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ORIGINAL PAPER

Change in surface latent heat flux and its association with tropical cyclone genesis in the western North Pacific

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Abstract The present study investigates the influence of June through November (JJASON) thermal state of the western North Pacific warm pool on surface latent heat flux and their association with tropical cyclone (TC) genesis by using 25 level water temperature data with European Centre for Medium-Range Weather Forecasts (ECWMF) operational ocean analysis (ORA-S3), the monthly mean fluxes from Objectively Analyzed Air-sea Fluxes (OAFlux) Project, and the tropical cyclone data from the International Best Track Archive for Climate Stewardship (IBTrACS). It is found that positive (negative) latent heat flux anomalies over the western North Pacific are associated with warm (cold) state of the warm pool. The analysis suggests that the change in sea-air humidity difference has a direct contribution to surface latent heat flux anomalies over the western Pacific in warm state years of the warm pool. However, the change in surface wind speed is the main cause of surface latent heat flux anomalies over central tropical Pacific. In cold state years, change in the sea-air humidity difference has a direct contribution to surface latent heat flux anomalies over the western Pacific and central and eastern tropical Pacific, and the change in surface wind speed appears not to be a cause of identified surface latent heat flux anomalies. Moreover, the results show that the sea-air humidity difference contributes to tropical cyclone genesis in warm state years, but in cold state years, tropical cyclone genesis occurs mainly in regions of sea-air humidity difference decrease and surface wind speed increase.

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1 Introduction

Surface latent heat flux plays an important role in the ocean surface energy balance (Cayan 1992a, b, c; Alexander and Scott 1997; Yu et al. 2007; Grodsky et al. 2009; Zeng and Wang 2009; Li et al. 2011a, b). It is an essential factor in the interactions between the atmosphere and ocean. The change in surface latent heat flux is associated with sea surface temperature (SST) and surface wind speed. Liu and Curry (2006) pointed out that positive surface latent heat fluxes were associated with increase in surface wind speed. Yu and Weller (2007) indicated that surface latent heat flux increase is mainly associated with increase in SST. Li et al. (2011a) argued that the increase in SST has a direct contribution to change in surface latent heat flux, while the strengthening in surface wind speed has an indirect contribution to change in surface latent heat flux.

The tropical western Pacific is known as “the warm pool” because the SSTs in this region are the highest in global oceans (e.g., Cornejo-Garrido and Stone 1977; Nitta 1987; Huang and Li 1988). Consequently, air-sea interaction is very strong and the ascending branch of the Walker circulation located over the region. This leads to strong convergence of moist air and strong convective activity and heavy rainfall there (e.g., Cornejo-Garrido and Stone 1977; Hartmann et al. 1984). Thus, tropical western Pacific has an important effect on local and remote climate variability. Besides, previous studies pointed out that the SST exceeding 26 °C is one of the favorable conditions for tropical cyclone (TC) genesis (e.g., Gray 1968; 1975). The tropical western Pacific thermal state generally satisfies the thermal condition of the TC genesis. Every year, about 30 TCs occur over this region, accounting for about one third of global total TCs. About 80 % of these TCs develop into tropical storms (typhoons). Every year, more than 10 TCs or typhoons make landfall in China, Korea, and Japan, which causes huge economic losses and death of several hundreds of people in these countries (e.g., Huang and Chen 2007; Chen et al. 2012). Therefore, the activity of TCs over the western Pacific is an important research issue for Chinese, Korean, and Japanese meteorologists and some countries in Southeast Asia.

Previous studies mainly focus on influences of SST and circulation on the TC genesis (e.g., Chan 2000; Wang and Chan 2002; Chen and Tam 2010; Chen 2011; Li and Zhou 2012). However, they do not consider the association of TC genesis with sea-air fluxes. More than 90 % of the TCs occur in summer and autumn over the western North Pacific (Lin and Zhang 2004). Therefore, this article mainly focuses on changes in surface latent heat flux and flux-related variables and their association with TC genesis from June to November (JJASON).

The organization of the rest of the text is as follows. Section 2 describes the datasets used in this study. In Section 3, the change in subsurface water temperature in the warm pool of the western Pacific is analyzed. Section 4 presents the influence of thermal state of the warm pool on surface latent heat flux. Section 5 shows the contribution of the sea-air humidity difference and surface wind speed to surface latent heat flux changes. Section 6 presents the relationship between surface latent heat flux and TC genesis. Summary is provided in Section 7.

2 Datasets

The present study uses observing system experiments with the European Centre for Medium-Range Weather Forecasts (ECWMF) operational ocean analysis (ORA-S3) of 25 level water temperature on a 1.0°×1.0° grid. This dataset covers the period 1959–2009 (Balmaseda et al. 2008; Vidard et al. 2009).

The monthly mean fluxes on a 1°×1° grid are derived from the Multidecade Global Flux Datasets from the Objectively Analyzed Air-sea Fluxes (OAFlux) Project: surface latent heat flux, and related surface meteorological variables, which covers the period 1958–2009 (Yu et al. 2008). Previous studies indicate that surface latent heat flux from OAFlux is suitable in the tropical western Pacific region (Smith et al. 2011).

The TC data are derived from the International Best Track Archive for Climate Stewardship (IBTrACS) from the National Climate Data Center (NCDC), which covers the period 1958–2007.

3 The change in subsurface water temperature in the western Pacific warm pool

The subsurface water temperature in the warm pool may impact on SST and surface sensible heat flux (Huang and Li 1988; Zhou 2013). Obvious interannual changes are present in subsurface water temperature (100–150 m) in the warm pool of the western Pacific. Moreover, the variation of subsurface water temperature can be used to represent the characteristics of the warm pool (Nitta 1987; Huang and Li 1988). Thus, in the present study, we analyze the thermal state of the western Pacific warm pool which is represented using averaged water temperature at 120 m over the region of 0-16°N, 125-165°E. Figure 1 shows the subsurface water temperature anomaly in JJASON during 1959–2009. The interannual change seen in Fig. 1 is similar to that shown in previous studies during other months (July through October, JASO) (Huang and Chen 2007; Chen and Huang 2006; Zhou 2013). The warm and cold warm pool state cases are identified according to Fig. 1 when the subsurface water temperature anomaly exceeds one standard deviation. The warm state cases are 1971, 1975, 1978, 1984, 1988, 1998, 1999, 2000, and 2008 (total 9 cases) and the cold state cases are 1969, 1972, 1980, 1982, 1987, 1991, 1993, 1994, 1997, and 2002 (total 10 cases). The cases considered in the present study are slightly different from previous studies that used JASO mean (Zhou 2013).

The variation in subsurface water temperature is accompanied by an obvious SST anomaly pattern. The SST anomalies in warm and cold states of the warm pool are shown in Fig. 2. In warm state years, positive anomalies dominate the western Pacific, and negative anomalies are observed in central and eastern tropical Pacific (Fig. 2a). Almost opposite SST anomalies are seen in cold state years with significant negative anomalies in the western Pacific and positive anomalies in central and eastern tropical Pacific (Fig. 2b).

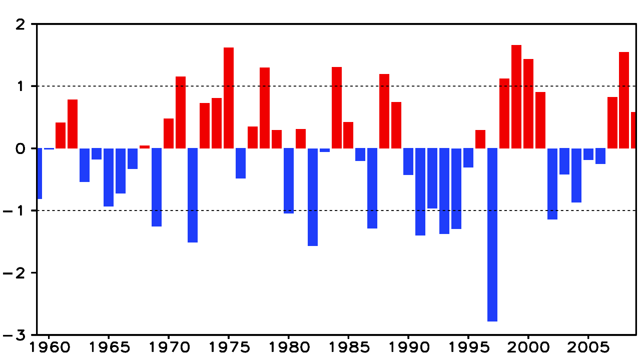

Fig. 1 The normalized time series of subsurface water temperature anomaly (degrees Celsius) at 120 m depth averaged over 0-16°N, 125-165°E in JJASON during 1959–2009

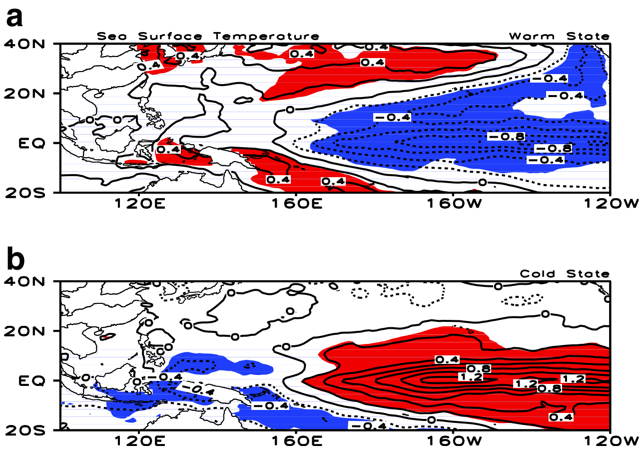

Fig. 2 Composite SST anomaly in warm (**a**) and cold (**b**) state years in JJASON. The contour interval is 0.2 °C. The *shaded regions* indicate the 5 % significant level according to the Student *t* test

4 The influence of thermal state of the warm pool on surface latent heat flux

4.1 The definition of sea surface latent heat flux

Sea-air flux is defined by exchange rate per unit surface area between the atmosphere and ocean (Smith et al. 2011). The evaporative moisture flux is the rate per unit area at which moisture is transferred from the ocean to the air. The latent heat flux is related to the moisture flux and its energy associated with the phase change of water transferred from the ocean to the atmosphere. In the Tropics, surface latent heat flux is typically an order of magnitude greater than sensible heat flux. Flux products are typically derived using the bulk formula as shown below (Liu et al. 1979):

$$Q_{lh} = \rho Le\, C_e (q_s - q_a)\, U \tag{1}$$

where Q_{lh} is surface latent heat flux, ρ is the density of moist air, Le is the latent heat of vaporization, and C_e is the moisture transfer coefficient. The variable U is surface wind speed at a reference height above the ocean surface (10 m). The surface and near-surface atmospheric (2 m) specific humidities are denoted by q_s and q_a, respectively. Note that q_s is computed from the saturation vapor humidity (q_{sat}), and surface specific humidity (q_s) is a function of SST (T_s):

$$q_s = 0.98 q_{sat}(T_s) \tag{2}$$

where a multiplier factor of 0.98 is used to take into account the reduction in vapor pressure caused by a typical salinity of 34 psu (Yu et al. 2008).

In order to derive surface specific humidity, the Michell Instruments Ltd.'s formulation to calculate saturation vapor humidity (q_{sat}) is applied. In this study, a simplified saturated vapor humidity formula is utilized. On the water:

$$\ln q_{sat}(t) = \ln 611.2 + \frac{17.62t}{243.12 + t} \tag{3}$$

where q_{sat} is saturated vapor humidity, t is sea surface temperature (T_s), and the temperature range is from -45 to 60 °C; the uncertainty is less than±0.6 %; the confidence interval is at 95 %.

4.2 The influence of thermal state of the warm pool on latent heat flux

The influence of thermal state of the warm pool on latent heat flux over the western Pacific is depicted by a composition analysis for warm and cold state years. Figure 3 shows the composition of latent heat flux anomalies in JJASON. In warm state years, positive anomalies dominate over the warm pool in the western Pacific, and negative anomalies are seen over the eastern Pacific (Fig. 3a). These indicate that the warm subsurface water temperature contributes to the increase in latent heat flux over the western Pacific. In cold state years, there are significant negative anomalies over the western Pacific and positive anomalies are seen over the eastern Pacific (Fig. 3b). Thus, cold subsurface water temperature contributes to the decrease in latent heat flux over the western Pacific.

4.3 The influence of thermal state of the warm pool on latent heat flux-related variables

Cayan (1992b, 1992c) pointed out that interannual variation in surface latent heat flux is associated with SST and atmospheric circulation. Surface latent heat flux is determined by sea-air

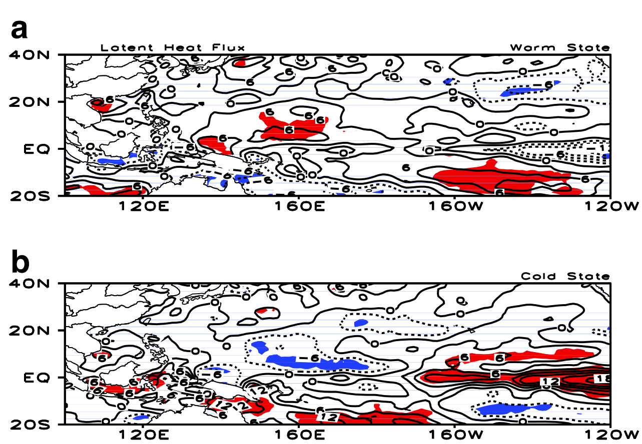

Fig. 3 Composite surface latent heat flux anomaly in warm (**a**) and cold (**b**) state years in JJASON. The contour interval is 3 W/m^2. The *shaded regions* indicate the 5 % significant level according to the Student *t* test

humidity difference and surface wind speed. Here, we analyze sea-air specific humidity difference and surface wind speed in order to understand causes for variations in latent heat flux.

The sea-air humidity difference was obtained from difference between surface and 2-m specific humidity. Figure 4 shows composite anomalies of sea-air humidity difference in warm and cold state years of the warm pool. In warm state years, positive sea-air humidity difference anomalies dominate over the western Pacific, and negative anomalies are seen over the eastern tropical Pacific (Fig. 4a). In contrast, in cold state years, significant negative anomalies dominate over the western Pacific, and positive anomalies are observed over the eastern tropical Pacific (Fig. 4b). These results suggest that the warm (cold) state in the warm pool contributes to increase (decrease) in sea-air humidity difference over the western Pacific.

The surface wind speed is another factor for latent heat flux. Figure 5 shows composite anomalies of surface wind speed. The surface wind speed displays anomalies opposite to those in sea-air humidity difference. In warm state years, negative wind speed anomalies dominate the western Pacific, and positive wind speed anomalies appear over the central and eastern tropical Pacific (Fig. 5a). In cold state years, surface wind speed anomalies show a distribution opposite to that in warm state years (Fig. 5b).

In order to quantify the relationship of surface latent heat flux with the sea-air humidity difference and surface wind speed, we show in Table 1 the correlation coefficients of latent heat flux with SST, sea-air humidity difference, and surface wind speed over the warm pool region (0-16°N, 125-165°E). The correlation coefficient between latent heat flux and SST is above the 99 % confidence level, and the correlation between latent heat flux and sea-air humidity difference is also above the 95 % confidence level. However, the correlation between latent heat flux and surface wind speed is small. The results indicate that SST and associated sea-air humidity difference have a major contribution to surface latent heat flux change over the western Pacific warm pool region.

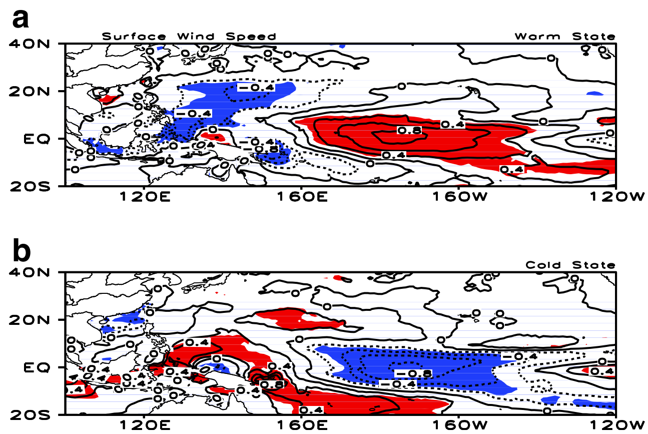

Fig. 5 Composite surface wind speed anomaly in warm (**a**) and cold (**b**) state years in JJASON. The contour interval is 0.2 m/s. The *shaded regions* indicate the 5 % significant level according to the Student *t* test

5 The contribution of sea-air humidity difference and surface wind speed to surface latent heat flux

In order to estimate the contribution of sea-air humidity difference and surface wind speed to surface latent heat flux, surface latent heat flux anomalies are decomposed as follows (Alexander and Scott 1997; Tanimoto et al. 2003; Li et al. 2011a; Zhou and Huang 2013):

$$Q' = (q_s - q_a)' \cdot \overline{U} + \overline{(q_s - q_a)} \cdot U' + \left[(q_s - q_a)' \cdot U' + \overline{(q_s - q_a)' \cdot U'}\right] \quad (4)$$

where Q′ is latent heat flux anomaly. The first term on the right-hand side ($(q_s - q_a)' \ \overline{U}$) represents the contribution of sea-air humidity difference anomaly. The second term ($\overline{(q_s - q_a)} \ U'$) signifies the contribution of surface wind speed anomaly. The third term is negligible (e.g., Cayan 1992b; Tanimoto et al. 2003; Li et al. 2011a; Zhou and Huang 2013). The composition of the every term in formula (4) in the warm and cold state years is shown in Fig. 6.

In warm states years, the $(q_s - q_a)' \ \overline{U}$ term shows significant positive anomalies over the western Pacific and negative

Table 1 The correlation coefficients of SST, sea-air humidity difference, and surface wind speed with surface latent heat flux averaged over 0-16°N, 125-165°E in JJASON during 1959–2009

	SST	Humidity difference	Wind speed
Latent heat flux	0.43[a]	0.30[b]	0.05

[a] Significant at the 99 % confidence level

[b] Significant at the 95 % confidence level

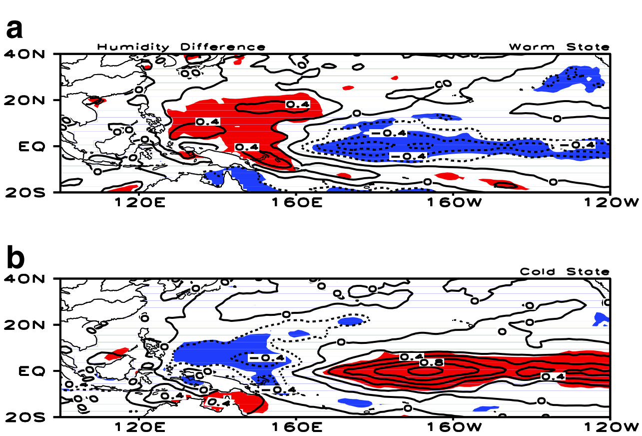

Fig. 4 Composite sea-air humidity difference anomaly in warm (**a**) and cold (**b**) state years in JJASON. The contour interval is 0.2 g/kg. The *shaded regions* indicate the 5 % significant level according to the Student *t* test

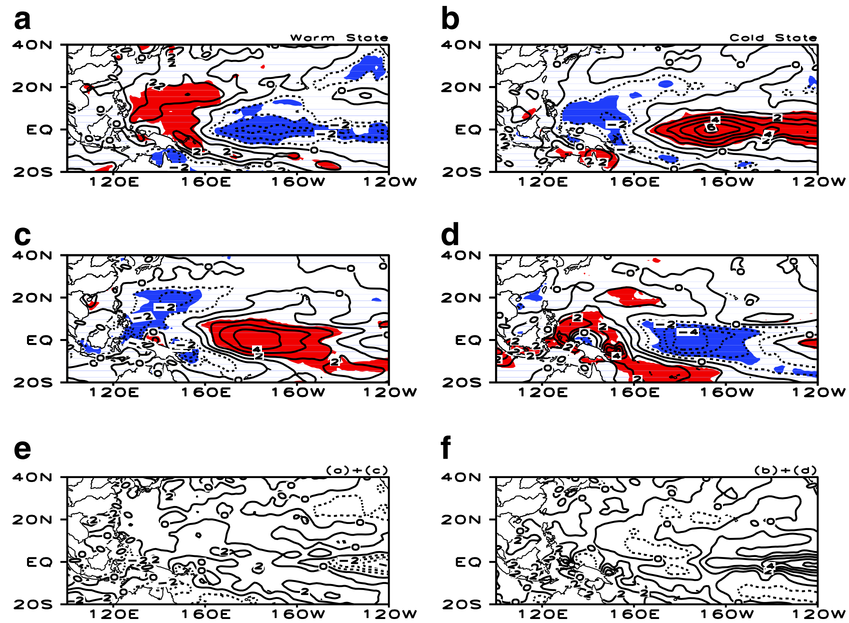

Fig. 6 Composite $(q_s-q_a)'\overline{U}$ (**a**), $\overline{(q_s-q_a)}\ U'$ (**c**), and $(q_s-q_a)'\overline{U}+\overline{(q_s-q_a)}\ U'$ (**e**) in warm state years in JJASON. **b**, **d**, and **f** are the same as **a**, **c**, and **e**, except for cold state years. The contour interval is 1 (g/Kg) (m/s). The *shaded regions* in **a**–**d** indicate the 5 % significant level according to the Student *t* test

anomalies over the central and eastern tropical Pacific (Fig. 6a). The $\overline{(q_s-q_a)}\ U'$ term shows an opposite distribution compared to that in Fig. 6a, with significant negative anomalies over the western Pacific and positive anomalies over the central and eastern tropical Pacific (Fig. 6c). The $(q_s-q_a)'\overline{U}+\overline{(q_s-q_a)}\ U'$ (Fig. 6e) shows a distribution similar to that in Fig. 3a, with significant positive anomalies over the western Pacific and the central and eastern tropical Pacific. These results suggest that the sea-air humidity difference has a direct contribution to positive surface latent heat flux anomalies over the western Pacific in warm state years of the warm pool and the surface wind speed is a main direct cause of identified positive surface latent heat flux anomalies over central tropical Pacific.

In cold state years, the contributions of sea-air humidity difference and surface wind speed display an overall opposite sign anomalies compared to Fig. 6a and Fig. 6c. Negative $(q_s-q_a)'\overline{U}$ anomalies dominate over the western Pacific, and positive anomalies occur over central and eastern tropical Pacific (Fig. 6b). Positive $\overline{(q_s-q_a)}\ U'$ anomalies are observed over the western Pacific and negative anomalies are seen over central and eastern tropical Pacific (Fig. 6d). The sum of the above two terms (Fig. 6f) shows a distribution similar to that in Fig. 3b, with significant negative anomalies over the western Pacific and positive anomalies over the central and eastern tropical Pacific. Moreover, the $(q_s-q_a)'\overline{U}+\overline{(q_s-q_a)}\ U'$ (Fig. 6f) exhibits a distribution considerably similar to that of $(q_s-q_a)'\overline{U}$ (Fig. 6b). The results indicate that the sea-air humidity difference has a direct contribution to surface latent heat flux anomalies over the western Pacific and eastern Pacific in cold state years of the warm pool. In comparison, the contribution of change in surface wind speed appears less in cold state years.

6 The relationship between latent heat flux and TC genesis

Previous studies suggest that the TC genesis is associated with the thermal state of the western Pacific warm pool (e.g., Chen and Huang 2006; Huang and Chen 2007; Chen 2011). They indicated that the dynamic factor plays a role for the TC genesis in cold and warm states of the warm pool. However, study on the relationship between latent heat flux and TC genesis is still rare. Thus, we explore the relationship between latent heat flux and TC genesis in this section. Figure 7 compares the location of TC genesis and latent heat flux, sea-air humidity difference and surface wind speed anomalies in warm and cold state years of the western Pacific warm pool.

In warm state years, the TC genesis tends to collocate with regions of positive anomalies of sea-air humidity difference (Fig. 7c), negative anomalies of surface wind speed (Fig. 7e) and positive anomalies of latent heat flux (Fig. 7a). In cold state years, most TC genesis are generated in regions of negative anomalies of sea-air humidity difference (Fig. 7d), positive anomalies of surface wind speed (Fig. 7f) and negative anomalies of latent heat flux anomalies (Fig. 7b). Thus, it appears that the relationship between the TC genesis and sea-air humidity difference and surface wind speed differs between warm and cold state years of the warm pool. The TC genesis is mostly in regions of above-normal sea-air humidity difference in warm state years of the warm pool, but in regions of enhanced surface wind speed in cold state years of the warm pool. The above results suggest that the thermal state of the western Pacific warm pool may have an asymmetric influence on the TC genesis. It may contribute to the TC genesis through sea-air humidity

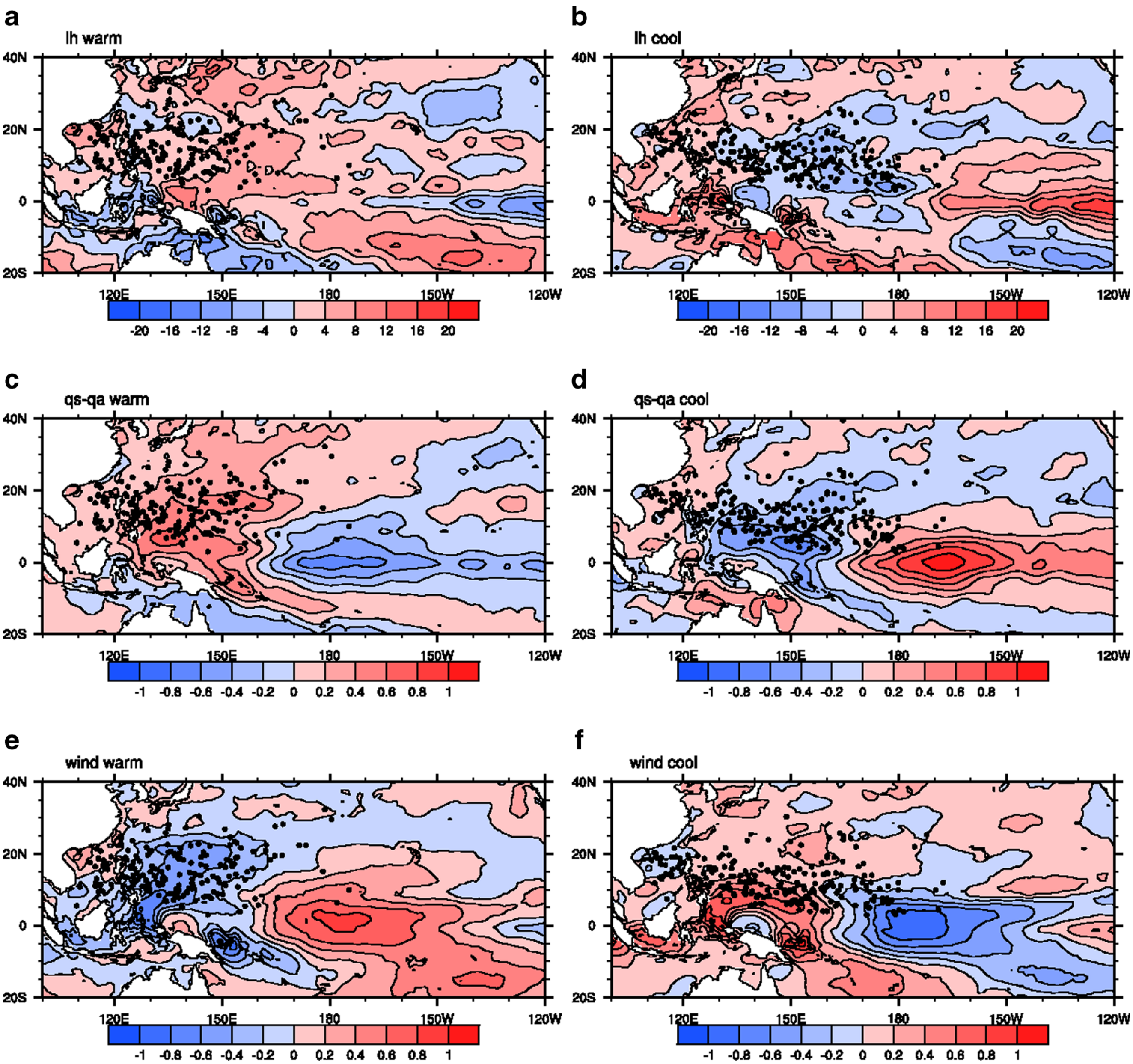

Fig. 7 The location of TC genesis and composite latent heat flux (**a**), sea-air humidity difference (**c**), and surface wind speed (**e**) anomalies in warm state years in JJASON. **b**, **d**, and **f** are the same as **a**, **c**, and **e**, except for cold state years

difference-induced enhancement of surface latent heat flux in the warm state years, complementary to the dynamic influence suggested by previous studies (e.g., Chen and Huang 2006). In the cold state years, such influence is absent and the dynamics factor is dominant for the TC genesis.

Another feature to note on Fig. 7 is that the main domain for the TC genesis tends to shift southeastward in cold state years compared to that in warm state years. This indicates the influence of the thermal state of the warm pool on the occurrence of the TCs, which is in agreement with previous studies (Chen and Huang 2006; Huang and Chen 2007; Chen 2011).

7 Summary

The present study investigates the influence of June-November (JJASON) thermal state of the western Pacific warm pool on surface latent heat flux and their association with TC genesis by using 25 level water temperature data with ECWMF operational ocean analysis (ORA-S3), the monthly mean fluxes from OAFlux Project, and the tropical cyclone data from the IBTrACS. The results suggest that surface latent heat flux over the western North Pacific is enhanced during the warm state years, but reduced during the cold state years.

The contribution of sea-air humidity difference and surface wind speed to latent heat flux changes with region. In warm state years, the sea-air humidity difference has a direct contribution to positive surface latent heat flux anomalies over the western Pacific, whereas surface wind speed is the main cause of identified positive surface latent heat flux anomalies over central tropical Pacific. In cold state years, the sea-air humidity difference has a direct contribution to surface latent heat flux anomalies over the western Pacific and eastern tropical Pacific, and surface wind speed is less important.

The analysis indicates that the TC genesis tend to occur in regions of increased sea-air humidity difference in warm state years of the warm pool, but in regions of enhanced surface wind speed in cold state years of the warm pool. It suggests that in warm state years, the thermal influence may play a complementary role in the TC genesis. However, in cold state years, the dynamic factor is dominant for the TC genesis.

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