Air–Sea Interaction over the Subtropical North Pacific during the ENSO Transition Phase

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ABSTRACT

In the present study, monthly mean objectively analyzed air–sea fluxes (OAFlux) and NCEP–Department of Energy (DOE) reanalysis datasets are employed to investigate air–sea interaction over the subtropical North Pacific during the El Niño–Southern Oscillation (ENSO) transition phase. A coupled low-frequency mode is identified, for which surface net heat flux and atmospheric circulation changes are strongly coupled during the ENSO transition phase. This mode features anomalous cooling (warming) and low-level anomalous cyclonic (anticyclonic) circulation over the subtropical North Pacific. When this mode is prominent, the atmospheric circulation anomalies lead to SST cooling (warming) through surface heat flux anomalies as- sociated with increases (decreases) in the sea–air temperature and humidity differences induced by anomalous cold (warm) advection. In turn, positive heat flux anomalies induce more surface heating, and the SST cooling (warming) causes less (more) deep convective heating. The anomalous surface heating and deep convective heating contribute significantly to anomalous circulation through the thermal adaptation mechanism (adaptation of atmospheric circulation to vertical differential heating). This positive feedback favors the maintenance of these anomalous winds over the subtropical North Pacific.

1. Introduction

The El Niño–Southern Oscillation (ENSO) is an important component of the global climate system. Warm ENSO events are characterized by weakening of the trade winds and warming of the surface layers in the equatorial eastern and central Pacific (e.g., Rasmusson and Carpenter 1982). Previous studies have found that ENSO is closely associated with zonal wind anomalies over the western equatorial Pacific (e.g., Zebiak and Cane 1987; Weisberg and Wang 1997; Wang et al. 1999). These wind anomalies generate Kelvin waves propagating eastward along the thermocline, posing a significant effect on sea surface temperature (SST) in the eastern equatorial Pacific (Zebiak and Cane 1987; Wang et al. 1999).

The zonal wind anomalies over the tropical western Pacific may originate from the eastward propagation of anomalous winds associated with the South Asian
monsoon (Huang and Fu 1996; Chao and Chao 2001). It has been indicated that the westerly wind anomalies over the western Pacific are influenced by anomalous East Asian monsoon (Huang and Fu 1996; Li 1998; Chen and Wu 2000; Xu and Chan 2001; Zhou and Wu 2010) and Australian summer monsoon (Chen and Wu 2000; Xu and Chan 2001). In particular, if the East Asian winter monsoon is strong (weak) in a given winter, that is, if northerly (southerly) wind anomalies appear over the subtropical western North Pacific (WNP), then westerly (easterly) wind anomalies occur over the equatorial western Pacific in the following seasons (Xu and Chan 2001; Mu 2001; Li 2002). This suggests that zonal wind anomalies over the equatorial western Pacific are influenced by the anomalous East Asian winter monsoon (EAWM). Zonal wind anomalies associated with the Madden–Julian oscillation have also been suggested to contribute to ENSO (Zhang and Gottschalck 2002; McPhaden et al. 2006).

During ENSO transition phases, both zonal wind anomalies over the equatorial western Pacific and meridional wind anomalies over the subtropical WNP are closely associated with an anomalous anticyclone/cyclone over the Philippine Sea. The factors that may contribute to the development of anomalous Philippine Sea anticyclone include anomalous descent induced by anomalous convective heating over the equatorial central Pacific associated with ENSO (Wang et al. 2000; Wu and Wang 2000), anomalous descent forced by Indian Ocean SST anomalies (Annamalai et al. 2005), the Kelvin wave response to warm SST anomalies in the tropical Indian Ocean (Xie et al. 2009), local cold SST anomalies (Wang et al. 2000; Wu and Wang 2000), and the enhanced cold air activity over East Asia (Wang and Zhang 2002).

To provide a sustained contribution to eastern equatorial Pacific SST changes and lead to ENSO turnaround, anomalous winds over the WNP need to be maintained for several months or seasons (Wang et al. 2001). Thus, it is important to understand what processes maintain the wind anomalies over the WNP. Because the remote forcing from the eastern equatorial Pacific SST anomalies is relatively weak during the ENSO transition phase, local air–sea interaction may be prominent in the WNP where the mean SST is high. Wang et al. (2000) proposed a positive thermodynamic feedback mechanism between atmospheric Rossby waves and the SST anomalies for sustaining anomalous Philippine Sea anticyclone during the decay of ENSO. This mechanism relies on a wind–evaporation feedback on SST. However, the roles of humidity and temperature changes in the SST changes have not been addressed. In fact, surface humidity and temperature variations may produce changes in sea–air humidity and temperature differences, inducing local changes in SST through surface latent and sensible heat flux variations (Emanuel et al. 1994; Brown and Bretherton 1997; Wu et al. 2007). The conventional view of wind speed as the dominant effect in ENSO-induced SST changes has been significantly modified by an important contribution from anomalous sea–air humidity difference to tropical Atlantic SST anomalies during ENSO events (Chikamoto and Tamimoto 2006). The roles of humidity-related surface evaporation change and temperature-related surface sensible heat flux changes over the tropical North Pacific during the ENSO transition phase remain unknown yet. In addition, the anomalous anticyclone discussed in Wang et al. (2000) is mainly confined to the Philippine Sea. However, in reality, the wind anomalies cover a much larger domain over the subtropical North Pacific.

As is well known, the meridional flows over the subtropics are in accord with the Sverdrup balance, and the North Pacific anticyclones develop as a remote response to the convective heating (Chen et al. 2001; Rodwell and Hoskins 2001). Recently, based on the complete form of vertical vorticity tendency equation, Wu et al. (1999) and Wu and Liu (2000) proposed a new mechanism for the formation and variation of subtropical high. This mechanism, called the thermal adaptation mechanism, depends on internal forcing associated with changes in static stability and baroclinicity as well as the external forcing associated with frictional dissipation and diabatic heating. Further, Liu et al. (2001, 2004) demonstrated that external diabatic heating is responsible for the enhancement of the North Pacific anticyclone. Therefore, the thermal adaptation mechanism provides a new physical interpretation for the change of atmospheric circulation over the subtropics. The above studies, however, are focused on the mean anticyclone over the North Pacific. Whether the thermal adaptation mechanism works for the interannual anomaly, especially for the maintenance of anomalous winds over the subtropical North Pacific is still unclear. The present study extends the thermal adaptation mechanism to anomalous winds over the subtropical North Pacific during the ENSO transition phases.

Two fundamental questions will be addressed in this study: 1) What are the prominent patterns of low-level wind anomalies over the subtropical North Pacific during the ENSO transition phase? 2) Is local air–sea interaction responsible for the maintenance of low-level wind anomalies over the subtropical North Pacific during the ENSO transition phases? In the current paper, we try to identify the local relationship between low-level wind and surface thermal heating anomalies over the subtropical North Pacific by using conditional singular value decomposition (CSVD; An 2003) and to
examine air–sea interaction that may affect anomalous winds over the subtropical North Pacific during the ENSO transition phases. The datasets and methods used in the present study are described in section 2. Section 3 documents dominant features of low-level circulation anomalies over the subtropical North Pacific and examines how related thermal forcing contributes to the persistence of the subtropical circulation anomaly. Section 4 presents the local relationship between low-level winds and surface net heat flux (NHF) anomalies over the North Pacific during the ENSO transition phases by means of CSVD. In section 5, a positive feedback mechanism for the maintenance of the anomalous winds over the subtropical North Pacific is proposed. Finally, the summary and discussion are presented in section 6.

2. Data and methodology

a. Datasets

Two datasets are used in the present study. One is the monthly mean variables from the National Centers for Environmental Prediction (NCEP)–Department of Energy (DOE) reanalysis (Kanamitsu et al. 2002), which is available on a 2.5° × 2.5° grid since January 1979. The second is the monthly mean surface radiative and turbulent heat fluxes from the objectively analyzed air–sea fluxes (OAFlux) for the global oceans that is produced by a synthesis of satellite retrievals, ship reports, and atmospheric model reanalysis products using a variational objective analysis (Yu and Weller 2007). These fluxes are available on 1° × 1° grids since January 1981. The convention for surface heat flux is positive (negative) for upward (downward) fluxes. The present analysis basically covers these data from 1984 to 2002, unless specified otherwise.

b. Methodology

The relationship between the atmospheric circulation anomalies and SST anomalies over the North Pacific has been investigated by Namias and Born (1988), Wallace et al. (1990, 1992), and Zhang et al. (1996, 1998). An intrinsic low-frequency mode without ENSO influences, which reveals atmospheric internal dynamics and its impact on SST anomalies in the midlatitude North Pacific, is identified statistically and physically from the observational standpoint by removing the influence of ENSO (Zhang et al. 1996; An and Wang 2005). It is meaningful to distinguish ENSO and non-ENSO influences. The significant air–sea coupled relationship in the North Pacific mode without ENSO influence is due to the coherence in the high-frequency band (An and Wang 2005). Since time series records indicate that the recurrent interval of ENSO primarily varies between 2 and 7 yr (Trenberth and Shea 1987), to obtain coherent patterns between the low-level wind and surface thermal heating anomalies and focus on signals related to non-ENSO variability on interannual time scales, a bandpass filter has been applied to all the variables to extract the variability on the 2–8-yr time scales. Then, CSVD method proposed by An (2003), which not only isolates the most coherent patterns between two fields but also excludes the unwanted signal by subtracting the regressed value of each employed field that depends on the unwanted signal, is adopted in this work. The method is described in detail in An (2003) and is briefly introduced here.

Consider two geophysical variables \( \xi(x, t) \) and \( \psi(x, t) \) that are functions of a constraint time series \( Z(t) \). We construct two new variables \( \tilde{\xi}(x, t) \) and \( \tilde{\psi}(x, t) \) by removing the portions of the signals in \( \xi(x, t) \) and \( \psi(x, t) \) that are covariant with \( Z(t) \):

\[
\tilde{\xi} = \xi - \text{ZCOV}(\xi, Z)/\text{VAR}(Z), \quad \text{and}
\tilde{\psi} = \psi - \text{ZCOV}(\psi, Z)/\text{VAR}(Z),
\]

where COV(\( \xi, Z \)) denotes the temporal covariance between variables \( \xi \) and \( Z \), and COV(\( \psi, Z \)) between variables \( \psi \) and \( Z \), and \text{VAR}(Z) denotes the variance of \( Z \). The methodology used in Eq. (1) resembles the method used in Wallace et al. (1992) and Zhang et al. (1996) for removing the signals of ENSO.

From Eq. (1), COV(\( \xi, Z \)) and COV(\( \psi, Z \)) become zero at each spatial grid of \( \xi \) and \( \psi \). Thus, variables \( \xi \) and \( \psi \) are not correlated with \( Z \). Using these newly defined variables, one may construct the temporal covariance matrix COV(\( \xi, \psi \)) between \( \xi \) and \( \psi \). This matrix is also referred to as the “covariance matrix between \( \xi \) and \( \psi \) conditional on \( Z \)” (An 2003). CSVD identifies pairs of spatial patterns that explain as much as possible of the mean-squared temporal covariance between two variables. Thus, CSVD provides coupled patterns between \( \xi \) and \( \psi \), in which the signals related to \( Z \) have been excluded. Only the first CSVD mode will be discussed in our study, as no significant relation is found in the higher modes.

c. Dominant factor in determining anomalous turbulent heat flux

According to the aerodynamic bulk formulae (Liu et al. 1979) as below:

\[
F_{\text{SH}} = \rho_u c_{\text{pa}} C_H U \Delta T, \quad \text{and}
\]

\[
F_{\text{LH}} = \rho_a L C_E U \Delta q,
\]

where the sensible heat (\( F_{\text{SH}} \)) and latent heat (\( F_{\text{LH}} \)) fluxes inherently depend on \( \Delta T \) (sea–air temperature
difference), $\Delta q$ (sea–air specific humidity difference), and $U$ (wind speed at 10 m). Here, $\rho_a$ is the density of air, $c_{pa}$ is its specific heat, $L$ is the latent heat of vaporization for water, and $C_H$ and $C_E$ are bulk coefficients for temperature and humidity, respectively. To assess which is the most dominant factor in determining the flux anomalies, anomalous fluxes at a particular instance at a given location can be expressed as follows (Tanimoto et al. 2003):

$$F'_{\text{SH}} = \rho_a c_{pa} C_H (U \Delta T' + U' \Delta T), \quad \text{and}$$  
$$F'_{\text{LH}} = \rho_a L C_E (U \Delta q' + U' \Delta q).$$

The two terms on the right-hand side of Eq. (4) represent the respective contributions from $\Delta T$ and $U$ to the sensible heat flux anomaly. The two terms on the right-hand side of Eq. (5) are contributions from $\Delta q$ and $U$ to the latent heat flux anomaly.

d. Atmospheric forcing on the SST

The SST is determined by a balance of horizontal and vertical ocean advection, vertical ocean mixing, and the net surface heat flux. The SST equation can be written as

$$\rho_w c_{pw} H \frac{\partial T}{\partial t} = \text{OP} - F_{\text{SW}} - F_{\text{LW}} - F_{\text{SH}} - F_{\text{LH}}$$

$$= \text{OP} - F_{\text{NH}}.$$  

(6)

Here, $\rho_w$ is the density of water, and $c_{pw}$ is its specific heat; $H$ is the mixed layer depth, which varies in space and time; $T$ is the mixed layer temperature, which equals the SST; OP is the SST tendency due to advection and mixing; and the $F$ terms refer to the surface shortwave ($F_{\text{SW}}$) and longwave ($F_{\text{LW}}$) radiative fluxes, the surface sensible ($F_{\text{SH}}$) and latent ($F_{\text{LH}}$) heat fluxes, and net heat fluxes ($F_{\text{NH}}$). The surface flux terms are defined as positive upward, but OP is defined as positive if it leads to an increase of SST. Since the SST variations are mainly forced by the atmospheric circulation (Seager et al. 2002), the SST equation can be simplified to the surface flux budget:

$$\rho_w c_{pw} H \frac{\partial T}{\partial t} \approx -F_{\text{NH}}.$$  

(7)

e. Dynamics relevant to the maintenance of the subtropical circulation

Near the ridgeline of the subtropical anticyclone, both the vorticity advection and transient processes are weak (Wu et al. 1999; Rodwell and Hoskins 2001; Liu et al. 2001). As such, the vorticity equation can be simplified to the Sverdrup balance (Liu et al. 2004):

$$\beta v \approx f + \xi \frac{\partial q}{\partial z} \frac{\partial}{\partial z} \theta_z (\theta_z \neq 0).$$  

(8)

This indicates that vertical differential heating ($\partial q/\partial z$) should be accompanied by meridional advection of planetary vorticity ($\beta v$). In the Northern Hemisphere ($f$ positive) and in a statically stable atmosphere ($\theta_z > 0$), southerly (northerly) winds will be generated by an increase (decrease) in heating with altitude. Consequently, differential heating in the vertical along the subtropics will contribute to the formation and variation of subtropical high. If only the surface heating and deep condensational heating are concerned, then low-level subtropical anticyclone center appears on the western side of surface heating and eastern side of deep condensational heating (Wu et al. 1999). This thermal adaption mechanism (Wu et al. 1999; Wu and Liu 2000), that is, adaptation of atmospheric circulation to vertical differential heating, provides a basis for understanding anomalous atmospheric circulation over the subtropics.

3. Dominant patterns of circulation anomalies over the subtropical North Pacific

a. Dominant modes of low-level winds variability over the North Pacific

To aim at interannual variations of low-level winds over the North Pacific, we applied an empirical orthogonal function (EOF) analysis to monthly mean winds anomalies at 850 hPa filtered by a 2–8-yr bandpass in the domain of 100°E–100°W and 30°S–60°N. The first two leading modes are the most relevant to ENSO dynamics in both spatial and temporal scales. The first two modes, which are shown in Fig. 1, together explain over 48% of the total variance. Also included in Fig. 1 is local variance percentage, that is, the ratio of the variance of the reconstructed time series for each EOF mode to the variance of the original time series at the same grid point.

For the first EOF mode (Fig. 1a), there is a massive anticyclone over the WNP, a cyclone near 50°N and 160°W, and an anticyclone over North America, displaying a teleconnection resembling the Pacific–North America (PNA) pattern. Westerly wind anomalies prevail over the central-eastern equatorial Pacific, implying weaker than normal Walker circulation in that region. The local variance percentage exceeds 35% in these regions. When the first principal component (PC1) time series lags the Niño-3.4 SST index by 4 months, the correlation coefficient is 0.65, indicating a close relationship between EOF1 and ENSO.

A remarkable feature for the second EOF mode is the westerly wind anomalies over the equatorial western
and central Pacific with a large local variance percentage (Fig. 1c). The correlation coefficient between the PC2 time series and the Niño-3.4 SST index reaches a value of 0.51 at a 5-month lag. Thus, the EOF2 is more closely related to the ENSO growth than the EOF1. According to the dynamic effect of zonal wind anomalies on the ENSO cycle (Zebiak and Cane 1987; Li 1988, 1990; Huang and Fu 1996; Huang et al. 1998, 2001), salient westerly wind anomalies prevailing over the western Pacific contribute to the growth of ENSO through generating ocean temperature anomalies propagating toward the eastern equatorial Pacific along the thermocline. Another significant feature is a pair of asymmetric circulation anomalies: an anticyclonic anomaly over the east coast of East Asia and a massive cyclonic anomaly over the North Pacific (two separate centers, one over the Philippine Sea and the other near 30°N and 160°W). The former indicates the establishment of the Philippine anomalous anticyclone during ENSO development (Wang and Zhang 2002). The latter depicts northerly wind anomalies prevailing over the WNP and westerly wind anomalies near the equatorial western and central Pacific. With a large local variance percentage of 35%–40%, both the meridional wind anomalies over the subtropical WNP and the zonal wind anomalies over the equatorial western and central Pacific are closely associated with a massive anticyclonic/cyclonic anomaly over the North Pacific during the development of ENSO. To contribute to the oceanic warming (cooling) in the equatorial eastern Pacific, these anomalous winds need to be sustained for several months or seasons (Wang et al. 2001). What processes are important for the maintenance of these wind anomalies over the North Pacific?

b. Thermal features related to EOF2

One fundamental factor that may contribute to the maintenance of circulation anomalies is the external thermal forcing. To examine how EOF2 is related to atmospheric and oceanic thermal forcing, we perform a regression analysis using the PC2 as a reference time series. Figure 2a displays the outgoing longwave radiation (OLR) anomalies obtained by regression with respect to the PC2 time series. Positive OLR anomalies extend northeastward into the WNP from the South China Sea, while negative anomalies are observed over the central tropical Pacific. Since anomalous convective heating (inferred from OLR anomalies) is located at the central tropical Pacific, an equatorial Rossby wave response of the lower troposphere to tropical heating, that is, a cyclonic anomaly to the north of the equator (Fig. 1c), is theoretically expected (Gill 1980). The Rossby wave response, however, cannot explain the amplification and maintenance of another anomalous cyclonic circulation over the subtropical North Pacific whose center is located at the northeastern part of equatorial convective heating.

To help understand the oceanic thermal heating that may relate to EOF2, we present the SST anomalies obtained by regression with respect to the PC2 time series.
in Fig. 2b. The SST anomaly distribution in the Pacific sector exhibits an El Niño–like situation, with significant positive anomalies in the central tropical Pacific. Moreover, comparing Fig. 1c and Fig. 2b, significant negative SST anomalies are found under the overlying anomalous cyclonic center. This implies that the subtropical circulation anomaly may depend strongly on local air–sea interaction, which is discussed in the next section.

4. Coupled pattern of surface net heat flux and 850-hPa wind variability associated with the ENSO transition

a. Characteristics of the coupled pattern

In the last section, two low-frequency modes of low-level wind variability associated with different phases of ENSO were obtained. The EOF2 features an anomalous cyclone over the North Pacific with meridional wind anomalies over the WNP. Such persistent circulation anomalies are likely maintained by local air–sea interaction. To inspect coupled atmospheric and oceanic variability, we present the CSVD results in the following.

The SST variations are mainly induced by the atmospheric processes via the surface heat fluxes (Seager et al. 2002). Hence, the NHF is used as a parameter to investigate the coupling between the ocean and atmosphere. To obtain coupled patterns between low-level winds and NHF that are uncorrelated with the remote tropical forcing, that is, ENSO, we apply the CSVD method to OAFlux and NCEP–DOE datasets. In this calculation, the Niño-3.4 index is used as the constraint variable. Heterogeneous wind vectors at 850 hPa and homogeneous NHF for the first CSVD mode are shown in Fig. 3. The covariance fraction of the first CSVD mode is 66%.

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**Fig. 2.** (a) OLR (W m$^{-2}$) and (b) SST (°C) anomalies obtained by regression against the time series of the second EOF mode of 850-hPa wind anomalies. Contour interval is 2 W m$^{-2}$ in (a) and 0.1°C in (b). Shading indicates that the correlation is significant at the 95% confidence level.

**Fig. 3.** (a) Heterogeneous correlation of 850-hPa winds and (b) homogeneous correlation of NHF for the first CSVD mode. Contour interval is 0.3 in (b). The shadings indicate the areas where the correlation is significant at the 95% confidence level. (c) The corresponding time coefficients of the first CSVD mode are shown.
As seen in Fig. 3, an anomalous lower-level cyclone is found over the subtropical North Pacific with westerly anomalies over the equatorial western Pacific, while the corresponding NHF anomaly exhibits a basinwide horseshoe pattern with a positive center in the WNP. The maximum significant correlation between the Niño-3.4 index and the expansion coefficients associated with the low-level winds appears at −13-month lag (Fig. 4), and the expansion coefficients associated with the NHF exhibit the same characteristic (not shown). Compared to EOF2 in the previous section, the CSVD1 leads by 5–7 months. Since most ENSO events tend to peak in the boreal winter (Rasmusson and Carpenter 1982), the result implies that the first CSVD mode is closely related to the oceanic and atmospheric variations in the winter preceding ENSO events.

b. Anomalous circulations related to the CSVD1

To highlight spatial structures related to the CSVD1, Fig. 5 shows the spatial patterns of the monthly mean surface winds, sea level pressure (SLP), and 500-hPa geopotential height anomalies obtained by regression onto the expansion coefficient associated with the low-level winds of CSVD1. As expected, significant positive SLP anomalies are observed over the Aleutian Islands and negative anomalies over the North Pacific Ocean, implying predominance of the meridional wind anomalies due to the southward shift of the Aleutian low (Fig. 5b). In the middle troposphere (Fig. 5c), negative geopotential height anomalies cover the WNP, which indicates a deepening of the East Asian trough that facilitates the intrusion of cold air into the subtropics from high latitudes.

The regression map of surface wind anomalies (Fig. 5a) indicates the prominence of an anomalous cyclonic circulation over the North Pacific. The northerly wind anomalies prevail over East Asia and further extend equatorward into the western tropical Pacific. The presence of significant circulation anomalies in low-latitude regions suggests a linkage between the East Asian winter monsoon system and tropical zonal winds anomalies (Chen and Wu 2000). Moreover, the distribution of northerly wind anomalies reflects a dominant pattern in association with the subtropical systems.

c. The local relationship between low-level winds and NHF anomalies

In accordance with CSVD1, northeasterly wind anomalies prevail over the WNP, implying stronger than normal northeasterly winter monsoon (Fig. 5a) or a cooler and drier than normal winter in that region. The cold and dry air advection extends over almost the entire

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subtropical WNP (Figs. 6a,b). As such, the heat loss of the ocean over the tropical western Pacific, mainly in the form of surface sensible and latent heat fluxes, is contributed from enhanced surface wind speed (Figs. 6c,e), where those over the subtropical central Pacific are also contributed from the increased sea–air temperature and humidity differences (Figs. 6d,f). Thus, in addition to the wind–evaporation–SST feedback mechanism (Wang et al. 2000; Wang et al. 2003), the sea–air humidity and temperature differences also contribute to the NHF anomalies over the subtropical Pacific. This indicates that the humidity and temperature changes play an important role in generating SST anomalies in the subtropical North Pacific. In summary, the CSVD1 features the local relationship between subtropical atmospheric circulation and NHF anomalies in the winter preceding ENSO events. In addition, the spectrum analysis shows that ENSO in this 19-yr record primarily varied with a 4-yr cycle (not shown). Hence, one year preceding the ENSO mature phase refers to the transition (or turnabout) phase between two opposite ENSO events, and thus this mode is termed as the coupled ENSO transition mode.

5. Air–sea interaction over the subtropical North Pacific

a. Response of SST anomalies to atmospheric forcing

The above discussion suggests a large-scale pattern of the NHF anomalies over the subtropical North Pacific induced by the atmosphere. To understand the response of the SST to atmospheric forcing, we show in Fig. 7 and Fig. 8 the evolution of the NHF and SST anomalies during ENSO transition phases. The pattern at various lags and leads is derived through regression on the time series of NHF associated with the first CSVD mode. Because the time series of the first CSVD mode peaks in the winter and there is a time lag of about 13 months between the first CSVD and ENSO, a time lag at +12
months approximately corresponds to the mature phase of ENSO warm events.

Based on an examination of the temporal evolution, two main centers of action are observed in both NHF and SST anomalies. One is located in the central and eastern equatorial Pacific, and the other is in the central and western North Pacific, as seen in Fig. 7 and Fig. 8. Both of these regions have a systematic evolution associated with the ENSO cycle. In Fig. 8a (lag = −9), the SST anomaly distribution exhibits a pattern typical of the La Niña mature phase with large negative SST anomalies in the central and eastern equatorial Pacific. From lag −6 to lag 0, with the weakening of the negative SST anomalies along the central and eastern equatorial Pacific, the cold episode enters into the decaying phase (Figs. 8b–d). At the same time, the negative SST anomalies are generated in the WNP by surface heat flux anomalies (Figs. 7b–d). From lag 3 to 9 months, positive SST anomalies develop along the central and eastern equatorial Pacific (Figs. 8e–g). In the central and western North Pacific, the development of negative SST anomalies is mainly contributed by the positive NHF anomalies (Figs. 7e–g).

To highlight the relationship between the NHF and SST anomalies, we display temporal evolutions of NHF and SST anomalies along the subtropical North Pacific.

FIG. 7. NHF anomalies at different lags obtained by regression on the expansion coefficients of NHF associated with the first CSVD mode. Units are W m⁻². Contour interval is 3 W m⁻². Shading indicates a correlation coefficient significant at the 95% confidence level.
in Fig. 9. The positive NHF anomaly from −6 to +12 months is apparent in Fig. 9a. This corresponds to negative SST anomalies after lag −3 in Fig. 9b. The phase lag clearly indicates the contribution of surface heat flux anomalies to the SST changes.

b. Dynamics relevant to the maintenance of the subtropical wind anomaly

To help understand the mechanism for the maintenance of the subtropical circulation anomaly, the atmospheric response to the external thermal forcing is investigated in this subsection. Since both the vorticity advection and transient processes regressed onto the expansion coefficients associated with the low-level winds of CSVD1 that are weak in the subtropics (not shown), the vorticity equation can be simplified to the Sverdrup balance (Wu et al. 1999; Wu and Liu 2000; Liu et al. 2004). Generally, along the subtropics, maximum diffusion heating usually occurs near the surface while maximum deep convective heating usually occurs at a height between 300 and 400 hPa where the heating rate can be several degrees per day (Liu et al. 2004), so we mainly focus on the corresponding diffusion heating between 850 and 1000 hPa \(Q_{dh}(850–1000 \text{ hPa})\) and deep convective heating between 300 and 500 hPa \(Q_{dch}(300–500 \text{ hPa})\) as presented in Fig. 10. As turbulent heat flux (THF) is the main mechanism that directly contributes to the increase of energy in the lower troposphere

![Fig. 8. As in Fig. 7, but for SST. Units are °C. Contour interval is 0.1°C.](image-url)
in a steady state, positive THF anomalies in the subtropical central North Pacific induce positive \( Q_{dh}(850–1000 \text{ hPa}) \) anomalies (Fig. 10a). The anomalous heating generates the low-level northerlies \( v = (f + \zeta \beta \theta_z)(\partial Q_{dh}/\partial z) < 0 \) (Fig. 10c) due to the \( \beta \) effect, which leads to a low-level anomalous subtropical cyclone with the center at the eastern side of the positive \( Q_{dh}(850–1000 \text{ hPa}) \) anomalies (Fig. 10c).

Regarding the deep convective heating, once the water evaporates from the sea and vapor rises to higher altitudes, deep convective heat is released in the free troposphere, which will affect local or leeward circulation (Liu et al. 2001; Wu et al. 2002). Hence, because of the occurrence of the negative SST anomalies in the WNP, the atmosphere becomes stable to the west, allowing less convection and thus less deep convective heating (Fig. 10b) in the atmosphere. This causes a negative vorticity at the lower troposphere, and then the low-level northerlies \( v = (f + \zeta \beta \theta_z)(\partial Q_{dch}/\partial z) < 0 \) over the subtropical central North Pacific are intensified (Fig. 10c) and the low-level anomalous subtropical cyclone appears at the eastern side of the negative \( Q_{dch}(300–500 \text{ hPa}) \) anomalies. In turn, this process enhances the anomalous cyclone.

Through inducing negative vorticity and low-level northerlies over the subtropical central North Pacific, both positive \( Q_{dh}(850–1000 \text{ hPa}) \) and negative \( Q_{dch}(300–500 \text{ hPa}) \) anomalies are favorable for the maintenance of northerly anomalies over the WNP. It proves that surface heating and deep convective heating anomalies are important sources of atmospheric energy, especially for the maintenance of subtropical circulation anomaly during ENSO transition phases.

c. SST impacts on atmosphere

The SST anomalies in the WNP can induce convection and heating in the atmosphere as demonstrated by previous modeling studies (Wang et al. 2000; Wu and Wang 2000). Wang et al. (2000) indicated that negative SST anomalies in the WNP suppress in situ convective heating. Wu and Wang (2000) showed that the local SST forcing in the WNP is effective in inducing specific humidity and temperature anomalies at low-level and modulate the convective instability.

The effects of in situ SST anomalies on the atmospheric boundary layer temperature and humidity can be seen by comparing 850-hPa humidity and temperature anomalies (Figs. 6a,b) with SST anomalies (Fig. 11a). Lower-tropospheric cooling and drying tend to collocate with low SST in the WNP. The low-level cooling and drying reduce the convective instability and thus suppress the deep convective heating (Figs. 11b,c).

6. Summary and discussion

The development of the anomalous Philippine Sea anticyclone during the ENSO transition phases has been well documented (Wang et al. 2000; Wu and Wang 2000;
Wang and Zhang 2002; Annamalai et al. 2005; Xie et al. 2009). However, the mechanisms for the maintenance of wind anomalies that cover a large domain over the subtropical North Pacific are still not clear. In this study, the interactions between ocean and atmosphere during ENSO transition phases are investigated and a positive feedback is proposed to explain the maintenance of anomalous winds over the subtropical North Pacific.

Our study on the interannual variability of low-level winds over the North Pacific indicates that there are at least two types of ENSO-related modes. In the first type, the PNA pattern and anomalous Walker circulation along the central equatorial Pacific develop after the peak of ENSO events. In the second type, a dominant pattern of meridional wind anomalies over the subtropical North Pacific is closely linked to the equatorial wind anomalies over the western equatorial Pacific during the development of ENSO.

Before the EOF2 becomes dominant, oceanic and atmospheric systems are greatly coupled by the local interaction, featuring anomalous surface warming (cooling) surrounded by anomalous cooling (warming) and overlying

![Fig. 11](image-url)

**Fig. 11.** (a) SST (°C) anomalies obtained by regression against the time series of NHF associated with the first CSVD mode. (b) As in (a), but for $Q_{\text{dch}}$(300–500 hPa) (K day$^{-1}$). Contour interval is 0.05°C in (a) and 0.1 K day$^{-1}$ in (b). Shading indicates that the correlation is significant at the 95% confidence level. (c) Vertical profile of $Q_{\text{dch}}$(K day$^{-1}$) anomalies (15°–30°N, 120°–150°E) obtained by regression against the time series of NHF associated with the first CSVD mode.

![Fig. 12](image-url)

**Fig. 12.** The conceptual diagram of air–sea interaction for the coupled ENSO transition mode.
low-level anomalous cyclonic (anticyclonic) circulation over the subtropical North Pacific. The coupled low-frequency mode represented by CSVD1 indicates that the low-level wind anomalies induce surface heat flux anomalies through changes in both surface wind speed and sea–air humidity and temperature differences in the transition (or turnabout) phase between two opposite ENSO events, and thus it is termed as the coupled ENSO transition mode.

Based on the analysis of the temporal evolution of air–sea coupled patterns during ENSO transition phases, a conceivable mechanism is proposed, which is shown in the conceptual diagram given in Fig. 12. During the La Niña–El Niño transition phases, northeasterly anomalies associated with the anomalous subtropical cyclone advect more cold and dry air to the WNP and the subtropical central North Pacific. The ocean loses more heat because of the increase in temperature and humidity differences at the interface in the subtropical central North Pacific as well as the increase in surface wind speed in the WNP. On the other hand, positive THF anomalies induce positive diffusion heating anomalies at lower troposphere, indicating a surface heating over the subtropical central North Pacific. The resultant SST cooling leads to less deep convective heating in the atmosphere. The increased surface heating and the decreased deep convective heating in these subtropical regions contribute to the maintenance of the anomalous cyclone via a thermal adaptation mechanism. Being associated with a northeasterly flow over the WNP and the subtropical central Pacific, the anomalous subtropical cyclone in turn cools the ocean by enhancing the positive NHF anomalies. In contrast, during the El Niño–La Niña transition phases, the above-mentioned physical processes involve anomalies of opposite sign. This positive feedback mechanism magnifies and maintains the existing anomalous atmospheric circulation over the subtropical central North Pacific.

The present study indicates that, in addition to the wind–evaporation feedback on SST that is emphasized by Wang et al. (2000), surface turbulent heat flux anomalies associated with the sea–air humidity and temperature difference changes induced by anomalous wind advection may also feedback positively on SST in the subtropical North Pacific. This study also shows that the thermal adaptation mechanism that is previously used to explain the development of mean subtropical anticyclone (Wu and Liu 2000; Liu et al. 2001, 2004) may be applicable to the maintenance of anomalous cyclone/anticyclone over the subtropical North Pacific during the ENSO transition phase. Different from the mean subtropical anticyclone over the North Pacific, which is related to heating in remote regions (condensational heating over the Asian land and surface sensible heating over North America; Liu et al. 2001, 2004), the anomalous anticyclone over the subtropical North Pacific is associated with local heating.

Although the above results seem to provide a consistent description of roles that ocean and atmosphere play in the amplification and maintenance of circulation anomalies over the subtropical North Pacific during ENSO transition phases, whether the physics behind this conceptual model is involved in determining the subtropical circulation anomalies in each ENSO event is an open question that deserves further observational and modeling studies. The Indian Ocean SST anomalies may also contribute to the maintenance of circulation anomalies over the subtropical North Pacific during the decay phase of ENSO, as suggested by previous studies (e.g., Xie et al. 2009), which is, however, beyond the scope of the present study.

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