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INDEX OF DIRECTION CHANGE OF ZONALLY AVERAGED WIND AND CHANGE OF SEASON

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Abstract: In this paper, a Wind Direction Change Index (WI), which can describe four-dimensional spatiotemporal changes of the atmospheric circulation objectively and quantitatively, is defined to study its evolution and seasonal variation. The first four modes can be obtained by EOF expansion of the zonally averaged WI. The first mode reveals the basic spatial distribution of the annually averaged WI. The second mode reflects the quasi-harmonic parts of the WI deviations. Tropical, subtropical and extratropical monsoon areas can be clearly reflected by this mode. The third mode reflects the non-harmonic parts of the WI deviations. It shows the so-called February reverse in stratospheric atmosphere as well as the asymmetric seasonal changes from spring to fall and from fall to spring due to both the land-sea distribution contrast between the Northern and Southern Hemispheres and the nonlinear effect of atmospheric and ocean fluids. The fourth mode reveals the northward advancing of the global reversed wind fields from spring to summer and their southward withdrawal from summer to autumn.

Key words: Wind Direction Change Index (WI); Empirical Orthogonal Function (EOF); four-dimensional space-time changes; February stratospheric reverse

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1 INTRODUCTION

Addressing the relationships between the abrupt changes in East Asian circulation and monsoon outbreaks, Zhu[1] and Tu et al.[2, 3] pointed out, as early as in the 1930s, that the East Asian monsoon regions and monsoons and Mei-yu in China are closely related to the atmospheric circulation on the global scale. Monsoon circulation does not appear just in the lower levels; it is also quite remarkable at the higher levels and often gets out-of-phase and has reversed wind direction with the lower levels. The monsoon has clear-cut vertical structure and is highly baroclinic[4, 5], and the subtropical monsoon in both the Northern Hemisphere (NH) and Southern Hemisphere (SH) is renowned for being a powerful, deep system[6]. Monsoon outbreaks are closely associated with seasonal change[7], which takes place in the stratosphere at the earliest[8, 9]. All of these findings have shown that the monsoon and its change are no longer processes confined to the troposphere (or just the mid- and lower-troposphere); instead, they are part of the overall process of seasonal change that includes changes in both the troposphere and stratosphere. The abrupt change in monsoon circulation is accomplished under the general background of atmospheric circulation adjusting across the globe and seasonal change is the result of such adjustment. It is therefore necessary to study the seasonal change and monsoon systems by way of four-dimensional spatiotemporal variations of the global atmospheric circulation, for it will be of great help to understanding and predicting short-term climate change.

Abrupt seasonal changes of the general circulation can be expressed by defining a standardized seasonal variability, similarity and dissimilarity parameters[10, 11, 12]. On this basis, the seasonal variability of the wind field and seasonal variability of a dynamic, standardized wind field are defined by Li et al.[4, 13] to study global monsoon regions and their annual variations. The abrupt change of the atmospheric circulation prior to and after the onset of the monsoon and dates of monsoon outbreaks are investigated by further defining the variation (Zeng et al.[8]). All of the above new concepts about the seasonal division and abrupt seasonal changes of the monsoon and objective and quantitative

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computational methods have described the properties of the monsoon in a general, concise and detailed manner and revealed many new facts. The research studies the monthly scale of the seasonal change by focusing on the reversed directions of two different fields of wind vectors in January and July. As a matter of fact, the general circulation keeps changing in both time and space and so does the reverse of the wind field. Monsoon represents the situation when the temporal dimension takes summer (usually with July as the representative month). Based on the variations of daily averaged wind-vector field, this study attempts to examine the law governing the spatiotemporal evolution and seasonal changes of the atmospheric circulation by defining a wind direction change index, WI, which describes four-dimensional changes objectively and quantitatively.

2 DATA AND METHODS

2.1 *Definition of WI, indicator of change in wind direction*

Li et al.[4, 13] have proposed an index that describes the dynamic, standardized seasonal variability of the seasonal change (which is applicable for the monthly mean field only) and presented the geographic distribution of global tropical monsoon, subtropical monsoon and mid- and high-latitude monsoon. Making use of the index, this study broadens the application from the monthly mean field to the daily mean field that has been processed with 5-day running mean, making it possessing the scale of pentads. One advantage of doing so is that the time scale is resolved in finer detail so that the evolution patterns of the atmospheric circulation can be reflected in more detail. Called the Wind Direction Change Index (WI), the modified index can be used to describe the abrupt seasonal change in the global circulation objectively, study the three-dimensional spatial variation of the circulation field with time, and depict how the season changes.

For the *t*th day the WI is defined as

$$\text{WI}=\frac{\|\overline{v}_1-\overline{v}_t\|}{\|(\overline{v}_1+\overline{v}_t)/2\|}-2 \qquad (1)$$

where $\overline{v}_1$ is a 5-day averaged wind vector field for January 1st–5th, which can be used to stand for the climatological state in winter, and $\overline{v}_t$ represents a wind vector field processed with 5-day running averaging centered on the *t*th day.

Take a given isobaric surface *z* and denote the domain on a spherical surface as *S*, i.e., $((x, y)\in S)$ where *x* is the longitude and *y* is the latitude. Then, quantity *A* has a norm of $\|A\|$ that is defined as follows.

$$\|A\|=(\iint_s |A|^2 \,\mathrm{d}S)^{1/2} \qquad (2)$$

where *S* is the domain to be determined by compution. In operational practice, a five-point formula is used to obtain an approximate value of the norm (the formula is derived with the areal integration of the trapezoidal area; see Zhu[14] for concrete steps of the derivation):

$$\|A_{i,j,t}\| \approx \Delta S[(|A^2_{i-1,j,t}|+4|A^2_{i,j,t}|+|A^2_{i+1,j,t}|)\cos\varphi_j + |A^2_{i,j-1,t}|\cos\varphi_{j-1}+|A^2_{i,j+1,t}|\cos\varphi_{j+1}]^{1/2} \qquad (3)$$

where φ_j is the latitude where point (*i*, *j*) is located, $\Delta S=a\Delta\varphi\Delta\lambda/4$, *a* is the average radius of the Earth, $\Delta\varphi$ and $\Delta\lambda$ stand for the resolutions at the longitude and latitude, respectively, with the unit being the radian. When the WI is computed, ΔS is not included. As both the numerator and denominator exist in Eq. (1), they can be ignored.

2.2 *Data processing and physical meaning of WI*

This study uses the global longitudinal and latitudinal wind field data from the National Centers for Environmental Prediction (NCEP, USA) for 1966–2005 (over a length of 40 years). The 40-year wind field data are daily averaged over 365 days a year (for both the normal and leap years) to obtain 365 daily samples over the globe (0–360° E, 90° S–90° N, at mesh intervals of $\Delta\varphi\times\Delta\lambda$=2.5° ×2.5° and 17 vertical layers). The daily samples are then processed with 5-day running averaging so that data for each day contain information for the previous two days, the previous day, the current day, the successive one day, and the successive two days, being able to reflect the variation on the pentad scale. Through Eq. (1), the wind field data averaged with 5-day running are used to obtain the four-dimensional flow form of the WI, i.e., its distribution in the latitudinal and longitudinal direction and with height as well as its daily variation with time.

The physical meaning of the WI is studied next. Set α the angle between $\overline{v}_1$ and $\overline{v}_t$. Then, when 0≤α≤90°, WI<0; when α=90°, WI=0; when 90°<α≤180°, WI>0 (See Zhu[14] for detailed mathematical proving). It is then seen that WI=0 is the critical value when wind field $\overline{v}_1$ gets reversed in direction with wind field $\overline{v}_t$. When WI>0, it shows a major circulation characteristic that significant changes are taking place in the field of vector wind of the *t*th day processed with 5-day running mean and the field of mean wind vector for first five days of January (which could be viewed as the climatological state of winter). When the time dimension takes 365 days, the WI—a daily expression—is able to describe the pattern of evolution of the atmospheric circulation in three dimensions throughout the year. When the time dimension takes daily basis for the summer (June through August), a WI>0 indicates how a prevailing wind field in winter is reversed from that of summer.

2.3 *EOF decomposition*

See Zeng[15] and Huang[16] for concrete steps of Empirical Orthogonal Function (EOF) analysis. Significance tests should be performed to see whether the decomposed EOFs (i.e., eigenvectors) have physical meaning or are just noise that does not make sense; such tests are especially important when the number of spatial points of a variable field is larger than that of associated samples. In this study, the significance test is carried out by computing the range of eigenvalue errors as proposed by North et al.[17]. The error of the eigenvalue λ_j is expressed by

$$e_j = \lambda_j \sqrt{2/n} \tag{4}$$

where n is the quantity of samples. When λ_{j+1} of two consecutive eigenvalues satisfies λ_j-$\lambda_{j+1} \geqslant e_j$, the EOFs corresponding to them are considered to be meaningful.

3 EOF ANALYSIS OF ZONALLY AVERAGED WI

With the time dimension fixed, the WI is used to obtain a three-dimensional spatial distribution of the region where the winter prevailing wind is in reverse direction with the summer one. Studies found that this index is basically distributed on the latitudinal circle. Based on this characteristic, the WI is averaged latitudinally to examine the temporal evolution of the height-latitude cross sections of the WI.

The WI is averaged latitudinally (by taking half weights at the terminating point) and the averaged WI field (made up of 365 days of data) is EOF-decomposed. The first four modes passed the significance test by variances of 49.57%, 29.44%, 8.02%, and 4.71%, respectively, with cumulative variance contribution as high as 92%. Next, each of these four modes is studied in detail.

3.1 *First mode*

In the distribution of the first-mode spatial field (Fig. 1a), the shaded zone (indicating the area larger than 0, same below) is located above 100 hPa in the mid- and higher-latitudes of SH, generally south of 20° S, and areas around 30° N in NH, with the edge of the shaded zone lying on the line dividing the easterly and westerly; the austral coverage is much broader than the boreal coverage with negative values appearing at levels below 100 hPa. The time coefficient is always positive for the first mode (Fig. 1b), which reaches its peak on March 13th and its valley on July 22nd.

By averaging the daily WI field, which has already been averaged over the latitudinal circle, over the entire year, an annually averaged WI field can be obtained that is also latitudinally averaged (Fig. 1c). For the ease of denotation, the former is called the WI field while the latter the annually averaged WI field. It is found that the distribution of the annually averaged WI field is roughly consistent with that of the spatial field of Mode 1 (Fig. 1a); the two is correlated by a coefficient as high as 0.99. It can then be known that what Mode 1 reveals is the annually averaged WI field, or the basic part of it—a basic state. The magnitude of the time coefficient of a particular day for Mode 1 shows the proportion of the WI field of that day in the basic state; its peak (occurring on March 13th, or eight days before the Spring Equinox) indicates the largest proportion of the WI field in the basic state while its valley (appearing on July 22nd, a month after the Summer Solstice) shows the smallest proportion.

If the Earth and the Sun had a zero obliquity of the ecliptic, the Earth would rotate around the Sun in a circular orbit, and the Earth would be covered with water of homogeneous depths, no seasonal changes would have taken place. When this WI field is studied for EOF, results thus yielded should reflect the basic state with its time coefficient being a horizontal straight line. (The line could in fact fluctuate mildly due to the non-linearity of the atmosphere and the existence of physical processes of different time scales.) However, the real obliquity of the ecliptic is 23.5° , which gives rise to seasonal changes. On the other hand, as the obliquity is quite moderate, the basic state takes up considerable proportion relative to the actual Earth. At the point of Spring Equinox, the Sun radiates normally on the Equator, exposing the NH and SH to the same amount of solar radiation and therefore presumably making the basic state in the maximum proportion. At the point of Summer Solstice, however, the midday zenith of overhead solar rays is the farthest to the Equator, presumably making the basic state in the minimum proportion. On the other hand, due to the lagging properties of the response of physical processes to solar radiation and the non-linearity of atmospheric and oceanic fluids, the transitions from spring to autumn and from autumn to spring are not symmetric in terms of temporal variation, resulting in the curves of time coefficient as shown in Fig. 1b. In addition, differences in land-sea proportion between the SH and NH lead to the fact that the spatial distribution of the mode is not entirely symmetric in the two hemispheres.

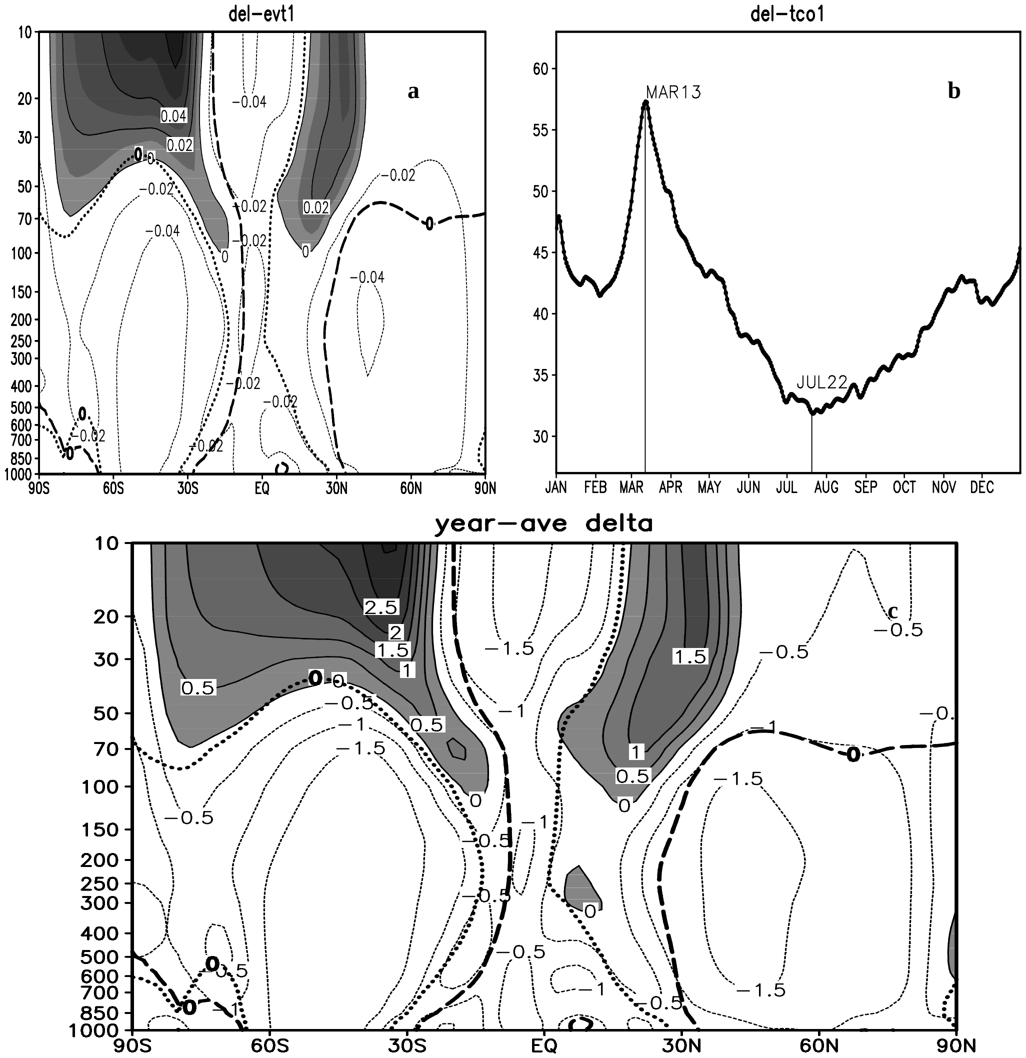

Fig. 1. First mode decomposed by 365-day data field of WI latitudinally averaged; a: spatial field; b: time series; c: averaged WI field. The shades are for regions greater than zero; dotted lines and dashed lines stand for the zero lines dividing the easterly and westerly in January and July, respectively.

3.2 *Second mode*

Next, let's see how the second mode distributes spatially. Fig. 2a shows that except for high-latitude areas, the spatial structure of the shaded area is roughly in "X"-shaped distribution with high-value areas around 30° in both the hemispheres. Likewise, the asymmetric distribution of land and sea in the hemispheres also result in the asymmetric distribution of the mode. The largest difference between the time coefficient of the second mode and that of the first mode is that it is not always positive throughout the year; instead, it is negative in the winter-half year but positive in the summer-half year (Fig. 2b) and roughly in the form of simple harmonic oscillation. Its value attains the maximum on July 21st but the minimum on January 1st while being zero on April 19th and October 14th. Each of these dates corresponds to the time after the summer solstice, winter solstice, vernal equinox and autumnal equinox, respectively, suggesting the lagging effect of seasonal changes to solar radiation. As indicated in the variation of this time coefficient, the "X"-shaped spatial pattern is the most remarkable in summer and the phase is reversed between summer and winter, displaying the vertical spatial structure in the region of reversed prevailing wind direction in the two seasons and the distribution of tropical, subtropical and extratropical monsoon areas. It is noteworthy that the change in the wind field—caused by seasonal changes—is very obvious in the mid-latitude stratosphere where there is significant reverse of prevailing wind direction, different from the first mode.

To further examine the nature of the second mode, the WI fields are first latitudinally averaged over different periods of time. It is done first by averaging the daily WI field—already averaged latitudinally—over the same period of time (called the averaged WI field for that period), and then by correlating this WI field with the spatial field of the second mode. Results so determined are listed in Table 1. It shows that the averaged WI spatial fields for June, July and August are correlated with the spatial field of the second mode by a coefficient as high as 0.92, with the highest in July (0.95). Next, the WI fields averaged over June, July and August are sought for correlation with the spatial field of the second mode, which shows a correlation coefficient of 0.96, even higher than that of July. All of the above correlation coefficients pass the significance test of $\alpha = 0.01$. The WI fields averaged over June, July and August can be called the summer averaged WI fields and the second mode reflects the basic part of these fields. It is known from the discussion above that the basic state in summer takes up the least proportion in the summer WI field, i.e., the WI field has the most deviation from the basic state; in spring, however, the basic state takes up the largest proportion, i.e., the WI field has the least deviation from the basic state. As indicated in the time coefficient of the second mode, it is the largest in summer but nearly zero in spring. It is then known that what the second mode shows is actually the quasi-simple harmonic fluctuation of the deviation of the WI field. In other words, it demonstrates the quasi-harmonic variation of the wind field in the seasonal changes caused by solar radiation.

Table 1. Correlation coefficients between the spatial field of the second mode and that of WI averaged over different months

Month	4	5	6	7	8	MJJ	JJA	JAS
Correlation coefficient	0.31	0.69	0.92	0.95	0.92	0.93	0.96	0.93

Notes: MJJ indicates the 3-month mean for May, June and July, JJA that of June, July and August, and JAS that of July, August and September, all passing the significance test of $\alpha = 0.01$.

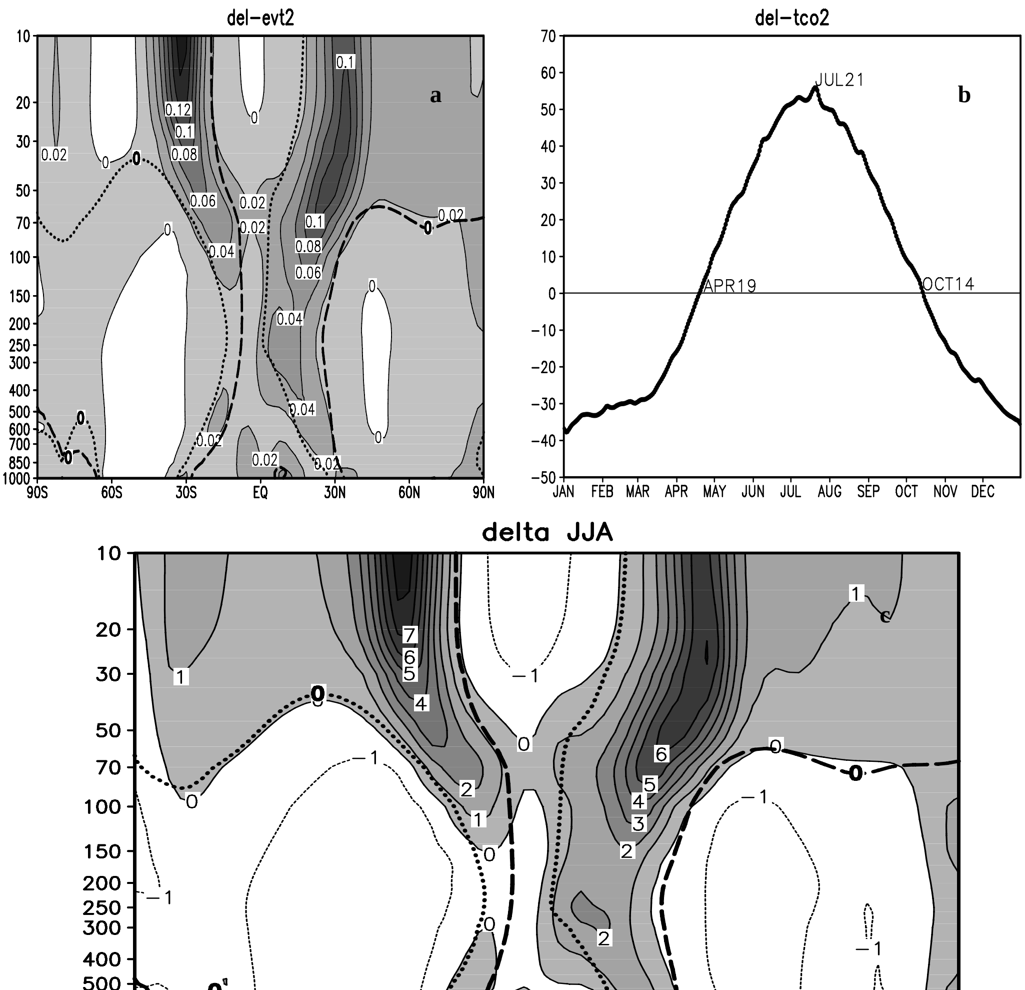

Fig. 2. Second mode decomposed by 365-day data field of WI latitudinally averaged. (a) spatial field; (b) time series; (c) height-latitude cross sections for summer (three-month average of June, July and August)

The sum of the contribution from the first and second mode is 49.57%+ 29.44%=70.01%, implying that these two modes suffice to explain the most contribution of the total variance.

3.3 *Third mode*

In the spatial field of the third mode (Fig. 3a), a large positive center is located at the upper levels of 10–50 hPa in the SH between 90° S and 40° S while a weak negative area exists in the blank region near 30° in both the hemispheres. What the spatial field of the third mode shows is that the phase is reversely distributed between the mid- and higher-latitudes and mid- and lower- latitudes. This spatial field also shows that the asymmetricity between the SH and NH is more obvious than the two modes above. For the curve of the time coefficient (Fig. 3b), a reverse of the prevailing wind first appears in the mid- and higher- latitude stratosphere of SH in early February, i.e., the wind field undertakes abrupt changes in February. In the last 10 days of February, the time coefficient turns from negative to positive, showing that the post-change prevailing wind direction is opposite from that of the winter climate state. In March, the time coefficient reaches the maximum in the positive sector, indicating that the mode is most significant in spring. From summer to the mid-autumn, the time coefficient stays negative, a sign that indicates a prevailing wind direction reversed from spring. In a short, warm stretch during late autumn, however, the time coefficient becomes mildly positive again when the prevailing wind direction is once again the same as in spring. Then, with the onset of winter, the time coefficient turns negative again and the prevailing wind direction goes opposite with that of spring. As shown in the variation of the time coefficient, what the third mode reflects is another part of the WI field deviations, i.e., the non-harmonic variation with time. This part mainly depicts the asymmetricity of the seasonal change from spring to autumn and from autumn to spring, which result from the differences in land-sea distribution between the SH and NH and the non-linear effect of fluids in the atmosphere and oceans.

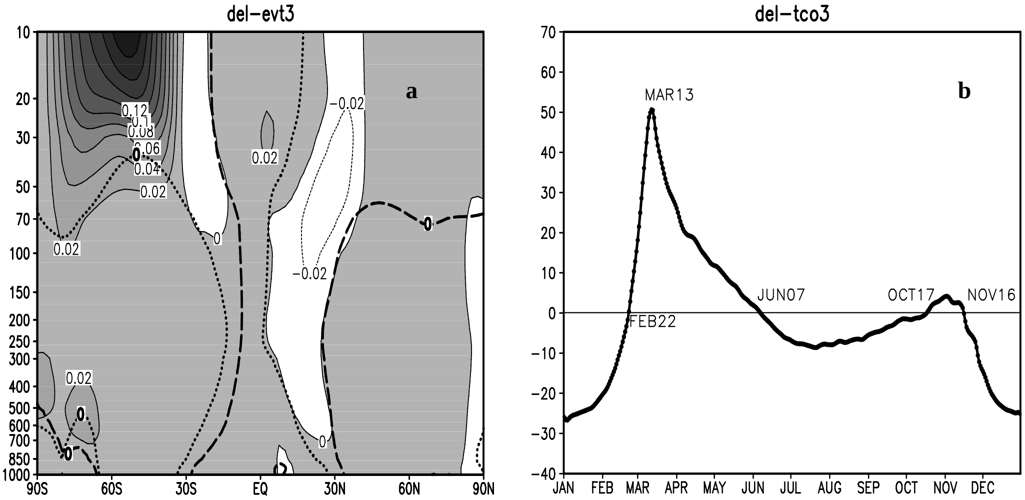

Fig. 3. Third mode decomposed by 365-day data field of WI latitudinally averaged. (a) spatial field; (b) time series

It is known from the above discussion of the first two modes that the seasonal change in the stratospheric wind field is very obvious. To examine the behavior of the third mode, the WI values at the levels of 10–50 hPa are averaged and then a latitude-time cross section is drawn (Fig. 4a). A well-defined reverse of prevailing wind direction first appears at the high latitudes of SH in early February and the WI gets the maximum in early- and mid-March. Afterwards, the northern boundary of the reversed wind direction zone pushes to the Equator and arrives at 15° S before shifting back towards the south. In the NH, the reverse of prevailing wind direction first occurs in mid-April with an area of large values around 30° N. The isolines of the WI in NH advance north before heading south, both moderately, but less obviously than the variation in SH.

Averaging is once again applied to the latitudinally averaged WI value over the region (50–10 hPa, 90–40° S) to determine the variation of the averaged WI value over time (Fig. 4b). Then, its correlation is sought with the time coefficient of the third mode to obtain a coefficient (as high as 0.97). It shows that for the third mode, the WI value in the above region—the mid- and higher-latitude stratosphere in SH—is playing a key role in the seasonal change of the mode.

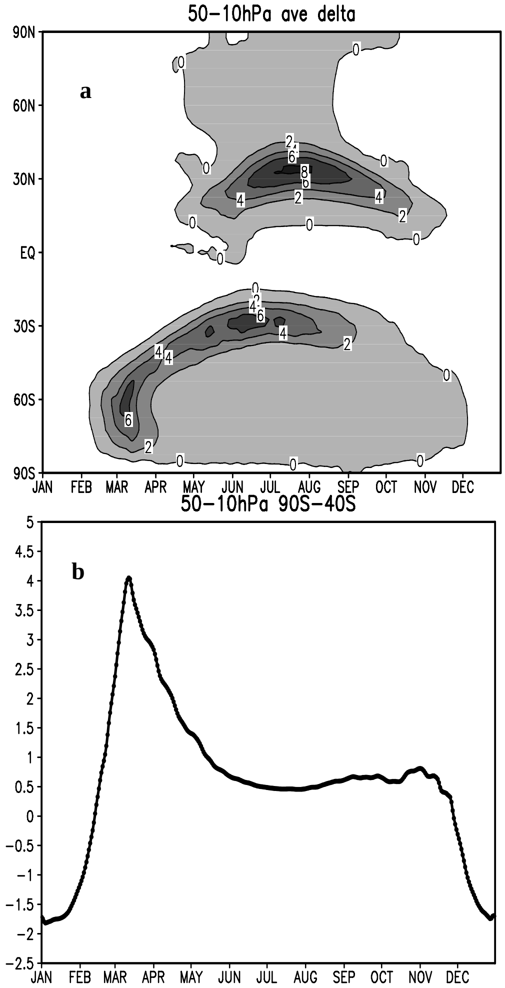

Fig. 4. Latitude-time cross sections (a) of the WI at the levels of 50–10 hPa and temporal evolution of WI in the region of 90–40° S (b), after it is latitudinally averaged

3.4 *Fourth mode*

The spatial field of the fourth mode (as shown in Fig. 5a) is negative in high-latitude SH with the center of a large positive area at 50–10 hPa, 40–30° S. For the NH, 35° N is the boundary that separates a negative area to its south from a positive one to its north (till 60° N). The time coefficient (Fig. 5b) is at the valley (negative) in early March and at the peak (positive) in mid-May, with April being the transitory month. Generally, February–April is negative, April–mid- and late-June is positive, and July–November is negative.

All of these indicate that the prevailing wind is reversed in the high latitudes of SH in February–April with the value of WI being the maximum in March; the prevailing wind direction in April–June is once again the same as that of winter (December–January) but the reverse occurs again in July–November. In the NH, the reverse of prevailing wind direction appears in April–June in the area south of 45° N in February–April and in the area north of 45° N, and the region of reversed prevailing wind direction moves back to the area south of 45° N in July–November. It is then clear that the fourth mode reflects how the reversed prevailing wind direction advances northward from spring to summer and retreats southward from summer to autumn at various levels of the globe. Due to the non-linearity of the atmospheric and oceanic fluids, these processes are not symmetric temporally.

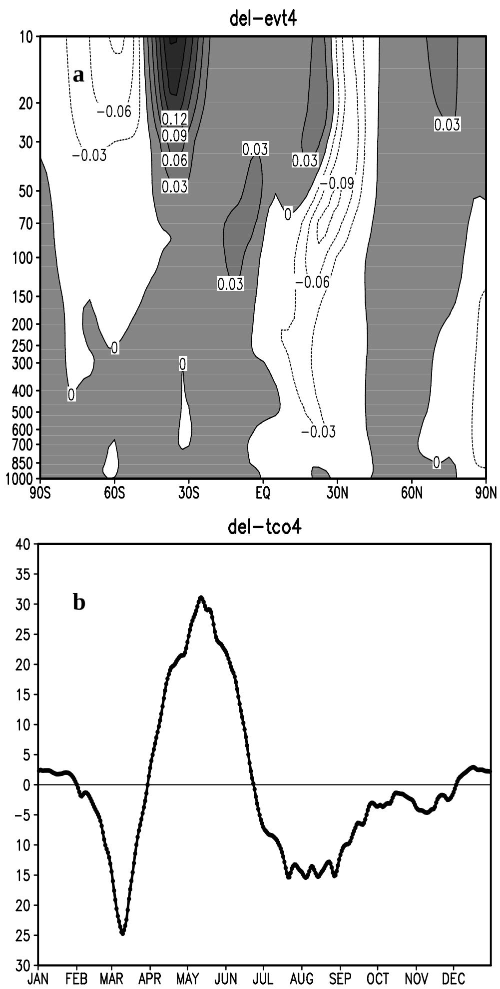

Fig. 5. Fourth mode decomposed by 365-day data field of WI latitudinally averaged. (a) spatial field; (b) time series

4 CONCLUSIONS

The WI, an index for wind direction change defined to have objective and quantitative description of four-dimensional temporal and spatial variations of the atmospheric circulation, is used to study its pattern of evolution and seasonal change. EOF analysis is performed on the latitudinally averaged WI to derive the first four modes. What the first mode reveals is the basic state of the spatial distribution of the WI averaged over the whole year; what the second mode shows is the part that shows quasi-simple harmonic fluctuation of the deviations of the WI field, i.e. the quasi-harmonic variation of the wind field for the seasonal change caused by solar radiation. Tropical, subtropical and extratropical monsoon regions are all well represented in this mode. What the third mode depicts is the deviation of the WI field, i.e. the non-harmonic variation that changes with time. This part shows the asymmetricity of the spring-to-autumn and autumn-to-spring seasonal changes resulting from the differences in land-sea distribution between the SH and NH and the non-linear effect of the atmospheric and oceanic fluids, as well as the abrupt change of the stratosphere in February. What the fourth mode demonstrates is the phenomenon of all levels of reversed wind regions advancing northward from spring to summer and retreating southward from summer to autumn on the global scale.

Of the first four EOF modes, the seasonal change of the stratospheric WI value is most dramatic in the mid- and higher-latitude of SH, which is also the location where the seasonal change takes place the earliest. In that region, drastic adjustment of the atmospheric circulation in spring can bring about a series of subsequent adjustment in global circulation and may even affect the outbreak of summer monsoons in Asia. Therefore, the seasonal change in the mid- and higher-latitude stratosphere in the SH deserves more attention than it is now.

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