SCIENCE CHINA
Earth Sciences

SPECIAL TOPIC: The 70th Anniversary of the Founding of The People's Republic of China
•REVIEW•

October 2019 Vol.62 No.10: 1514–1550
https://doi.org/10.1007/s11430-019-9483-5

# Review of Chinese atmospheric science research over the past 70 years: Climate and climate change

Jianping HUANG[1*], Wen CHEN[2], Zhiping WEN[3], Guangjun ZHANG[4], Zhaoxin LI[5], Zhiyan ZUO[6] & Qingyun ZHAO[1]

[1] *College of Atmospheric Sciences, Lanzhou University, Lanzhou 730000, China;*
[2] *Center for Monsoon System Research, Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing 100190, China;*
[3] *Department of Atmospheric and Oceanic Sciences, Fudan University, Shanghai 200438, China;*
[4] *Scripps Institution of Oceanography, University of California, San Diego 92093, USA;*
[5] *Laboratoire de Météorologie Dynamique, CNRS, Sorbonne Université, Paris 75005, France;*
[6] *Chinese Academy of Meteorological Sciences, Beijing 100081, China*

Received June 5, 2019; revised August 16, 2019; accepted September 16, 2019; published online September 24, 2019

**Abstract** Climate and climate change have always been a research focus of atmospheric sciences. This paper summaries research efforts, achievements and international contributions of the Chinese scientific community on climate and climate change over the past 70 years. The review is based on papers published officially in national or international scientific journals, and is organized to cover six aspects: (1) general climate studies; (2) impact of the Qinghai-Tibetan Plateau; (3) impact of the East Asian monsoon; (4) influences of teleconnection oscillation and westerlies; (5) climate dynamics and development of climate models; and (6) climate change. It is, however, to be noted that the present review can not be considered as an exhaustive one, since there is a huge body of literature in the field.

**Keywords** Climate of China, Qinghai-Tibetan Plateau, East Asian Monsoon, Climate change

**Citation:** Huang J, Chen W, Wen Z, Zhang G, Li Z, Zuo Z, Zhao Q. 2019. Review of Chinese atmospheric science research over the past 70 years: Climate and climate change. Science China Earth Sciences, 62: 1514–1550, https://doi.org/10.1007/s11430-019-9483-5

## 1. Introduction

Climate and climate change have always been a research focus of atmospheric sciences. Climate refers to the statistic state of the atmosphere over a long period of time and for a certain location on Earth, which includes both mean and extreme conditions of various weather processes and events over the years. Climate is changing due to changes in solar radiation, surface conditions, atmospheric circulation, and human activity. Climate change refers to the change of long-term mean in a specific location, in a region or globally. It includes changes in both spatial and temporal scales. It is often measured by changes of certain properties related to average weather conditions. It distinguishes from weather variation by its longer time scale.

This paper first reviews the significant progress brought by Chinese scientists in climate studies over the past 70 years. The Qinghai-Tibetan Plateau, standing in western China, is the highest orography in the world. It has important influences on the evolution of global atmospheric circulation and plays an important role in climate change and climatic anomalies in China for its both dynamic and thermodynamic aspects. The research on the influence of the Qinghai-Tibetan Plateau on climate change has always been a key scientific topic. Chinese scientists have made pioneering and original scientific achievements in this field, which largely promoted

* Corresponding author (email: hjp@lzu.edu.cn)

the research on the impact of the Qinghai-Tibetan Plateau on the regional climate in China. This paper focuses on the progress in this field in Section 3.

Monsoon is an important circulation system for the global climate. China is located in the East Asian monsoon region. Interannual and interdecadal variations of the East Asian monsoon can lead to climate disasters such as drought, flood, and heat-wave in China. This research field saw a lot of interesting achievements brought by Chinese scientists. This paper reviews works on the East Asian monsoon in Section 4. China is a very active country in studying the impact of teleconnection patterns and perturbations from the westerlies on the regional climate in East Asia and has made remarkable achievements, which will be presented in Section 5.

Chinese scientists attached great importance to climate dynamics and conducted a series of systematic researches. They have established a theoretical framework for climate dynamics. The development and application of climate system modeling is a significant part of modern climatology. China has a long history of climate modeling. In fact, since the late 1970s, climate models have been developed and applied to simulating climate processes. The works on climate dynamics and climate modeling will be reviewed in Section 6. One of the most important progress in atmospheric sciences in the 20th century is that scientists and governments all around the world have realized the human-induced global warming and its influence on the global environment. Additionally, they have realized that climate change is a result of the interactions among multi-spheres in the Earth's system. This paper discusses the progress of Chinese scientists in this field in Section 7.

Finally, the major results from the past work are summarized and prospective scientific issues are proposed in Section 8. Of course, there are specialized review papers in other fields, including the biosphere, the cryosphere, etc., related to the topic of climate change. In this paper, we focus on the atmosphere research and the above-mentioned aspects are not covered.

## 2. General climate studies

Climate research is largely based on statistical analyses of long-term data, including paleoclimate proxy data, historical climate record, and the reanalysis data in modern times. Chinese scientists made statistical analyses of climate changes in temperature and precipitation (drought and flood) based on long-term data. They systematically studied the formation mechanisms of climate disasters and extreme climate events, which laid the physical foundation for climate disaster prediction in China.

Based on the geographical phenomena described in relevant literature, including the decline in Arctic sea ice, the northward shift of the southern boundary of tundra in the Soviet Union, the retreat of global mountain glaciers and snow lines and the sea-level rise, Zhu (1962) first proposed the idea of gradual warming of climate in the 20th century in the field of international climate research. His research further suggests that changes in the intensity of solar radiation may be the major cause of climate vacillation. When the sunspots are intensified, the ozone layer of the Earth's atmosphere absorbs a large amount of ultraviolet light, which can affect the global atmospheric circulation, and further influence the distribution of temperature and rainfall on the Earth's surface. The relationship between solar radiation and the climate on the Earth's surface is very complex. Based on historical and archaeological excavation materials, Zhu (1973) analyzed the temperature variations in China over the past 5000 years and pointed out that in the first 2000 years, the annual average temperature was about 2°C higher than that of today. After that, the annual average temperature fluctuated by 2–3°C. The cold period occurred in 1000BC, AD400, AD1200, and AD1700. Each cycle of fluctuation lasted about 400 to 800 years, with small cycles of 50 to 100 years within the larger cycle. The causes of large fluctuations were mainly controlled by solar radiation, while the causes of small fluctuations were related to atmospheric circulation activities (Figure 1).

After Zhu, Chinese scientists have also produced a large number of results via data analysis. Wu and Lin (1978) analyzed the historical climate change in Tibet based on the tree-rings data and changes in natural signs. They pointed out that in the past hundreds of years, Tibet has been in a warm and dry period, and the temperature trend in Tibet is generally in line with that of East China, especially since the warming trend in 17th century. Wang et al. (1978) analyzed climate change over the past 6000 years based on the pollen data in the cultural sites in Shanghai. They found that there were three warm-humid and two cold-dry phases between 5460 BP and 2500 BP. Wang and Zhao (1979) analyzed the drought and flood data of China in the past 500 years. They found a cycle of 36-year drought and flood in East China, especially in the lower reaches of the Yangtze River. They further discovered that the equatorial central Pacific region was closely related to the cyclical changes of drought and flood in China. Zhang and Zhang (1979) also analyzed the warm-humid and cold-dry climate changes in the past 500 years. They found that there were significant fluctuation cycles of 20–40 years and 200 years in addition to the fluctuation of 2–5 years in climate change in China.

Yao (1982) used modern statistics to analyze drought and flood records in China based on historical documents over the past 500 years. He elaborated the statistical variance characteristics of climate data, periodic cycle characteristics and the statistical theory and means to obtain these characteristics. Using 26 sequences of drought and flood ranking

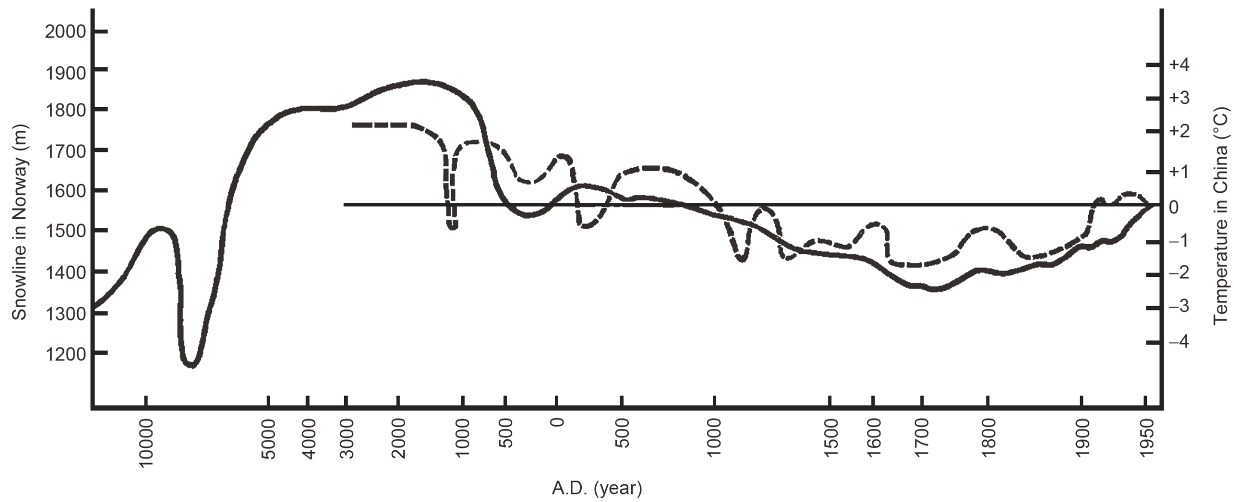


**Figure 1** Snow line in Norway over the past 10000 years (solid line) and the temperature of China in the past 5000 years (dotted line). Source: Zhu (1973). The snowline height is measured in meters; the current height of the Norwegian snow line is about 1600 meters. The temperature is measured in Celsius; the 0 line is taken as the current temperature level. The scale of horizontal time is exponential; the scale decreases to the left.

and a combined winter temperature index sequence in China since the year of 1471, Zhen and Feng (1985) analyzed the relationship between the precipitation variability and averaged temperature over the past 500 years. They found that the precipitation variability and average temperature in China were negatively correlated. Namely, the climate was more unstable in the cold phase, especially in the Little Ice Age, when the extreme climate was more frequent.

Based on historical documents, Wang and Wang (1987) established a relationship between the drought/flood classification and the observed precipitation over the same period. Thus, they restored the continuous climate series of equivalent annual precipitation variability with quantitative properties in the Central Plains region of China for more than 2200 years. At the same time, they combined the historical research and modern analysis methods to obtain the precipitation variation in the Central Plains region of China for more than 5000 years. Zhang and Crowley (1989) published the historical climate records of China and the climate reconstruction data of nearly a thousand years. They made a valuable summary of the existing studies and a comprehensive review of how to obtain climate information through the descriptive historical documents. Since the 1990s, great progress has been made in the research on climate change in China based on the development and utilization of climatic proxy data.

Wang and Gong (2000) analyzed the climatic characteristics of four typical periods (Megathermal Period, Medieval Warm Period, Little Ice Age and Modern Warming Period) of climate change in China in the past 10000 years. They found that the temperature during the Megathermal Period was more than 2°C higher than the average temperature in the past 100 years and that the 20th century was the warmest century in the past 12 centuries, which was 0.5°C higher than the average temperature in the past 1200 years.

Wang et al. (2005) reconstructed a continuous historical record of Asian monsoon over the past 9000 years based on the oxygen isotope records of a cave in South China. They found a good correlation between the climatic monsoon oscillations and solar activities in both decadal- and centennial-scale. Based on the stalagmite records, Cai et al. (2010) found that the East Asian monsoon experienced a significant change during the Last Glacial Maximum. According to other stalagmite data, it is indicated that summer monsoon precipitation in East Asia changed differently in Holocene. Li et al. (2013) used tree-ring data to analyze the changes in ENSO over the past seven centuries. They found that ENSO activity was most active in the late 20th century, which was the response to global warming.

As one of the most vulnerable regions to climate change around the world, China suffers severely from climatic disasters due to climate anomalies, especially droughts and floods. The research on the formation mechanism and prediction theory of the climatic disasters are the important frontier scientific issues (Huang et al., 2003; Huang, 2006). The distribution characteristics of major climatic disasters (drought, flood, and sandstorm) in China were obtained by the statistics of climate data from 1951 to 1990. Drought mainly occurs in Northwest and North China. Northwest China, where droughts can occur all year round, is classified as an arid climate with low annual precipitation. The precipitation in North China displays significant seasonal and interannual variations, and drought often occurs in spring and summer. The frequency of flood, which occurs once every 5 years, is slightly lower than the drought in China. The flood is mainly distributed in the middle and lower reaches of the Yangtze River and the coastal region of Southeastern China. For example, heavy floods occurred in the Yangtze River Basin in the summer of 1954, 1980, and 1991. In particular, catastrophic floods struck the Yangtze River Basin, Nenjiang River, and Songhuajiang River Basins in the summer of 1998. Sandstorms mainly occur in spring. The Tarim Basin in Southern Xinjiang, the Hexi Corridor, Ningxia, and the West of Inner Mongolia are the high-frequency areas of Sandstorms. Sandstorm occurs for up to 30–50 days annually. Sandstorm affects a wide range of areas. Most areas in the north of the Huaihe River are affected by sandstorms or blowing sand (Zhou Z J et al., 2002).

Since 1949, two heavy floods occurred in the Yangtze River Basin and Huaihe River Basin in 1945 and 1998. Comprehensive analysis shows that the anomalous circulation during the flood in the Yangtze River and Huaihe River Basin in 1954 was manifested in the splitting of East Asian jets, which was caused by the formation and maintenance of the Okhotsk high. As a result, the upper frontal zone over East Asia was about ten degrees latitude south of the climatological location. In addition, the axis of Pacific subtropical high was also to the south of climatological location, leading to the persistence of precipitation (Chen, 1957). Combined with the formation process of the heavy floods in the Yangtze River Basin in the summer of 1998, a climatological model of flood occurrence in the Yangtze River Basin was proposed (Huang, 2006): When the heat content of the tropical western Pacific Ocean is lower than normal, the El Niño event is weakening or the La Niña event is developing. Meanwhile, the convection activity around the Philippines weakens and the Qinghai-Tibetan Plateau is covered with heavy snow in winter and spring for a long time. Under this circumstance, the western Pacific subtropical high is westward and southward, which is conducive to the maintenance of the summer monsoon rain belt in the Yangtze River Basin and Huaihe River Basins. The low-pressure trough of mid-latitude westerly is located above the Inner Mongolia and northwest China, which is conducive to a southward movement of the weak cold, thus keeps the Meiyu front in the Yangtze River and Huaihe River for a long time. In addition, the 30–60-day low-frequency oscillation from the Indian Ocean to the Yangtze River Basin is both strong and frequent, making the strong water vapor transport from the Bay of Bengal and the South China Sea converge in the Yangtze River Basin. As a result, extreme heavy floods occur in the Yangtze River Basin.

Zou et al. (2005) calculated the Palmer Drought Index of China from 1951–2003. They found that the arid area in North China had extended significantly during this period. Except Northwest China, most parts of North China have experienced severe persistent drought since the late 1900s. According to the comprehensive analysis of observation and dynamic theory, since the second half of the 1970s, there have been interdecadal warming in the central and eastern tropical Pacific, namely the El Niño phenomenon. As a result, the Asian summer monsoon and water vapor transport in East China from south to north were both weakened, resulting in sustained and severe persistent drought in North China. There are significant changes in the northern hemisphere summer since the late 1970s. The East Asia deep trough was eastward and the continental high pressure extended eastward, which caused the summer climate anomalies in heat and drought (Huang, 2006). In addition, the depth of snow cover on the Tibetan Plateau has been increasing since the second half of the 1970s, which was unfavorable to precipitation in the Yangtze River Basin. Yu et al. (2004) found a unique cooling trend in the troposphere in East Asia during the summer of July and August, which was most significant near 300 hPa in the upper troposphere. Meanwhile, the upper westerly jet over East Asia was southward and East Asian summer monsoon was weakened. Eventually, the drought in north China and flood in the Yangtze River Basin were both intensified.

In recent years, the frequency of droughts in northeast China has increased. Especially in the summer of 2014, northeast China suffered from the severest drought in the past 60 years. Wang and He (2015) found that synergistic effects of the significantly enhanced Pacific-Japan teleconnection pattern, the southward subtropical high, the decreased East Asian summer monsoon circulation and the Eurasian teleconnection type enhanced by Arctic sea ice changes caused the extreme drought in Northeast China. With global warming, Arctic sea ice anomalies have also become a key factor leading to the increasingly severe extreme drought events in northern China (Li et al., 2018).

Wang et al. (1995, 2003) analyzed the climatic data of northern China and revealed the spatiotemporal distribution characteristics of dust storms. Also, they revealed the climate background and the underlying surface condition of the dark storms that frequently occur in April and May in Northwest China. Dust storm occurs mainly in hyper-arid, arid and semi-arid areas, which are associated with desert and desertified land; Northwest China is an arid and semi-arid region. The East Asian subtropical westerly jet axis is located around 35°N, which is the primary cause of the strong wind in the northwest. The solar radiation flux on the ground gradually increases; the atmospheric stratification in the lower troposphere becomes more unstable. Convection is prone to occur in the afternoon, which provides an effective way for the downward momentum transportation of the jet stream.

Sun et al. (2001) summarized and analyzed the dust storm reports in China over the past 40 years. They found that dust storms in China were mainly affected by frontal systems and Mongolian cyclones. Dust storms mainly come from the Gobi Desert and the Taklimakan Desert, and dust storms from different sources have different characteristics. Qian et al. (2002) analyzed the relationship between dust weather in

China and precipitation, temperature and disturbance vortex. They found that the frequency of dust weather in China is closely related to the temperature of the lower atmosphere in winter and the cyclone activity in spring.

The analysis by Zhang and Ren (2003) shows that dust storm days had decreased during 1954–2001, especially in spring. The direct natural causes are the reduction in the average wind speed and windy days in the sand source areas and the occurrence areas, the increases in precipitation in the main dust source areas, especially in spring and pre-winter, and the increase in atmospheric humidity and soil moisture due to the increased precipitation in the sand source areas. Dust frequency in spring is significantly positively correlated with wind speed in the occurrence region and negatively correlated with precipitation and soil moisture anomaly in the previous period, and the regional vegetation index in the areas from the border of China and Mongolia to Taklamakan desert in spring (Liu et al., 2004). In the spring of 2000, the frequency of dust weather increased sharply, which had caused extensive impacts. The reason was that: the increase and decrease in the windy days are the reflections of the periodic climate change. The sharp increase in heavy dust weather is due to the peak of the anti-El Niño event. The partial improvement and overall deterioration of the surface coverage are also another important reason for the occurrence of severe dust weather. The dusty weather affecting North China mainly originates from the midwestern of Inner Mongolia and northwest Hebei Province. The dust source and the surface dust along the transport path are the main body of dust. The bare soil and building construction dust in urban expansion areas provide the material source of local blowing sand (Ye et al., 2000). The dynamic condition of blowing sand in a sandstorm is related to the climatic factors, such as cold air activity in spring. It is also significantly correlated with the anomalies of the dry soil layer coverage and friction velocity in North China (Zhou X J et al., 2002).

Fan and Wang (2004) pointed out that the Antarctic Oscillation and its related meridional teleconnection, as well as the atmospheric circulation anomalies of Pacific, are also important causes of spring dust weather in northern China. Using the historical dust-fall records, historical climate data and modern meteorological records, the distribution map of dust-fall locations in China in the last 3000 years and the curve of dust-fall frequency in the last 1700 years were analyzed. The results show that the historical locations of dust-fall are very close to the distributions of loess as well as the modern suspended dust days. Additionally, the frequent periods of dust-fall usually correspond with the cold and dry climate periods. The dust storm activities in China and Mongolia have fluctuated in the past 50 years. The main reasons for the fluctuation of dust activity include the changes in desertification environment and atmospheric circulation, the latter of which is more dominant (Song et al., 2007).

Studies on smog days in recent years show that the number of smog days in winter in East China remained basically unchanged from 1980 to 1999, but it increased rapidly between 2000 and 2012. Among the possible climate factors, the changes in cover range of the Arctic sea in autumn, the local precipitation in winter and the surface wind speed are the three important factors that modulate the haze pollution (see Figure 2) (Wang and Chen, 2016). Recent studies show that the occurrence of winter haze pollution in northern China is related to changes in snow cover in Eurasia, and the relationship between the two was significantly enhanced after the mid-1990s (Yin and Wang, 2018). With a better understanding of the mechanism of haze pollution weather, the predictive ability of haze weather has also been significantly improved in recent years (Yin and Wang, 2016, 2017).

## 3. Impact of the Qinghai-Tibetan Plateau

The Qinghai-Tibetan Plateau, standing in the west of China, is the highest and largest plateau in the world. It exerts a substantial impact on the global evolution of atmospheric circulation and plays a dominant thermodynamic and dynamic role in climate change and climate anomalies. Since the 1950s, Chinese scientists have been concerned with the impact of the unique topography of the Qinghai-Tibetan Plateau on atmospheric circulation, weather, and climate. They first proposed the theory of dynamic and thermodynamic effects of the topography of the Qinghai-Tibetan Plateau, showing that the Qinghai-Tibetan Plateau forcing led to the enhancement of the coupling between the circulation of the lower and upper troposphere and enhancement of the coupling between the circulation of the tropical and subtropical monsoon. They systematically explained the significant impact of the dynamic and thermodynamic effects of the Qinghai-Tibetan Plateau on the interdecadal, interannual and intra-seasonal variations of the Asian monsoon. Chinese scientists pioneered the Qinghai-Tibetan Plateau Meteorology and established the leading position of China in the study of plateau meteorology around the world. The Qinghai-Tibetan Plateau Meteorology with the thermodynamic and dynamic effects of the Qinghai-Tibetan Plateau at its core has become one of the important research fields in climatology.

Since then, supported by several large projects, Chinese scientists have carried out comprehensive research on multi-scale atmospheric coupling processes from ground layer to stratosphere, centering on the modulation of atmospheric circulation by the plateau topography, influence of the change in land-atmosphere coupling system on the plateau on global energy and water cycle, and the influence me-

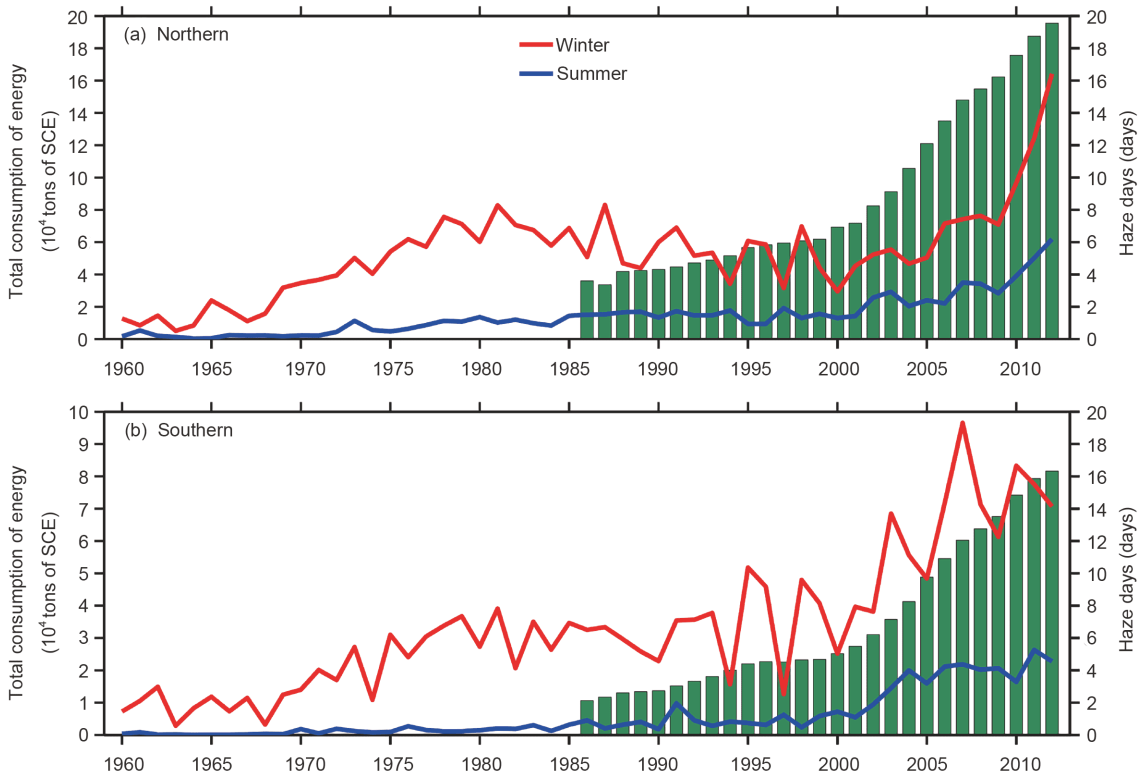


**Figure 2** Time series for winter haze days (red curve), summer haze days (blue curve) and total energy consumption (bar) for (a) region R1 (30°N–40°N) and (b) region R2 (south of 30°N) in east of 109°E of mainland China. Source: Wang and Chen (2016).

chanism of disastrous weather and climate in China (Zhao et al., 2018). Great progress has been achieved, which has greatly promoted the development of atmospheric sciences and interdisciplinary research of geosciences in the frontier research field of the Qinghai-Tibetan Plateau.

As early as the 1950s, Yeh (1950) proposed that the Qinghai-Tibetan Plateau had a significant diffluence effect on the westerlies. Two distinct westerly jets form in the north and south of the plateau and converge in the east of the plateau, thus forming the strongest westerly jet in the northern hemisphere over Japan. Gu (1951) pointed out that the dynamic influence of the Qinghai-Tibetan Plateau on westerly circulation was manifested in several aspects: barrier effect, fluctuation inhibition effect, jet diffluence effect and convergence effect. Ye et al. (1957) first proposed that the dynamic and thermodynamic effects caused by the topography of the plateau were equally important to the atmospheric circulation. The atmospheric circulation is an entirety of the interaction between the dynamic disturbance of the plateau topography and the thermodynamic causes of the land-sea distribution. The atmospheric circulation on the plateau is dominated by ascending motions in summer and descending motions in winter. It is certain that the plateau is a heat source in summer and a cold source in winter (Figure 3). The dynamic effect of the topography is closely related to the airflow over the mountains. Although the topography is fixed, the influence of the Qinghai-Tibetan Plateau on atmospheric circulation shows seasonal variations due to the seasonal variations of the airflow over the plateau. For example, in summer, the westerly jet has moved to the north of the plateau. In this situation, the plateau no longer diverges the westerly. The plateau inhibition and barrier effects that are often observed in winter disappear. Instead, the southwest monsoon in India moves northward, forming a thermal low in India and a southwest vortex on the east side of the Qinghai-Tibetan Plateau (Ye, 1952). The Qinghai-Tibetan Plateau has a strong seasonal impact on the atmospheric circulation. This proposal of this concept is a significant contribution of Chinese scholars to international scientific research; it corrected the view of the international meteorological community that the terrain had a constant influence on the atmospheric circulation.

The Qinghai-Tibetan Plateau also has an important impact on the Asian climate. Ye and Gao first proposed that Qinghai-Tibetan Plateau not only had a significant dynamic impact but also exerted important thermodynamic impact on the formation and variation of East Asian atmospheric circulation. The activity and stability of the south and north jets caused by the topography of the Qinghai-Tibetan Plateau have a great influence on precipitation in the South and East China. The Meiyu weather in China is affected by the convergence of two airflows in the south and north plateau in the

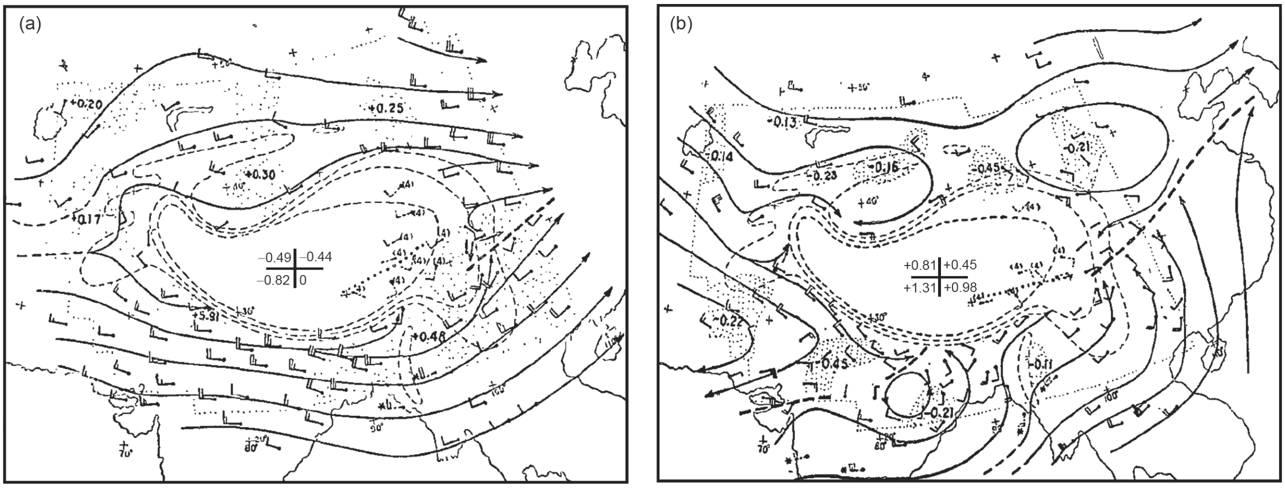


**Figure 3** The averaged flow field of 3 km ((a) winter, (b) summer). Source: Ye et al. (1957). The entire line represents 4 m $s^{-1}$; the half-line represents 2 m $s^{-1}$; speed below 1 m $s^{-1}$ is not marked with lines. The numbers in brackets represent the height (km); dotted lines indicate the streamline at different heights; the slender dotted lines represent topographic contour; the inner circle refers to contour over 5 km; middle circle refers to contour over 3 km; outer circle refers to contour over 1.5 km. The shaded area refers to the vertical speed (winter: $w>0$, the rest $w<0$; summer: $w<0$, the rest $w>0$). The 4 numbers in the middle of the plots refer to the average speed of descending (winter) and ascending (summer) of the four equal areas.

Yangtze River and Huaihe River Basin (Tao and Chen, 1957). The formation and intensity of the East Asia major trough in winter are closely related to the dynamic and thermodynamic effects of the plateau (Yang et al., 1980). Reiter and Ding (1980) pointed out that the Qinghai-Tibetan Plateau had a great impact on the generation of planetary waves, which belong to the quasi-stationary Rossby wave pattern. The role of large topography in the formation of planetary waves can be explained by the conservation of potential vorticity. Luo et al. (1983) pointed out that the forcing dynamics of the Qinghai-Tibetan Plateau was different from that of the Rocky Mountains, resulting in more frequent zonal circulation in East Asia than in North America. The dynamic effects of the Tibetan Plateau in summer have a significant impact on the subtropical monsoon in East Asia (Zhu and Yang, 1990; Zhu and Hu, 1993). The theory, observation, and model simulation experiments carried out by Wu et al. (2007) showed that in the winter half-year, the asymmetric dipole stationary wave can be induced by the dynamic forcing of Qinghai-Tibetan Plateau on the westerly airflow. The anticyclone on the north side of the Qinghai-Tibetan Plateau transports warm air to mid-latitude Eurasia and cold air to northern and northeastern China. As a result, the inland in middle-high latitudes is warmer than the coastal areas in winter. The cyclonic circulation in the south side of the plateau transported dry air from low-latitude to India and warm-humid air to the Indo-China Peninsula, leading to the formation of regional dry and wet climate in tropical winter. In spring, the airflow on the north and south sides of the plateau converge in southern China, leading to the formation of early spring rain in South China. Meanwhile, the air-sea-land interaction among the plateau and South Asia formed a spring warm pool in Bay of Bengal, which determined the first outbreak of Asian summer monsoon in the eastern Bay of Bengal (Figure 4).

The surface thermal condition of Qinghai-Tibetan Plateau has a very important impact on the climate anomalies in the northern hemisphere. The anomalies of heat source over the Qinghai-Tibetan Plateau in summer can cause anomalous atmospheric circulation in the middle and high latitudes of the Northern Hemisphere. In summer, during the years when the heating on the Qinghai-Tibetan Plateau is strong (weak), the pumping effect on the warm and humid air in the lower layer and the emission effect of the upper atmosphere to the surrounding areas are strengthened (weakened). Thus, the above-mentioned effects can influence the circulation of the plateau and its surrounding areas as well as the large-scale circulation system of the Asian monsoon region (Liu et al., 2002; Zhu et al., 2018).

At the height of plateau, the change from a cold source in winter to a heat sources in summer in the plateau can cause the seasonal transition from the cold high to the thermal low, resulting in the monsoon phenomenon (Xu and Gao, 1962). The impact of topography of Tibetan plateau on summer monsoon circulation is dominated by the thermodynamic effects. The enhancement and variation of heat sources over the Qinghai-Tibetan Plateau will cause the enhancement of the South Asian high and the resulted conjoint changes (Zhang et al., 2002; Liu et al., 2007; Ren et al., 2019). The deepening of troughs in northern China is prone to cause cold summer in Northeastern China and northern Japan, as well as strengthen the high pressure over Okhotsk Sea and cause trough in Alaska (Huang, 1985a, 1985b). Fu and Fletcher (1985) pointed out that the Qinghai-Tibetan Plateau was a heat source and the eastern tropical Pacific was a heat sink. The temperature difference between the two areas had great

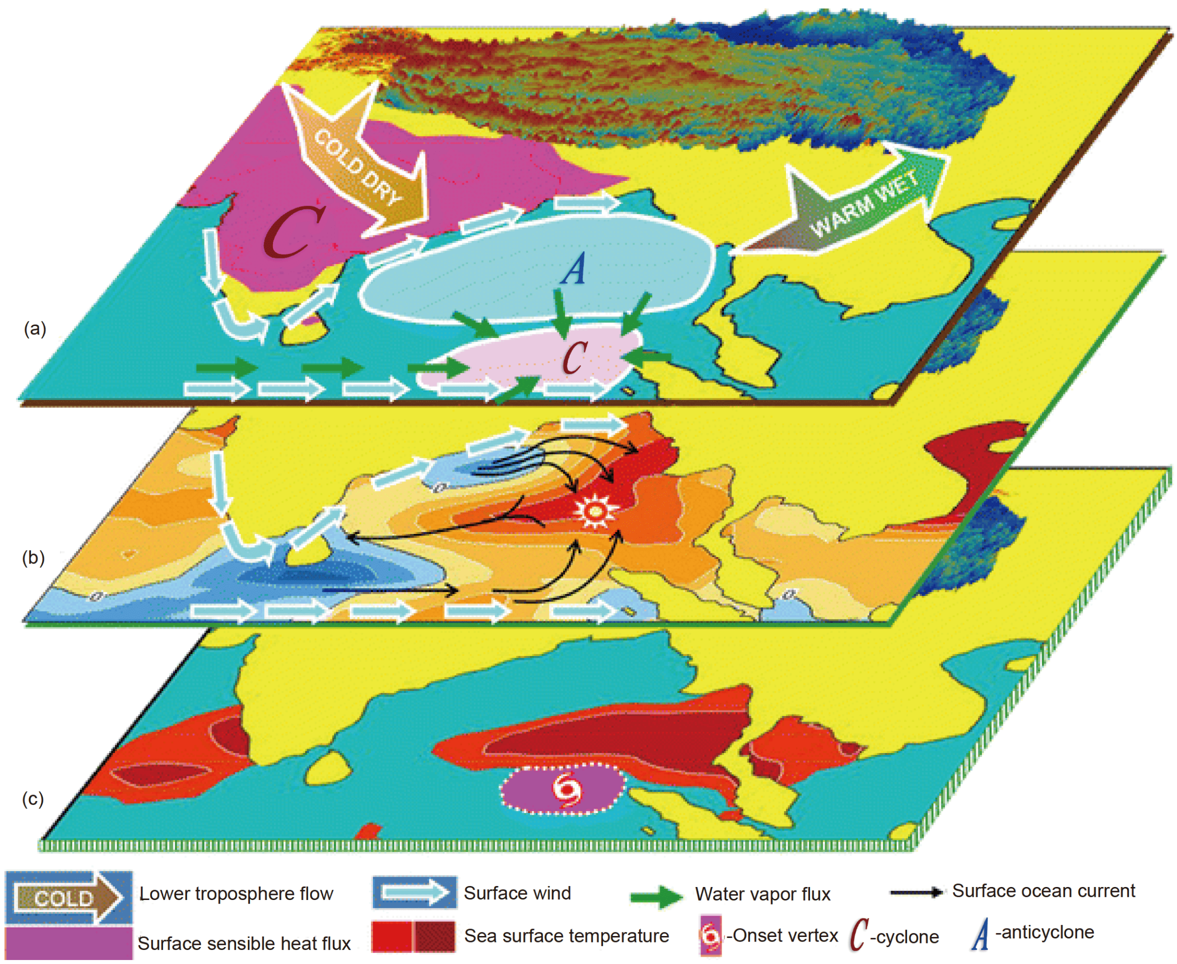


**Figure 4** The formation of warm pool in Bay of Bengal (a), the outbreak of monsoon vortex (b), and the activation of the winter vortex under the co-effects of Qinghai-Tibetan Plateau forcing and land-sea thermal contrast in south Asia in spring. Source: Wu et al. (2012a).

modulation on the south Asian summer monsoon. Land-sea distribution and the thermodynamic effect of large typography in Asia have an important impact on the East Asian monsoon (Wu et al., 2012b, 2012c). Southeastern China is strongly affected by monsoon, and the monsoon in North China is weak. There is a monsoon boundary between China and India, which is related to the influence of the Qinghai-Tibetan Plateau. The transformation of the monsoon is closely related to the formation and disappearance of the southern branch jet stream of the plateau (Zhang, 1959). The Indian monsoon region and Pacific zone of trade wind have significantly different characteristics. In the monsoon region, vertical monsoon circulation rises in the northern plateau and sinks in the southern plateau, which may be closely related to the direct heating effect of the plateau (Chen et al., 1964). An experiment of fluid mechanics simulation on the influence of the heating effect of the Tibetan Plateau on the atmospheric circulation in East Asia was performed. The results indicated that the formation of Qinghai-Tibet high was mainly due to the plateau heating in the middle parts of the troposphere. The formation and activity of southwest monsoon were also closely related to the plateau heating (Ye and Zhang, 1974). The Qinghai-Tibetan Plateau playing a crucial role in modulating the intra-seasonal and interannual variations of Asian monsoon (Wu and Ni, 1997). The thermodynamic forcing of the Qinghai-Tibetan Plateau significantly regulates the spring rains in southern China and leads to the formation of quasi-biweekly oscillations of high pressure in South Asia during summer (Pan et al., 2013; Liu et al., 2007).

Xu et al. (2015) investigated the influence of thermodynamic "drive" of Qinghai-Tibet topography on the rain band, water vapor transport characteristics and their interdecadal variations in eastern China. The results are as follows: (1) The topography of plateau in western China has sharpened the land-sea thermal contrast. The topography of plateau results in the northeast extension of the season variation of land-atmosphere thermal contrast, which evolves synchronously with the northwest extension of the monsoon rain band from the southeast coast. Both of them seem to have a "dynamic attraction" to the intra-seasonal evolution. (2) The temporal-spatial variation characteristics of rain band in eastern China and the trend of monsoon intensity change are both affected by the anomalies of heat source intensity in the Qinghai-Tibetan Plateau. Water vapor transport path from low latitude ocean to land and its intensity are also affected by the anomalies of heat source intensity in Qinghai-Tibetan Plateau. The spatial distribution of precipitation variability in China is "flood in the north and drought in the south" during the years when the plateau heat source is strong. The spatial distribution follows the patterns of "flood in the south and drought in the north" during the years when the heat source is weak. (3) The correlation vector between the heat source of Qinghai-Tibetan Plateau and water vapor flux in the lower-middle reaches of Yangtze River Basin in summer is similar to the significant differences in water vapor convergence areas between snowy years and less snowy years in Qinghai-Tibetan Plateau. The winter snow cover in Qinghai-Tibetan Plateau might significantly affect the structure of the subsequent summer transport for the Meiyu rainfall in the lower reaches of the Yangtze River. (4) The interdecadal variation of precipitation in China showed a trend of "flood in the south and drought in the north", while the trend in northwestern China is "getting humid in the west". Due to the increase in snow depth in the Qinghai-Tibetan Plateau in the past 20 years (1984–2004), the atmospheric heat source of the Qinghai-Tibetan Plateau has been continuously weakened, which is one of the important reasons for the formation of the climate pattern of "flood in the south and drought in the north" in eastern China (Zhu Y X et al., 2007; Liu et al., 2012). However, in recent 10 years (2004–2014), the apparent heat source on the Qinghai-Tibetan Plateau in spring declined and then rebounded, resulting in a turning trend of the precipitation pattern of "flood in the south and drought in the north" in eastern China.

Based on the observations and numerical simulation, it is found that the dynamic and thermodynamic effects of the plateau also have an important impact on the drought and dust weather on the north side of the plateau in early summer. During the outbreak of monsoon in early summer, it provides a favorable condition for the coming of the rainy season on the east side of Qinghai-Tibetan Plateau, as well as the drought in the Hexi Corridor on its north side (Zhen and Yan, 1994). Due to the strong flow around the Qinghai-Tibetan Plateau and the relatively high frequency of cold front processes, the dust transport to the south is more vigorous, which results in the frequent dust weather on the northeast side of the Qinghai-Tibetan Plateau (Jiang and Chen, 2008). In summer, the entire troposphere over the Qinghai-Tibetan Plateau is dominated by updraft. The airflow climbs up to the plateau along the slopes around the plateau and rise to the upper troposphere and the lower stratosphere. Around this height of the atmosphere, Qinghai-Tibetan Plateau is controlled by the powerful South Asia high, where the airflow diverges. In addition, the convective activities are also active on the plateau in summer. All these characteristics conduce to the convergence of materials around the plateau and low-altitude pollutants to the plateau. They rise to the lower stratosphere and radiate to the surroundings, which provides a favorable circulation background for the occurrence of low-value ozone center over the Qinghai-Tibetan Plateau in summer. The Qinghai-Tibetan Plateau in summer may be an important channel for the transport of pollutants from the lower troposphere to the stratosphere in East Asia (Zhou et al., 2004, 1995).

Yao et al. (2013) have made new achievements and innovations in fieldwork, indoor analysis, and scientific theory by studying the relationship between the environmental change and global change of climate recorded by the ice cores on the Qinghai-Tibetan Plateau. They pioneeringly established a quantitative model of the relationship between stable oxygen isotope ratio and temperature during precipitation in the Qinghai-Tibetan Plateau, which corrected the theoretical model conjecture of western scholars. The climate change characteristics of Qinghai-Tibetan Plateau over the past 100000 years and a series of major abrupt climate change events are clarified by the high-resolution ice core record (with an interval of 50 years) (Yao et al., 2008). The variation characteristics of methane concentration in mid-latitude regions recorded by ice core and its relationship with climate change suggest that the amplitude of variation of atmospheric methane concentration in the Qinghai-Tibetan Plateau is higher than that in the polar regions. The variation of monsoon strength will have an important impact on the variation of methane concentration (Yao et al., 2002). Yao et al. revealed the relationship between the change in ice core microbial community density and climate change, and proposed new indicators for studying paleoclimate change through microbial variations (Yao et al., 2016). They also suggested that the enhancement of the westerly wind and the weakening of the monsoon were the main driving forces for the glacier retreat on the Qinghai-Tibetan Plateau and its surrounding areas (Yao et al., 2012).

## 4. Impact of East Asian monsoon

Monsoon is an important circulation system in the global climate system, which is formed by the difference in heat absorption and release between land and sea (Zhu, 1934). China is located in the East Asian monsoon region. Prevailing winds and precipitation in East Asian monsoon system both change with seasons. Interannual and interdecadal changes and anomalies in the East Asian monsoon region have caused frequent and severe weather disasters in China, including droughts, floods, heatwave, low temperature, sleet and freezing, etc. (Huang R H et al., 2014). Chinese scientists have developed research on the influence of the Qinghai-

Tibetan Plateau on atmospheric circulation, weather, and climate. They proposed the thermal adaptation theory and "Sensible Heat driven Air-Pump" theory to explain the influence of the Qinghai-Tibetan Plateau, which proved the difference between land-sea thermal contrast and the topography over their contribution to the formation of different branches of Asian summer monsoon system. They pioneeringly divided the onset of Asian summer monsoon into three stages of organic connection and proved that due to the strong geostrophy and baroclinity at mid-high latitudes, the characteristics of air-sea interaction were significantly different from those of the tropics (Wu et al., 1997, 2007; Wu and Zhang, 1998, Wu et al., 2015). Chinese scientists have made original and leading achievements internationally in monsoon research, especially in East Asian monsoon research.

Since the 1980s, the vigorous development of climate research has promoted the research on East Asian monsoon. Tao and Chen (1987) first pointed out that the East Asian monsoon was independent of the South Asian monsoon. There were both connections and differences between the two monsoons. They first proposed the concept of the East Asian monsoon system. The East Asian monsoon system is not only prevailed by the southerly in summer and northerly in winter, but also composed of several circulation systems. The East Asian summer monsoon system includes the southwest monsoon flow from India and the Bay of Bengal, the Australian cold high, the cross-equatorial flow along 100°E, South China Sea monsoon trough, the western Pacific subtropical high and the easterly airflow to its south, the Meiyu, mid-latitude westerly disturbance, etc. The East Asian winter monsoon includes the Siberian high, the northerly airflow over East Asia and the East Asian major trough. Recent studies have pointed out that the East Asian monsoon is different from the South Asian and North Australian monsoons in terms of wind field structure, annual cycle of monsoon in summer and winter, and water vapor transport characteristics. Thus, the concept of the East Asian monsoon climate system was proposed. The East Asian monsoon system is more than a seasonal circulation system over East Asia. It is also a regional climate system affected by sea, land, ice, snow, and plateau. Its changes are related to the changes of the sea-land-atmosphere coupling system. The system includes: (1) in the atmosphere, the Asian monsoon circulation, western Pacific subtropical high and mid-latitude disturbances, etc. in the atmosphere; (2) in the ocean the thermodynamic effects of the tropical western Pacific warm pool and the Indian Ocean on the monsoon, the tropical Pacific ENSO cycle, etc. in the ocean; (3) in lithosphere, the dynamic and thermal effects of Qinghai-Tibetan Plateau on monsoons (mainly on land surface), Eurasian snow cover (especially Qinghai Tibet-plateau snow cover), land-air temperature difference in arid and semi-arid areas and polar ice, etc. (Figure 5) (Huang et al., 2004, 2007, 2012). Chinese scientists have made important contributions to international climate research, which are mainly on western Pacific warm pool, the interaction between ENSO and the East Asian monsoon, and the thermodynamic and dynamic effects of the Qinghai-Tibetan Plateau on the East Asian monsoon.

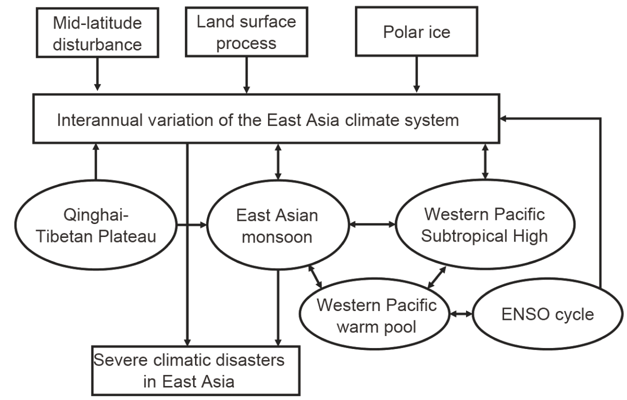


**Figure 5** Schematic diagram of the East Asian climate system. Source: Huang (2006).

The establishment of monsoon circulation mainly relies on nonlinear effects and large-scale external forcing (Yang and Wang, 1989). Wu et al. (1997, 2007) pointed out that the seasonal variation of atmospheric heat sources that caused the updrafts over the Qinghai-Tibetan Plateau, especially the seasonal variation of surface heat sources, was an important driving force for the seasonal transition of the Asian monsoon circulation. The rising-cooling effect of the plateau in winter caused the air in the upper atmosphere to sink, slide down the plateau slope and diverge in all directions. In summer, the strong surface sensible heat of the plateau slope drives the warm and humid air around to converge to the plateau, and rise over the plateau along the plateau slope, forming clouds and precipitation. Like an air-pump, this plateau heat-driven winter emission and summer pumping on the lower atmosphere (TP-SHAP: Tibetan Plateau- Sensible Heat driven Air-Pump) adjusts the seasonal changes of Asian atmospheric circulation, affects the climate pattern of Asia, and regulates the outbreak and evolution of Asian summer monsoon (Wu and Zhang, 1998; Wu et al., 2015).

Wu et al. (2012b, 2012c) showed that the entire Asian summer monsoon was regulated by the thermodynamic effects of sea-land distribution and topography. The East Asian summer monsoon was jointly controlled by the land-sea thermal contrast and the Qinghai-Tibetan Plateau forcing (Figure 6). Li (1988) and Li et al. (1988) first pointed out that, the East Asian monsoon anomalies in winter were clearly related to the El Niño event. The strong anomaly in East Asian monsoon during winter had an activation effect on the occurrence of El Niño events. Subsequently, Li (1990b) made an important conclusion about the interaction between East Asian monsoon anomalies in winter and El

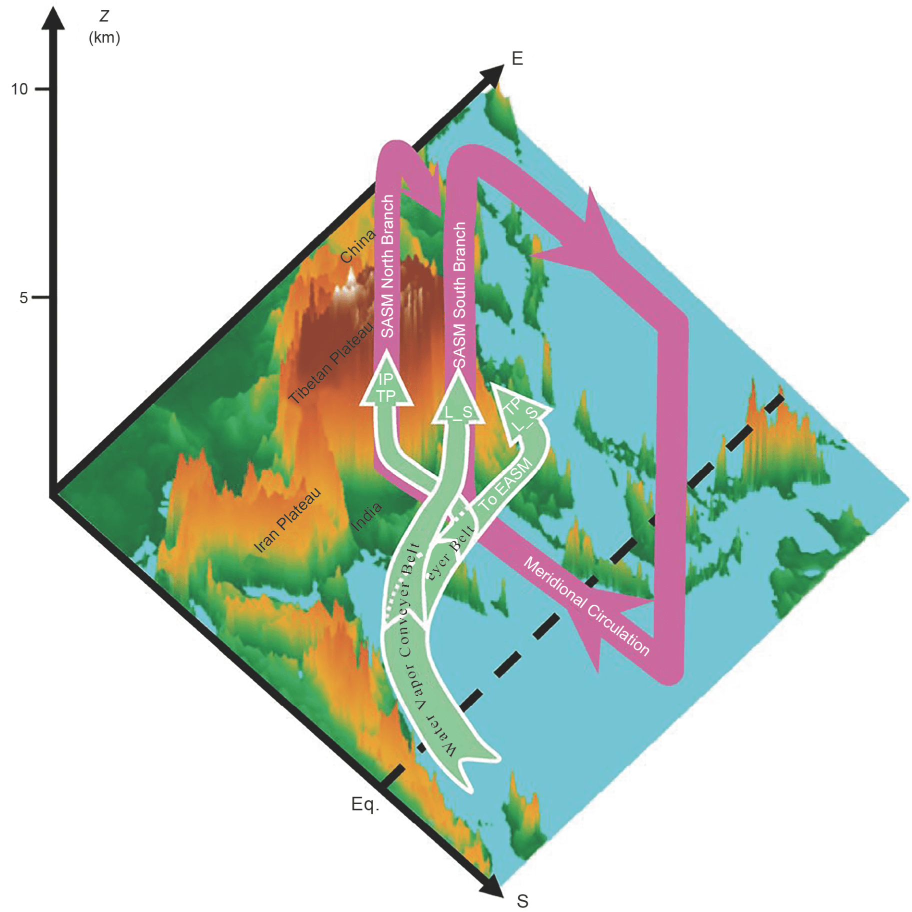


**Figure 6** Schematic diagram of the basic structure of South Asia summer monsoon. Source: Wu et al. (2012b).

Niño and presented some related major physical processes. The above results have been applied in ENSO prediction in the late 1990s, and the numerical simulation (Li and Mu, 1998) also confirmed the results of data analysis. Ju and Slingo (1995) used the model to explore the relationship between ENSO and Asian summer monsoon and found that the response of large-scale summer monsoon circulation to different phases of ENSO was very sensitive. They proposed that the meridional shift of ITCZ in the eastern Indian Ocean and western Pacific in early spring was the key physical process that determined the influence of ENSO on the Asian monsoon in summer.

Huang et al. (1996) proposed a conceptual model of the interaction between ENSO and Asian monsoon: When ENSO occurs, the sea surface temperature in the central and eastern equatorial Pacific is higher than normal, and the convection is abnormally active in the Central Pacific, which influences the teleconnection wave-train. Thus, the East Asian monsoon is influenced. Conversely, when the East Asian monsoon and the Australian monsoon change, the westerly anomaly is continuously spread to the west-central equatorial Pacific region by the Eurasian teleconnection wave-train. The enhancement of local westerly anomalies will trigger the Kelvin wave and Rossby wave in the ocean, which in turn provides a necessary ocean fluctuation condition for the ENSO cycle. At the maturity of ENSO in winter, the anomalous response of the atmospheric circulation to ENSO will change the Asian winter monsoon and the Oceania summer monsoon. Meanwhile, ENSO will affect the precipitation or snowfall on the Qinghai-Tibetan Plateau in winter and spring, resulting in the change of the land-sea thermal contrast during the ENSO decaying period in summer, thus causing the anomaly of the Asian summer monsoon (Tao and Zhang, 1998). Liu and Ding (2007) conducted in-depth research on the outbreak mechanism of summer monsoon through the analysis of land-sea thermal contrast, intra-seasonal oscillation, etc. They proposed the key factors for the outbreak of Asian tropical summer monsoon in climatology. On this basis, they presented a conceptual model of the early outbreak of the summer monsoon in the tropical East Indian Ocean- Indochina Peninsula-South China Sea (Figure 7).

Some studies on the major changes in the East Asian summer monsoon and winter monsoon in recent decades show that the main changes in summer monsoon and summer climate are: After the end of the 1970s, the interdecadal time

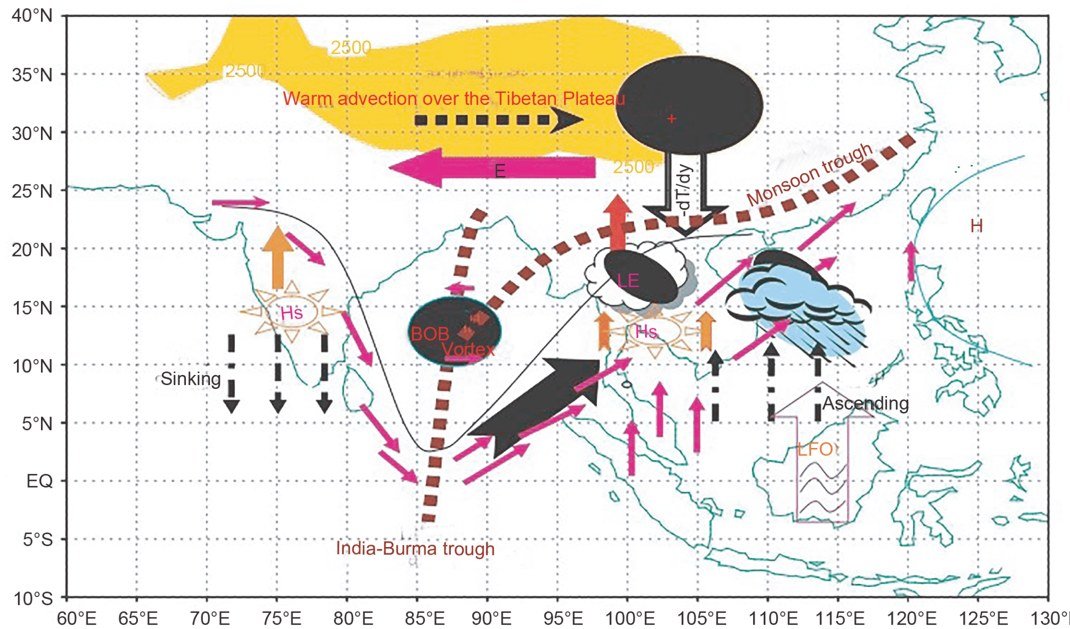


**Figure 7** Schematic diagram of the outbreak mechanism of the Asian summer monsoon. Source: Liu and Ding (2007).

scale of the East Asian summer monsoon weakened; summer precipitation increased in the Yangtze River Basins and Huaihe River Basins and decreased in North China accordingly; after 1992, summer precipitation increased in South China; after 1999, the summer precipitation in the middle and lower reaches of the Yangtze River decreased, while the summer precipitation in the Huaihe River Basin increased; there exists instability in the correlation between the interannual variations of East Asia summer monsoon and ENSO (Wang and Fan, 2013; Wang et al., 2011). Li et al. (2010) used NCAR CAM3 and GFDL AM2.1 to reveal the reason for the interdecadal variations of East Asian summer monsoon and summer precipitation in the second half of the 20th century. They pointed out that the warming of sea surface temperature in tropical regions, especially in the middle eastern Pacific Ocean, was the main cause of this change. The direct effects of greenhouse gases and aerosols increased the land-sea thermal contrast and also affected the East Asian summer monsoon circulation. The global air-sea coupled atmospheric circulation model is used to explore the influence of the Atlantic Multidecadal Oscillation (AMO) on the Asian summer monsoon. The simulation results are consistent with the observed climate change in China corresponding to different AMO phases (Lu et al., 2006). Wang et al. (2013) used the coupled model to reproduce the interdecadal weakening of the East Asian summer monsoon in the late 1970s and the accompanying phenomenon of "flood in the South and drought in the North" in eastern China. They further pointed out that human activities were important for the interdecadal variations of the East Asian summer climate.

The main changes in winter monsoon and winter climate include the weakening of East Asian winter monsoon and its interannual variability after the mid-1980s and the weakening of the correlation between the interannual variability of the winter monsoon and ENSO after the mid-1970s. Based on the CMIP5 multi-model results, it is found that changes in human activities and natural external forcing factors are highly likely to be the key factors for the reduction of the interannual variability of winter monsoon in East Asia after the mid-1980s (Miao et al., 2018). There exists instability in the correlation between the interannual variations of East Asia summer monsoon and ENSO. The Pacific-East Asian teleconnection circulation anomaly is likely to be an important cause of the instability of the above-mentioned ENSO and East Asian winter monsoon (He and Wang, 2013). Wang et al. (2008) studied the influence of the modulation of the interdecadal oscillations in the Pacific Ocean on the East Asian winter monsoon. They pointed out that when PDO was in a positive phase, ENSO had no significant correlation with the East Asian winter monsoon; when PDO was in the negative phase, the ENSO had a very strong influence on the East Asian winter monsoon. The global terrestrial monsoon precipitation showed an overall weakening trend from 1951 to 2000. This trend can be reproduced by an atmospheric circulation model driven by the observations of sea surface temperature data. It is indicated that the weakening of monsoon precipitation could be deduced from the response of the atmosphere to the sea surface temperature (Zhou et al., 2008).

The thermal state of the warm pool and the convective activity over it have a significant effect on the interannual variation of the East Asian summer monsoon. When the sea surface temperature (SST) of the warm pool is higher than normal, the convective activities are vigorous in the east of the Philippines and the western Pacific subtropical high moves northward. As a result, the summer precipitation in East Asia is lower than normal. Especially, the Yangtze River Basin and Huaihe River Basin in China, Korean Peninsula, and Japan are prone to drought. And vice versa. The influence of El Niño on the East Asian monsoon depends on the convective activities in the western Equatorial Pacific region, while the convective anomaly in the western Pacific is largely controlled by the anomalies of SST in the equatorial Pacific region (Zhang et al., 1996). There is a significant interaction between the East Asian winter monsoon and tropical oceans, and the air-sea coupling system associated with East Asian winter monsoon may be a self-sustaining mode (Ji et al., 1997). The SST of the Atlantic Ocean can trigger two wave-trains. One is the Eurasian wave train, which strengthens the low-level monsoon depression and high-level anti-cyclonic circulation in the East Asian monsoon region; the other wave train extends from the Atlantic Ocean to the northern Arabian Sea, resulting in a local anomaly of the monsoon circulation in western India (Yang et al., 1992).

Zhang and Zuo (2011) found that soil moisture anomalies in the areas from the middle and lower reaches of the Yangtze River to the vast areas of North China had an important impact on surface energy balance. Anomalous moist soils increase the surface evaporation, which reduces surface air temperatures. The decrease in surface temperature in late spring will reduce the land-sea thermal contrast. This will cause the anomalous enhancement of the western Pacific subtropical high and the weakening of the East Asian monsoon. The subtropical high is also in the south of its normal location, which will increase rainfall in the Yangtze River Basin. On the contrary, the anomalous weakening of the East Asian summer monsoon causes the southward drift of the western Pacific subtropical high towards the Yangtze River basin, resulting in anomalous decreasing precipitation in eastern China.

Arctic sea ice is also associated with East Asian summer monsoon. When polar ice in the arctic Greenland Sea-Barents Sea increases, the Indian peninsula monsoon, and East Asian summer monsoon circulation are strengthened, and precipitation in southeast China decreases. Polar ice can be regarded as the thermal forcing source of the underlying surface in high latitude areas, which can cause the baroclinic response of the atmospheric circulation in the monsoon region (Yang et al., 1994). The cold air activity in the mid-latitudes of the southern hemisphere has a quasi-40-day periodicity, which can become a periodic external forcing of the summer monsoon in the northern hemisphere. By increasing Musklin high or Australian high, the cross-equatorial airflow is strengthened and the northern hemisphere summer monsoon is more active (He and Chen, 1989). Zeng and Li (2002) conducted statistics on reanalysis data and found that the seasonal variation of the atmospheric circulation and the cross-equatorial airflow were mainly caused by the annual variation of incident solar radiation due to the obliquity of the ecliptic. The planetary-scale heat convection circulation is the "first driving force" of the tropical monsoon, and the quasi-stationary planetary wave caused by the surface thermal difference is the "second driving force".

Lau and Nath (2012) used the atmospheric circulation model (CM2.1) to study the air-sea interaction related to the climatological characteristics and interannual variability of the South Asian monsoon and found that precipitation and SST signal have a tendency to migrate northward. The enhanced monsoon precipitation is accompanied by a decrease in short-wave radiation income and an increase in upward-latent heat flux, as well as ocean cooling. The northward advancement and southward retreat of the East Asian monsoon rain band are consistent with the annual cycle of East Asian winter and summer monsoon (Huang et al., 2004). Chinese scientists have discovered early that the precipitation anomalies in eastern China have a mode like "−, +, −" or "+, −, +". Huang et al. (2011a, 2011b, 2004, 2007) pointed out that the droughts and floods in the Yangtze River Basin or the Yangtze River and Huaihe River Basin are related to the intra-seasonal changes in the northward movement of the East Asian monsoon. In the years when the tropical western Pacific is warmer and the convective activity in the Philippines is more vigorous than normal, the summer monsoon precipitation in the Yangtze River Basin or the Yangtze-Huaihe Basin is weaker than normal, which often leads to drought. On the contrary, in the years when the convective activity of the Philippines is weaker and the tropical western Pacific is colder than normal, the summer monsoon precipitation in the Yangtze River Basin or the Yangtze-Huaihe Basin is relatively stronger than normal, which often leads to severe floods. In this situation, the precipitation in North China is relatively low, which leads to drought. The interannual variation of the East Asian summer monsoon precipitation not only exhibits the temporal quasi-biennial oscillation temporally, but also has obvious meridional tripolar mode of "−, +, −" or "+, −, +" spatially. The tripolar mode can well reflect the distribution of the climatic disasters of droughts and floods in China along the meridional tripolar. With the decline of the monsoon, the meridional distribution of precipitation anomalous from north to south changes from "+, −, +" to "−, +" (Ding et al., 2008, 2009), that is, the precipitation anomaly pattern of "flood in the south and drought in the north". Li and Zeng (2002) presented a unified definition of the monsoon index. In the previous research, different monsoon indices in different monsoon regions around the world are defined correspondingly to characterize their changes. The unified monsoon index is based on the standardized seasonal variability of the wind field and can well reflect the seasonal and interannual variability of monsoons in different regions.

Both summer monsoon and winter monsoon are strong in East Asia. Strong winter monsoon not only brings cold wave, snow disaster and freeze injury to the Mongolian Plateau, northwest China, north China, northeast China, the Korean Peninsula, and Japan, but also brings sandstorms or blowing sand weather to the above areas. It will also bring strong convective activities and rainstorm to Southeast Asia (Huang R H et al., 2014). Chen et al. (2000) defined an East Asian winter monsoon index (EAWM index), which can well indicate the intensity of the interannual variation of East Asian winter monsoon. The variation of the East Asia winter monsoon will bring warm or cold winter to East Asia. Snowstorms and cold waves frequently occur in East Asia during cold winter. In inter-decadal scale, the integrated index of East Asian winter monsoon (EAWMII) defined by He and Wang (2012) can better indicate the comprehensive characteristics of East Asian winter monsoon, which reflects the interdecadal weakening of the East Asian winter monsoon after the mid-1980s. And this weakening has also brought warm winter to East Asia for many years (Huang et al., 2007).

## 5. Influences of teleconnection oscillation and westerlies

Since the 1950s, China has conducted many internationally leading researches on the variations of atmospheric circulation. Chinese scientists first proposed that the seasonal conversion of atmospheric circulation in East Asia was abrupt, which improved and developed Rossby's theory of geostrophic adjustment of atmospheric movement (Ye, 1957). They developed the theories of semi-geostrophic adjustment, spherical atmospheric adjustment, and geostrophic adaptation with external forcing, etc. They also put forward the East Asian/Pacific type (EAP type) teleconnection and its theory of the summer atmospheric anomalies in the northern hemisphere to explain how the summer drought and flood in China is affected. Chinese scientists are the first to reveal the mechanism of the influence of El Niño on the East Asian monsoon through the anticyclonic anomaly in the northwest Pacific (Zhang et al., 1996).

The research on the ENSO-centered tropical air-sea interaction and its impact on global atmospheric circulation and climate anomalies has confirmed that the air-sea interaction is one of the strong signals of interannual climate change (Fu, 1987). Chen (1977, 1982, 1983) pointed out that, the westward extension of the spring equatorial cold water and the warm water expansion along the west coast of South America were closely related to the summer precipitation in China. The variation of equatorial sea surface temperature is mainly controlled by the lower subtropical anticyclone in the southeast of the North Pacific. The feedback of the equatorial sea surface temperature to the subtropical high is mainly in the vicinity of the tropospheric subtropical high-pressure center in the central Pacific Ocean. Fu (1979) calculated the averaged zonal and meridional circulation in the equatorial Pacific during the period of large-scale anomalous warming and cooling of the equatorial sea surface using wind data. The results showed that the variation of the sea surface temperature in the eastern equatorial Pacific had a significant impact on the two vertical circulation cells, and the long-term changes of the North Pacific subtropical high were influenced by the interaction of the two circulation cells. Li and Lau (2012) used the coupled atmospheric circulation model to study the dynamic mechanism of the teleconnection between the El Niño and ENSO, and the North Atlantic Oscillation (NAO) in late winter. Observations and simulations both indicate that the NAO is in a negative phase in late winter during the El Niño event, while NAO is in a positive phase during La Niña events. In the winter of El Niño, due to the relatively strong warming of sea surface temperature in the eastern equatorial Pacific region, the eastward expansion of the vortex activity is intensified by the enhanced near-surface baroclinic system. Wang et al. (1983) studied the relationship between the formation of atmospheric circulation anomalies and the air-sea interaction. They pointed out that the ocean was the heat source in the obvious ocean current area, which has an important influence on the formation of atmospheric circulation anomalies; while in the non-current area of mid-ocean, the ocean was controlled by the atmospheric circulation instead. Zhang et al. (2017) proposed that the Rossby wave over the tropical western Pacific during El Niño caused an anomalous anticyclone over the western Pacific. They further revealed the mechanism that the influence of El Niño on the precipitation in China is through the abnormal anticyclone over the northwest Pacific. These researches laid a foundation for Chinese scholars to study ENSO and its impact on climate change in China and filled China's research gap in ENSO, one of the most important climate variability research fields.

Zhou et al. (2009) first pointed out the reasons for the westward extension of the western Pacific subtropical high since the late 1970s: The change of Walker circulation caused by the warming of sea surface temperature in the Indo-Western Pacific led to the decrease in convection in central and east Pacific in the tropics, which affected the western Pacific subtropical high through the ENSO/Gill mode. If the averaged zonal variation of geopotential height was removed, the Western Pacific subtropical high would show the characteristics of eastward retreat after the late 1970s (Huang et al., 2015). Huang et al. (2018) found that the relationship between the western Pacific subtropical high and the Asian summer monsoon showed significant interdecadal changes in the late 1990s. Its connection with the East Asian summer monsoon weakened, while its connection with the South Asian summer monsoon significantly increased. Huang and Wu (1989), Jin and Tao (1999) all pointed out that the impact of the ENSO events in different phases on summer precipitation in the Yangtze River-Huaihe River Basin was completely different: During the development of ENSO in summer, the convection in the western Pacific was inhibited, and the western Pacific subtropical high moved southward. This led to more precipitation in The Yangtze River-Huaihe River Basin, while the precipitation in South China was relatively less. It was the exact opposite in the decline phase of ENSO in summer. The precipitations in quasi-normal years of ENSO in the north of Yangtze River shows positive deviation. Except for a few areas in Jiangnan, precipitation distribution is generally normal.

The ENSO warm phase also has a good correspondence with winter precipitation in China. Zhang et al. (1996, 1999, 2002) pointed out that El Niño had a more significant impact on the precipitation in China during its mature stage. During the mature stage, there was more precipitation in southern China during the winter, spring and autumn, and more precipitation in the Yangtze and Huaihe River Basins in summer (Figure 8). Zhang et al. (1996, 1999, 2002) first revealed the mechanism of El Niño's influence on the East Asian monsoon through the northwest Pacific anticyclone anomaly. They pointed out that in the fully developed period of El Niño, the anomalous convective cooling over the tropical western Pacific stimulated the response of the tropical atmosphere of Rossby wave. As a result, anomalous anticyclones are generated in the western North Pacific, which strengthened the southerly winds along the East Asian coast, thus affecting the East Asian monsoon. They also proposed that the water vapor transport anomaly accompanied by the anomalous anticyclone in the Northwest Pacific converged in southern China, resulting in an increase in atmospheric precipitable water and a significant increase in precipitation in southern China. This mechanism explains the physical mechanism of the delayed effect of ENSO on East Asian summer monsoon, which has not been solved internationally. The neighborhood response of atmospheric circulation precipitation to sea surface temperature anomalies in different regions indicates that the sea surface temperature in the eastern equatorial Pacific is warmer, and the response field of tropical atmospheric circulation is eastward, which has little impact on the weather in China. The mid-equatorial Indian Ocean sea surface temperature is warmer, which leads to less rain in South China and more rain in Yangtze-Huaihe Basins. The Sea surface temperature in the northwest Pacific and the western equatorial Pacific is warmer, which leads to more rain in south China and less rain in Yangtze-Huaihe Basins (Wu and Liu, 1995; Wu et al., 1995; Liu et al., 2016).

Studies show that sea surface temperature anomalies in other areas can also have an impact on the climate in China. The characteristics of Pacific Decadal Oscillation (PDO) in the ocean and its correlation with East Asian atmospheric circulation and the variability of the climate in China indicate that PDO is closely related to the interdecadal variability of the climate in China. The phase change of PDO can directly affect the atmospheric circulation in East Asia and modulate the spatial distribution pattern of summer monsoon precipitation in eastern China (Zhu et al., 2011, 2015). In addition, the influence of ENSO events at different stages on summer climate anomalies in China is obviously modulated by PDO (Zhu and Yang, 2003). The interannual variations of the North Atlantic Oscillation (NAO) and the North Pacific Oscillation (NPO) are related to the interdecadal variations of the climate in China. The amplitudes of both NAO and NPO increased significantly in the 1960s, which can explain the abrupt climatic events in the northern hemisphere in the 1960s (Li and Li, 2000). Li and Wang (2003a) defined a new NAO index based on the difference in the normalized zonal mean sea level pressure anomalies of the North Atlantic (80°W–30°E) between the two latitudes (35°N–65°N). The study on the relationship between the Atlantic Multi-decadal Oscillation (AMO) and the winter climate in eastern China shows that the AMO warm phase corresponds to the decadal warm winter in eastern China with more precipitation in the north and less precipitation in the south. It is the exact opposite in the cold phase (Li and Bates, 2007). Sui et al. (2008) used model simulation to study the effect of sea surface temperature on tropical convective radiation cooling. When the surface temperature difference between warm pool and cold pool increases from 2.5°C to 3.5°C, the warm pool convection is enhanced. The radiation-driven subsidence area increases with the increase in sea surface temperature difference between warm current and cold current, thus enhancing the mass exchange between warm current and cold current. Lin et al. (2013) used the observation data during the experiment to establish a new ocean coupling potential intensity index through a comprehensive analysis of ocean temperature data. The index can be used as an effective new index to improve the estimation and prediction of the maximum intensity of tropical cyclone (TC). There is a very low-frequency air-sea coupled-wave in the tropics, and its activity can directly determine the intensity of tropical intra-seasonal oscillations. The intra-seasonal oscillation intensity in the South China Sea and the western Pacific is negatively correlated to the summer precipitation in southern China (Li and Li, 1997).

The Spring Predictability Barrier (SPB) is one of the basic characteristics of ENSO prediction. As for the causes of SPB in the world, meteorologists agreed that SPB was an intrinsic property of the ENSO system before the 1990s. However, in

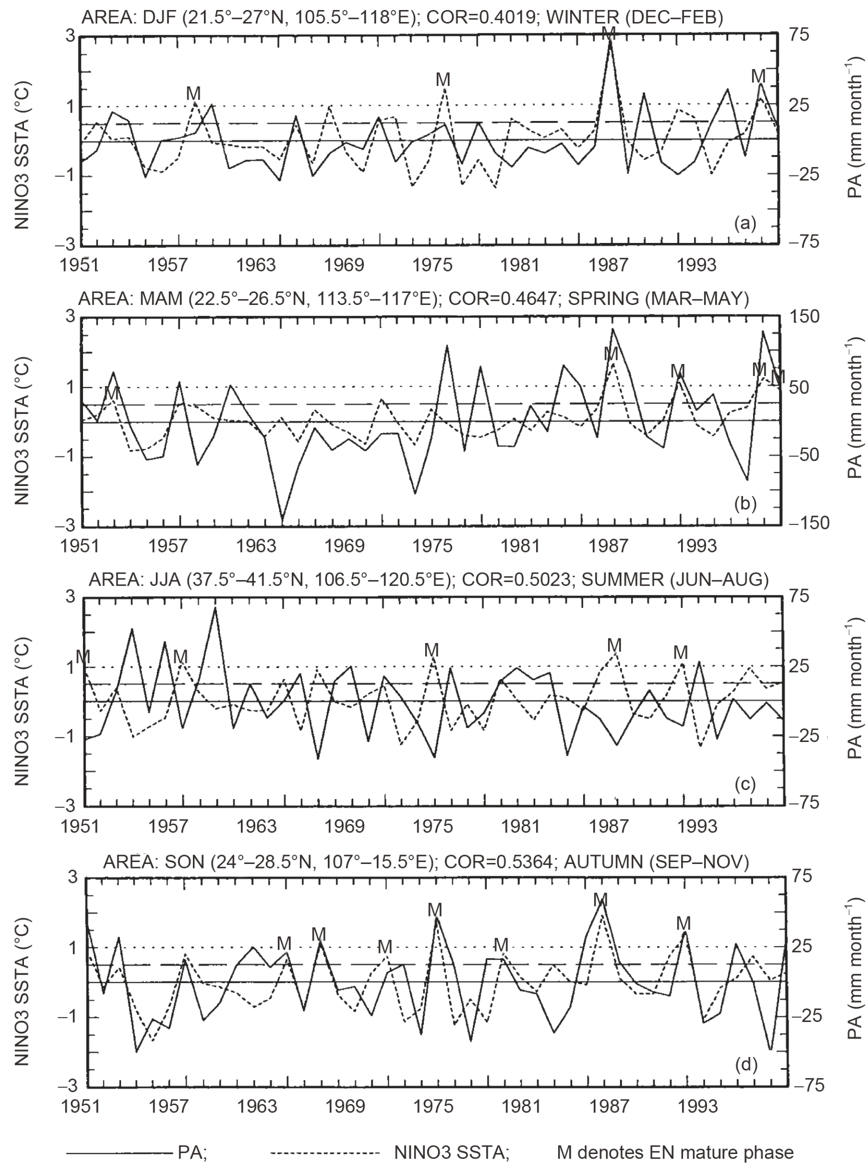


**Figure 8** The time series of seasonal precipitation anomalies (solid line) and seasonal NIÑO sea surface temperature (dotted line) in (a) winter (December, January and February), (b) spring (March, April and May), (c) summer (June, July and August), and (d) Autumn (September, October and November) in 1951–1993. M refers to the mature period of El Niño. Source: Zhang et al. (1999).

the 21st century, a new view has been put forward that, SPB is caused by the combination of the climatic annual cycle, the ENSO event itself, and the specific spatial structure of the initial error (Mu et al., 2007). The discovery of the specific spatial structure of the initial error provides a new idea for improving the ENSO predicting technique. In other words, by optimizing the ENSO observation network in a specific region, the influence of SPB can be reduced, and the prediction skill of ENSO can be effectively improved (Duan and Mu, 2018). Subsequently, Mu et al. (2015) conducted a series of in-depth studies on target observations of high-impact air-sea environmental events (ENSO, Indian Ocean dipole, Kuroshio path variation, etc.). The results showed that, if the initial field error was reduced in the area of large value disturbance determined by the fastest-growing initial error and the optimal early signs of these events, the prediction technique of these events would be greatly improved. Due to the spatial similarity between the optimal early signs and the fastest growing initial error, additional observations in the same sensitive region can not only help to capture the early signals of the above abnormal events but also effectively reduces the initial errors, thus improving the prediction skills of the event. Wang et al. combined the paleoclimatic simulation study with modern climate change research to reveal the instability of the correlation between the East Asian summer monsoon and ENSO and the interdecadal variations of the East Asian monsoon system (Wang, 2002). The significant impacts of the Hadley circulation, the Antarctic

Oscillation (AO) and the North Atlantic Oscillation (NAO) on east Asian climate were pointed out (Fan and Wang, 2004; Sun and Wang, 2012). The idea and method of tropical similarity and interannual incremental climate prediction were proposed, which significantly improved the climate prediction level of East Asian climate and typhoon activities (Wang et al., 2012a).

Atmospheric circulation, especially the atmospheric teleconnection oscillation over Asia and the western Pacific, is another important factor affecting the climate in China. In the 1950s, Chinese scholars conducted voluminous international leading research on atmospheric circulation changes. Ye et al. (1958) analyzed a large number of evolution facts of atmospheric circulation in East Asia and proposed that the seasonal conversion of atmospheric circulation in East Asia was abrupt. Every year in June and October, abrupt changes take place in atmospheric circulation in the northern hemisphere. The change of atmospheric circulation in June is characterized by the sudden northward transition of the east-west wind belt, and then the typical summer circulation pattern is established. In October, the east-west wind belt suddenly moves southward, and then the high-level flow pattern is a typical winter circulation pattern. This discovery is more than 20 years earlier than the nonlinear mutation of atmospheric circulation proposed by many international scholars in the 1980s. How is the quasi-geostrophic equilibrium formed in Rossby's theory of geostrophic adjustments of atmospheric motion? Yeh (1957) pointed out that for large-scale motion, the wind field adjusts to the pressure field, and for small-and-medium-scale motion, it is the adjustment of the pressure field to the wind field, which is a problem of motion scale. Zeng (1963a, 1963b, 1983) used complete nonlinear equations of dynamics and thermodynamics to reveal the internal mechanism of the continuous destruction of geostrophic adjustment processes and the geostrophic equilibrium in atmospheric motion. The theory of Rossby and Ye of the geostrophic adjustment process in the movement of atmosphere and ocean has been developed. The direction of the adjustment process depends on the disturbance scale and a characteristic scale determined by the environment. In the case of barotropy, this characteristic scale is the Rossby deformation radius; In the case of baroclinicity, it also depends on the stratification state and on the vertical structure of the disturbance. Therefore, the problem of long-term debate on the relationship between wind field and pressure field in meteorology is solved, and the most systematic adjustment theory of wind field and pressure field is established. Furthermore, the geostrophic adaptation problem is evolved to the adjustment problem in the rotating atmosphere, and some basic rules of various atmospheric movements from global scale to mesoscale system are derived. This theory is an important achievement recognized at home and abroad. Huang and Sun (1992) and Nitta simultaneously proposed that the thermal state of tropical western Pacific warm pool and the convective activity over the warm pool play an important role in the interannual and intra-seasonal changes of the East Asian summer atmospheric circulation and climate. The East Asia/Pacific (EAP) teleconnections affecting summer atmospheric anomalies in the northern hemisphere which affect the summer drought and flood in China is proposed.

In winter, there are two jet streams over China, one in the north of the Qinghai-Tibetan Plateau, the other one is in the south. The southern jet stream is the most important, whose speed increases in the direction of the flow (Yeh, 1950). In summer, there are three basic airflows that form the three-dimensional airflow over the Asian continent: Mid-latitude westerlies, tropical and subtropical easterlies in the upper atmosphere, and southwest monsoons below the easterlies. From spring to summer, there is a sudden change in the atmospheric circulation over Asia. At the same time, the southwest monsoon in India and the Meiyu period in China's Yangtze River Basin begin to appear (Tao and Chen, 1957). The beginning and ending of the Meiyu period in East Asia are regular and closely related to the seasonal variation of atmospheric circulation over Asia. The beginning date of the Meiyu period coincides with the establishment date of the Indian monsoon in Kolkata, and the end date is close to the date when the upper westerly jet over Japan disappears and the easterly appears. The revelation of this phenomenon has improved our understanding and forecasting ability of the variation law of Meiyu in East Asia (Figure 9) (Tao et al., 1958).

Wang (1962) studied the changes in the location of the teleconnection oscillations in East Asia over the years and compared it with the climatic oscillation in China. The results showed that the location of the teleconnection oscillations in East Asia changed significantly over a 35-year period, and the change in the locations of oscillations is closely related to the change of temperature and precipitation in many stations in China. The polar vortex activity in the northern hemisphere has an important impact on the sustained low temperature in China. When the northern hemisphere polar vortex breaks into two centers and the center in north Asia is the stronger one, a sustained period of low temperature will subsequently occur in China (Mou et al., 1975). Fu (1979) pointed out that there are two basic types of average meridional circulation in the tropical Pacific: the classical Hadley circulation circle and Hadley anti-circulation circle. In fact, they are the manifestation of alternate winter and summer monsoon in this region, but they also have nonseasonal long-term changes and oscillations. Gong and Ho (2002) found that the summer precipitation in the middle and lower reaches of the Yangtze River and the eastern part of China experienced an obvious interdecadal transition in the late 1970s, which was consistent with the

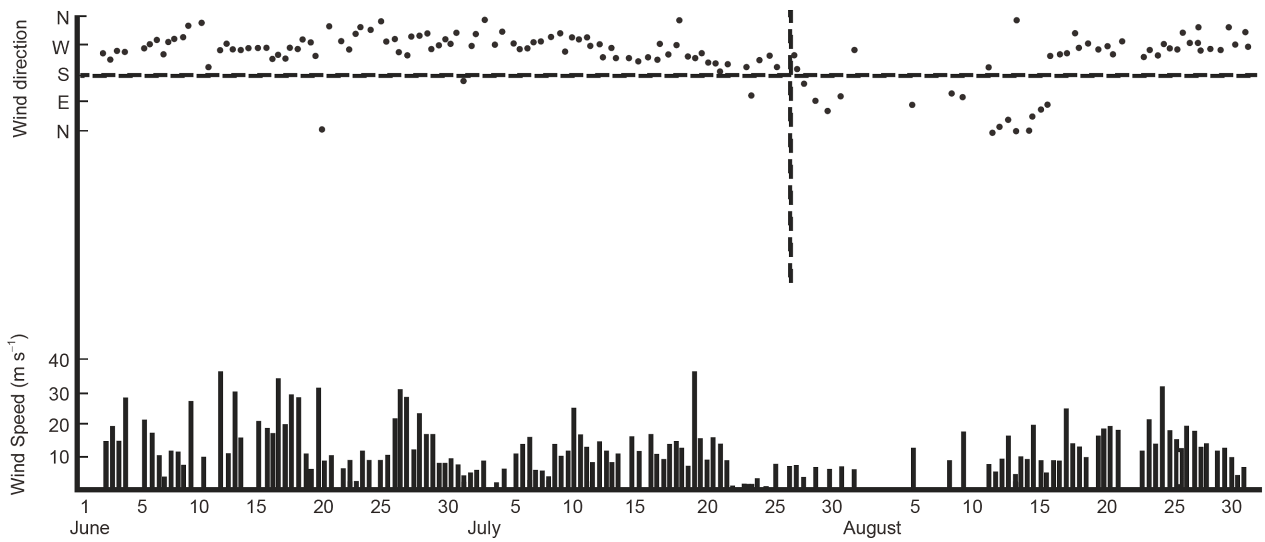


**Figure 9** The distribution of 300 hPa winds in Shanghai from June to August 1956 (The vertical dotted line represents the end date of the Meiyu period). Source: Tao et al. (1958).

abrupt change in 500 hPa geopotential height field. Zhu et al. (2011) analyzed that precipitation in eastern China increased in the Huanghuai River Basin and precipitation in Yangtze River Basin decreased from 2000 to 2008, which was closely related to the interdecadal variations of the circulation field (jet axis, subtropical high and water vapor path) and sea surface temperature (Pacific interdecadal oscillation, PDO).

In summer, the northward movement of rain-band in mainland China is closely related to the northward retreat of the westerly belt and the corresponding weakening of the westerly belt (Tao and Chen, 1957). The blocking process is a persistent anomaly of atmospheric circulation in the westerly belt. The upward transport of quasi-stationary planetary waves and the interaction with the basic airflow are one of the reasons for the formation and maintenance of the blocking situation (Zou and Huang, 1988). The circulation pattern of East Asian summer precipitation and the summer precipitation in the middle and lower reaches of the Yangtze River are affected by the geopotential height of Ural Mountains and the Okhotsk Sea. Especially, the anomalous precipitation during the Meiyu period in East Asia is closely related to the establishment of the blocking pattern in mid-high latitudes. When Okhotsk sea high pressure is established and stabilized, the anomaly fields of middle and high latitudes in Asia and the eastern part of East Asia are likely to form anomaly waves of "+, −, +,". This pattern and its interaction often cause high precipitation in Meiyu period in East Asia. On the contrary, when the Okhotsk Sea is controlled by low-pressure, the anomaly field in the middle and high latitudes of Asia and the eastern East Asia is likely to form an anomaly wave train of "−, +, −", which is not conducive to the precipitation during the Meiyu period in East Asia (Zhang and Tao, 1998).

The analysis of the dynamic mechanism of the interaction between the disturbance and zonal airflow during the seasonal abrupt change of the atmospheric circulation in the Northern Hemisphere shows that the northward jump of the subtropical jet is closely related to the enhanced transport of mid-latitude disturbance energy to the subtropical tropopause. The direction of such transport is restricted by the zonal airflow structure (Zhang and Zhou, 1988). When the Qinghai-Tibetan Plateau geopotential height is higher than normal, the potential height in the western Pacific is also high. Therefore, the western Pacific subtropical high is westward and northward, causing more precipitation in northern China and higher temperatures in the areas from North China to the Yangtze River. On the contrary, the southern region is rainy, and the temperature in the areas from the North China to the Yangtze River is low, indicating that the summer precipitation and temperature changes in China are closely related to the long-term oscillation of the potential height field of the Qinghai-Tibetan Plateau (Zhao, 1995). There is a significant correlation between the summer precipitation in India and the 500 hPa geopotential height in East Asia. Therefore, an Indian-East Asian teleconnection type (IEA type) is formed. To some extent, the IEA type affects the longitude of the subtropical high ridge and the average height anomaly over mainland China in summer. The Indian summer monsoon has a large amount of condensation latent heat release to stimulate the regional teleconnection type, namely the IEA type, which affects the average geopotential height field in East Asian summer. When the Indian summer monsoon is strong, the geopotential height field in East Asia is high. The subtropical high is easy to be northwestward or mainland China is controlled by positive geopotential height anomaly. Yangtze-Huaihe Basin is prone to drought, and vice versa (Dai et al., 2002). Li and Wang (2003b) proposed an improved zonal index (ZI) for characterizing the atmospheric circulation in the Northern Hemisphere. The index is used to measure the "seesaw" phenomenon of atmospheric mass fluctuation between mid-latitude (35°) and high-latitude (around 65°) regions on the hemispheric scale. The analysis shows that Ferrer circulation is the primary signal that affects ZI.

The long-term changes of the six major teleconnection oscillations in the northern hemisphere in the past 110 years and the relationship between the oscillations and the Chinese climate are studied. It is found that there is a significant negative correlation between the intensity of Siberia high pressure and the winter temperature in China, but a good positive correlation between the North Pacific high pressure and winter precipitation in China (Zhu et al., 1997). The long-term changes of the atmospheric circulation in the northern hemisphere show that the WA, PNA types show obvious trend and interdecadal trend. The WA type has a negative trend while the PNA type has a positive one. At the same time, the intensity of the meridional circulation in Asia and the Eurasia region suddenly weakened in 1983. This interdecadal change in atmospheric circulation and teleconnection intensity is an important cause of winter climate change in China (Shi, 1996). The interdecadal variations of the East Asian winter monsoon are closely related to the regional model changes of the atmospheric circulation and the Pacific Sea Surface Temperature (SST). When the Northern Hemisphere Annular Mode/Arctic Oscillation (NAM/AO) and Pacific Decadal Oscillation (PDO) are in its negative (positive) phase, the East Asian winter monsoon is strong (weak), but winter temperature in China is low (high) (Ding et al., 2014). Since 2008, the frequent period of regional extreme cold events in China, atmospheric circulation has been achieved through a quasi-barotropic wave Rossby wave train across Eurasia. When the blocking in the Ural region is anomalously strong, the wave train is not only transported upward to the stratosphere but also be transported to the east significantly. It will cause a negative geopotential height anomaly in East Asia, which will strengthen the East Asian trough and enhance the East Asian winter monsoon (Tan and Chen, 2014).

Gong and Wang (1999) gave an index that can objectively characterize Antarctic Oscillation (AO). It was defined as the zonal mean sea level pressure difference between 40°S and 65°S. The AO or SAM (Southern Annular Mode) helps to clarify the climate mechanism in the southern hemisphere, which is an important contribution of Chinese scientists in this field. Since then, Gong (1999) used reanalysis data to study the temperature and precipitation changes in the Antarctic region under the background of global warming, and its relationship with the atmospheric circulation in the mid-high latitudes of the southern hemisphere. He points out that the Antarctic temperature has an upward trend in winter, spring, and autumn, but a downward trend in summer. The annual average temperature is also rising. The precipitation has an increasing trend in all seasons and throughout the year. On an interannual scale, the annual mean temperature, and precipitation are negatively correlated with the Antarctic Oscillation (SAM) index, and the ways and extent of the Antarctic Oscillation impact on different regions are also different. From the long-term trend, the temperature, precipitation, and the Antarctic Oscillation Index all have an upward trend, indicating that global warming affects the Antarctic Oscillation from a larger time scale and spatial scale.

From the perspective of large-scale circulation systems, Chen et al. (2019) believe that the Asian continent can be basically divided into "Westerlies Asia" mainly controlled by mid-latitude westerly circulation and "Monsoonal Asia" controlled by monsoon circulation. Westerlies Asia has a relatively dry climate in the early Holocene, relatively humid in the mid-late Holocene, and a "dislocation phase" or "antiphase" with the monsoon climate change in Asia (Chen et al., 2008, 2016). Namely, there is a significant climate change "dominant modes of westerly" in this region on the suborbital scale unlike the monsoon region (Figure 10). In the past thousand years of characteristic, the hydrological climate variability of Westerlies Asia is also significantly different from Monsoonal Asia in terms of the spatial pattern (Chen et al., 2010). The external drive of the climate system (Northern Hemisphere solar radiation) is the dominant factor in the formation of the "dominant modes of westerly" on the suborbital scale. And the "dominant modes of westerly" on the centennial-decadal scale is mainly controlled by the internal variability of the climate system (global teleconnection/silk road teleconnection) (Chen and Huang, 2017).

## 6. Climate dynamics and development of climate models

In the international science community, the development of climate dynamics and climate system model originated in the 1970s and constitutes the theoretical basis and numerical tools for modern climatology research. The development and application of the climate system model is an important direction of modern climatology. Chinese scientists attach the utmost importance to climate dynamics research. They perfected the CISK-wave theory for tropical atmospheric intraseasonal oscillations, and proposed an appropriate theory and dynamic mechanism for atmospheric low-frequency teleconnection. In addition, they established a theoretical framework for studies of climate dynamics. Since the late 1970s, they began to develop climate models and applied them to studies of climate processes and to climate predictions.

Tropical sea surface temperature anomalies (SSTAs),

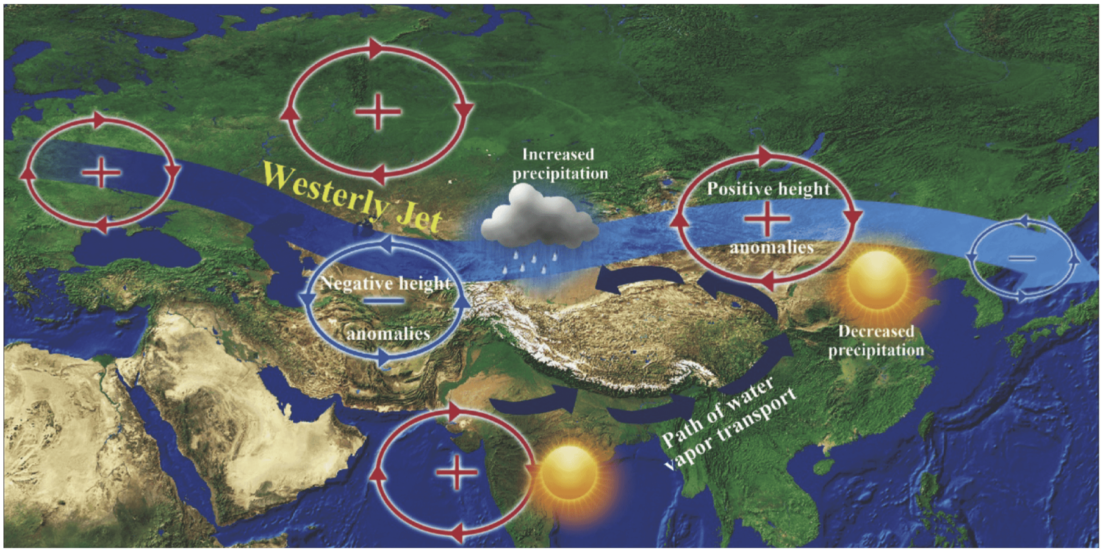


**Figure 10** Dominant modes of westerly. Source: Chen et al. (2019).

especially those related to ENSO, have long been valued by Chinese scholars because they can cause changes in atmospheric circulation and thus changes of climate patterns in China. Zhu et al. (1981) studied the dynamic instability caused by sea temperature disturbance using a coupled model involving a two-layer baroclinic atmosphere and a two-layer ocean. Their results show that the most important physical factors for the development of sea temperature disturbance are the oceanic Sverdrup transport, the heat exchanged between the mixed layer and deep layers, and the regulation effect of clouds on short-wave radiation. The main horizontal scale of disturbance development is 3000–6000 km, and the time scale is months or even years. Zhang et al. (2013) used Argo data to improve the physical process parameterization scheme in the ocean dynamic model, which effectively improved the ability of the ocean model to simulate the real ocean and the ability to predict El Niño/La Niña. Li (1987) used a non-linear dynamic system coupling ocean and atmosphere to analyze autonomous properties of the system under stationary forcing and non-autonomous properties under periodic forcing. Some characteristics of coupled ocean-atmosphere oscillations and interannual variations of atmospheric circulation can thus be elaborated.

By developing a nonlinear temperature-salt coordinated assimilation scheme and using altimetry data to adjust temperature and salinity of their model, Zhang et al. (2013) established a global ocean data variational assimilation system that can integrate various oceanographic observations including Argo data, Which completes their global coupled ocean-atmosphere model. Jin and Zhu (1988a, 1988b) used a topography-forced quasi-geostrophic barotropic atmosphere and an interactive surface sea temperature to establish an air-sea coupled system. With simplification through low-order spectral decomposition and multi-scale analysis, this coupled ocean-atmosphere system could then be solved analytically in the phase space, which showed two types of stable equilibrium states in the ocean-atmosphere system. This result was then used to explain some characteristics of long-term circulation anomalies. Huang and Chou (1989) explored the dynamic mechanism of the formation of analogous rhythms phenomena by using a coupled ocean-atmosphere model in the form of analog deviation. It is pointed out that the analogous rhythms phenomena are generated due to inhomogeneous oscillations of analog deviation disturbances caused by nonlinear coupling interactions in the air-sea system under the forcing of seasonal variation of the monthly averaged circulation.

Miao and Liu (1989) studied the occurrence and development of air-sea coupled instability for ENSO. They pointed out that under high sea surface temperature background, the wave-CISK mechanism involving latent heat release, sea-surface evaporation, and sensible heat flux can cause positive feedback in the air-sea coupled system, which stimulates the very low frequency and strong instability of the air-sea coupled Kelvin wave. This result of air-sea coupling instability can well explain the occurrence, development, and evolution of the 1982/1983 ENSO event. Zhang (1995) found that the coupled Kelvin wave propagating eastward can be unstable. Due to the air-sea interaction, a coupled Kelvin wave propagating westward can be generated in the long-wave part. Properties of the coupled Kelvin wave are closely related to parameters tuned in the model. When the frequencies of free waves differ significantly in the atmosphere and in the ocean, properties of the coupled waves are very close to those of the free waves without air-sea interaction. Strong air-sea coupling and instability can occur only when the free waves in the atmosphere and the ocean have similar frequencies. In addition, phase evolution of ENSO is also significantly affected and modulated by external forcing factors outside the climate system such as solar wind and strong volcanic eruptions (He et al., 2018; Wang et al., 2018). Li (1985) first introduced the cumulus convection heating feedback mechanism into the dynamics of the intra-seasonal oscillations in the tropical atmosphere, and also found for the first time that the cumulus convection heating feedback (CISK, Conditional Instability of Second Kind) was an important dynamic mechanism that can stimulate the intra-seasonal oscillations of the tropical atmosphere. Further research by Li (1993, 1996a) pointed out that, with the cumulus convection heating feedback, the tropical atmosphere can produce CISK-Rossby waves. These waves can propagate westward or eastward and disperse energy. Therefore, it is believed that the CISK-Rossby wave is an important excitation and driving mechanism for the 30–60-day oscillation of the atmosphere outside the equator (Figure 11). These studies improved the CISK-wave theory of the tropical atmospheric intra-seasonal oscillation. Li (1996b) studied the dynamic characteristics of evaporation-wind feedback. It is found that the evaporation-wind feedback itself cannot be a dynamic mechanism of atmospheric intra-seasonal oscillation. It can explain the activity of tropical intra-seasonal oscillations only when it is combined with the CISK mechanism. Li et al. (2002) used a theoretical model to further the dynamic mechanism of tropical intra-seasonal oscillations. The model includes cumulus convection heating feedback (CISK), the evaporation-wind feedback as well as the air-sea coupling. Results show that the cumulus convection heating feedback is the most important driving factor for the tropical intra-seasonal oscillations. However, the air-sea coupling is beneficial to the frequency reduction of the excitation wave. Therefore, it may also become the dynamic mechanism of the tropical atmosphere ISO. Low-frequency oscillations at mid-high latitudes and in the tropics are mainly related to and interact with each other through low-frequency wave trains. Among those wave trains, the low-frequency East Asia-Pacific teleconnection (EAP) and Pacific-North American teleconnection (PNA) are the main "pathways" that connect low-frequency oscillations in the tropics and those at mid-high latitudes (Li, 1990a). The mid-latitude air-sea interanion is the key process for the formation of interdecadal signals (e.g. PDO). However, a mid-latitude system has generally a dynamic structure with low (high) pressure located above cold (warm) sea surface, which cannot be explained by the dynamic theory. How an anomaly of mid-latitude sea surface temperature affects the atmosphere has not been understood clearly.

Chinese scholars (Fang and Yang, 2011, 2016; Wang et al., 2016; Xiao et al., 2016; Yao et al., 2016; Wang et al., 2017; Yao et al., 2017) found that mid-latitude SST influences the atmosphere via the dynamic forcing of transient eddies in relation to ocean fronts, low-level baroclinicity, and atmospheric instability. These works established a dynamic framework in which transient eddies operate actively for unstable mid-latitude air-sea interactions. They help to develop the thermal-driven air-sea interaction dynamics and lay an important theoretical foundation for clarifying the cause of strong interdecadal oscillations in the air-sea system. Yang and Huang (1993) showed that there are two kinds of responses of summer atmosphere to tropical sea surface temperature and Arctic sea ice anomalies. One is from the direct thermal forcing, and the other is from indirect forcing in relation to interactions between the external forcing and atmospheric internal dynamics. The physical processes of the snow cover of Eurasia in spring and the sea surface temperature of the western Pacific Ocean in summer affecting the precipitation in China have been studied. The result shows that spring snow in Eurasia can excite the teleconnection wave train in the atmosphere at 500hPa. The excited wave trains can last from spring to summer, which causes high pressure to control northern China and weak low pressure to control the south. This makes the precipitation appear in southern China. The increase in the sea surface temperature of the western North Pacific in summer can reduce the land-sea thermal contrast, which weakens the summer monsoon, leading to an increase in precipitation in southern China (Zhang et al., 2008).

China has been involved, since a long time, in climate modeling activities. The late 1970s saw the development of first climate models. Ji and Chao (1979) established a zonally averaged air-sea coupled model considering various processes of non-adiabatic heating in the atmosphere and feedback processes to the ocean. The system exhibits a long period (longer than a month) oscillation, and the length of the period depends on the depth of the ocean mixed layer, the latitude of the ocean, and the strength of various physical processes. With the help of equations describing the interrelationship between precipitation and ground temperature or air temperature based on the atmospheric water balance and the earth-atmosphere system heat balance, Tang et al. (1982, 1988) established a seasonal precipitation forecasting model. They produced good results using ground temperature to predict the precipitation amount of the wet season. Zeng (1985) published a comprehensive review of studies on numerical modeling in atmospheric sciences, including theoretical basis and numerical techniques. Zhang et al. (1986) published their studies on the sensitivity of the dynamic framework to initial values, which serves as a part of a series of basic studies to establish a numerical model of the atmospheric general circulation. They mainly presented three kinds of sensitivity test of the dynamic framework of the model. Huang and Wang (1991) considered the dynamic

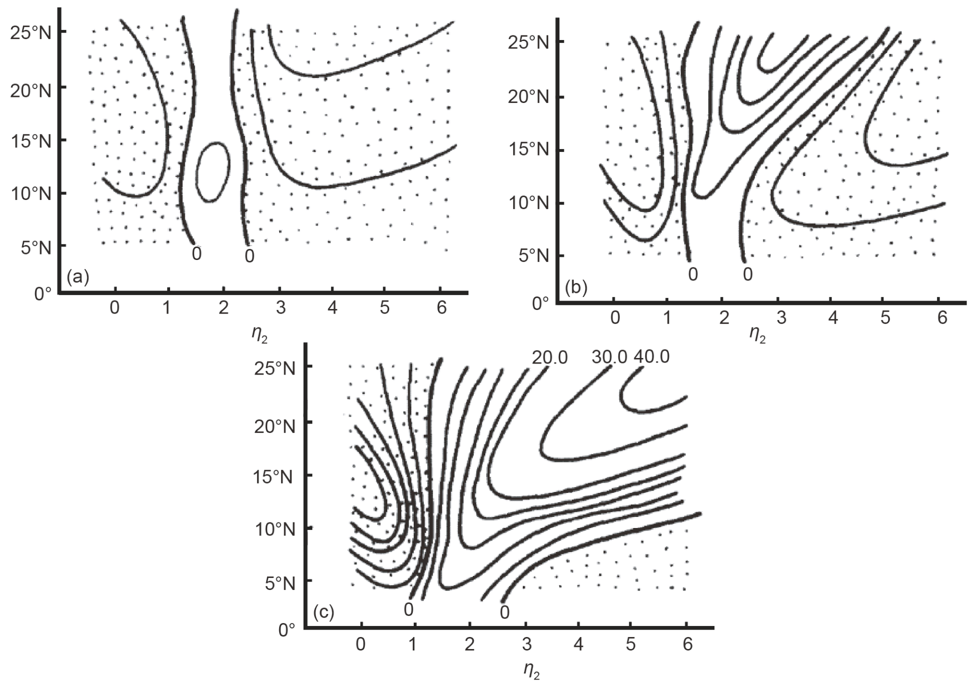


**Figure 11** Variation of zonal speed (m $s^{-1}$) of CISK-Rossby wave with heating intensity and latitude Source: Li (1990b). (a) The meridional scale is 4000 km. (b) The meridional scale is 8000 km. (c) The meridional scale is 20000 km. In addition to the values already marked, other contour intervals are 4m·$s^{-1}$. The shaded areas represent negative $C_x$ (westward shift).

forecast field as a small perturbation superimposed on the historical one. With such a consideration, they succeeded to establish a mixed analogic and dynamic seasonal numerical forecasting model taking into account air-sea interactions. With that model, they carried out a seasonal forecasting experiment for a total of 8 years from 1981 to 1988. The forecasting performance was revealed higher than that of the statistical-similarity forecast. A global terrestrial hydrological model developed by Sun and Lu (1989) can realistically depict the exchange process of energy, moisture, and momentum between complex underlying surface (including vegetation cover) and the atmosphere. Its aim was to provide a land-water heat exchange model that can be coupled to the atmospheric circulation model. Scientists have established different models from different perspectives, conducting a series of basic research on the development of climate models in China.

Very early, Chou (1974) already used the concept of functional analysis and variational method in numerical forecasting issues. Later, guided with basic theories and methodological approaches, Chou (1986, 1989) revealed some main difficulties of climate prediction in relation to main characteristics of the climate system. He also theoretically proved the equivalence of the atmospheric pressure field evolution and the thermal condition of the underlying surface, which lays a theoretical foundation for solving the initial value problem of climate prediction. These works largely promoted statistical-dynamic modeling for seasonal prediction. Furthermore, Chou (1994) and Chou et al. (1994) proposed and studied the qualitative theory of atmospheric dynamics equations, namely the asymptotic dynamics of the long-term evolution of the atmosphere. These innovative climatic dynamics theories reveal the overall and global behavior of nonlinear atmospheric dynamics equations, which studies climate formation and climate change from a dynamic perspective. In response to the particularity of climate issues, they introduced the latest mathematical achievements, chaos theory, cell mapping theory and bifurcation theory, and comprehensively studied the nonlinear characteristics of climate systems, evolution mechanisms, predictability problems and climate status prediction methods based on new concepts and new methods. They initially formed the quasi-dynamic-quasi-random theory of the climate system, which is a new development of climate dynamics.

By carefully analyzing and considering the multi-scale characteristics of the climate system, Chinese scientists have proposed numerous theories explaining the dynamics of the climate system. Furthermore, they used such theories to elaborate climate prediction methodology suitable for predicting the monsoon variability in China. In 1985, Zeng presented China's first climate system model involving atmospheric circulation, oceanic circulation, land surface process and their coupling (Zeng, 1985). Some of the modeling developments, such as "Standard State Deduction Method", "Square-Conservative Format" and "Free Sea Surface Scheme" are of high originality in the international community. This numerical platform, with complete self-consistent coupling, is still in use by a large community. Zeng was the leader in building the first numerical climate prediction system. In 1989, the system was successfully used in the cross-season summer drought and flood forecast in China. These works not only have great significance at basic science level, but also are of great application values, providing important tools for Chinese studies in atmospheric science, climate science and even environmental science (Zeng et al., 2003a, 2003b). Zeng has been advocating the development of the National Big Science Device-Earth System Numerical Simulation Device with many other Chinese veteran scientists since 2009. This ambitious platform is planned to be completed in 2022. The Earth System Numerical Simulation Device will promote the inter-disciplinary and integration between different disciplines of the Earth system. In addition, it will accelerate the overall leap of China's Earth System Science to the international first-class level.

In the early 2000s (Ding et al., 2004), the National Climate Center of China Meteorological Administration established the first generation of a comprehensive climate model for operational prediction, filling a gap in China's climate community. This system includes a Coupled General Circulation Model (CGCM), a High-Resolution East Asian Regional Climate Model (RegCM_NCC) and five simplified ENSO Prediction Models (SAOMS) for global climate predictions at seasonal-annual time scales. The global air-sea coupled model and the regional climate model are nested to provide high-resolution East Asian seasonal climate predictions (Ding et al., 2004). Zeng et al. (2008) outlined the current status of the Earth system dynamics model development in China. In general, the existing climate system model has already been able to simulate the global climate pattern under current and paleoenvironment conditions, and can even be used to do short-term climate forecasts for seasonal-annual time-scale and to simulate scenarios for global warming trends. However, there are still some uncertainties or biases to be eliminated in simulations or predictions. For example, the clouds, radiation, and related processes in the atmosphere are very complex, and the description and simulation of atmospheric boundary layer processes, ocean mixing processes and complex surface characteristics need to be further improved to be more precise and accurate.

Piao et al. (2010) argue that climate change will have important impacts on China's water resources and agriculture. Future regional climate models must improve the responses of farmland to climate, disease, livestock, and atmospheric composition. Peng et al. (2013) analyzed the effects of daytime and nighttime warming asymmetry on global northern warming through photosynthesis and respiration, and pointed out that such asymmetric daily warming changes need to be taken into account in the global carbon cycle pattern.

Im et al. (2018) evaluated the performance of the MIT regional climate model (MRCM) to simulate the temporal and spatial structure of the diurnal variation of rainfall in the western Maritime Continent. The simulated climatological characteristics were compared with the TRMM 3B42 3-hour observation. The analysis focuses on the regional characteristics of diurnal variation of rainfall characterized by variables of phase and amplitude, and the emphasis is on the difference between land and sea. Both simulations can capture the main features of the similarity of daily precipitation changes to TRMM observations in several respects. Studies have shown that the increase in resolution is evident in the improvement of the simulation results.

Zhou et al. (2018) reviewed the history and progress of the atmosphere-ocean coupled model FGOALS2 developed by the Key Laboratory of Numerical Modeling for Atmospheric Sciences and Geophysical Fluid Dynamic, Institute of Atmospheric Sciences in the Chinese Academy of Sciences (LASG/IAP) during 2010–2014. FGOALS2 showed good performance and improvement in terms of cloud amounts, short-wave and long-wave radiative forcing, and simulation of ENSO. In addition, the model better reproduced the seasonal cycle of the equatorial Pacific region, and significantly improved the simulation of the southerly wind component in the northwest Pacific monsoon trough and the East Asian summer monsoon (EASM). The model also improved the simulation of the inter-annual variation of EASM, and the Atlantic meridional overturning circulation (AMOC) was perfected as well. The simulation of the distribution of sea ice in the northern hemisphere and its seasonal variation was significantly enhanced (Figure 12). Wu et al. (2013) reported the research and development achievements and operational progress of the 2nd-generation short-term climate prediction model system of the National Climate Center. The assimilation performance of temperature and sea salt of the second-generation ocean data assimilation system, is generally better than that of the 1st-generation. The 2nd-generation monthly dynamic extension prediction system is based on the National Climate Center atmospheric circulation model BCC-AGCM2.2, and it entered the quasi-operational stage in August 2012. The 2nd-generation seasonal prediction model system was established based on the climate system model of National Climate Center, BCC-CSM1.1(m), and was put into pre-operation at the end of 2013. A preliminary evaluation shows that the second-generation of monthly dynamic extension prediction model system and the seasonal climate prediction model system respectively have certain predictive ability for the climate variability at pentad-, 10-day-, month-, season-, and even inter-annual scale. The prediction skill of precipitation, temperature, circulation and other factors of the 2nd-generation is generally higher than that of the 1st-

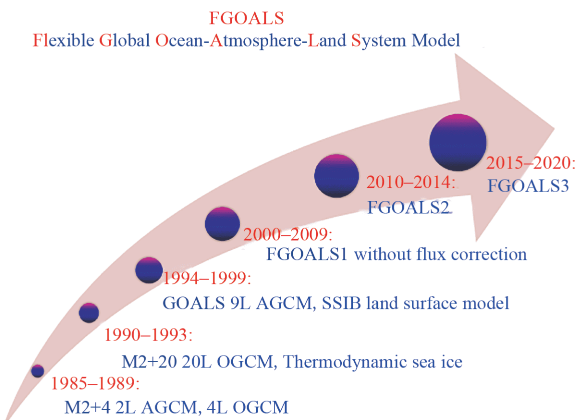


**Figure 12** The schematic diagram of the development history of the LASG/IAP air-sea coupled model. Source: Zhou et al. (2018).

generation prediction system.

The Earth system model is becoming an irreplaceable tool for studying the characteristics and behaviors of the current climate, understanding its past evolution, and predicting its future changes. Five climate system models from China participated in the 5th Coupled Model Intercomparison Project (CMIP5), which are (1) the FGLALS climate system model from the IAP/CAS, (2) two models from the National Climate Center: the climate system model BCC-CSM and the Earth System Model BCC-ESM, (3) Earth System Model BNU-ESM from Beijing Normal University, (4) Earth System Model FIO-ESM from the First Institute of Oceanography, Ministry of Natural Resources. These five models show good performance on many aspects, including average climate, variability from intra-seasonal oscillation to annual variation of ENSO, global and East Asian monsoons, 20th-century climate evolution characterized by temperature changes, and major atmospheric teleconnections. However, there are large differences in the sensitivity of models to increase of greenhouse gases (Zhou et al., 2014; Chen et al., 2014). Based on performances of all CMIP5 models, it seems that there is still room for further progress for all Chinese participating models, especially when compared to international leading models. Under the ongoing CMIP6 research program, other Chinese research institutions have successfully joined the modeling community, including the Chinese Academy of Meteorological Sciences and the Nanjing University of Information Science and Technology.

## 7. Climate change

One of the important advances in atmospheric science in the 20th century is that scientists and governments around the world have realized that ongoing global warming has caused changes in the Earth's environment. This issue has not only attracted great attention from the scientific community, but also the people and governments around the world and has become one of the international diplomatic concerns (Ye, 1996). As a result, the research on global climate change and its impact on the environment have rapidly developed globally, and it has now become an important direction of atmospheric science (Huang R H et al., 2014). One of the breakthroughs in atmospheric sciences since the late 1970s is that people have realized that climate change is not only formed by dynamic and thermodynamic processes that occur within the atmosphere, but more importantly is the interactions of Earth's atmosphere, oceans, snow ice and land surface (Huang et al., 1996; Huang, 2001, 2006). In 1988, the United Nations Intergovernmental Panel on Climate Change (IPCC) was established. As a member of IPCC, Chinese scientists participated in and presided over the preparation of the IPCC Assessment Report. The *IPCC 1st Assessment Report* and the *Supplementary Report* were released in 1992. The report first stated that the concept that "continuous accumulation of anthropogenic greenhouse gas emissions in the atmosphere will lead to climate change". This report directly contributed to the entry into force of the *United Nations Framework Convention on Climate Change* in 1994. As the co-chair of the IPCC Working Group I, Qin Dahe participated in and successfully organized the IPCC scientific assessment activities. He made great contributions to the construction and dissemination of important scientific conclusions that human activities are affecting the Earth's climate. Thus, it has laid a solid foundation for mankind to actively respond to climate change (Qin et al., 2002, 2005, 2014, 2018; Qin and Stocker, 2014).

The research by Chinese scientists on the evolution of climate and environment in China and the assessment of environmental evolution in western China has produced a wide range of influences, and promoted the continuous progress of research on climate change domestically and internationally. Therefore, they made outstanding contributions to the promotion of global change research. In the field of climate change research, Chinese scientists have achieved many world-leading research results, so the voice of China is becoming more and more powerful.

Observation records show that since 1951 the average temperature in China has risen by 1.38°C, with an increasing rate of 0.23°C per decade. The warming since the 1980s is particularly significant. The warming rate of Arctic region over the past 10 years is twice as high as estimated in the IPCC's fifth report, so the warming in the polar area has contributed significantly to the global warming speed over the past 10 years, instead of slowing down the global warming. The semi-arid region has experienced the most significant warming in the world except for the Arctic region in the past 100 years. Especially, in arid and semi-arid regions at a mid-high latitude in the northern hemisphere, the temperature increases by 1.67°C, which is twice the average global land warming, contributing 45% of the global warming (Huang J P et al., 2017, 2014). The average global temperature increase from 1999 to 2008 is close to zero, but the average temperature in this decade is still the highest in the recent 30 years. The average temperature increase in China is 0.4–0.5°C/10 yr. Global and Chinese observation records confirm that global warming still continues (Wang et al., 2010).

Under the background of global warming, the annual average temperature in China has increased significantly in the past 100 years, and the temperature rise is slightly higher than the global average. The trend of precipitation is not obvious, but the spatial characteristics of precipitation changes are distinct and relatively stable. The frequency and intensity of major extreme weather and climate events in China have changed evidently in the past 50 years (Duan et al., 2006; Ren et al., 2005; Wang et al., 2012b). Global warming has slowed down since 1998, but the Qinghai-Tibetan Plateau has shown an accelerated warming trend. The accelerated warming of the plateau has caused the snow to melt rapidly. With the significant increase in precipitation, the plateau heat source has shown a weakening trend (Duan et al., 2016). In the region east of 100°E in China, aridification has been the prevailing trend in the past 50 years. The regions with significant aridification are distributed in the northwestern region, the whole of North China and the southeastern part of the Northeast region. The aridification trend in these areas is closely related to the continuous reduction of precipitation. Another important reason for the aggravation of drought and its expansion is the continuous rise in temperature (Fu and Ma, 2008). The interannual and interdecadal variations and seasonal differences of the average surface moisture index (1951–1997) in the two typical arid regions of North China and Northwest China indicate that the interannual and interdecadal variations in the Northwest and North China are basically opposite. The former has a tendency to become wet while the latter shows a drying trend. The drying trend in North China mainly occurs in summer and autumn. But in the northwest, except the autumn in the east and summer in the west, there is a tendency to become wet in other seasons (Figure 13) (Ma and Fu, 2001). The analysis of three climate mutations during the instrument observation period found that the decadal climate mutation is closely related to global temperature variations. The monsoon region is sensitive to climate mutation. The climate mutation is a globally large-scale climate event with the spatial structure of planetary-scale (Fu, 1994).

Since the 1980s, the global warming problem caused by the increase in atmospheric concentrations of $CO_2$ and other greenhouse gases has become one of the important research hotspots in international sciences of the Earth. Liu et al. (2005) compared the millennium long-term integrated climate simulation test of the Global sea-air coupled model, ECHO-G, with the temperature reconstruction data of eastern China. The results show that at the millennium scale, solar radiation and volcanic activities are the main factors in modulating the global and regional temperature change. However, the change in greenhouse gas content in the recent century-scale plays a more important role in rapid warming. Wang and Zeng (1992) and Wang et al. (1992) applied the two-layer atmospheric circulation model from the Institute of Atmospheric Physics to simulate the ice age July climate. Comparing with the present July simulation results, the ice age atmosphere is found to have a substantially lower temperature, precipitation and cloud cover, higher sea-level pressure, especially the temperature at high latitude land region of Northern Hemisphere and the Antarctic. There are some common characteristics between the $CO_2$ induced climatic changes and the ice age surface condition-induced climatic changes, which may enlighten our understanding of how the climate system responds to external forcing. The ice age climate would have been changed little if the $CO_2$ content is set at modern value, which shows the problem of $CO_2$ sensitivity should be studied by means of coupled models.

The two-layer global atmospheric circulation model is coupled with the mixed layer sea model of 60-meter depth and the thermodynamic sea ice model to simulate the modern climate ($1\times CO_2$) and the climate of double $CO_2$ content. It is pointed out that after the $CO_2$ content doubles, the global surface temperature rises by 1.75°C. And there are large regional and seasonal differences in global climate change. The temperature increase in the high latitude area of the northern hemisphere and the Antarctic region is larger, and the temperature increase in the terrestrial region is greater than that in the marine region. Generally speaking, precipitation increases in the tropics and high latitude areas while decreases in the subtropical zone. Based on multiple sets of observation and reanalysis data, it has also been found that changes of $CO_2$ over the past 60 years have also contributed significantly to the interdecadal variations of East Asian climates (Zhu et al., 2016). Ding et al. (2006) find that the annual $CO_2$ emissions in China are increasing, and the aggregation of positive radiative forcing of greenhouse gases is the main cause of climate warming. The predictions of climate change in the 21st century indicate that in the next 20–100 years, the surface temperature in China will increase significantly, and precipitation will also increase. Specifically, the increase in the intensity of extreme precipitation has made an important contribution to the increase in precipitation in China in the next 100 years (Chen and Sun, 2013).

Huang et al. (2016, 2017) put forward a feedback mechanism between land-atmosphere interaction and aridification. It was found that surface warming and destruction of underlying vegetation by human activities would inhibit soil carbon storage, which would release more

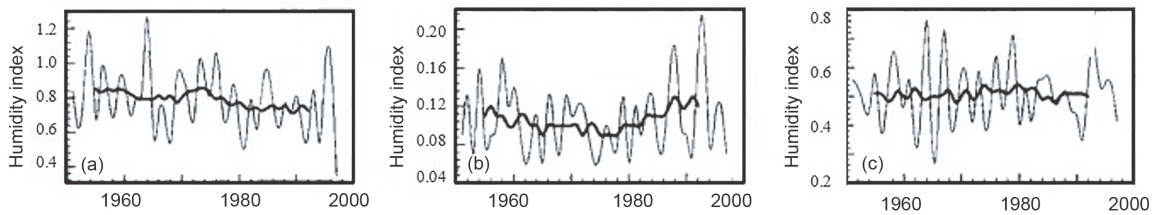


**Figure 13** The variation and trend test of average surface moisture index during flood season in 1951–1997. (a) North China, (b) Northwestern China, (c) east region of Northwestern. The thin lines indicate the original time series; the thick lines indicate 10-year moving averaged. Source: Ma and Fu (2001).

$CO_2$ to the atmosphere and aggravate regional aridification. It is estimated that the expansion of the arid and semi-arid regions will accelerate under the high-emission scenario in the future. The dry land will cover more than 50% of the global land area by the end of the century, and 3/4 expansion will occur in developing countries. When the global average temperature increase reaches 2°C, the temperature in arid and semi-arid areas will increase by 3.2–4°C, which will cause severe climate disasters (Figure 14). Zhang W et al. (2018) studied the CMIP5 model data and finds that reducing the limit of global warming from 2°C to 1.5°C will greatly reduce the damage caused by disasters of extreme precipitation events in the populated monsoon region, especially in South Africa, followed by South Asia and East Asia; In addition, the population exposure of extreme drought in China will also be significantly reduced (Chen and Sun, 2019). Im et al. (2018) studied and evaluated the future changes in thermal stress response to different emissions scenarios in the western maritime continental region. The daily maximum wet bulb temperature was tested. The maximum reduction in the wet-bulb temperature of the plain and coastal areas was relatively small, but that of mountainous area was relatively large. The temperature prediction in RCP8.5 scenario is higher than that in the RCP4.5 scenario, so the importance of controlling greenhouse gas emissions to reduce adverse effects on human health and heat-related deaths is particularly evident. Ren et al. (2005) systematically analyzed the temporal and spatial characteristics of the evolution of the main surface climatic elements in the mainland China since 1951 and found that the increase in atmospheric greenhouse gas concentration caused by human activities may affect the climate in China for the past 50 years to some extent.

Atmospheric aerosols affect the radiation budget of the earth-atmosphere system and further affect the climate of Earth through direct, semi-direct and indirect effects. In addition, the presence of aerosol particles will also cause changes in the atmospheric heating rate and cooling rate, directly affecting the atmospheric dynamic process. Atmospheric aerosols such as sand and dust may also carry nutritive salt. When they precipitate into the ocean, they will affect the primary productivity of the ocean and the exchange flux of the radioactive gas between the sea and the air, and thus affect the ocean and global carbon cycle, and ultimately exert an important impact on the climate system of the Earth (Shi et al., 2008). Systematic observations of the dust and sand confirm that the dust aerosol can accelerate the evaporation of cloud droplets and the reduction of cloud water path in the low-level water cloud by absorbing solar radiation. This semi-direct effect has played an important role in aggravating the aridification in the semi-arid regions of northwest China (Huang J P et al., 2014).

A significant effect of aerosols on the monsoon is reflected in the large-scale darkening phenomenon in South Asia and East Asia, namely the overall reduction in solar radiation reaching the ground. The forcing mechanism of aerosols on the East Asian and South Asian summer monsoons is different. Despite the influence of pollution emissions, the increase in haze day in China is also closely related to the change in East Asian monsoons (Wu et al., 2016; Li, 2016). Lau et al. (2006) used the GCM model to simulate the radiation effects of aerosols on the Tibetan Plateau. The results show that the transported dust aerosols and the local anthropogenic aerosols emitted from the Ganges Plain cause a temperature inversion at the upper troposphere by heating the atmosphere. Then the Indian monsoon is affected, thus causing the rainy season to advance. On the southern slope of the Qinghai-Tibetan Plateau, aerosols can be lifted up to an altitude of 5 km. Therefore, these aerosol particles can absorb solar radiation to heat the atmosphere, so that the cloud cover, deep convective activities, and precipitation are increased and the melting of snow in northern India is accelerated (Lau et al., 2010). The effects of anthropogenic aerosols on the Asian summer monsoon are mainly caused by the response of atmospheric thermal and dynamic processes. The effect of elevated anthropogenic aerosol concentrations changes the distribution of atmospheric heat sources, thereby changing the thermal structure of the monsoon region and weakening the heating in the area of southeastern China and the northern part of the Indo-China peninsula. Finally, the weakening of the summer monsoon intensity is caused (Guo et al., 2017).

Research has been done to reveal the impacts of dust aerosols on marine ecosystems and their climate and environmental effects, as well as the impact of bioaerosols on human health and their climate effects. The result suggests

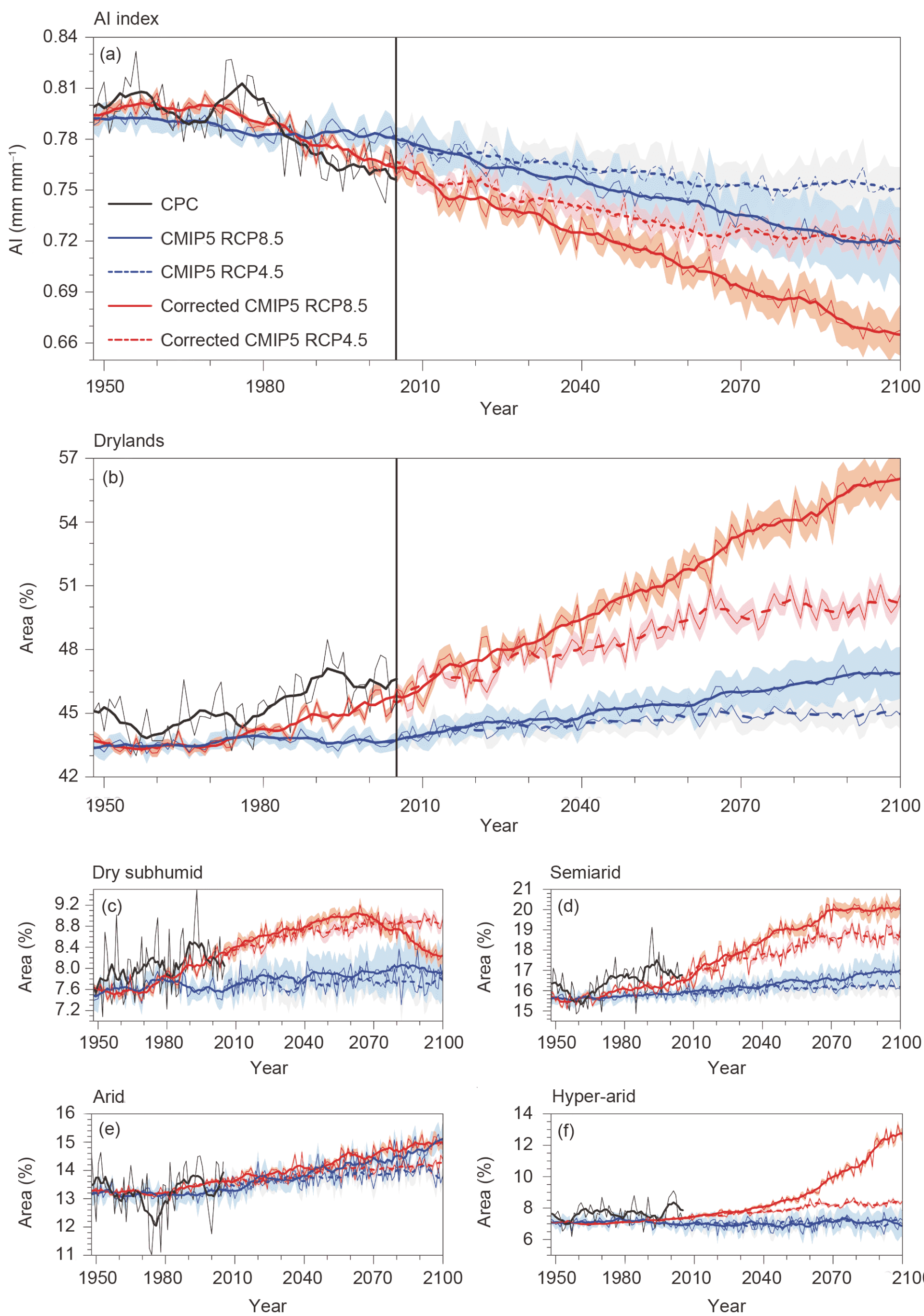


**Figure 14** Temporal variation in the global mean AI and the areal coverage of drylands. (a)–(f), global mean AI is shown in a, and areal coverage (percentage of global land area) is shown for total drylands (b), dry subhumid regions (c), semiarid regions (d), arid regions (e) and hyper-arid regions (f). The thin black lines are the CPC observations. The thin blue solid (dashed) lines are the CMIP5-EM from the historical and RCP8.5 (RCP4.5) projections. The thin red solid (dashed) lines are the corrected CMIP5-EM from the historical and RCP8.5 (RCP4.5) projections. The shading denotes the 95% confidence intervals of the 20 models. Seven-year running means (thick colored lines) are shown to emphasize the aridity trends. Source: Huang et al. (2016).

that there is a strong link between dust aerosols and bioaerosols. Dust can be used as a carrier of microorganisms in the air. After the dust aerosols affect the marine ecosystem, they will affect the production of bioaerosol over the sea. The ecological environment and climatic effects of atmospheric aerosols are very complicated problems. The atmospheric aerosols may also be a double-edged sword. On the one hand, the increase in the release of mineral dust and bioaerosol will lead to atmospheric particulate pollution, which can be a carrier for microorganisms, endangering the human living environment and physical health; on the other hand, dust precipitation will promote biological productivity and affect marine carbon absorption even marine fisheries, which is beneficial to humans (Shi et al., 2018). Reducing the release of anthropogenic aerosols will undoubtedly reduce the pollution of particulate in the atmosphere, which is conducive to human living environment and health. However, scattering aerosols such as sulfate have a strong cooling effect on the climate system (Figure 15) (Shi et al., 2002). Therefore, whether the reduction in its emissions will accelerate the process of global warming is also a concern (Shi et al., 2008). Cai et al. (2017) found that the increase in the frequency of severe haze in Beijing is consistent with the trend of the Arctic Oscillation and the weakening of the East Asian winter monsoon as well as the rapid warming of the lower troposphere. It indicates the circulation changes caused by global greenhouse gas emissions will increase the frequency of severe haze in Beijing.

Based on observational data, Chen and Tung (2014), revealed that the warming slowdown may be due to changes in energy redistribution within the climate system. Studies show that sea temperature and salinity in the northern North Atlantic continued to rise in the late 1990s. Thus, the ocean thermohaline circulation is enhanced to deliver large amounts of heat to the deep oceans, slowing global surface temperature rise. Zeng et al. (2017) found that since 1982, global greening has slowed the rate of increase in surface temperature. The cooling effect mainly comes from the increase in total evaporation (70%), the change in atmospheric circulation (44%) and the weakening rate (21%) of shortwave transmission. However, the warming effect mainly comes from the increase in atmospheric long-wave radiation release (−29%) and the decrease in albedo (−6%). The total feedback from biophysics associated with global greening has slowed the global surface warming by 12% over the past 30 years. Chen et al. (2015) used a variety of historical proxy data in the past thousand years of Central Asian and Chinese monsoon regions to analyze the spatial characteristics of climate change in the warm climate period in Middle Ages and the little ice age period in China and its surrounding areas. It is found that ENSO may be an important factor affecting hydrological and climate change in China and its surrounding areas on the centennial-scale. Tan et al. (2016) assessed changes of offshore sea surface temperature (SST) in China and its response characteristics to global climate change. Studies have shown that during the significant acceleration period of global warming (the 1980s and 1990s), The average SST of offshore regions in China exhibits a faster temperature rise characteristic with a rate of 0.60°C/10 yr, which is more than 5 times the global average warming rate during the same period; during the warming hiatus period (1998–2014), the SST of offshore in China showed a significant downward trend. The interdecadal variation of SST of the offshore areas in China is consistent with the phase transition of the Pacific Decadal Oscillation (PDO). The rapid rise (fall) phase of the SST corresponds to the maximum period of the positive (negative) phase of PDO. PDO may influence the interdecadal variations of offshore SST in China through East Asian monsoon and Kuroshio.

Scientists have confirmed the facts of global warming in the past 100 years from a multi-faceted and multi-angle perspective. They provided new evidence for human-induced climate warming in the aspects of ocean warming, water cycle changes, shrinking of the cryosphere, rising sea level and changes in extreme weather events. They further confirmed that human activities are the main reason causing climate warming since the mid-20th century. Estimates of future climate change using the CMIP5 models and the RCP scenarios suggest that the increase in greenhouse gas concentrations will exacerbate warming (Qin and Stocker, 2014; Qin, 2018).

The IPCC and World Climate Research Program Seminar held in 2014 identified eight challenging themes: cloud, circulation and climate sensitivity; understanding and predicting the extreme weather and climate events; changes in cryosphere; regional climate information; the rise of regional sea level and its impact on coastal areas; the amount of water availability; biogeochemistry; understanding the interdecadal changes; attribution and prediction. These topics cover the major frontiers of present natural sciences of climate change (Sun et al., 2013, 2015; Qin et al., 2014; Qin, 2018).

## 8. Summary and perspective

Seventy years ago, the founding of the People's Republic of China opened the historical journey of the great rejuvenation of the nation. Forty years ago, the curtain of the reform and opening was pulled aside. Our predecessor endured great hardships in pioneer work and stupendous changes have taken place. How time flies! With the national support for technology and meteorology, Chinese achievements in various fields of atmospheric sciences have attracted worldwide attention. Chinese scientists have achieved many outstanding achievements in the field of climate and climate change, especially in the research of East Asian atmospheric circulation and monsoon, variation of land-atmosphere coupling system in Qinghai-Tibetan Plateau and its global climate effects, climate change, etc. Their achievements are summarized as follows.

(1) Chinese scientists used long-term scale data to statistically analyze the warm and cold periods as well as dry and flood periods of climate. They also systematically studied the formation mechanism of climate disasters and extreme weather events, which laid a physical foundation for climate disaster prediction in China.

(2) Since the 1950s, Chinese scientists have paid attention to the influence of the unique terrain of the Qinghai-Tibetan Plateau on atmospheric circulation and climate. Firstly, the

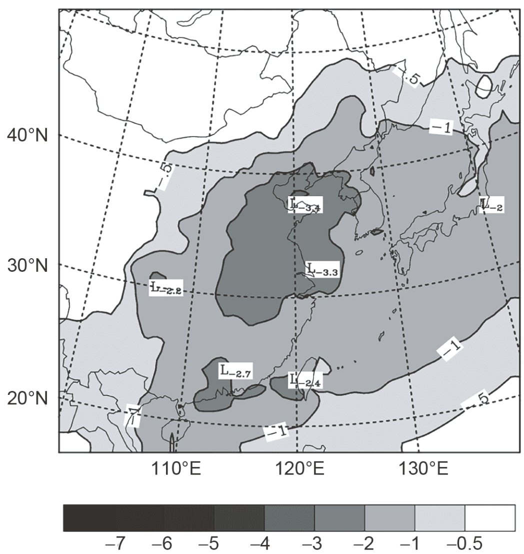


**Figure 15** Annual averaged ground temperature change due to anthropogenic sulfate (°C). Source: Shi et al., (2002).

classical dynamic and thermodynamic effects theory of the Qinghai-Tibetan Plateau was proposed. The theory revealed that the Qinghai-Tibetan Plateau forcing leads to the enhancement of the coupling of the circulation of the lower and upper troposphere and the coupling of the tropical and subtropical monsoon circulation. They systematically elaborated significant impacts of dynamic and thermodynamic effects of the Qinghai-Tibetan Plateau on the interdecadal, interannual and intra-seasonal changes of the Asian monsoon. Systematic studies on the variation of the land-atmosphere coupling system and its global climate effects on the Qinghai-Tibetan Plateau were developed. They also initiated the meteorology of the Qinghai-Tibetan Plateau and established the world-leading position of China in plateau meteorological researches. All these contributions greatly promoted the development of interdisciplinary fields such as atmospheric sciences and geosciences in the frontier research field of the Qinghai-Tibetan Plateau.

(3) For the first time in the world, a quantitative model of the relationship between the stable oxygen isotope ratio in precipitation and the temperature during precipitation periods in the whole Qinghai-Tibetan Plateau was established. The high-resolution ice core record clarifies the climate change characteristics of the Qinghai-Tibetan Plateau over the past 100000 years. It is proposed that the variation amplitude of atmospheric methane concentration in the Qinghai-Tibetan Plateau is larger than that in the polar region. The intensity variation of monsoon will have an important impact on the concentration of methane. They revealed that the relationship between microbial community density changes in ice cores and climate change. They also propose new indicators for studying paleoclimate change through microbial changes. It is suggested that the strengthening of the westerlies and the weakening of the monsoon are the main driving forces for the glacier retreat in the Qinghai-Tibetan Plateau and its surrounding areas.

(4) They proposed the thermal adaptation theory and "Sensible Heat driven Air-Pump" theory to explain the influence of the Qinghai-Tibetan Plateau, which proved the difference between land-sea thermal contrast and the topography over their contribution to the formation of different branches of Asian summer monsoon system. They pioneeringly divided the onset of Asian summer monsoon into three stages of organic connection. They systematically propose the definition of the East Asian monsoon system and its variation mechanism. It is pointed out that the two systems of the East Asian monsoon and the South Asian monsoon are both connected with and distinct from each other. It proves that the characteristics of air-sea interaction are significantly different from those in the tropics due to the strong geostrophic and baroclinic properties at mid-high latitudes. Chinese scientists have achieved original and international leading results on monsoon researches. Especially in the research of the East Asian monsoon, Chinese scientists are playing a dominant role internationally.

(5) Since the 1950s, China has conducted voluminous international leading research on atmospheric circulation changes. Firstly, it is proposed that the seasonal transition of the East Asian atmospheric circulation is abrupt, which perfected and developed the developed Rossby's theory of geostrophic adjustment of atmospheric movement. In addition, they developed the theories of semi-geostrophic adjustment, spherical atmospheric adjustment, and geostrophic adaptation with external forcing, etc. They also put forward the East Asian/Pacific type (EAP type) teleconnection and its theory of the summer atmospheric anomalies in the northern hemisphere to explain how the summer drought and flood in China is affected. They are the first in the world to reveal the mechanism of El Niño influencing East Asian monsoon through the anti-cyclone anomaly in the western Pacific. Firstly, it is proposed that the Asian continent can be basically divided into "Westerlies Asia" which is mainly controlled by mid-latitude westerly circulation and "Monsoonal Asia" which is mainly controlled by monsoon circulation. Westerlies Asia has a relatively dry climate in the early Holocene, and relatively humid in the mid-late Holocene. There is a "dislocation phase" or "anti-phase" of climate changes between Westerlies Asia and Monsoonal Asia.

(6) Chinese scientists are the earliest to propose that the convective heating feedback is an important mechanism to stimulate tropical intra-seasonal oscillations. The intra-seasonal oscillation CISK wave theory in tropical atmospheric is improved, and the theory and dynamic mechanism of atmospheric low-frequency teleconnection are proposed. Since the late 1970s, China has begun to develop climate models and apply them to simulation studies of climate processes.

Chinese scientists have established a theoretical framework for climate dynamics, and have taken the lead in conducting cross-quarter numerical climate predictions internationally. They also established a short-term numerical climate prediction system and applied it to summer drought and flood forecasting business in China. The 2nd generation short-term climate prediction model system has been put into operation. 5 climate system models from China participated in the Coupled Model Intercomparison Project, Phase 5.

(7) Chinese scientists have participated in and successfully organized the IPCC scientific assessment activities, and made great contributions in efforts to construct and disseminate important scientific conclusions about the anthropogenic impact of the Earth's climate, thus laying a solid foundation for human actions to actively respond to the climate change. With regard to the evolution of climate and environment in China, the assessment study of environmental evolution in western China has had a wide-ranging impact on the international community. It promoted the continuous progress of domestic and international research on climate change contributed to the progress of global change research. In the field of climate change, Chinese scientists have reaped the numerous world-leading fruits. Thus, the right to speak internationally is becoming more and more powerful.

Although the research on the climate and the climate change has produced a series of original and internationally leading results, there still remain many problems that will lead the way in the future research on the climate and the climate change.

(1) Based on existing results, a scientific and reasonable complete physical image needs to be constituted by questions of how the dynamic and thermodynamic effects of the land-atmosphere coupled process on the Qinghai-Tibetan Plateau affect Asian monsoons and multi-scale disaster weather systems, etc. The mechanism discussion and numerical simulation verification of the land-atmosphere coupling process of the Qinghai-Tibetan Plateau and the synergistic effect of the ocean on the global climate should be carried out under the guidance of the concept of multi-sphere interaction. There are urgent needs for breakthroughs in the following fields: the vertical structure of cloud precipitation in plateau and the temporal and spatial changes of the latent heat structure; the temporal and spatial changes of cloud parameters and the effects of radiation budget; and the precipitation efficiency and the water cycle. The aim is to obtain innovative research results in the physical mechanism of the cloud precipitation process on the Qinghai-Tibetan Plateau.

(2) The East Asian monsoon is also a regional climate system affected by oceans, land, ice, and plateau. The interaction of these different layers has an important impact on the anomalies of the East Asian monsoon climate. Especially, the impact of the interaction of these layers on the East Asian monsoon climate in the context of global warming is a scientific issue that needs to be studied in the future. In addition, the East Asian monsoon is an important member of the global climate system. The changes in the East Asian monsoon also have important feedback effects on global climate change, which deserves in-depth studies.

(3) With the CMIP5 model as the reference standard, there is still a big gap between current climate model in China and the international leading model. The development of high-resolution models has been slow for a long time, and China is lagging behind the international average. On the one hand, there is a lack of sufficient high-performance computing resources. On the other hand, the level of design and development of corresponding software lags far behind the progress of hardware. Therefore, it is necessary to carry out integrated researches on the development of climate system models, and integrate the decentralized researches on the development, evaluation and application of climate system models into an organic whole, and develop high-resolution land-atmosphere coupled climate system models through extension, crossover and upgrading, making Chinese comprehensive level of climate model development and simulation rank among the top in the world.

(4) How much global warming caused by greenhouse gas generated by human activities will be produced is still a problem that has not been clarified. Even if there are many studies, the results of these studies are different and there is great uncertainty. It may be a major scientific issue in atmospheric science and global climate change research in the future. What are the different responses of global warming to climate variability in different regions of China? To what extent does climate change affect air pollution? To what extent does the latter affect climate change? The warming of different regions of China, the attribution analysis of drying or wetting of different regions, and the differences between these factors and the global climate change factors are all urgent scientific questions to answer.

(5) With global warming, record-breaking extreme weather, and climate events occur frequently, which had widespread and serious impacts on human health, agriculture, ecosystems, and infrastructure. The causes and changes in extreme weather and climate events are complex. In the context of global warming, how to study the causes and changes of extreme weather and climate events from the perspective of multi-factor synergy is a difficult and important point in international climate research.

**Acknowledgements** *This work was supported by the National Natural Science Foundation of China (Grant No. 41521004), the China University Research Talents Recruitment Program (Grant No. B13045) and the Fundamental Research Funds for the Central Universities (Grant No. LZUJBKY-2019-kb30).*

## References


Cai W, Li K, Liao H, Wang H, Wu L. 2017. Weather conditions conducive to Beijing severe haze more frequent under climate change. Nat Clim Change, 7: 257–262

Cai Y, Tan L, Cheng H, An Z, Edwards R L, Kelly M J, Kong X, Wang X. 2010. The variation of summer monsoon precipitation in central China since the last deglaciation. Earth Planet Sci Lett, 291: 21–31

Chen F H, Chen J H, Holmes J, Boomer I, Austin P, Gates J B, Wang N L, Brooks S J, Zhang J W. 2010. Moisture changes over the last millennium in arid central Asia: A review, synthesis and comparison with monsoon region. Quat Sci Rev, 29: 1055–1068

Chen F H, Huang W. 2017. Multi-scale climate variations in the arid Central Asia. Adv Clim Change Res, 8: 1–2

Chen F, Chen J, Huang W, Chen S, Huang X, Jin L, Jia J, Zhang X, An C, Zhang J, Zhao Y, Yu Z, Zhang R, Liu J, Zhou A, Feng S. 2019. Westerlies Asia and monsoonal Asia: Spatiotemporal differences in climate change and possible mechanisms on decadal to sub-orbital timescales. Earth-Sci Rev, 192: 337–354

Chen F, Wu D, Chen J, Zhou A, Yu J, Shen J, Wang S, Huang X. 2016. Holocene moisture and East Asian summer monsoon evolution in the northeastern Tibetan Plateau recorded by Lake Qinghai and its environs: A review of conflicting proxies. Quat Sci Rev, 154: 111–129

Chen F, Yu Z, Yang M, Ito E, Wang S, Madsen D B, Huang X, Zhao Y, Sato T, John B. Birks H, Boomer I, Chen J, An C, Wünnemann B. 2008. Holocene moisture evolution in arid central Asia and its out-of-phase relationship with Asian monsoon history. Quat Sci Rev, 27: 351–364

Chen H Y. 1957. Circulation characteristics of the Yangtze River and Huaihe River Basin during flood period in 1954 (in Chinese). Acta Meteorol Sin, 28: 1–12

Chen H, Sun J. 2013. Projected change in East Asian summer monsoon precipitation under RCP scenario. Meteorol Atmos Phys, 121: 55–77

Chen H, Sun J. 2019. Increased population exposure to extreme droughts in China due to 0.5°C of additional warming. Environ Res Lett, 14: 064011

Chen J, Chen F, Feng S, Huang W, Liu J, Zhou A. 2015. Hydroclimatic changes in China and surroundings during the Medieval Climate Anomaly and Little Ice Age: Spatial patterns and possible mechanisms. Quat Sci Rev, 107: 98–111

Chen L T. 1977. Influence of seawater temperature anomalies in the equatorial region of the Eastern Pacific on Tropical Atmospheric Circulation and precipitation in flood season in China (in Chinese). Chin J Atmos Sci, 1: 1–12

Chen L T. 1982. Interaction between the North Pacific subtropical high and the SST in the Eastern Equatorial (in Chinese). Chin J Atmos Sci, 6: 148–156

Chen L T. 1983. Temporal and spatial variation of the air-sea interaction in the Pacific Ocean (in Chinese). Acta Meteorol Sin, 41: 296–304

Chen Q S, Miao J H, Li W L. 1964. The average flow field and average meridional circulation in the Southwest Monsoon Region and the Pacific Trade Wind Region in Southeastern Asia in July 1958 (in Chinese). Acta Meteorol Sin, 34: 51–61

Chen W, Graf H F, Huang R. 2000. The interannual variability of East Asian winter monsoon and its relationship to the summer monsoon. Adv Atmos Sci, 17: 48–60

Chen X L, Zhou T J, Guo Z. 2014. Climate sensitivities of two versions of FGOALS model to idealized radiative forcing. Sci China Earth Sci, 57: 1363–1373

Chen X, Tung K K. 2014. Varying planetary heat sink led to global-warming slowdown and acceleration. Science, 345: 897–903

Chou J F, Liu S D, Liu S S. 1994. Nonlinear Dynamics (in Chinese). Beijing: China Meteorological Press. 15–120

Chou J F. 1974. Problems with past data used in weather numerical forecasts. Sci China, 6: 635–644

Chou J F. 1986. Long-term Numerical Weather Forecasts (in Chinese). Beijing: China Meteorological Press. 1–85

Chou J F. 1990. New Progress in Atmospheric Dynamics (in Chinese). Lanzhou: Lanzhou University Press. 68–112

Chou J. 1989. Predictability of the atmosphere. Adv Atmos Sci, 6: 335–346

Dai X G, Chou J F, Wu G X. 2002. The teleconnection between the Indian Monsoon and the East Asian summer circulation (in Chinese). Acta Meteorol Sin, 60: 544–552

Ding Y H, Li Q Q, Li W J, Luo Y, Zhang P Q, Zhang Z Q, Shi X L, Liu Y M, Wang L N. 2004. The progress of China's business power season forecasts (in Chinese). Acta Meteorol Sin, 62: 598–612

Ding Y H, Liu Y J, Liang S J, Ma X J, Zhang Y X, Si D, Song Y F, Zhang J. 2014. The interdecadal variations of the East Asian winter monsoon and its possible links to global climate change (in Chinese). Acta Meteorol Sin, 72: 835–852

Ding Y H, Ren G Y, Shi G Y, Gong P, Zheng X H, Zhai P M, Zhang D E, Zhao Z C, Wang S W, Wang H J, Luo Y, Chen L, Gao X J, Dai X S. 2006. National assessment report on climate change (I): History and future trends of climate change in China (in Chinese). Clim Change Res, 2: 3–8

Ding Y, Wang Z, Sun Y. 2008. Inter-decadal variation of the summer precipitation in East China and its association with decreasing Asian summer monsoon. Part I: Observed evidences. Int J Climatol, 28: 1139–1161

Ding Y, Sun Y, Wang Z, Zhu Y, Song Y. 2009. Inter-decadal variation of the summer precipitation in China and its association with decreasing Asian summer monsoon Part II: Possible causes. Int J Climatol, 29: 1926–1944

Duan A M, Xiao Z X, Wu G X. 2016. Climate change characteristics of the Tibetan Plateau in the context of global warming from 1979 to 2014 (in Chinese). Clim Change Res, 12: 374–381

Duan W S, Mu M. 2018. Predictability of El Niño-Southern Oscillation Events. Oxford Research Encyclopedia of Climate Science, 1–38

Fan K, Wang H. 2004. Antarctic oscillation and the dust weather frequency in North China. Geophys Res Lett, 31: L10201

Fang J B, Yang X Q. 2011. The relative roles of different physical processes in unstable midlatitude ocean-atmosphere interactions. J Clim, 24: 1542–1558

Fang J, Yang X Q. 2016. Structure and dynamics of decadal anomalies in the wintertime midlatitude North Pacific ocean-atmosphere system. Clim Dyn, 47: 1989–2007

Fu C B. 1979. The transformation of the average circulation type through the ring and the long-term weather process (in Chinese). Acta Meteorol Sin, 37: 74–85

Fu C B. 1987. The El Niño/Southern Oscillation phenomenon and interannual climate changes (in Chinese). Chin J Atmos Sci, 11: 209–220

Fu C B. 1994. Study of climate mutations (in Chinese). Chin J Atmos Sci, 18: 373–384

Fu C B, Ma Z G. 2008. Global change and regional drought (in Chinese). Chin J Atmos Sci, 32: 752–760

Fu C, Fletcher J O. 1985. The relationship between tibet-tropical ocean thermal contrast and interannual variability of indian monsoon rainfall. J Clim Appl Meteor, 24: 841–847

Gong D Y. 1999. The climate change in Antarctica in the context of global warming (in Chinese). Chin Geogr Sci, 19: 102–107

Gong D, Wang S. 1999. Definition of Antarctic Oscillation index. Geophys Res Lett, 26: 459–462

Gu Z C. 1951. The influence of the Tibetan Plateau on the East Asian circulation and its importance (in Chinese). Acta Meteorol Sin, 22: 43–56

Guo Z Y, Liu Y, Li W L. 2017. A numerical study of Aerosols affecting the mechanism of Summer Wind in Asia (in Chinese). Acta Meteorol Sin, 75: 797–810

He J H, Chen L Z. 1989. The Quasi-40-day Oscillation in the mid-latitudes of the southern hemisphere and its relationship with the northern hemisphere Summer Monsoon (in Chinese). J Nanjing Inst Meteorol, 12: 11–18

He S P, Wang H J, Gao Y Q, Li F, Li H, Wang C. 2018. Influence of solar wind energy flux on the interannual variability of ENSO in the subsequent year. Atmos Ocean Sci Lett, 11: 165–172

He S P, Wang H J. 2012. The East Asian Winter Wind Composite Index and its expressed characteristics of the interannual change of East Asian winter wind (in Chinese). Chin J Atmos Sci, 36: 523–538

He S, Wang H. 2013. Oscillating relationship between the East Asian winter monsoon and ENSO. J Clim, 26: 9819–9838

Huang J P, Chou J F. 1989. Researches on similar rhythm phenomenon of air-sea coupled system (in Chinese). Sci China Ser B, 19: 1001–1008

Huang J P, Wang S W. 1991. Seasonal forecast tests of similar-dynamic mode (in Chinese). Sci China Ser B, 2: 216–224

Huang J, Wang T, Wang W, Li Z, Yan H. 2014. Climate effects of dust aerosols over East Asian arid and semiarid regions. J Geophys Res-Atmos, 119: 11398–11416

Huang J, Yu H, Guan X, Wang G, Guo R. 2016. Accelerated dryland expansion under climate change. Nat Clim Change, 6: 166–171

Huang J, Zhang X, Zhang Q, Lin Y, Hao M, Luo Y, Zhao Z, Yao Y, Chen X, Wang L, Nie S, Yin Y, Xu Y, Zhang J. 2017. Recently amplified arctic warming has contributed to a continual global warming trend. Nat Clim Change, 7: 875–879

Huang R H, Chen J L, Liu Y. 2011a. The interdecadal variation of the main mode of summer precipitation anomalies in Eastern China and its relationship with water vapor transport in East Asia (in Chinese). Chin J Atmos Sci, 35: 589–606

Huang R H, Chen J L, Zhou L T, Zhang Q Y. 2003. The research on the relationship between major climate disasters in China and the climate system in East Asia (in Chinese). Chin J Atmos Sci, 27: 770–787

Huang R H, Chen W, Ma Y M, Gao X Q, Lv S H, Wei Z G, Zhang Q, Wei G A, Hu Z Y, Zhou L T, Zhou D G. 2011b. Land-Air Interactions in Arid Regions of Northwest China and Their Effects on Climate Change in East Asia (in Chinese). Beijing: China Meteorological Press. 356

Huang R H, Fu Y F, Zang X Y. 1996. The interaction between the Asian Monsoon and the ENSO cycle (in Chinese). Clim Environ Res, 1: 38–54

Huang R H, Wu G X, Chen W, Liu Y M, Zhou L T, Wang L. 2014. Advances and Frontiers in Atmospheric Science and the Global Clim Change Research (in Chinese). Beijing: Science Press. 85–115

Huang R H. 1985a. The effect of heat source anomalies over the Tibetan Plateau on the atmospheric circulation anomalies in the northern hemisphere (in Chinese). Acta Meteorol Sin, 43: 208–220

Huang R. 1985b. The numerical simulation of the three-dimensional teleconnections in the summer circulation over the Northern Hemisphere. Adv Atmos Sci, 2: 81–92

Huang R H. 1996. Development trends, characteristics and frontier research topics of basic research in modern atmospheric sciences. In: National Natural Science Foundation of China, ed. Frontiers and Prospects of Modern Atmospheric Science (in Chinese). Beijing: China Meteorological Press. 7–11

Huang R H. 2001. The review and outlook of the development of atmospheric science (in Chinese). Adv Earth Sci, 16: 643–657

Huang R H. 2006. The formation mechanism and prediction theory studies of major climate disasters in China (in Chinese). Adv Earth Sci, 21: 564–575

Huang R, Chen J, Huang G. 2007. Characteristics and variations of the East Asian monsoon system and its impacts on climate disasters in China. Adv Atmos Sci, 24: 993–1023

Huang R H, Chen J, Wang L, Lin Z D. 2012. Characteristics, processes and causes of the spatio-temporal variabilities of the East Asian monsoon system. Adv Atmos Sci, 29: 1–32

Huang R H, Huang G, Wei Z G. 2004. Climate variations of the summer monsoon over China. In: East Asian Monsoon. Singapore: World Scientific Publishing Co Pte Ltd. 213–270

Huang R, Sun F. 1992. Impacts of the tropical western Pacific on the East Asian summer monsoon. J Meteorol Soc Jpn, 70: 243–256

Huang R, Wu Y. 1989. The influence of ENSO on the summer climate change in China and its mechanism. Adv Atmos Sci, 6: 21–32

Huang Y, Wang B, Li X, Wang H. 2018. Changes in the influence of the western Pacific subtropical high on Asian summer monsoon rainfall in the late 1990s. Clim Dyn, 51: 443–455

Huang Y, Wang H, Fan K, Gao Y. 2015. The western Pacific subtropical high after the 1970s: Westward or eastward shift? Clim Dyn, 44: 2035–2047

Im E S, Eltahir E A B. 2018. Simulation of the diurnal variation of rainfall over the western maritime continent using a regional climate model. Clim Dyn, 51: 73–88

Im E S, Kang S, Eltahir E A B. 2018. Projections of rising heat stress over the western maritime continent from dynamically downscaled climate simulations. Glob Planet Change, 165: 160–172

Ji F, Wu Z, Huang J, Chassignet E P. 2014. Evolution of land surface air temperature trend. Nat Clim Change, 4: 462–466

Ji J J, Chao J P. 1979. Long-period oscillations in tropical air-sea coupled systems and equatorial convergence in the atmosphere (in Chinese). Acta Meteorol Sin, 37: 32–43

Ji L, Sun S, Arpe K, Bengtsson L. 1997. Model study on the interannual variability of Asian winter monsoon and its influence. Adv Atmos Sci, 14: 1–22

Jiang X G, Chen S J. 2008. Terrain affects the observation and simulation of sand and dust transmission (in Chinese). Acta Meteorol Sin, 66: 1–12

Jin F F, Zhu B Z. 1988a. Coupled air-sea nonlinear oscillation and annual variation of atmospheric circulation (in Chinese). Chin J Atmos Sci, 12: 346–356

Jin F F, Zhu B Z. 1988b. Equilibrium state of a nonlinear dynamic system of coupled air-sea oscillations (in Chinese). Sci China Ser B, 18: 777–786

Jin Z H, Tao S Y. 1999. Study on the relationship between ENSO cycle and summer and winter precipitation in eastern China (in Chinese). Chin J Atmos Sci, 23: 663–672

Ju J, Slingo J. 1995. The Asian summer monsoon and ENSO. Q J R Met Soc, 121: 1133–1168

Lau K M, Kim M K, Kim K M. 2006. Asian summer monsoon anomalies induced by aerosol direct forcing: The role of the Tibetan Plateau. Clim Dyn, 26: 855–864

Lau N C, Nath M J. 2012. A model study of the Air-Sea interaction associated with the climatological aspects and interannual variability of the South Asian summer monsoon development. J Clim, 25: 839–857

Lau W K M, Kim M K, Kim K M, Lee W S. 2010. Enhanced surface warming and accelerated snow melt in the Himalayas and Tibetan Plateau induced by absorbing aerosols. Environ Res Lett, 5: 025204

Li C Y. 1985. The trough and ridge of the South Asian summer monsoon and tropical cyclones activities with moving CISK wave (in Chinese). Sci China Ser B, 28: 668–675

Li C Y, Chen Y X, Yuan C G. 1988. An important reason for the El Niño incident-the frequent activities of the East Asian Cold Wave (in Chinese). Chin J Atmos Sci (Suppl), 125–132

Li C Y, Mu M Q. 1998. Numerical simulation of ENSO induced by abnormal East Asian winter monsoon (in Chinese). Chin J Atmos Sci, 22: 481–490

Li C Y. 1987. Several major research topics in contemporary atmospheric science (in Chinese). Chin J Atmos Sci, 11: 430–440

Li C Y. 1988. Frequent strong East Asian trough activities and the occurrence of El Niño (in Chinese). Sci China Ser B, 6: 667–674

Li C Y. 1989. Warm winter in eastern China with the El Niño (in Chinese). Chin Sci Bull, 4: 283–296

Li C Y. 1990a. Intraseasonal Oscillations in the atmosphere (in Chinese). Chin J Atmos Sci, 14: 32–45
Li C Y. 1990b. Interaction between anomalous winter monsoon in East Asia and El Niño events. Adv Atmos Sci, 7: 36–46
Li C. 1993. A further inquiry on the mechanism of 30–60 day oscillation in the tropical atmosphere. Adv Atmos Sci, 10: 41–53
Li C Y. 1996a. Dynamic mechanism of intraseasonal oscillation in the tropical atmosphere. From Atmospheric Circulation to Global Change. 351–364
Li C Y. 1996b. Further research on the Evaporation-Wind feedback mechanism (in Chinese). J Trop Meteorol, 12: 193–199
Li Z Q. 2016. The forcing and impact of Aerosols on the Asian Monsoon: Understanding and challenges (in Chinese). Acta Meteorol Sin, 74: 1017–1022
Li C, Cho H R, Wang J T. 2002. CISK kelvin wave with evaporation-wind feedback and air-sea interaction-A further study of tropical intraseasonal oscillation mechanism. Adv Atmos Sci, 19: 379–390
Li C, Li G. 1997. Evolution of intraseasonal oscillation over the tropical western pacific/south china sea and its effect to the summer precipitation in southern China. Adv Atmos Sci, 14: 246–254
Li C, Li G. 2000. The NPO/NAO and interdecadal climate variation in China. Adv Atmos Sci, 17: 555–561
Li H X, Chen H P, Wang H J, Sun J Q, Ma J H. 2018. Can Barents Sea ice decline in spring enhance summer hot drought events over Northeastern China? J Clim, 31: 4705–4725
Li H, Dai A, Zhou T, Lu J. 2010. Responses of East Asian summer monsoon to historical SST and atmospheric forcing during 1950–2000. Clim Dyn, 34: 501–514
Li J, Wang J X L. 2003a. A new North Atlantic Oscillation index and its variability. Adv Atmos Sci, 20: 661–676
Li J P, Wang J X L. 2003b. A modified zonal index and its physical sense. Geophys Res Lett, 30: 34–1
Li J, Xie S P, Cook E R, Morales M S, Christie D A, Johnson N C, Chen F, D'Arrigo R, Fowler A M, Gou X, Fang K. 2013. El Niño modulations over the past seven centuries. Nat Clim Change, 3: 822–826
Li J, Zeng Q. 2002. A unified monsoon index. Geophys Res Lett, 29: 115-1–115-4
Li S, Bates G T. 2007. Influence of the Atlantic Multidecadal Oscillation on the winter climate of East China. Adv Atmos Sci, 24: 126–135
Li Y, Lau N C. 2012. Impact of ENSO on the atmospheric variability over the North Atlantic in late winter—Role of transient eddies. J Clim, 25: 320–342
Lin I I, Black P, Price J F, Yang C Y, Chen S S, Lien C C, Harr P, Chi N H, Wu C C, D'Asaro E A. 2013. An ocean coupling potential intensity index for tropical cyclones. Geophys Res Lett, 40: 1878–1882
Liu J, Storch H V, Chen X, Zorita E, Zheng J Y, Wang S M. 2005. A comparative study of the millennium climate simulation and the temperature reconstruction sequence in eastern China (in Chinese). Chin Sci Bull, 50: 2251–2255
Liu Q M, Liu B Q, Ren R C, Duan A M, Mao J Y. 2016. The impact of the current major El Niño events on China's spring and summer climate (in Chinese). Bull Chin Acad Sci, 31: 241–250
Liu X W, Li W P, Wu G X. 2002. Correlation analysis of the annual Qinghai-Tibetan Plateau heating and the interannual variation of the northern hemisphere circulation (in Chinese). Acta Meteorol Sin, 60: 266–277
Liu X, Yin Z Y, Zhang X, Yang X. 2004. Analyses of the spring dust storm frequency of northern China in relation to antecedent and concurrent wind, precipitation, vegetation, and soil moisture conditions. J Geophys Res, 109: D16210
Liu Y J, Ding Y H. 2017. Analysis of the basic climatic characteristics of the Asian summer monsoon (in Chinese). Acta Meteorol Sin, 65: 511–526
Liu Y M, Hoskins B J, Blackburn M. 2007. Impact of Tibetan orography and heating on the summer flow over Asia. J Met Soc Japan, 85B: 1–19
Liu Y, Wu G, Hong J, Dong B, Duan A, Bao Q, Zhou L. 2012. Revisiting Asian monsoon formation and change associated with Tibetan Plateau forcing: II. change. Clim Dyn, 39: 1183–1195
Lu R Y, Dong B W, Ding H. 2006. Impact of the Atlantic Multidecadal Oscillation on the Asian summer monsoon. Geophys Res Lett, 33: L24701
Luo M X, Zhu B Z, Zhang X H. 1983. The dynamic effect of the Qinghai-Tibetan Plateau on the formation of the Zonal Circulation in East Asia (in Chinese). Chin J Atmos Sci, 7: 145–152
Ma Z G, Fu C B. 2001. Trend analysis of surface wet conditions in the arid regions of northern China (in Chinese). Acta Meteorol Sin, 59: 737–746
Miao J H, Liu J M. 1989. The development of air-sea coupled instability of ENSO. Sci China Ser B, 19: 1112–1120
Miao J, Wang T, Wang H, Zhu Y, Sun J. 2018. Interdecadal weakening of the East Asian winter monsoon in the mid-1980s: The roles of external forcings. J Clim, 31: 8985–9000
Mou W F, Chen Y S, Yi Q J. 1975. The effect of polar vortex activity on the continuous low temperature in central China (in Chinese). Meteorol Sci Technol , 4: 11–714
Mu M, Duan W, Chen D, Yu W. 2015. Target observations for improving initialization of high-impact ocean-atmospheric environmental events forecasting. Nat Sci Rev, 2: 226–236
Mu M, Duan W, Wang B. 2007. Season-dependent dynamics of nonlinear optimal error growth and El Niño-Southern oscillation predictability in a theoretical model. J Geophys Res, 112: D10113
Pan W J, Mao J Y, Wu G X. 2013. Characteristics and mechanism of the 10–20-day oscillation of spring rainfall over southern China. J Clim, 26: 5072–5087
Peng S, Piao S, Ciais P, Myneni R B, Chen A, Chevallier F, Dolman A J, Janssens I A, Peñuelas J, Zhang G, Vicca S, Wan S, Wang S, Zeng H. 2013. Asymmetric effects of daytime and night-time warming on Northern Hemisphere vegetation. Nature, 501: 88–92
Piao S, Ciais P, Huang Y, Shen Z, Peng S, Li J, Zhou L, Liu H, Ma Y, Ding Y, Friedlingstein P, Liu C, Tan K, Yu Y, Zhang T, Fang J. 2010. The impacts of climate change on water resources and agriculture in China. Nature, 467: 43–51
Qian W, Fu J, Yan Z. 2007. Decrease of light rain events in summer associated with a warming environment in China during 1961–2005. Geophys Res Lett, 34: L11705
Qian W, Quan L, Shi S. 2002. Variations of the dust storm in China and its climatic control. J Clim, 15: 1216–1229
Qin D H, Chen Y Y, Li X Y. 2005. Climate and Environmental Evolution in China (in Chinese). Beijing: Science Press. 1–148
Qin D H, Stocker T. 2014. Highlights of the First Working Group Report of the IPCC Fifth Assessment Report (in Chinese). Clim Change Res, 10: 1–6
Qin D H. 2002. Environmental Evolution Assessment of Western China. Comprehensive Volume. Comprehensive Report on Environmental Evolution Assessment in Western China (in Chinese). Beijing: Science Press. 1–92
Qin D H. 2018. Introduction to Climate Change Science. Beijing: Science Press. 1–120
Qin D, Yao T, Chen F, Zhang T, Meng X. 2014. Uplift of the Tibetan Plateau and its environmental impacts. Quat Res, 81: 397–399
Reiter E R, Ding Y H. 1980. The role of the Tibetan Plateau in influencing the feedback mechanism of Planetary Circulation (in Chinese). Chin J Atmos Sci, 4: 300–309
Ren G Y, Guo J, Xu M Z, Chu Z Y, Zhang L, Zou X K, Li Q X, Liu X N. 2005. The basic characteristics of surface climate change of China in the past 50 years (in Chinese). Acta Meteorol Sin, 63: 942–956
Ren R, Zhu C, Cai M. 2019. Linking quasi-biweekly variability of the South Asian high to atmospheric heating over Tibetan Plateau in summer. Clim Dyn, 53: 3419–3429

Shi G Y, Tan S C, Chen B. 2018. Environmental and climatic effects of dust and bioaerosols (in Chinese). Chin J Atmos Sci, 42: 559–569

Shi G Y, Wang B, Zhang H. 2008. Atmospheric aerosol radiation and climate effects (in Chinese). Chin J Atmos Sci, 32: 826–840

Shi G Y, Wang X H, Zhang L S, Huang X Y, Zhao Z C, Gao X J, Xu Y. 2002. The research of impacts of human activities on climate II. The impact on climate change in East Asia and China (in Chinese). Clim Environ Res, 7: 255–266

Shi N. 1996. Long-term changes in the remote correlation of the atmospheric circulation in the northern hemisphere and its relationship with climate change in China (in Chinese). Acta Meteorol Sin, 54: 675–683

Song M H, Qian Z A, Cai Y, Liu Z M. 2007. Analysis of the average circulation and dust activity in the spring of strong and weak sandstorms in China and Mongolia (in Chinese). Acta Meteorol Sin, 65: 94–104

Sui C H, Li X, Ho C H, Lau K M. 2008. Effects of radiative cooling on the tropical convective response to sea surface temperature: 2-D large domain cumulus ensemble simulations. J Geophys Res, 113: D08116

Sun J Q, Wang H J. 2012. Changes of the connection between the summer North Atlantic oscillation and the East Asian summer rainfall. J Geophys Res, 117: D08110

Sun J, Zhang M, Liu T. 2001. Spatial and temporal characteristics of dust storms in China and its surrounding regions, 1960–1999: Relations to source area and climate. J Geophys Res, 106: 10325–10333

Sun S F, Lu Z B. 1989. A land-water heat exchange model that can be coupled to the atmospheric circulation pattern (in Chinese). Sci China Ser B, 19: 216–224

Sun Y, Qin D H, Zhou B T. 2015. The main direction and challenges of future climate change science researches (in Chinese). Clim Change Res, 11: 324–330

Sun Y, Yin H, Tian Q H, Hu T, Shi Y, Liu H B, Zhou B T. 2013. The research progress on Climate Change Detection Attribution in the global and Chinese regions in the past 50 years (in Chinese). Clim Change Res, 9: 235–245

Tan B K, Chen W. 2014. Atmospheric Teleconnection Dynamics at mid-high latitudes and its research progress on winter weather in East Asia (in Chinese). Acta Meteorol Sin, 72: 9908–925

Tan H J, Cai R S, Huang R H. 2016. The significant response of offshore sea surface temperature to climate warming and suspension in China (in Chinese). Clim Change Res, 12: 500–507

Tang M C, Zhang J, Wang J X, Zhang L. 1988. A correlation analysis between the average 0.8m Geothermal Anomaly Field and the Latter Season Precipitation Field in China (in Chinese). Acta Meteorol Sin, 46: 481–485

Tang M C, Zhong Q, Wu S J. 1982. A Thermodynamic model of long-term precipitation forecasting (in Chinese). Acta Meteorol Sin, 40: 49–58

Tao S Y, Chen L X. 1957. The structure of the Atmospheric Circulation over the Asian continent in summer (in Chinese). Acta Meteorol Sin, 28: 233–247

Tao S Y, Zhang Q Y. 1998. Asian Winter and Summer Winds respond to ENSO events (in Chinese). Chin J Atmos Sci, 22: 399–407

Tao S Y, Zhao Y J, Chen X M. 1958. The relationship between the Mould Rains period in East Asia and the seasonal variation of Atmospheric Circulation over Asia (in Chinese). Acta Meteorol Sin, 29: 119–134

Tao S, Chen L. 1987. A Review of Recent Research on the East Asian Summer Monsoon in China. In: Chang C P, ed. Krishnamurti T N. Monsoon Meteorology. Oxford: Oxford University Press

Wang C, Wang S M. 1987. The change of climate of Central Plains in China in terms of Annual Precipitation in the past 5000 years (in Chinese). Sci China Ser B, 17: 104–112

Wang H J, Chen H P. 2016. Understanding the recent trend of haze pollution in eastern China: Roles of climate change. Atmos Chem Phys, 16: 4205–4211

Wang H J, Fan K, Lang X M, Sun J Q, Chen L J. 2012a. New Theories, New Methods and New Technologies for Short-term Climate Prediction in China (in Chinese). Beijing: China Meteorological Press. 226

Wang H J, Fan K. 2013. The main changes in the East Asian Monsoon in recent decades (in Chinese). Chin J Atmos Sci, 37: 313–318

Wang H J, Sun J Q, Chen H P, Zhu Y L, Zhang Y, Jiang D B, Lang X M, Fan K, Yu E T, Yang S. 2012b. Extreme climate in China: Facts, simulation and projection. Meteorol Z, 21: 279–304

Wang H J, Zeng Q C, Zhang X H. 1992. Numerical simulation of climate change caused by doubling $CO_2$ content (in Chinese). Sci China Ser B, 6: 663–672

Wang H J, Zeng Q C. 1992. Numerical simulation of Glacial Climate (in Chinese). Acta Meteorol Sin, 50: 279–289

Wang H, He S. 2015. The North China/Northeastern Asia severe summer drought in 2014. J Clim, 28: 6667–6681

Wang H. 2001. The weakening of the Asian monsoon circulation after the end of 1970's. Adv Atmos Sci, 18: 376–386

Wang H J. 2002. The instability of the East Asian summer monsoon–ENSO relations. Adv Atmos Sci, 19: 1–11

Wang K F, Zhang Y L, Ye Z H, Jiang H. 1978. Inferring climate change in Shanghai area for nearly 6000 years based on sporopollen analysis (in Chinese). Chin J Atmosph Sci, 2: 139–144

Wang L Y, Hu H B, Yang X Q, Ren X J. 2016. Atmospheric eddy anomalies associated with the wintertime North Pacific subtropical front strength and their influences on the seasonal-mean atmosphere. Sci China Earth Sci, 59: 2022–2036

Wang L, Chen W, Huang R. 2008. Interdecadal modulation of PDO on the impact of ENSO on the east Asian winter monsoon. Geophys Res Lett, 35: L20702

Wang S G, Wang J Y, Zhou Z J, Shang K Z, Yang D B, Zhao Z S. 2003. Regional characteristics of dust weather in China (in Chinese). Acta Geogr Sin, 58: 193–200

Wang S G, Yang D B, Jin J, Xu Q Y, Yang Y F. 1995. The causes and countermeasures of the Black Storm in northwestern China (in Chinese). J Desert Res, 15: 19–30

Wang S W, Gong D Y. 2000. The temperature of China in several characteristic periods of the Holocene (in Chinese). Prog Nat Sci, 4: 325–332

Wang S W, Luo Y, Tang G L, Zhao Z C, Huang J B, Wen X Y. 2010. Has global warming stopped in the past 10 years? (in Chinese). Clim Change Res, 6: 95–99

Wang S W, Zhao Z C, Chen Z H. 1983. The persistence and rhythm of monthly average Circulation Anomalies and Air-Sea interaction (in Chinese). Acta Meteorol Sin, 41: 33–42

Wang S W, Zhao Z C. 1979. The 36-year cycle of Drought and Flood in China and its mechanism (in Chinese). Acta Meteorol Sin, 37: 64–73

Wang S W. 1962. Years of changes in the East Asian Atmospheric Activity Center and climate vibration in China (in Chinese). Acta Meteorol Sin, 32: 19–36

Wang T, Guo D, Gao Y, Wang H, Zheng F, Zhu Y, Miao J, Hu Y. 2018. Modulation of ENSO evolution by strong tropical volcanic eruptions. Clim Dyn, 51: 2433–2453

Wang T, Wang H J, Otterå O H, Gao Y Q, Suo L L, Furevik T, Yu L. 2013. Anthropogenic agent implicated as a prime driver of shift in precipitation in eastern China in the late 1970s. Atmos Chem Phys, 13: 12433–12450

Wang Y, Cheng H, Edwards R L, He Y, Kong X, An Z, Wu J, Kelly M J, Dykoski C A, Li X. 2005. The Holocene Asian Monsoon: Links to Solar changes and North Atlantic climate. Science, 308: 854–857

Wu A, Ni Y. 1997. The influence of Tibetan Plateau on the interannual variability of Asian Monsoon. Adv Atmos Sci, 14: 491–504

Wu G X, Li Z Q, Fu C B, Zhang X Y, Zhang R Y, Zhang R H, Zhou T J, Li J P, Li J D, Zhou D G, Wu L, Zhou L T, He B, Huang R H. 2016. Advances in studying interactions between aerosols and monsoon in

China. Sci China Earth Sci, 59: 1–16
Wu G X, Guan Y, Liu Y, Yan J, Mao J. 2012a. Air-sea interaction and formation of the Asian summer monsoon onset vortex over the Bay of Bengal. Clim Dyn, 38: 261–279
Wu G X, Li W P, Guo H, Liu H, Xue J S, Wang Z Z. 1997. Qinghai-Tibetan Plateau Sensible Air Pump and Asian Summer Monsoon. Ye D Z, ed. Zhao Jiuzhang Memorial Collection (in Chinese). Beijing: Science Press. 116–126
Wu G X, Liu H Z. 1995a. Neighborhood response of precipitation to tropical Sea Surface Temperature Anomalies: I Numerical Simulation (in Chinese). Chin J Atmos Sci, 19: 422–434
Wu G X, Liu Y, Wang T, Wan R, Liu X, Li W, Wang Z, Zhang Q, Duan A, Liang X. 2007. The influence of mechanical and thermal forcing by the Tibetan Plateau on Asian climate. J Hydrometeor, 8: 770–789
Wu G X, Sun F Y, Wang J F, Wang X C. 1995b. Neighborhood response of precipitation to tropical Sea Surface Temperature Anomalies: II Data Analysis (in Chinese). Chin J Atmos Sci, 19: 663–676
Wu G X, Zhang Y. 1998. Tibetan Plateau forcing and the timing of the monsoon onset over South Asia and the South China Sea. Mon Weather Rev, 126: 913–927
Wu G X, Duan A, Liu Y, Mao J, Ren R, Bao Q, He B, Liu B, Hu W. 2015. Tibetan Plateau climate dynamics: Recent research progress and outlook. Nat Sci Rev, 2: 100–116
Wu G X, Liu Y, Dong B, Liang X, Duan A, Bao Q, Yu J. 2012c. Revisiting Asian monsoon formation and change associated with Tibetan Plateau forcing: I. formation. Clim Dyn, 39: 1169–1181
Wu G X, Liu Y, He B, Bao Q, Duan A, Jin F F. 2012b. Thermal controls on the Asian summer monsoon. Sci Rep, 2: 404
Wu T W, Song L C, Liu X W, Li Q P, Liang X Y, Chen Y J, Zhou W, Nie S P, Zhang L, Jie W H, Fang Y J, Zhang Y W, Lu Y X, Chu M, Li J H. 2013. National Climate Center short-term climate prediction model system business progress (in Chinese). J Appl Meteor Sci, 24: 34–543
Wu X D, Lin Z Y. 1978. Probing into the Climate change and its trend in modern Tibet. Chin Sci Bull, 12: 746–750
Xu S Y, Gao Y X. 1962. Monsoon phenomenon on the Tibetan Plateau (in Chinese). Acta Geogr Sin, 28: 111–123
Xu X D, Zhao T L, Shi X H, Lu C G. 2015. The modulation of the Tibetan Plateau Thermal Forcing on precipitation and Water Vapor Transport in eastern China (in Chinese). Acta Meteorol Sin, 73: 20–35
Yang D S, Wang H J. 1989. Positive Pressure Low-order Interception Mode of Monsoon Circulation (in Chinese). Acta Meteorol Sin, 47: 424–435
Yang G J, Wang X D, Wang G F, Zhou M Y. 1980. Simulation experiment of the influence of the Qinghai-Tibetan Plateau on the Flow Field around it in winter (in Chinese). Acta Meteorol Sin, 38: 16–26
Yang X Q, Huang S S. 1993. Summer Atmospheric Circulation Anomalies caused by External Forcing and its mechanism (in Chinese). Chin J Atmos Sci, 17: 697–702
Yang X Q, Xie Q, Huang S S. 1992. Numerical experiments on the effects of Atlantic SST Anomalies on the Atmospheric Circulation in East Asia during summer (in Chinese). Acta Meteorol Sin, 50: 349–354
Yang X Q, Xie Q, Huang S S. 1994. Numerical simulation of the effects of Arctic Ice Anomalies on Asian Summer Monsoons (in Chinese). Acta Oceanol Sin, 16: 34–40
Yang X Q, Xie Q, Zhu Y M, Sun X, Guo Y. 2005. The Interdecadal Variation characteristics of precipitation in North China and related anomalous types of Air-Sea (in Chinese). Chin J Geophys-Ch, 48: 789–797
Yang X Q, Zhu Y M, Xie Q, Ren X J, Xu G Y. 2004. Research progress in the Interdecadal Oscillations of the Pacific Ocean (in Chinese). Chin J Atmos Sci, 28: 979–992
Yao C S. 1982. A statistical approach to historical records of flood and drought. J Appl Meteor, 21: 588–594
Yao T, Duan K, Xu B, Wang N, Guo X, Yang X. 2008. Precipitation record since AD 1600 from ice cores on the central Tibetan Plateau. Clim Past, 4: 175–180
Yao T D, Duan K Q, Xu B Q, Wang N L, Pu J C, Kang S C, Qin X, Lonnie G T. 2002. Temperature and methane changes over the past 1000 years recorded in Dasuopu glacier (central Himalaya) ice core. Ann Glaciol, 35: 379–383
Yao T, Masson-Delmotte V, Gao J, Yu W, Yang X, Risi C, Sturm C, Werner M, Zhao H, He Y, Ren W, Tian L, Shi C, Hou S. 2013. A review of climatic controls on $\delta^{18}O$ in precipitation over the Tibetan Plateau: Observations and simulations. Rev Geophys, 51: 525–548
Yao T, Thompson L, Yang W, Yu W, Gao Y, Guo X, Yang X, Duan K, Zhao H, Xu B, Pu J, Lu A, Xiang Y, Kattel D B, Joswiak D. 2012. Different glacier status with atmospheric circulations in Tibetan Plateau and surroundings. Nat Clim Change, 2: 663–667
Yao T D, Xiang S R, Zhang X J, Wang N L, Wang Y Q. 2006. Microorganisms in the Malan ice core and their relation to climatic and environmental changes. Glob Biogeochem Cycle, 20: GB1004
Yao Y, Zhong Z, Yang X Q. 2016. Numerical experiments of the storm track sensitivity to oceanic frontal strength within the Kuroshio/Oyashio Extensions. J Geophys Res-Atmos, 121: 2888–2900
Ye D Z, Zhang J Q. 1974. Preliminary simulation experiment of the influence of the Qinghai-Tibetan Plateau heating on the East Asian atmospheric circulation in summer (in Chinese). Sci China, 3: 301–320
Ye D Z. 1952. Seasonal changes in the influence of the Tibetan Plateau on Atmospheric Circulation (in Chinese). Acta Meteorol Sin, 23: 33–47
Ye D Z. 1954. The influence of land and sea distribution on the topography and heat of Atmospheric Circulation (in Chinese). Acta Meteorol Sin, 25: 123–140
Ye D Z. 1996. Some Questions About Global Change // National Natural Science Foundation of China, Department of Earth Sciences, etc. Frontiers and Prospects of Modern Atmospheric Science (in Chinese). Beijing: China Meteorological Press. 17–22
Ye D Z, Chou J F, Liu J Y, Zhang Z X, Zhou Z J, Ju H B, Huang Q. 2000. The causes and countermeasures of Sand Dust Weather in North China (in Chinese). Acta Geogr Sin, 67: 513–521
Ye D Z, Gao Y X. 1979. Qinghai-Tibetan Plateau Meteorology (in Chinese). Beijing: China Meteorological Press. 279
Ye D Z, Luo S W, Zhu B Z. 1957. The Flow Field Structure in the Tibetan Plateau and its Vicinity and the heat balance in the Troposphere Atmosphere (in Chinese). Acta Meteorol Sin, 28: 108–121
Ye D Z, Tao S Y, Li M C. 1958. A sudden change in Atmospheric Circulation in June and October (in Chinese). Acta Meteorol Sin, 30: 249–263
Ye D Z, Xie G D.1959. The atmospheric circulation research work in China in the past ten years (in Chinese). Acta Meteorol Sin, 30: 263–276
Yeh T C. 1950. The circulation of the high troposphere over China in the winter of 1945–46. Tellus, 2: 173–183
Yeh T C. 1957. On the formation of quasi-geostrophic motion in the atmosphere. J Meteor Soc Japan, 35A: 130–134
Yin Z, Wang H. 2016. Seasonal prediction of winter haze days in the north central North China Plain. Atmos Chem Phys, 16: 14843–14852
Yin Z, Wang H. 2017. Statistical prediction of winter haze days in the North China plain using the generalized additive model. J Appl Meteorol Climatol, 56: 2411–2419
Yin Z, Wang H. 2018. The strengthening relationship between Eurasian snow cover and December haze days in central North China after the Mid-1990s. Atmos Chem Phys, 18: 4753–4763
Yu R C, Wang B, Zhou T J. 2004. Tropospheric cooling and summer monsoon weakening trend over East Asia. Geophys Res Lett, 31: L22212
Zeng Q C, Lin Z H, Zhou G Q. 2003b. Cross-quarter dynamic climate prediction system IAP DCP-II (in Chinese). Chin J Atmos Sci, 27: 289–303

Zeng Q C, Wang H J, Lin Z H, Li C, Huang R, Wu G, Zhou T. 2003a. Research on Climate Dynamics and climate prediction theory (in Chinese). Chin J Atmos Sci, 27: 468–483
Zeng Q C, Zhou G Q, Pu Y F, Chen W, Li R F, Liao H, Lin C H, Liu H Z, Wang B Z, Xie Z H, Xu Y F, Xue F, Zeng X D, Zhang F. 2008. Earth System Dynamics Model and simulation study (in Chinese). Chin J Atmos Sci, 32: 653–690
Zeng Q C. 1963a. Adaptation process and development process in the atmosphere (1)—Physical Analysis and Linear Theory (in Chinese). Acta Meteorol Sin, 33: 163–174
Zeng Q C. 1963b. Adaptation process and development process in the atmosphere (2)—Nonlinear problems (in Chinese). Acta Meteorol Sin, 33: 281–289
Zeng Q C. 1983. The evolution of a rossby-wave packet in a three-dimensional baroclinic atmosphere. J Atmos Sci, 40: 73–84
Zeng Q C. 1985. Numerical simulation in Atmospheric Science—A combination of theoretical research and practicality (in Chinese). Chin J Atmos Sci, 9: 186–194
Zeng Q, Li J. 2002. Interactions between the Northern and Southern hemispheric atmospheres and the essence of monsoon (in Chinese). Chin J Atmos Sci, 26: 433–448
Zeng Z, Piao S, Li L Z X, Zhou L, Ciais P, Wang T, Li Y, Lian X, Wood E F, Friedlingstein P, Mao J, Estes L D, Myneni R B, Peng S, Shi X, Seneviratne S I, Wang Y. 2017. Climate mitigation from vegetation biophysical feedbacks during the past three decades. Nat Clim Change, 7: 432–436
Zhang D E. 1984. A preliminary analysis of the Weather Climatology of dustfall since the historical period in China (in Chinese). Sci China Ser B, 14: 278–288
Zhang J C, Zhang X G.1979. Several kinds of vibrations of China's climate in the past five hundred years and their relationship (in Chinese). Acta Meteorol Sin, 37: 49–57
Zhang J C. 1959. Several questions about the nature of the Chinese Monsoon (in Chinese). Acta Meteorol Sin, 30: 350–361
Zhang J J, Zhou S T.1988. The latitude and longitude interaction in the "June Mutation" (in Chinese). Acta Meteorol Sin, 46: 1–8
Zhang J, Crowley T J. 1989. Historical climate records in China and reconstruction of past climates. J Clim, 2: 833–849
Zhang L, Ren G Y. 2003. Frequency evolution of sandstorms in northern China and analysis of its climate genesis (in Chinese). Acta Meteorol Sin, 61: 744–750
Zhang Q Y, Tao S Y. 1998. The effect of Asian mid-high latitude Circulation on summer precipitation in East Asia (in Chinese). Acta Meteorol Sin, 56: 199–211
Zhang Q, Wu G, Qian Y. 2002. The bimodality of the 100 hPa South Asia high and its relationship to the climate anomaly over East Asia in summer.. J Meteorol Soc Jpn, 80: 733–744
Zhang R H, Min Q Y, Su J Z. 2017. Impact of El Niño on atmospheric circulations over East Asia and rainfall in China: Role of the anomalous western North Pacific anticyclone. Sci China Earth Sci, 60: 1124–1132
Zhang R H, Wu B Y, Zhao P, Han J. 2008. The Interdecadal Transition of the summer climate in eastern China in the late 1980s and its possible causes (in Chinese). Acta Meteorol Sin, 66: 697–706
Zhang R H, Zhu J, Xu J P, Liu Y M, Li Q Q, Niu T. 2013. Assimilation of Argo ocean observation data and its application in short-term climate prediction and ocean analysis (in Chinese). Chin J Atmos Sci, 37: 411–424
Zhang R H. 1995. Coupled waves in a simple tropical Air-Sea coupled model and its instability (II) (in Chinese). Chin J Atmos Sci, 19: 563–574
Zhang R, Sumi A, Kimoto M. 1996. Impact of El Niño on the East Asian Monsoon. J Meteorol Soc Jpn, 74: 49–62
Zhang R, Sumi A, Kimoto M. 1999. A diagnostic study of the impact of El Niño on the precipitation in China. Adv Atmos Sci, 16: 229–241
Zhang R, Sumi A. 2002. Moisture circulation over East Asia during El Niño episode in Northern Winter, Spring and Autumn. J Meteorol Soc Jpn, 80: 213–227
Zhang R, Zuo Z. 2011. Impact of spring soil moisture on surface energy balance and summer monsoon circulation over East Asia and precipitation in East China. J Clim, 24: 3309–3322
Zhang W, Zhou T, Zou L, Zhang L, Chen X. 2018. Reduced exposure to extreme precipitation from 0.5°C less warming in global land monsoon regions. Nat Commun, 9: 3153
Zhang X H, Bao N, Yuan C G, Zeng Q. 1986. The sensitivity research of the Atmospheric Circulation model dynamic frame to the initial value (in Chinese). Sci China Ser B, 16: 1337–1346
Zhao P, Li Y Q, Guo X L, Xu X D, Liu Y M, Tang S H, Xiao W M, Shi C X, Ma Y M, Xu X, Liu H Z, Jia L, Chen Y, Liu Y J, Li J, Luo D B, Cao Y C, Zheng X D, Chen J M, Xiao A, Yuan F, Chen D H, Pan Y, Hu Z Q, Zhang S J, Dong L X, Hu J Y, Han S, Zhou X Y. 2018. Land-air coupled system on the Qinghai-Tibetan Plateau and its weather and climate effects: The third Qinghai-Tibetan Plateau atmospheric science experiment (in Chinese). Acta Meteorol Sin, 76: 833–860
Zhao Z G. 1995. Long-term oscillation and climate change of high *in-situ* potential height field in Qinghai-Tibet in summer (in Chinese). Acta Meteorol Sin, 53: 108–114
Zhen Q L, Yan Q M. 1994. The numerical study on the influence of the Qinghai-Tibetan Plateau on the dry weather in early summer in the northeastern plateau (in Chinese). Acta Meteorol Sin, 52: 25–32
Zhen S Z, Feng L W. 1985. Historical evidence of Climate Instability in China during the cold period (in Chinese). Sci China Ser B, 15: 1038–1044
Zhou T J, Wang B, Yu Y Q, Liu Y M, Zheng W P, Li L J, Wu B, Lin P F, Guo Z, Man W M, Bao Q, Duan A M, Liu H L, Chen X L, He B, Li J D, Zou L W, Wang X C, Zhang L X, Sun Y, Zhang W X. 2018. The FGOALS climate system model as a modeling tool for supporting climate sciences: An overview. Earth Planet Phys, 2: 276–291
Zhou T J, Zou L W, Wu B, Jin C X, Song F F, Chen X L, Zhang L X. 2014. Progress in China's Earth Climate System Model: A review of the CMIP program for nearly 20 years (in Chinese). Acta Meteorol Sin, 72: 892–907
Zhou T, Yu R, Li H, Wang B. 2008. Ocean forcing to changes in global monsoon precipitation over the recent half-century. J Clim, 21: 3833–3852
Zhou T, Yu R. 2005. Atmospheric water vapor transport associated with typical anomalous summer rainfall patterns in China. J Geophys Res-Atmos, 110: 1–10
Zhou X J, Li W L, Chen L X, Liu Y. 2004. The study on Atmospheric Ozone changes in the Qinghai-Tibetan Plateau (in Chinese). Acta Meteorol Sin, 62: 513–527
Zhou X J, Luo C, Li W L, Shi J E. 1995. Changes in total ozone in China and low-value centers in the Qinghai-Tibetan Plateau (in Chinese). Chin Sci Bull, 40: 1396–1398
Zhou X J, Xu X D, Yan P, Weng Y H, Wang J L. 2002. Dynamic characteristics of sandstorms in spring 2000 (in Chinese). Sci China Ser D-Earth Sci, 32: 327–334
Zhou Z J, Wang X W, Niu R Y. 2002. The climate characteristics of sandstorms in China in the past 47 years (in Chinese). J Appl Meteor Sci, 13: 193–200
Zhu B Z, Luo M X, Huang R H. 1981. The dynamic instability of large-scale Sea Temperature Disturbance and Formation of Sea Temperature Anomalies (in Chinese). Sci China, 11: 716–723
Zhu C, Ren R, Wu G. 2018. Varying Rossby Wave trains from the developing to decaying period of the upper atmospheric heat source over the Tibetan Plateau in boreal summer. Adv Atmos Sci, 35: 1114–1128
Zhu K Z. 1934. The Southeast Monsoon and the amount of rain in China

(in Chinese). Acta Geogr Sin, 1–27
Zhu K Z. 1962. The Fluctuation of the world's climate in the historical era (in Chinese). Acta Meteorol Sin, 31: 275–287
Zhu K Z. 1973. A preliminary study of climate change in China over the past 5000 years (in Chinese). Sci China Ser A, 2: 15–38
Zhu Q G, Hu J L. 1993. Numerical experiments on the influence of the large terrain of the Qinghai-Tibetan Plateau on the summer Atmospheric Circulation and the Asian Summer Monsoon (in Chinese). J Nanjing Inst of Meteo, 16: 120–129
Zhu Q G, Shi N, Xu J J, Shen T L. 1997. Long-term changes in the Atmospheric Activity Center in the northern hemisphere in the past 100 years and its relationship with climate change in China (in Chinese). Acta Meteorol Sin, 55: 750–758
Zhu Q G, Yang S. 1990. Numerical Simulation of the large-scale Topography on the Qinghai-Tibetan Plateau (in Chinese). Acta Meteorol Sin, 48: 164–171
Zhu Y M, Yang X Q. 2003. The relationship between the Pacific Decadal Oscillation and China's Climate Variability (in Chinese). Acta Meteorol Sin, 61: 641–654
Zhu Y X, Ding Y H, Xu H G. 2007. The Interdecadal Variation of Atmospheric Heat Source over the Tibetan Plateau and winter and spring snowfall with precipitation in eastern China (in Chinese). Acta Meteorol Sin, 65: 946–958
Zhu Y, Wang H, Ma J, Wang T. 2015. Contribution of the phase transition of Pacific Decadal Oscillation to the late 1990s' shift in East China summer rainfall. J Geophys Res, 120: 8817–8827
Zhu Y, Wang H, Zhou W, Ma J. 2011. Recent changes in the summer precipitation pattern in East China and the background circulation. Clim Dyn, 36: 1463–1473
Zhu Y, Wang T, Wang H. 2016. Relative contribution of the anthropogenic forcing and natural variability to the interdecadal shift of climate during the late 1970s and 1990s. Chin Sci Bull, 61: 416–424
Zhu Y M, Yang X Q. 2003. Joint propagating patterns of SST and SLP anomalies in the North Pacific on bidecadal and pentadecadal timescales. Adv Atmos Sci, 20: 694–710
Zou H, Huang R H. 1988. The E-P Flux Diagnostic study on the establishment and maintenance of the northern hemisphere blocking situation (in Chinese). Sci China Ser B, 18: 202–215
Zou X K, Zhai P M, Zhang Q. 2005. Variations in droughts over China: 1951–2003. Geophys Res Lett, 32: L04707

(Responsible editor: Mu MU)