An Analysis of Interdecadal Variations of the Asian-African Summer Monsoon*

SONG Yan[1,2†](宋 燕), JI Jinjun[3](季劲钧), and SUN Xia[4](孙 霞)

1 *Laboratory for Climate Studies, China Meteorological Administration, Beijing* 100081

2 *China Meteorological Administration Training Center, Beijing* 100081

3 *Key Laboratory of Regional Climate-Environment Research for Temperate East Asia (RCE-TEA), Chinese Academy of Sciences, Beijing* 100029

4 *Jilin Meterological Observatory, Changchun* 130062

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ABSTRACT

The response of the Asian-African summer monsoon (AASM) to the fast global warming in the 1980s is studied based on several datasets, which span a long time period of nearly 100 yr, with two special periods 1980–1985 and 1990–1995 being focused on. Wavelet analyses are employed to explore the interdecadal variations of the AASM.

It is found that after the mid-1980s, the global annual mean surface temperature rises more significantly and extensively over most parts of the African Continent, north of the Indian Ocean, and the Eurasian Continent excluding the Tibetan Plateau. Correspondingly, the global precipitation pattern alters with increased rainfall seen over the Sahel and North China in 1990-1995, though it is not recovered to the level of the rainy period before the mid-1960s.

Changes of monsoonal circulations between the pre- and post-1980s periods display that, after the fast global warming of the 1980s, the African summer monsoon intensifies distinctly, the Indian summer monsoon weakens a little bit, and the East Asian summer monsoon remains almost unchanged. The summer precipitation over the Asian-African Monsoon Belt (AAMB) does not change in phase coherently with the variations of the monsoonal circulations.

Wavelet analyses of the land-sea thermal contrast and precipitation over North China and the Sahel indicate that interdecadal signals are dominant and in positive phases in the 1960s, leading to an overall enhanced interdecadal variation of the AASM, although the 1960s witnesses a global cooling. In the 1980s, however, in the context of a fast global warming, interdecadal signals are in opposite phases, and they counteract with each other, leading to a weakened interdecadal variation of the AASM.

After the mid-1960s, the AASM weakened remarkably, whereas after the mid-1980s, the AASM as a whole did not strengthen uniformly and synchronously, because it is found that the interannual variations of the AASM in the 1980s are stronger than those in the 1960s, and they superimposed on the counteracting interdecadal signals, causing different regions of the AAMB behaving differently. Therefore, the response of the AASM to the accelerated global warming post the mid-1980s is not simply out-of-phase with that after the mid-1960s; it may involve more complicated multiscale physical elements.

Key words: global warming, Asian-African summer monsoon, interdecadal oscillation, abrupt climate change, wavelet analysis

1. Introduction

Global climate is experiencing an obvious warming trend in the 20th century with a much sharpened warming since the 1980s (Jones and Moberg, 2003). Some studies showed that the 1990s was the warmest decade in the recent 1000 years (Jones et al., 1998; Mann et al., 1998). The climate on earth has experienced two fast warmings in the 20th century, i.e., the first in the 1920s and the second in the 1980s (Song and Ji, 2005). Between these two warming events the climate was relatively cool, with an abrupt cooling in the mid-1960s, during which the Asian-African summer monsoon (AASM) weakened remarkably (Yan et

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†Corresponding author: songyan@cma.gov.cn.

al., 1990a, b; Song and Ji, 2001).

Some researchers examined the fast warming in the 1980s with various datasets and methods. Wang and Ye (1992) showed that the global temperature in the 1980s was about 0.56°C higher than that in the 1880s, and the 1980s witnessed the fastest rising of global surface temperature in the past 100 years. The global warming was therefore characterized by an uneven temporal change in surface temperature. Wang (2001) found that the global general circulation underwent an obvious change around the end of the 1970s, and since then the AASM circulation weakened, with trade winds over the tropical eastern Pacific also experiencing a weakening trend.

The response of climate to the global warming varies from region to region around the world. Wang and Ye (1992) and Tang and Ren (2005) found that the surface air temperature variations over China were not completely similar to the global warming. In China, for example, the warming mainly occurred during the 1920s–1930s, while the warming magnitude in the 1980s was a little bit lower than the global and Northern Hemisphere averages. Lin et al. (1995) showed that the annual mean temperature over China in the 1980s was lower than that in the 1940s. Some researches also showed that the snow cover in the Northern Hemisphere shrank suddenly in the 1980s, which was consistent with the warming in the Northern Hemisphere (Robinson and Dewey, 1990). After the 1980s the snow covers over Europe, Asia, and the Northern Hemisphere as a whole, regressed gradually, and by 1986 they were well below normal value (Zhai and Zhou, 1997). Zeng et al. (2003) thought that the recent global warming began in the 1970s, and it firstly occurred at the sea basin in the southern Indian Ocean, and the continental area in the Antarctic, and then shifted to the Northern Hemisphere to affect all the tropical and subtropical oceans.

There were different explanations for the fast global warming in the 1980s. Based on the analyses of mean global temperature change, volcano activities, CO_2 concentration, and sunspots activities in the last 100 years, Wang and Ye (1995) and Zhao et al. (2005) suggested that the global warming beginning in the 1980s might be caused by increasing greenhouse effects. Other studies showed that in the 1980s and at the beginning of the 1990s, North Atlantic Oscillation (NAO) and ENSO-like events caused surface temperature increases over the Northern Hemisphere continents in winter, bringing on persisting circulation anomalies, and then leading to increases of hemispheric mean surface temperature. These studies implied that interdedacal changes of NAO, North Pacific Oscillation (NPO), and sea surface temperature over the North Pacific might have affected the observed interdecadal climate variations (Huang et al., 1999; Li et al., 2002; Li and Xian, 2003; Sun and Chen, 2004; Li and Li, 1999). The variations of the NAO and NPO in the mid-1960s and the weakening of sea-land thermal contrast between the Eurasian Continent and the Indian Ocean could explain why the AASM suddenly weakened in the 1960s (Song and Ji, 2003; Qian, 1997).

On longer time scales, the AASM variations can be regarded as the background of the East-Asian monsoon. The belt stretching from North Africa through North India to North China is called the Asian-African monsoon belt (AAMB) (Yan and Nicole, 1995). Although the Asian summer monsoon and the African summer monsoon are sort of independent systems, on decadal and interdecadal time scales and even longer time scales, synchronous summer rainfall variations along the AAMB are obvious.

Previous studies indicated that the global warming in the 1920s corresponded to a strong AASM (Song and Ji, 2005), and the global cooling in the 1960s corresponded to a weakened AASM after the mid-1960s (Yan et al., 1990a, b; Song and Ji, 2001). Recent studies suggested that the East Asian summer monsoon experienced a weakening trend around 1976 on interdecadal time scale (Guo et al., 2004; Chen, 1999). Two dry events happened in North China around the mid-1960s and at the end of 1970s, respectively (Zhang, 1999). There was little rain during 1980–1993 as well (Hurrel, 1996). Although North China was drier in the 1980s than in the 1970s, it has become wet and has more rainfall since the mid-1990s (Huang et al., 1999), in spite of the fact that annual precipitation in this region as a whole once again significantly dropped during the period 1999–2003 (Ren et al., 2005). Question arises as for how the AAMB climate and the AASM circulations changed after the accelerated global warming of the 1980s? Whether the rainfall over these areas changed coherently? Under different backgrounds of a cooling period in the 1960s and a warming period in the 1980s, how did the AAMB rainfall respond to the global change on interdecadal time scale? In this paper we will try to answer these questions primarily through data analyses and a diagnosis for the pre- and post-1980s.

2. Data and method

The precipitation data used in this paper are global monthly precipitation grid data from 1900 to 1995 from U.S. NASA. The grid resolution is 2.5° (latitude)× 2.5° (longitude). EOF (empirical orthogonal function) analysis verified that this dataset could present global precipitation patterns and trends pretty well (Dai et al., 1997). In this paper the summer rainfall in an individual year was the total amount of precipitation for three months from June to August of the year.

The surface temperature anomalies used in this paper are from CO_2 Information Analysis Center of U.S. from 1900 to 1996, The grid resolution for the dataset is 5° (latitude) × 5° (longitude), covering the global area within 87.5°N–87.5°S. The dataset includes terrestrial and marine observations (Jones an Moberg, 2003).

The Northern Hemisphere sea level pressure data were obtained from the National Climate Center of China Meteorological Administration. We also used the monthly data from the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis to present the general circulation (Kalnay et al., 1996).

As interdecadal variations were investigated in this paper, the data used were all subject to a 5-yr running mean (an exception was for the wavelet analysis) in order to remove interannual variability, including the QBO (quasi-biennial oscillation) and ENSO signals.

3. The global warming event in the 1980s

The global summer mean temperature anomalies for 1900–1995 are shown in Fig.1. It is clear that around 1909 the global mean surface temperature was low, and since then it increased persistently. Around 1943 the temperature anomaly reached the first peak, followed by some small fluctuations. It reached the second peak around 1960, and after that the temperature decreased. Since 1976 it increased again till today, and the warmest years were registered in the late of the 20th century. Three episodes of the global mean temperature variations can be clearly seen. They are respectively the colder period of 1900–1935, the normal period of 1936–1975, and the warmer period from 1976 to present. The most significant warming happened at the beginning of 1980s and the warmest period was reached in the 1990s.

The global warming beginning in the 1980s is thought to be the strongest in the recent 100 years (Wang and Ye, 1992), but the temporal and spatial analyses of the warming are seldom related to other periods of fast climate change. The EOF analysis of the global summer temperature field from 1970 to 1996 was made in a previous paper (Song and Ji, 2005). The temporal and spatial distributions and the rapid climate change testing on Pc1 (principal component 1) showed that there was an obvious rapid change around the mid-1980s, after that the global climate became much warmer.

Figure 2 shows the global mean surface temperature difference between 1990–1995 and 1980–1985. The period 1980–1985 is taken to represent the period before the fast global warming, and the period 1990–1995 is taken to represent the period after the fast global warming. Figure 2 shows that except for the Tibetan Plateau and a small area over Northeast China, the whole Eurasian Continent became warmer. The same is true for the African and American Continents. Over the oceans, the temperature in the equator increased obviously, but it decreased remarkably in middle and high latitudes over the northern Atlantic, Pacific, and the southern Indian Ocean. It is worthy to note that in the northern Indian Ocean there was a very evident and persistent warming, especially over middle and eastern parts of the region; on the other hand, the North Atlantic and North Pacific underwent a cooling, indicating that NPO and NAO positive phases should be getting stronger. Recent studies showed that interdecadal variability of ENSO and NAO caused the rapid global warming for the recent 20 years (Wallace et al., 1995, 1996). Overall, the cooling over the Tibetan Plateau and the warming over the North Indian Ocean were obviously unfavorable to the persistence and reinforcement of the Asian summer monsoon system.

It is important to further understand the spatial distributions of summer precipitation under the background of the fast global warming. Song and Ji (2005) assessed the first mode of precipitation spatial distribution of EOF analysis and rapid climate change testing on Pc1 for 1970–1995. The variance contribution of the first mode reaches 16%. An obvious abrupt precipitation change occurred around the mid-1980s.

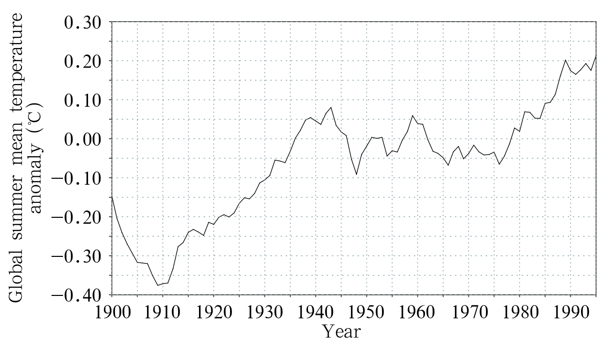

Fig.1. 1900–1995 global summer 5-yr running mean temperature anomalies (°C).

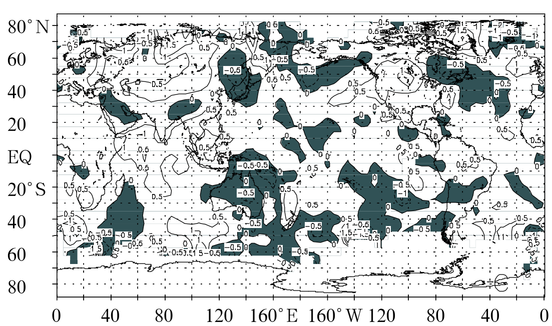

Fig.2. The summer surface temperature difference field between 1990–1995 and 1980–1985. The shaded areas mean negative values, and the interval of isoline is 0.5 °C.

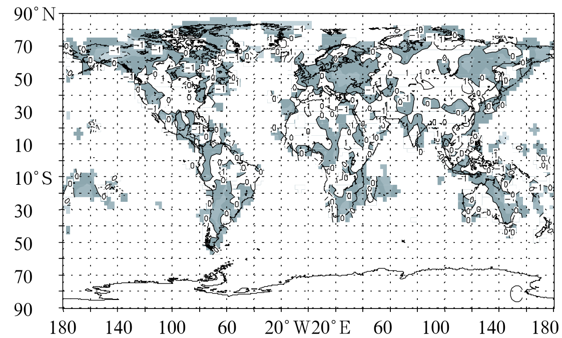

Fig.3. The normalized summer precipitation difference field between 1990–1995 and 1980–1985. The shaded areas mean negative values, and the interval of isoline is 1 mm.

After that the summer precipitation over the northern North China increased, and it decreased over the southern area. Synchronously increased precipitation over the central and southern India and decreased precipitation over the northern India could be seen. In particular, the summer rainfall increased over the Sahel of the North Africa. Therefore, in arid and semi-arid areas of AAMB, the summer precipitation generally increased, though a more complex situation could be found over North China and North India. Most areas of North China had more rain, but North India underwent a decrease in summer rain.

The normalized summer precipitation difference between 1990–1995 and 1980–1985 is shown in Fig.3. A very similar pattern to that described above can be seen. Therefore, it is quite complicated for precipitation variation over the AAMB after the fast global warming in the 1980s. The summer precipitation generally increased evidently in the African Sahel, the central and southern India, and most areas of North China, but it decreased in the northern India and the southern North China.

The above analyses suggest that the interdecadal changes of observed temperature and precipitation fields for the fast global warming in the pre- and post-1980s were approximately consistent with the first mode of EOF analysis, implying that the fast global warming and corresponding remarkable change of global precipitation in the 1980s are real and significant.

4. Variations of the monsoon circulations

Figure 4 presents interdecadal variations of summer precipitation in North China and the Sahel of North Africa, and the land-sea thermal difference between the Indian Ocean and the Asian-African Continent. It is clear that with precipitation decreasing over the Sahel and North China over the past 100 years, the land-sea thermal contrast increased accordingly. They are out-of-phase obviously.

The land-sea thermal difference is calculated as follows:

Firstly, we calculated the mean surface temperature over the Indian Ocean key area (32.5°S–7.5°N, 50°–90°E) to represent the thermal intensity over sea, and the mean surface temperature over the Asian Continent key area (22.5°–37.5°N, 80°–120°E) and the African-European Continent key area (22.5°–47.5°N, 20°–50°E) to represent the thermal intensity over land. Secondly, the averaged land temperature was subtracted from the averaged sea temperature to obtain the land-sea temperature difference. The normalized land-sea temperature difference I_{AA} is taken as an index of the AASM magnitude. Note that a 5-yr running mean was made to get this sea-land thermal contrast index I_{AA} (Song and Ji, 2005). If I_{AA} is in high phase, the surface temperature over sea is higher than that over land, and the Asian-African summer monsoon is weak; oppositely, if I_{AA} is in low phase, the land-sea thermal contrast and the Asian-African summer monsoon are both strong.

The two average precipitation curves in Fig.4 are for areas 12°–22.5°N, 10°W–20°E and 32.5°–42.5°N, 110°–120°E, which represent the Sahel and North China, respectively. A 5-yr running mean was made for the two curves as well.

Figure 4 shows that the rainfall over the Sahel and North China was larger from the end of 1980s to early 1990s than that before the early 1980s, although the AASM tends to be weakened and precipitation over the two regions decreased distinctly on the interdecadal time scale after the middle to the end of 1970s. During 1980–1985, the precipitation over the two areas was at the valley of the curves, but during 1990–1995 the precipitation enriched obviously. In this figure, the two episodes are marked by two black arrows to highlight the comparison. Compared with the mid-1960s the precipitation is much less in the episode 1990-1995, indicating that the interdecadal precipitation variation tends to be drier in the recent two decades. Similarly, I_{AA} curve has been in high phase since the mid-1960s, and the AASM was weak.

Figure 5a shows the global summer sea level pressure difference between 1990–1995 and 1980–1985. Over the European and African Continents, as well as the Arctic region, there were negative pressure anomalies, while positive anomalies prevailed over the American Continent, especially over the northern Canada where there was a positive pressure anomaly center of more than 1 hPa. Over the Central, North, and South Pacific there were obvious negative anomaly regions, especially at the middle and high latitudes in the Southern Hemisphere. Along the coast of the eastern Asian Continent the pressure anomalies were generally

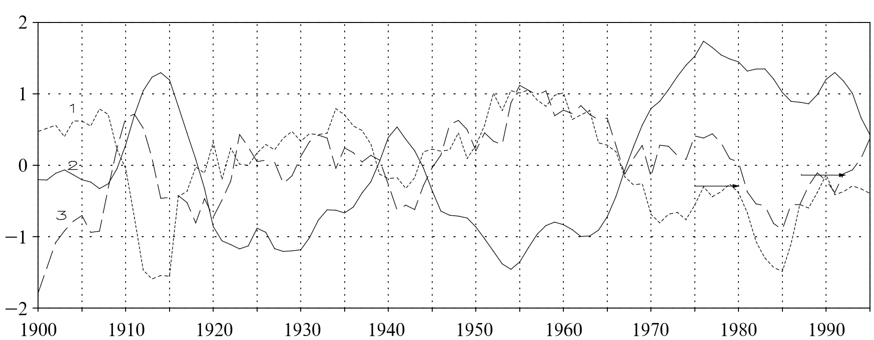

Fig.4. The 1900–1996 summer normalized time series (5-yr running mean). Curve 1: precipitation of the Sahel (dot line); curve 2: the thermal contrast between the Indian Ocean and the Eurasian Continent (solid line); and curve 3: precipitation of North China (dashed line).

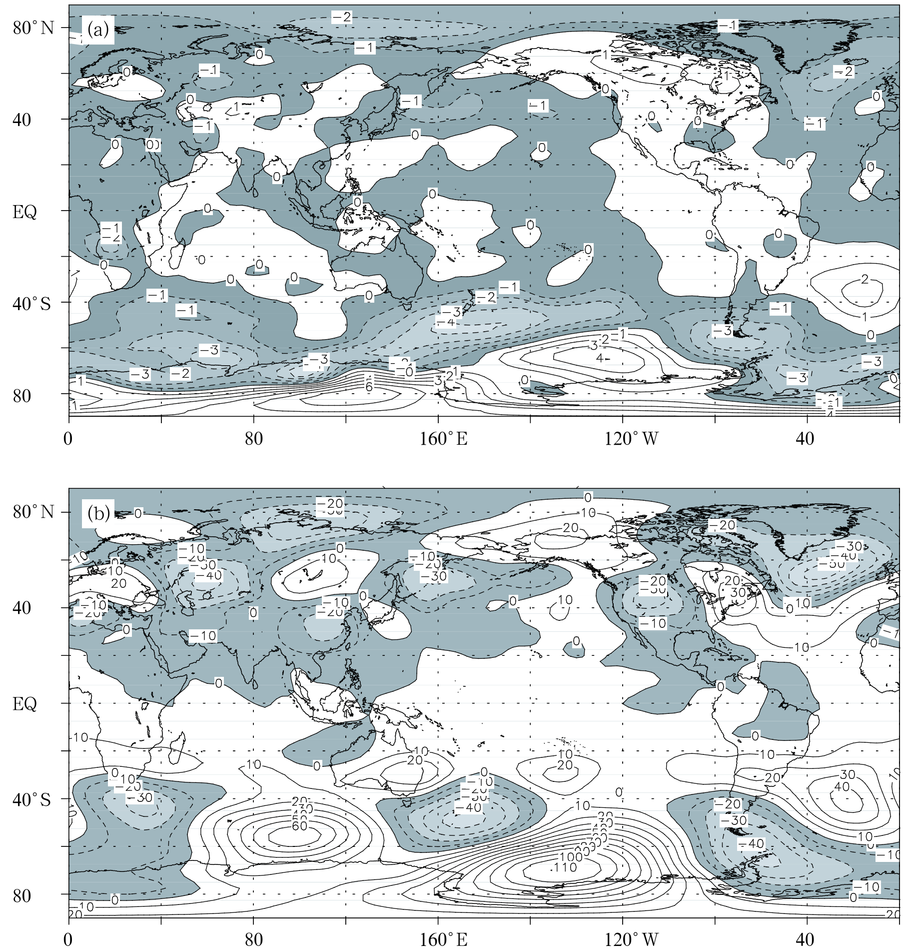

Fig.5. (a) The summer sea level pressure difference (interval: 1 hPa) and (b) the 200-hPa summer potential height difference (interval: 10 gpm) between 1990–1995 and 1980–1985. Shaded areas mean negative values.

negative. From the Tibetan Plateau through inland to Northeast China there were positive pressure anomalies. Northwest China and the Balkhash Lake region were a positive anomaly center of more than 1 hPa. Positive pressure anomalies also occurred in the west and south of the Indian Ocean.

In fact, some factors were unfavorable for the maintenance of the Asian summer monsoon. Firstly, for the Asian summer monsoon, in the middle of Asian Continent 20°–60°N from the Tibetan Plateau to the northeast there were positive pressure anomalies, while negative anomalies occurred over North Pacific along 30°–50°N. Thus a pattern of pressure anomalies decreasing in the east and increasing in the west, could produce an anomalous pressure gradient which pointed to the east from west, and could also produce a southward geostrophic wind component with an opposite direction of southwesterly flow of Asian monsoon. That did not avail warm and moist air mass from the south to penetrate into the north of inland. Similarly, over the Indian Peninsula there were negative pressure anomalies, but positive anomalies prevailed over the southwest of the Indian Ocean. That could generate a pressure gradient from the north to the south with a westward geostrophic wind component, which could weaken the Indian summer monsoon. In addition, over northern China, the Indian Peninsula, and the Indo-China Peninsula there were negative pressure anomalies, while around 20°N over the Asian Continent and Pacific, positive pressure anomalies prevailed, which could generate a southward anomalous pressure gradient with an westward geostrophic component over the mid-latitude 30°N, unfavorable to the persistence of monsoon southwesterly flow.

Secondly, the pressure anomaly pattern was quite beneficial to the African summer monsoon. There were extensive negative pressure anomalies over the African Continent, but positive anomalies over Northwest Indian Ocean, which were favorable to the prevailing of the southerly flow and reinforcement of the African summer monsoon. Generally speaking, after the fast global warming of the 1980s, the African summer monsoon intensified, but the intensification of the Asian summer monsoon was not obvious.

Figure 5b gives the 200-hPa geopotential height difference between the two periods of 1990–1995 and 1980–1985. Over the Asian Continent there were negative anomalies, which implies that the South Asian high has been weakening significantly since the 1980s. While on the northern margin of North Africa there were negative anomalies, and positive anomalies were seen in the Sahel region. Such a pattern indicated that pressure over the Sahel in the upper troposphere increased. The overall distributions of pressure anomalies suggested that after the 1980s the Asian summer monsoon somehow weakened and the North African monsoon intensified.

Compared with climate change in the mid-1960s, the fast global warming in the 1980s is more complicated, and it is not just the opposite oscillation of mid-1960s. In the 1980s the summer precipitation pattern over the AAMB was complicated and not so clearly. It seemed not changed in phase and there were some differences between the African summer monsoon and the Asian summer monsoon. It implied that in different areas there was different patterns of precipitation variations. For a detailed description and related figures of climate patterns before and after the climatic cooling around the mid-1960s, please refer to previous papers (Song and Ji, 2003, 2005).

From Fig.6, we can see that, in the meridional vertical circulation difference over the African summer monsoon (Fig.6a), there were three meridional cells at low levels. On the north of 10°N there were two Hadley cells; and on the south, there was one Hadley cell. The strongest vertical ascending was still around 10°N, indicating that the monsoon cell for 1990-1995 intensified at middle and low levels. The Sahel is just located at 10°N. Therefore, after the fast global warming in the 1980s the African summer monsoon intensified, but the intensity was still weaker than that in the mid-1960s (figure omitted). At the same time, Hadley cells also reinforced on the northern side of 10°N. These two cells intensified the ascending motion around 30°N.

Figures 6b, c depict respectively the Indian summer monsoon and East Asian summer monsoon circulations. It is obvious that the two monsoon circulations did not intensify obviously. Oppositely, over the Indian Peninsula, there was distinct anomalous descending motion. Over the East Asian Continent, horizontal anomalous flows prevailed in the whole troposphere, and the vertical motion anomaly was very weak, implying that the summer monsoon circulation kept unchanged during that period.

Based on the analyses above, we can conclude that compared with the mid-1960s, the AASM did not reinforce coherently in response to the fast global warming in the 1980s. The African summer monsoon was indeed reinforced somewhat. But rain regaining in North China might be mainly caused by interannual variability, rather than by interdecadal variability. The above normal rainfall in some individual year led to decadal rainfall increasing in North China, which seemed like an interdecadal intensification. In fact, it might have been a false appearance. Therefore, the interdecadal climate changes for the period of the fast global warming in the 1980s and the AASM interdecadal weakening in the 1960s were different obviously, and the interdecadal oscillations were not out-of-phase. In the mid-1960s when the global cooling occurred, the AASM weakened significantly; in the 1980s when the fast global warming occurred, the AASM did not intensify clearly as expected. What are the reasons for such a phenomenon? In the following section, we try to explain the possible reasons by investigating

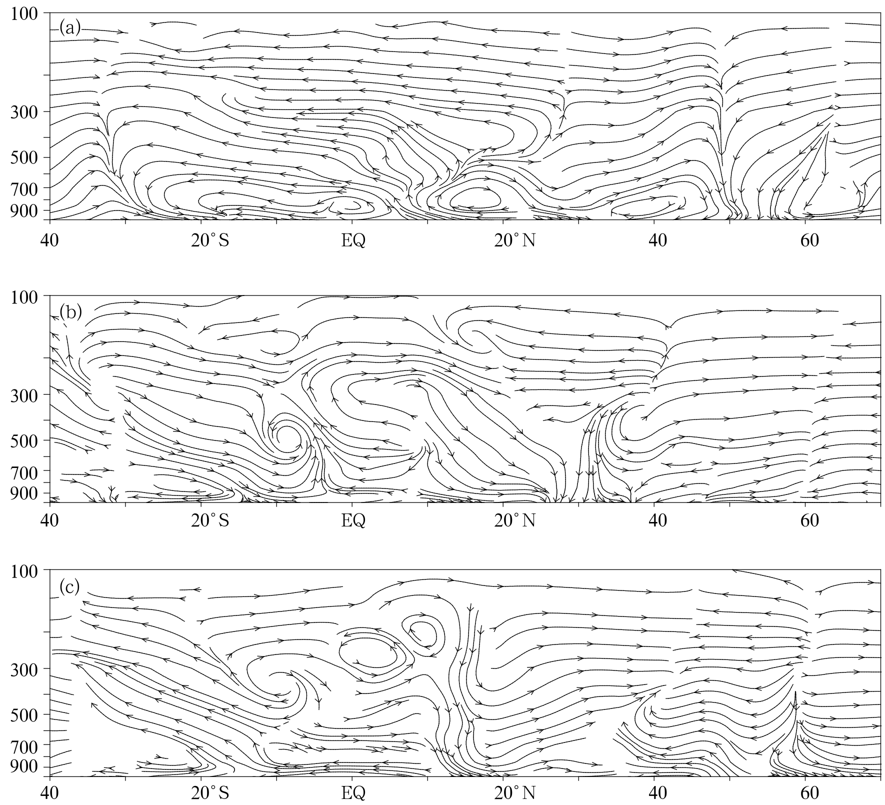

Fig.6. The summer meridional vertical circulation differences between 1990–1995 and 1980–1985 for (a) 10°–30°E, (b) 80°–90°E, and (c) 105°–125°E.

into the interaction of different time-scale signals of land-sea thermal contrast and summer precipitation over North China and African Sahel.

5. Wavelet analyses

Figure 7 shows the wavelet analysis result for land-sea thermal contrast between the Asian-African Continents and the Indian Ocean. Different time-scale signals can be discerned clearly in the figure. Noticeably, various time-scale signals were outstanding from the 1950s to 1970s, and almost in phase to reinforce the interdecadal variation. They interacted with each other to make land-sea thermal contrast quite strong and in low phase before the mid-1960s. Therefore, in this episode 1950s–1960s the AASM was very strong. Around the mid-1960s, the interdecadal signals were strong but had an abrupt shift, indicating that climate had a sudden interdecadal change, while the land-sea thermal contrast and the AASM remarkably weakened. The situation in the 1980s, however, is rather different. After the fast global warming, the interdecadal signals were also significant, but the signs were opposite and out-of-phase. They counteracted with each other to produce smaller amplitudes and weaker intensity, while the interannual variability on shorter time scales became stronger. Therefore, the variation of the 1980s was quite complicated compared to that of the 1960s. The interdecadal signals counteracted to become weaker, but the interannual signals were playing a more important role in maintance of the AASM. These might have been the reasons why the AASM variation was unremarkable after the fast global warming in the 1980s, and why the interdecadal variations of the AASM in the mid-1960s and 1980s were different.

Figures 8a, b give the results of wavelet analyses for summer precipitation over North China and the Sahel, respectively. The features and patterns are the same as Fig.7, further verifying that the interdecadal change of the land-sea thermal contrast could reflect the interdecadal change of the AASM intensity. For the AASM interdecadal variation, the AAMB precipitation variation on interdecadal time scale was closely related to interdecadal variation of the land-sea thermal contrast. Although there were distinct 32–48-yr interdecadal signals in the 1960s and 1980s, and the multi-decadal to centurial oscillations were also quite clear in the 1980s, which had opposite signs to the 32–48-yr signals. Different time-scale variations therefore counteracted with each other to weaken long-term climate influences. Furthermore, interannual signals amplified relatively in the 1980s. This further verified that the intensity of the AASM after the fast global warming in the 1980s was mainly affected by the interannual variability. Therefore, the two time-scale (interdecadal and interannual) variations interacted with

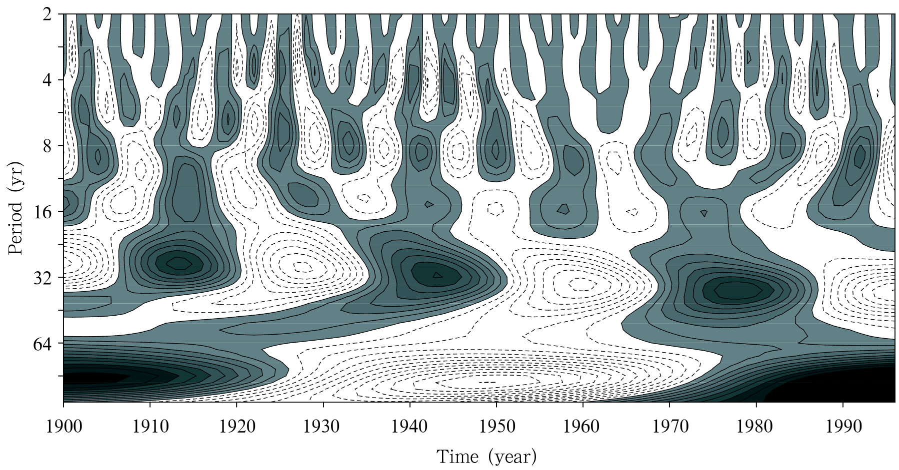

Fig.7. Distribution of wavelet analysis of the the real part of the thermal contrast between the Indian Ocean and Eurasian Coneinent for 1900–1996.

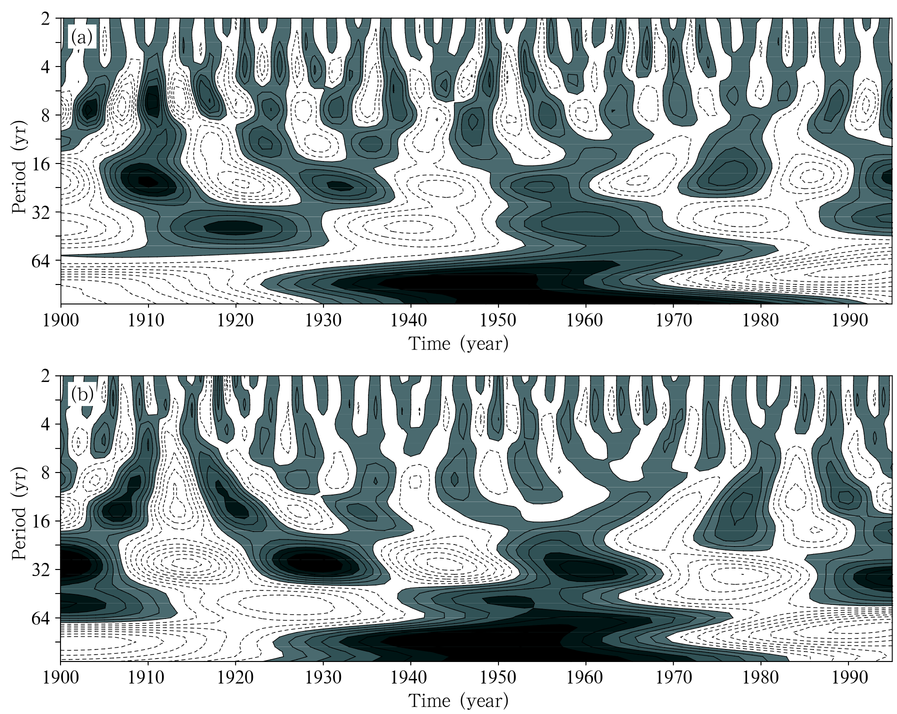

Fig.8. The wavelet analysis of the real part of summer precipitation for 1900–1995 for (a) North China and (b) the Sahel.

each other in the AASM system to produce different climate features in the 1980s and 1960s. The AASM showed a more complicated feature in the 1980s than 1960s, with the recent variation controlled dominantly by the interannual physical factors.

Therefore, it can be concluded from the analyses above that the global cooling in the 1960s appeared to be strong interdecadal signals with the AASM weakening remarkably in the mid-1960s; in the global warming of the 1980s, however, interdecadal signals counteracted to stand out much interannual influence. The interannual oscillation played a more important role in climate change in the 1980s.

6. Conclusions

Based on the comprehensive analyses above, the results can be summarized below:

(1) The fast global warming occurred in the 1980s, with the global annual mean surface temperature increasing remarkably after the mid-1980s. Correspondingly, the global precipitation pattern changed, and rainfall regaining was seen over the Sahel region of North Africa and North China, though it was not recovered to the level of rainy period before the mid-1960s.

(2) The variation of monsoon circulations between the pre- and post-1980s periods shows that, after the fast global warming of the 1980s, the African summer monsoon intensified distinctly, the Indian summer monsoon weakened a little bit, and the East Asian summer monsoon almost kept unchanged. The summer precipitation over the AAMB did not change in phase coherently. The reason for the summer rainfall regaining over North China might have been the result of a stronger interannual variability.

(3) Wavelet analyses indicate that the interdecadal oscillation was predominant in the 1960s for the Asian-African summer monsoon, and the interdecadal signals were in positive phase and interacted with each other to intensify the interdecadal variation. In the 1980s, however, the interdecadal signals were weaker and in opposite phases, and they counteracted with each other to weaken the interdecadal variation.

(4) After the mid-1960s, the AASM weakened remarkably, whereas after the mid-1980s, the AASM as a whole didn't strengthen uniformly and synchronously, because it is found that the interannual variations of the AASM in the 1980s are stronger than those in the 1960s, and they superimposed on the counteracting interdecadal signals, causing different regions of the AAMB behaving differently. Therefore, the response of the AASM to the accelerated global warming post the mid-1980s is not simply out-of-phase with that after the mid-1960s; it may involve more complicated multiscale physical elements.

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