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Relationship between the zonal displacement of the western Pacific subtropical high and the dominant modes of low-tropospheric circulation in summer

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Abstract

The zonal displacement of the western Pacific subtropical high remarkably influences the climate anomalies in China. In this paper, a new zonal index of the subtropical high is defined by modifying previous indices, and is used to investigate the relationship between the zonal displacement of the subtropical high and the dominant modes of 850-hPa circulations. It is found that the zonal displacement of the subtropical high is significantly correlated with the first two leading modes of circulations. In particular, the correlation coefficient between the index and the time series associated with the second mode is as high as 0.78 in 1958–2003 (46 years). Since the second mode is not associated with significant anomalies of sea surface temperatures, the above results imply the difficulty in seasonal forecasting of the zonal displacement of the subtropical high. In addition, the interannual variability in the zonal displacement of the subtropical high has been considerably enhanced since 1978, due to the effects of both dominant modes, especially the second mode. This is likely to account for the frequent occurrence of anomalous climate in China during the recent two decades.

Keywords: Western Pacific subtropical high; General circulation; Dominant mode; Interannual variability; Interdecadal variation

1. Introduction

The subtropical high over the western north Pacific (WNPSH) is one of the dominant components in the East Asian summer monsoon system, with the lower-tropospheric southwesterlies at its northwest side transporting a large amount of water vapor into East Asia. Therefore, its location, shape and intensity dominate the large-scale quasi-stationary front in East Asia [1,2].

Less attention has been paid to the displacement of the WNPSH in the zonal direction, in comparison with that in the meridional direction. However, a zonal displacement of the WNPSH also plays an important role in affecting the East Asian monsoon by influencing the path of water vapor flux and the resultant precipitations in East Asia. Thus, there were some recent studies on the zonal displacement of the WNPSH. Zhang et al. [3,4] examined the impacts of mature events of the El Niño-Southern Oscillation (ENSO) on the atmospheric circulation over East Asia and precipitations in China, and indicated that during the ENSO mature periods, the WNPSH exhibits a westward

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displacement, resulting in more precipitations in Changjiang River Basin and less precipitations in North China and South China. Lu [5] and Lu and Dong [6] found that atmospheric convection anomalies over the Philippine Sea lead to significant zonal displacement of the WNPSH, through triggering lower-tropospheric cyclonic or anticyclonic anomalies over the western North Pacific. Furthermore, Xue and He [7] suggested that on the sub-seasonal timescale, the zonal displacement of the WNPSH is affected by the changes in the Mascarene high and Australian high in the Southern Hemisphere.

500-hPa geopotential heights have been widely used in China to depict the change in the WNPSH [1,8–11]. For instance, China Meteorological Administration defined the WNPSH indices by using 500-hPa geopotential heights. However, the WNPSH appears to be much more stable and stronger at the low troposphere than in the middle troposphere. In addition, the southwesterlies associated closely with the WNPSH transport a large amount of water vapor into East Asia, and thus have a remarkable effect on summer precipitations in China. Therefore, in this study, 850-hPa circulations are adopted to describe the zonal displacement of the WNPSH.

Most recently, Lu et al. [12] examined the leading modes of the interannual variability of the summertime lower-tropospheric circulation over the western North Pacific, and investigated the potential predictability of these modes. The first mode, which is characterized by tropical anomalies and referred to as the "tropical mode", is affected significantly by sea surface temperatures (SSTs). On the other hand, the second mode, which is characterized by a meridional teleconnection pattern over the western Pacific, and is referred to as the "meridional mode", is dominated by internal atmospheric variability. Their results were based on reanalysis and modeling data during 15 years (1986–2000) so as to be consistent with the modeling period. This period might not be adequately long for depicting the interannual variability. In this study, thus, we use a longer period (1958–2003) of reanalysis data.

What is the relationship between the variability in the WNPSH and the above-mentioned leading modes of circulation variability? Furthermore, to what extent, can the leading modes depict the variability in the WNPSH? These two questions are to be answered in this study, with focus being laid on the zonal displacement of the WNPSH.

2. Modification in the definition of the WNPSH zonal index

To objectively measure the year-to-year displacement of the WNPSH in the zonal and meridional directions, Lu [13] defined a zonal index and a meridional index based on the JJA-mean 850-hPa geopotential height anomalies over specified regions. For the zonal index, the specified region is (110–150°E, 10–30°N), while for the meridional index, the specified region is (120–150°E, 30–40°N). These indices, however, may be affected by the artificial trends in the WNPSH variations. These variations are likely to be a consequence of the lifted isobaric surface at the low latitudes, which in turn is due to the global warming as well as other reasons [14,15]. To avoid artificial decadal variations, Yang and Sun [14,15] used the 500-hPa anomalies of relative vorticity, rather than geopotential height, averaged in the area (115–140°E, 22.5–30°N) as an index for the zonal displacement of the WNPSH.

The NCEP–NCAR reanalysis data for 46 years from 1958 to 2003 are used in this study. Summer represents three months from June to August (JJA). Fig. 1 shows the spatial distribution of correlations between the former zonal index, which is defined by the 850-hPa geopotential height anomalies averaged over (110–150°E, 10–30°N) [13], and time series of 850-hPa relative vorticity at each grid point. Locally, i.e., over the western North Pacific and the north part of the South China Sea, the correlation coefficients are negative, while they are positive over the south part of the South China Sea, central China, Korean Peninsula and southern Japan.

We follow the approach of Yang and Sun [14,15], and adopt relative vorticity to define the zonal index of WNPSH, to avoid artificial trends of the WNPSH. In addition to this, we adopt the level of 850 hPa, rather than 500 hPa as in Refs. [14,15], due to the reasons mentioned in Section 1. Furthermore, based on the correlations shown in Fig. 1, the averaging area is designated as (125–150°E, 15–27.5°N), which is different from previous studies.

In summary, the zonal index of the WNPSH is defined by JJA-mean 850-hPa relative vorticity anomalies averaged over (125–150°E, 15–27.5°N). The western border of this region is shifted relatively eastward in comparison with borders documented in previous studies, for the purpose of diminishing the possible noises caused by topography. However, we found that slight modifications of the western border, for instance, designating it as 110°E, did not change appreciably the present results. The correlation coefficient between the present index and the index defined by geopotential height [13] is −0.69. The negative sign of the correlation coefficient results from the negative correlation between relative vorticity and height. In addition, the

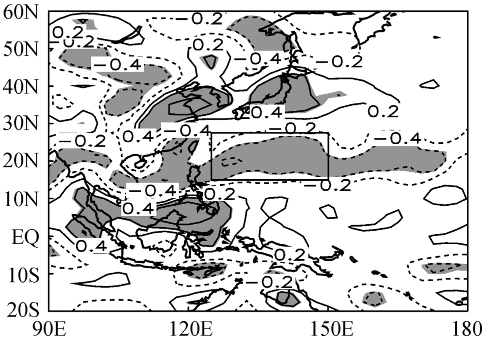

Fig. 1. Spatial distribution of the correlations between 850-hPa height averaged over (110–150°E, 10–30°N) and relative vorticity at each grid in summer. The shading indicates the regions of 99% significance level. The box in the figure indicates the averaging area used to define the zonal index of the WNPSH in this study.

correlation coefficient between the present index and the index defined by the 500-hPa relative vorticity [14] is 0.52. These correlation coefficients are statistically significant at the 99.9% level, which demonstrates that the present index is reasonable.

3. Relationship of the leading modes of circulation over the western Pacific

An Empirical Orthogonal Function (EOF) analysis was performed on 46-year time series of JJA-mean 850-hPa zonal wind over the area (90–180°E, 20°S–60°N). Fig. 2 shows the spatial structures of the two leading EOF modes of the JJA-mean 850-hPa zonal wind. The present EOF analysis is the same as that in Lu et al. [12], but with a much extended period of data: 46 years in this study, while 15 years in the study of Lu et al. [12]. Despite the extended data period, the two leading modes shown in Fig. 2 exhibit almost identical spatial patterns to those in Lu et al. [12]. The first mode is characterized by tropical anomalies, which is the so-called "tropical mode"; while the second mode is characterized by a meridional teleconnection pattern over the western Pacific, the so-called "meridional mode". The first two leading modes explain totally 40% of the total variance. They explain less variance than the first two leading modes obtained by short data period [12], which is likely to be due to the involvement of an artificial interdecadal variation in Asia when using the 46-year NCEP–NCAR reanalysis data [16] (shown as the third leading mode which explains over 10% of total variance, which is not given here). However, there are not any appreciable signals in the lower troposphere over the eastern Eurasian continent in the spatial patterns for the first two leading modes (Fig. 2(a) and (b)), suggesting that the present results are not noticeably affected by the spurious data.

In order to investigate the relationship between the zonal displacement of the WNPSH and the first two EOF modes, the time series of the zonal index and the principal components (PCs) associated with the two leading modes are shown in Fig. 3. The zonal index is closely correlated to the PC-1 and PC-2, with the correlation coefficients, 0.48 and 0.78, respectively, both significant at the 99.9% level. These correlation coefficients suggest that the "meridional mode" may account for 61% of the variance for the zonal displacement, and the "tropical mode" may account for 23% of the variance. Thus, the zonal displacement of the WNPSH is dominated by the two leading modes, with 84% of variance explained, indicating that the zonal displacement of the WNPSH is one of the dominant features of lower-tropospheric circulation anomalies over the western Pacific.

The "meridional mode" explains a greater amount of the variance in the WNPSH zonal displacement than the "tropical mode" does, with the variance explained by the former being almost three times greater than that by the latter. The "tropical mode" is significantly affected by SSTs, and thus has a higher predictability, while the

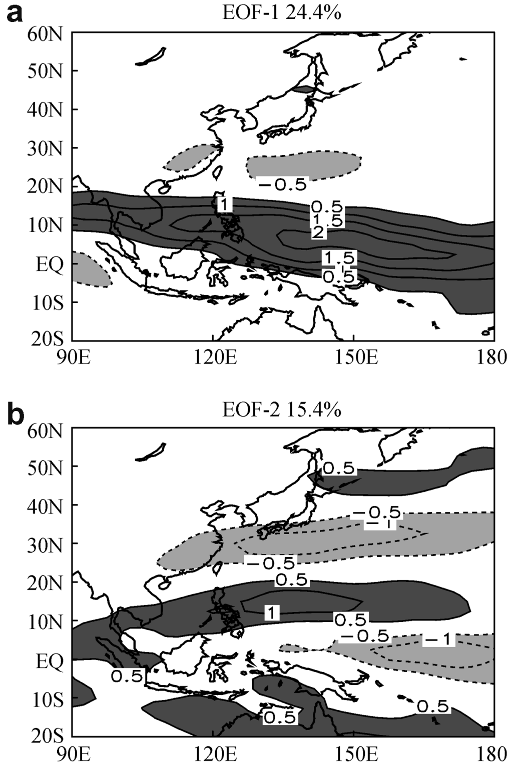

Fig. 2. Spatial patterns of the leading modes of JJA-mean zonal wind at 850 hPa. Unit is arbitrary. The fractions of variance explained by respective modes are also given. (a) The first mode; (b) the second mode.

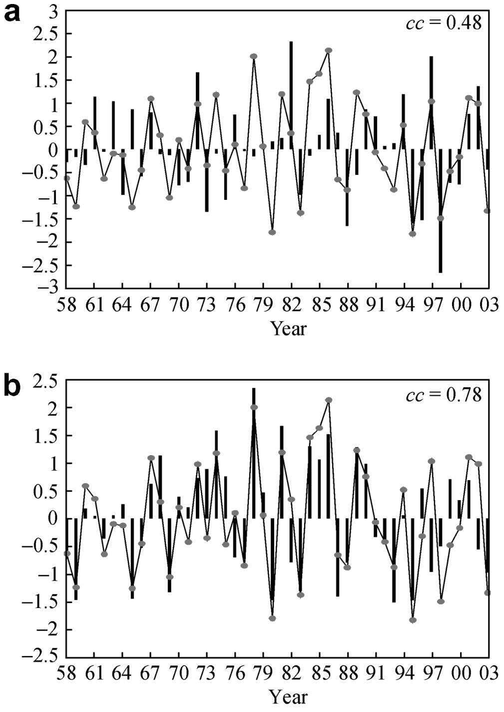

Fig. 3. Time series of the zonal index of the WNPSH (bars) and the principal components of the leading modes (lines). (a) The first model; (b) the second mode. All values are standardized. The correlation coefficients between the zonal index and principal components are also given.

"meridional mode" is dominated by internal atmospheric variability, and thus has a lower predictability [12]. Therefore, it can be implied that the zonal displacement of the WNPSH may be dominated by internal atmospheric variability and have a low predictability, although SSTs affect the zonal displacement to some extent.

Fig. 3 also shows that the zonal index tends to show a stronger interannual variability after the late 1970s, and the PC-2 also exhibits a similar tendency. The standard deviation of the zonal index during 1978–2003 is 1.6 times larger than that during 1958–1977. This change in the WNPSH may be related to the sudden climatic change in the late 1970s [17,18].

The interdecadal changes are further examined by standard deviation in a running 7-year window (Fig. 4). That is, the values of 1982 in Fig. 4 are standard deviation during 1979–1985, and can be used to measure the intensity of interannual variability around 1982. Fig. 4 indicates that the interannual variability becomes more intense after the late 1970s, is suppressed in the late 1980s, and is slightly intensified in the 1990s.

Fig. 4 also shows the standard deviation of PC-1 and PC-2 in a running 7-year window. It indicates that the zonal index exhibits a reasonably similar interdecadal variation in the intensity of interannual variability to that of the PC-2. A slight difference appeared in the 1990s: interannual variability being suppressed in PC-2 but slightly intensified in the zonal index. This difference is likely to be due to the much stronger interannual variability of PC-1 for the most recent decade, in comparison with the preceding three decades (Fig. 4). This suggests that the PC-1 may also contribute to the interdecadal variation of interannual standard deviation of the zonal index, but to a much weaker extent in comparison with the PC-2.

We have calculated standard deviations in running 5- and 9-year windows, and similar results are obtained.

4. Conclusions

We have examined the zonal displacement of the WNPSH, by using the NCEP–NCAR reanalysis data from 1958 to 2003. First, we present a new definition of zonal index to measure the zonal displacement of the WNPSH, after modifying previous indices. The present zonal index is defined by JJA-mean 850-hPa relative vorticity anomalies averaged over the area (125–150°E, 15–27.5°N), and it is highly correlated with previous ones. In addition, the present results are not sensitive to the slight changes in the averaging scopes. Thus, we can conclude that the definition of zonal index in this study is reasonable.

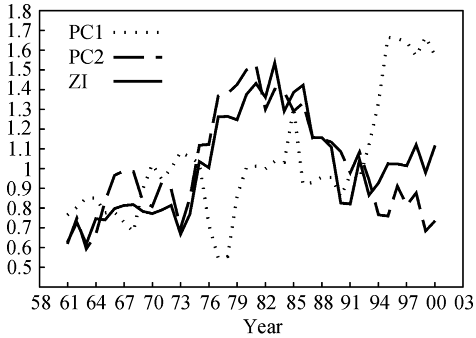

Fig. 4. Standard deviation in a running 7-year window. Dotted, dashed and solid lines are for the PC-1, PC-2 and zonal index, respectively. To facilitate comparison, three lines show the time series after standardization.

Second, we used the zonal index to investigate the relationship between the zonal displacement of the WNPSH and leading modes for 850-hPa zonal wind anomalies. It is found that the zonal displacement of the WNPSH is significantly correlated with the two leading modes. Both the correlation coefficients are significant at the 99.9% level. In particular, the correlation coefficient between the zonal index and the second mode is as high as 0.78. The two leading modes may explain 84% of the variance of the WNPSH zonal displacement, indicating that the WNPSH zonal displacement is one of the main features of the interannual variability in lower-tropospheric circulation over the western Pacific. On the other hand, it would be quite difficult to make reliable seasonal forecasts on the WNPSH zonal displacement, since the zonal displacement is more closely related to the second mode, which does not respond significantly to SST anomalies.

The intensity of the interannual variability of the WNPSH zonal displacement exhibits a clear interdecadal variation. The intensity of the interannual variability become enhanced in the late 1970s and suppressed in the late 1980s, followed by a slight increase in the 1990s. This interdecadal variation is dominated by the second mode, but modified by the first mode in the 1990s. Due to the limited period of reanalysis data, the roles of the leading modes on the interdecadal timescale mentioned in this study need to be confirmed. In addition, more studies are required to understand the physical mechanisms responsible for the interdecadal variations of interannual standard deviations in the leading modes.

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