection induced by the eastward ocean current was approximately offset by anomalous cold vertical advection through which mean upwelling could advect colder subsurface water upward (Fig. 14c, e; Table 3). As a result, the typical LN decayed slowly (Fig. 1b). In contrast, in the decaying phase of the special 2005/06 LN, a positive TDA was clearly seen in the equatorial CP (Fig. 14b). This led to a stronger anomalous warm zonal advection due to stronger eastward geostrophic current anomalies. Meanwhile, warm subsurface water penetrated further into the EP (Fig. 14d), which the anomalous warm vertical advection induced by mean upwelling (Fig. 14f).

Due to the distinctive MLT tendencies between the typical and special 2005/06 LN, by summer of year +1, the typical LN retained the negative SSTa in the equatorial EP, whereas the special 2005/06 LN transitioned into a weak positive SSTa (Fig. 1b). In northern fall, because the mean state favors strong positive Bjerknes and zonal advective feedbacks (Li 1997), a weak SSTa can rapidly grow.

Table 4 shows MLHB result for the typical LN re-intensification phase and special 2005/06 LN transition phase (August–November in year +1). In this period, the surface net heat flux term always acted to reduce the MLT tendency, and the major contributor to the MLT growth was ocean advection terms. In the ocean advection terms, the major contributors were these three positive feedback terms: $-u'\partial\bar{T}/\partial x$, $-\bar{v}\partial T'/\partial y$, and $-\bar{w}\partial T'/\partial z$.

In typical LN re-intensification phase, negative thermocline signal appeared in equatorial EP (Fig. 15a), and this induced westward ocean geostrophic currents in the upper ocean (Fig. 15c). Because of the negative TDA, the ocean temperature in the subsurface is colder than the surface. Thus the mean upwelling could cool down SST (Fig. 15c). For the transition phase of special 2005/06 LN, because the TDA in the EP was positive (Fig. 15b), eastward geostrophic current anomalies were induced, and favored the growth of a positive SSTa through the anomalous warm zonal advection (Fig. 15d). Given the warmer ocean temperature in the subsurface at the equator, both the mean meridional advection terms can further amplify the warming (Fig. 15f).

Fig. 12 SSTA (contours; °C) and OLR anomalies (shading; W/m^2) for each individual LN events in mature winter (DJF). The black and green solid points denote the centers of SSTA and OLR anomaly, respectively. For comparison, the SSTA centers for each individual

LN events are also shown in the bottom panel (i.e., red solid points for individual LN events in the typical group, whereas blue solid point for special 2005/06 LN)

5 Conclusion

The 1986 EN and 2005 LN are two special ENSO events in recent decades, and they have the distinctive evolution features compared to the typical ENSO events. The typical EN has a fast decaying after its peak, and translates into a LN episode by winter of year + 1, whereas special 1986 EN decays slowly in the earlier of the second year, and intensifies again in the later of year + 1. In the LN decaying year, typical LN decays slowly and re-intensifies in boreal winter,

but the special 2005 LN decays fast and translates into an EN episode in the winter.

In this study, by conducting an oceanic MLHB analysis, with use of two sets of oceanic reanalysis and two sets of surface heat flux datasets, we investigate physical mechanisms responsible for special evolutions of 1986 EN and 2005 LN events. The MLHB analysis indicates it is the dynamic processes (3D ocean advections) that caused the distinctive MLT tendencies between the typical and special ENSO events during their decaying phase. The contribution

Fig. 13 The same as in Fig. 8, but for (left) composite typical and (right) special 2005/06 LN in year +1

Table 3 The same as in Table 2, but for typical and special 2005/06 LN decaying phase (February–June in year +1; °C/month)

La Niña	dT'/dt	Adv	Hflx	Sum	$-u'\partial\bar{T}/\partial x$	$-\bar{v}\partial T'/\partial y$	$-\bar{w}\partial T'/\partial z$
Typical	0.12 ± 0.08	0.04 ± 0.12	0.10 ± 0.08	0.14 ± 0.06	0.10 ± 0.06	-0.02 ± 0.05	-0.08 ± 0.08
2005/06	0.20	0.17	0.07	0.24	0.16	0.02	-0.02

The standard deviations for the typical event are in italics

by the thermodynamic processes (i.e., surface heat fluxes) is relative small. In the ocean advection terms, the major contributors are the wind induced anomalous zonal advective and the thermocline feedback processes.

An important difference of low-level circulation anomalies between typical EN and 1986/87 EN is that in the former there is an anomalous WNPAC while in the latter there is an anomalous WNPC in their mature phase. Easterly anomalies south of WNPAC during typical EN induced eastward-propagating upwelling Kelvin waves, which helped the EN decay fast. It is worth noting that the generation mechanism of the WNP anticyclone is still an open issue and under debate (e.g., Stuecker et al. 2015,

2016; Li et al. 2016), and it deserves further investigation. In contrast, westerly anomalies south of the cyclone in 1986/87 induced downwelling Kelvin waves, which helped maintain the positive SSTA in the equatorial EP. Through careful examination of each individual EN since 1980, we note that all typical EN events experienced the eastward propagation of an anomalous anticyclone from tropical Indian Ocean in boreal summer to WNP in boreal winter, and only exception is in late 1986 when there was clear eastward propagation of an anomalous cyclone from tropical IO to WNP. The anomalous cyclone propagated eastward and merged with the local anomalous convection in WP forced by warm SSTA in CP. As a result, there were

Fig. 14 The same as in Fig. 9, but for (left) composite typical and (right) special 2005/06 LN decaying phase (February–June in year + 1)

Table 4 The same as in Table 2, but for typical LN re-intensification phase and special 2005/06 LN transition phase (August–November in year + 1; °C/month)

La Niña	dT'/dt	Adv	Hflx	Sum	$-u'\partial\bar{T}/\partial x$	$-\bar{v}\partial T'/\partial y$	$-\bar{w}\partial T'/\partial z$
Typical	-0.15 ± 0.1	-0.26 ± 0.2	0.10 ± 0.1	-0.16 ± 0.22	-0.13 ± 0.06	-0.05 ± 0.05	-0.07 ± 0.05
2005/06	0.17	0.35	-0.18	0.17	0.15	0.09	0.08

The standard deviations for the typical event are in italics

large-scale westerly anomalies over the WP in the northern winter of 1986/87.

In addition, we also examine the strength of SWS in CP and HF WWEs for each of individual EN cases. We note that the special 1986/87 EN had one of the weakest SWS and the strongest WWE among all the individual

EN events, both of which might help maintain the warm episode. But given that 1991/92 EN had a similarly weak SWS and 2002/03 EN had a similarly strong WWE, it is conceivable to conclude that the weak SWS and the strong WWE are not a sufficient and necessary condition for generating a special event like 1986/87. Therefore, the

Fig. 15 The same as in Fig. 9, but for (left) composite typical LN re-intensification phase and (right) special 2005/06 LN transition phase (August–November in year + 1)

key difference between 1986/87 and typical EN events lies in the occurrence of the equatorial westerly (easterly) anomaly in the WP during EN mature phase, which was associated with the eastward propagation of the anomalous cyclone (anticyclone) from the tropical IO during EN developing phase.

Compared to the typical LN composite that has a maximum SSTA center at 150°W during its mature winter, the maximum SSTA of the 2005 LN was located at 120°W. This difference leads to the zonal shift of anomalous convection and wind response. The eastward shift of anomalous convection in boreal winter of 2005/06 allowed the

development of WNPC. Westerly anomalies south of the anomalous cyclone in the WP forced downwelling Kelvin waves and promoted a fast phase transition of SSTA in EP by summer of year + 1. Strong positive dynamic air-sea feedback processes in northern fall led to continued growth and by end of 2006, an EN formed.

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