Asymmetry of the El Niño-Spring Rainfall Relationship in Taiwan

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Abstract

Spring rainfall in Taiwan can be either enhanced or suppressed by an El Niño event, revealing an asymmetric relationship. This observational study aims at examining this asymmetric relationship and associated large-scale dynamic processes. Analysis results disclose four major El Niño/Southern Oscillation (ENSO)-spring rainfall relationship types during 1950–2003: El Niño-anomalous wet (EN-w) type, La Niña-anomalous dry (LN-d) type, El Niño-anomalous dry (EN-d) type, and La Niña-anomalous wet (LN-w) type. The EN-w and LN-d (EN-d and LN-w) types exhibit a positive (negative) correlation between the spring rainfall anomaly and the ENSO-related sea surface temperature anomaly (SSTA). The overall ENSO-spring rainfall relationship is dominated by the positive correlation.

The cause of the asymmetric ENSO impacts between the positive- and negative-correlation groups is attributed to a connection between ENSO and the Indian Ocean (IO) SSTA and associated large-scale atmospheric circulation. The positive-correlation types tend to concur with an evident ENSO-IO connection, featuring significant in-phase SSTA centers in the tropical eastern Pacific and eastern IO. During the El Niño (La Niña) event, these SST anomalies force a descending (ascending) branch over the western Pacific and help initiate and maintain a lower-level anticyclone (cyclone) anomaly in the Philippine Sea (southeast of Taiwan). Flows west of this anomalous anticyclone (cyclone) enhance (suppress) moisture transport from the South China Sea into Taiwan, resulting in increased (decreased) spring rainfall. For the negative-correlation types, the ENSO-IO connection tends to be weak or broken. The significant SSTA appears only in the tropical eastern Pacific, which induces a major vertical motion branch over the maritime continent. As a result, an anomalous lower-level anticyclone (cyclone) occurs over the Asian continent (west of Taiwan) during the El Niño (La Niña) event. Flows east of this anomalous anticyclone (cyclone) weaken (strengthen) moisture transport from the South China Sea into Taiwan, leading to suppressed (enhanced) spring rainfall.

It is also noted that the variability of the Pacific subtropical high (PSH) over the western Pacific is closely linked to these four relationship types. The EN-d (LN-w) type concurs with a moderate westward expansion (eastward retreat) in the western-Pacific sector, while the EN-w (LN-d) type is concurrent with a southward (great eastward) displacement.

1. Introduction

In Taiwan, rainfall in February, March, and April (FMA) is conventionally referred to as spring rainfall in connection with the rice growing season during spring. Its appearance signifies the transition from the winter dry season into the warm rainy season. Insufficient spring rainfall may prolong and intensify the precedent winter dry condition, leading to various degrees of water supply shortage during the early part of the year. Spring rainfall variability is an important prediction challenge in Taiwan.

In general, the spring climate resembles the winter climate more than the autumn climate (Fleming et al. 1987). As revealed by the climatology (1950–2003) of the National Centers for Environmental Prediction-National Center for Atmospheric Research (NCEP-NCAR) reanalysis data (Kalnay et al. 1996), the spring (FMA) lower-level circulation (Fig. 1a) features a continental high over northern Asia and a Pacific subtropical high (PSH) centering in the eastern subtropical Pacific. The outer flows of the western-Pacific sector of the PSH move warm and moist air along the southeastern coasts of China toward the open oceans south of Japan, leading to northeastward moisture fluxes in these regions (Fig. 1b). These flows encounter cold air from the north to result in frontal activities and rainfall across the regions from the northwestern Pacific along the north flake of the PSH to southeastern China and Taiwan (Fig. 1c). As such, total spring rainfall and its variability become more significant over northern Taiwan than southern Taiwan (Hung et al. 2004).

Jiang et al. (2003) and Chen et al. (2003) found that spring rainfall variability in Taiwan tends to be positively correlated with the preceding winter Niño-3 sea surface temperature (SST). During a strong El Niño event, the appearance of an anomalous lower-level anticyclone over the Philippine Sea and the intrusion of a weak midlatitude front system into the eastern coastal areas of China are jointly responsible for the more frequent occurrence of heavy rainfall events and more amount of rainfall in Taiwan. The anomalous Philippine Sea anticyclone (PSAC; Wang et al. 2001; Wang and Zhang 2002) induces anomalous warm southwesterly flows to enhance moisture transport from the South China Sea into Taiwan and central China, leading to intensified moisture convergence and rainfall activities over there (e.g., Tian and Yasunari 1998; Chang et al. 2000; Zhang and Sumi 2002). East Asia tends to be warmer in winter and wetter in spring during a strong El Niño event (e.g., Ropelewski and Halpert 1987; Tomita and Yasunari 1996; Zhang et al. 1996). The appearance of the PSAC indicates the intensification of the PSH (e.g., Wang et al. 2000; Lu 2001). This intensification is affected by convective anomalies in warm pool and SST anomalies over the Pacific (e.g., Nitta 1987; Lu and Dong 2001). These results suggest that El Niño-Southern Oscillation (ENSO) may affect spring rainfall in Taiwan via its related variability in SST, convection, and lower-level circulations over the Pacific.

On the other hand, Chen et al. (2002) analyzed the El Niño events (defined by Trenberth 1997) during the period of 1970-98, and found that spring rainfall in Taiwan can be either enhanced or suppressed by these events. The El Niño event associated with the above-normal spring rainfall in Taiwan is comparable in case number to that associated with the near-normal or below-normal spring rainfall. However, the increased amount of rainfall (with respect to the long-term mean) is, in average, much larger in amplitude than the decreased amount. These features suggest that the El Niño-spring rainfall relationship in Taiwan is more complicated than that revealed by a simple correlation analysis.

The main purpose of this study is to examine the complex ENSO-spring rainfall relationship in Taiwan and associated large-scale dynamic processes. The asymmetry of the spring rainfall relationship with El Niño and La Niña was not fully investigated before and thus needs to be explored. Major questions to be addressed are as follows:

- What are the major relationship types between spring rainfall in Taiwan and ENSO?
- If ENSO can either enhance or suppress spring rainfall in Taiwan, what are the major differences in SST anomaly (SSTA) features? What are the corresponding large-scale ocean-atmosphere processes that convey ENSO's impacts on spring rainfall in Taiwan?
- What is the associated PSH variability in different relationship types?

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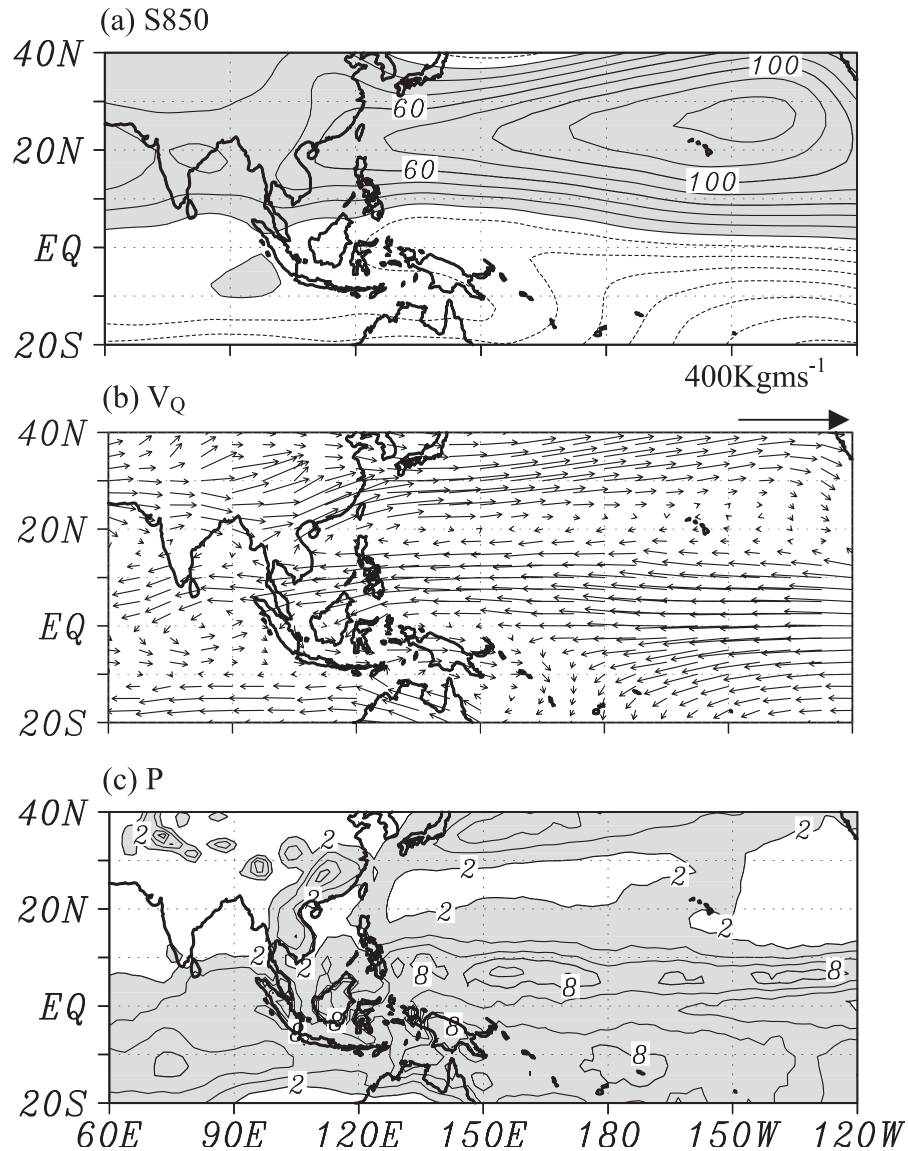

Fig. 1. The 1950–2003 spring (February–April) climatology: (a) the lower-level circulation represented by 850-mb streamfunction, (b) vertically-integrated moisture flux, and (c) precipitation. In (a), contour intervals are 20×10^5 m^2 s^{-1} and positive values are shaded. In (c), contour intervals are 2 mm day^{-1} and values larger than 2 mm day^{-1} are shaded.

Answers to these questions would help us to better understand how ENSO affects the East Asian climate, and to advance the climate prediction tasks in these regions.

2. Data

Three monthly-mean datasets are analyzed in this study. The first dataset includes rainfall records from 10 major meteorological stations in Taiwan. These data are used to portray the variability characteristics of spring rainfall in Taiwan. The second dataset is the global SST data reconstructed with the Empirical Orthogonal Functions analysis (Reynolds and Smith 1995; Smith et al. 1996), which is in a $2° \times 2°$ grid. The SST data are utilized to delineate how ENSO causes different types of spring rainfall variability in Taiwan. The third dataset is the NCEP-NCAR reanalysis data (Kalnay et al. 1996), which is hereafter referred to as the reanalysis data. It includes tropospheric

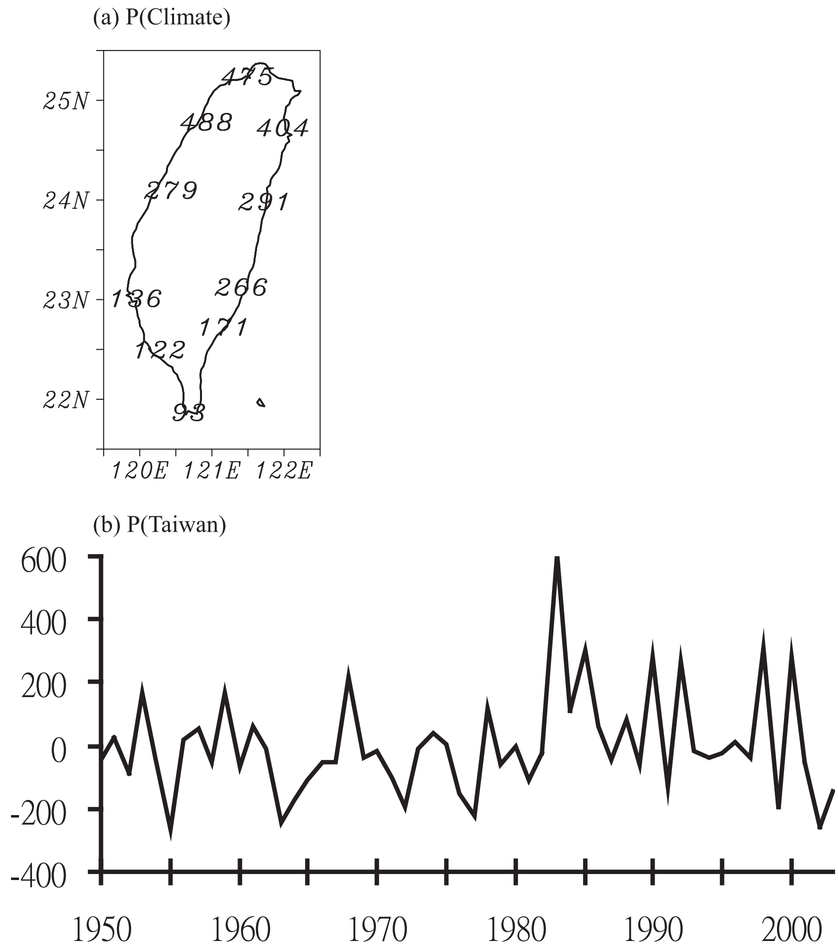

Fig. 2. The 1950–2003 (a) climatological mean of total spring rainfall at 10 major stations in Taiwan, and (b) anomaly time series of total spring rainfall averaged from the five northern stations (north of 23.5 °N). Unit: mm.

wind, vertical motion, precipitation, and moisture fields. These data at a 2.5° × 2.5° grid are employed to illustrate the atmospheric processes conveying ENSO's impacts on spring rainfall in Taiwan. This study analyzes the period of 1950–2003, aiming at obtaining as many sample cases as possible. The spring season hereafter refers to the months of February, March, and April.

3. The ENSO-spring rainfall relationship

Maximum spring rainfall appears over northern Taiwan, as revealed from the 1950–2003 climatology at 10 major stations in Fig. 2a. An index of averaged rainfall from five stations over northern Taiwan (north of 23.5°N) is constructed to study the ENSO-spring rainfall relationship. During 1950–2003, this spring rainfall index has a long-term mean of 387 mm and a standard deviation (SD) of 164 mm. Its anomaly time series is shown in Fig. 2b. The year with rainfall anomaly deviated from the long-term mean more than 55 mm (about 1/3 SD) is selected as the evident spring rainfall event. The major ENSO event is defined as the year with Niño-3.4 SST variability larger than 0.5°C in the precedent winter (December–January) and larger than 0.2°C in the spring. These criteria assure that the selected ENSO cases have SST anomalies significant enough in spring to influence Taiwan's rainfall. The above measures conclude 15 evident spring rainfall years in northern Taiwan associated with ENSO. These years exhibit four ENSO-spring rainfall relationship types (Table 1): El Niño-anomalous wet (EN-w) type, La Niña-anomalous dry (LN-d) type, El Niño-anomalous dry (EN-d)

Table 1. Four major relationship types between ENSO and spring (February–April) rainfall variability in Taiwan during 1950–2003: their associated member years, Niño-3.4 SST anomalies in the precedent winter (December–January) and spring (February–April) of that year, and spring rainfall anomalies averaged from five stations over northern Taiwan.

year	Niño3.4 SST(DJ)	Niño3.4 SST(FMA)	Taiwan P(FMA)	type	group
1983	2.25	1.39	604	EN-w	Positive correlation
1992	1.60	1.43	268		
1998	2.23	1.43	311		
AVG	2.03	1.42	394		
1955	–0.97	–0.58	–267	LN-d	
1971	–1.24	–1.13	–100		
1976	–1.78	–0.75	–150		
1989	–1.64	–1.00	–57		
1999	–1.29	–0.73	–201		
AVG	–1.38	–0.84	155		
1952	0.68	0.40	–86	EN-d	Negative correlation
1977	0.78	0.22	–222		
1991	0.53	0.35	–131		
2003	1.03	0.50	–147		
AVG	0.76	0.37	–147		
1968	–0.50	–0.62	217	LN-w	
1985	–0.87	–0.67	301		
2000	–1.38	–0.87	283		
AVG	–0.92	–0.72	–267		
Unit	°C	°C	mm		

type, and La Niña-anomalous wet (LN-w) type. The EN-w and LN-d types contain a positive correlation between the ENSO SSTA and spring rainfall variability and are thus categorized as the positive-correlation group, while the EN-d and LN-w types are sorted as the negative-correlation group. Note that El Niño and La Niña can either enhance or suppress spring rainfall in northern Taiwan. For the period of 1950–2003, the simultaneous correlation coefficient between the spring rainfall index and Niño-3.4 SST is 0.28, which exceeds 90% statistical significance level (> 0.23). The overall ENSO-spring rainfall relationship is dominated by the positive correlation.

Composite anomalies of spring rainfall in Taiwan corresponding to the four relationship types are shown in Fig. 3. The rainfall anomaly that is significant at the 90% level is underlined. In general, spring rainfall anomalies are more significant and much larger over northern Taiwan than southern Taiwan. Regardless of statistical significance, composite anomalies tend to be uniform in sign over the entire island in the EN-w, EN-d and LN-d types. The island-wide pattern suggests possible role of the large-scale background ocean-atmosphere processes in controlling climate variability in Taiwan (e.g., Hsu and Chen 2002; Chen et al. 2005).

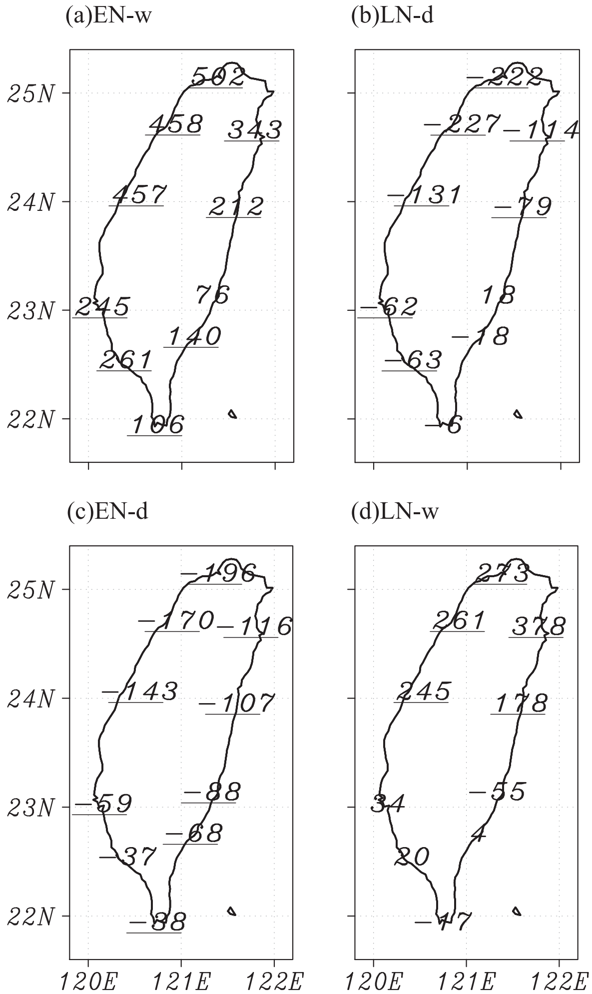

Fig. 3. Composite anomalies of total spring rainfall in Taiwan corresponding to the four major relationship types: (a) EN-w, (b) LN-d, (c) EN-d, and (d) LN-w. Rainfall anomalies significant at the 90% level are underlined. Unit: mm.

4. Large-scale dynamic processes

4.1 ENSO-associated SST anomaly

The first question related to large-scale control is how ENSO-associated SST anomalies modulate spring rainfall in Taiwan. For each of the positive- and negative-correlation groups, composite SST anomalies of its two member types exhibit, to a large extent, opposite spatial characteristics (not shown). As such, composite difference anomalies for these two groups are analyzed in this study. This difference method allows us to have more sample cases, as well as higher statistical robustness, in the composite analysis than that only using the individual type. Figure 4 displays composite SST difference anomalies for the positive- (EN-w minus LN-d) and negative-correlation (EN-d minus LN-w) groups. Hereafter, the difference anomaly exceeding 90% significance level is shaded. Composite SST difference anomalies of these two groups contain a common El Niño feature as a strong and elongated warm SSTA in the tropical eastern Pacific. Their major discrepancies appear in two features: 1) a significant warm anomaly in the IO concurrent with the El Niño feature in the positive-correlation group, but not in the negative-correlation group; 2) ENSO-related SST anomalies stronger in the positive-correlation group than in the negative-correlation group.

Kug and Kang (2006) and Kug et al. (2006) pointed out that the appearance (disappearance) of significant in-phase IO SST anomalies during the ENSO event indicates the occurrence (absence) of a strong connection between ENSO and the IO. The coupled atmosphere-ocean general circulation model experiments revealed that the ENSO simulation forced by both the tropical Indian and Pacific Oceans tends to have stronger variability than that forced by the tropical Pacific only (Yu et al. 2002; Wu and Kirtman 2004). These results suggest that the occurrence of the ENSO-IO connection and the subsequent feedback from the IO onto ENSO is likely to enhance the ENSO intensity. Table 1 shows that all the eight cases in the positive-correlation group have a winter Niño-3.4 SSTA magnitude near or larger than 1°C, but only two out of seven cases in the negative-correlation group reach that magnitude. The presence of a strong Niño SSTA and a significant IO SSTA in Fig. 4a suggests that the positive-correlation group tends to concur with an ENSO-IO connection. On the contrary, this connection is likely to be weak or inappreciable in the negative-correlation group. The statistical significance of the SSTA difference in the positive-correlation group is higher in both the tropical Indian Ocean and eastern Pacific than that in the negative-correlation group. Impacts of these two groups on spring rainfall in Taiwan are analyzed below in terms of the atmospheric dynamic and hydrological processes.

4.2 Atmospheric dynamic processes

Equatorial SST anomalies can affect the overlying atmosphere via the modulation of Walker circulation (e.g., Wang 1992; Klein et al. 1999; Chen

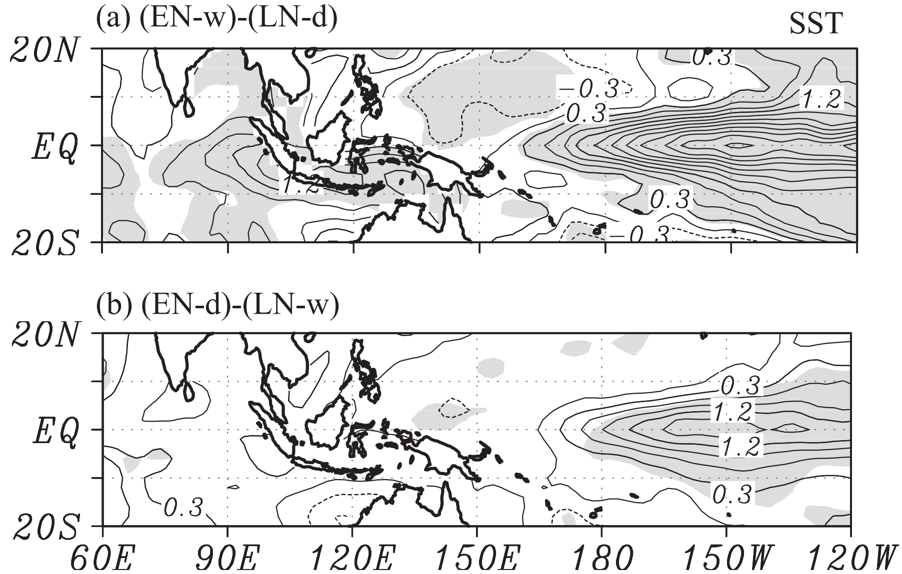

Fig. 4. Composite difference patterns of SST anomalies for (a) the positive-correlation group (EN-w minus LN-d), and (b) the negative-correlation group (EN-d minus LN-w) of spring rainfall variability in Taiwan. Contour intervals are 0.3°C. Shading indicates areas where SST difference anomalies are significant at the 90% level.

and Lu 2000). This modulation is also a major mechanism conveying ENSO's impacts on the IO (e.g., Lau and Nath 2000, 2003; Krishnamurthy and Kirtman 2003; Li et al. 2003, 2006). The Walker circulation may be expressed by a mass flux function $\psi_m = \int_p^{p_0} u_d dp$ (Newell et al. 1974), where u_d is the zonal divergent wind and the vertical integral is from a given pressure level to $p_0 = 1000$ mb. A positive (negative) ψ_m cell indicates a two-dimensional counterclockwise (clockwise) motion when viewed from the south.

Composite difference anomalies for ψ_m and vertical motion at 500 mb (Ω500) along the equator are shown in Fig. 5. The positive-correlation group exhibits two significant and well-organized ψ_m anomalies (Fig. 5a), including a positive cell to the east of 150°E and a negative cell to the west. These ψ_m anomalies generate a major descending branch over the western Pacific (120°–160°E), as revealed by Ω500 anomalies in Fig. 5b. Accompanied ascending branches include a dominant one over the eastern Pacific (150°–120°W) and a moderate one over the eastern IO (90°–105°E), where significant warm tropical SST anomalies exist (see Fig. 4a). Tropical SST anomalies in both the eastern Pacific and the IO jointly exert impacts on the tropical western Pacific via Walker circulation variability. This feature also indicates the existence of an ENSO-IO connection in the positive-correlation group. For the negative-correlation group, a significant and well-organized positive ψ_m anomaly exists in the tropical western Pacific (Fig. 5c). Its ascending branch, as revealed by Ω500 anomalies in Fig. 5d, is prominently strong over the tropical central Pacific to the east of the date line, in association with an underlying warm SSTA (see Fig. 4b). The accompanied descending branch is somewhat weak and scatters over the tropical western Pacific. Moreover, no noticeable vertical motion occurs in the IO, implicating a weak or indiscernible ENSO-IO connection in the negative-correlation group. The above analyses disclose that the tropical western Pacific is mainly affected by the eastern Pacific SSTA in the negative-correlation group, but under the combined influence of the IO and ENSO SST anomalies in the positive-correlation group.

Variations in Walker circulation between the positive- and negative-correlation groups signify a change in tropical forcing between them. Impacts of tropical forcing variability onto the lower-level large-scale circulation may be diagnosed in terms of 850-mb velocity potential (*X*850) and streamfunction (*S*850) anomalies. For the positive-correlation group, composite *X*850 difference anomalies (Fig. 6a) characterize a significant divergence

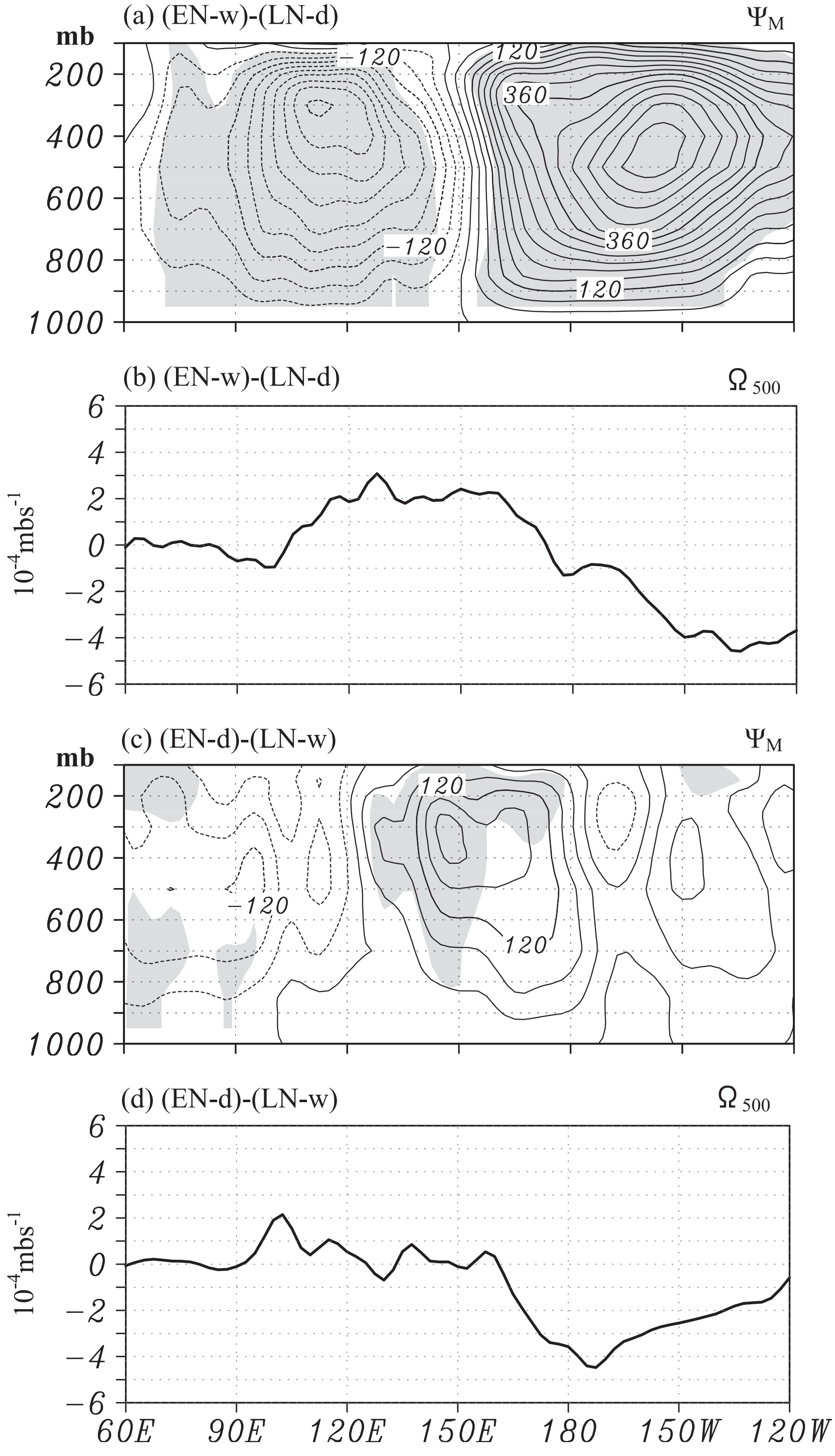

Fig. 5. As in Fig. 4, but for composite difference anomalies of (a) vertically-integrated mass flux function (ψ_m) from 100 mb to 1000 mb and (b) vertical motion at 500 mb (Ω500) along the Equator for the positive-correlation group. ψ_m and Ω500 anomalies for the negative-correlation group are shown in (c) and (d), respectively. Contour intervals in (a) and (c) are 40 m s^{-1} mb.

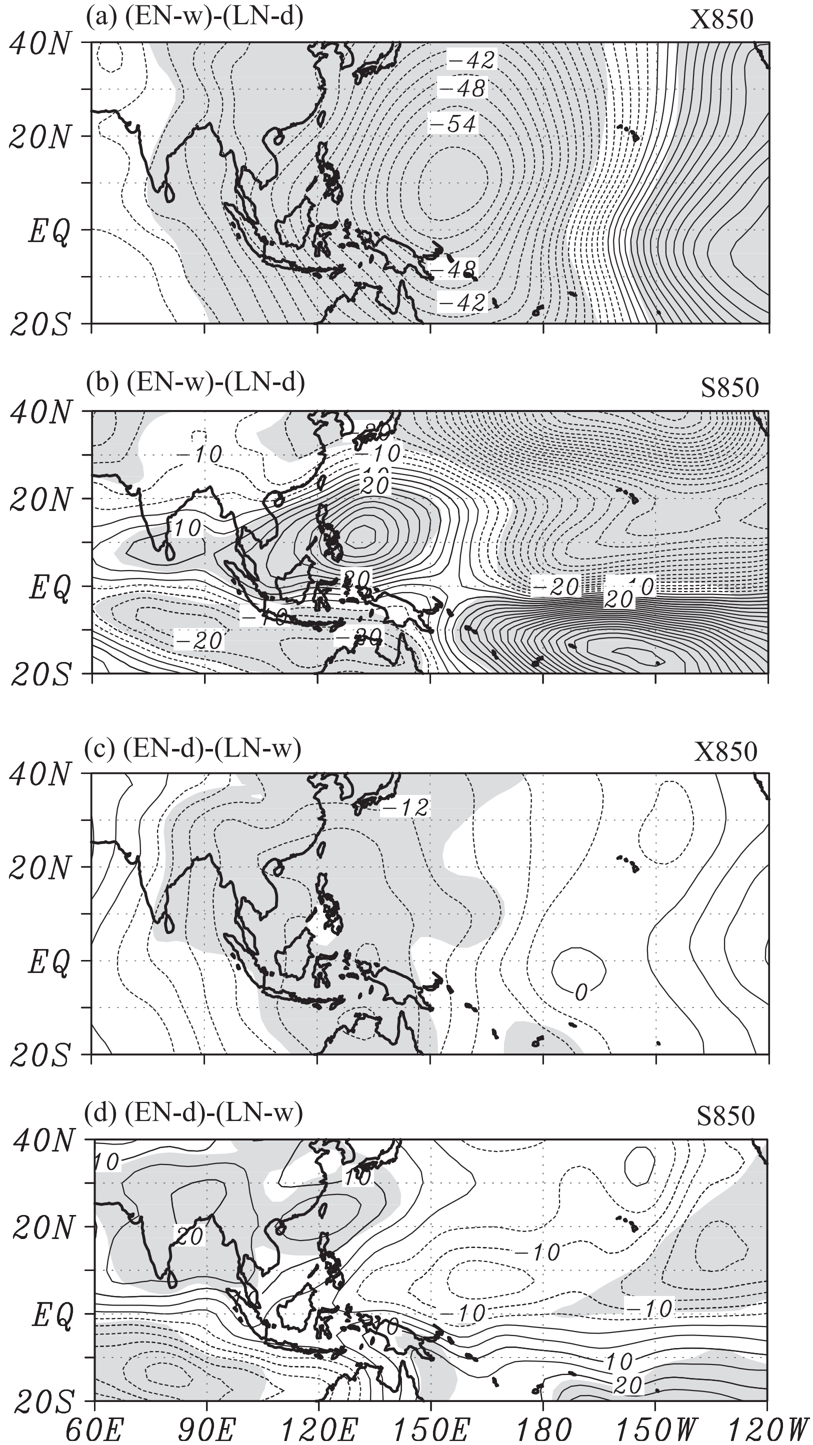

Fig. 6. As in Fig. 4, but for composite difference anomalies of 850-mb (a) velocity potential (X850) and (b) streamfunction (S850) for the positive-correlation group. X850 and S850 anomalies for the negative-correlation group are shown in (c) and (d), respectively. Contour intervals are 3×10^5 m^2 s^{-1} in (a) and (c) and 5×10^5 m^2 s^{-1} in (b) and (d).

anomaly over the tropical western Pacific. Its center is located near 155°E and spatially coincident with the major descending ψ_m branch in Fig. 5a. The anomalous descending (ascending) tropical forcing can excite a Matsuno-Gill-type circulation pattern (Matsuno 1966; Gill 1980), which consists of a twin pair of anticyclonic (cyclonic) circulations straddling the equator to its west side, as a Rossby wave response. The Matsuno-Gill-type circulation patterns stand out in the composite $S850$ difference anomalies in Fig. 6b. There is a pair of anomalous anticyclones (cyclones) to the west (east) of the anomalous divergence center near 155°E. Taiwan is located to the northwest of the anomalous Philippine Sea anticyclone (PSAC; Wang et al. 2001; Wang and Zhang 2002). Its spring climate is mainly modulated by the Philippine Sea circulation anomaly in the positive-correlation group. For the negative-correlation group, the significant $X850$ difference feature is an anomalous divergence center over the maritime continent (Fig. 6c), which is spatially consistent to the major downward ψ_m branch in Fig. 5c. An associated Matsuno-Gill-type circulation pattern appears in $S850$ anomalies in Fig. 6d. Its significant feature which may affect spring climate in Taiwan is an anomalous anticyclone over the Asian continent. Taiwan is underneath its eastern sector.

Figure 6 depicts that spring climate in Taiwan is affected by a lower-level circulation anomaly centering over the Philippine Sea in the positive-correlation group, but by one centering over the Asian continent in the negative-correlation group. According to the linear model experiments by Watanabe and Jin (2002), a lower-level Matsuno-Gill-type pattern featuring an anomalous anticyclone over Asia is mainly forced by the tropical Pacific SST anomalies (see their Fig. 2c), while one characterizing the anomalous PSAC is jointly forced by SST anomalies in both the tropical Pacific and IO (see their Fig. 2d). These numerical experiments support the notion that the presence of the anomalous PSAC in the positive-correlation group is likely a result of the ENSO-IO connection. On the contrary, the anomalous anticyclone over the Asian continent in the negative-correlation group tends to be a response to the anomalous Indonesia heat sink in association with the sole tropical Pacific SSTA forcing.

4.3 Atmospheric hydrological processes

The Asian monsoon rainfall variability is strongly affected by moisture transport of the large-scale circulation anomalies (e.g., Fasullo and Webster 1999; Simmonds et al. 1999; Lau et al. 2000; Fasullo 2005). Impacts of circulation variability on spring rainfall in Taiwan are thus portrayed in terms of atmospheric hydrological processes. Atmospheric moisture transport can be depicted by vertically-integrated water vapor flux ($\overrightarrow{V_Q} = \int_p^{p_0} \vec{V} q \, dp$, where $\vec{V}$ is the horizontal wind vector, q is the specific humidity, and the vertical integral is from a given pressure level to $p_0 = 1000$ mb). This flux field is computed from the monthly-mean data and thus does not include the submonthly components. Composite difference anomalies of $\overrightarrow{V_Q}$ and precipitation (P) are shown in Fig. 7. Major paths of moisture transport may be interpreted from their statistically-significant patterns.

In the positive-correlation group, the significant features include warm SST anomalies in the eastern IO and the South China Sea (see Fig. 4a) and the anomalous PSAC to the southeast of Taiwan (see Figs. 6b and 7a). Both the warm SST and wind speed anomalies enhance the surface evaporation and thus increase the atmospheric boundary layer moisture content southwest of Taiwan. Meanwhile, the anomalous southwesterly flows associated with the PSAC advect the background moisture into Taiwan (see Fig. 1). The anomalous moisture advection by both the mean and anomalous flows thus intensify moisture transport from the moisture-rich South China Sea into Taiwan (Fig. 7a), resulting in significant positive P anomalies stretching from southeastern China and Taiwan into the northwestern Pacific (Fig. 7b). Under this circumstance, the outer flows of the anomalous lower-level Philippine Sea anticyclone (cyclone) in the EN-w (LN-d) type intensify (hinder) moisture transport from tropical oceans into Taiwan, leading to its excessive (deficient) spring rainfall. The important role of this Philippine Sea circulation anomaly in affecting spring rainfall in Taiwan was previously addressed by Chen et al. (2002), Chen et al. (2003), and Jiang et al. (2003). Figure 7b also displays significant negative P anomalies in the regions underneath the center of the anomalous PSAC. In the negative-correlation group, the anomalous anticyclone over the Asian continent generates northeasterly flows to suppress moisture transport from the South China Sea into Taiwan (Fig. 7c), resulting in negative P anomalies extending from the northwestern Pacific into Taiwan and the South China Sea (Fig. 7d). One

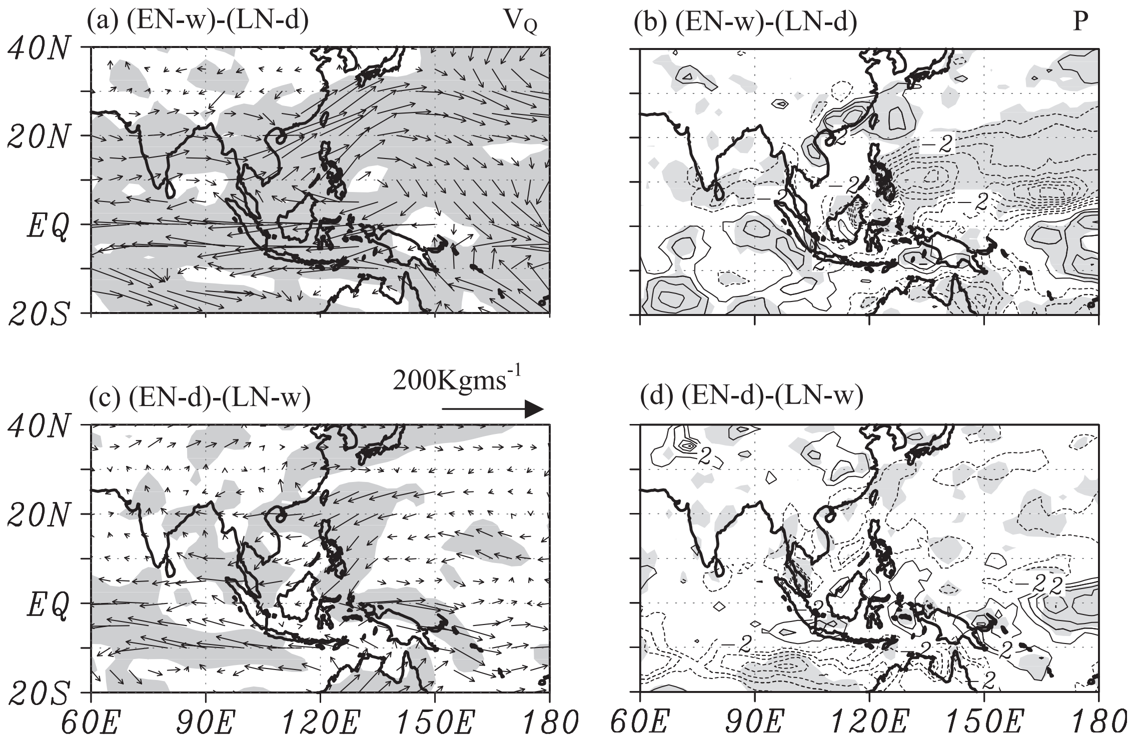

Fig. 7. As in Fig. 4, but for composite difference anomalies of (a) moisture transport (V_Q) and (b) precipitation (P) for the positive-correlation group. V_Q and P anomalies for the negative-correlation group are shown in (c) and (d), respectively. Moisture transport is represented by vertically-integrated water vapor flux from 300 mb to 1000 mb. In (b) and (d), contour intervals are 1 mm day^{-1} and the zero contour is suppressed.

can interpret that the anomalous lower-level anticyclone (cyclone) over the Asian continent in the EN-d (LN-w) type weakens (strengthens) moisture transport from the South Chain Sea into Taiwan, yielding an evident decrease (increase) in Taiwan' s spring rainfall. It is concluded that moisture transport modulated by the lower-level circulation anomaly over Asia or the Philippine Sea acts as the major regulating process for prominent spring rainfall variability in Taiwan during the major ENSO event.

5. Variability of the Pacific subtropical high

The asymmetric ENSO-spring rainfall relationship in Taiwan is depicted to be affected by the lower-level circulation variability over the Asian-western Pacific region, which is generally related to the variability of the PSH (e.g., Lu 2001; Lu and Dong 2001). It is of interest to examine the connection between the four relationship types and the PSH variability over the western Pacific. In the following, the geographical distribution of the PSH is represented by the 75×10^5 m^2 s^{-1} $S850$ contour. Spatial distributions of this contour for the climatology and the four relationship types are illustrated in Fig. 8. Its climatological position (solid line) is just off the southeastern coasts of Taiwan. For the positive-correlation group (Fig. 8a), the presence of the anomalous PSAC in the EN-w type corresponds to a southward shift (about 5 degrees in latitude) in the western-Pacific sector of the PSH. In the LN-d type, the appearance of an anomalous Philippine Sea cyclone indicates a great eastward withdraw in the PSH (about 15 degrees in longitude). For the negative-correlation group (Fig. 8b), this contour expands westward (about 10 degrees in longitude) with respect to the climatology in the EN-d type, but retreats eastward (about 7 degrees in longitude) in the LN-w type. The moderate westward expansion (eastward retreat) of the PSH in the EN-d (LN-w) type is noted by the appearance of an anomalous anticyclone (cyclone) over the Asian continent.

The contour analyses manifest that the western-

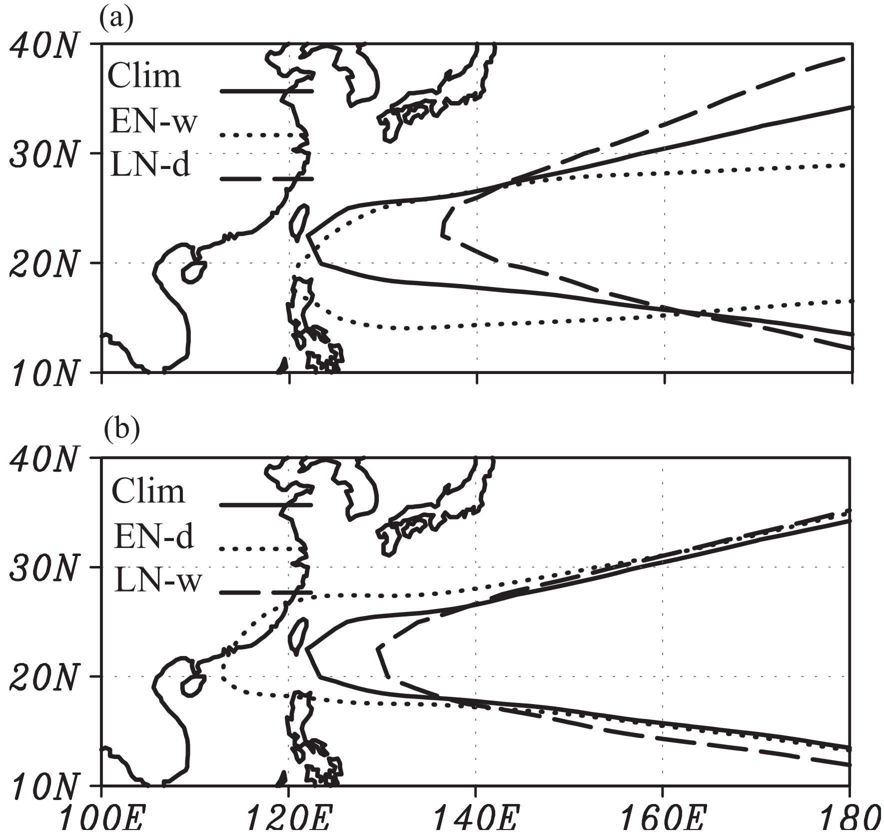

Fig. 8. The 75×10^5 m^2 s^{-1} contours of 850-mb streamfunction for the climatological mean (solid line) and (a) the positive-correlation group (EN-w and LN-d), and (b) the negative-correlation group (EN-d and LN-w).

Pacific sector of the PSH tends to intensify or expand westward (weaken or withdraw eastward) after the El Niño (La Niña) mature phase. This result is consistent with the previous findings (e.g., Chang et al. 2000; Chia and Ropelewski 2002; Zhang and Sumi 2002). The ENSO-spring rainfall relationship in Taiwan can be summarized in terms of the PSH variability as follows. During the spring after the El Niño peak phase, a southward displacement (a moderate westward expansion) of the western-Pacific sector of the PSH tends to induce abundant (deficient) spring rainfall. For the spring ensuing the La Niña mature phase, a moderate (strong) eastward retreat of the PSH over the western Pacific tends to enhance (suppress) spring rainfall.

6. Concluding remarks

Spring (February–April) rainfall in Taiwan can either increase or decrease during the El Niño or La Niña events, revealing a complicate ENSO-rainfall relationship. An attempt is made in this study to comprehensively investigate such asymmetric ENSO-spring rainfall relationships, with a focus on the role of large-scale regulating processes induced by ENSO on Taiwan climate. The associated variability features of the Pacific subtropical high (PSH) are also examined.

Spring rainfall in northern Taiwan and ENSO exhibit four major relationship types during 1950–2003: El Niño-anomalous wet (EN-w) type, La Niña-anomalous dry (LN-d) type, El Niño-anomalous dry (EN-d) type, and La Niña-anomalous wet (LN-w) type. The EN-w and LN-d types are classified as the positive-correlation group due to the positive correspondence between the ENSO SST and spring rainfall anomalies. The EN-d and LN-w types are sorted as the negative-correlation group. The overall ENSO-spring rainfall relationship is dominated by the positive correlation.

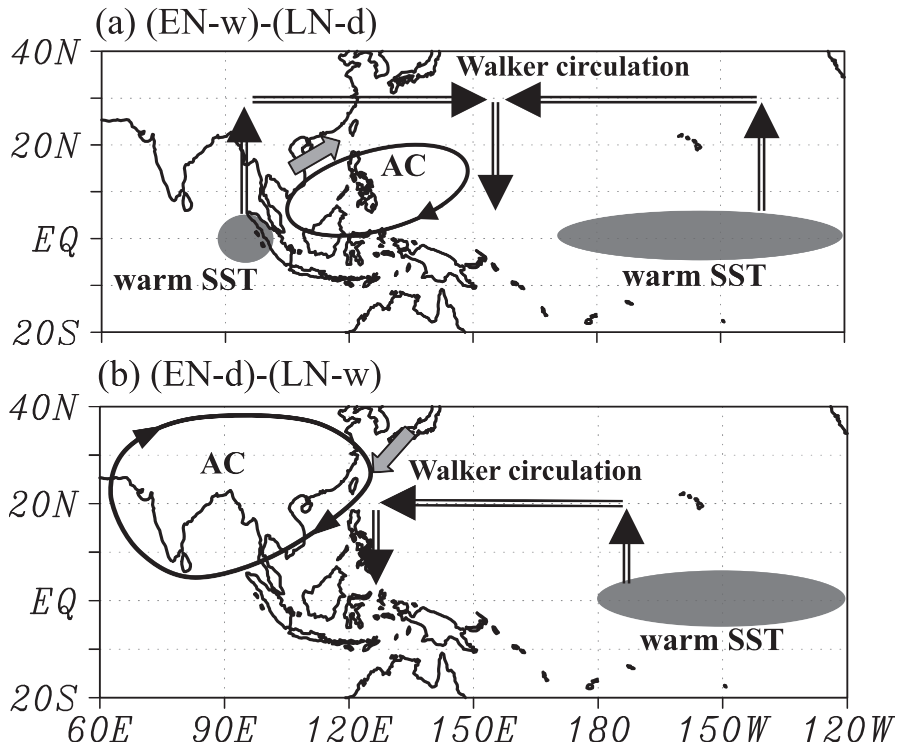

Fig. 9. Schematic illustration for the major regulating processes imposed by the ENSO-related SST anomalies on spring rainfall variability in Taiwan: (a) the positive-correlation group, and (b) the negative-correlation group.

Major large-scale regulating processes for spring rainfall in Taiwan are illustrated by schematic diagrams in Fig. 9. The positive-correlation group (Fig. 9a) is interpreted from the difference between the EN-w and LN-d types (EN-w minus LN-d). Significant warm SST anomalies occur in the tropical eastern Pacific and eastern IO, indicating the occurrence of an ENSO-IO connection. The combined El Niño and IO SSTA forcing constraints the descending branch of the Pacific Walker circulation over the western Pacific. This subsidence acts to modulate tropical convection and diabatic heating, and initiates and maintains a lower-level anomalous anticyclone over the Philippine Sea. The anomalous southwesterly flows to the west of the anticyclone enhance moisture transport from the South China Sea into Taiwan, leading to an evident increase in spring rainfall. The negative-correlation group (Fig. 9b) is represented by the difference between the EN-d and LN-w types (EN-d minus LN-w). A major warm SSTA exists in the tropical eastern Pacific, while no significant SSTA appears in the IO. The ENSO-IO connection tends to be weak or indiscernible in this group. This sole Pacific SSTA forcing induces a major descending branch over the maritime continent, which is accompanied by a lower-level anomalous anticyclone to its northwestern side over the Asian continent. Anomalous northeasterly flows to the eastern edge of this anticyclone weaken moisture transport from the South China Sea into Taiwan, leading to an apparent decrease in spring rainfall. The regulation processes of the LN-d (LN-w) type are largely opposite in polarity to those of the EN-w (EN-d) type.

It is also found that the complex ENSO-spring rainfall relationship is related to the variability of the PSH over the western Pacific. In general, the PSH tends to intensify (weaken) after the peak El Niño (La Niña) phase. For the negative-correlation group, the EN-d (LN-w) type concurs with a moderate westward expansion (eastward retreat) in the western-Pacific sector of the PSH, marked by the appearance of an anomalous lower-level anticyclone (cyclone) over the Asian continent. For the positive-correlation group, the EN-w (LN-d) type coincides with the appearance of an anomalous lower-level anticyclone (cyclone) over the Philippine Sea, which corresponds to a southward (great eastward) displacement of the PSH.

According to the Matsuno-Gill solution, a direct circulation response to the tropical diabatic heating anomaly is confined within 10–15 degrees of latitude in the tropics. These circulation anomalies may modulate extratropical moisture transport and affect convective activity there. As such, the extratropical convective and rainfall activities may be indirectly affected by ENSO-related tropical SST anomalies, as illustrated in Fig. 9. In studying the ENSO-East Asian teleconnection, Wang et al. (2000) suggested a local positive air-sea feedback among a cold SSTA, suppressed convection, and an anomalous anticyclone over the Philippine Sea/western North Pacific, lasting from northern winter to early summer. The initial triggering of a cold SSTA in the region may arise from the atmospheric Rossby wave response to El Niño heating in the tropical central Pacific. Anomalous subsidence associated with the combined eastern Pacific and IO SSTA forcing may also trigger the similar positive feedback by inducing a lower-level anomalous anticyclone near the Philippine Sea, which further maintains itself through interacting with a cold SSTA generated to its east side. A moist-convective feedback model experiment by Watanabe and Jin (2002) supports the notion that SST anomalies in both the tropical eastern Pacific and IO significantly affect the circulation anomaly over the Philippine Sea/western Pacific.

A careful examination of individual cases reveals that eight out of nine member years in the positive-correlation group are noticed by the co-existence of prominent in-phase tropical SST anomalies in the eastern Pacific and eastern IO. The year of 1999 is exceptional. Its SST anomalies exhibit an opposite phase between the eastern Pacific and the IO. The ENSO-IO connection tends to be weak or indiscernible in the negative-correlation group. Five out of seven member years have a relatively weak IO SSTA or a reversed phase in SST anomalies between the eastern Pacific and the IO. The years of 1968 and 2003 are exceptional, which have in-phase SST anomalies in the eastern Pacific and IO. These results indicate that the East-Asian climate variability is not solely determined by tropical SST anomalies. The mechanisms related to extratropical processes or atmospheric internal dynamics may also play a role (e.g., Wang and Zhang 2002; Chen et al. 2003). In other words, some mechanisms other than tropical SSTA forcing are possibly involved in the regulation processes for the ENSO-spring rainfall relationships. These mechanisms should be explored in the future research.

Findings in this study may provide potentially useful information for the climate prediction over East Asia. It is found that the appearance of the lower-level Philippine Sea circulation anomaly is closely related to evident spring rainfall variability in Taiwan. This circulation anomaly was found to move eastward across the IO into the South China Sea during fall and anchor in the Philippine Sea during winter (Chen et al. 2007). Such developing processes allow us to detect the occurrence of the Philippine Sea circulation anomaly at least one to two seasons prior to spring. The development of the Philippine Sea circulation anomaly appears as a useful monitoring feature for the short-term climate prediction of spring rainfall in Taiwan during the ENSO periods. Another useful monitoring feature is the variability feature of the PSH over the western Pacific. Its intensification, weakening, and meridional displacement may be utilized to predict Taiwan's spring rainfall variability.

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