Reappraisal of Asian Summer Monsoon Indices and the Long-Term Variation of Monsoon*

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(Received March 27, 2007)

ABSTRACT

The Webster and Yang monsoon index (WYI)−the zonal wind shear between 850 and 200 hPa was calculated and modified on the basis of NCEP/NCAR reanalysis data. After analyzing the circulation and divergence fields of 150-100 and 200 hPa, however, we found that the 200-hPa level could not reflect the real change of the upper-tropospheric circulation of Asian summer monsoon, especially the characteristics and variation of the tropical easterly jet which is the most important feature of the upper-tropospheric circulation. The zonal wind shear U_{850}-$U_{(150+100)}$ is much larger than U_{850}-U_{200}, and thus it can reflect the strength of monsoon more appropriately. In addition, divergence is the largest at 150 hPa rather than 200 hPa, so 150 hPa in the upper-troposphere can reflect the coupling of the monsoon system. Therefore, WYI is redefined as DHI, i.e., $I_{\rm DH}=U^*_{850}-U^*_{(150+100)}$, which is able to characterize the variability of not only the intensity of the center of zonal wind shear in Asia, but also the monsoon system in the upper and lower troposphere. DHI is superior to WYI in featuring the long-term variation of Asian summer monsoon as it indicates there is obvious interdecadal variation in the Asian summer monsoon and the climate abrupt change occurred in 1980. The Asian summer monsoon was stronger before 1980 and it weakened after then due to the weakening of the easterly in the layer of 150-100 hPa, while easterly at 200 hPa did not weaken significantly. After the climate jump year in general, easterly in the upper troposphere weakened in Asia, indicating the weakening of summer monsoon; the land-sea pressure difference and thermal difference reduced, resulting in the weakening of monsoon; the corresponding upper divergence as well as the water vapor transport decreased in Indian Peninsula, central Indo-China Peninsula, North China, and Northeast China, indicating the weakening of summer monsoon as well. The difference between NCEP/NCAR and ERA-40 reanalysis data in studying the intensity and long-term variation of Asian summer monsoon is also compared in the end for reference.

Key words: monsoon indices, interannual and interdecadal variation, climate abrupt change

1. Introduction

It is of importance in monsoon research to describe the intensity and variability of summer monsoon quantitatively. The Asian summer monsoon has expansive variability on both spatial and temporal scales. Therefore, it is rather difficult to describe quantitatively the complicated characteristics of large-scale monsoon and its variations using a simple index. Many scholars have defined various monsoon indices from different aspects, but there is no unified index yet. So far, these indices can be concluded as the following three types.

First, the intensity of summer monsoon is denoted by precipitation or convection. All Indian monsoon rainfall index was often used as a measure of the South Asian monsoon (Parthasarathy et al., 1992); Tao and Chen (1985) defined a rainfall index to describe the intensity of the East Asian summer monsoon; Wang and Fan (1999) suggested convective indices could reflect the interannual variations of South Asian monsoon and Southeast Asian monsoon.

Secondly, the intensity of summer monsoon is depicted on the basis that monsoon is the outcome of the thermal contrast between land and sea. Guo (1983) defined a monsoon index based on the differences of

*Supported jointly by the South China Sea Monsoon Experimental Research of the National 9th Five Years Program B and the Project of Chinese National Programs for Fundamental Research and Development under Grant No. 2004cb418303.

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the atmospheric pressure at sea level. Sun et al. (2000) defined an East Asian land-sea thermal contrast index utilizing the land-sea temperature contrasts between the east and west and between the north and south.

Thirdly, the intensity of summer monsoon is described directly from the monsoon circulations such as wind field, divergence or vorticity. Webster and Yang (1992) defined a monsoon index by the zonal wind shear between 850 and 200 hPa. Goswami et al. (1999) defined the meridional wind shear as monsoon index. Li and Zhang (1999) suggested that South China Sea summer monsoon could be described by the divergence differences between the upper and lower troposphere. Lau et al. (2000) defined two regional monsoon indices RM1 (meridional wind shear) and RM2 (zonal wind shear) to picture the South Asian monsoon and East Asian monsoon, respectively. Zhu et al. (2000) combined the differences of the atmospheric pressure at sea level between the east and west and the zonal wind shear between the upper and lower troposphere in the low latitude to define an East Asian monsoon index. Zhang et al. (2003) defined a summer monsoon index by the zonal wind difference between the tropics and subtropics in East Asia.

The indices above have their merits and demerits. For instance, those denoted by rainfall amount have certain limits due to lack of data and the difficulty to distinguish topography, and there are some problems when atmospheric pressure or temperature is used to describe the summer monsoon as the variation of the surface pressure is rather small in the tropical regions. At the present time, Webster and Yang index (WYI) is widely applied in research and operation. WYI is an effective index which represents the variability of the zonal wind shear and measures the intensity of the large-scale Asian summer monsoon as well (Wang and Fan, 1999). However, problems do exist whether the level of 200 hPa could characterize the upper circulation of the Asian summer monsoon system. Simply speaking, a tropical system is constituted by the lower layer and upper layer which couple together by the thermal and dynamic processes and by the activity of convection. The 850-hPa level is usually chosen as the lower layer, so the choice of the upper layer is extremely important. Therefore, we will determine first which layer in the upper troposphere is the most appropriate to represent the variations of the upper circulation of the Asian summer monsoon system; then a monsoon index is redefined based on WYI, and the interannual and interdecadal variations and the climate abrupt change of the Asian summer monsoon are further discussed in the end.

2. Data

The data used in this study are monthly mean datasets from the reanalysis products of the National Center for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) for 1958-2002 (Kalnay et al., 1996) and the European Center of Medium-Range Weather Forecast Reanalysis (ERA-40) (Simmons and Gibson, 2000). Previous studies have shown that these two reanalysis products use different observational data, analysis systems, and models, and their results are influenced to a certain degree by the inhomogeneity caused by the change of observational system and analysis system (Uppala, 1997; Kistler et al., 2001). For instance, the change of models will produce illusive climate jump, which has been emphasized in the projects of NCEP and ECMWF. Kistler et al. (2001) pointed out that NCEP/NCAR data from 1948 to 1967 had the problem of the atmospheric pressure at sea level <http: // www. emc. ncep. noaa. gov/ gmb/ bkistler/ psfc/ psfc. html>. Until now, many studies have compared these two reanalysis data and found that they may draw different conclusions when analyzing the same meteorological element and that they have certain problems compared to the real observational data (Annamalai et al., 1999; Newman et al., 2000; Yang et al., 2002; Sturaro, 2003).

This paper is primarily studied using NCEP/NCAR reanalysis data. The differences between NCEP/NCAR and ERA-40 reanalysis data in studying the intensity and long-term variation of the Asian summer monsoon will be compared in Section 6 for reference.

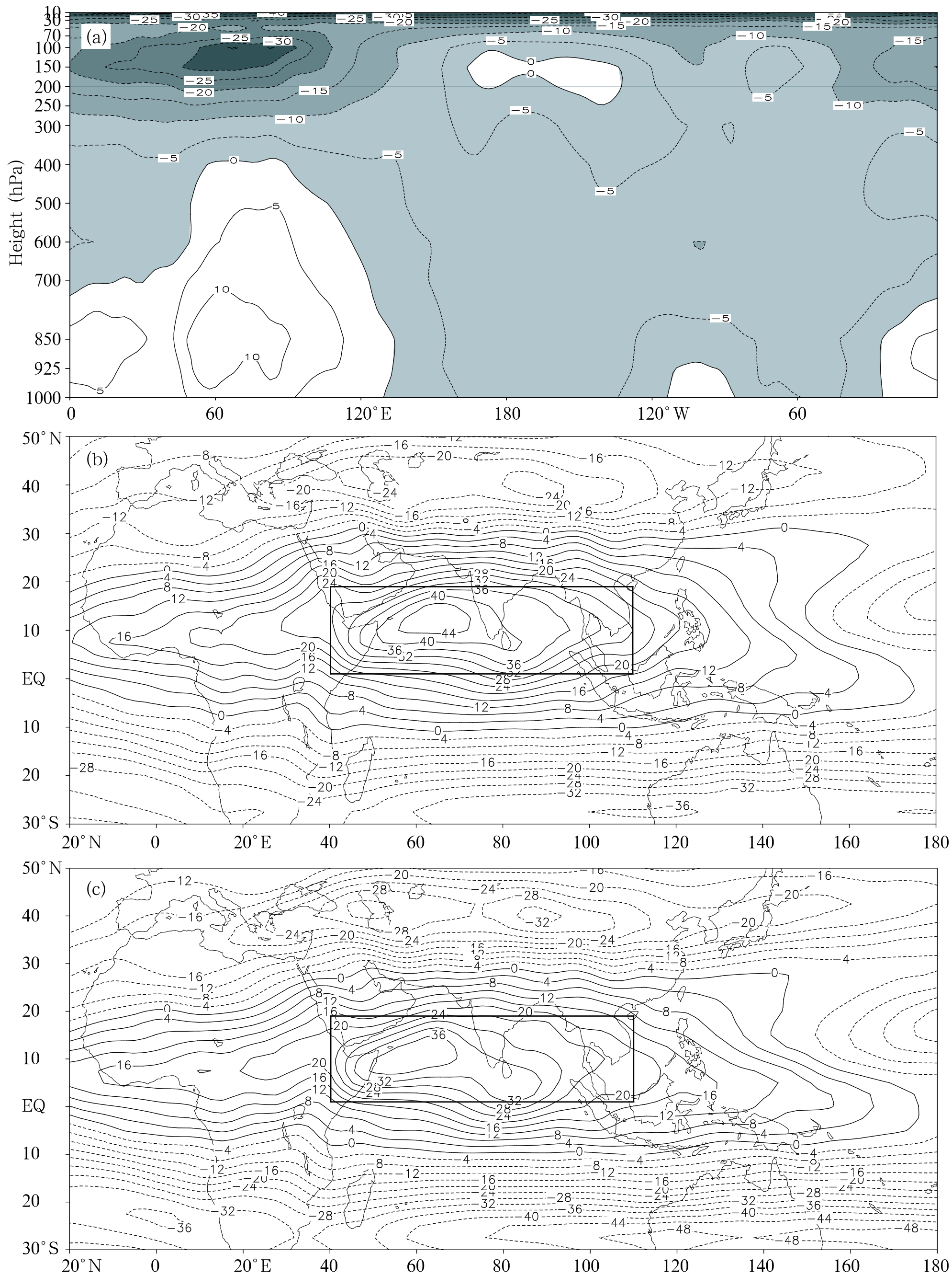

Fig.1. (a) Longitude-height section of climatologically (1958-2002) summer (JJA) meridionally averaged U over 5°-15°N (where easterly is shaded); and horizontal distributions of zonal wind shears (b) $U_{850}-U_{(150+100)}$ and (c) U_{850}-U_{200}. The rectangle is the maximal area of the zonal wind shear; unit: m s^{-1}.

3. Modification of WYI

According to WYI, the monsoon index is defined as the zonal wind shear between the upper and lower troposphere. Webster and Yang (1992) chose 200 hPa to represent the upper layer. However, after analyzing the upper-tropospheric circulation in South Asia and the adjacent North Africa, Koteswaram (1958) discovered that the tropical easterly jet (TEJ) has its maximum intensity in the layer of 150-100 hPa.

After then, Tanaka (1982) and Sathiyamoorthy (2004) showed that the core of TEJ was located at 150 and 100 hPa, respectively. The TEJ is the primary circulation in the upper levels of the Asian summer monsoon system, and is located on the south of the South Asian anticyclone (Krishnamurti and Bhalme, 1976). Since TEJ is strongest in the southern Indian Peninsula at 5°-15°N (Koteswaram, 1958; Tanaka, 1982; Krishnamurti and Bhalme, 1976), we draw the section of the zonal wind along 5°-15°N (Fig.1a). It can be seen that easterly is strongest in the layer of 150-100 hPa and westerly is strongest in the layer of 925-850 hPa, which is the most prominent feature in the Asian summer monsoon system. If 200 hPa is employed to represent the upper level, it cannot depict the characteristics of TEJ appropriately.

As monsoon index is defined as the zonal wind shear between the upper and lower troposphere, the value of the wind shear can reflect the value of monsoon index, and furthermore, the intensity of monsoon. The zonal wind shear is calculated by choosing 150-100 and 200 hPa as the upper layer and 850 hPa as the lower layer (Figs.1b, c). It shows that U_{850}-$U_{(150+100)}$ is much larger than $U_{850} - U_{200}$, which indicates the wind shear $U_{850} - U_{(150+100)}$ is stronger, and therefore, monsoon index can reflect the intensity and variation of monsoon more exactly and more clearly if defined as $U_{850} - U_{(150+100)}$.

On the other hand, the coupling between the upper and lower circulations is realized by the divergence circulation (Krishnamurti, 1971), so we can verify the coupling relationship through analyzing the divergence field. It can be seen from the divergence profile averaged in the area of the largest wind shear (i.e., the rectangular area in Fig.1) that convergence is largest at 925-850 hPa and divergence is largest at 150 hPa (Fig.2), and hence, the lower troposphere is coupled strongest with the layer of 150 hPa rather than 200 hPa, then monsoon index which is defined at 150 hPa in the upper level can better reflect the coupling of the monsoon system.

From the analysis above, it can be seen that 150-100 hPa is more reasonable than 200 hPa when defining the Asian monsoon: (1) The TEJ, which is the most prominent circulation feature in the upper troposphere in boreal summer, has its core located in the layer of 150-100 hPa; (2) the zonal wind shear $U_{850} - U_{(150+100)}$ is much larger than $U_{850} - U_{200}$, then it can reflect the intensity of monsoon more exactly and more clearly; and (3) the upper divergence coupled with the lower convergence is largest in the layer of 150 hPa, and thus monsoon index which is defined at 150 hPa can better reflect the coupling of the monsoon system. In addition, the South Asian high, which is a strong and stable circulation system in the upper troposphere in boreal summer (Mason and Anderson, 1958), is strongest in the layer of 150-100 hPa. Therefore, we define a modified monsoon index $I_{\rm DH}$: $I_{\rm DH}$=$U^*_{850} - U^*_{(150+100)}$, in which $U_{(150+100)}$ is the average of the zonal winds at 150 and 100 hPa, and U^* is the anomaly after subtracting the climatological mean from U. $I_{\rm DH}$ is defined in the area of the largest zonal wind shear, i.e., the rectangular area (0°-20°N, 40°-110°E) in Fig.1. As the monsoon system couples the wind fields in the upper and lower troposphere through the convergence in the lower level and divergence in the upper level, the monsoon index $I_{\rm DH}$ can represent not only the variability of the zonal wind shear in Asia, but also the variability of the coupling of the monsoon system in the upper and lower troposphere. In order to prove monsoon index $I_{\rm DH}$ is more appropriate than WYI, we will utilize both DHI and WYI in the following to discuss the interannual, interdecadal variation, and climate abrupt change of the Asian summer monsoon, and their ability to denote the long-term variation of monsoon will be compared.

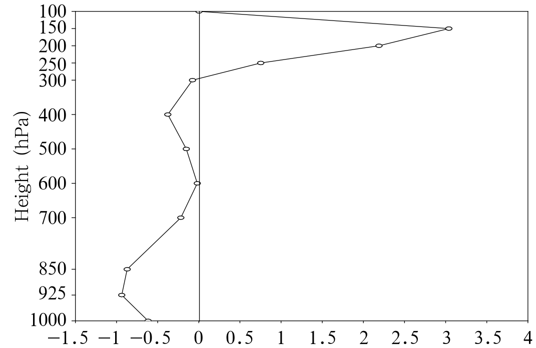

Fig.2. Vertical distribution of averaged divergence (10^{-6} s^{-1}) over the maximal area (0°-20°N, 40°-110°E) of zonal wind shear.

4. Interannual and interdecadal variation of Asian summer monsoon

Since data used in this paper are monthly averaged, it is unable to discuss the intraseasonal variation. After doing wavelet analysis (figure omitted), we found that DHI and WYI have obvious annual and decadal periods, in which the 2-5-yr annual cycle passes the 95% significant level but the decadal cycle does not. The annual cycles of the two indices are the same, indicating that they are consistent in describing the interannual variation of monsoon.

Hence, we put our emphasis on studying the interdecadal variation of monsoon and comparing the differences between both indices from the interdecadal aspect. There have been many investigations on the interdecadal variation of monsoon and the monsoon system (Torrence and Webster, 1999; Wang, 2001; Chase et al., 2003), all of which show the monsoon circulation has weakened in Asia. It can be seen from the time-longitude section of the zonal wind shear along 5°-15°N that when the upper level is defined in the maximal layer of TEJ, i.e., 150-100 hPa (Fig.3a), the zonal wind shear in Asia has obvious interdecadal variation and weakens significantly after the late 1970s, which is in accordance with previous studies. However, if the upper level is defined at 200 hPa (Fig.3b), it is unable to see the weakening of the zonal wind

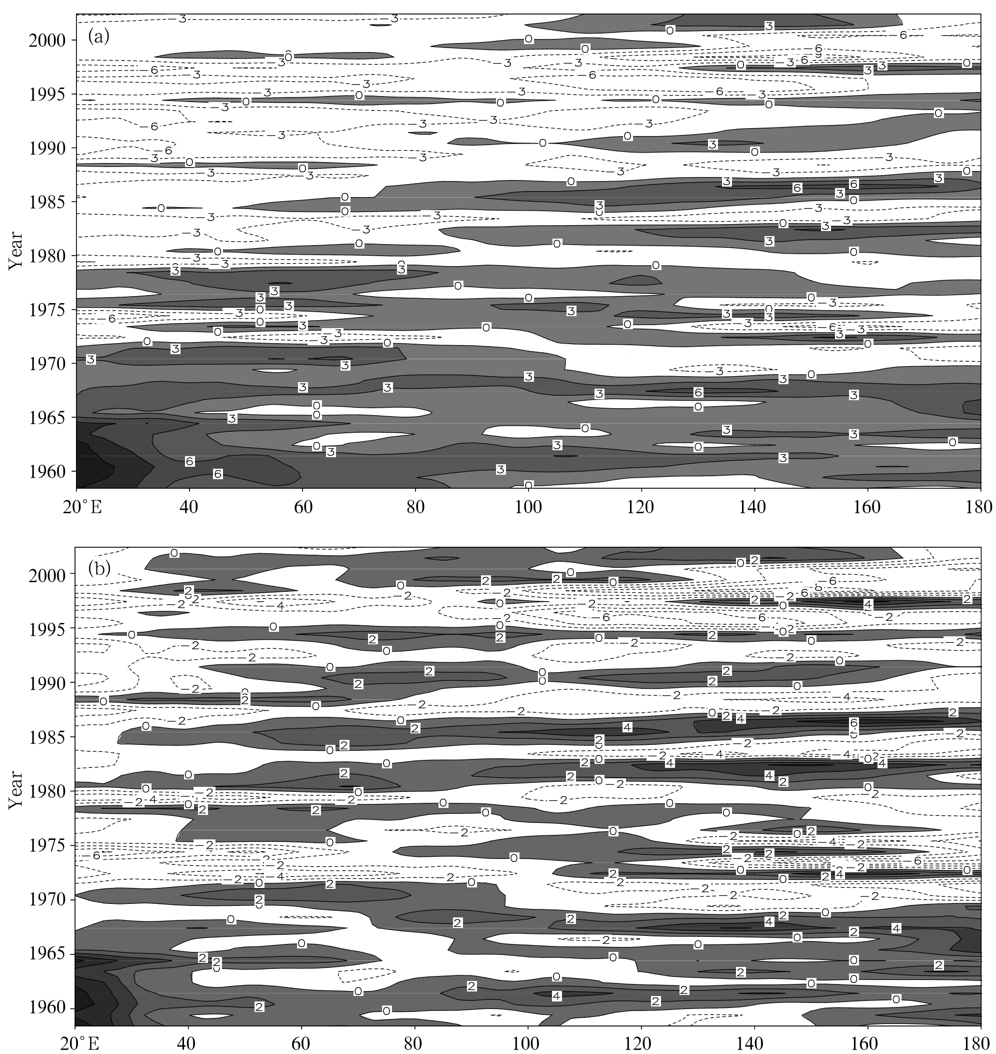

Fig.3. Time-longitude sections of zonal wind shears $U^*_{850} - U^*_{(150+100)}$ (a) and $U^*_{850} - U^*_{200}$ (b) in summer (JJA) along 5°-15°N. The positive zonal wind shear is shaded; unit: m s^{-1}.

shear in Asia, especially in South Asia, so the variation of monsoon cannot be actually reflected. Therefore, the zonal wind shear DHI is superior to WYI in depicting the long-term variation of monsoon.

The normalized time series of the monsoon index DHI shows that DHI has obvious descending trend and interdecadal variation (Fig.4a). It is almost all positive before and almost all negative after the late 1970s, denoting that Asian summer monsoon is stronger before the late 1970s and weakens after then, which is in agreement with previous studies (Torrence and Webster, 1999; Wang, 2001; Chase et al., 2003). The descending trend of WYI does not pass 95% significant level (Fig.4b), indicating its descent is unobvious and WYI cannot reflect exactly the weakening of Asian summer monsoon circulation. Therefore, it further proves that DHI is superior to WYI in depicting the long-term variation of monsoon.

5. Climate abrupt change of the Asian summer monsoon circulation

An obvious climate jump in 1976/1977 is observed in the North Pacific SST and in the large-scale winter circulation (Trenberth and Hurrel, 1994). The following part will discuss whether such a climate abrupt change also exists in the Asian summer monsoon by

Fig.4. Time series of the normalized monsoon indices DHI (a) and WYI (b). The solid line is the linear trend and the curve is the polynomial smooth.

using Mann-Kendall Rank statistics test (Fig.5). It is found that the climate jump years of the two monsoon indices are different: 1980 is the jump year of DHI and DHI decreases significantly after then, while WYI has not a specific mutant point but a mutant period of 1972-1986 when the trend of WYI is unobvious. The mutant year determined by DHI is in correspondence with the conclusion that climate jump occurred in the late 1970s by many other researches (Trenberth and Hurrel, 1994; Wang, 2001; Chase et al., 2003). Therefore, we believe the monsoon index DHI is superior to WYI in reflecting the climate abrupt change of Asian summer monsoon.

According to DHI, the Asian summer monsoon circulation mutates in 1980 and weakens after then. The difference fields of wind, geopotential height, divergence in the upper level, the surface pressure, the thickness, and the water vapor transport before and after the climate abrupt change are drawn respectively (Fig.6). The layer of 150-100 hPa over the entire tropical Asia is covered by the westerly anomaly, showing that easterly weakens in the upper level. In the tropical and subtropical Asia, the upper divergence strengthens in the northern Bay of Bengal, Maritime Continent, middle and lower reaches of the Yangtze River and South China, while it weakens in India, Indo-China Peninsula, and North China. The weakening of upper divergence in North China probably

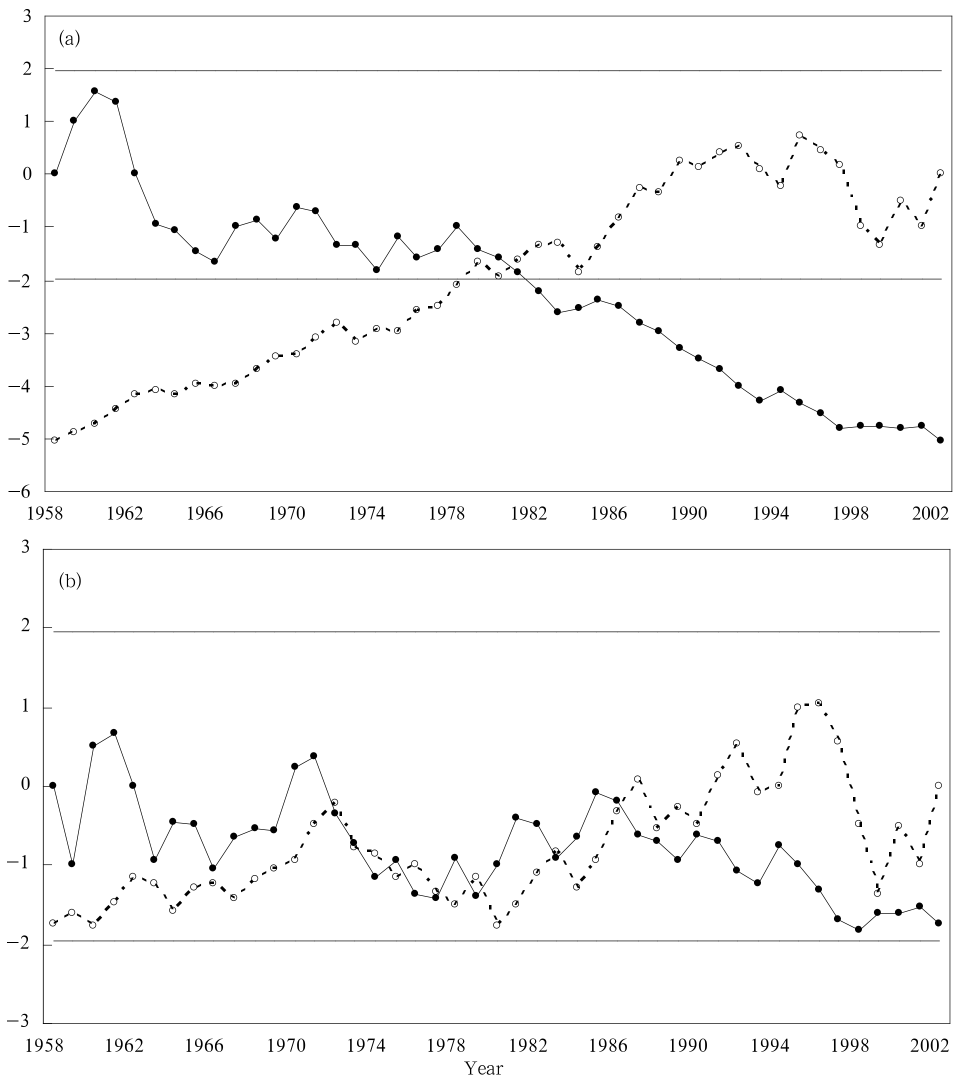

Fig.5. Mann-Kendall test of monsoon indices DHI (a) and WYI (b). The solid line is UF, the dashed line is UB, and the bold straight line is α=0.05 significant level.

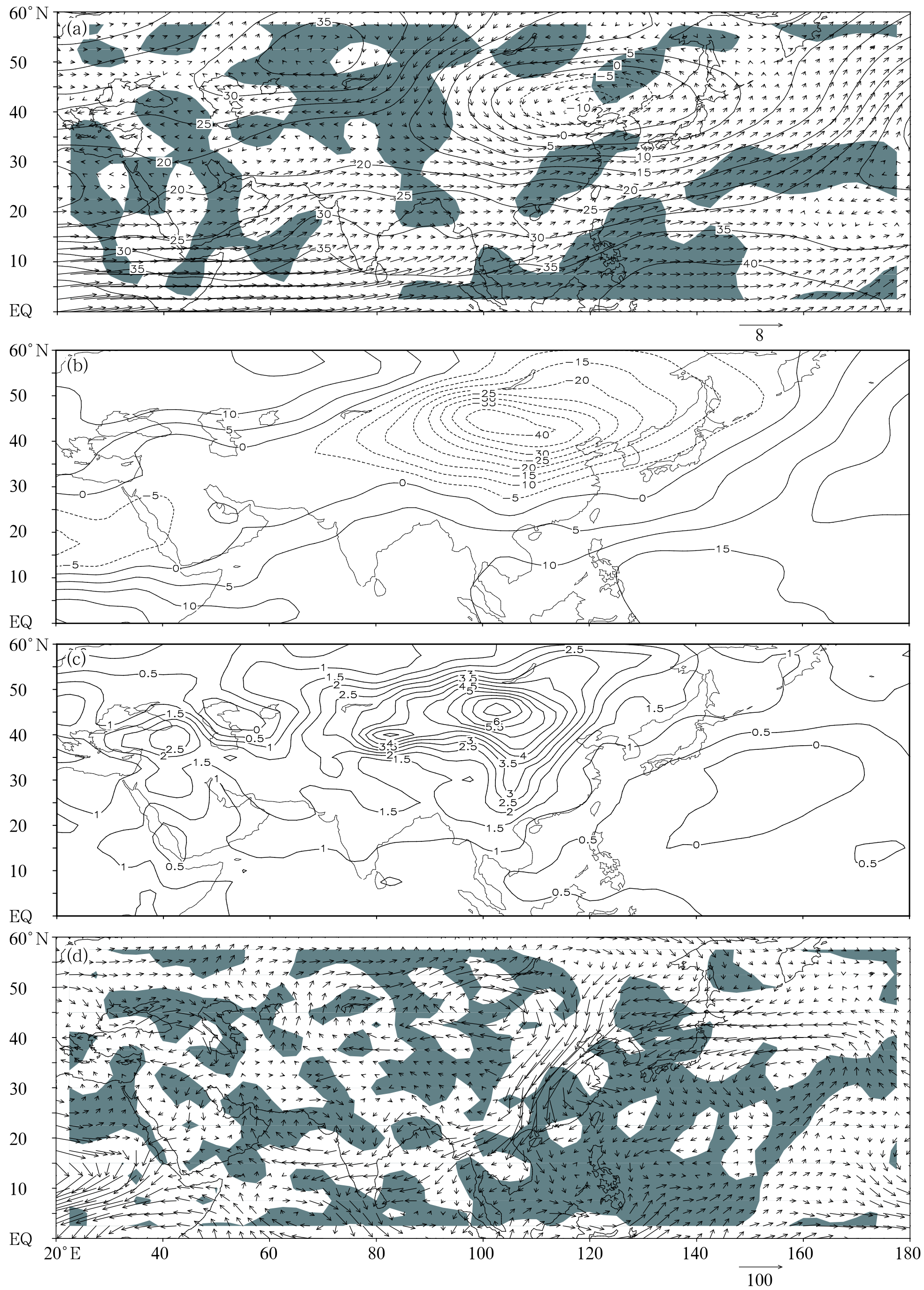

Fig.6. Difference fields of (a) the wind (m s^{-1}), geopotenial height (gpm), and divergence (s^{-1}) in the layer of 150-100 hPa, (b) the thickness between 500 and 150 hPa (gpm), (c) the surface pressure (hPa), and (d) vertically-integrated (ground surface to 300 hPa) water vapor transport (m s^{-1}) before and after the climate abrupt change. The shaded area indicates the increase of upper-level divergence in (a), and the increase of the convergence of water vapor flux (s^{-1}) in (d). Student t test was employed, and most regions of all figures pass the 95% significant test (figure omitted).

has relationship with the continual decrease of rainfall in this region after the 1970s (Ding and Sun, 2003). The geopotential height is negative in North China and Northeast China, showing its relationship with the development of the anomalous cyclonic circulation. The thickness between 500 and 150 hPa is positive in the ocean and has a negative center in North China, Northeast China, and Mongolia, indicating that heating over land decreases and heating over ocean increases, which reduced land-sea thermal contrast, leading to the weakening of monsoon. The surface pressure is positive in the entire continent with its center in North China, Northeast China, and Mongolia, which indicates that the land-sea pressure contrast decreases, resulting in the weakening of monsoon. In the chart of the vertically-integrated water vapor transport, water vapor is transported southward in East China (i.e., the primary summer monsoon region in Asia). The significant decrease of the northward transportation of water vapor results in drought in the northern China. The moisture flux convergence decreases in the Indian Peninsula, central Indo-China Peninsula, North China, and Northeast China, which leads to drought in these regions.

6. Differences between NCEP/NCAR and ERA-40 reanalysis data

On studying the variation of monsoon indices and monsoon system, conclusions drawn by ERA-40 are basically the same as those by NCEP/NCAR, yet there are some differences as follows:

(1) The vertical velocity by NCEP/NCAR is the biggest in the layer of 850 hPa rather than in the non-divergence level, and it is the second biggest in the layer of 400 hPa; while the vertical velocity by ERA-40 has only one peak in the layer of 300-400 hPa, indicating that ERA-40 is more reasonable in describing the vertical velocity.

(2) The index DHI by ERA-40 experiences two weakening processes in the middle 1960s and middle 1980s, respectively, while DHI by NCEP/NCAR has only one weakening process in the late 1970s.

(3) The index DHI by ERA-40 has not a specific mutant point but a mutant period of 1968-1990 when the trend of DHI is unobvious; while 1980 is the jump year of DHI by NCEP/NCAR, which is in agreement with the time of climate abrupt change by other researches. Therefore, NCEP/NCAR is more reasonable than DHI in featuring the climate abrupt change of Asian summer monsoon.

(4) The surface pressure by ERA-40 has a negative center in Mongolia, which differs from the positive center in North China, Northeast China, and Mongolia by NCEP/NCAR. Yang et al. (2002) suggested that NCEP/NCAR data had the problem of sea surface pressure in the East Eurasia continent from 1948 to 1967. Hence, the surface pressure by ERA-40 is more reasonable than NCEP/NCAR.

7. Conclusions

On the basis of NCEP/NCAR reanalysis data, the monsoon index WYI is reappraised in this study. After analyzing the circulation and divergence fields of 150-100 and 200 hPa, we found that monsoon index defined at 150-100 hPa in the upper troposphere is more reasonable than that at 200 hPa, so WYI is modified and redefined as $I_{\rm DH}$, $I_{\rm DH} = U^*_{850} - U^*_{(150+100)}$. Then through analyzing the interannual and interdecadal variation and climate abrupt change of the Asian summer monsoon, the superiority of DHI to WYI is further testified. The principal conclusions are summarized as follows:

(1) 150-100 hPa is more reasonable than 200 hPa when defining the monsoon index: ① the TEJ, which is the most prominent circulation feature in the upper troposphere in boreal summer, has its core located in the layer of 150-100 hPa; ② the zonal wind shear $U_{850} - U_{(150+100)}$ is much larger than $U_{850} - U_{200}$, and thus it can reflect the intensity of monsoon more exactly and more clearly; and ③ the upper divergence coupled with the lower convergence is the largest in the layer of 150 hPa, so monsoon index which is defined at 150 hPa can better reflect the coupling of the monsoon system. Therefore, the index DHI can represent not only the variability of the zonal wind shear in Asia, but also the variability of the coupling of the monsoon system in the upper and lower troposphere.

(2) The indices DHI and WYI are consistent in

describing the interannual variation of monsoon.

(3) The monsoon index DHI is superior to WYI in featuring the long-term variation of Asian summer monsoon and its climate abrupt change. DHI shows that the Asian summer monsoon circulation mutates in 1980 and weakens after then, which is primarily caused by the weakening of easterly in the layer of 150-100 hPa. But the weakening of easterly is unobvious in the layer of 200 hPa.

(4) After the climate abrupt change in general, easterly in the upper level weakens in Asia, showing the weakening of summer monsoon; the land-sea pressure contrast and thermal contrast decrease, resulting in the weakening of monsoon; the corresponding upper divergence and water vapor transport decrease in the Indian Peninsula, central Indo-China Peninsula, North China, and Northeast China, indicating the weakening of summer monsoon as well.

Acknowledgements. The NCEP/NCAR reanalysis data were provided by the NOAA-CIRES Climate Diagnostics Center, Boulder, Colorado, USA, from their web site <http: // www. cdc. noaa. gov/>. The ERA-40 reanalysis data were obtained from ECMWF at <http: // data. ecmwf. int/ data/ d/ era40>. The authors would like to thank Mr. Li Dan for revising the English edition of this paper.

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