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Quasi-four-year Coupling between El Niño-Southern Oscillation and Water Vapor Transport over East Asia-WNP

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ABSTRACT

Summer moisture circulation anomaly over East Asia and the western North Pacific (WNP) couples well with the El Niño-Southern Oscillation (ENSO) in a quasi-four-year period. The moisture circulation is dominated by two well-separated modes. The first mode exhibits an anticyclonic (cyclonic) moisture circulation over tropical-subtropical East Asia-WNP, with an easterly (westerly) transport over the tropical WNP-Indian Ocean; the second mode displays an alternating pattern, with an anticyclonic (cyclonic) moisture circulation over the subtropical WNP layered between two cyclonic (anticyclonic) circulations. Both modes couple well with the ENSO signal during its quasi-four-year cycle. Within the cycle, in the summer of a developing warm episode, the positive phase of the second mode plays a key role, while in the transitional summer between a decaying warm episode and a developing cool episode, the positive phase of the first mode tends to take effect. In the summer of a developing cool episode, the negative phase of the second mode plays an important role, while the negative phase of the first mode tends to take effect in the transitional summer between a decaying cool episode and a developing warm episode.

The anticyclone (cyclone) over the Philippine Sea region serves as a bridge in the quasi-four-year coupling. Its establishment and eastward extension modify moisture circulation over East Asia-WNP. Conversely, the easterly (westerly) wind to the south of the anticyclone (cyclone) is beneficial for the formation and eastward propagation of the Kelvin wave hence to the development of the quasi-four-year periodic ENSO episode.

1. Introduction

Variability in precipitation has long resulted in either severe floods or droughts, which bring devastating impacts to regional societies and economies (Ding 1992; Kripalani and Kulkarni 2001). The amount of precipitation over a region is determined to some extent by the available moisture; it will not rain at all unless there is a sufficient supply of moisture. Generally, precipitation over any region is derived from two moisture sources: local evaporation and externally advected moisture. It is stated by Benton et al. (1950) and Budyko (1974) that even on the most extensive continents where the relative role of local evaporation is maximized, the majority of precipitation is derived from water vapor of external origin rather than from local evaporation. Hence, the transportation of water vapor by atmospheric circulation plays a vital role in determining rainfall patterns.

Water vapor transport over East Asia is extremely complex and energetic. It is dominated jointly by the western Pacific subtropical high (WPSH) and three Asian summer monsoon subsystems: the southwest summer monsoon, the southeast summer monsoon, and the East Asia summer monsoon (EASM), all of which display pronounced year-to-year variation (e.g., Chen et al. 1992; Murakami and Matsumoto 1994; Ueda and Yasunari 1996; Wang et al. 2008). Because it is mainly advected by the monsoon flow, water vapor transport over East Asia also exhibits remarkable annual variability (e.g., Simmonds et al. 1999; Zhou and Yu 2005). Though the climatic mean moisture transport over East China is primarily from the Indian Ocean, the water vapor associated with the anomalous precipitation is derived from the western Pacific Ocean instead (Simmonds et al. 1999). Investigation had disclosed that when the Mei-Yu/Baiu rain band was heavier than normal, the anomalous flows originated from the Philippine Sea; when the heavier rain band shifted northward, the anomalous flows came from the East China Sea (Zhou and Yu 2005). Year-to-year variations in westerly moisture transport from the Indian Ocean and southerly moisture transport across the equator had also been investigated, and these variations had been shown to be closely related to different types of precipitation over the western North Pacific (WNP; Hattori et al. 2005, Zhou et al. 2009a). Hence, tying to anomalous precipitation patterns, the moisture circulation over East Asia-WNP experiences remarkable interannual variation.

It was pointed out by a number of recent studies that El Niño-Southern Oscillation (ENSO) exhibited a remarkable influence on the interannual variability of the climate over East Asia (e.g., Huang and Wu 1989; Zhang et al. 1996; Feng et al. 2010, 2011). During different stages of the ENSO cycle, sea surface temperature (SST) anomalies in the tropical Pacific have different impacts on the summer monsoon and thus the summer rainfall pattern over East Asia-WNP (Yang et al. 2004). In the summer of a developing El Niño event, the EASM is weak and above-normal monsoon rainfall is observed in the Yangtze River and Huaihe River valleys, while below-normal rainfall takes place to the south and the north. During the summer of a decaying El Niño event, the EASM tends to be strong and severe flooding may occur to the south of the Yangtze River, while there may be drought in the Yangtze River and Huaihe River valleys. Similarly, La Niña events can also strongly affect the monsoon and rainfall over East Asia, but in the opposite direction (e.g., Huang and Zhou 2002; Huang et al. 2004; Chen 2002). In the study of the mechanisms of ENSO-East Asia climate interaction, an anomalous lower-tropospheric anticyclone was found to develop rapidly over the WNP in the late fall of the year when a strong El Niño event matured (Wang et al. 2000). The anomaly persisted until the ensuing summer, resulting in an enhanced subtropical high, which in turn carried abundant moisture from the WNP to East Asia, causing above-normal rainfall over the middle latitudes extending from the Yangtze River valley to the east of Japan (Zhang 2001). Concurrently, warming in the tropical Indian Ocean acted like a capacitor anchoring atmospheric anomalies over the Indo-western Pacific Ocean. It caused a baroclinic Kelvin wave, which induced suppressed convection and the anomalous anticyclone in the subtropical northwest Pacific (Xie et al. 2009). In a La Niña event, the opposite pattern will be found. Hence, significant variation in the atmospheric circulation over East Asia-WNP may occur during different stages of the ENSO cycle, which may significantly affect the transport and divergence of moisture.

It is explored that the ENSO's period varies irregularly between 2 and 7 years, with a quite robust average of around 4 years (Macmynowski and Tziperman 2008; Climate Prediction Center 2005). Multichannel singular spectrum analysis (M-SSA) was applied to the equatorial sea surface temperature anomaly (SSTA) and zonal wind (Jiang et al. 1995). It was shown that the quasi-biennial (QB) mode together with the quasi-quadrennial (QQ) mode provided a very good approximation to ENSO events. Although the QQ mode was more fundamental and dominated the variance, more attention had been paid to the QB mode (Rasmusson et al. 1990, Ropelewski et al. 1992). Hence, to investigate an area lacking in previous research, this study focuses mainly on the coupling between the interannual variation of summer moisture circulation over East Asia-WNP and ENSO events during a quasi-four-year period.

In section 2, the datasets and methodology used in this study are described. The spatial and temporal variations of summer moisture circulation over East Asia-WNP are investigated in section 3. In section 4 the quasi-four-year coupling between ENSO and water vapor transport over East Asia-WNP and the possible mechanisms maintaining this coupling are revealed. Cases studies of this quasi-four-year coupling are examined in section 5. Our discussion and conclusions are presented in section 6.

2. Data and methodology

In this study, the 1979–2009 Japanese 25-year Reanalysis Project (JRA-25) dataset [1] is applied. The JRA-25 products have a spectral resolution of T106 (equivalent to a horizontal grid size of around 120 km), and 40 vertical layers in a hybrid sigma-pressure coordinate. This dataset provides the foundation for a high-quality analysis of the Asian region. In addition to conventional surface and upper air observations, precipitable water retrieved from orbital satellite microwave radiometer radiance, brightness temperature from the TIROS Operational Vertical Sounder (TOVS), and other satellite data were assimilated using a three-dimensional variational method in the dataset. A detailed description can be found in Onogi et al. (2007). The variables employed are monthly special humidity, wind fields, and vertically integrated water vapor flux.

To determine the relationship between the sea surface temperature and moisture transport, the monthly extended reconstructed sea surface temperature version 3b (ERSST V3b; Smith et al. 2008), with a resolution of 2° latitude × 2° longitude, was employed. The Oceanic Niño Index (ONI; 3 months running mean of SSTA in the Niño 3 region [5°S–5°N, 120–170°W])[2] was also employed in this study. The time range of these two datasets is from the winter of 1978 to the spring of 2010.

To determine the spatial and temporal patterns of summer moisture circulation over East Asia, real-vector EOF analysis was applied to the vertically integrated water vapor flux anomaly over East Asia-WNP. The principle of the real-vector empirical orthogonal function (R-EOF) technique, applied to two-dimensional vector fields,

[1] http://jra.kishou.go.jp
[2] http://www.cpc.ncep.noaa.gov

(e.g., [u;v]), is presented briefly as follows: first, construct a new 2P × N matrix **U** by adding v to the end of u, that is,

$$U = (u, v) = \begin{bmatrix} u_{11} & u_{12} & \cdots & u_{1N} & v_{11} & v_{12} & \cdots & v_{1N} \\ u_{21} & u_{22} & \cdots & u_{2N} & v_{21} & v_{22} & \cdots & v_{2N} \\ \vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \ddots & \vdots \\ u_{P1} & u_{P2} & \cdots & u_{PN} & v_{P1} & v_{P2} & \cdots & v_{PN} \end{bmatrix}_{2P\times N} .$$

where P is the total number of grid points, and N is the total number of time points. Then calculate the eigenvectors, eigenvalues, and the corresponding principal components (PCs) of **U** using EOF analysis. More details can be found in Kaihatu et al. (1998) and Marmorino et al. (1999).

3. Dominant modes of moisture circulation

The first two leading modes of the vertically integrated water vapor flux anomaly over East Asia-WNP (90–150°E, 5–45°N) based on the JRA-25 reanalysis dataset will be investigated in detail (Fig. 1). They are well separated according to North et al. (1982). Together, these two modes account for more than 57% of the total variance and therefore explain a large percentage of the variation in water vapor transport over East Asia-WNP. To militate against the possible reliance of the EOF technique on the particular study area and period, as well as the uncertainty within the dataset, the ECMWF 40 Year Re-analysis (ERA-40) dataset is also applied to the EOF analysis over the same region, as well as over a larger region, and over an expanded time period of 1958–2002 (figures not shown). Though focusing on different domains and time spans, the results based on ECMWF ERA-40 dataset are similar to those in our study.

The first dominant mode (EOF1) captures 43% of the total variance, exhibiting an extensive anomalous moisture circulation over the WNP. When the corresponding principal component (PC1) is positive, a strong easterly water vapor transport band dominates between around 5–20°N over the WNP. This transport band is separated into two branches to the east of Indochina. One of these continuously transports moisture westward to the northern Indian Ocean, which is the reverse of the climatological moisture transport, indicating that the westerly transport of water vapor to East Asia-WNP by the South Asia summer monsoon flow is weakened. The other branch moves northward over the South China Sea (SCS), bringing abundant moisture to southeastern China, and turns east at around 30°N to the south of Japan. It forms an extensive anticyclonic moisture circulation, elongated along around 20°N over the WNP, enhancing the southeast summer monsoon flow from the WNP to East Asia, that is, the enhanced western North Pacific summer monsoon (WNPSM) flow. Associated with this water vapor transport pattern, anomalous water vapor divergence is found over the SCS and the tropical WNP where the abnormal water vapor originates, while abnormal convergence is located in the mid-latitudes from the Yangtze River valley to the south of Japan, implying the possibly strengthened Mei-Yu/Baiu. The reverse will occur when the PC1 is negative.

The principal component of EOF1 shows an obvious interannual variation, with the principal period at around 4 years. It is strongly correlated with the WNPSM index, with a correlation coefficient of -0.97 (> 99% confidence level, figure not shown). This mode thus mainly represents the linkage between anomalous water vapor transport over East Asia-WNP and the intensity of the WNPSM. When the WNPSM is weak, westerly water vapor transport from the Indian summer monsoon region to the WNP is weakened, while more moisture goes northward to South China, resulting in stronger convergence over eastern China and Japan. These results confirm the finding that in weak WNPSM years, the convection along 10–20°N extending from the SCS to the central Pacific is suppressed while rainfall along the Mei-Yu/Baiu front is enhanced (Wang et al. 2001).

The second mode (EOF2) accounts for 14% of the total variance. It exhibits a alternating pattern over East Asia-WNP. That is, when PC2 is positive, an anticyclonic moisture circulation anomaly prevails at around 15–30°N, with two cyclonic anomalies lying to its south and north. The anticyclonic moisture circulation in the middle is the strongest and most widespread, with its ridge lying stably at about 25°N, which is near the climatological location of the WPSH ridge (24.3°N). It brings abundant moisture from the subtropical WNP to East Asia, where it meets the cyclonic water vapor transport anomaly from higher latitudes over the lower Yangtze River and Huaihe River valleys, then travels onward to the southern and central portions of Japan. To the south of the anticyclonic moisture circulation, anomalous moisture flow comes from the subtropical WNP, then turns southeastward over the Philippines and moves eastward to the mid-Pacific along the equator, suggesting that moisture transport from the tropical WNP to East Asia is weakened and the abnormal moisture is mainly from the subtropical WNP. The associated water vapor divergence also presents a alternating pattern, with negative-positive-negative anomalies elongating in a zonal direction around 10°N, 20°N, and 30°N, respectively.

The principal component of EOF2 (PC2) shows a significant decadal variation, with pronounced interannual change before 1997. This EOF mode reflects the influence of the strength of the WPSH and the southward invasion of cooler air from middle to high latitudes on moisture circulation. When the WPSH is strong, with its ridge stably lying at around 25°N, and the cooler air invades southward with greater frequency, the moisture circulation anomaly over East Asia shows the alternating pattern described above, and vice versa.

Generally, moisture circulation over East Asia-WNP exhibits energetic variability. It is dominated jointly by the activity of three Asian summer monsoon systems of comparable strength: the Indian summer monsoon, the WNPSM, and the EASM. The meridional displacement of the WPSH and its strength also make a significant contribution. These results are consistent with previous studies (e.g., Murakami and Matsumoto 1994; Ueda and Yasunari 1996; Chang 2004).

4. Moisture circulation and ENSO

a. How does the change in moisture circulation relate to the ENSO cycle?

ENSO is widely accepted as one of the most important factors affecting the summer climate over East Asia (e.g., Fu and Teng 1988; Huang and Fu 1996; Huang and Zhang 1997; Wang et al. 2000; Zhou et al. 2008; Li et al. 2010). It is closely related to monsoon activity over East Asia, which carries abundant moisture from remote sources to the rainfall regions. A better understanding of how and to what extent the ENSO cycle influences water vapor transport may give us insight into how it affects the climate of East Asia.

To investigate the possible relationship between ENSO and moisture circulation over East Asia-WNP, the SSTA from pre-summer to post-spring were regressed based on the PCs of two dominant modes of summer moisture circulation (Fig. 2 and Fig. 3). As shown in Fig. 2, the most remarkable relationship between PC1 and SSTA was the leading positive SSTA and the lagging negative SSTA over the tropical east-central Pacific. From summer (-1) (-1 represents the year before) to winter (-1), the positive SSTA over the tropical east-central Pacific increased, with the amplitude in winter (-1) reaching 0.6°C, doubling that in summer (-1), indicating the development of an El Niño event. These positive SSTA decreased dramatically in the following spring (0) (0 represents the year in which summer moisture circulation is studied) and even turned into a weak negative SSTA in summer (0), revealing the decay of an El Niño event. From autumn (0) to winter (0), the negative SSTA developed rapidly, with the amplitude over -0.8°C over the east-central Pacific, which implied the development of a La Niña event. This negative SSTA persisted even into the spring (+1) (+1 represents the year after). In summary, the positive phase of the first mode of moisture circulation over East Asia-WNP tends to occur in the summer that was preceded by an El Niño event and followed by a La Niña event. That is, when the SSTA over the east-central Pacific shifts from positive to negative, especially during the more pronounced shift from El Niño to La Niña, an abnormal anticyclonic moisture circulation may dominate tropical-subtropical East Asia-WNP. In this case, westerly water vapor transport from the northern Indian Ocean to East Asia-WNP is weakened and more moisture is transferred northward into southeastern China and to the south of Japan, and vice versa.

Analysis of the relationship between SSTA and the second mode showed a significant positive SSTA in the tropical east-central Pacific from pre-autumn to post-winter. The positive SSTA developed steadily from autumn (-1) to winter (0), with its center propagating from the central to the eastern Pacific and its amplitude increasing from 0.3°C to 0.5°C. However, in the succeeding spring (+1), the positive SSTA showed obvious decay. Hence, it can be concluded that the positive phase of the second mode of moisture circulation over East Asia-WNP tends to occur in those summers when the positive SSTA over the tropical east-central Pacific develops continuously from the previous year to the succeeding winter. Therefore, in the summers when a low-frequency El Niño event (4-yr period, which will be discussed in following sections) steadily develops, an alternating pattern, that is, an anticyclonic moisture circulation anomaly lying over the subtropical WNP with two cyclonic anomalies to its south and north, may exist. In this case, the moisture transport over East Asia from the subtropical WNP is enhanced, while that from the tropical WNP is decreased. The opposite may happen in the case of a low-frequency La Niña event.

To verify these results, the relationship between ENSO and moisture circulation over East Asia-WNP was further investigated by analyzing the extreme cases. These cases were selected based on their PC values (greater/less than one standard deviation, Table 1). In seven cases with extreme positive PC1, six cases occurred in summers that were preceded by positive SSTA and followed by negative SSTA in the Niño 3 region; even more notable, four cases occurred in the summers preceded by El Niño and followed by La Niña events. In the case of extreme negative PC1, four out of six cases took place in summers which were preceded by negative SSTA and followed by positive SSTA in the Niño 3 region. For the positive/negative PC2, three out of four extreme cases occurred in summers when El Niño/La Niña events developed continuously. The distribution of composite tropical SSTA patterns from Jan (-2, two years before) to Dec (+2, two years after), based on the extreme years defined in Table 1, is also investigated (Fig. 4). Locked phase relationships between SSTA over the east-central Pacific and the first two leading modes of moisture circulation were also found in the composite study, which is consistent with the result from the regression study. Furthermore, a comparison of Fig. 4a and 4b demonstrates that these locked phase relationships do not develop independently but construct a quasi-four-year coupling. That is, during a quasi-four-year periodic ENSO cycle, when the warm episode is developing continually, the positive phase of the second mode tends to play a key role in the moisture circulation anomaly over East Asia-WNP; in the transitional summer between a decaying warm phase and a developing cool phase, the positive phase of the first mode tends to take effect; during the summer of a developing cool episode, the negative phase of the second mode tends to play an important role; and the negative phase of the first mode tends to take effect in the transitional summer of a decaying cool episode and a developing warm episode.

b. Why does the ENSO cycle affect moisture circulation over East Asia?

As discussed above, the SSTA over the east-central Pacific couples well with the moisture circulation over East Asia-WNP during the quasi-four-year ENSO period. To support our argument, the possible teleconnection within this quasi-four-year coupling will be illustrated by regressing the SSTA and lower atmospheric circulation based on the PCs of two leading modes of moisture circulation (Fig. 5). The lower atmospheric circulation is selected for regression considering that the wind field not only can represent the response of the atmosphere to the SSTA, but also can reflect the vertically integrated water vapor transport as most of the moisture is concentrated on the lower level. It is interesting to note that from Fig. 5f–j to Fig. 5a–e and to the opposite sign of Fig. 5f, and so on, the regressed SSTA and atmospheric circulation form a quasi-four-year cycle. Furthermore, these regressed circulation patterns, especially the zonal wind anomalies over the tropical Pacific, couple well with the development of the quasi-four-year ENSO episodes.

As shown in Fig. 5g, the regressed 850-hPa wind circulation over East Asia-WNP shows an alternating pattern with an anticyclone over the subtropical WNP and two cyclonic circulations to its south and north, which is exactly the same as the pattern of the positive phase of the second mode of moisture circulation. It should be emphasized that to the south of the southern cyclonic circulation, a strong westerly wind anomaly prevails over the tropical west-central Pacific. This westerly wind anomaly propagates farther eastward to the eastern Pacific in the following autumn and winter, implying that the equatorial easterlies over the Pacific are weakened in the lower atmosphere. This is beneficial to the formation and eastward propagation of a warm Kelvin wave. This eastward propagation can initiate the westerly transportation of warm water from the western Pacific warm pool to the eastern Pacific and cause the continuous development of an El Niño event (Huang et al. 2004). Meanwhile, an anticyclonic circulation forms abruptly over the Philippine Sea during the following winter (Fig. 5i), which is termed the Philippine Sea Anticyclone (PSAC; Wang et al. 2000). The PSAC, persisting from the mature phase of El Niño until the ensuing summer, plays a vital role in the teleconnection between ENSO events and the climate of East Asia (Wang et al. 2000, Zhou et al. 2009b; Li and Yang 2010). It undergoes an eastward shift in the succeeding seasons (Wang and Zhang 2002; Lau and Weng 2002) and develops into a strong anticyclonic circulation over the tropical-subtropical WNP (Fig. 5b), which is identical to the pattern of moisture circulation shown in the positive phase of the first mode. Associated with the establishment and eastward extension of the PSAC, an easterly wind anomaly starts to prevail over the maritime continental region and then stretches to the central Pacific in the east, and to the Bay of Bengal in the west. This easterly wind anomaly is favorable for the formation and eastward propagation of a cold Kelvin wave in the western Pacific warm pool (Huang et al. 2004). Therefore, this strong easterly wind band not only ushers in the weakening of the WNPSM and the reduction in water vapor transported from the Indian monsoon region to the WNP, but also results in the disappearance of an El Niño event and the establishment of a La Niña event. During the next autumn and winter (Fig. 5c and 5d), along with the sustainable extension of the easterly wind to the east, the cooling effect on the Niño region strengthens. At the same time, the

PSAC shifts eastward to the east of the Philippine Sea; a cyclonic circulation first forms over the north of South China Sea, then strongly develops northeastward and replaces the anticyclone, dominating a large area of the WNP during the following spring (Fig. 5e). Figures 5f and 5e show nearly the same pattern, but with the opposite sign. Thus, the opposite phase of the quasi-four-year coupling between ENSO and the two dominant modes of moisture circulation over East Asia-WNP can be illustrated by reversing the sign of the patterns shown in Fig. 5. That is, the negative phase of the second mode tends to play an important role during the summer of a developing cool episode (the opposite of Fig. 5g), and the negative phase of the first mode tends to take effect in the transitional summer of a decaying cool episode and a developing warm episode (the opposite of Fig. 5a). Hence, the quasi-four-year coupling between ENSO and water vapor transport over East Asia-WNP is convincing, and the anticyclone/cyclone over the Philippine Sea region plays an important role in this quasi-four-year coupling.

5. Case study

In this section, further examination of the quasi-four-year coupling between ENSO and water vapor transport over East Asia-WNP is carried out by analyzing the cases in observation. The annual distribution of the primary EOF mode of moisture circulation over East Asia-WNP (the mode that accounts for the largest percent of the total variance) is shown in Fig. 6. The evolution of the primary EOF mode during 1983–1984 is from the positive phase of the first mode to the negative phase of the second mode. During 1986–1990, it is from the negative phase of the first mode to the positive phase of the second mode, to the positive phase of the first mode, and to the negative phase of the second mode. During 2002–2003, it is from the negative phase of the first mode to the positive phase of the second mode. Comparing these with the evolution of the EOF modes in the quasi-four-year coupling, it can be stated that the years 1983–1984, 1986–1990, and 2002–2003 match the quasi-four-year coupling. We therefore selected the years 1983–1984 and 1986–1987 for detailed analysis in the following study.

a. Water vapor transport during 1983–1984

The SSTA over the Niño 3 region shifted from strongly above normal to weakly below normal in 1983 and remained below normal in 1984 (Fig. 7a). Hence, the summer of 1983 was the transitional summer between a decaying warm phase and a developing cool phase of an ENSO episode, when the positive phase of the first mode tends to play a key role in moisture circulation according to the quasi-four-year coupling. On the other hand, the summer of 1984 was the summer of a steadily developing cool phase, when the negative phase of the second mode tends to take effect. These can be verified by noting the water vapor transport anomaly patterns in the summers of 1983 and 1984, which are shown in Fig. 7b and 7c. In Fig. 7b, it can be found that an extensive anticyclonic moisture circulation dominated the tropical and subtropical WNP-East Asia and a vast band of easterly zonal transport anomaly over the tropical WNP and the Bay of Bengal. This is nearly identical to the spatial distribution of the positive phase of the first mode shown in Fig. 1a. In Fig. 7c, a strong cyclonic moisture circulation anomaly prevails in the subtropical WNP, with two anticyclonic anomalies lying to its south and north, which is the exact opposite of the pattern shown in Fig. 1b, indicating that the negative phase of the second mode played an important role in the summer of 1984.

b. Water vapor transport during 1986–1987

The SSTA over the Niño 3 region shifted from below normal to above normal in the spring of 1986, and positive SSTA developed continually during the second half of 1986 and all through 1987 (Fig. 8a). Hence, the summer of 1986 was the transitional summer between a decaying La Niña and a developing El Niño event, when the negative phase of the first mode tends to play a key role in the moisture circulation according to the quasi-four-year coupling described in the last section. On the other hand, the summer of 1987 was the developing summer of an El Niño event, when the positive phase of the second mode should take effect. Similarly, this can be confirmed by the abnormal summer moisture circulation in 1986 and 1987, as shown in Fig. 8b and 8c.

Hence, the quasi-four-year coupling between SSTA over the east-central Pacific and moisture circulation over East Asia-WNP can be confirmed by these cases studies.

6. Summary

Summer moisture circulation over East Asia-WNP exhibits an energetic annual variation. To study its spatial and temporal distribution, the R-EOF technique was applied to the vertically integrated water vapor fluxes. It was found that moisture circulation over East Asia-WNP is dominated primarily by two well-separated modes. These two modes couple well with the low-frequency ENSO during its quasi-four-year cycle. Further study showed that the anticyclone (cyclone) over the Philippine Sea and the easterly (westerly) wind anomaly to its south play an important role in maintaining this quasi-four-year coupling. The main results are summarized below.

Moisture circulation over East Asia is dominated by two well-separated modes.

One exhibits an anomalous anticyclonic (cyclonic) moisture circulation over the tropical-subtropical WNP and an easterly (westerly) transport anomaly over the tropical Indian Ocean and WNP. This is tightly connected to the weaker (stronger) WNPSM. The second mode exhibits an alternating pattern, with an anticyclonic (cyclonic) moisture circulation anomaly over the subtropical WNP and two cyclonic (anticyclonic) anomalies to its south and north. This mode is closely associated with the strength of the WPSH.

These two dominant modes of moisture circulation closely relate to the leading and lagging SSTA over the tropical east-central Pacific. A quasi-four-year coupling between moisture circulation over East Asia and the ENSO signal was found. That is, during the quasi-four-year ENSO cycle, the positive phase of the second mode tends to take effect when a warm episode is developing continually, while the positive phase of the first mode tends to play a key role in the transitional summer between a decaying warm phase and a developing cool phase. In the summer of a developing cool episode, the negative phase of the second mode tends to take effect, while the negative phase of the first mode tends to play an important role in the transitional summer between a decaying cool episode and a developing warm episode.

The anticyclone (cyclone) over the Philippine Sea region serves as a bridge between moisture circulation over East Asia-WNP and ENSO events in the quasi-four-year coupling. Its establishment in the mature phase and eastward extension in the following phase of the warming (cooling) episode play an important role in the variation of moisture circulation over East Asia-WNP. Conversely, the easterly (westerly) wind anomaly to the south of the anticyclone (cyclone) is favorable for the formation and eastward propagation of a cold (warm) Kelvin wave, hence stimulating the development of the warming (cooling) episodes associated with the ENSO cycle.

However, as shown in section 5, examples of perfect quasi-four-year coupling are limited in the observation. This may be due to the rarity of the self-contained quasi-four-year cycle ENSO events. Jiang et al. (1995) concluded that multiple time scale oscillations may be involved in the ENSO variability. In addition to the quasi-four-year period mentioned above, the spectral peaks at 28, 24, and 15 months are also major modes of interannual variability of the ENSO events; within these, the 28-month oscillation is statistically significant in all cases and, if combined with the 24-month oscillation, could be as robust as the 4-year mode. What is more, the 15-month mode may interact with the 4-year cycle nonlinearly. Therefore, the quasi-four-year coupling of moisture transport over East Asia-WNP and ENSO events may be disturbed by other modes of the ENSO signal, which may be the reason for the limited number of observed examples of perfect quasi-four-year couplings. However, this hypothesis needs further testing.

The southwest flow of the Indian summer monsoon, which brings abundant evaporated moisture from the Indian Ocean, is one of three important branches of water vapor transport over East Asia (Li et al. 2011). It is not surprising that in addition to the SSTAs over the tropical east-central Pacific, the thermal state of the Indian Ocean may also play a vital role in modifying moisture transport over East Asia-WNP. Previous studies have noted that the Indian Ocean SSTA that developed in response to both atmospheric and oceanic processes of ENSO events need to be considered for a complete understanding of regional climate variability. The SSTA over the Indian Ocean may contribute to the development of a low-level anticyclone (cyclone) over the Philippines via its adjustment in the Walker circulation (Annamalai et al. 2005; Yuan et al. 2008) and via the Kelvin wave–induced Ekman divergence mechanism (Xie et al. 2009). Furthermore, the anomalous heating (cooling) over the north Indian Ocean can decrease (increase) the north-south heating gradient, which is favorable for a weak (strong) Indian summer monsoon flow and thus leads to weak (strong) water vapor transport (Zhang 2001). Zhang also found that the weaker (stronger) the Indian summer monsoon water vapor transportation is, the stronger (weaker) the WPSH becomes in its southwestern portion, which leads to more (less) water vapor transport to East Asia (refer to Fig. 3 in Zhang 2001). This is exactly the pattern of abnormal water vapor transport in the first mode described in section 3. As we can see in Fig. 3e, the regression of SSTA over the northern Indian Ocean based on PC1 is significantly positive, indicating that the first mode of summer moisture circulation over East Asia-WNP closely relates to the concurrent SSTA over the northern Indian Ocean. It should be pointed out that the second mode significantly correlates with the SSTA over the Indian Ocean too. However, the correlated SSTA initially exists over the tropical eastern Indian Ocean in the previous spring and persists until the summer, with its strength slightly weakened but its location expanded to include the whole north Indian Ocean. Hence, the two dominant patterns of water vapor transport over East Asia-WNP couple with not only the SSTA over the east-central Pacific, but also the SSTA over the Indian Ocean. Unlike the first mode, which is closely related only to the simultaneous SSTA over the north Indian Ocean, the second mode is also related to the SSTA over the eastern Indian Ocean in the previous spring. It seems that the difference in the time span of abnormal heating over the Indian Ocean may lead to different effects on the moisture circulation over East Asia-WNP. This needs further examination in a future study.

In this study, we focused on the coupling between water vapor transport over East Asia-WNP and warming events over the East Pacific and pointed out that the development of the PSAC during different phases of the warming events played an important role in this coupling. However, recent studies have shown that there are two different types of warming events over the Pacific Ocean, El Niño and El Niño Modoki, the impacts of which are significantly different on atmospheric circulation and precipitation over East Asia. In particular, these differences are attributed mainly to the discrepancy in the evolution and location of the PSAC and WPSH associated with the two types of events. In comparison of the major El Niño Modoki events defined by Feng et al. (2010) with the cases that obey the quasi-four-year coupling descried in section 5, 2002–2003 is found to be an El Niño Modoki event and obeys the quasi-four-year coupling. It seems that both El Niño and El Niño Modoki events could couple with water vapor transport over East Asia-WNP in a quasi-four-year cycle. Hence, it is necessary to study in detail the different roles played by the two types of warming events in our quasi-four-year coupling in a future study.

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Catalog of graphs:

Fig. 1. Spatial and temporal distribution for EOFs of summer water vapor flux anomalies over East Asia-WNP during 1979–2009. (a) EOF1 and (b) EOF2. Figures in the upper panel are the eigenvectors, unit: kg m^{-1} s^{-1}; figures in the lower panel are the associated principal components (PCs). The shading in the upper panel represents the associated divergence of water vapor fluxes over 8×10^{-6} kg m^{-2} s^{-1} (light gray) and less than -8×10^{-6} kg m^{-2} s^{-1} (dark gray). The dashed lines in the lower panel indicate $\pm\sigma$ of PCs.

Fig. 2. Regression of seasonal sea surface temperature anomalies (SSTAs) based on the time coefficient of EOF1 (PC1) of summer moisture circulation over East Asia-WNP from pre-summer to post-spring. Unit: K. Shaded areas indicate regions where the regressions of SSTA are statistically significant at the 95% confidence level by a t-test. (a–h) presents pre-summer to post-spring, respectively. (-1) indicates the year before, (+1) indicates the year after, and (0) indicates the year in which summer moisture circulation is studied.

Fig. 3. Same as Fig. 2, but based on the PC2.

Fig. 4. Distribution of composite positive-minus-negative anomaly patterns of tropical (-5~5°N averaged) SST from two years before to two years after based on the extreme years selected based on the (a) PC1 and (b) PC2. Unit: K. -2, -1, 0, +1, and +2 represent two years before, the year before, the year when summer moisture circulation is studied, the year after, and two years after, respectively.

Fig. 5. Regression of the lower-troposphere wind field (unit: m s^{-1}) and SSTA (unit: K) from pre-spring (spring [0]) to post-spring (spring [+1]) based on PC1 and PC2, respectively. Only those with regressed wind speed over 0.2 m s^{-1} are displaced. The shaded areas indicate regions where the regression is statistically significant at the 95% confidence level by a t-test. The contours indicate the regressed SSTA, with the interval of 0.2 K. (a) through (e) are based on PC1, and (f) through (j) are based on

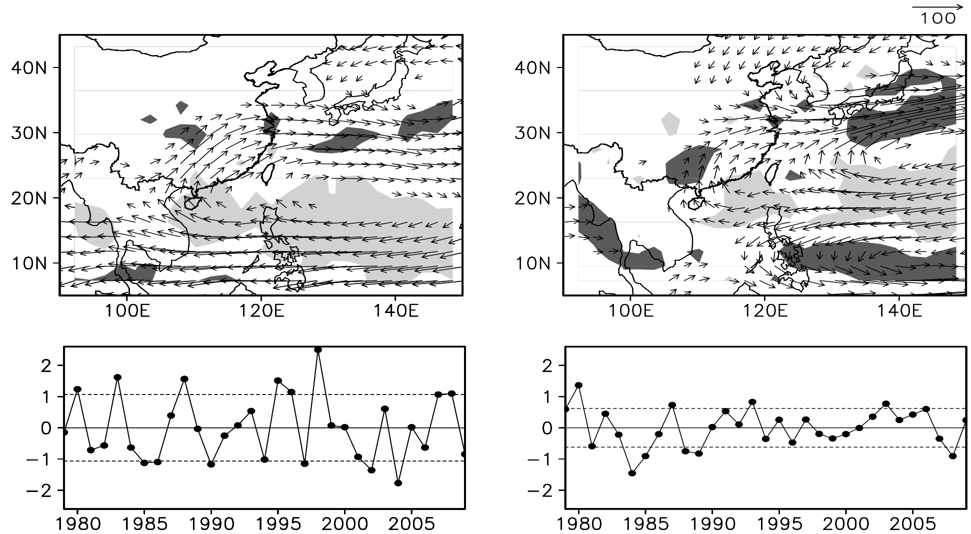
PC2.

Fig. 6. Annual distribution of the primary EOF mode of moisture circulation over East Asia-WNP (bar, axis on the right) and monthly distribution of SSTA over the Niño 3 region (contour, axis on the left, unit: K) from 1979–2009. The primary EOF mode is decided by ranging the time coefficient of EOF mode 1 to mode 5; the maximum is then considered to be the primary EOF mode; a value > 0 indicates the positive phase of the EOF mode, and a value < 0 indicates the negative phase of the EOF mode.

Fig. 7. (a) Time series of monthly SSTA anomalies over the Niño 3 region (unit: K) during Jan 1983 to Dec 1984. Abnormal water vapor transport over East Asia-WNP in the summer of (b) 1983, and (c) 1984.

Fig. 8. Same as Fig. 7, but for the period of Jan 1986–Dec 1987.

Table 1. Extreme years selected based on the PC1 and PC2 (greater/less than one standard deviation), and their relationship with the SSTA over the tropical east-central Pacific.



(a) (b)

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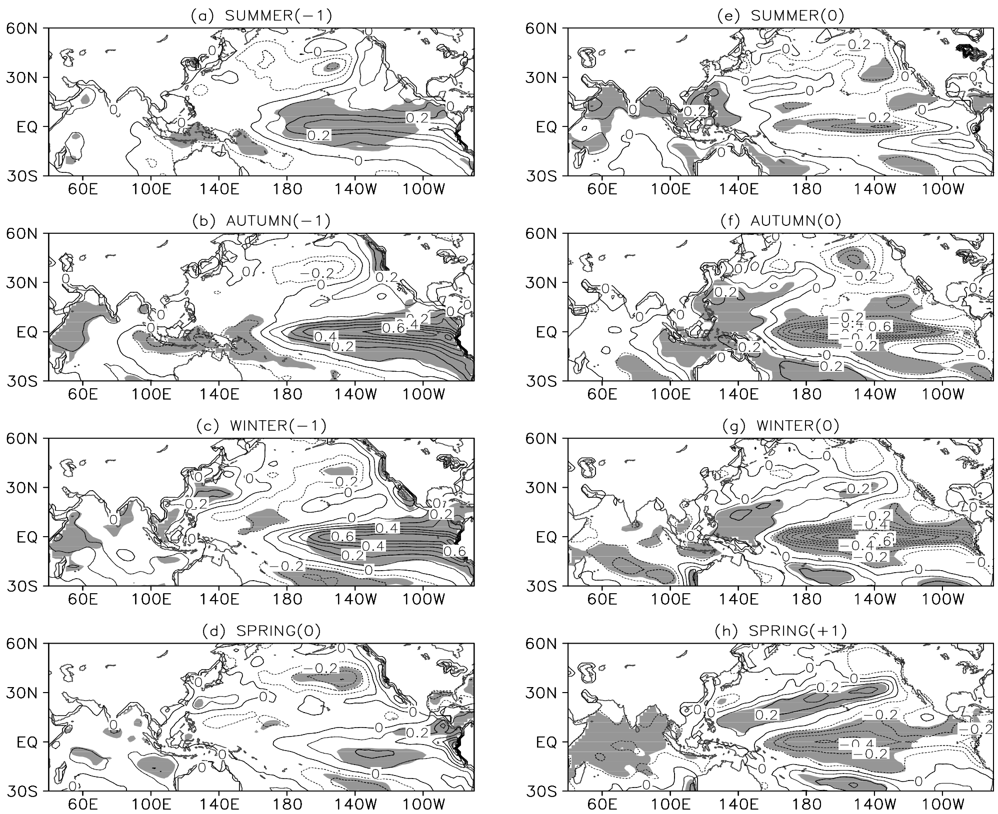

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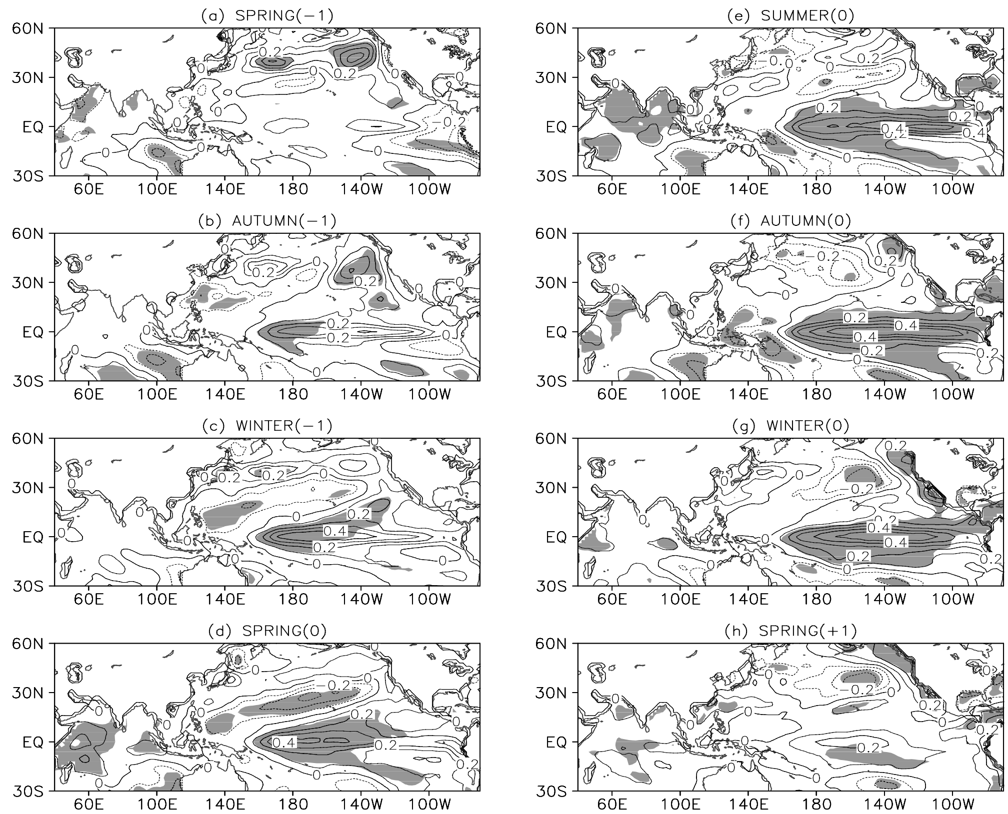

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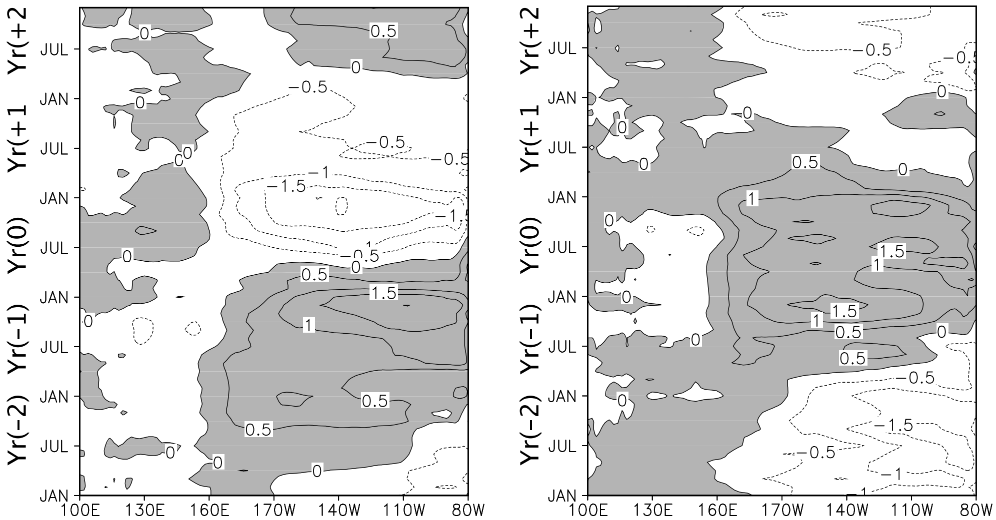

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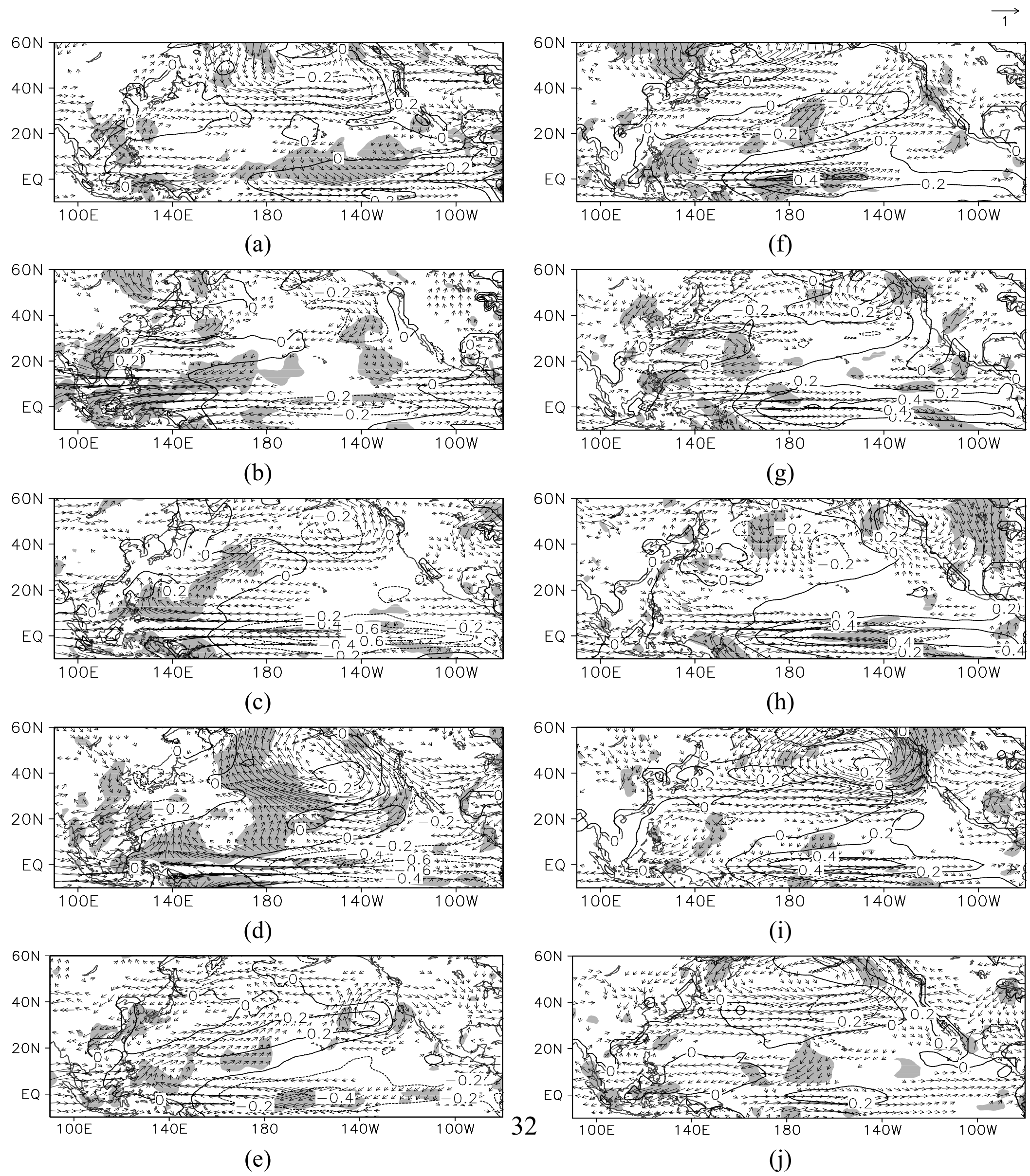

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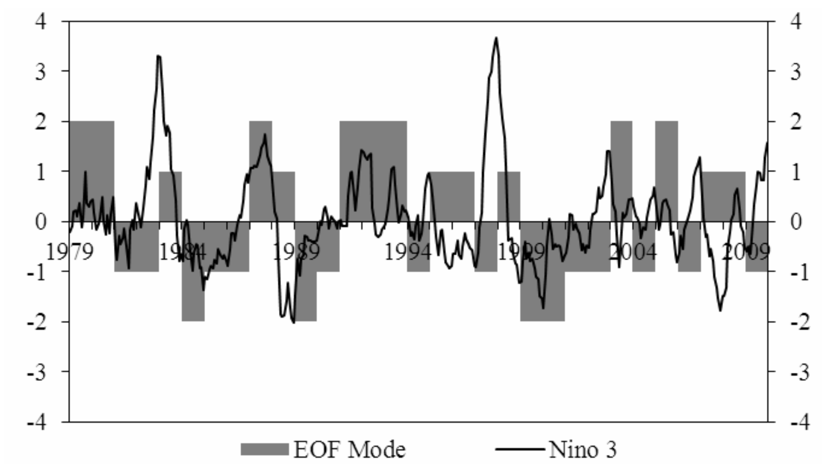

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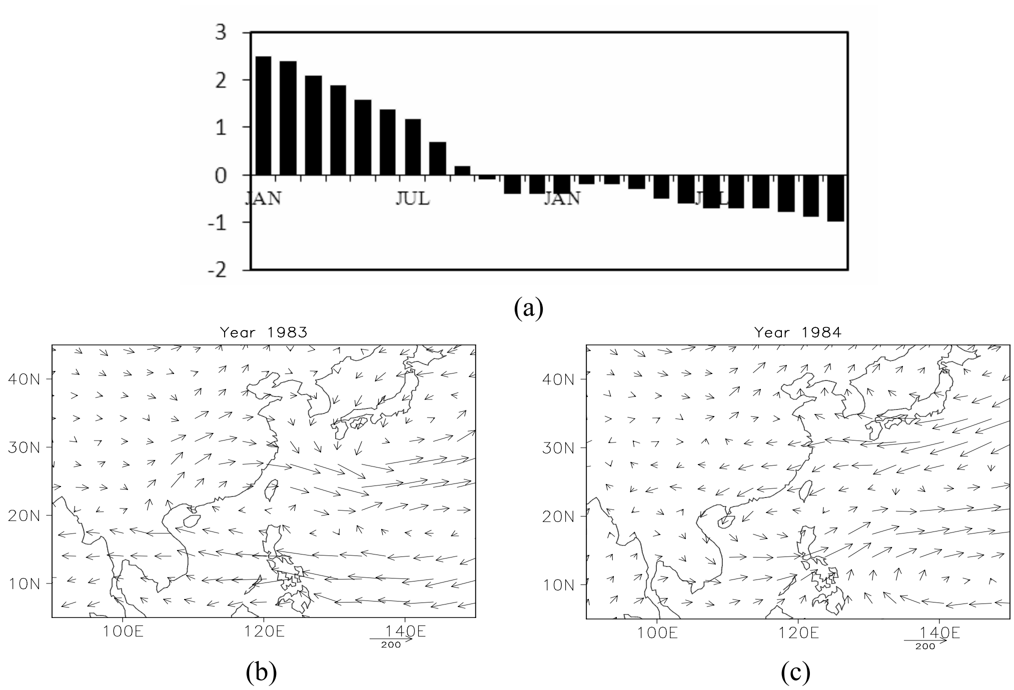

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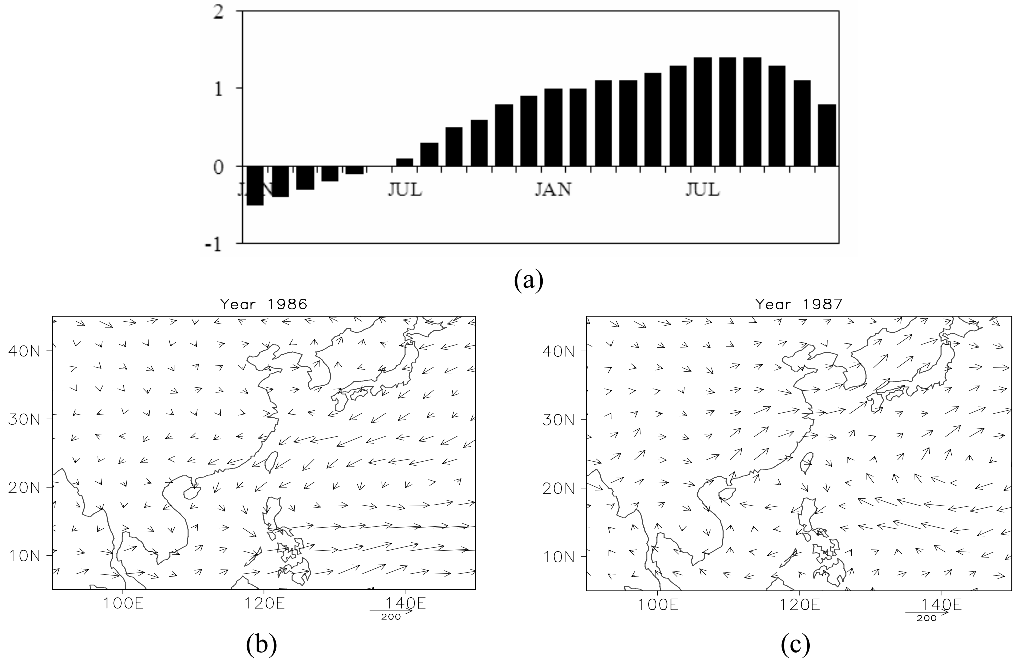

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Table 1. Extreme years selected based on the PC1 and PC2 (greater/less than one standard deviation), and their relationship with the SSTA over the tropical east-central Pacific.

	PC1	**PC2**
Positive(>δ)	1980* 1983* 1988** 1995** 1996 1998** 2007**	1980 1987** 1993** 2003**
Negative(<-δ)	1985 1986** 1990* 1997* 2002* 2004	1984** 1985** 1988 1989**

* PC1(+): the summer preceded by +SSTA and followed by –SSTA in the Niño 3 region; ** PC1(+): the summer preceded by El Niño and followed by La Niña. Reverse for the case of PC1(-1); * PC2(+): the summer in a developing +SSTA; ** PC2(+): the summer in a developing El Niño case. Reverse for the case of PC2(-1).