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Tropospheric biennial oscillation of the western Pacific subtropical high and its relationships with the tropical SST and atmospheric circulation anomalies

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There is the significant period of tropospheric biennial Oscillation (TBO) over East Asian monsoon region at the interannual timescales, which has the important influences on East China climate. Based on a set of reconstructed indices which describes the western Pacific subtropical high (WPSH) objectively, this paper focuses on the TBO component of WPSH, one of the key members of the East Asian Monsoon system, and its relationships with the tropical SST and atmospheric circulation anomalies. It is found that (1) As an important interannual component of WPSH, the time series of TBO has the obvious transition in the late 1970s, and the variability of the WPSH's TBO component is more significant after the late 1970s. (2) The time-lag correlations between the WPSH's TBO and the tropical sea surface temperature (SST) anomalies in several key ocean regions are more significant and have longer correlation duration than the raw data. The response of the western boundary index to ENSO is earlier than the intensity index, and the time-lag correlations of them are up to maximum when lagging ENSO by 3–5 months and 5–6 months, respectively. (3) In the course of the WPSH's TBO cycle, the occurrence of the El Niño-like anomaly in the tropical central-eastern Pacific in winter is always coupled with the weak East Asian winter monsoon, with the most significant enhancing phase of the WPSH' TBO. In contrast, the La Niña-like anomaly in the central-eastern Pacific in winter is coupled with the strong East Asian winter monsoon, with the most weakening phase of the WPSH's TBO. (4) The distribution of the tropical SST and atmospheric circulations anomalies are asymmetric in the TBO cycle. The WPSH's TBO is more significant in the period of the developing El Niño-like anomaly in central-eastern Pacific than in the period of the developing La Niña-like anomaly. Therefore, during the period of developing El Niño-like anomaly, more attention should be paid to the interannual component of TBO signal in the short-term climate prediction.

western Pacific subtropical high (WPSH), tropospheric biennial oscillation (TBO), East Asian monsoon, tropical sea surface temperature (SST) anomaly, intensity index, western boundary index

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Quasi-biennial oscillation presents the opposite wind directions in every two years in the tropical lower-stratospheric zonal wind, which was firstly found by Reed et al. [1]. Then Belmont and Dartt [2] define officially such the quasi-period phenomenon as quasi-biennial oscillation (QBO). The quasi-biennial oscillation in the troposphere was also founded at the same time. Both the sea level pressure (SLP) in boreal Northern Hemisphere [3] and the precipitation in whole India averaged from June to September [4] have the quasi-biennial period, and the phenomenon commonly exist in the atmospheric circulations, the tropical SST and surface meteorological elements. Therefore, it is called tropospheric biennial oscillation (TBO) to distinguish it from QBO in the lower-stratosphere [5,6]. The researches of TBO over the East Asian monsoon region began to appear in the late 1980s, and it is found that the East Asian monsoon precipitation has the interannual period of the quasi-biennial oscillation [7–10]. The observational precipitation data in most China

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*Corresponding author (email: liuyuny@cma.gov.cn) also has obvious TBO component [11,12]. Kuang et al. [13] and Jia et al. [14] further analyzed the spatial distribution and the long-term evolution of the precipitation TBO in China.

As one of the dominant members of the East Asian monsoon system, the western Pacific subtropical high (WPSH) also exhibits the significant periods at the interannual and interdecadal timescales, and its variation in the location and intensity has important impacts on the precipitation over China in summer [15,16]. The interannual variability of WPSH directly decides the distribution of droughts and floods over East China [17], while its interdecadal variability in 1990s provides a favorable climatic background of more rainfall in the middle and low reaches of the Yangtze River basin and less rainfall in North China [18]. Based on a set of reconstructed indices which describes WPSH objectively [19], it is found that there are obvious TBO signals in the monthly time series from 1951 to 2011. Therefore, this paper focuses on the characteristics of WPSH's TBO, and investigates whether the TBO component has significant changes under the background of the climatological interdecadal transition. The corresponding relationships of TBO with the atmospheric circulation and tropical SST anomalies are further analyzed to attempt to provide some valuable signals for the short-term climatic prediction in China.

1 Data and definition of WPSH indices

It is pointed out that the NCEP/NCAR reanalysis has good consistency with the ERA40 reanalysis at the interannual timescale [20]. Liu and Ding [21] also found that they are similar with each other in the performance of Asian monsoon system at the interannual and interdecadal timescales when investigating the leading modes of the Asian-Pacific summer monsoon system. the primary dataset in this paper is the monthly geopotential height at 500 hPa and zonal and meridional wind at 500 hPa derived from NCEP/NCAR reanalysis from 1951 to 2011 [22], and the extended reconstructed sea surface temperature data (ERSSTv3) Published by NOAA, with the horizontal resolution of 2°×2° [23]. Based on the NCEP/NCAR reanalysis, the monthly reconstructed WPSH indices are calculated from 1951 to 2011, including the area index, intensity index, ridge line index and western boundary index [19].The main methods in this paper include the power spectrum analysis, Sbutterworth band-pass filtering, low-pass filtering, time-lag correlation analysis and composite analysis.

2 The characteristics of the WPSH's TBO components

2.1 Power spectrum analysis

The power spectrum analysis can clearly demonstrate the main cycles of the subtropical high during the whole period. Considering that the seasonal variability of the WPSH is more significant than other timescales, the low-pass filter is firstly used to remove the seasonal variability from the raw data for highlighting the interannual signals. The power spectrum analysis for the filtered monthly WPSH's intensity index and western boundary index show that there are mainly two peak values at the interannual timescale during the 61-year period of 1951–2011(Figure 1), the quasi-four-year and quasi-biennial year (i.e. TBO), with the maximum backward length of the power spectrum analysis is 150 months (the length of the time series is 732 months). While the TBO component of WPSH is corresponding to the dominant interannual cycle of the summer monsoon precipitation in East Asia and China [8–10,13], and their interaction between each other is more closer than the quasi-four year component, so the WPSH's TBO component is further analyzed in the follows.

2.2 Interdecadal variability

It is known that many meteorological variables, including a

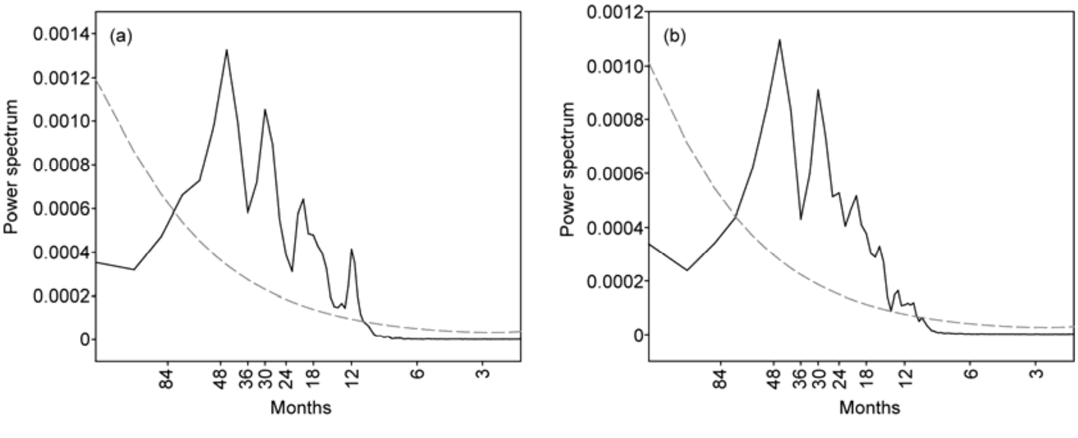

Figure 1 Power spectrums (solid lines) of the WPSH intensity (a) and western boundary (b) indices during 1951–2011 with removing the seasonal variability (the dashed lines denote the test of 0.05 significant level).

variety of atmospheric circulation systems, precipitation in Asian monsoon region, have the significant interdecadal variations during the past 60 years, with the turning time in the late 1970s [19,24,25]. Figure 2 shows the monthly anomalies and accumulative anomalies curves of the WPSH intensity and western boundary indices. It is seen that the intensity index is almost negative and the western boundary index is nearly positive before the late 1970s, which indicates that the subtropical high is under the weaker and more easterly background. But the interdecadal condition turned to opposite after the late 1970s. The positive intensity index and negative western boundary index demonstrate that the subtropical high becomes stronger and more westerly than normal during recent 30 years. The accumulative curves of these two indices also show the obvious interdecadal transition in the late 1970s. Then whether the WPSH's TBO components also present any significant differences or not under the climatic background of the interdecadal transition? Therefore, the Sbutterworth band-pass filter is used to isolate the TBO timescale variability from the raw data of the WPSH intensity and western boundary indices. The time-sliding widow is set to 24–36 months, and the frequency response function shown in Figure 3.

It can be seen from the filtered time series (Figure 4) that the TBO components of WPSH also appear the obvious transition in the end of the 1970s. Both the time series of the intensity and western boundary indices, their amplitude are relatively small before the year of 1980, but they significantly increased in the following years. The variance contributions of their TBO components in the interannual and interdecadal timescales during the period of 1951–1980 are 9.8% and 14.1%, while they increase to 44.1% and 44.7% during the period of 1981–2011, respectively. The interdecadal variation of the WPSH' TBO components seem to be consistent with the interdecadal ascending trend of the QBO in the stratosphere. Using the QBO timescale component of zonal wind anomalies at 100–10 hPa from ERA40 reanalysis to represent the QBO, Huang et al. [26] found that both its intensity and vertical distribution exhibit the significant interdecadal modulations, with the turning point in the end of 1970s. Hu et al. [27] further examined the connection of the long-term QBO variations with the tropical SST and atmospheric circulation, and found that the relationship between them also have the similar interdecadal modulation in the end of 1970s. The TBO signal of the precipitation in China exists the interdecadal variations, too [28]. The coherent

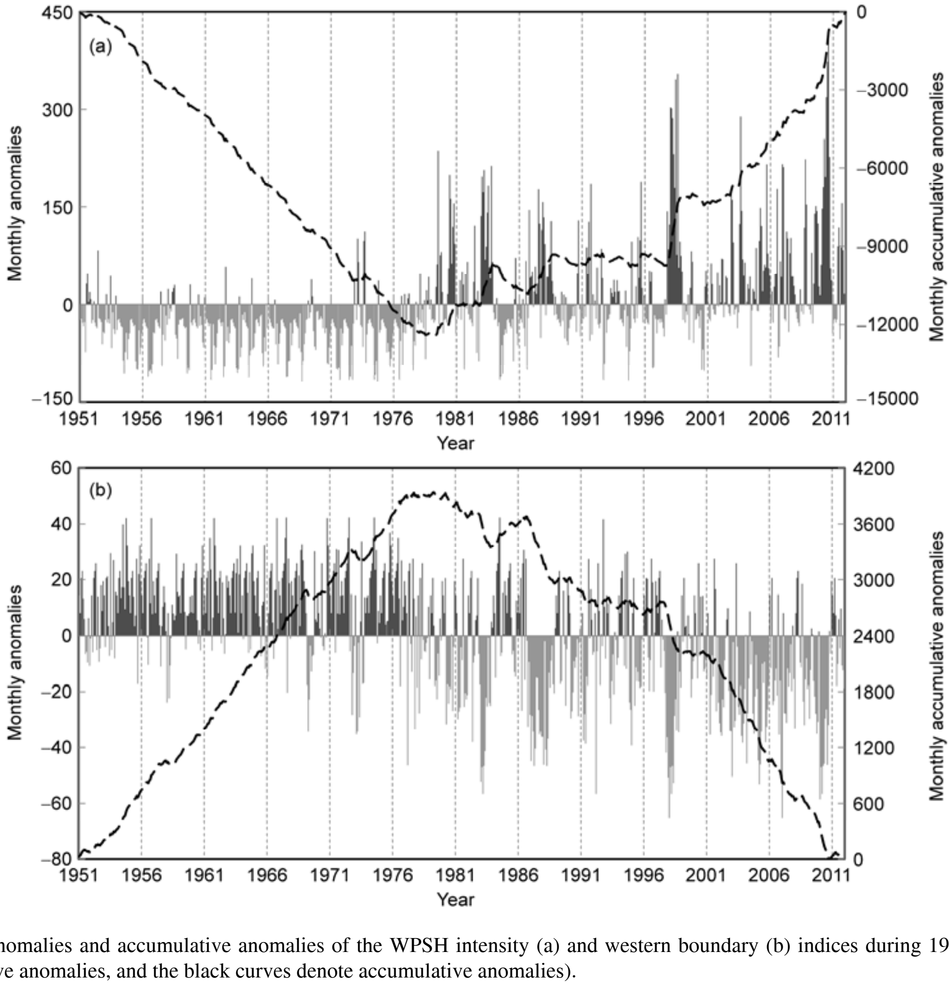

Figure 2 Monthly anomalies and accumulative anomalies of the WPSH intensity (a) and western boundary (b) indices during 1951–2011 (the gray bars denote positive/negative anomalies, and the black curves denote accumulative anomalies).

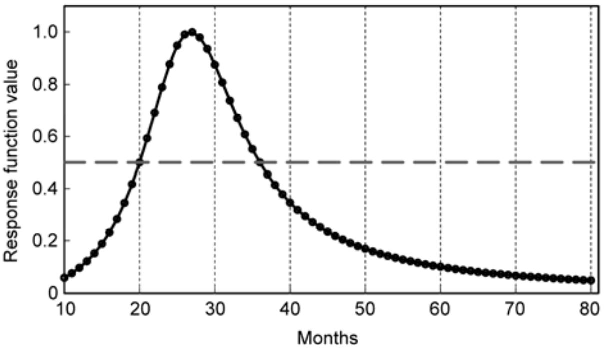

Figure 3 Response function of the Sbutterworth band-pass filter with sliding window of 24–36 months.

interdecadal variations in these meteorological variables are to some extent the results of the ocean-atmospheric interaction.

It is suggested through the above analysis that the TBO, as one of the dominant interannual components of WPSH, exists in the entire period of 1951–2011, but due to its own interdecadal evolution, it does not always significantly affect the atmospheric circulation and precipitation over monsoon regions. The TBO signal of WPSH is increasingly significant in recent 30 years, which is worthy of paying more attention and analysis in the short-term climatic prediction. Therefore, we select the period of 1981–2011 in the following analysis to investigate the connection of the TBO and the atmospheric circulation, as well as the tropical SST anomaly, which is able to deepen the understanding of the interannual signals in the short-term climatic prediction.

3 TBO-related tropical SST and atmospheric circulation anomaly

In the previous studies, the physical mechanism of the TBO in the Asian monsoon region still resided a lot of disagreements. One of the arguments is that TBO seems to be the result of the ocean-atmospheric interaction over the region from the South China Sea to western Pacific warm pool [29–31]. Meehl and ArbLaster [32] emphasized that the contribution of the ocean-atmospheric interaction (over the Inida-Pacific region) is greater than the land-atmospheric interaction (referring to South Asia). Raumusson et al. [33] and Yasunari [34] also proved the contribution of ENSO on TBO. However, Chang and Li [8] and Li et al. [35] took a different view that TBO is a local phenomenon. Without the role of the equatorial Pacific SST anomaly, there is still TBO signals over the Indian Ocean. For this kind of argument, Meehl et al. [36] further pointed out that if there is no ENSO, TBO in the Asian-Australian monsoon region would be weakened. It is summarized that TBO's existence in the Asian monsoon region is mainly the result of the sea-land-

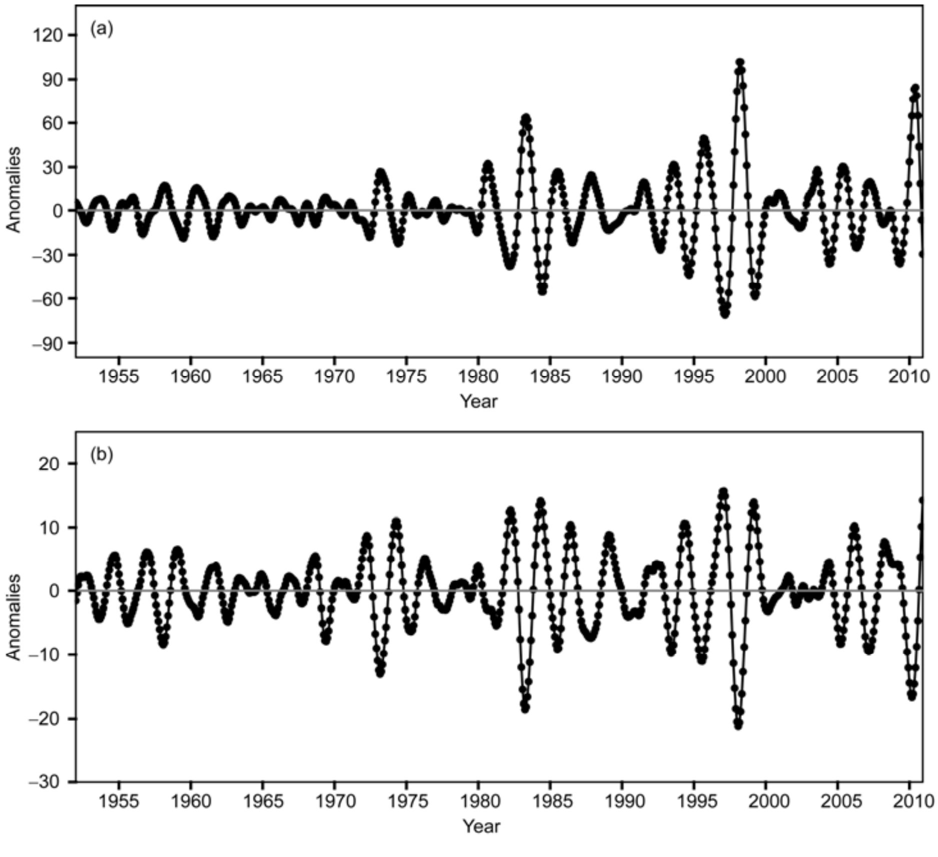

Figure 4 Time series of the TBO components of the WPSH intensity (a) and western boundary (b) indices during 1951–2011.

air interaction, while the contributions of the tropical oceans and the atmospheric circulation anomalies on TBO are relatively significant. Therefore, in the following we mainly analyze the association of TBO with the tropical SST and atmospheric circulation, and try to reveal the corresponding relationships of them.

3.1 Time-lag correlation between WPSH indices and tropical SST anomaly

In order to clearly understand the corresponding relationship between the WPSH's TBO component and the tropical SST anomaly, we calculate the lead-lag correlation of the WPSH raw indices with SST anomalies in several key ocean regions (Niño3.4: 5°S–5°N, 170°–120°W; warm pool area (WP): 5°S–5°N, 120°–160°E; tropical western Indian Ocean (WIO): 5°S–5°N, 40°–60°E). it is indicated that all of the WPSH indices are significantly influenced by ENSO and western Indian Ocean SST anomaly except the ridge line index, while the correlation with the SST in warm pool is relatively weaker than others (Figure 5).The response of the western boundary index to ENSO is earlier than other WPSH indices, with the most obvious correlation appearing to 2–5 lagging months. It is lagging 4–7 months when the time-lag correlation of the intensity and area indices with the SST anomalies is prominent.

The lead-lag correlations are also calculated between the WPSH TBO components and SST anomalies in the same key areas (Figure 6). It is seen that the correlations between them are more significant and longer duration, which means the important influence of the tropical SST anomalies on WPSH's TBO components.

3.2 WPSH's TBO-related spatial distributions of SST and atmospheric circulation anomalies

For a more detailed description of the relationship between the WPSH' TBO components and the spatial distribution of the SST and atmospheric circulations, we divide the composited WPSH's TBO cycle into eight phases. It is known from the TBO time series (Figure 4) that it is often in the summer when the amplitude of the TBO arrives maximum. Therefore, the summer of the previous year is defined as the first phase of TBO with the most negative period. The TBO

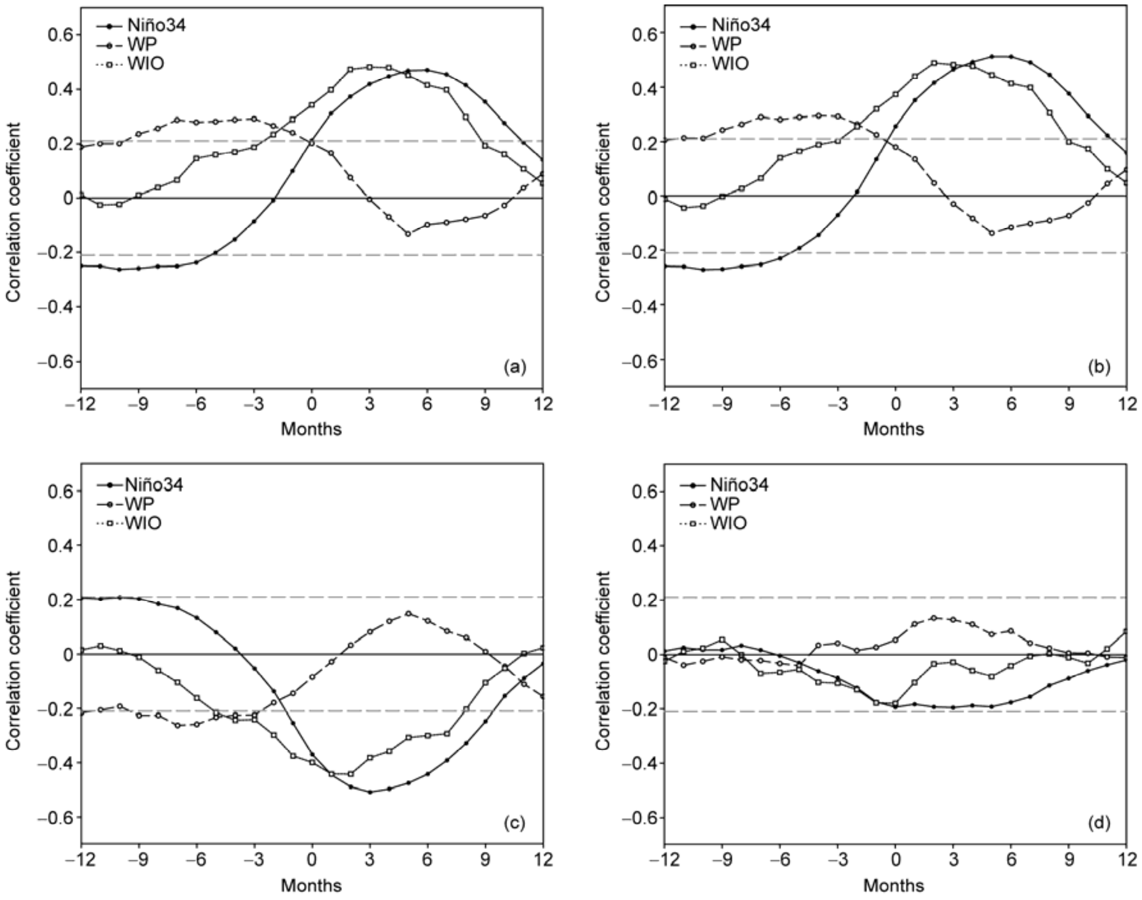

Figure 5 Time-lag correlations between the raw time series of the WPSH intensity (a), area (b), western boundary (c) and ridge line (d) indices and the tropic SST anomaly in some key regions (-*n* (*n*) under *x*-axis denote the leading (lagging) *n* months relative to SST anomaly. The gray dashed lines are the 0.05 *t*-test significant level).

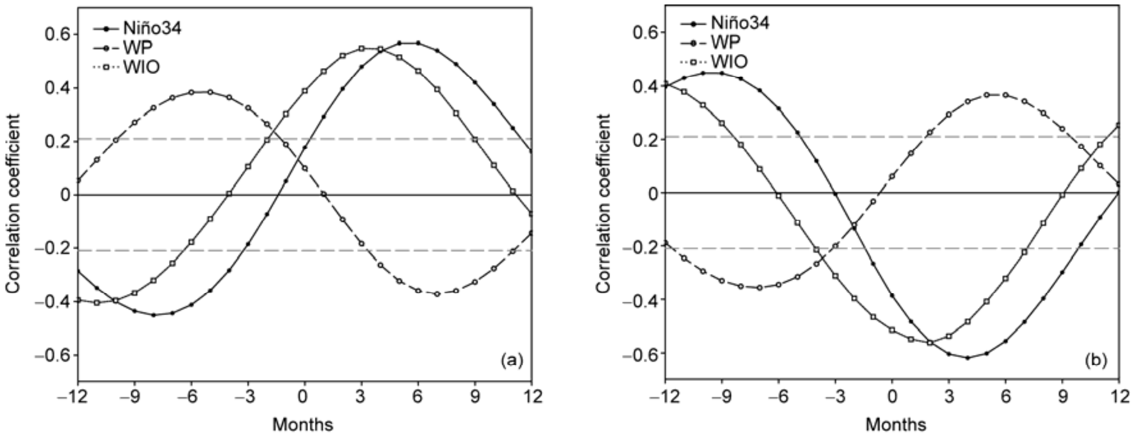

Figure 6 Same as in Figure 5, but for the TBO components of the WPSH intensity (a) and western boundary (b) indices.

phase is turning to positive in the following winter, corresponding with the largest variability as the third phase. The Fifth phase is the strongest positive phase of the TBO component when in the summer of this year, and thereafter the TBO begins to weakening. In the seventh phase the positive TBO turns to negative, so as to form a complete eight-phase cycle (Figure 7).

Figure 8 shows the association of the eight-phase cycle for the WPSH' TBO with the SST and wind anomalies at 850-hPa. It is seen that in the summer of the previous year (Figure 8(a)) when TBO is the most negative phase, the equatorial central-eastern Pacific is in the El Niño-like state, the warm pool SST anomaly begins to appearing negative at the same time, and the Indian Ocean SST is approaching the climate arerage. In the lower-level wind field, the across-equatorial flow in the Bay of Bengal is stronger than normal, and an anomalous cyclone locates over the area from the South China Sea to the western Pacific Ocean, and an anomalous anticyclone is on the north of 30°N, which is the typical mode of the strong East Asian summer monsoon. The anomalous westerly flow in the south side of the cyclone, which locates on the south of 30°N, contributes to eastward extension of the warm water in the surface warm pool, making maintenance and further potentiation of the El Niño-like state in the tropical central-eastern Pacific.

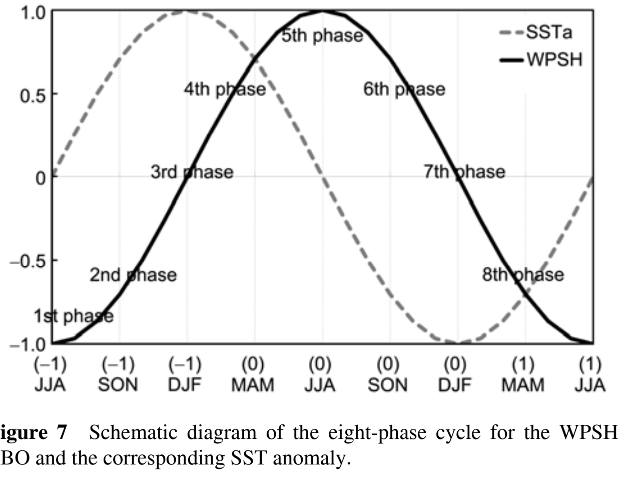

Figure 7 Schematic diagram of the eight-phase cycle for the WPSH's TBO and the corresponding SST anomaly.

In the fall of the previous year (Figure 8(b)), the distribution of cold anomaly in the west and warm anomaly in the east of the Pacific is further strengthened under the driving of the equatorial westerly flow, and the SST anomaly in Indian Ocean is more significant than in the preceding summer. Meanwhile, an anomalous divergent center appears over the warm pool, and the equatorial westerly flow continues to strengthening at the lower-level wind anomaly field. Then in the winter (Figure 8(c)), the El Niño-like state reaches a peak with the further warming of the SST in Indian Ocean. An anomalous anticyclone is stimulated on the east of Philippines and the East Asian winter monsoon is weaker than normal. When in the spring of this year (Figure 8(d)), the El Niño-like state begins to decaying, while the Indian Ocean basin-wide (IOBW) mode reaches peak. It is lagging about a season to the evolution of the maximum SST anomaly in the equatorial central-eastern Pacific, which is consistent with the lagging time in Figure 6 of WPSH's correlation with Niño3.4 and SST anomaly in WIO, respectively. The anomalous anticyclone which exists over the east of Philippines in pre-winter has moved northward to South China Sea, and the Somali cross-equatorial flow is weaker than normal.

In the summer of this year (Figure 8(e)), the evolution of the SST anomaly in the equatorial Pacific begins to La Niña-like state, when is the strongest positive period of the WPSH's TBO. An anomalous anticyclone locates on the south of 30°N over the western Pacific, corresponding with the weaker East Asian monsoon. The southerly flow on the western side of the anticyclone and the northerly flow from the high latitude converges over the Yangtze River basin, which is conducive to the more precipitation than normal there. The anomalous easterly flow seems to be appearing over the warm pool area, accelerating the SST warming. With the appearance of the negative SST anomaly of the

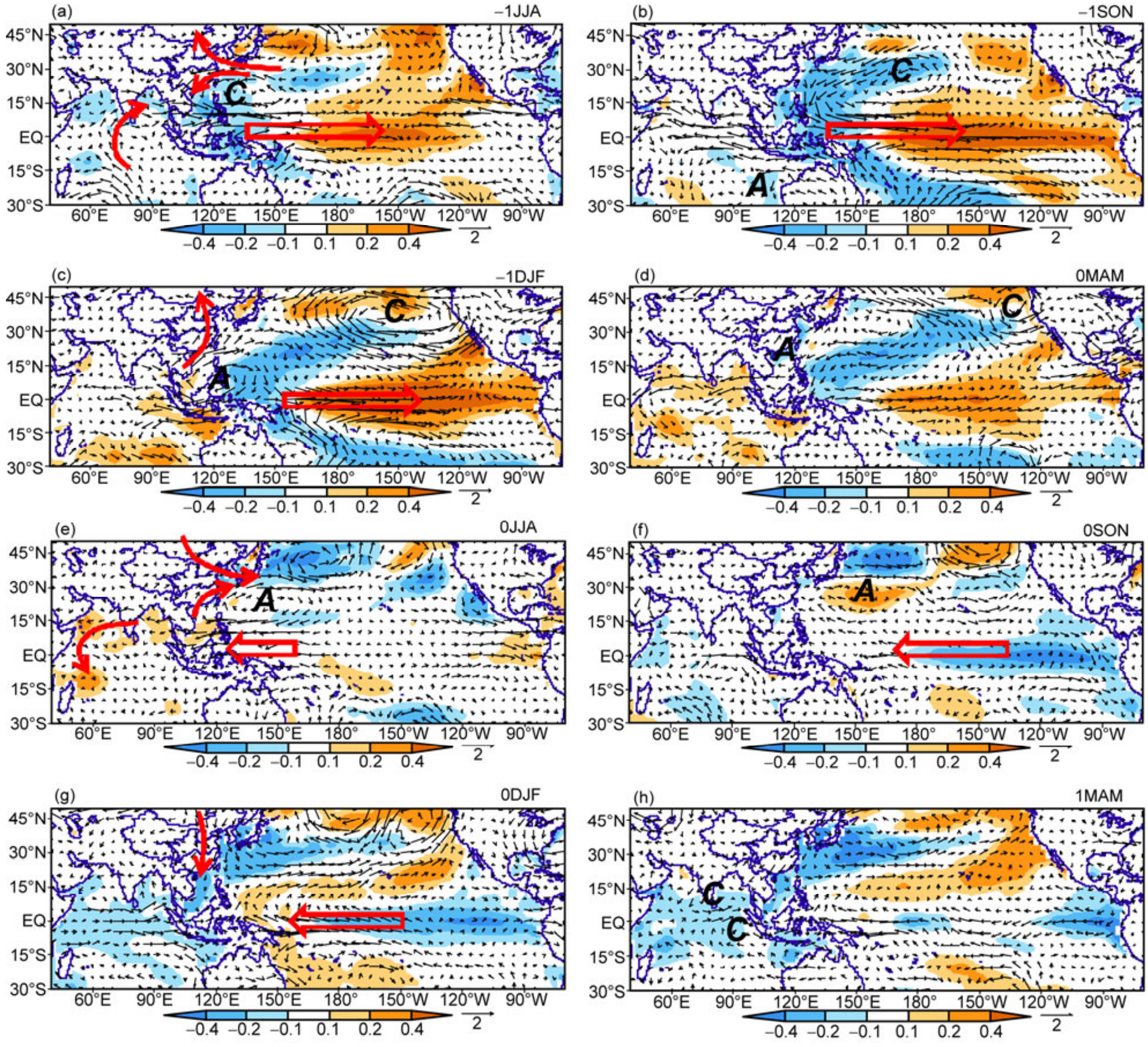

Figure 8 Distribution of the SST (°C) and 850 hPa wind anomalies (m/s) corresponding to the eight different phases of the WPSH's TBO. (a)–(h) denote the first to the eighth phase, respectively.

central-eastern Pacific, the SST of Indian Ocean region also turns to lower than that in previous spring, and the Somali cross-equatorial flow is weaker than normal. Such the distribution of the atmospheric circulation and the tropical SST anomaly is almost opposite to that in the summer of previous year (Figure 8(a)).

In the fall of this year (Figure 8(f)), the equatorial easterly flow anomaly further strengthens and the La Niña-like state in the central-eastern Pacific continue developing, which exhibits the anti-phase distribution in the same period of the previous year, but the degree of abnormality was much weaker than that in the El Niño-like period. When the La Niña-like state in the equatorial central-eastern Pacific reaches to the peak (Figure 8(g)), the East Asian winter monsoon is stronger than normal, and the lower-level flows converge over the warm pool area. While in the spring of the next year, La Niña-like state starts to decay, the anomalous anticyclone presents again over the east of the Philippines, the intensity of WPSH is weaker than normal, and a double of cyclones appear over the equatorial Indian Ocean region, which indicates the relatively earlier outbreak and stronger Asian summer monsoon than normal. It will once again demonstrate the anomalous distribution as in Figure 8(a), so as to form a complete process of the TBO cycle.

It is known from the above analysis that in a complete WPSH's TBO cycle, the most significant variation of SST anomaly is in the equatorial central-eastern Pacific. The process is that the SST anomaly there begins to appearing the El Niño-like state in the previous summer, then strengthening in the previous fall and reaching to the peak in the previous winter; turning to descending in the following spring and summer, and then developing to the La Niña-like state, and coming to its strongest period in winter of that year; while advancing again in the next spring and summer, and exhibiting the conversion from the La Niña-like to El Niño-like state. In the corresponding lower-level wind anomaly fields, it experiences the change of strong summer monsoon-weak winter monsoon-weak summer monsoon-strong winter monsoon-strong summer monsoon from the previous summer to the next summer. Such the TBO cycling variation of the East Asian monsoon just coincides with the viewpoint of Li et al. [37] based on an East Asian monsoon index (EAMI) research. During the WPSH's TBO cycle, the El Niño-like state in winter and the weak winter monsoon are always coupling occurrence at a time, when is just the third phase of the WPSH's TBO with the most developing variability. On the contrary, the La Niña-like state always couples with the strong winter monsoon, corresponding the seventh TBO phase with the most decaying variability. In a word, the entire TBO cycle performance is the results of the typical ocean-atmosphere interaction.

It is seen from the contrast between the previous and the next year in the TBO cycle that during the eight-phase TBO cycle, the abnormality degree of the El Niño-like mode in the central and eastern Pacific in the previous year is significantly stronger than that of the La Niña-like mode in the next year. The anomalous cyclones and anticyclones at the lower-level wind fields in the previous year exhibit more clearly than those in the next year. Such the asymmetric distribution of the tropical SST and atmospheric circulation anomalies in the two years indicates that WPSH's TBO is more significant in the period of the development of the El Niño-like state and the transition from the strong summer monsoon to weak winter monsoon than that during the period of the development of the La Niña-like state and the transition from the weak summer monsoon to the strong winter monsoon. In other words, we should pay more attention to the interannual component of TBO signal in the short-term climatic forecast when it is in the developing period of the El Niño-like state.

4 Conclusions and discussion

The WPSH system has two dominant interannual cycles, with one being the quasi-four years oscillation and the other being the TBO. This paper focuses on the TBO component, which has a close relationship with the East Asian monsoon rainfall. Based on a set of the reconstructed WPSH indices which is able to objectively describe the western Pacific subtropical high (WPSH), the TBO timescale variability of WPSH is isolated from the raw monthly data from 1951 to 2011 through the Sbutterworth band- pass filter, and its interdecadal differences is compared under the climatic background of the interdecadal transition. Its association with the tropical SST and lower-level atmospheric circulation anomalies are also further analyzed for revealing the relationships between the WPSH' TBO and them. The conclusions are as follows:

(1) As an important interannual component, the WPSH's TBO exists within the entire period of 1951–2011. With the interdecadal evolution of the WPSH raw data, the TBO component also shows the obvious transition in the end of 1970s, and the amplitude of variability of the WPSH TBO has increased significantly after 1980.

(2) The time-lag correlation between the WPSH's TBO and the tropical SST anomaly in some key areas is more significant than the WPSH's raw data, with longer correlation duration, which indicates the important influence of the SST anomaly on the TBO components. The TBO of the WPSH intensity index lags the Niño3.4 SST anomaly by about two months, and when lagging 5 or 6 months, the correlation coefficient achieves the maximum. The response of the TBO of the western boundary index to ENSO is earlier than the intensity index, with the most significant negative correlation between them when lagging by 3–5 months. It takes shorter time to achieve the maximum of the lead-lag correlation between the TBO and the SST anomaly in the western Indian Ocean. That is because the changing signals of the tropical SST anomalies always appear in the central-eastern Pacific firstly, and then propagate to the western Indian Ocean.

(3) The behavior of the WPSH TBO cycle is the results of the typical ocean-atmosphere interaction. In the course of a WPSH's TBO cycle, the occurrence of the El Niño-like anomaly in the tropical central-eastern Pacific in winter is always coupled with the weak East Asian winter monsoon, when the WPSH' TBO is in the third phase with the most significantly enhancing period. In contrast, the La Niña-like anomaly in the central-eastern Pacific in winter is coupled with the strong East Asian winter monsoon, when TBO is in the seventh phase with the most decaying period.

(4) The tropical SST and atmospheric circulation anomalies present the asymmetric distribution in the TBO cycle. The WPSH's TBO is more significant in the period of the developing El Niño-like state in central-eastern Pacific than in the period of the developing La Niña-like state. Therefore, in the period of developing El Niño-like state, more attention should be paid to the interannual component of TBO signal in the short-term climatic prediction.

It is seen from the above statistics that the most significant variation of SST anomaly is in the equatorial central-eastern Pacific in a complete WPSH's TBO cycle. The SST anomaly evolution in the tropical Indian Ocean and warm pool area always lag by about one season to the El Niño-like or La Niña-like state, and their degree of abnormality are also much weaker than the SST anomalies in tropical central-eastern Pacific. Therefore, the modulation of the SST in tropical central-eastern Pacific on the WPSH's TBO seems to be earlier and more important than others.

The SST anomalies evolution in the Indian Ocean plays an enhancing role in the TBO cycle, which is consistent with the findings by Meehl et al. [36].

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