Asymmetry of Atmospheric Circulation Anomalies over the Western North Pacific between El Niño and La Niña

Bo Wu$^{1,2}$, Tim Li$^3$, Tianjun Zhou$^1$

1 LASG, Institute of Atmospheric Physics, Chinese Academy of Sciences, China
2 Graduate University of Chinese Academy of Sciences, China
3 IPRC and Department of Meteorology, University of Hawaii, 2525 Correa Rd., Honolulu, HI 96822, USA

Corresponding author:
Dr. Tianjun ZHOU
LASG, Institute of Atmospheric Physics
Chinese Academy of Sciences
Beijing 100029, China.
Phone: 86-10-8299-5279
Fax: 86-10-8299-5172
Email: zhoutj@lasg.iap.ac.cn
Abstract

The asymmetry of the western North Pacific (WNP) low-level atmospheric circulation anomalies between El Niño and La Niña mature winter is examined. An anomalous cyclone (WNPC) center during La Niña tends to shift westward relative to an anomalous anticyclone (WNPAC) center during El Niño. Two factors may contribute to this asymmetric response. The first factor is the longitudinal shifting of El Niño and La Niña anomalous heating. The composite negative precipitation anomaly center during La Niña is located further to the west of the composite positive precipitation anomaly center during El Niño. The westward shift of the heating may further push the WNPC westward relative to the position of WNPAC. The second factor is the amplitude asymmetry of sea surface temperature anomalies (SSTA) in the WNP, viz. the amplitude of local cold SSTA during El Niño is greater than that of warm SSTA during La Niña. The asymmetry of SSTA is originated from the asymmetric SSTA tendencies during the ENSO developing summer. Although both the precipitation and surface wind anomalies are approximately symmetric, the surface latent heat flux anomalies are highly asymmetric over the key WNP region, where the climate mean zonal wind speed is small. Both the anomalous westerly during El Niño and the anomalous easterly during La Niña in the region lead to an enhanced surface evaporation, strengthening (weakening) the enhancement of the cold (warm) SSTA in situ during El Niño (La Niña). The asymmetry of the SSTA in the WNP is further amplified due to anomalous wind differences between El Niño and La Niña in
their mature winter. Atmospheric general circulation model experiments demonstrate that both the factors contribute to the asymmetry between the WNPAC and WNPC. The asymmetric circulation in the WNP contributes to the asymmetry of temporal evolutions between El Niño and La Niña.
1. Introduction

During the mature phase of El Niño, the most prominent low-level atmospheric circulation anomalies over the tropical western Pacific and East Asia is an off-equatorial anomalous anticyclone (hereafter referred to as WNPAC) (Wang et al. 2000; Chang et al. 2000a). The WNPAC is a key bridge that links El Niño and the East Asian summer monsoon (Chang et al. 2000a, b; Wang et al. 2000; Wu et al. 2003). It influences the East Asian climate from El Niño mature winter to the following summer. Concurring with the formation of the WNPAC, a positive anomalous rainfall belt extends from southeastern China to Kuroshio extension region in boreal winter and spring due to anomalous moisture transport by the southerly component in the northwestern flank of the WNPAC (Zhang et al. 1996; Lau and Nath 2000; Zhang and Sumi 2002). During the subsequent summer, the WNPAC favors an westward extension of the western Pacific subtropical high which blocks the Meiyu front from moving southward and thereby prolongs the frontal rainfall along the lower reaches of the Yangtze River and the Huaihe River valleys (Chang et al. 2000a, b; Zhou and Yu 2005; Sui et al. 2007; Wu and Zhou 2008).

As a response to El Niño forcing, the WNPAC may play a role in the phase reversal of El Niño (Wang et al. 2001). Easterly anomalies to the south of the WNPAC may stimulate oceanic upwelling Kelvin waves and thus reverse warm SST anomalies (SSTA) in the equatorial central-eastern Pacific (Weisberg and Wang 1997a, b; Wang et al. 1999a; Kim and Lau 2001; Li et al. 2007; Ohba and Ueda 2009).
The WNPAC is tightly coupled with underlying ocean surface cooling. The northeasterly anomalies over the southeastern flank of the WNPAC increase the background mean northeasterly trades, and generate a colder sea surface temperature (SST) in situ through enhanced evaporation. The negative SSTA further suppress convection and stimulate a descending Rossby wave to the northwest and thus reinforce the WNPAC (Wang et al. 2003). This positive wind-evaporation-SST feedback maintains the WNPAC through the El Niño mature winter and the subsequent spring (Wang et al. 2000). The “wind-evaporation-SST” feedback was first proposed to study the equatorial asymmetry of Inter-tropical convergence zone (Xie and Philander 1994; Li 1997), and then used to study the decadal variability over the tropical Atlantic (Chang et al. 1997; Xie 1999) and the phase locking of ENSO (Wang et al. 1999b). In the study, we will explore the nonlinear feature of the wind-evaporation process over the western North Pacific (WNP).

While the WNPAC is maintained by the local air-sea interaction, it is initiated possibly through following three routes. Firstly, circulation anomalies in response to the El Niño heating over the equatorial central Pacific generates cold SSTA in the western Pacific, which further set up the WNPAC (Wang et al. 2000). Secondly, the deepening of the East Asian trough and the intrusion of mid-latitude cold air into the Philippine Sea might trigger the WNPAC (Wang and Zhang 2002; Lau and Nath 2006). Thirdly, the WNPAC results from the eastward movement of an anomalous anticyclone established
over the northern Indian Ocean (Chou 2004; Chen et al. 2007).

Most previous studies assumed a symmetric circulation feature between El Niño and La Niña, viz. there is an anomalous anticyclone (cyclone) over the WNP during the El Niño (La Niña) mature winter. However, it is important to note that El Niño and La Niña have a significant asymmetry in the amplitude, structure and temporal evolution (e.g., Hoerling et al. 1997; Bergers, and Stephenson 1999; Kang and Kug 2002; Jin et al. 2003; An and Jin 2004; An et al. 2005). The anomalous convection over the equatorial central Pacific during La Niña tends to shift to the west of its El Niño counterpart (Hoerling et al. 1997). Numerical model experiments indicated that this asymmetry is attributed to nonlinear atmospheric responses to underlying SSTA (Hoerling et al. 1997; Kang and Kug 2002).

The anomalous convective heating over the equatorial central Pacific is a crucial factor that impacts the circulation over the WNP (Lau and Nath 2000; Wu and Zhou 2008; Zhou et al. 2009a, b). Given the asymmetric SSTA pattern between El Niño and La Niña, one may wonder whether the WNP atmospheric response to the El Niño and La Niña is asymmetric. In the paper, we attempt to address the following questions: (1) Are WNPAC and WNPC during El Niño and La Niña mature winter asymmetric? (2) If they show an asymmetric characteristic, what are the physical mechanisms that cause the asymmetry?

The rest of the paper is organized as follow. Datasets, analysis methods and an atmospheric general circulation model (AGCM) are described in section 2. Section 3
presents the asymmetric circulation features over the WNP between El Niño and La Niña. In section 4, we discuss two possible factors that cause the asymmetry. The two factors are further examined through a series of AGCM numerical experiments in section 5. The impacts of the asymmetry on ENSO evolution are discussed in section 6. Summary and concluding remarks are given in Section 7.

2. Data, method and model experiments

a) Data and method

The datasets used in the present study consist of 1) the 850 hPa and 1000 hPa wind fields and the surface heat flux from the National Centers for Environment Prediction-National Center for Atmospheric Research (NCEP-NCAR) reanalysis data (Kalnay et al. 1996) for the period of 1948-2004, 2) SST data from Hadley Centre Sea Ice and Sea Surface Temperature data set (HadISST) (Rayner et al. 2003) for the period of 1948-2004, 3) monthly precipitation anomalies over global land and oceans for the period of 1948-2004 from the precipitation reconstruction (PREC) dataset (Chen et al. 2002), 4) oceanic subsurface temperature data from a simple ocean data assimilation analysis of global upper ocean (SODA) (Carton et al. 2000) for the period of 1950-2000, and 5) the 560-station precipitation data for the period of 1950-2002 provided by China Meteorological Administration. All the data are monthly mean fields.

A composite analysis method is applied. We chose nine El Niño events and nine La Niña events in the period of 1948-2002. The selection of El Niño and La Niña events is
based on the threshold of one standard deviation of wintertime (December-February, hereafter DJF) mean Nino-3.4 index, which is defined as area-averaged SSTA over the region of 5°N-5°S, 120-170°W. The selected ENSO years are listed in Table 1.

To focus on the interannual time scale, variations longer than 8 years are filtered out from the original datasets with a Lanczos filter (Duchon 1979). Following Hoerling et al. (1997), the difference between the composite El Niño and La Niña events is regarded as a symmetric component, and the sum of them is regarded as an asymmetric component.

b) Model description and experiment design

The AGCM used in the study is ECHAM version 4.6 (hereafter ECHAM4) developed by the Max Planck Institute for Meteorology (MPI) (Roeckner et al. 1996). The model was run at a horizontal resolution of spectral triangular 42 (T42), roughly equivalent to 2.8 latitude x 2.8 longitude, with 19 vertical levels in a hybrid sigma-pressure coordinate system extending from surface to 10 hPa. The SST data used as the lower boundary condition is same with that used in the observational analysis.

As listed in Table 2, four sets of model experiments are designed:

1) Control run (hereafter CTRL run): the ECAHM4 was integrated for 10 years, forced by monthly climatological SST. The climatological SST is based on the period of 1948-2005.

2) Global SSTA forcing runs for El Niño and La Niña: composite El Niño or La Niña SSTA was added to the climatological SST in the global ocean (hereafter GB experiment).
The run with SSTA derived from El Niño (La Niña) is referred to as GBEL (GBLA) run.

3) Tropical central-eastern Pacific SSTA forcing runs for El Niño and La Niña: The experiments were the same as the GB experiments except that only the positive (negative) SSTA in the tropical central-eastern Pacific (hereafter CE experiment) associated with El Niño (La Niña) was added to the climatological mean SST field. The runs with SSTA derived from El Niño (La Niña) are referred to as CEEL (CELA) runs.

4) Western North Pacific SSTA forcing runs for El Niño and La Niña: The experiments were the same as the GB experiments except that only the negative (positive) SSTA in the western North Pacific (hereafter WP experiment) associated with El Niño (La Niña) was added to the climatological mean SST field. The runs with SSTA derived from El Niño (La Niña) are referred to WPEL (WPLA) runs.

For each sets of experiment, an ensemble simulation with 10 members was done. Among the 10 members, each realization only differed in initial condition but was forced by identical SST field. The model was integrated from October to February in each simulation. The ensemble mean of December, January and February is analyzed.

3. Asymmetry of circulation anomalies between El Niño and La Niña

The composite 850hPa streamfunction anomalies during the mature phase (DJF) of El Niño and La Niña are shown in Fig.1a, b. In the El Niño composite, an off-equatorial anomalous anticyclone is evident over the WNP, with a center located in the Philippine Sea. The anomalous easterlies in the southern flank of the anticyclone extend eastward to
155°E. Twin cyclone couplets straddle over the central equatorial Pacific, accompanied with westerly anomalies on the equator. In contrast, in the La Niña composite, the northern branch of the twin anticyclone couplets over the central equatorial Pacific shift westward by 15 degrees in longitude, with pronounced equatorial easterly anomalies extending to 135°E. As a result, the WNPC shifts westward relative to the WNPAC during El Niño, with a center located in the South China Sea (SCS).

The asymmetric component of the low-level circulations (Fig. 1c) is characterized by an anomalous anticyclone over the WNP, cyclone couplets over the equatorial central-eastern Pacific, and strong southwesterly winds from the Bay of Bengal to southeastern China. Note that the asymmetry between WNPAC and WNPC is the most significant feature in the asymmetric component of the low-level anomalous circulation fields between El Niño and La Niña. In contrast, the symmetric component (Fig. 1d) represents the averaged condition of El Niño and La Niña, with an anticyclone located between the composite WNPAC and the composite WNPC.

As the maximum asymmetry of the 850hPa streamfunction appears over the WNP (2-20°N, 125-155°E, rectangle box in Fig. 1c), we calculate the box-averaged vorticity for each event and show them as a scatter diagram in Fig. 2, together with corresponding Nino-3.4 indices. Nearly all El Niño events show negative vorticity anomalies over the WNP, except for the 1986 event. If the circulation anomalies were symmetric between El Niño and La Niña, we would expect positive vorticity anomalies during La Niña.
However, only four out of nine La Niña events show positive vorticity anomalies. This asymmetry is consistent with the fact that the anomalous cyclones during most La Niña events shift westward away from the WNP. Figure 2 shows that there is no significant linear relationship between the amplitude of Nino-3.4 indices and the WNP vorticity. We explore the cause of the circulation asymmetry in next section.

4. Mechanisms responsible for the asymmetry between WNPAC and WNPC

The anomalous circulation over the WNP during ENSO mature winter results from both the local forcing of negative SSTA in the WNP and the remote forcing of positive SSTA in the equatorial central-eastern Pacific (Wang et al. 2000; Lau and Nath 2000, 2003; Lau et al. 2004). To explore the asymmetric characteristics of the remote and local forcing between El Niño and La Niña, we show composite precipitation and SST anomalies and their asymmetric components in Fig. 3. Positive precipitation anomalies associated with El Niño extend from the equatorial central Pacific to the far eastern Pacific. In contrast, negative precipitation anomalies associated with La Niña are restricted to the west of 140°W and their center located further west, compared with the El Niño counterpart. Their asymmetric component exhibits a zonal dipole pattern, with a positive (negative) pole over the equatorial central-eastern (western) Pacific (Fig. 3f).

The SSTA over the tropical central-eastern Pacific also present an asymmetric feature. The positive SSTA in the tropical eastern Pacific during El Niño are stronger than the negative SSTA during La Niña, whereas the negative SSTA during La Niña are stronger
in the tropical central Pacific, and extend further westward. As a result, the asymmetric component of SSTA also shows a zonal dipole pattern in the equatorial Pacific (Fig. 3e).

Above results imply that the asymmetry of the WNP circulation anomalies may be partially caused by the zonal asymmetries of the precipitation and SST anomalies between El Niño and La Niña. The anomalous SST and precipitation centers shift further westward during La Niña. It is likely that the westward shift of the precipitation anomalies during La Niña causes the twin anomalous anticyclone couplets expanding into the tropical western Pacific. As a result, the center of the WNPC is pushed further to the SCS (Fig. 1b).

To illustrate the effect of the zonal asymmetry of the anomalous precipitation center between El Niño and La Niña on the WNP circulations, a scatter diagram of the WNP vorticity versus the longitudinal location of the anomalous precipitation center over the equatorial central Pacific is shown in Fig. 4. Five out of nine El Niño events have positive convection centers located east of 170°W, while nearly all La Niña events have negative convection centers located near the dateline. It is interesting to note that when the precipitation centers are located to the east of 170°W, there is a close relationship between the sign of the WNP vorticity anomalies and the SSTA in the equatorial central-eastern Pacific, viz. an anticyclone (cyclone) is associated with El Niño (La Niña). However, when the anomalous precipitation centers shift to the west of 170°W, the relationship becomes complicated, suggesting that some other factors rather than the
longitudinal location of the heating must play active roles.

In addition to the equatorial east-west asymmetry, a significant asymmetry of SSTA also appears in the off-equatorial WNP (Fig. 3e). The cold SSTA in the WNP during El Niño are much stronger than the warm SSTA during La Niña. Due to the weaker SSTA, the precipitation anomalies over the WNP during La Niña are also much weaker than that during El Niño (Fig. 3b, d). There are two negative precipitation centers during El Niño, located in 15°N, 120°E, and 5°N, 150°E, respectively (Fig. 3a). The former has a mirror image during La Niña, but the latter does not have (Fig. 3b). It is crucial to understand why the asymmetric SSTA, which cause asymmetric precipitation anomalies, emerge in the WNP.

To clearly illustrate the asymmetric evolution of the SSTA in the WNP (Fig. 3e), we define a WNPSST index as the area-averaged SSTA in the region of 2-15°N, 130-155°E. Figure 5 shows the evolution of the WNPSST index during El Niño and La Niña. The WNPSST index reaches a peak phase in January, slightly lagging the mature phase of ENSO (Rasmusson and Carpenter 1982). It experiences two fast growing stages, one in June-August (JJA) and the other in November-December (NDJ). During both the stages, the absolute values of WNPSST tendencies during El Niño are much larger than that during La Niña. Thus, the amplitude of the WNPSST in DJF during El Niño is about twice as large as that during La Niña.

Why does the WNPSST experience a stronger (weaker) growth during El Niño (La
Niña) developing summer? To explore the possible mechanisms for the asymmetric evolutions of the WNPSST indices in JJA, we show composite SST, 1000hPa wind and precipitation anomalies during El Niño and La Niña in Fig. 6. Note that the warm SST have already established in the equatorial central-eastern Pacific during the El Niño developing summer (Fig. 6b). The warm SST enhance convection over the equatorial central Pacific (Fig. 6a) and thus stimulate twin low-level cyclone couplets in both sides of the equator, consistent with the classical Matsuno (Matsuno 1966)-Gill (Gill 1980) pattern. The northern branch of the cyclonic circulation anomalies is stronger than the southern one, which can be inferred from northward cross-equatorial flow anomalies over the maritime continent. The asymmetry is possibly attributed to the hemispheric asymmetry of the boreal summer mean flow such as the easterly vertical shear (Wang et al. 2003). The asymmetric flow over the maritime continent may be further enhanced by air-sea interactions in the tropical southeastern Indian Ocean (Li et al. 2002; Li et al. 2003; Wu et al. 2009).

The pattern of SSTA during La Niña is generally symmetric with respect to that during El Niño (Fig. 6d). In particular in the WNP, the amplitudes of the cold SSTA during El Niño and the warm SSTA during La Niña are quite close. Corresponding to the generally symmetric SSTA patterns, the precipitation and surface wind anomalies in the WNP between El Niño and La Niña are also quite symmetric (Fig. 6a, c).

Given the symmetric SST and wind patterns between El Niño and La Niña, a natural
question that needs be addressed is what cause the asymmetric SST A tendency in JJA. In
the following we argue that the SST A tendency asymmetry is primarily attributed to the
asymmetry of the surface latent heat flux (LHF) anomaly. The LHF may be expressed as:

\[ LHF = \rho_0 L_v C_e U (Q_s - Q_a) \]  

(1)

where \( \rho_0, L_v, C_e \) and \( U \) denote air density, the latent heat of vaporization, the surface
exchange coefficient and surface wind speed, respectively; \( Q_s \) is saturated specific
humidity at SST and \( Q_a \) is air specific humidity at 10m.

The anomalous surface wind speed and LHF fields during the El Niño and La Niña
developing summers and their asymmetric components are shown in Fig. 7. The
similarity of the patterns for anomalous wind and LHF suggests that the surface wind
speed anomaly dominates the LHF anomaly in the WNP. Note that there is a large
asymmetric component in the anomalous LHF field between the El Niño and La Niña
(Fig. 7f). The asymmetric LHF component is positive over the key region of the WNP
(2-15°N, 130-155°E), implying a stronger cooling (weaker warming) tendency in WNP
during El Niño (La Niña).

Why are the anomalous surface wind speed and LHF fields greatly asymmetric in
WNP while the surface wind anomalies are quite symmetric in JJA between El Niño and
La Niña (Fig. 6a, c)? Below we construct a simple ideal theoretical model to understand
the non-linear relationship between the LHF anomaly and the wind anomaly (Wang et al.
1999b).
Consider an idealized case in which only the mean and anomalous zonal winds are involved and the mean wind is westerly. Denote $\bar{u}$ and $u'$ as the magnitude of the mean and anomalous winds, $sp_s$ ($sp_o$) as the wind speed anomaly when the anomalous zonal wind is in the same (opposite) direction with the mean wind. Then we have

$$sp_s = |\bar{u} + u'| - \bar{u}$$

$$sp_o = |\bar{u} - u'| - \bar{u}$$

In the case when the amplitude of the mean wind is stronger than that of the anomalous wind (i.e., $\bar{u} > u'$), one may obtain a symmetric anomalous wind-wind speed relationship:

$$sp_s = u'$$

$$sp_o = -u'$$

In the case when the amplitude of the mean wind is weaker than that of the anomalous wind (i.e., $\bar{u} < u'$), one may obtain an asymmetric wind speed relationship:

$$sp_s = u'$$

$$sp_o = u' - 2\bar{u}$$

Considering an extreme condition that the mean wind is zero, the total wind speed would increase, no matter what direction the anomalous wind blows toward.

The theoretic model above indicates that there exist two dynamic regimes in the evaporation-wind feedback. The key difference between the two regimes lies in the relative amplitudes of the mean and anomalous winds. In the key region of the WNP
(2-15°N, 130-155°E), the amplitude of the anomalous zonal wind is about 3 ms⁻¹. However, the strength of the mean zonal wind is much smaller than 3 ms⁻¹ in most of the region, except in the northeastern corner of the region (Fig. 8a). Area-averaged zonal wind in the region is about 0.7 ms⁻¹.

Figure 8b shows the theoretical model result based on the parameter values derived from the observation (i.e., the mean wind of 0.7 ms⁻¹ and the anomalous wind amplitude of 3 ms⁻¹). When the anomalous wind is in the range of -0.7-0.7 ms⁻¹ (i.e., weaker than the mean wind), resultant wind speed anomalies are symmetric. A westerly anomaly leads to a positive wind speed anomaly whereas an easterly anomaly leads to a negative wind speed anomaly (Fig. 8b). When the anomalous wind is beyond the range of -0.7-0.7 ms⁻¹, resultant wind speed anomalies are asymmetric. Both strong westerly and easterly anomalies lead to a positive wind speed (and thus LHF) anomaly (Fig. 8b).

To compare the theoretic solution with real data, we show a scatter diagram of the zonal wind anomaly versus the wind speed anomaly for each grid in the WNP (2-15°N, 130-155°E) (Fig. 8b). As shown in Fig. 6, the anomalous winds in the region are dominated by their zonal component. Thus, we use the zonal wind anomalies to represent the total anomalous winds. The relationship between the zonal wind anomalies and wind speed anomalies is quite consistent with the theoretic model, that is, the enhancement of both positive and negative zonal wind anomalies during El Niño and La Niña leads to the increase of the wind speed and LHF anomalies. The positive LHF anomaly enhances the
WNP SST cooling during El Niño but weakens the WNP SST warming during La Niña. Thus the non-linear relationship causes the asymmetry of the SST tendency in the WNP between El Niño and La Niña.

The analyses above indicate that the area of 2-15°N, 130-155°E is a key region to generate asymmetric LHF anomalies between El Niño and La Niña during their developing summer. It is located in a transitional zone between the monsoon westerly and the easterly trade wind, where the mean zonal wind is very weak (Fig. 8a). Even though the easterly anomalies during La Niña and the westerly anomalies during El Niño in JJA are approximately symmetric (Fig. 6a, c), the wind speed anomalies are enhanced in both the cases. The asymmetry of LHF anomalies caused by the wind speed asymmetry may further induce the asymmetric SSTA tendencies in the WNP between El Niño and La Niña.

Another WNPSST tendency asymmetry between El Niño and La Niña occurs in NDJ (Fig. 5), which is primarily attributed to the asymmetry of anomalous wind fields. Note that in the WNP, the easterly anomaly appears in both El Niño and La Niña composite (Fig. 9a, b). The northeasterly anomaly over the WNP during El Niño connects the WNPAC to the west and a cyclonic circulation anomaly to the east (Fig. 9a). The former is a Rossby wave response to the local negative heating anomaly, whereas the latter is likely a result of a Rossby wave response to the positive heating anomaly over equatorial central Pacific. The easterly anomaly over the WNP during the La Niña, on the other
hand, is the part of the anomalous circulation of the twin anticyclone couplet, which is a direct response to the negative heating over the central equatorial Pacific (Fig. 9b). As the mean wind is northeasterly in the region, the anomalous wind would lead to enhanced wind speed and LHF during both El Niño and La Niña (Figure not shown). Correspondingly, the asymmetric components of the surface wind speed and the LHF anomalies are positive in the WNP region (2-15°N, 130-155°E) (Fig. 9c). The asymmetry of LHF anomalies leads to an enhanced cooling during El Niño but a reduced warming during La Niña in this region. As a result, the asymmetry of the WNP SSTA between El Niño and La Niña becomes even greater, leading to a more significant difference between the WNPAC and the WNPC.

5. The results of AGCM experiments

Observational analyses above suggest that both the asymmetries of the remote forcing from the tropical central Pacific and the local SST forcing in the WNP may cause the asymmetry between WNPAC and WNPC. In this section we examine their relative roles by analyzing the results of the numerical experiments listed in Table 2.

The GB experiment is analyzed first to test basic model skill in reproducing the asymmetry between WNPAC and WNPC during the ENSO mature winter (DJF). The simulated precipitation and 850hPa wind anomalies in the GBEL and GBLA runs and their asymmetric components are shown in Fig. 10. The anomalies are calculated as departures from the CTRL run. The simulated circulation and precipitation anomalies can
be compared against Fig. 1 and right panel of Fig. 3, respectively. The GB experiment reproduces the WNPAC (WNPC) during El Niño (La Niña) and corresponding negative (positive) precipitation anomalies over the WNP and positive (negative) precipitation anomalies over the equatorial central Pacific. The model reproduces the major asymmetric characteristic between the WNPAC and WNPC, i.e. the WNPC is much weaker than the WNPAC and is located further to the west of the WNPAC. It should be noted that the simulated asymmetric component between WNPAC and WNPC is much larger than that in the observation, due to the weaker WNPC in the GBLA runs. The model reproduces well the zonal shift of the anomalous heating over the equatorial central Pacific and the strength difference of the anomalous heating over the WNP, indicating that it is capable of capturing the impacts of both remote central-eastern Pacific and local WNP SST forcing. The results give us confidence to further explore their relative roles through sensitive experiments.

The precipitation and 850hPa wind anomalies simulated by the CEEL and CELA runs and their asymmetric components are shown in Fig. 11a-c. The CEEL (CELA) reproduces the WNPAC (WNPC) and the corresponding negative (positive) precipitation anomalies over the WNP and positive (negative) precipitation anomalies over the equatorial central Pacific, though some biases exist. Compared with the GBEL runs, the WNPAC simulated by the CEEL runs shifts westward to some extent, and the negative precipitation anomalies over the WNP are weaker, especially in the region of 130°-140°E.
The differences between CELA and GBLA are larger. The easterly anomalies induced by the negative heating over the equatorial central Pacific extend into the maritime continent. The WNPC shifts further northward. The differences occur due to the lack of the local forcing in the WNP. In summary, the asymmetry between the WNPAC and WNPC generally can be reproduced in the CE experiments, although the center of the asymmetric component shifts westward relative to the GB experiment.

The results of the WP experiments are shown in Fig 11d-f. The WNPAC is reproduced, but with amplitudes far weaker than their counterparts in the CEEL runs. In the CELA runs, the WNPC is weakly simulated, with weak westerly seen in the WNP. However, compared to the CE experiments, the locations of the WNPAC in the CEEL runs and the WNP westerly anomalies in the CELA runs are closer to those in the GB experiments. The asymmetry of the WNP circulation anomalies is also reproduced by the WP experiments, though the asymmetric component is weaker than that in the GB and CE experiments.

The model results support our hypothesis based on observational diagnosis that both the asymmetries of the remote forcing from the equatorial central-eastern Pacific and the local SSTA forcing in the WNP contribute to the asymmetry between the WNPAC and WNPC. The numerical experiments demonstrate that the remote forcing from the equatorial central-eastern Pacific play greater roles than the local WNP SST.
6. Impact of the asymmetry on ENSO phase reversal

Previous studies noted the essential role of equatorial zonal wind stress over the equatorial western Pacific in ENSO phase reversal (Weisberg and Wang 1997a, b; Kim and Lau 2001; Lau and Wu 2001; Kug and Kang 2006). To investigate relationship between the WNPC/WNPAC and the zonal wind stress anomalies over the equatorial western Pacific, we show the scatter diagram of the box-averaged zonal pseudo wind stress anomalies over the equatorial western Pacific (5°S-5°N, 125-155°E) against 850hPa vorticity anomalies over the WNP (2-20°N, 125-155°E) (Fig. 12). Their correlation coefficient reaches 0.79, which is statistically significant at 1% level, indicating that the WNP vorticity accounts for about the half variance of the zonal wind stress over the equatorial western Pacific during ENSO mature winter.

The easterly wind stress anomalies prevail during seven out of nine El Niño events, except for 1986 and 1994 events. In contrast, only three La Niña events have westerly wind stress anomalies in the equator. Some La Niña events even have strong equatorial easterly wind stress anomalies.

The asymmetry of equatorial wind stress anomalies over the western Pacific is likely responsible for the asymmetry of ENSO evolution (Ohba and Ueda 2009). Fig. 13 shows that following El Niño and La Niña peak phase in boreal winter, canonical El Niño experiences a fast decay and translates to a negative phase in boreal summer. In contrast, La Niña tends to persist through the next year. To quantify the decaying rate of Nino-3.4
index, we calculated the tendency of the Nino-3.4 indices of composite El Niño and La Niña, respectively (Fig. 13). Both El Niño and La Niña reach the fastest decaying rate in March, with the former being much larger than the latter. In addition, El Niño tends to keep the strong decaying rate in much longer time than La Niña. As an exception, the 1986 El Niño does not decay after DJF and maintains until 1988 summer.

To show the different evolutional characteristics of oceanic subsurface during El Niño and La Niña under the asymmetric forcing of the equatorial zonal wind stress anomalies over the western Pacific, we show the temporal evolution of composite 20°C isotherm depth anomalies along the equator (Fig. 14). The change of the subsurface temperature is primarily caused by the thermocline variation, which is intimately linked to the passage of Kelvin waves. In September, two months before ENSO mature phase, the 20°C isotherms in the western Pacific during El Niño and La Niña is both close to the climatological state. In December, after the formation of the WNPAC and the associated equatorial easterly wind stress anomalies over the western Pacific, the underlying thermocline during El Niño significant rises (Fig. 14a), and the subsurface temperature in the equatorial western Pacific decreases (figure not shown). In contrast, the amplitude of thermocline depth anomalies during La Niña changes much smaller (Fig. 14b). In the course of eastward propagation, the upwelling Kelvin waves during El Niño are Persistently stronger than the downwelling Kelvin waves during La Niña. Thus, El Niño decays much more quickly than La Niña.
7. Summary and concluding remarks

This paper deals with the asymmetry of the WNP atmospheric circulation anomalies between El Niño and La Niña mature winter. The physical mechanisms responsible for the asymmetry are inquired from two plausible aspects, the intrinsic asymmetries of ENSO remote forcing and local air-sea interaction. Both processes are demonstrated with idealized numerical experiments. The impacts of the asymmetry on the ENSO phase reversal are also investigated. The major findings are summarized below.

- The WNPC during La Niña tends to shift westward relative to the WNPAC during El Niño. While the WNPAC center is located over the Philippine Sea, the WNPC center is located over the SCS. Correspondingly, equatorial westerly anomalies in the southern flank of the WNPC withdraw westward about 20° relative to their El Niño counterparts.

- Two possible mechanisms responsible for the phase shift are examined. Firstly, as a Rossby wave response to the negative heating over the equatorial central Pacific, twin anticyclone couplets during La Niña shift westward relative to twin cyclone couplets during El Niño due to the spatial phase shift of SST and precipitation anomalies over the equatorial central Pacific. Secondly, the intensities of negative SSTA and associated negative precipitation anomalies in the WNP during El Niño are stronger than the La Niña counterparts. The asymmetry of the SSTA arises from asymmetric SSTA tendency in JJA and NDJ.
In JJA, though SSTA, precipitation and wind anomalies are generally symmetric between El Niño and La Niña (i.e. a mirror image), surface wind speed anomalies and corresponding latent heat flux are highly asymmetric. The asymmetric latent heat flux further causes the asymmetric SSTA tendency. In NDJ, the asymmetric SSTA tendency is primarily attributed to the asymmetry of anomalous wind fields between El Niño and La Niña - the WNP is covered by easterly anomalies during both El Niño and La Niña. The easterly anomalies would enhance surface wind speed and latent heat flux. As a result, the asymmetry of the local SSTA between El Niño and La Niña is further amplified.

Two distinctive wind evaporation feedback regimes are identified to explain the asymmetry of the latent heat flux anomaly during ENSO developing summer (JJA). Since the wind speed anomalies are determined by both anomalous wind and background mean wind, when the mean wind is stronger (weaker) than the anomalous wind, wind speed anomalies are symmetric (asymmetric) with respect to the opposite anomalous winds. Therefore, the wind speed anomalies exhibit dominant asymmetric characteristics between El Niño and La Niña in the transitional zone between the monsoon westerly and the trade easterly, where the mean wind is very weak. The asymmetry of the wind speed anomalies further cause the asymmetry of the latent heat flux anomalies.

The hypotheses based on data diagnosis are further confirmed by the results of numerical experiments, which indicate that both the asymmetries of the remote forcing from the equatorial central Pacific and the local SSTA forcing in the WNP contribute to
the asymmetry between the WNPAC and WNPC. The impact of the former is larger than the latter in terms of the amplitudes of model responses.

- Due to the westward shift of the WNPC center, westerly wind stress anomalies over the equatorial western Pacific during La Niña mature phase are much weaker than easterly wind stress anomalies during El Niño. The weak (strong) wind stress anomalies during La Niña (El Niño) may stimulate weak (strong) oceanic Kelvin waves, leading to a slower (faster) phase transition to El Niño (La Niña). This may partially explain the evolution asymmetry between El Niño and La Niña.

It should be noted that in this study, we focus on the asymmetry of the WNP circulation anomalies between El Niño and La Niña, but pay less attention to the non-linearity among El Niño or La Niña events. For instance, the 1986 winter is an El Niño winter during which the WNP is covered by an anomalous cyclone, instead of an anomalous anticyclone. The SSTA in the equatorial eastern Pacific did not decay after the winter, but persisted through the next year. The cause of this special event is not clear at present and warrants further studies. While the endeavor in this regard has been puzzled by the limitation of sample size, long-term coupled model simulation map help us to understand the issue.

In addition, we only focus on the tropical processes in our above analysis. It was found that during the fall of El Niño events, the East Asian trough is deepened, which may enhance the cold air outbreak and initiate the WNPAC (Wang and Zhang 2002). In
fact, by checking the composite maps for September-October mean 500hPa geopotential height anomalies for El Niño and La Niña, we note that the deepening of the East Asian trough during El Niño is much stronger than the shoaling of the trough during La Niña. This asymmetric characteristic may also contribute to the asymmetry between the WNPAC and WNPC. More detailed analysis of this mid-latitude impact is needed in future work.
Acknowledgement

This work was supported by NSFC Grant 40628006, 40821092, 40523001, the National Basic Research Program of China (2006CB403603), R&D Special Fund for Public Welfare Industry (meteorology) (GYHY200706010, GYHY200806010). TL was supported by ONR grants N000140710145 and N000140810256 and by the International Pacific Research Center that is sponsored by the Japan Agency for Marine-Earth Science and Technology (JAMSTEC), NASA (NNX07AG53G) and NOAA (NA17RJ1230). This is SOEST contribution number xxxx and IPRC contribution number xxx.
Reference


249-266.


Kim, K. M. and K. M. Lau, 2001: Dynamics of monsoon-induced biennial variability in


5131-5149.


——, ——, and T. Li, 2009: Contrast of rainfall-SST relationships in the western North Pacific between the ENSO developing and decaying summers. J. Climate, 16, 398-4405.


——, 1999: A dynamic ocean-atmosphere model of the tropical Atlantic decadal variability. J. Climate, 12, 64-70.

Xie, P., and P. A. Arkin, 1997: Global Precipitation: A 17-year monthly analysis based on


pacific subtropical high has extended westward since the late 1970s. *J. Climate*, 22, 2199-2215
Table 1 El Niño and La Niña events in the period of 1949-2002, used in the study.

|---------------|--------------------------------------------|

Table 2 List of numerical experiments.

<table>
<thead>
<tr>
<th>Experiment</th>
<th>SST forcing field</th>
<th>Integration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control run (CTRL)</td>
<td>Global climatological SST</td>
<td>10 years</td>
</tr>
<tr>
<td>Global SSTA forcing for El Niño (GBEL) and La Niña (GBLA)</td>
<td>Add the composite SSTA to the climatological SST in the global ocean</td>
<td>10 realizations for both GBEL and GBLA</td>
</tr>
<tr>
<td>Tropical central-eastern Pacific forcing for El Niño (CEEL) and La Niña (CELA)</td>
<td>Add the composite positive (negative) SSTA in the tropical central-eastern Pacific (160°E-100°W, 30°S-30°N) to the climatological SST in CEEL (CELA)</td>
<td>10 realizations for both CEEL and CELA</td>
</tr>
<tr>
<td>Western North Pacific forcing for El Niño (WPEL) and La Niña (WPLA)</td>
<td>Add the composite negative (positive) SSTA in the WNP (120-160°E, 0-20°N) to the climatological SST in WPEL (WPLA)</td>
<td>10 realizations for both WPEL and WPLA</td>
</tr>
</tbody>
</table>
**Figure captions**

Fig. 1. Composite DJF mean 850hPa streamfunction anomalies for (a) nine El Niño events and (b) nine La Niña events, listed in table 1 (Units: $10^6 \text{m}^2 \text{s}^{-1}$). (c) Asymmetric component estimated by the sum of (a) and (b). The shading represent 10% significance level. (d) Symmetric component estimated by the difference of (a) and (b). The solid lines denote poistive values and the dashed lines denote negative ones. The contour interval is 0.5.

Fig. 2. Scatter diagram of the DJF mean Nino-3.4 index (units: °C) vs. the box-arearaged vorticity anomalies over the western North Pacific (2-20°N, 125-155°E, rectangle boxed in Fig. 1, units: $10^6 \text{s}^{-1}$) for 18 ENSO events listed in table1. Dots denote El Niño events and crosses denote La Niña events.

Fig. 3. (a, c, e) Same as Fig. 1a-c, except for SST anomalies (units: °C). (b, d, f) Same as Fig. 1a-c, except for precipitation anomalies (units: mm day$^{-1}$). The solid lines denote positive values and the dashed lines denote negative ones. The interval of the contour is 1.

Fig. 4. Scatter diagram of the longitudinal location of the maximum amplitude of DJF mean 10°N-10°S averaged precipitation anomalies over the Pacific vs. the box-averaged vorticity anomalies over the western North Pacific (2-20°N, 125-155°E, units: $10^6 \text{s}^{-1}$) for 18 ENSO events, listed in table 1. Dots denote El Niño events and crosses denote La Niña events.

Fig. 5. The monthly mean time series (3-point smoother) of WNPSST index, (solid line, units: °C) and the temporal evolution of WNPSST tendency (dashed line, units: °C month$^{-1}$) for (a) El Niño composite and (b) La Niña composite. The WNPSST index is defined as box-averaged SST
anomalies in the region of 2-15°N, 130-155°E. Y(0) and Y(1) represent ENSO developing and
decaying year, respectively.

Fig. 6. (a) Composite JJA mean 850hPa wind anomalies (vector, units: ms⁻¹) and precipitation
anomalies (shading, units: mm day⁻¹) for El Niño events. (b) Composite JJA mean SSTA (units:
°C) for El Niño events. (c, d) are same as (a, b), expect for La Niña events.

Fig. 7. (a) Composite JJA mean 1000hPa wind speed anomalies (units: ms⁻¹) for El Niño events.
(b) Corresponding latent heat flux anomalies (units: Wm⁻²). (c, d) are same as (a, b), expect for La
Niña events. (e) Asymmetric component of the wind speed anomalies estimated by the sum of (a)
and (c). (f) Asymmetric component of the latent heat flux anomalies estimated by the sum of (b)
and (d).

Fig. 8. (a) Climatological JJA mean 1000hPa wind. The box represents the target region of the
WNP (2-15°N, 130-155°E). (b) Scatter diagram of the JJA mean 1000 hPa zonal wind anomalies
against the 1000hPa wind speed anomalies for each grid in the target region of WNP in 18 ENSO
events. The thick line is calculated based on a theoretical model in which that mean wind is set to
be 0.7 ms⁻¹.

Fig. 9. (a) El Niño composite NDJ mean 1000 hPa wind anomalies (vector, units: ms⁻¹) and
preicipiation anomalies (contour, units: mm day⁻¹). (b) Same as (a), except for La Niña composite.
(c) Asymmetric components of 1000hPa wind speed anomalies (contour, units: ms⁻¹) and latent
heat flux anomalies (shading, units: Wm⁻²) between El Niño and La Niña.

Fig. 10. a) Difference of the precipitation (shading, units: mm day⁻¹) and 850hPa wind (vector,
units: \( \text{ms}^{-1} \) fields in DJF between the GBEL and CTRL runs. b) Same as a), but for the GBLA runs. c) Asymmetric component of the a) and b), estimated by their sum. In c), only values in the 10% significance level are shown.

Fig. 11. a-c) Same as Fig. 10, but for the CEEL and CELA runs. d-f) Same as Fig. 10, but for the WPEL and WPLA runs.

Fig. 12. Scatter diagram of the DJF mean box-averaged zonal pseudo wind stress anomalies over the equatorial western Pacific \((5^\circ \text{N}-5^\circ \text{S}, 125-155^\circ \text{E})\) vs. the box-averaged 850hPa vorticity anomalies over the western North Pacific \((2-20^\circ \text{N}, 125-155^\circ \text{E})\) for ENSO events, listed in table 1. Dots denote El Niño events and crosses denote La Niña events.

Fig. 13. Temporal evolution of monthly mean Nino-3.4 \((5^\circ \text{S}-5^\circ \text{N}, 190-240^\circ \text{E})\) SST anomalies (units: \(^\circ \text{C}\)) from the January of ENSO developing year to the December of following year for (a) El Niño events and (b) La Niña events (thin lines). Composite Nino-3.4 SST anomalies (solid thick line) and the tendency of the solid thick line (dashed thick line) are also shown. Nino-3.4 indices are filtered by 5-point smoother. \(Y(0)\) and \(Y(1)\) indicate ENSO developing year and decaying year, respectively.

Fig. 14. Time-longitude distributions of 20 \(^\circ \text{C}\) isotherm anomalies (units: m) averaged over 2\(^\circ\)-2\(^\circ\)S for (a) El Niño composite and (b) La Niña composite (July(0) -June(1)). The data are derived from SODA reanalysis. Contour interval is 8. The negative values are shaded.
Fig. 1. Composite DJF mean 850hPa streamfunction anomalies for (a) nine El Niño events and (b) nine La Niña events, listed in table 1 (Units: $10^6 \text{m}^2\text{s}^{-1}$). (c) Asymmetric component estimated by the sum of (a) and (b). The shading represent 10% significance level. (d) Symmetric component estimated by the difference of (a) and (b). The solid lines denote positive values and the dashed lines denote negative ones. The contour interval is 0.5.
Fig. 2. Scatter diagram of the DJF mean Nino-3.4 index (units: °C) vs. the box-arearaged vorticity anomalies over the western North Pacific (2-20°N, 125-155°E, rectangle boxed in Fig. 1, units: 10^{-6} s^{-1}) for 18 ENSO events listed in table1. Dots denote El Niño events and crosses denote La Niña events.
Fig. 3. (a, c, e) Same as Fig. 1a-c, except for SST anomalies (units: °C). (b, d, f) Same as Fig. 1a-c, except for precipitation anomalies (units: mm day$^{-1}$). The solid lines denote positive values and the dashed lines denote negative ones. The interval of the contour is 1.
Fig. 4. Scatter diagram of the longitudinal location of the maximum amplitude of DJF mean $10^\circ$N-$10^\circ$S averaged precipitation anomalies over the Pacific vs. the box-averaged vorticity anomalies over the western North Pacific ($2$-$20^\circ$N, $125$-$155^\circ$E, units: $10^{-6}$ s$^{-1}$) for 18 ENSO events, listed in table 1. Dots denote El Niño events and crosses denote La Niña events.
Fig. 5. The monthly mean time series (3-point smoother) of WNPSST index, (solid line, units: °C) and the temporal evolution of WNPSST tendency (dashed line, units: °C month$^{-1}$) for (a) El Niño composite and (b) La Niña composite. The WNPSST index is defined as box-averaged SST anomalies in the region of 2-15°N, 130-155°E. Y(0) and Y(1) represent ENSO developing and decaying year, respectively.
Fig. 6. (a) Composite JJA mean 850hPa wind anomalies (vector, units: ms$^{-1}$) and precipitation anomalies (shading, units: mm day$^{-1}$) for El Niño events. (b) Composite JJA mean SSTA (units: °C) for El Niño events. (c, d) are same as (a, b), except for La Niña events.
Fig. 7. (a) Composite JJA mean 1000hPa wind speed anomalies (units: ms$^{-1}$) for El Niño events. (b) Corresponding latent heat flux anomalies (units: Wm$^{-2}$). (c, d) are same as (a, b), expect for La Niña events. (e) Asymmetric component of the wind speed anomalies estimated by the sum of (a) and (c). (f) Asymmetric component of the latent heat flux anomalies estimated by the sum of (b) and (d).
Fig. 8. (a) Climatological JJA mean 1000hPa wind. The box represents the target region of the WNP (2-15°N, 130-155°E). (b) Scatter diagram of the JJA mean 1000 hPa zonal wind anomalies against the 1000hPa wind speed anomalies for each grid in the target region of WNP in 18 ENSO events. The thick line is calculated based on a theoretical model in which the mean wind is set to be 0.7 ms⁻¹.
Fig. 9. (a) El Niño composite NDJ mean 1000 hPa wind anomalies (vector, units: ms$^{-1}$) and precipitation anomalies (contour, units: mm day$^{-1}$). (b) Same as (a), except for La Niña composite. (c) Asymmetric components of 1000hPa wind speed anomalies (contour, units: ms$^{-1}$) and latent heat flux anomalies (shading, units: Wm$^{-2}$) between El Niño and La Niña.
Fig. 10. a) Difference of the precipitation (shading, units: mm day$^{-1}$) and 850hPa wind (vector, units: ms$^{-1}$) fields in DJF between the GBEL and CTRL runs. b) Same as a), but for the GBLA runs. c) Asymmetric component of the a) and b), estimated by their sum. In c), only values in the 10% significance level are shown.
Fig. 11. a-c) Same as Fig. 10, but for the CEEL and CELA runs. d-f) Same as Fig. 10, but for the WPEL and WPLA runs.
Fig. 12. Scatter diagram of the DJF mean box-averaged zonal pseudo wind stress anomalies over the equatorial western Pacific (5°N-5°S, 125-155°E) vs. the box-averaged 850hPa vorticity anomalies over the western North Pacific (2-20°N, 125-155°E) for ENSO events, listed in table 1. Dots denote El Niño events and crosses denote La Niña events.
Fig. 13. Temporal evolution of monthly mean Nino-3.4 (5°S-5°N, 190-240°E) SST anomalies (units: °C) from the January of ENSO developing year to the December of following year for (a) El Niño events and (b) La Niña events (thin lines). Composite Nino-3.4 SST anomalies (solid thick line) and the tendency of the solid thick line (dashed thick line) are also shown. Nino-3.4 indices are filtered by 5-point smoother. Y(0) and Y(1) indicate ENSO developing year and decaying year, respectively.
Fig. 14. Time-longitude distributions of 20 °C isotherm anomalies (units: m) averaged over 2°N-2°S for (a) El Niño composite and (b) La Niña composite (July(0) - June(1)). The data are derived from SODA reanalysis. Contour interval is 8. The negative values are shaded.