



# Mechanism for asymmetric atmospheric responses in the western North Pacific to El Niño and La Niña

Xiaohui Wang<sup>1</sup> · Tim Li<sup>1,2</sup> · Mingcheng Chen<sup>1</sup>

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## Abstract

The cause of asymmetric atmospheric circulation responses over the tropical western North Pacific (WNP) to El Niño and La Niña was investigated through observational analyses and idealized modeling experiments. Firstly, column integrated moisture and moist static energy budget analyses were carried out to reveal the cause of asymmetric precipitation anomalies over the WNP. The result indicates that negative nonlinear moist enthalpy advection anomalies occur in both El Niño and La Niña, and they tend to induce a negative precipitation anomaly in the key WNP region and thus an anomalous anticyclone during both El Niño and La Niña winters. This, together with linear moist enthalpy advection, results in an asymmetric atmospheric circulation response. Secondly, the relative roles of the nonlinear moist enthalpy advection and the zonal shift of longitudinal location of anomalous heating over the central-eastern Pacific between El Niño and La Niña were investigated through an anomaly general circulation model. It is found that both the nonlinear advection and the zonally asymmetric heating contribute equally to the observed zonal shift of the anomalous WNP anticyclonic and cyclonic circulation centers between El Niño and La Niña.

**Keywords** Asymmetry · El Niño · La Niña · Moist enthalpy · Moist static energy

## 1 Introduction

It is often observed that an anomalous anticyclone appears in the western North Pacific (WNP) during El Niño mature winter and that the anomalous anticyclone (hereafter WNPAC) may persist from boreal winter to subsequent summer to impact rainfall over subtropical East Asia (Wang et al. 2000; Chang et al. 2000a, b; Li and Wang 2005). Thus different from a simultaneous El Niño–Indian monsoon relationship during El Niño developing summer, El Niño exerts

a delayed impact on subtropical East Asian monsoon during its decaying summer, and the WNPAC is a key circulation system that conveys the delayed El Niño impact (Li and Hsu 2017).

The delayed El Niño impact on East Asian climate through the WNPAC was originally discovered from two schools of studies. The one is based on the reference time series of summer rainfall anomalies over central China (Chang et al. 2000a, b). By regressing precursory low-level wind anomalies associated with the summer rainfall in central China, Chang et al. (2000a) found the persistence of an anomalous anticyclone over the WNP from the preceding winter to the concurrent summer and pronounced westerly anomalies and a warm sea surface temperature anomaly (SSTA) in the equatorial central-eastern Pacific (CEP) in the preceding boreal winter. Another is based on the composite of El Niños in their mature winters (Zhang et al. 1996; Wang et al. 2000). It is found that an anomalous low-level anticyclone occurs in the WNP during El Niño mature winter and this anomalous anticyclone can persist from the winter to the subsequent summer, even though the El Niño itself may dissipate in its decaying summer.

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✉ Tim Li  
timli@hawaii.edu

<sup>1</sup> Key Laboratory of Meteorological Disaster, Ministry of Education (KLME), Joint International Research Laboratory of Climate and Environmental Change (ILCEC), Collaborative Innovation Center on Forecast and Evaluation of Meteorological Disasters (CIC-FEMD), Nanjing University of Information Science and Technology, Nanjing, China

<sup>2</sup> International Pacific Research Center, Department of Atmospheric Sciences, School of Ocean and Earth Science and Technology, University of Hawaii at Manoa, Honolulu, HI 96822, USA

It was argued physically that the WNPAC could influence the East Asian summer monsoon through the following three processes (Chang et al. 2000a). Firstly, anomalous southerlies to the west of the WNPAC transport high mean moisture from tropical oceans to subtropical East Asia. Secondly, it strengthens pressure gradients to the south of the Meiyu front, a climatological stationary rain-band over East Asia. Thirdly, it promotes the westward shift of the western Pacific subtropical high, which may slow down the eastward movement of synoptic-scale disturbances along the Meiyu front, which prolongs stationary rainfall over the lower reaches of the Yangtze River and the Huaihe River Valleys.

Various mechanisms have been proposed to understand the formation of the WNPAC (He et al. 2015; Xie et al. 2016; Li et al. 2017; Zhang et al. 2017). Two theories are mostly relevant to the WNPAC formation during El Niño mature winter. The first one is rooted in local atmosphere–ocean interactions (Wang et al. 2000). An enhanced heating anomaly associated with positive SST anomalies over the equatorial CEP may induce an anomalous cyclone to its west. The northerly anomalies to the western flank of the anomalous cyclone strengthen the mean northeasterly trade wind and enhance the surface evaporation, the latter of which may further induce a negative SSTA in WNP and suppress convection in situ. The negative heating anomaly in WNP can further induce an anomalous anticyclone over the WNP. The second theory involves pure atmospheric processes, namely moist enthalpy advection and Rossby wave modulation mechanism (Wu et al. 2017a, b; Li et al. 2017). The key process involving in the second theory is the advection of low mean moist enthalpy by anomalous northerly anomalies, which are induced by El Niño induced diabatic heating anomaly in the CEP. A negative moist enthalpy advection anomaly favors the development of suppressed convection and thus is responsible for the generation of an anomalous low-level anticyclone in the WNP in boreal winter.

It has been shown that the response of circulation anomaly in the WNP to El Niño and La Niña is asymmetric (Wu et al. 2010). The center of an anomalous cyclone (WNPC) during La Niña tends to shift westward relative to the center of an anomalous anticyclone (WNPAC) during El Niño. This asymmetric response is partially attributed to the zonal shifting of El Niño and La Niña anomalous heating (Wu et al. 2010). Observations showed that the center of composite negative precipitation anomaly during La Niña is located to the west of the center of composite positive precipitation anomaly during El Niño. In addition, the asymmetry of local SSTA in the WNP between El Niño and La Niña may also contribute to the circulation asymmetry (Wu et al. 2010). It was found that the amplitude of the WNP cold SSTA during El Niño is greater than that of local warm SSTA during La Niña. This asymmetry is caused by asymmetric SSTA tendencies during the ENSO developing summer. Although

the precipitation and surface wind anomaly patterns are approximately symmetric in ENSO developing summer, the surface latent heat flux anomalies are highly asymmetric over the WNP region, in particular in the region where the mean wind speed is small. Over the region both anomalous westerly during El Niño and anomalous easterly during La Niña lead to enhanced surface evaporation, strengthening (weakening) the cold (warm) SSTA in situ during El Niño (La Niña). The asymmetry of local SSTA is further amplified during ENSO developing fall.

The asymmetry in WNP circulation response may have a profound impact on the El Niño and La Niña evolution asymmetry, as indicated by Chen et al. (2016). It is also responsible for distinctive rainfall responses between El Niño and La Niña over East Asia in northern winter (Wu et al. 2010) and subsequent seasons (Tao et al. 2017).

Previous studies suggested that nonlinear advection is critical for amplitude asymmetry (Su et al. 2010). Given a perfectly symmetric El Niño and La Niña pattern (i.e., El Niño and La Niña rainfall and wind patterns are just like a mirror image), will atmospheric nonlinear dynamics associated with moist enthalpy advection generate an asymmetric circulation response in the WNP? In this paper we intend to address this science question. In particular we intend to quantitatively assess the relative roles of atmospheric nonlinear moist enthalpy advection and the zonal asymmetry of anomalous heating between El Niño and La Niña in causing the asymmetric circulation response in the WNP.

The remaining paper is organized as follows. Section 2 introduces observational and reanalysis datasets, methods and numerical models to be used in this study. The symmetric and anti-symmetric circulation features between El Niño and La Niña and moisture and moist static energy (MSE) budget analyses based on observational data are described in Sect. 3. In Sect. 4, idealized numerical model experiments are carried out to understand the effects of linear and nonlinear moist enthalpy advection and zonally asymmetric ENSO heating in causing the asymmetric wind response in the WNP. Finally a conclusion and discussion are given in Sect. 5.

## 2 Datasets, methods and model

### 2.1 Datasets

The datasets used in the current study include (1) monthly precipitation from the Global Precipitation Climatology Project (GPCP) (Adler et al. 2003), (2) monthly SST from the Met Office Hadley Centre's sea ice and SST dataset (HadISST) (Rayner et al. 2003), and (3) monthly wind, temperature, geopotential height, specific humidity, vertical pressure

velocity, and surface heat fluxes from the interim European Centre for Medium-Range Weather Forecasts (ECMWF) re-analysis products (ERA\_I) (Dee et al. 2011). The horizontal resolutions of the GPCP, HadISST and ERA-I datasets are 2.5°×2.5°, 1°×1° and 1.5°×1.5°, respectively. All analyses in this study cover a period from 1979 to 2012.

### 2.2 Methods

Eight El Niño events and five La Niña events are selected during the period of 1979–2012. The method for selecting El Niño and La Niña events is based on the threshold of 3-month running mean Niño 3.4 index, which is defined as the area-averaged SSTA over the region 5°N–5°S, 120°–170°W. When Niño3.4 index is larger (smaller) than 0.5 (– 0.5) in consecutive 5 months, it is regarded as an El Niño (a La Niña) event. Here Year 0 and 1 represent the ENSO developing and decaying year, respectively. The selected ENSO events are listed in Table 1.

Following Wu et al. (2017a), to reveal physical processes responsible for generating precipitation anomalies, a column integrated moisture equation was diagnosed. The anomalous moisture equation is written as:

$$\partial_t \langle q \rangle' + \langle \bar{V} \nabla_h q \rangle' + \langle \omega \partial_p q \rangle' = E' - P' \tag{1}$$

where a prime denotes the monthly anomaly (relative to the climatological annual cycle), angle brackets represent the mass integral from 1000 to 100 hPa, and *E* and *P* represent evaporation and precipitation, respectively. The time tendency term (first term in the left hand side of Eq. 1) is relatively small on the interannual timescale and to the first order of approximation the term is negligible. After linearization, Eq. (1) can be simplified as:

$$P' \cong E' - \langle \bar{V} \nabla_h q' \rangle - \langle \bar{V}' \nabla_h \bar{q} \rangle - \langle \bar{\omega} \partial_p q' \rangle - \langle \omega' \partial_p \bar{q} \rangle + NL \tag{2}$$

where a bar denotes the climatological annual cycle, *NL* denotes the sum of nonlinear terms. As it will be shown in Sect. 3, the precipitation anomalies over the tropics are primarily determined by the anomalous vertical advection term (term 5 in the right hand side of Eq. 2). To further diagnose the cause of anomalous vertical velocity, a MSE tendency equation (Neelin and Held 1987; Wu et al. 2017a) was used. Following Neelin (2007), the anomalous MSE equation can be written as:

$$\partial_t \langle (c_p T + L_v q) \rangle' + \langle \bar{V} \nabla_h (c_p T + L_v q) \rangle' + \langle \omega \partial_p h \rangle' = F'_{net} \tag{3}$$

where  $h = c_p T + L_v q + \theta$  represents MSE,  $\theta$  denotes the geopotential height, *T* represents air temperature,  $c_p$  and  $L_v$  denote the specific heat at constant pressure and the latent heat of vaporization, respectively,  $c_p T + L_v q$  represents moist enthalpy, and  $F'_{net}$  denotes the net MSE flux, primarily controlled by atmospheric longwave radiative flux. Similar to the moisture equation, the MSE equation can be simplified as:

$$\begin{aligned} \langle \omega' \partial_p \bar{h} \rangle &\cong F'_{net} - \langle \bar{V} \nabla_h (c_p T + L_v q)' \rangle \\ &- \langle \bar{V}' \nabla_h (c_p T + L_v q) \rangle \\ &- \langle \bar{\omega} \partial_p h' \rangle - \langle \omega' \partial_p h' \rangle \\ &- \langle \bar{V}' \nabla_h (c_p T + L_v q)' \rangle \end{aligned} \tag{4}$$

where the last two terms at the right hand side of Eq. (4) are nonlinear vertical and horizontal advection terms.

To quantitatively measure the symmetric and anti-symmetric patterns between El Niño and La Niña, we define a symmetric and an anti-symmetric component for each dynamic and thermodynamic field, following Hoerling et al. (1997) and Wu et al. (2010). The symmetric component is defined as a half of difference between El Niño and La Niña composite. The anti-symmetric component is defined as a half of summation of El Niño and La Niña composite fields.

### 2.3 An anomaly general circulation model

To study how the atmospheric wind responds to a specified heating anomaly under a given seasonal mean background state, an anomaly atmospheric general circulation model (AGCM) was used. This model was developed by Tim Li based on the Geophysical Fluid Dynamics Laboratory (GFDL) global spectral dry AGCM (Held and Suarez 1994). For detailed description of this anomaly model, readers are referred to Jiang and Li (2005) and Li et al. (2006).

Observed winter (December, January and February) mean state is specified as the model background state. An idealized diabatic heating anomaly is specified in the model. Its horizontal pattern is derived based on the pattern of anomalous moist enthalpy advection, as it is part of diabatic heating in the moist enthalpy Eq. (3). An idealized vertical profile with a maximum center in middle troposphere is specified for the diabatic heating anomaly.

The anomaly model has been used for various studies including the investigation of asymmetric response of monsoon circulation to El Niño induced heating over the Maritime Continent (Wang et al. 2003), circulation response to MJO heating over the eastern Indian Ocean (Jiang and Li 2005), origin of synoptic scale wave train in the WNP (Li et al. 2006), and distinctive responses of WNP circulation

**Table 1** Selected El Niño and La Niña events during 1979–2012

El Niño	1982	1991	1994	1997	2002	2004	2006	2009
La Niña	1983	1995	1998	2007	2010			

to El Niño heating under summer and winter background states (Wu et al. 2017b). In the current study, we adopt this model to examine how the atmospheric low-level wind responds to linear and nonlinear MSE (or moist enthalpy) advection forcing and asymmetric longitudinal locations of anomalous heating to mimic the El Niño and La Niña pattern asymmetry.

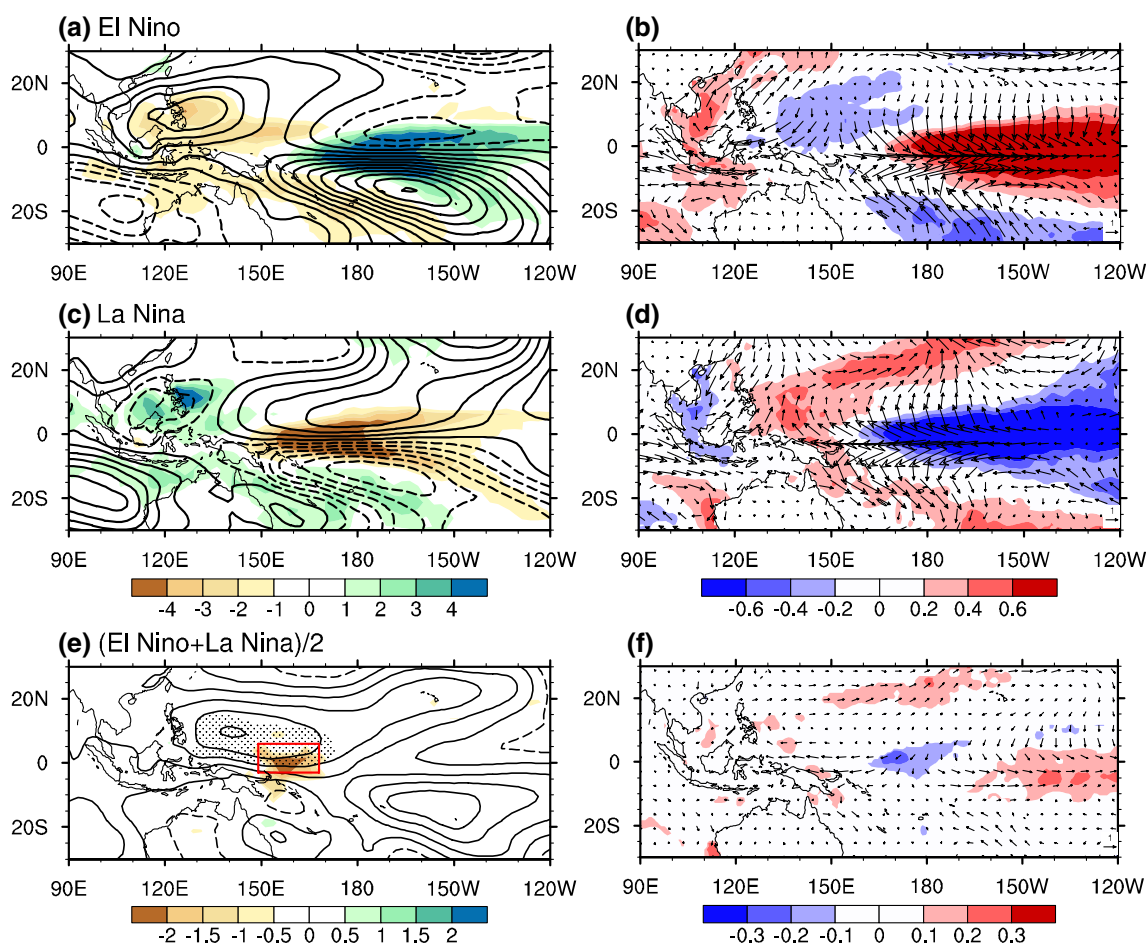
### 3 Cause of circulation asymmetry between El Niño and La Niña—observational diagnosis

#### 3.1 Observed asymmetric circulation patterns

The top and middle panels of Fig. 1 show the spatial distributions of composite precipitation, low-level streamfunction,

wind, and SST anomalies during El Niño and La Niña mature winters. During El Niño, an off-equatorial anomalous anticyclone and negative precipitation anomalies appeared over the tropical WNP (Fig. 1a). The center of the WNPAC is located to the east of Philippines. Positive precipitation anomalies occurred in the equatorial CEP, and the precipitation anomalies are a direct response to positive SSTAs over the eastern equatorial Pacific (Fig. 1b). In the WNP, cold SST anomalies appeared to the east of the anomalous anticyclone.

In contrast, an anomalous cyclone appeared in the WNP (WNPC) during La Niña (Fig. 1c). Compared to the WNPAC, the center of the WNPC shifted westward and located over the South China Sea (SCS). The size of the WNPC is much smaller than that of the WNPAC. The pattern of the SSTA during La Niña is in general opposite to that of El Niño, but slightly shifted westward (Fig. 1d). The



**Fig. 1** Left panels: D(0)JF(1)-mean precipitation (shading,  $\text{mm day}^{-1}$ ) and 925 hPa streamfunction [contour, interval:  $0.4 \times 10^6 \text{ m}^2 \text{ s}^{-1}$ , solid (dashed) lines represent positive (negative) values] anomalies for **a** El Niño and **c** La Niña composite and **e** their antisymmetric component. Year 0 and 1 represent the ENSO developing and decaying years, respectively. In **e**, values reaching the 5%

significance level for stream function anomalies are dotted (interval:  $0.2 \times 10^6 \text{ m}^2 \text{ s}^{-1}$ ). Right panels: as in the left panels except for SSTA (shading, unit:  $^{\circ}\text{C}$ ) and 925 hPa wind (vector, unit:  $\text{m s}^{-1}$ ) anomalies. For the anomalous precipitation and SSTA fields in **e**, **f**, only values reaching the 5% significance level are shown



negative precipitation anomaly in the CEP and associated circulation anomalies also shift westward by 15° in longitude during La Niña comparing to those during El Niño.

To quantitatively measure the asymmetry between El Niño and La Niña, we first calculated the symmetric and anti-symmetric components for key dynamic and thermodynamic fields. The bottom panel shows the anti-symmetric component of precipitation, SST, and low-level streamfunction and wind fields (Fig. 1e, f). Note that a negative precipitation anomaly and a marked anticyclonic anomaly appear over the WNP (Fig. 1e). Given that tropical circulation anomalies can be regarded as a direct response to diabatic heating anomalies (Gill 1980), a key to explain the circulation asymmetry between El Niño and La Niña lies into understand the cause of the anti-symmetric rainfall anomaly over the key WNP region (denoted by a red box in Fig. 1e). Note that the negative precipitation anomaly in the box region is not co-located with the anti-symmetric SSTA field shown in Fig. 1f, implying that the anti-symmetric rainfall anomaly in the key WNP region arises from atmospheric processes.

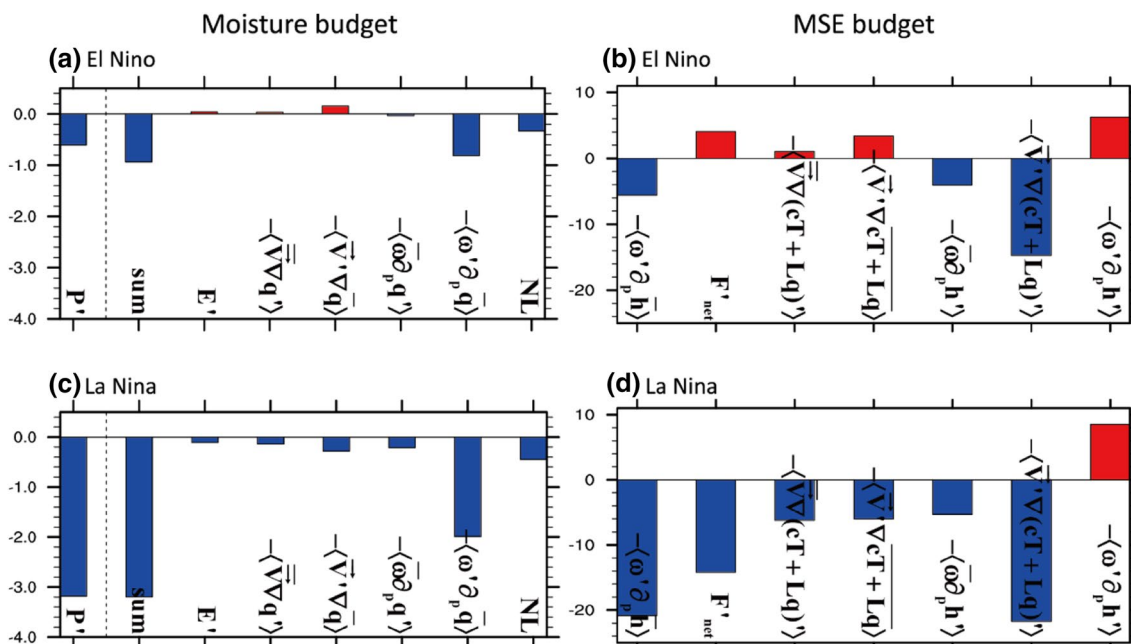
### 3.2 Moisture and MSE budget analyses

To understand the mechanism responsible for the anti-symmetric precipitation anomalies over the key WNP region, a column integrated moisture budget analysis was performed over the red box shown in Fig. 1e (3°S–6°N, 149°–168°E). The result indicates that the negative precipitation anomalies

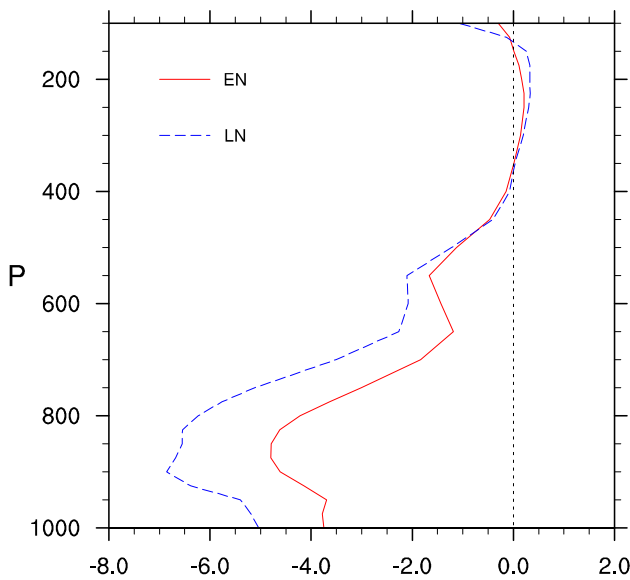
are primarily attributed to the negative advection of climatological mean moisture by descending anomalies in both El Niño and La Niña winters (Fig. 2a, c).

To further reveal the cause of the descending anomalies, the MSE equation was diagnosed. The diagnosis result (Fig. 2b, d) shows that the following two terms primarily contribute to the anomalous descending motion during both El Niño and La Niña, (1) horizontal advection of anomalous moist enthalpy by anomalous wind ( $-\langle \vec{V}' \nabla_h (c_p T + L_v q)' \rangle$ ) and (2) vertical advection of anomalous MSE by climatological vertical motion ( $-\langle \bar{\omega} \partial_p h' \rangle$ ). In the following we discuss how the two processes contribute to the anomalous descending motion in the key region.

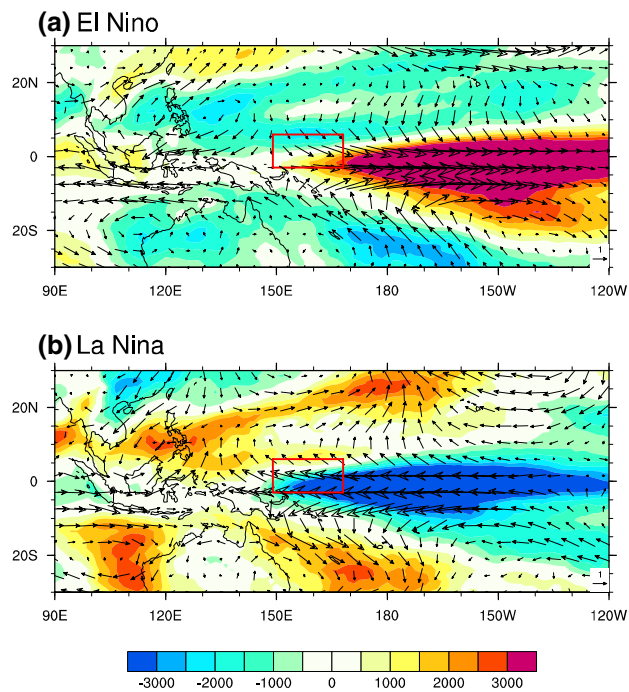
Term  $-\langle \vec{V}' \nabla_h (c_p T + L_v q)' \rangle$  has the largest contribution among all terms for both El Niño and La Niña. Because monthly data are used, the nonlinear advection terms contain mostly the interannual signals, even though some higher-frequency and interdecadal components may remain. This nonlinear advection term has maximum amplitude in lower troposphere, as shown in the vertical profile of this term (Fig. 3). To further investigate how the nonlinear moist enthalpy advection induces anomalous descending motion during both El Niño and La Niña winters, we plotted low level (850 hPa) wind and moist enthalpy anomalies in Fig. 4. During El Niño (La Niña), there are positive (negative) moist enthalpy anomalies over the tropical CEP and negative (positive) moist enthalpy anomalies in the off-equatorial region. The spatial pattern of the moist enthalpy anomalies



**Fig. 2** Left panels: moisture budget analysis results (unit: mm day<sup>-1</sup>) for **a** El Niño and **c** La Niña composite averaged over 3°S–6°N, 149°–168°E (red box in Fig. 1e). Right panels: as in the left panels but for moist static energy budget analysis results (unit: W m<sup>-2</sup>)



**Fig. 3** Vertical profiles of box-averaged  $-\bar{V}'\nabla_h(c_pT + L_vq)'$  (unit:  $10^{-3} \text{ W kg}^{-1}$ ) over the key WNP region (red box in Fig. 1e) during El Niño (red) and La Niña (blue) winters. “EN” represents El Niño, while “LN” denotes La Niña



**Fig. 4** Composite D(0)JF(1)-mean 850 hPa wind (vector,  $\text{m s}^{-1}$ ) and moist enthalpy (shading,  $\text{J kg}^{-1}$ ) anomalies during **a** El Niño and **b** La Niña. The red box is same as that in Fig. 1e

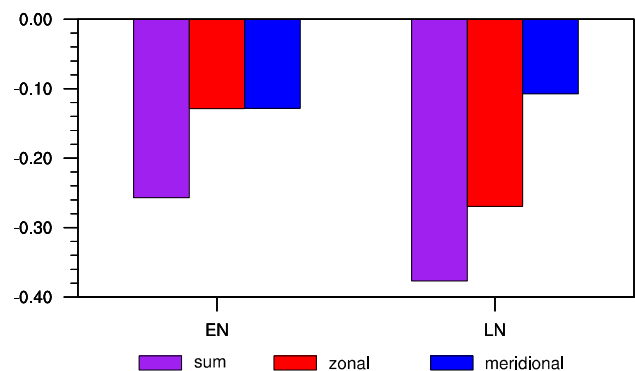
resembles the spatial distribution of SSTA (Fig. 1b, d). According to the Gill model response, a pair of anomalous cyclones (anticyclones) appears to the west of the SSTA

induced heat source in CEP. Both northwesterly anomalies during El Niño and southeasterly anomalies during La Niña in the red box region tend to transport dry or low moist enthalpy air, leading to a negative moist enthalpy advection anomaly and thus anomalous descending motion in both El Niño and La Niña.

A further separation of zonal and meridional components shows that both the zonal and meridional advection terms are negative (Fig. 5), suggesting that both the terms contribute to the anti-symmetric precipitation anomaly in the key WNP region. In lower troposphere, the nonlinear zonal advection is greater than the nonlinear meridional advection during La Niña and is approximately same as the nonlinear meridional advection during El Niño.

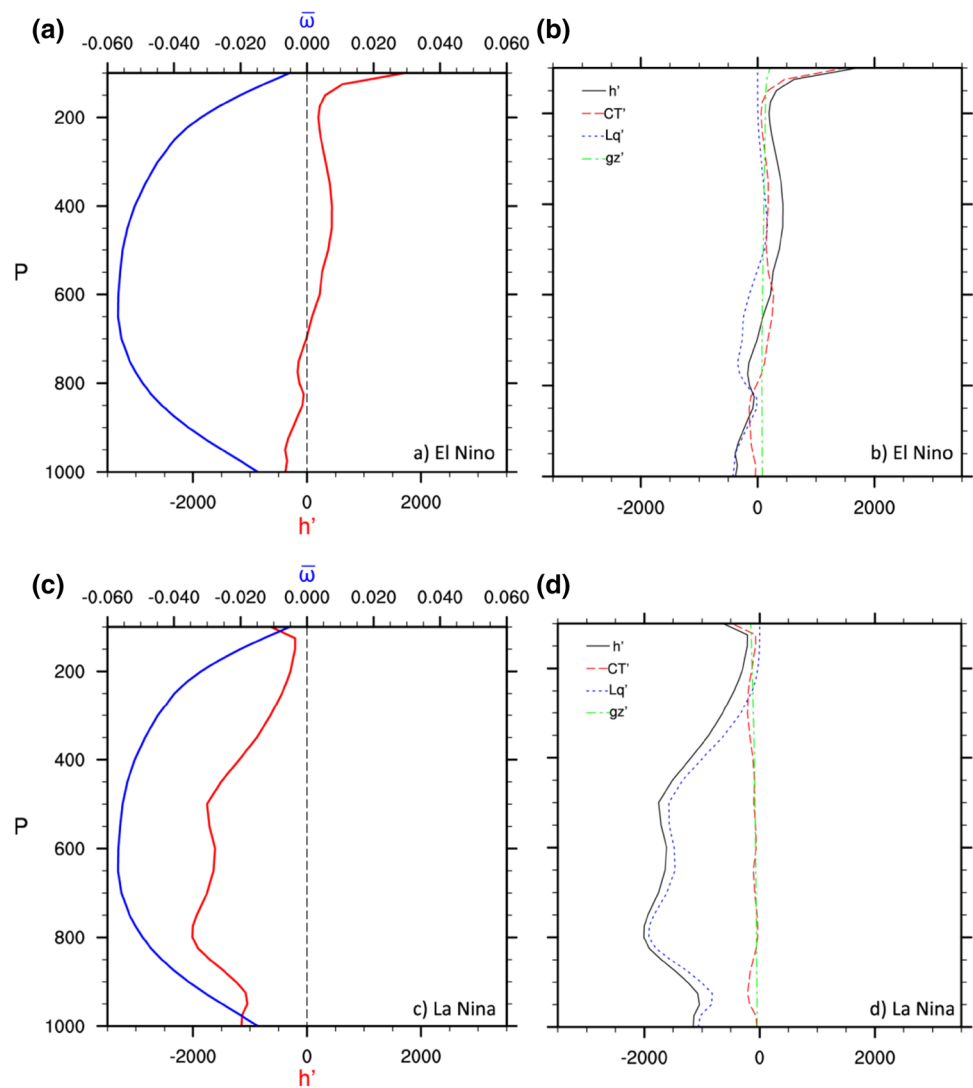
Term  $-\langle \bar{\omega}\partial_p h' \rangle$ , although much weaker, also contributes to the asymmetric descending anomaly in the key WNP region. This term is related to the change of vertical gradient of anomalous MSE. Figure 6a, c shows the vertical profiles of the box-averaged climatological mean vertical motion and anomalous MSE. While the climatological mean vertical motion is always ascending, the anomalous MSE increases with the height in both El Niño and La Niña winters. Thus, the climatological mean ascending motion advects anomalous low moist enthalpy air upward, leading to anomalous negative vertical MSE advection and thus suppressed convection for both El Niño and La Niña.

What causes the positive vertical MSE gradient during both El Niño and La Niña? Figure 6b, d show the vertical profiles of the anomalous MSE, together with each of the individual terms (i.e., temperature, specific humidity, and geopotential height). While the vertical profile of anomalous MSE is primarily determined by anomalous temperature during El Niño, it is mainly controlled by anomalous moisture field during La Niña. As a result, the anomalous



**Fig. 5** D(0)JF(1)-mean nonlinear moist enthalpy advection anomalies (unit:  $\text{W m}^{-2}$ ) integrated from 950 to 800 hPa averaged over  $3^\circ\text{S}–6^\circ\text{N}$ ,  $149^\circ–168^\circ\text{E}$  (red box in Fig. 1e). The red, blue and purple bars represent zonal advection, meridional advection and the sum of zonal and meridional advection. “EN” (“LN”) denotes El Niño (La Niña)

**Fig. 6** Left panels: Vertical profiles of D(0)JF(1) climatological mean omega (blue,  $\text{Pa s}^{-1}$ ) and anomalous MSE (red,  $\text{J Kg}^{-1}$ ) averaged over  $3^{\circ}\text{S}$ – $6^{\circ}\text{N}$ ,  $149^{\circ}$ – $168^{\circ}\text{E}$  (red box in Fig. 1e) for **a** El Niño and **c** La Niña composite. Right panels: vertical profiles of  $h'$  (black,  $\text{J kg}^{-1}$ ),  $c_p T'$  (red,  $\text{J kg}^{-1}$ ),  $L_v q'$  (blue,  $\text{J kg}^{-1}$ ) and  $g z'$  (green,  $\text{J kg}^{-1}$ ) averaged over the same box region during **b** El Niño and **d** La Niña mature winter



MSE increases with the height during both El Niño and La Niña winters.

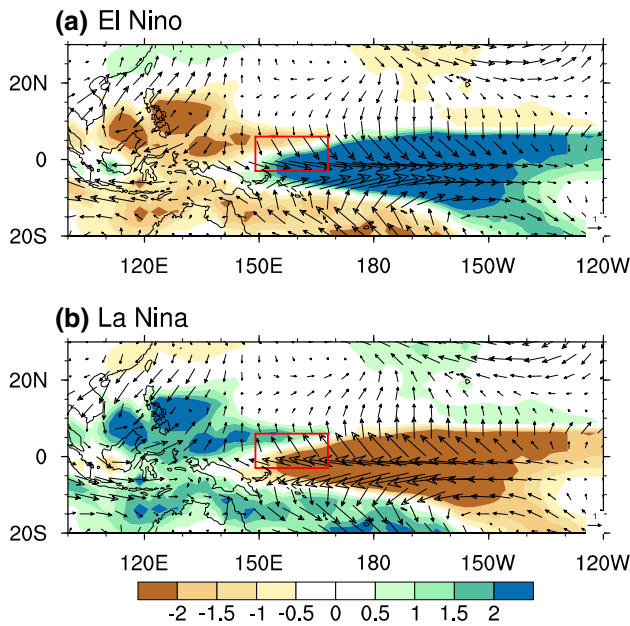
The analysis result above indicates that the nonlinear horizontal moist enthalpy advection ( $-\langle \vec{V}' \nabla_h (c_p T' + L_v q') \rangle$ ) is the most important process that contributes to the asymmetry of precipitation anomalies between El Niño and La Niña. Because of this nonlinear process, negative WNP precipitation anomalies induced by El Niño shift eastward, while positive WNP precipitation anomalies induced by La Niña shift westward. This leads to the asymmetry of the low-level circulation response, with a strengthened and eastward-shifted WNPAC and a weakened and westward-shifted WNPC. In the next section we will examine the relative roles of this nonlinear advection process versus zonally asymmetric heating using an anomaly atmospheric general circulation model.

#### 4 Relative roles of nonlinear moist enthalpy advection and zonal asymmetry of El Niño and La Niña heating—anomaly AGCM experiments

The observational analysis above reveals that the nonlinear moist enthalpy advection can induce an asymmetric precipitation anomaly response in the key WNP region. In addition, the zonal asymmetry of the WNP circulation anomaly can be also caused by the zonal shifting of anomalous heating location associated with El Niño and La Niña, which is ultimately related to the SSTA pattern asymmetry (Fig. 1f). To isolate the two factors, we conducted two sets of idealized numerical model experiments using an anomaly atmospheric general circulation model

(Li et al. 2006). The background mean state in the model is specified from the climatological mean state in boreal winter (DJF) derived from the NCEP–NCAR reanalysis.

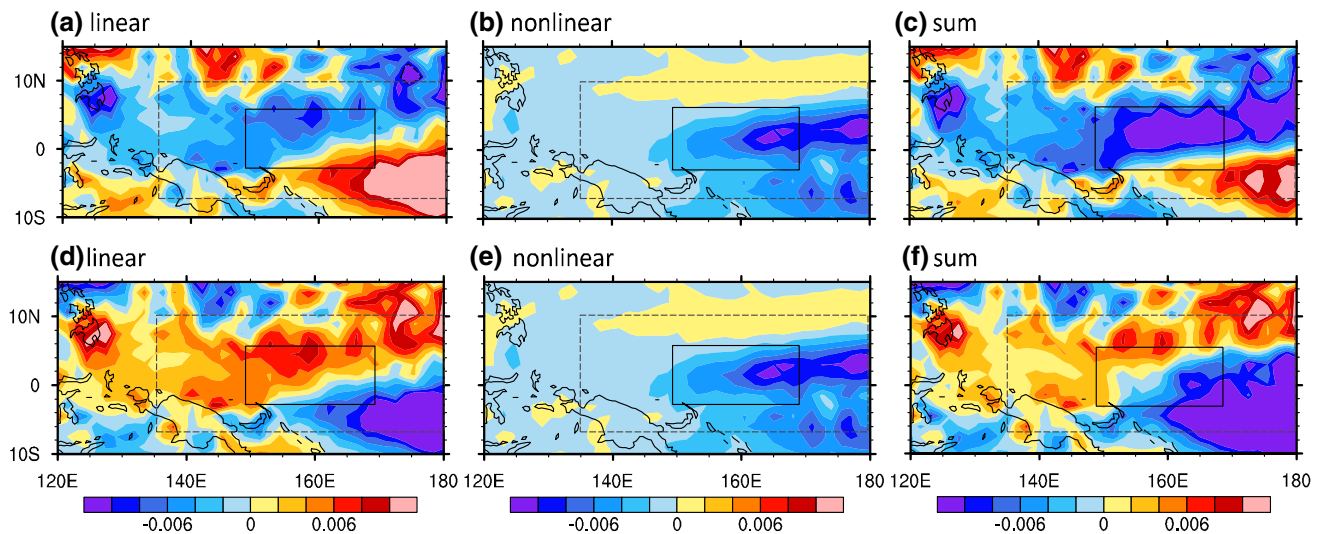
Firstly, we examine the role of the nonlinear moist enthalpy advection. Consider a perfectly symmetric El Niño and La Niña pattern, which is shown in Fig. 7. In this idealized setting, anomalous wind and precipitation fields



**Fig. 7** The symmetric component of D(0)JF(1) precipitation (shading, mm day<sup>-1</sup>) and 925 hPa wind (vector, m s<sup>-1</sup>) anomalies for **a** El Niño and **b** La Niña composite. The red box is same as that in Fig. 1e

image. Based on the symmetric fields, one may calculate linear moist enthalpy advection terms (i.e.,  $-\bar{\bar{V}}\nabla_h(c_p T + L_v q)'$  and  $-\bar{V}'\nabla_h(c_p T + L_v q)$ ) and nonlinear moist enthalpy advection term ( $-\bar{V}'\nabla_h(c_p T + L_v q)'$ ) for both El Niño and La Niña cases. The results are shown in Fig. 8. While the linear advection fields during El Niño and La Niña are 180° out of phase (Fig. 8a, d), the nonlinear advection fields are exactly the same (Fig. 8b, e). The summation of the linear and nonlinear advection terms represents a clear asymmetry between El Niño and La Niña (Fig. 8c, f).

How do linear and nonlinear moist enthalpy advection terms contribute to the formation of the WNPAC (WNPC) during El Niño (La Niña)? For term  $-\bar{\bar{V}}\nabla_h(c_p T + L_v q)$ , the northerly mean wind causes negative (positive) advection of anomalous moist enthalpy over the WNP region (red box in Fig. 4) during El Niño (La Niña) winter. For term  $-\bar{V}'\nabla_h(c_p T + L_v q)$ , because the climatological mean moist enthalpy is the largest on the equator and decreases with increased latitudes, northerly (southerly) anomalies associated with El Niño (La Niña) (Fig. 4) lead to negative (positive) moist enthalpy advection anomalies in the region. Thus, both the linear terms work together to promote a negative (positive) diabatic heating anomaly and thus the occurrence of an anomalous anticyclone (cyclone) in the WNP during El Niño (La Niña). For the nonlinear advection term, it favors the development of a negative heating anomaly in the key WNP region for both El Niño and La Niña, promoting a strengthened WNPAC during El Niño but a weakened WNPAC during La Niña.



**Fig. 8** D(0)JF(1)-mean vertically (900–850 hPa) integrated **a** linear ( $-\bar{\bar{V}}\nabla_h(c_p T + L_v q)'$ ), **b** nonlinear ( $-\bar{V}'\nabla_h(c_p T + L_v q)'$ ), and **c** combined linear and nonlinear moist enthalpy advection terms (unit: W kg<sup>-1</sup>) during (top) El Niño and associated with El Niño and La Niña are exactly in a mirror

(bottom) La Niña. All calculations here are based on the symmetric fields as illustrated in Fig. 7. The black solid and dashed boxes denote the specified heating region



Given that both the linear and nonlinear moist enthalpy advection terms represents a certain form of anomalous diabatic heating, one may examine how the WNP atmospheric circulation responds to such a forcing in an anomaly general circulation model. Figure 9a, d shows 850-hPa streamfunction responses to the linear forcing. The heating is specified over the key WNP region (black solid box in Fig. 8), with a transitional zone (black dashed box) over which the heating decays gradually to zero. Because the linear heating is symmetric between El Niño and La Niña, the stream function responses are exactly a mirror image—an anomalous anticyclone (cyclone) with the same strength and horizontal pattern occurs over the WNP during El Niño (La Niña). In contrast, the nonlinear advection effect is asymmetric, that is, an anomalous anticyclone appears in both El Niño and La Niña (Fig. 9b, e). As a result of the combined linear and nonlinear advection forcing, a greater anticyclone occurs during El Niño, while a weaker cyclone with a smaller size appears during La Niña (Fig. 9c, f).

The second set of experiments is to reveal the effect of the zonal shifting of the anomalous heating location associated with El Niño and La Niña. Observations (e.g., Fig. 1a, c) show that there is a 15° zonal shift along equatorial Pacific between a positive precipitation anomaly center during El Niño and a negative precipitation anomaly center during La Niña. To mimic this effect, we keep the same precipitation and wind patterns as in Fig. 7 but shifting the patterns eastward (westward) for El Niño (La Niña) by 7.5° in longitude (Fig. 10). The linear and nonlinear moist enthalpy advection terms are then re-calculated

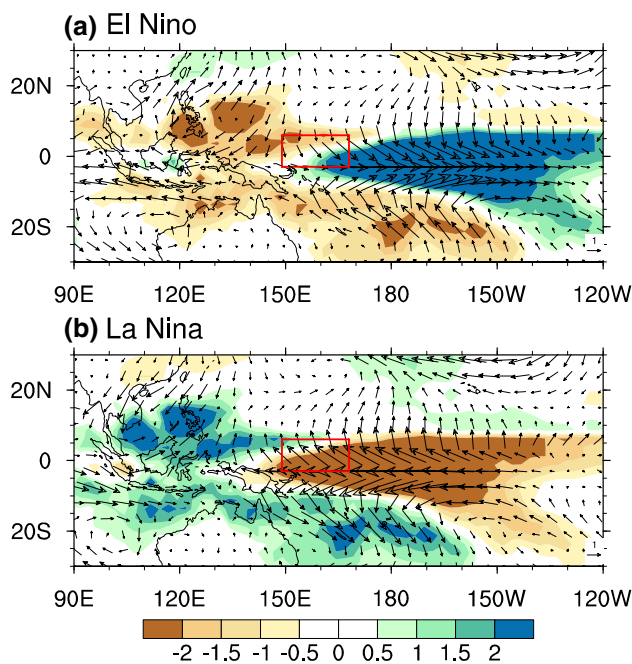


Fig. 10 As in Fig. 7 except that the symmetric wind and precipitation fields are shifted eastward (westward) by 7.5° in longitude for El Niño (La Niña)

based on the shifted patterns and the results are shown in Fig. 11.

The low-level stream function responses to the so-calculated linear and nonlinear heating fields are shown in Fig. 12. The linear responses show a 10° zonal shift in the anomalous

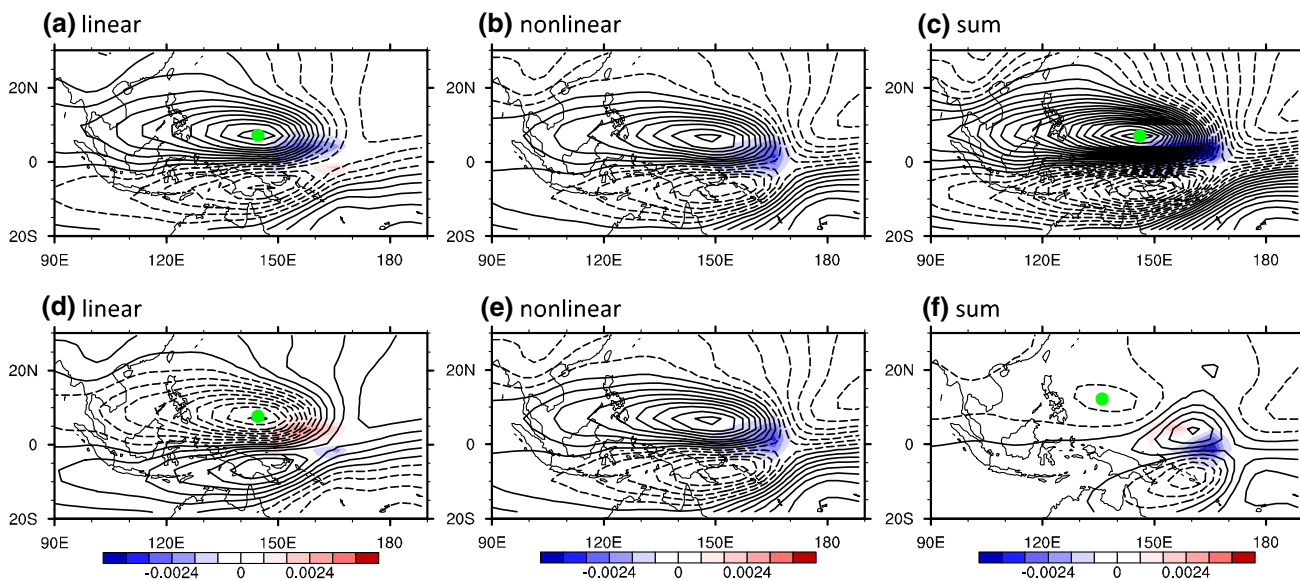
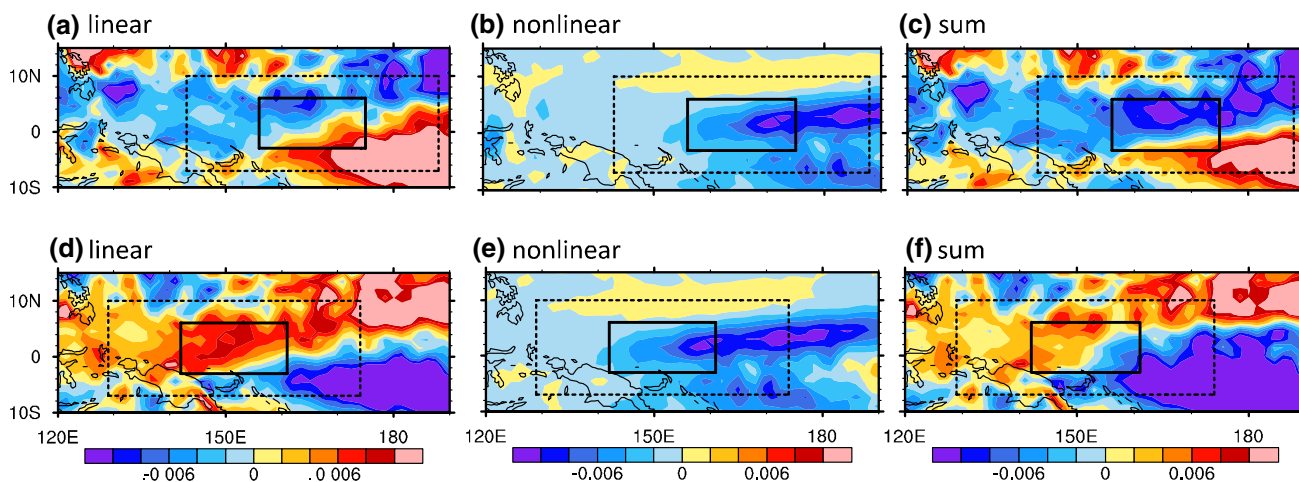
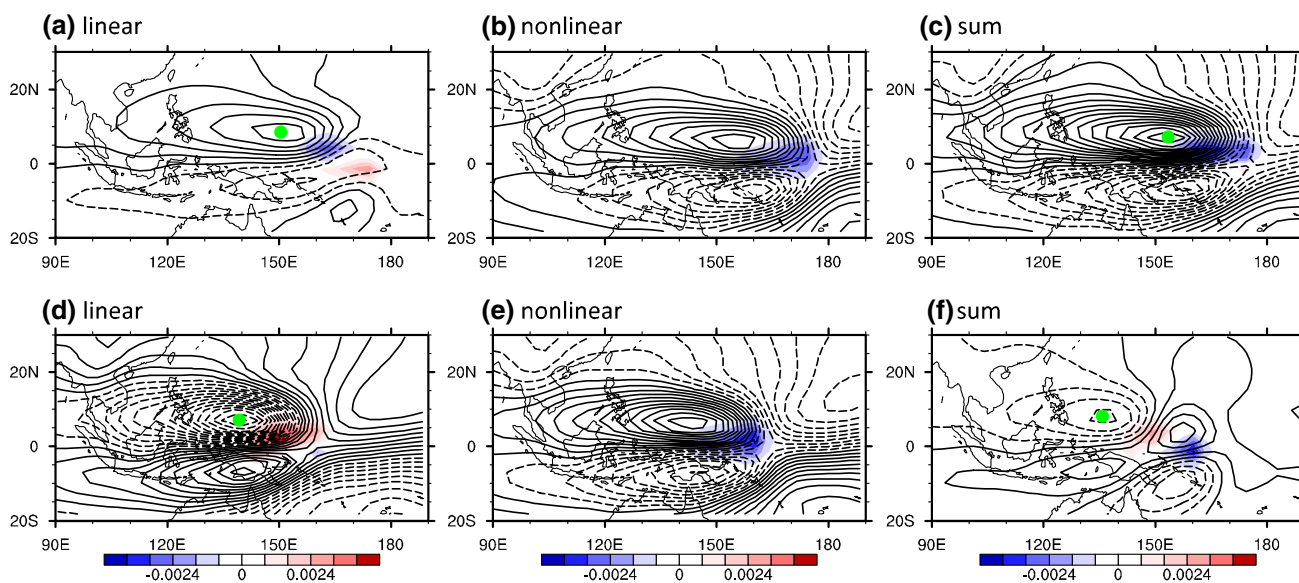


Fig. 9 Simulated 850 hPa stream function anomalies (contour,  $10^5 \text{ m}^2 \text{ s}^{-1}$ ) in response to a linear, b nonlinear and c combined linear and nonlinear moist enthalpy advection forcing during (top) El Niño and

(bottom) La Niña winter. Solid (dashed) lines represent positive (negative) values (interval: 0.4). Green dots represent the centers of the WNPAC or WNPC



**Fig. 11** As in Fig. 8 except that all advection terms were calculated based on the zonally shifted symmetric fields as shown in Fig. 10. Because of the shifting of El Niño and La Niña centers, the forcing region is also shifting accordingly



**Fig. 12** As in Fig. 9 except that the model is forced with specified heating fields shown in Fig. 11

circulation centers (Fig. 12a, d). Adding the nonlinear advection induced heating leads to a greater zonal shift between El Niño and La Niña (Fig. 12c, f).

To quantitatively measure the relative roles of the nonlinear moist enthalpy advection versus the zonally asymmetric heating, we calculated the stream function centers for each experiment and the result is shown in Table 2. While the linear advection effect leads to the same longitudinal location for the WNPAC and WNPC, both the nonlinear advection effect and the zonally asymmetric heating cause an approximately  $10^\circ$  zonal shift each. Figure 13 displays the contributions of the zonal shifting by the nonlinear advection, the zonally asymmetric heating, and the combination

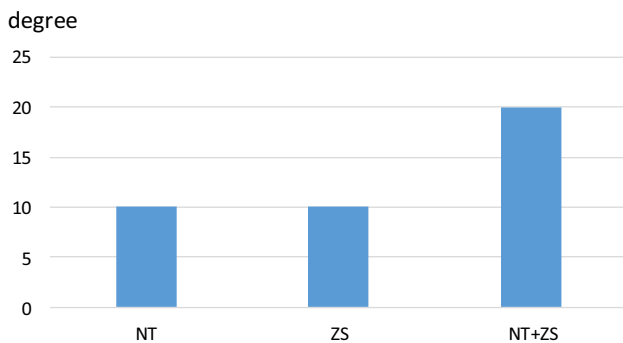
of the two above. The results indicate that the nonlinear moist enthalpy advection and zonally asymmetric heating are equally important in contributing the circulation asymmetry in the WNP between El Niño and La Niña.

Besides the zonal shifting, the intensities of WNPAC and WNPC are asymmetric in the observation (Fig. 1a, c). The relative contribution of different factors for intensities of anomalous anticyclone and cyclone is compared in Table 3. Whereas the linear advection of moist enthalpy causes the same strength for WNPAC and WNPC (Exp A1), the combined linear and nonlinear advection terms tend to strengthen WNPAC but weaken WNPC (Exp A2). The zonal shifting of El Niño and La Niña heating tends to have an

**Table 2** Longitudes of centers of anomalous anticyclone during El Niño or anomalous cyclone during La Niña derived from anomaly AGCM experiments

	Center longitude
LT	
El Niño	145°E
La Niña	145°E
LT and NT	
El Niño	145°E
La Niña	135°E
LT and ZS	
El Niño	150°E
La Niña	140°E
LT and NT and ZS	
El Niño	155°E
La Niña	135°E

LT the model response to linear moist enthalpy advection term, NT the response to nonlinear moist enthalpy advection term, ZS the model response to zonal shift of CEP heating location



**Fig. 13** Longitudinal differences (unit: degree) of anomalous circulation centers in the WNP between El Niño and La Niña derived from different modeling experiments. NT the case when the nonlinear advection term is considered, ZS the case when the zonal shifting of heating location is considered

opposite effect, that is, strengthening WNPAC but weakening WNPAC (Exp B1). The combination of the aforementioned three forcing factors leads to a stronger WNPAC and

a weaker WNPC, with a ratio of 2.5:1, which is close to the observed ratio (2:1, see Fig. 1).

### 5 Conclusion and discussion

The WNPAC (WNPC) was fully established during the mature phase of El Niño (La Niña), and their intensities and structure asymmetry was critical for subsequent ENSO evolution (Wu et al. 2010; Chen et al. 2016) and East Asian summer monsoon variability (Chang et al. 2000a, b; Wang et al. 2000, 2003; Li and Hsu 2017). In this study, the cause of asymmetric atmospheric circulation responses in the WNP between El Niño and La Niña were investigated through the observational analysis and idealized modeling experiments.

Firstly a key region for the anti-symmetric circulation and precipitation responses in the WNP was identified. Then a diagnosis of column integrated moisture and MSE budget was performed, to reveal the fundamental process responsible for the anti-symmetric precipitation anomaly over the region. The result indicates that nonlinear horizontal moist enthalpy advection ( $-\langle \vec{V}' \nabla_h (c_p T + L_v q) \rangle$ ) is critical to contribute to the anti-symmetric rainfall anomaly. Physical mechanism for this nonlinear moist enthalpy advection process is explained as following. Northwesternly (southeasterly) anomalies to the western flank of an anomalous cyclone (anticyclone) associated with a Rossby wave response to El Niño (La Niña) heating in CEP induce a negative moist enthalpy advection anomaly for both El Niño and La Niña composites (Fig. 4). This leads to a suppressed rainfall anomaly for both El Niño and La Niña, and thus strengthens the WNPAC during El Niño but weakens the WNPC during La Niña.

In addition to the nonlinear moist enthalpy advection effect, the zonal asymmetry of anomalous heating between El Niño and La Niña may also contribute to the circulation asymmetry. To reveal the relative roles of the aforementioned two factors, numerical experiments with an anomaly atmospheric general circulation model were carried out. In the first set of experiments, linear and nonlinear moist

**Table 3** The intensities of anomalous anticyclone in El Niño and cyclone in La Niña based on experiment results

Experiment name	Forcing factors	El Niño (WNPAC) (unit: $10^{-6} \text{ s}^{-1}$ )	La Niña (WNPC) (unit: $10^{-6} \text{ s}^{-1}$ )
Exp A1	LT	- 1.3	1.3
Exp A2	LT and NT	- 2.4	0.3
Exp B1	LT and ZS	- 0.8	1.8
Exp B2	LT and NT and ZS	- 1.8	0.7

The intensity of anomalous anticyclone (cyclone) is defined as area averaged vorticity  
 LT the model response to linear moist enthalpy advection term, NT the response to nonlinear moist enthalpy advection term, ZS the model response to zonal shift of CEP heating location

enthalpy advection terms were calculated based on the symmetric El Niño and La Niña patterns (Fig. 7), and the moist enthalpy advection terms were regarded as a diabatic heating source to force the anomaly model. The numerical results indicate that the nonlinear advection is able to generate an asymmetric atmospheric circulation response in the WNP (Fig. 9). In the second set of experiments, the effect of zonally asymmetric heating between El Niño and La Niña was examined. By shifting the symmetric El Niño and La Niña patterns zonally by 15°, we calculated the linear and nonlinear moist enthalpy advection fields in this idealized setting and forced the model with the corresponding heating fields. In the third set of experiments, both the moist enthalpy advection and the zonally asymmetric heating were considered. The result indicates that the two processes are equally important in inducing the asymmetric circulation anomaly response in the WNP (Fig. 13).

In the current study we focus on examining two factors that affect the circulation asymmetry in the WNP. Firstly, given the symmetric SST and wind patterns for El Niño and La Niña (Fig. 7), how nonlinear moist enthalpy advection causes a circulation asymmetry. Secondly, given the same symmetric El Niño and La Niña patterns but with a zonal shift, how the WNP circulation anomaly centers may shift. While the two factors can explain to a large extent the observed circulation asymmetry in the WNP, some biases remain. For instance, the resulted cyclonic center during La Niña is located to the east of the Philippines (Fig. 12), while the observed center appears over South China Sea (Fig. 1). Such biases may arise from the effect of El Niño and La Niña amplitude difference and/or the neglecting of interactive heating induced by anomalous circulation and air–sea interactions. For example, northeasterly anomalies associated with WNPAC during El Niño may strengthen trade wind and thus increase surface evaporation, leading to a cold SSTA in situ. The colder SSTA can further strengthen the WNPAC through suppressed atmospheric heating. Anomalous descending motion at the center of WNPAC could induce a negative heating anomaly, which may further strengthen the anomalous anticyclone. These factors need to be carefully examined in future endeavor.

The current study demonstrated that even given a perfectly symmetric El Niño and La Niña pattern, the circulation anomaly in the WNP can still be asymmetric, owing to the asymmetry caused by nonlinear moist enthalpy advection. The El Niño and La Niña SSTA pattern asymmetry may further strengthen the circulation asymmetry. So far it is unclear what causes the El Niño and La Niña pattern asymmetry. Another unsolved issue is how central Pacific and eastern Pacific types of El Niño act differently to affect anomalous atmospheric circulation response in the WNP. Further in-depth observational, modeling and theoretical studies are needed to address these issues.

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