Interdecadal Variations of Precipitation and Temperature in China Around the Abrupt Change of Atmospheric Circulation in 1976

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ABSTRACT

The interdecadal characteristics of rainfall and temperature in China before and after the abrupt change of the general circulation in 1976 are analyzed using the global 2.5°×2.5° monthly mean reanalysis data from the National Centers for Environmental Prediction of US and the precipitation and temperature data at the 743 stations of China from the National Climate Center of China. The results show that after 1976, springtime precipitation and temperature were anomalously enhanced and reduced respectively in South China, while the reverse was true in the western Yangtze River basin. In summer, precipitation was anomalously less in South China, more in the Yangtze River basin, less again in North China and more again in Northeast China, showing a distribution pattern alternating with negative and positive anomalies ("–, +, –, +"). Meanwhile, temperature shows a distribution of warming in South China, cooling in the Yangtze and Huaihe River basins, and warming again in northern China. In autumn, precipitation tended to decrease and temperature tended to increase in most parts of the country. In winter, precipitation increased moderately in South China and warming was the trend across all parts of China. The interdecadal decline of mean temperature in spring and summer in China was mainly due to the daily maximum temperature variation, while the interdecadal increase was mainly the result of the minimum temperature change. The overall warming in autumn (winter) was mostly influenced by the minimum (maximum) temperature variation. These changes were closely related to the north-south shifts of the ascending and descending branches of the Hadley cell, the strengthening and north-south progression of the westerly jet stream, and the atmospheric stratification and water vapor transport conditions.

Key words: temperature and precipitation in China; seasons; Hadley cell, upper-level westerly jet stream, water vapor transport

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1. Introduction

Significant interdecadal variations took place in the late 1970s in the global atmospheric circulation and sea surface temperature (SST). Especially, there were rapid increases in the ground surface temperature and sea temperature in the Northern Hemisphere around 1976 (Nitta and Yamada, 1989; Trenberth and Hurrell, 1994; Lau and Weng, 1999). Moreover, there were an abrupt warming in the eastern tropical Pacific, an anomalous cooling in the mid-latitude North Pacific, and an anomalous increase in the intensity of the Aleutian low, which moved further south (Trenberth and Hurrell, 1994; Graham, 1994; Zhang et al., 1997).

As pointed out in the Third Assessment Report of the Intergovernmenta Panel on Climate Change (IPCC, 2001), there has been a rise of 0.6±0.2°C in mean surface temperature across the globe since the end of the 19th century; the warming is fluctuating with sharp differences in both space and season. Under such a climate background, corresponding changes have also taken place in the regional climate of China. Climate changes in China are in general consistent

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with but different in detail from the global picture. The temperature correlation coefficient is 0.3–0.4 between China and the globe. While the warming in Northeast China, North China, and Xinjiang may agree with that in the Northern Hemisphere, temperature actually has dropped in the Yangtze River basin, as reported by Wang (1994). The most obvious climate warming occurs in Northwest China, North China, and Northeast China, while the warming is insignificant in the south of the Yangtze River (Ding and Dai, 1994).

On the interdecadal scale, changes in mean temperature of China are consistent with those over the land surface of the Northern Hemisphere since their correlation coefficient is as high as up to 0.93, as revealed by Tu et al. (1999, 2000). Their study of the regional characteristics of annual mean temperature changes for the past 117 years also suggested that over the past 46 years, Northeast China, northern North China, and Xinjiang Uygur Autonomous Region were the three main regions where temperature rose by a magnitude of 1.2°C, and Sichuan and Guizhou Provinces witnessed a temperature decrease by a magnitude of 0.3–0.4°C. As shown in a study by Shi et al. (1995) in which Empirical Orthogonal Function (EOF) expansion was used to interpolate monthly mean temperature over 100 years for 28 stations in China, temperature had been rising over most of China in the 20th century. Similarities are also found in the changes in annual temperature between China and the Northern Hemisphere (Lin et al., 1995).

The climate change has its regional features in China if viewed in the background of cooling and warming on the scale of dozens of years (Shi et al., 1995). From a study of annual mean temperature data taken at 160 observation stations across China for the past 40 years, conclusions were made that temperature in China had been low, high, and low again for the time prior to the 1970s, while afterwards it persistently climbed up till the present ever since the mid-1970s, with a larger amplitude of variation in the northern than in the southern part of China (Li et al., 1990). The daily maximum temperature was on a general rise west of 95°E and north of the Yellow River while it showed a cooling trend south of the Yellow River in eastern China. The daily minimum temperature showed a warming trend across China and the warming was the most pronounced in higher latitudes (Zhai and Ren, 1997).

Likewise, precipitation also experienced interdecadal changes, decreasing by about 0.3% every 10 years over the subtropical zone of the Northern Hemisphere while increasing by 0.5%–1.0% every 10 years over most of the mid- and high-latitudes (IPCC, 2001). According to Hulme (1992), there was a slight decrease in the mean precipitation, with a trend of −1.33 mm yr^{-1} for the Northern Hemisphere, contributed mainly from the tropics, while there was a slight increase for the mid latitudes. Located in both the subtropics and the mid-latitude monsoon region, China shows an overall trend of falling annual precipitation, but with a significant increasing trend in Northwest China (Chen et al., 1991; Zhai et al., 1999; Zhang et al., 2005). After the 1990s, the mid- and high-latitudes shifted from dry to wet conditions while precipitation increased significantly in the subtropics (Wang et al., 2006). Subject to the interdecadal variations of the East Asian summer monsoon, there was a significant increase of precipitation over the Yangtze River basin after 1977 but a persistent, severe drought in North China and the Yellow River basin (Huang et al., 1999). A significant change that happened in the mid 1970s divided the East Asian summer monsoon into two stages: it was anomalously strong before 1976 and brought much more rain to North China but anomalously weak afterwards and turned the region into a period of less rain (Li and He, 2001).

It is then understood that climate change in China is not only similar to the global change but also marked by regional characteristics. Causes for such a change are complicated, which may be associated with thermodynamic gradient shifts, interdecadal variations of equatorial central and eastern Pacific SST, air-sea interactions, Arctic Oscillation and western Pacific subtropical high variations (Yan et al., 1990; Wang and Fang, 2004; Li and Liao, 1996). Few studies, however, have been devoted to the research on the interdecadal characteristics of precipitation and temperature changes in China around the abrupt change of the atmospheric circulation in the 1970s. In this paper, the $2.5^{\circ}\times2.5^{\circ}$ global monthly mean reanalysis data from the National Centers for Environmental Prediction (NCEP) of US, and the precipitation and temperature data at the 743 stations of China from the National Climate Center of China are used to address the issue.

2. Interdecadal characteristics of precipitation in contrast to those of temperature

Previous studies (Nitta and Yamada, 1989; Trenberth and Hurrell, 1990; Lau and Weng, 1999) reveal that significant interdecadal changes took place around 1976 in the global atmospheric circulation and Pacific SST. A Mann-Kendall abrupt change test (figure omitted) of the Southern Oscillation Index (SOI) shows that another abrupt change, with a less remarkable effect, took place around 2000. For this reason, a composite analysis will be conducted with the 18-yr period (1958–1975) as Phase I and the 20-yr period (1980–1999) as Phase II.

It is shown in Fig. 1 that significant regional characteristics of precipitation changes are found in all the four seasons in China. In spring (Fig.1a), negative precipitation anomalies mainly occur in the Yangtze River basin, particularly in its western section; positive anomalies appear in South China but the eastern coastal region is the only place where the 90% significance level has been met, suggesting reduced precipitation in the western Yangtze River basin, and increased precipitation in the coastal areas of South China in the springtime after 1976. In summer (Fig. 1b), precipitation is low in South China, high in the Yangtze River basin, low in North China, and high in Northeast China, showing a distribution pattern of "–, +, –, +", which agrees with the findings of other researchers (Huang et al., 1999; Lu, 1999; Wang and Fang, 2004) and reflects a weak summer monsoon. The change of

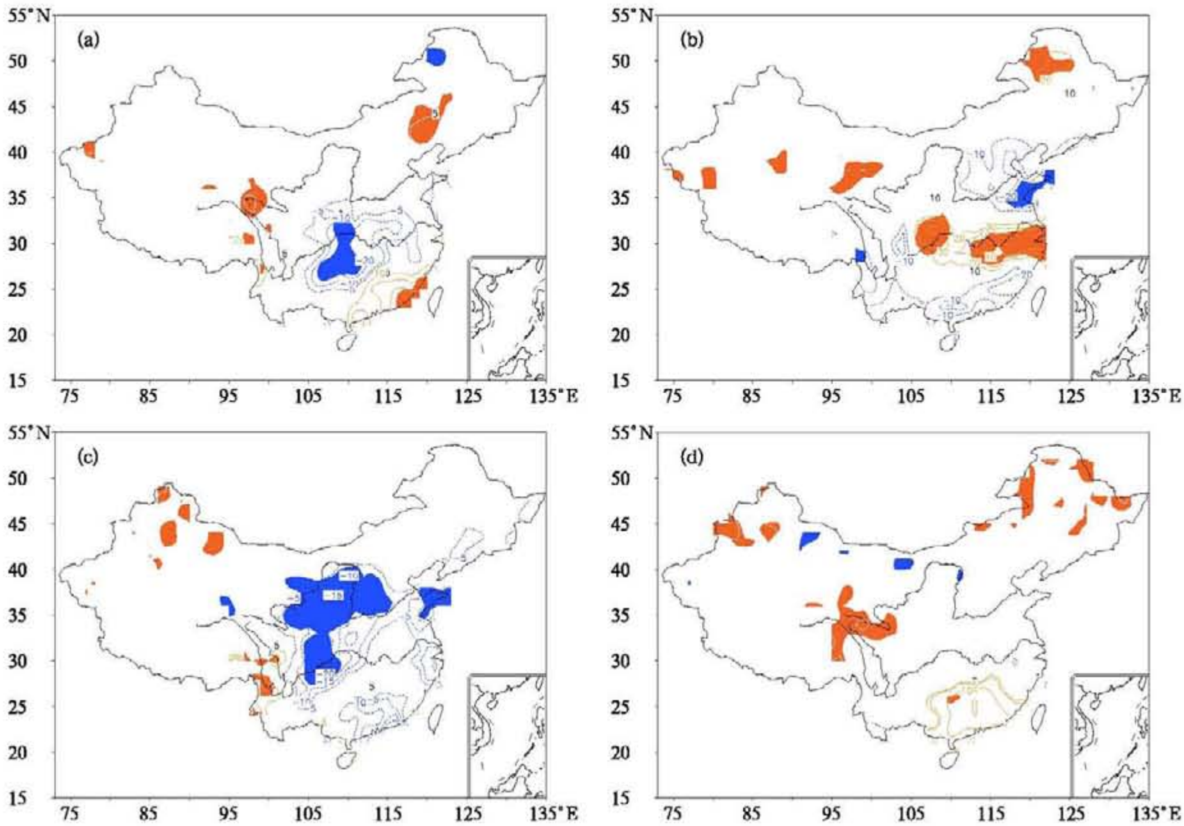

Fig. 1. The difference (Phase II minus Phase I) of spring (a), summer (b), autumn (c), and winter (d) precipitation (mm) for the 743 weather stations across China. Blue (orange) isolines indicate the negative (positive) values and shadings indicate areas with negative (positive) anomalies exceeding the 90% significance level.

precipitation is most significant in the Yangtze River basin, coastal eastern North China, and northwest corner of Northeast China, while it is less significant in South China. In autumn (Fig. 1c), precipitation tends to decrease in most parts of the country, most significantly in the Yellow River basin. Compared with the other three seasons, winter (Fig. 1d) is the time when the interdecadal precipitation difference is generally insignificant. Although large positive precipitation anomalies are mainly over South China, they do not pass the 90% significance level.

The distribution of temperature (Fig. 2) shows that, instead of getting higher as far as the overall pattern is concerned in the background of a global warming, the temperature in China is marked by significant seasonality and locality. In spring (Fig. 2a), there is a slight temperature drop in southern China, being most substantial in the western Yangtze River basin, whereas there is a sharp increase in northern China, especially in Northeast China where the maximum rise is up to 1.2°C or so. In summer (Fig. 2b), the warming in South China, Southwest China, Northeast China, North China, and Xinjiang is consistent with the global pace, while cooling is observed in the Yangtze and Huaihe River basins where the maximum drop is around 0.8°C. In contrast, autumn and winter (Figs. 2c and 2d) are the two seasons when most parts of China experience warming consistently, especially in winter, which has the most pronounced rise of temperature among all the seasons.

The maximum and minimum temperatures also experience different interdecadal variations in different seasons around 1976 (figure omitted). In spring, the maximum temperature has the most dramatic fall in the southern Yangtze River basin, while it rises insignificantly over Northeast China. The minimum temperature falls insignificantly in the southern Yangtze River basin but rises significantly in Northeast China. In summer, the maximum temperature falls significantly in the Yangtze and Huaihe River basins while the minimum temperature rises remarkably in South China and northern China. In autumn

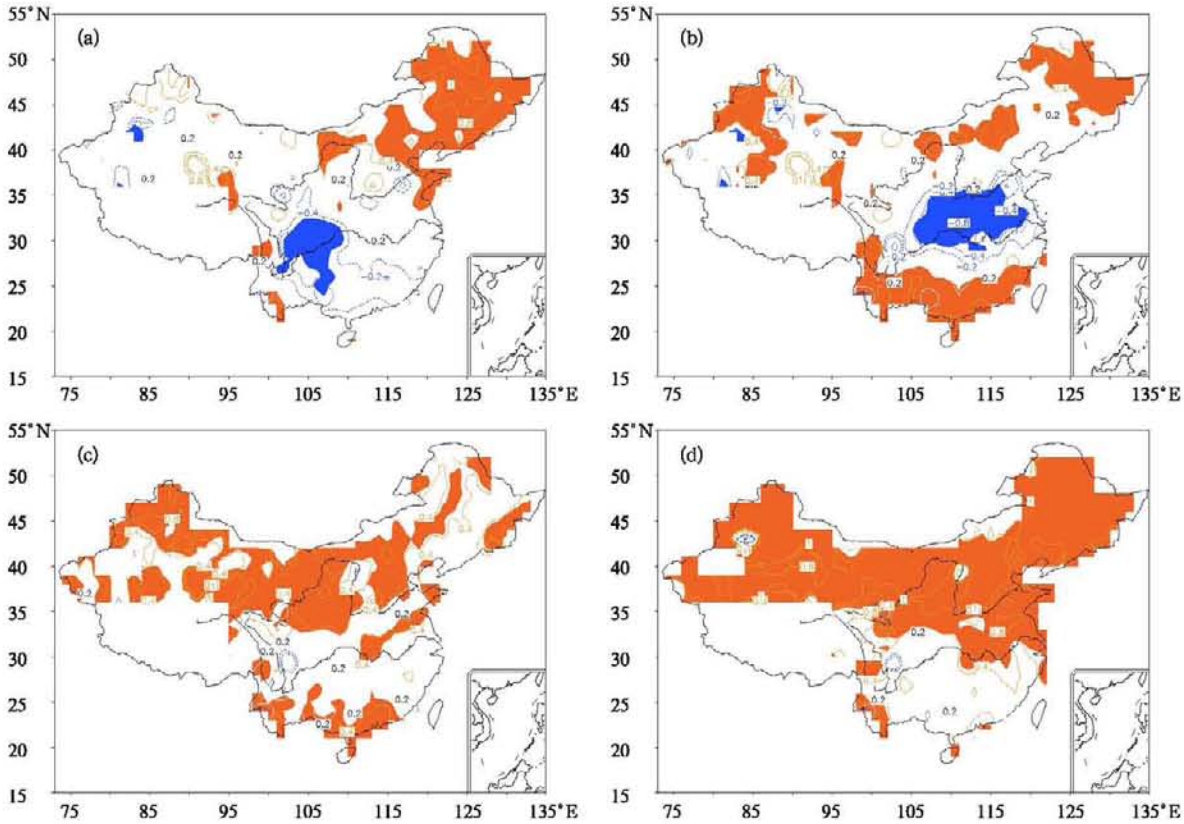

Fig. 2. As in Fig. 1, but for temperature (°C).

and winter, the maximum and minimum temperatures are getting higher in the general trend, although the maximum temperature varies more obviously in winter than in autumn while the minimum temperature changes more substantially in autumn than in winter.

It is therefore known that the interdecadal decreases of mean spring and summer temperature in China are mainly affected by the variation of the maximum temperature while the interdecadal increases are mainly subject to that of the minimum temperature; the overall autumn warming is affected more by the minimum temperature while the overall winter warming is influenced more by the maximum temperature.

The above analysis also shows that in China the interdecadal variations of precipitation agree with those of temperature in the regional distribution characteristics across the seasons except winter. In other words, temperature decreases on the interdecadal scale in regions with interdecadally more precipitation while it rises in regions with interdecadally less precipitation.

3. Circulation changes responsible for the interdecadal variations of precipitation and temperature

3.1 Interdecadal variation of the Hadley cell

Connecting the wind fields of low latitudes with those of the mid- and high-latitudes, the circulation in the vertical meridional sphere plays an important role in adjusting the general circulation and balancing the global energy. There are close links between the movement of summertime rain belts in East Asia and the evolution of local meridional circulation (Liao et al., 1991; Wang and Liu, 2000). How did the Hadley cell vary around the time of abrupt climate change? How was the climate in China affected by this for all the seasons? These issues are what we are concerned about in this section.

Figure 3 gives the interdecadal difference of the seasonal meridional circulation averaged zonally between 105° and 140°E. It shows that after 1976 significant interdecadal variations appear with the Hadley cell for all the seasons, corresponding well to the regional variations of precipitation and temperature. In spring, after 1976 (Fig.3a), there is a main anomalous ascending branch over the area south of 32°N and a main anomalous descending branch over the area north of 32°N and south of 45°N, resulting in more-than-normal precipitation and lower-than-normal temperature in South China, and lower-than-normal temperature but less-than-normal precipitation in the western Yangtze River basin. In summer (Fig. 3b), the ascending branch of the Hadley cell shifts further north by about 5° to the Yangtze River basin while the descending branch migrates over North China. The anomalous ascending airflow in South China weakens at lower levels while being replaced by the anomalous descending airflow at higher levels, resulting in less precipitation and higher temperature in South China and North China, but more precipitation and lower temperature in the Yangtze River basin (Fig. 3b). In autumn (Fig. 3c), the anomalous ascending airflow appears in mainland China south of 27°N while the anomalous descending airflow is dominant in the rest of the country, resulting in a decreasing trend of precipitation and an increasing trend of temperature on the interdecadal scale. In winter (Fig. 3d), the Hadley cell is similar as in spring, corresponding to positive precipitation anomalies in South China. Note, in spite of the prevalence of an anomalous descending airflow over North China, precipitation there in winter does not experience a substantial interdecadal variation, whereas temperature is getting higher, like in the rest of the country. This is a phenomenon that is not observed in other seasons. It can then be inferred that the interdecadal variation of the Hadley cell during the four seasons might be an important factor contributing to the interdecadal variations of precipitation and temperature in China.

3.2 Interdecadal variations of zonal wind, geopotential height, vertical velocity, and specific humidity

In order to probe into the important factors that affect the interdecadal variations of precipitation and temperature of China, interdecadal differences in the zonal geopotential height, vertical velocity, and specific humidity are graphically depicted in Figs. 4–7.

In spring (Fig. 4), the zonal wind field shows a large westerly anomaly in parts of China south of 25°N

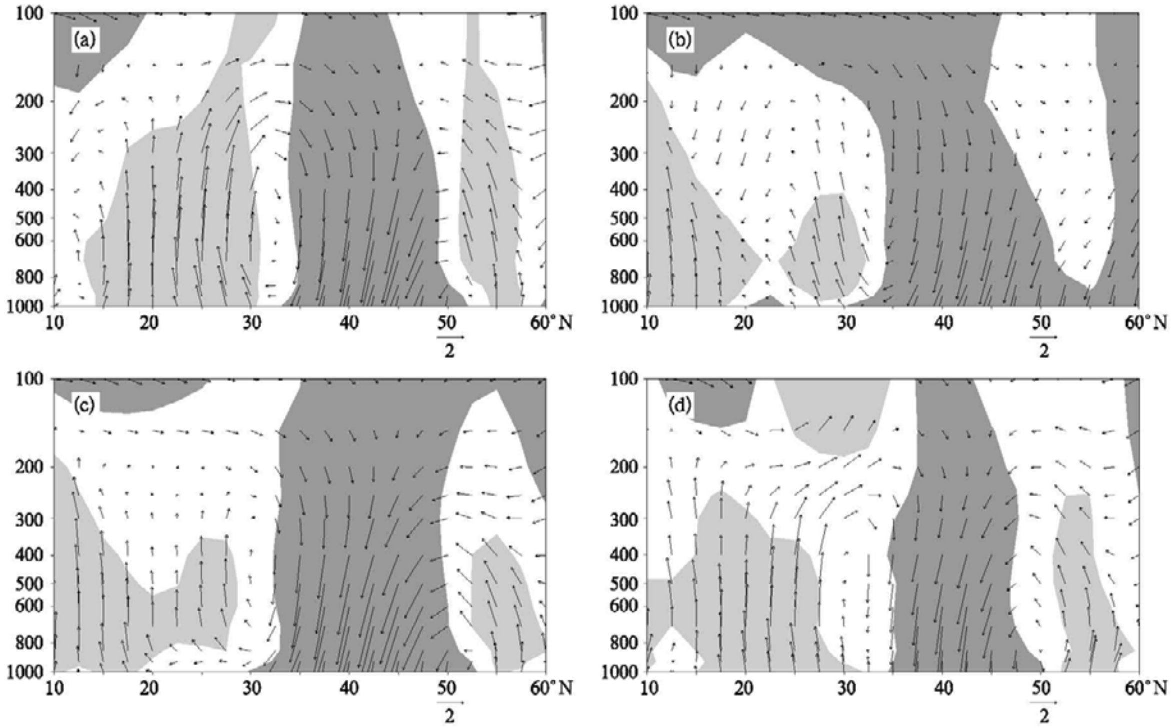

Fig. 3. The difference (Phase II minus Phase I) of the Hadley cell for spring (a), summer (b), autumn (c), and winter (d), as represented by the meridional-vertical streamfunction ($\mathrm{m\,s^{-1}}$) averaged over 105°–140°E. Shadings indicate areas with anomalies exceeding the 90% significance level.

and a large easterly anomaly north of 25°N but south of 45°N. The zonal wind is declining northward with height, leading to anomalously cyclonic flows at low levels but anomalously anti-cyclonic flows at high levels over the area south of 32°N, and a reversed flow patter north of that (Fig. 4a). Correspondingly, geopotential height is anomalously low (high) at low levels but anomalously high (low) at high levels in the area south (north) of 32°N (Fig. 4c). Such an anomalously baroclinic system results in large anomalous ascending (descending) motion south (north) of 32°N (Fig. 4b). As shown in the specific humidity field (Fig. 4d), in spring, it is positively anomalous (and with a large magnitude) throughout the air column in South China but negatively anomalous in the Yangtze and Huaihe River basins. This suggests that after 1976, interdecadal precipitation anomalies are positive and temperature is lower in South China, but they are negative and lower respectively in the Yangtze and Huaihe River basins, because more (less) water vapor was supplied to the former (latter) even though the two regions were both under the influence of the anomalous ascending airflow. Besides, a belt of large westerly anomalies is active around the level of 200 hPa at 25°N, suggesting the presence of an enhanced westerly jet stream located further south and the intensification of upper-level divergence. Following the mass conservation law, lower-level convergence will be intensified consequently with increased ascending motion, which results in more-than-normal precipitation in South China.

In summer, in the Yangtze River basin (Figs. 5a and 5b), the lower atmospheric levels are featured by an anomalous cyclone with significant easterly (westerly) anomalies in the north (south), while the higher levels are marked by an anomalous anti-cyclone with significant westerly (easterly) anomalies in the north (south). Such an allocation of low-level convergence versus high-level divergence increases the ascending motion over the region. The northward shift of the westerly jet stream to around 35°N also has contributed to the strengthening of the low-level

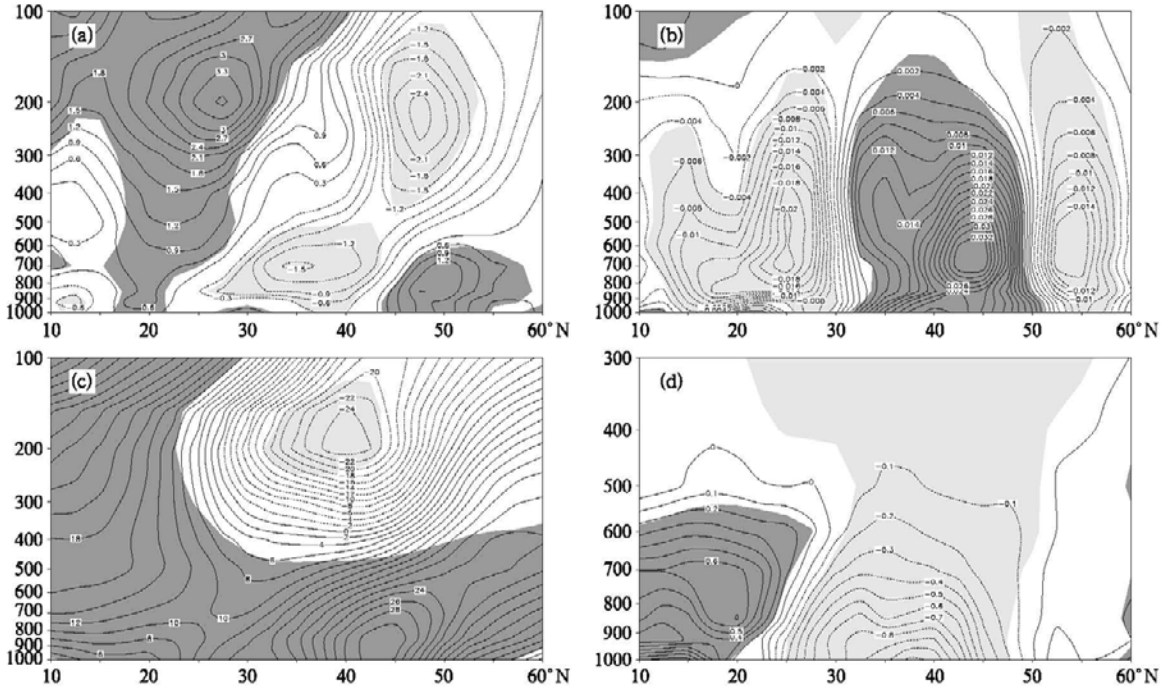

Fig. 4. Latitude-height cross sections of the differences (Phase II minus Phase I) in (a) zonal wind (m s^{-1}), (b) p-vertical velocity (Pa s^{-1}), (c) geopotential height (gpm), and (d) specific humidity (g kg^{-1}) averaged between 105° and 120°E in spring. Shadings denote areas with anomalies exceeding the 90% significance level.

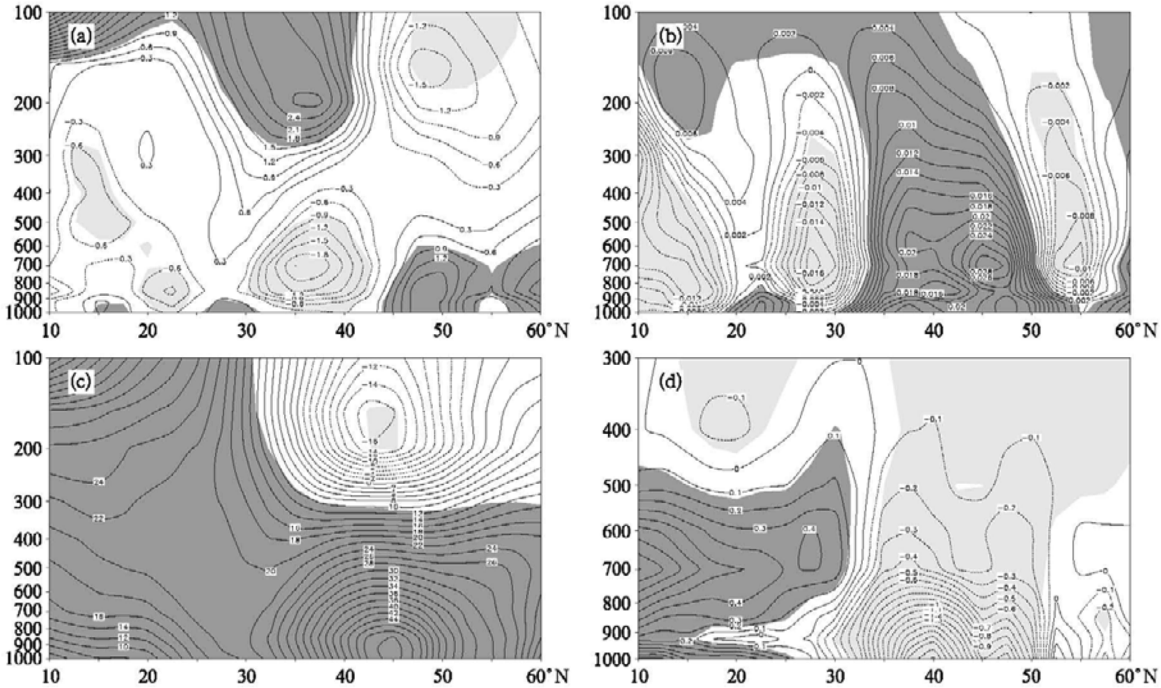

Fig.5. As in Fig. 4, but for summer.

ascending motion, which, together with the interdecadal increase of water vapor transport (Fig. 5d), cause more precipitation and lower temperature in the Yangtze River basin. In North China, pressure is anomalously high at lower levels but anomalously low at higher levels (Fig. 5c), constituting a deep, anomalously baroclinic system in which the anomalously descending motion is intense. Plus, water vapor has an interdecadal decrease. These consequently cause overall reduced precipitation and increased temperature over North China. In South China although water vapor is on an interdecadal rise, anomalous descending motion was the main feature (Fig. 5b), causing less precipitation and higher temperature than normal there.

In autumn (Fig. 6a), the vertical distribution of zonal wind is similar to that in summer except that the system is less strong. In addition, the westerly jet stream moves southward to 30°N. Correspondingly, the interdecadal variation of vertical velocity (Fig. 6b) shows that in the area south of 27°C there is weak anomalous ascending motion at the middle level and anomalous descending motion at the lower level, and in the area north of 30°N but south of 50°N anomalous descending motion existes. Furthermore, water vapor has been decreasing generally on the interdecadal scale over the mainland China (Fig. 6d). All of the above factors cause precipitation to decrease and temperature there to increase in this season in China.

In winter, the zonal wind field (Fig. 7a) shows a pattern alternating with positive ("+") and negative ("–") anomalies at levels above 200 hPa. At lower levels, there are westerly (easterly) anomalies in the south (north) of the Yangtze River basin. The reverse is true at 200 hPa and above. Correspondingly, geopotential height is anomalously low below 200 hPa but anomalously high at and above that level on the interdecadal scale (Fig. 7c). It results in the dominance of anomalous ascending motion south of the Yangtze River (Fig. 7b). Although water vapor also tends to increase in the same region on the same time scale, it fails to pass the significance t-test, so the interdecadal increase of precipitation there is not significant either. North of the Yangtze River basin, an anomalous high is in control, giving rise to anomalous descending motion (Figs. 7b and 7c) and generally high temperature. It is noteworthy that more-than-normal precipitation is accompanied by insignificant decreasing mean temperature south of the Yangtze River basin in winter, in contrast to the situations in other three seasons. The variation of mean temperature is not so significant in southern China (Fig. 2d) as in northern China, only that there is a small interdecadal fall in the minimum temperature (figure omitted). This may be attributed to the transfer of warm and humid air from the ocean in winter.

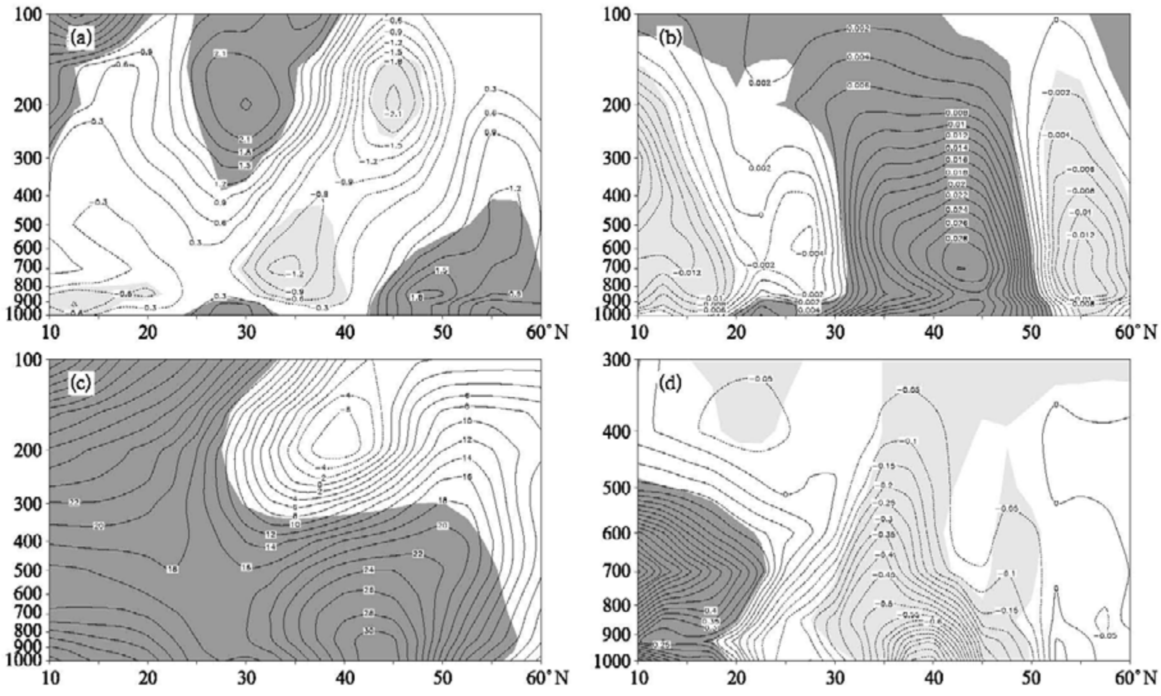

Fig. 6. As in Fig. 4, but for autumn.

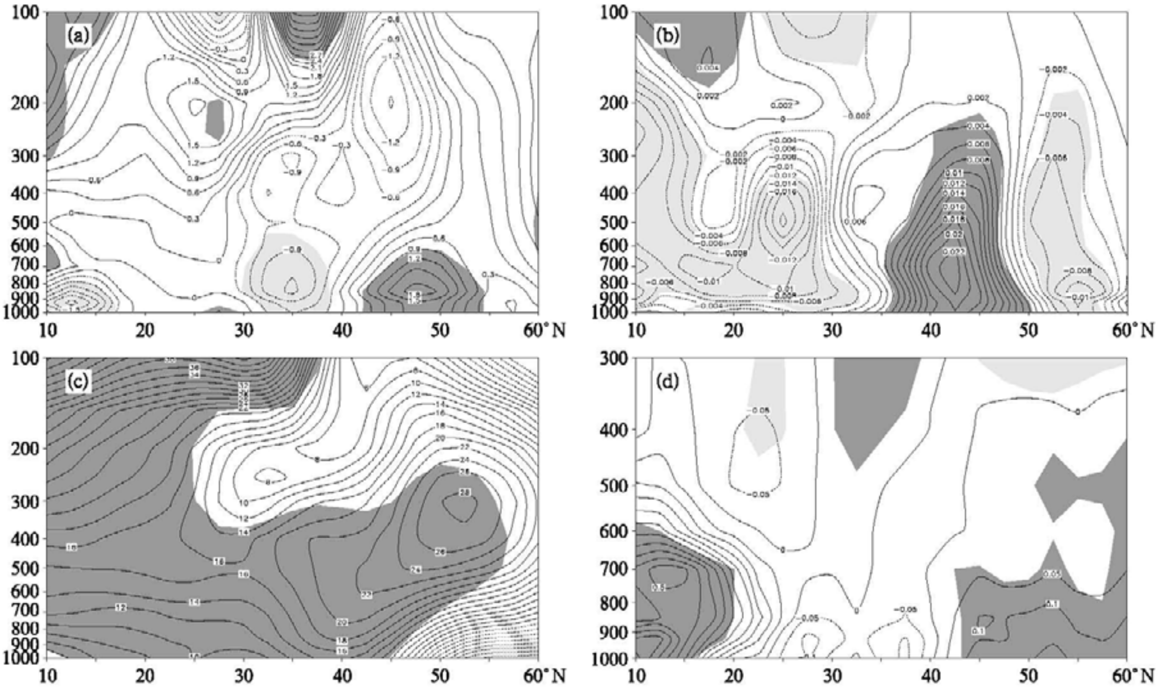

Fig. 7. As in Fig. 4, but for winter.

3.3 Interdecadal variation of water vapor transport

Water vapor transport is also an important factor influencing the distribution and variation of precipitation. It is necessary to study the interdecadal variation of water vapor transport across the seasons in order to interpret the regional interdecadal distribution of precipitation. Figure 8 gives the interdecadal difference of water vapor transport in the four seasons in the area of 5°S–55°N, 70°–150°E.

It is shown in Fig. 8a that in spring, two channels of anomalous water vapor transport, one from the tropical South Pacific, the other from the tropical western Pacific, merge over South China in spring, supplying this region with uninterrupted warm and humid water vapor from the ocean. The springtime precipitation of South China increases on the interdecadal scale as a result of stronger anomalous ascending motion and larger specific humidity there (Figs. 4b and 4d). Because the two water vapor transport anomalies fail to pass the significance t-test, the interdecadal increase of precipitation is significant only in the coastal part of South China.

In summer (Fig. 8b), while the ocean is getting warmer (cooler) south (north) of 35°N after 1976, there is less precipitation in North China as water vapor is originated from drier and colder air from the North Pacific. In contrast, two patches of water vapor transport, one drier from the north, the other warmer and more humid from Northwest Pacific, merge over the Yangtze River basin and result in more precipitation, in addition to the effect of the anomalous ascending motion (Fig. 5b) there.

In autumn, over either the Yangtze River Basin or South China (Fig. 8c), precipitation was less, as water vapor was mainly transported from the north where the air was drier, in addition to the presence of anomalous descending motion and reduced specific humidity (Figs. 6b and 6d).

In winter (Fig. 8d), precipitation is more over South China as its main source of water vapor is the western Pacific where the air is warm and humid, plus there is enhanced anomalous ascending motion there (Fig. 7b). Different from a consistent pattern shown in other three seasons of more (less) precipitation in association with lower (higher) temperature, more precipitation accompanies (unexpectedly) higher

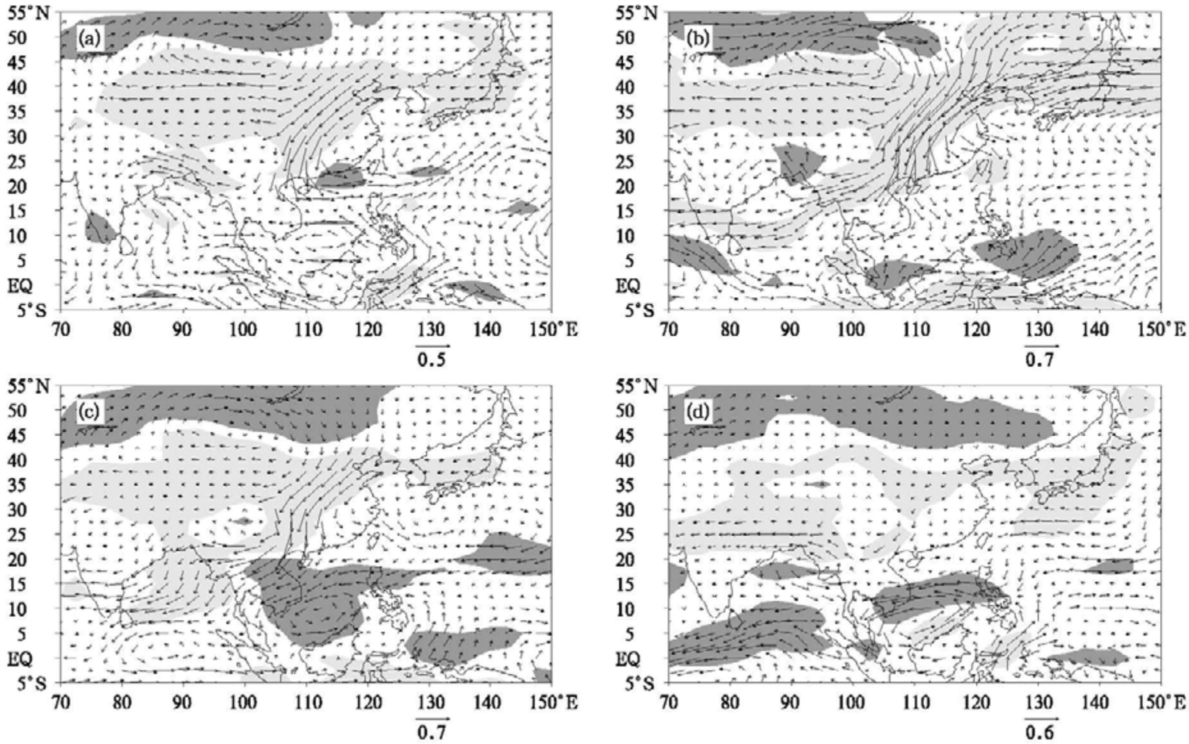

Fig. 8. The difference (Phase II minus Phase I) of spring (a), summer (b), autumn (c), and winter (d) water vapor fluxes (kg cm^{-1} s^{-1}). Shadings indicate areas with anomalies exceeding the 90% significance level.

temperature in winter in South China due to the transport of warm and humid oceanic airflow. Because of the small difference in the interdecadal transport of water vapor in winter between the Yangtze River basin and North China, the contrast in the regional precipitation between the two regions around 1976 is also small. It appears that the interdecadal variation of seasonal transport of water vapor corresponds well to that of precipitation in China.

4. Conclusions

Analyzing and comparing the interdecadal variations of China's precipitation and temperature around 1976, the year of abrupt change of atmospheric circulation, have led to the finding that after 1976, springtime precipitation was enhanced and temperature was reduced in South China. In the western Yangtze River basin, precipitation decreased and temperature was similarly lower. There was a pattern of "−, +, −, +" in summer in which precipitation was less in South China, more in the Yangtze River basin, less in North China, and more in Northeast China, while it was getting warmer in southern China, cooler in central China, and warming in northern China. In autumn, precipitation decreased while temperature increased in most of the country. In winter, precipitation increased mildly in South China and warming was almost a nationwide trend. In China, the interdecadal decreases of mean temperature in spring and summer were mainly subject to the change of daily maximum temperature while the interdecadal increases were chiefly governed by the daily minimum temperature variation; the overall warming was affected mostly by the minimum temperature change in autumn while being influenced mostly by the maximum temperature variation in winter.

The following factors are mainly responsible for the changes noted above. In springtime after 1976, the main anomalous ascending branch of the Hadley cell was over the area south of 32°N and the main anomalous descending branch was north of 32°N and south of 45°N. The intensified westerly jet stream was near 25°N and more southward than usual. A lower-level anomalous cyclone was accompanied by an upper-level anomalous anti-cyclone south of 32°N while an upper-level anomalous cyclone was associated with a lower-level anomalous anti-cyclone north of 32°N. Such an anomalous baroclinic system resulted in anomalous ascending (descending) motion south (north) of 32°N. In the meantime, spring also witnessed increased (decreased) amount of water vapor throughout the air column over South China (the Yangtze and Huaihe River basins). Incessantly, warm and humid water vapor was being supplied from the tropical South Pacific and the tropical West Pacific to South China to result in more precipitation.

In summer, the Hadley cell shifted to the north by about 5° to the Yangtze River basin, with North China having an anomalous descending branch. The anomalous ascending airflow in South China weakened at lower levels while being replaced by the anomalous descending airflow at higher levels. The westerly jet stream moved to around 35°N and the anomalous ascending motion intensified over the Yangtze River basin with water vapor showing interdecadal growth. Anomalous descending motion was intense and water vapor was low over North China. There was less precipitation in North China, to which water vapor, dry from the north and both dry and cold from the North Pacific, was transported. There was more precipitation in the Yangtze River basin, over which water vapor, dry from the north and warm and humid from the northwestern Pacific, merged. South China had less precipitation for its main source of water vapor was from the drier north.

In autumn, mainland China south of 27°N was dominated by anomalous ascending airflow while the remaining areas were in the control of anomalous descending airflow. Generally speaking, anomalous ascending airflow was decreasing on the interdecadal scale over China. At this time of the year, water vapor was mainly transported from the drier north, leading to less precipitation in both the Yangtze River basin and South China.

In winter, the anomalous distribution of the Hadley cell was like that of spring, anomalous ascending motion dominated south of the Yangtze River basin with increased water vapor, while anomalous descending motion was in charge in areas north of the basin with decreased water vapor. There was more precipitation in South China, as warm and humid water vapor was mainly from the West Pacific. On the interdecadal scale, there was little difference in the water vapor transport over the Yangtze River basin and North China.

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