Causes and Changes of Drought in China: Research Progress and Prospects

Qiang ZHANG[1,2], Yubi YAO[3*], Yaohui LI[1], Jianping HUANG[4], Zhuguo MA[5], Zhilan WANG[1], Suping WANG[1], Ying WANG[1], and Yu ZHANG[1]

1 *Lanzhou Institute of Arid Meteorology of China Meteorological Administration (CMA), and Key Laboratory of Arid Climate Change and Disaster Reduction of Gansu Province and CMA*, *Lanzhou* 730020
2 *Gansu Provincial Meteorological Service*, *Lanzhou* 730020
3 *Lanzhou Resources & Environment Voc–Tech College*, *Lanzhou* 730021
4 *College of Atmospheric Sciences*, *Lanzhou University*, *Lanzhou* 730000
5 *Institute of Atmospheric Physics*, *Chinese Academy of Sciences*, *Beijing* 100029

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ABSTRACT

Drought is one of the most serious and extensive natural hazards in the world. Subject to monsoon climate variability, China is particularly influenced by drought hazards, especially meteorological drought. Based on a comprehensive understanding of the current status of international drought research, this paper systematically reviews the history and achievements of drought research in China since the founding of the People's Republic of China, from four main perspectives: characteristics and spatiotemporal distribution of historical and recent drought events, drought formation mechanism and change trend, drought hazard risk, and the particular flash drought. The progress and problems of drought research in China are analyzed and future prospects are proposed, with emphasis on the multi-factor synergetic effect for drought formation; the effect of land–atmosphere interaction; identification, monitoring, and prediction of flash drought; categorization of drought and characteristics among various types of drought; the agricultural drought development; drought response to climate warming; and assessment of drought hazard risks. It is suggested that strengthening scientific experimental research on drought in China is imperative. The present review is conducive to strategic planning of drought research and application, and may facilitate further development of drought research in China.

Key words: drought, meteorological drought, formation mechanism, change trend, drought hazard risk, flash drought

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1. Introduction

Arid meteorology is a major branch of meteorological science and an area of great social concern. Generally speaking, arid meteorological research falls into two categories—it may refer to 1) studies on the formation and evolution of arid and semi-arid regions and the weather and climate in these regions (known as arid climate) or 2) studies on meteorological drought events (or simply droughts) in any region around the globe (Zhang et al., 2011b). Research on arid climate has been systematically reviewed in recent publications (Zhang et al., 2012a; Qian et al., 2017a, b; Guan et al., 2019; Huang et al., 2019; Yan et al., 2019). In this study, we discuss the latter, i.e., the meteorological drought events (hereinafter referred to as droughts) in China.

Meteorological hazards account for about 70% of global total natural hazards, and 50% of global meteorological hazards are drought hazards (Qin et al., 2002). The average annual economic loss caused by drought was US $17.33 billion globally for 1980–2009, and this amount increased to US $23.125 billion in 2010–2017, far more than other meteorological hazards (Wilhite, 2000; Su et al., 2018). In today's world of global warm-

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*Corresponding author: yaoyubi@163.com.

ing, the occurrence of extreme weather and climate events is increasing (Zhang et al., 2011a, 2015a, 2019b), and the drought hazards also happen more frequently and at higher intensity. Serious droughts are becoming common, and the abnormalities of drought hazards are becoming apparent, aggravating the damage caused to the economic activities and human life (IPCC, 2012).

China is one of the countries with frequent occurrences of drought and suffers seriously from the hazard. Due to global warming and the resulting accelerated water cycle, the water equilibrium maintained by plant transpiration and surface evapotranspiration is changing. This increases the risk of drought, as well as the risk and unpredictability in agricultural production. Since the 1970s, the atmospheric circulation in the troposphere and stratosphere over East Asia that affects most of China has undergone significant interdecadal shifts. The droughts and floods in China happen in such a way that northern China is vulnerable to droughts while southern China is subject to the co-occurrence of both droughts and floods. Large-scale drought hazards are seen every year. An average area of 20.9 million hm^2 of crops suffers from droughts each year, with a maximum of 40.54 million hm^2 reached in some years. The annual reduction in food production ranges from a few millions to more than 30 million tons, resulting in approximately 44 billion yuan per year of direct economic loss (Su et al., 2018). Drought poses serious threats to food and ecological security and has become one of the dominant factors restricting the sustainable development of a socioeconomic system.

Considerable research has been conducted worldwide on drought (Tannehill, 1947; Charney, 1975; Wilhite and Glantz, 1985; Wilhite, 2000; Gao and Yang, 2009; Dezfuli et al., 2010; Ummenhofer et al., 2011; Belayneh et al., 2014), and the understanding of this phenomenon has gradually moved from being qualitative and superficial to being quantitative, regarding its characteristics and formation mechanisms. Since the founding of the People's Republic of China in 1949, significant progress has been made on drought research, with a shift from scattered earlier studies on a few major drought events to more recent systematic and integrated investigations being fully geared to the drought research at the international level.

The formation and development of drought involve complex dynamic processes and water and energy cycle mechanisms across multiple scales, as well as many research fields such as meteorology, agriculture, hydrology, ecology, and socioeconomic systems (Zhang et al., 2015b). China is located, for the most part, in a region under the influences of both the East Asian tropical monsoon (South China Sea monsoon) and subtropical monsoon, the two subsystems of the East Asian Monsoon. In addition, due to the joint effects of the westerly circulation, the Tibetan Plateau (TP) topography, the sensitivity of the diverse ecosystem, and the influence of high-intensity human activities, drought hazards in China are highly regional and complex in nature. General scientific knowledge on droughts among the international community cannot fully explain the behavioral characteristics of droughts in China. Numerous new scientific questions have been raised in the course of drought hazard research (Qian et al., 2001; Ding et al., 2003, 2014a, b, 2015; Huang et al., 2003a, 2005; Ding and Li, 2016).

Up to the present, many papers studying droughts have been published, but the study results are fragmentary. Different and even contradictory viewpoints exist, leading to a general lack of authority, as well as the absence of integrated scientific understanding and comprehensive, systematic theory and concepts in this research area. This paper attempts to review and summarize the key achievements of and progress in drought research in China during the past 70 years. The major stages of drought research are summarized and defined. The important achievements of drought research in China are systematically retrospected. Problems and challenges still facing drought research in China are analyzed on this basis, and solutions and possible breakthroughs in the future are mentioned. This paper aims to offer a comprehensive review of the results of drought research in China and a systematic analysis of the challenges present, building a theoretical groundwork for the planning of future drought research in China. It intends to provide scientific and technological support for coping with and defending against drought hazards, promoting breakthroughs and progress in drought research.

2. Drought research in China and the key scientific results

Researchers in China have studied droughts for a long time, but systematic investigation and analysis into this topic really began after the founding of the People's Republic of China. Since then, the research on drought events in China can be roughly divided into four major topics/perspectives, as delineated in the following four subsections.

2.1 *Characteristics and spatiotemporal distribution of drought events*

In the 1930s, prolonged droughts occurred in the United States, causing severe hazards in five states of the central and northern Great Plains, and about 2.5 million people left their home. This event made drought hazard the center of global attention. In 1955, the United States held the International Arid Lands Meeting in New Mexico, during which it was made clear that global drought research should focus on drought hazards (Dregne, 1970; Hodge and Duisberg, 1963). Frequent natural hazards occurred in the newly found People's Republic of China in the 1950s and 1960s. To secure agricultural production and maintain the harvest during droughts and floods for high and stable crop yield, drought hazard research was carried out (Yang and Xu, 1956; Xiao et al., 1964). Limited by the availability of measured precipitation data, these initial investigations were based largely on historical records, experience of the general public, and a small number of precipitation records. Starting with the signs and characteristics of drought events, the features and damage of drought hazards were analyzed. As the observation networks and detection methods continued to improve, knowledge was built on the temporal and spatial distribution of droughts. Based on historical records and up-to-date observations, the research on drought events in China achieved the following facts and results.

(1) Regional drought events occur at high annual frequency and have a serious impact. Large-scale droughts, though not happening at high annual frequency, are severe in adversity. The worst drought in China happened during the reign of Emperor Chongzhen of the Ming Dynasty. Beginning with the drought in northern Shaanxi in the first year of the Emperor's reign (1628), the hazard expanded to Shaanxi, Shanxi, Hebei, Henan, Shandong, and Jiangsu provinces in the next 10 years. At the center of the affected region, land remained arid for 17 yr. Vast areas became barren, hardly supporting the life of the local people. This eventually led to the peasant revolt that ended the dynasty. In the 20th century, large-scale droughts occurred in 1900, 1928–1929, 1934, 1956–1961, and 1972, at an annual frequency of 11% (Ren and Luo, 1989). In the 654 years that spanned the Yuan, Ming, and Qing Dynasties, summer drought was the most common in Henan Province, followed by spring drought, and winter drought was the least frequent. Most of the interseasonal persistent droughts happened in summer–autumn and spring–summer (Xiao et al., 1964). In Hebei Province during the period 1368–1900, 379 yr saw the occurrence of drought, with summer drought being the most frequent, followed by spring drought. The years 1640, 1641, 1832, and 1877 were the times of the most serious drought events in Hebei Province in the Ming and Qing Dynasties. The hazards affected large areas of land and lasted a long time (Tang and Bo, 1962). During 1951–1980, northern Ningxia ranked the highest in terms of the occurrence of spring drought in the Loess Plateau region (75%), followed by Longzhong (57%) and Jinzhong (56%), with Guanzhong being the least (30%); while the frequency of drought in most of the other areas of the region was 37%–52%. Summer drought in most parts of the Loess Plateau became grave in 1960–1980, with higher frequency and significantly increased percentage of severe droughts. The summer drought became more severe. The Yellow River basin, however, experienced spring drought (Yang and Xu, 1956; Ren and Luo, 1989). Generally, the annual frequency of regional drought events in China is higher than 50%, and the annual frequency of spring drought on the Loess Plateau is 75%. Summer drought is the most prevalent type in North China and the central plain area. The annual frequency of large-scale drought events in China is 11%, which is not very high. Nevertheless, the harm they pose is very serious, demanding close attention.

(2) The northern region is a drought-prone area, but the frequency of drought in the southern region has also increased significantly in recent years. Clear regional differences exist in the spatial distribution of drought in China. The average number of arid days in the western part of Northeast China, North China, the Huanghuai Region, the eastern part of Northwest China, central and eastern parts of Inner Mongolia, and Southwest China generally exceeds 40 days per year. The number of arid days in the central and southern parts of North China, the northeastern part of Huanghuai Region, the eastern part of Northwest China, and the western part of Jilin Province exceeds 60 days per year (Wang et al., 2011; Qian and Zhang, 2012; Liao and Zhang, 2017; Han et al., 2019). The number of seasonal drought events in southern China has increased significantly in the 21st century (Huang et al., 2010; Sun and Yang, 2012; Chen and Sun, 2015). The frequency of drought in South China has increased substantially, especially in Southwest China, the southern part of Sichuan Province, Yunnan Province, and the western part of Guizhou Province (Han et al., 2014, 2019), where the frequency of drought reached 50 events per year during 2011–2014, and major drought events have become common (Huang et al., 2012; Qian and Zhang, 2012). In 2006, Chongqing experienced a severe drought with a return period of 100 yr, and Sichuan suffered the most serious summer drought since 1951. In 2009, the most serious drought persisting through autumn, winter, and spring ever recorded in meteorology was seen in Southwest China, where Yunnan Province

experienced five consecutive years of drought during 2009–2012. In 2002, there was a rare drought that lasted for two successive seasons (winter and spring) in Guangdong Province; in 2004, the entire South China suffered the most serious autumn–winter drought since 1951; and in 2007, a catastrophic drought with a recurrence interval of 50 yr affected almost the entire southern China, such as the regions south of the Yangtze River, South China, and Southwest China.

(3) Persistent drought is more frequently seen in the North than in the South. Drought that lasts for more than three months mostly happens in the semi-arid and semi-humid regions of the North and the Southwest. The formation and development of drought is a process of slowly increasing surface water deficit. A drought event that lasts longer will lead to more serious damage. Persistent drought events are more frequently seen in North China than in South China. The semi-arid and semi-humid regions in North China often experience drought processes that last more than 3 months, with a probability higher than 51.7% for most parts of these regions. This number exceeds 77.6% for the mountainous areas of Yanshan, Taihang, Qinling, Wushan, and Hengduan Mountains. Droughts that last for more than 6 months usually occur in the Northwest and the semi-humid regions in the eastern part of the Northeast, at a probability of > 17.2% (> 31% for some locations). Droughts that last for more than 12 months occur mainly in most parts of the Northwest and some areas of the North, Northeast, and Huanghuai Region, at a probability of less than 15% (Yu M. X. et al., 2014; Li and Ma, 2015; Wang and Yuan, 2018). In addition, regional differences have been noticed in the start and end time of persistent droughts in China. In Southwest and South China, more persistent droughts have their onset in autumn and winter, and the majority of these events end in spring, i.e. (Li Y. J. et al., 2014; Li Y. P. et al., 2014), they occur mostly during autumn–winter and winter–spring. For most areas of the central and western parts of Northwest China, persistent droughts start mainly in autumn as opposed to other seasons and tend to end in winter and spring as compared to summer and autumn. Droughts occur more frequently in autumn and winter and least frequently in summer. Persistent droughts in Northeast China are least common in autumn. Their occurrences are uniform across other seasons (Li Y. P. et al., 2014).

(4) There is an overall increase in the area affected by drought and the affected and disaster areas of crops. Since the 1950s, drought in China has been aggravating, and the affected and disaster areas of crops have been increasing (Fig. 1). North China, Northeast China, the eastern part of Northwest China, Southwest China, and South China have become significantly more arid (Fig. 2). More severe droughts are experienced and at a higher frequency (Ma and Ren, 2007; Zou and Zhang, 2008; Chen and Sun, 2015; Li and Ma, 2015; Li et al., 2015; Huang et al., 2016, 2018). The area affected by drought has increased substantially, especially in the 21st century, where major drought events have significantly increased (Wang et al., 2011; Han et al., 2019), and the area of

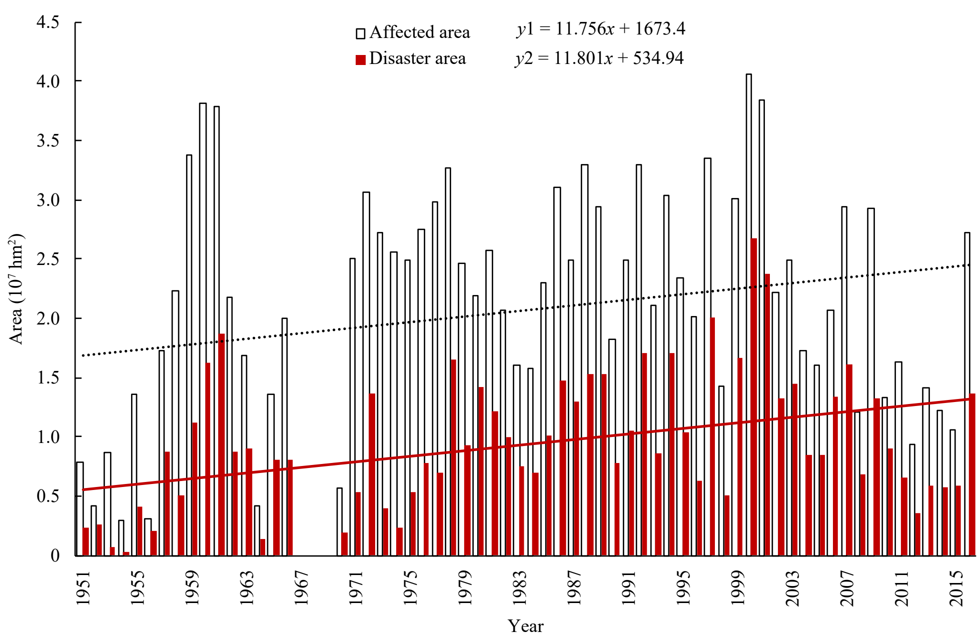

Fig. 1. Variations in the drought-affected areas and drought-damaged (i.e., disaster) areas in China from 1951 to 2016.

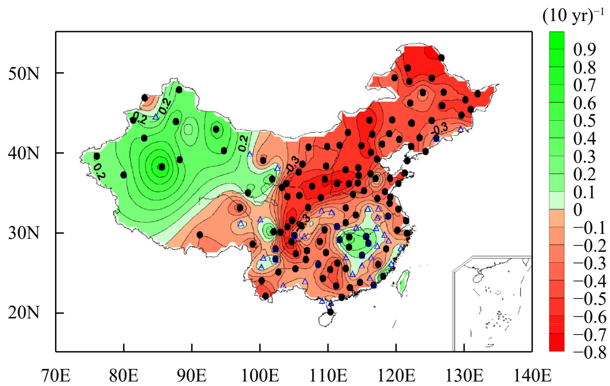

Fig. 2. Distribution of the linear trend of the self-calibrating PDSI (Palmer Drought Severity Index) over China during 1951–2016. The black dots indicate the 95% confidence level. The blue triangles indicate stations with insignificant trends. The red color indicates drought trend while the green color indicates wetness trend (Ma et al., 2018).

severe to extreme drought increases by 3.72% every 10 yr (Yu M. X. et al., 2014).

2.2 *Formation and variation trend of drought events*

Drought could be the result of factors such as climate fluctuation, climate anomaly, climate change, external forcing, and change in water supply and demand, as well as the synergic effects of the above. The onset and development of drought often occur at different temporal and spatial scales. Even under the same circulation anomaly, drought often breaks out in ecologically more fragile areas and then spreads to the surrounding region. The many temporal and spatial scales of drought and the coupling among them further obscure the formation mechanism of drought. The cause of drought events is far less understood than the cause of arid climate, and many conclusions are rather qualitative or even vague (Wang and Zhao, 1979). For this reason, researchers in China have been carrying out in-depth research on the formation and variation of drought in China since the 1980s. Since then, the research on drought events in China has yielded the following scientific results.

(1) Anomalies in atmospheric circulation lead to changes in the spatiotemporal distribution of precipitation. Some regions experience decreased precipitation and drought. Most climate hazards in China are caused by changes in the climate system over East Asia (Ye and Huang, 1996), and drought is no exception. Members of this climate system are: 1) East Asian monsoon (including winter and summer monsoons), western Pacific subtropical high (WPSH), and midlatitude disturbances in the atmosphere; 2) El Niño–Southern Oscillation (ENSO) over the tropical Pacific, and thermodynamics of the tropical West Pacific warm pool and Indian Ocean in the oceanic circle; and 3) for land and in the lithosphere, the dynamic and thermodynamic processes of Qinghai–Tibetan Plateau (QTP), the Arctic sea ice, the snow accumulation over Eurasia, and the land surface processes (in particular, those in arid and semi-arid regions) (Huang et al., 2003b; Zhang et al., 2003a). In years of weak East Asian summer monsoon, the WPSH sits more toward the south. North China receives less summer rainfall and experiences drought as a direct result (Zhang et al., 2003a, b). During years of summer drought in North China, the mid- and high-latitudes are dominated by zonal circulation. The circulation over North China is characterized by high pressure in the west and low pressure in the east. This region is under the influence of anomalous northerly winds and prevailing subsidence of air brought about by the geopotential height ridge over Lake Baikal. Moreover, the ridge axis of the WPSH is located toward the south, and its western end lies slightly to the east. These circulation patterns are not favorable for summer precipitation over North China, and drought events are prone to occur (Shen et al., 2012; Shao et al., 2014). The circulation field during drought in Northwest China is characterized by an intense ridge in the 500-hPa geopotential height field over the midlatitude Xinjiang Region (40°N), a deep East Asian trough, and strong northerly winds over East Asia. In the geopotential height field, Xinjiang shows up as a positive anomaly, and the Sea of Japan a negative anomaly, forming a field with a positive anomaly in the west and negative anomaly in the east. In the summer of arid years in the eastern part of Northwest China, a western-type South Asian high and the eastward advance of Xinjiang ridge or Iran high to the TP often prevail. In the summer of arid years in the western part of Northwest China, a hybrid circulation pattern formed by the western-type South Asian high and the eastward advance of central Asian ridge and Xinjiang ridge or Iran high is common (Qian et al., 2001). When the ridge axis of the WPSH is located to the south, the rainbelt eight to nine degrees north of the ridge axis is also located to the south and appears at a location south of the eastern part of Northwest China. As the rainbelt is unable to move northward and affect the eastern part of Northwest China during summer, drought occurs in this region. A ridge axis that is located further south causes more severe drought (Qian et al., 2001; Cai et al., 2015; Zhang et al., 2019a). When there is a positive anomaly in the Northwest and a negative anomaly in the coastal area of East Asia, a dipole-type thermal forcing anomaly forms, which can lead to summer drought in the east of Northwest China.

In reality, Southwest China has become one of the regions with high drought frequency in China since the 21st century. This unusual phenomenon has concerned many researchers. The two major droughts of 2006/2007 and 2009/2010 and the persistent drought spanning autumn, winter, and spring of 2012/2013 have far-reaching impacts and result in serious economic losses. The circulation features shared by these events include a weakened southern branch trough, with less water vapor transport from the Bay of Bengal. The polar vortex also appears weakened, and brings about abnormal wave activities that lead to negative Arctic Oscillation (AO) and a subsequent eastward deflection in the cold air path (Huang et al., 2012; Hu et al., 2014, 2015). By exciting the ANH teleconnection (AMO–Northern Hemisphere teleconnection, a global-scale baroclinic teleconnection pattern), the Atlantic Multi-decadal Oscillation (AMO) affects the precipitation over East Asia and the interdecadal variability in the precipitation over entire Northern Hemisphere, from the Atlantic Ocean and Eurasia to North America. In East Asia, the circulation anomaly triggered by ANH teleconnection brings about anomalous cyclonic circulation at the low level of the atmosphere for regions to the north of the Yangtze River, as well as anomalous anticyclonic circulation over the Yangtze River basin. These atmospheric circulation anomalies result in higher precipitation over the Huaihe River basin and less precipitation over the Yangtze River basin. The positive phase of the AMO always causes drought in the regions south of the Yangtze River (Ding et al., 2018).

(2) Changes in land surface factors, such as vegetation degradation, increase in snow accumulation, or land use change, lead to increases in surface albedo and augmented atmospheric subsidence, inhibiting precipitation and causing drought. The degradation of vegetation (land covered by plants now becoming bare) in Northwest China reduces the radiation absorbed by the land surface, resulting in a weak surface thermal effect, which causes the anomalous anticyclonic circulation in the mid troposphere for most of the arid regions in Northwest China, leading to decreased precipitation in many areas there (Li and Xue, 2010, 2014). The vegetation degradation in the arid regions of Northwest China also causes anomalous anticyclonic circulation in the upper troposphere over the northeastern part of the TP and anomalous cyclonic circulation in the mid troposphere there, leading to abnormal vertical upward flow of the atmosphere. The changes in these circulations lead to an increase in precipitation in the northeastern part of the QTP (Huang et al., 2012). Snow accumulation stimulates atmospheric teleconnection and influences soil moisture, temperature distribution, and radiation. It thus affects the precipitation by atmospheric circulation and the East Asian summer monsoon during this and later periods and also the occurrence and development of drought and flood in China (Zhang R. H. et al., 2016). Numerical simulation reveals that with higher snow accumulation during winter and spring in the southern part of the QTP, more precipitation is experienced during summer over the Yangtze River and the regions to its north, with less during summer for most of South China. However, when higher snow accumulation is present during winter and spring in the northern part of the plateau, more precipitation falls during summer in North and Northeast China, but less falls during summer in the regions to the south of the lower Yangtze River, i.e., the rainbelt moves northward (Wang C. H. et al., 2017). Lower (higher) surface sensible heat in Eurasia and stronger (weaker) action of the thermal sink, together with summer blocking and the stronger (weaker) Mongolian cyclone, make the penetration of warm and humid air into the North easier (more difficult), which attenuates (aggravates) the drought there (Jin et al., 2015).

(3) The dynamic and thermodynamic processes of the QTP affect the drought events in East Asia. First, the QTP influences China's drought events through factors such as topographic barrier effect, lateral boundary dynamics, and descending zones. The QTP hinders the northward movement of the southwesterly monsoon in South Asia, and the abnormal changes of its dynamic uplift directly affect the formation of droughts in the downstream areas of the plateau. To be specific, in the summer of dry years, in the troposphere on the northern side of the plateau, the meridional circulation is stronger than normal years and the descending motion in the upper layer is also stronger than normal years. In addition, the surface sensible heat anomaly in the QTP in winter and spring also affects the formation of drought in China.

Second, the dynamic and thermal processes of large terrain affect the formation of regional-scale circulation and drought. The uplift of the QTP is one of the major events in the evolution of the Cenozoic solid earth and is considered an important driving force for the evolution of the earth's climate and environment, not only changing the landform and natural environment of the QTP, but also having a profound impact on the Asian monsoon, the Asian inland drought, and the Cenozoic global climate change (Ye and Gao, 1979; Xu and Zhang, 1983). The thermal uplift of the QTP affects most of Asia, and the heating of the plateau in summer intensifies drought events in central Asia, Northwest China, and North China by inducing abnormal atmospheric circulation (Wu and Zhang, 1998; Wu et al., 2007, 2012; Liu et al., 2007; Wang T. M. et al., 2008). When the surface sensible heat in the QTP is abnormally strong in winter and spring, it causes the height field in the upper and mid troposphere in the later period to be abnormally high, and the response to this anomaly is transmitted from the lower layer to the upper layer over time, causing the WPSH to be strong and westward-inclined in summer and the South Asia high to be strong, which makes summer in South China abnormally dry; whereas when the surface sensible heat in the QTP is abnormally weak in winter and spring, the summer in North China is abnormally dry (Wang L. et al., 2008; Wang C. H. et al., 2017; Wang and Li, 2019).

Third, the westerly wind prevails in the boundary layer on the northern side of the QTP, forming an east–west negative vorticity zone. As a result, in Ningxia and the central part of Gansu Province in the east of southern Xinjiang Region and the northeast of the plateau, the negative vorticity is increased and the descending motion is strengthened due to the circulation and divergence of the airflow over the mountains, which aggravate the drought events in the region.

Fourth, in the summer mean vertical motion field of the plateau and its adjacent areas, strong ascending motion prevails on the plateau in the summer half year (April–September), while descending motion is distributed around the western, northern, and northeastern sides of the plateau, forming a descending zone. The three descending centers generally correspond to the three arid and semi-arid areas of central Asia, Northwest China, and North China, respectively; and the abnormal changes in the descending motion of this descending motion zone are significantly correlated with the degree of drought events in the three regions.

Fifth, in summer, the plateau is a heat source, forming a warm high ridge in the 500-hPa geopotential height field, while the western Pacific coastal area is relatively cold, making it a heat sink area. Meanwhile, a cold trough area appears in the midlatitude coastal area of East Asia. In the 500-hPa height anomaly field, the northwestern area shows a positive anomaly, and the East Asian coastal area shows a negative anomaly, which results in the strengthening of the northerly airflow over the east of the northwestern area. This dipole-type forcing consists of a regional heat sink and a regional heat source. The location of the heat sink corresponds to the coastal area of the West Pacific Ocean, and the location of the heat source corresponds to the plateau area. Such an upper-level air pressure pattern, namely, high in the east and low in the west, can lead to drought events in Northwest China (Luo, 2005).

(4) Anomalies in the sea surface temperature (SST) and oceanic circulation are an important factor for the formation of drought events. Oceanic conditions, especially the SSTs of the Pacific Ocean, Atlantic Ocean, and Indian Ocean, have an important impact on global precipitation (Ting and Wang, 1997; Seager et al., 2005; Mo et al., 2009; Dai, 2013). The SST anomaly exerted a great influence on the large-scale droughts in southern Europe, southwestern Africa, and the United States in 1998–2002 (Hoerling and Kumar, 2003). The meteorological drought in southwestern Iran is related to Southern Oscillation Index (SOI) and North Atlantic Oscillation (NAO). Specifically, the autumn precipitation shows a clear negative correlation with the SOI of June–August; a correlation coefficient higher than 0.5 is observed between spring droughts and the NAO of October–December, but winter droughts do not appear to be lag-correlated with either SOI or NAO (Dezfuli et al., 2010). Drought in southeastern Australia happens under the joint influence of the Indian Ocean Dipole (IOD) and ENSO (Ummenhofer et al., 2011). There is a significant lag-correlation between the global SST in winter and the summer drought in Europe (Findell and Delworth, 2010; Ionita et al., 2012). Under global warming, the interdecadal variability of North Pacific is weakened, the frequency of Pacific Decadal Oscillation (PDO) increases, and the amplitude weakening in the interdecadal variability of SST for Kuroshio Extension and the western subpolar oceans is the most significant. The lowered interdecadal variability over the North Pacific leads to a weakened East Asian summer monsoon, which directly results in reduced summer precipitation in North China. ENSO is the main mode of tropical air–sea interaction. In the winter of an El Niño year, the East Asian winter monsoon is weak, and the WPSH is stronger and located to the north; more water vapor is transported, which facilitates precipitation by the East Asian monsoon. In the year of La Niña, less water vapor is transported, which does not favor precipitation in North China (Tao and Zhang, 1998; Gong and Wang, 2003; Ju et al., 2004; Chen and Kang, 2006; Lin et al., 2018). ENSO events are the major players in the promotion and intensification of drought in North China (Yang et al., 2005; Gao and Yang, 2009; Shao et al., 2014). For example, the persistent drought in autumn and winter of 2010 in North China was an extreme drought event that was overlapped with the climate trend of precipitation reduction. It occurred as a result of the combined influence of a strong AO negat-

ive phase and a La Niña happening in this period (Shen et al., 2012). Different stages of an ENSO event affect the summer droughts in North China, the Yangtze–Huaihe River valley, and the Yellow River basin differently (Huang, 2006; Huang et al., 2012). In May, the North Pacific Oscillation (NPO) has a strong positive correlation with the summer droughts and floods in North China. In a year when anomalies in the positive (negative) phase of NPO index are observed, and the Palmer Drought Severity Index (PDSI) is larger (smaller) than usual, more summer floods (more summer droughts) are experienced in North China. The NAO correlates well with the first mode of summer precipitation in Northwest China, while the NPO correlates well with the second mode (Zheng et al., 2014).

In addition, as an important source of water vapor, the ocean can affect the occurrence of drought events in East Asia by changing the strength, path, source, and confluence of water vapor transport in climate systems such as the monsoons in East Asia (East Asian monsoon and South Asian monsoon) and the westerlies (Huang, 2006; Zhang H. L. et al., 2016; Xing and Wang, 2017). The weakening of the East Asian summer monsoon causes the convergence of water vapor carried by the monsoonal flows in the Yangtze River basin and the decrease of water vapor transported to North China, resulting in a decrease in summer precipitation and the occurrence of drought in North China (Zhu et al., 2012; Zuo et al., 2012; Ding et al., 2014b). The South Asian monsoon affects the dry and wet conditions of central Asia and East Asia in summer by affecting the water vapor transport in the Bay of Bengal (Zhang, 2001; Zhao et al., 2014). Since the 1980s, the enhancement of the South Asian monsoon and the weakening of the westerly circulation have caused more water vapor to be transported from the Indian Ocean to central Asia via the Bay of Bengal and the Arabian Sea, which is one of the important causes for the increase in precipitation in the arid regions of central Asia in recent years (Staubwasser and Weiss, 2006; Liu Y. Z. et al., 2018). The dry and wet summer in the northwestern arid region of China is closely related to the water vapor transport along the southeastern coast. Water vapor from the Bay of Bengal and the South China Sea is transported to the northwestern inland arid area by a number of weather systems such as the typhoon westward, the WPSH extending to the west, and the Qaidam low, as well as three air streams including the southeasterly jet stream on the southwestern side of the WPSH, the low-level southerly jet stream on the western side of the WPSH, and the easterly wind over the Hexi Corridor, which affect the formation of drought in this area (Cai et al., 2015).

(5) Human activities alter land surface and thus change the energy, momentum, and water exchanges between the atmosphere and land surface, which significantly impacts drought at the regional scale (Findell et al., 2007; Van Loon et al., 2016; Huang et al., 2017a, b). Human activities have and will continue to alter the land surface. Over-exploitation of land, over-grazing, and excessive groundwater development result in deterioration of the land and damage of the ecological environment. Especially in semi-arid areas, the degraded land forms a feedback mechanism with regional drought, affecting the occurrence of the latter (Charney, 1975; Taylor et al., 2002; Olson et al., 2008; Sherwood and Fu, 2014; Huang et al., 2017c). A similar positive feedback is seen in the arid/semi-arid regions of East Africa. The positive feedback mechanism by land–air interaction, the relationship of dust storms in the United States during the 1930s, and the major drought in North Africa with human activities have been verified by climate simulation (Charney, 1975). In addition, human activities increase the amount of dust particles and aerosols, leading to excessive catalytic action on clouds. The concentration of aerosols (particles in the atmosphere) increases. These particles have a direct effect on the radiation balance and sensible and latent heat fluxes of the earth's surface by scattering or absorbing solar radiation, as well as an indirect effect on the heat and water vapor in the atmosphere and the hydrological and ecological processes of the land surface by changing the microphysical properties and precipitation efficiency of clouds. In the formation of drought hazard, an increase in atmospheric particles inhibits precipitation and accelerates the development of drought, thus aggravating drought intensity (Fu and Feng, 2014; Lin et al., 2015; Zhao et al., 2015; Huang et al., 2016).

(6) Comprehensive scientific research and observation experiments have been carried out on drought meteorology. In order to improve the hazard prevention and mitigation capacity of drought-prone areas in northern China, a major project called DroughtEX_China was launched in 2015. This project is led by the China Meteorological Administration. Interdisciplinary, comprehensive, and systematic drought meteorological research, and comprehensive observation tests (Fig. 3) were carried out through routine, high-density, and special observations as well as field simulation tests in the arid and semi-arid areas of northern China. Significant progress has been made in improving the knowledge on the formation and development process of drought hazards, the mechanism of multi-scale air–soil–vegetation moisture and energy cycle interactions, the relationships among

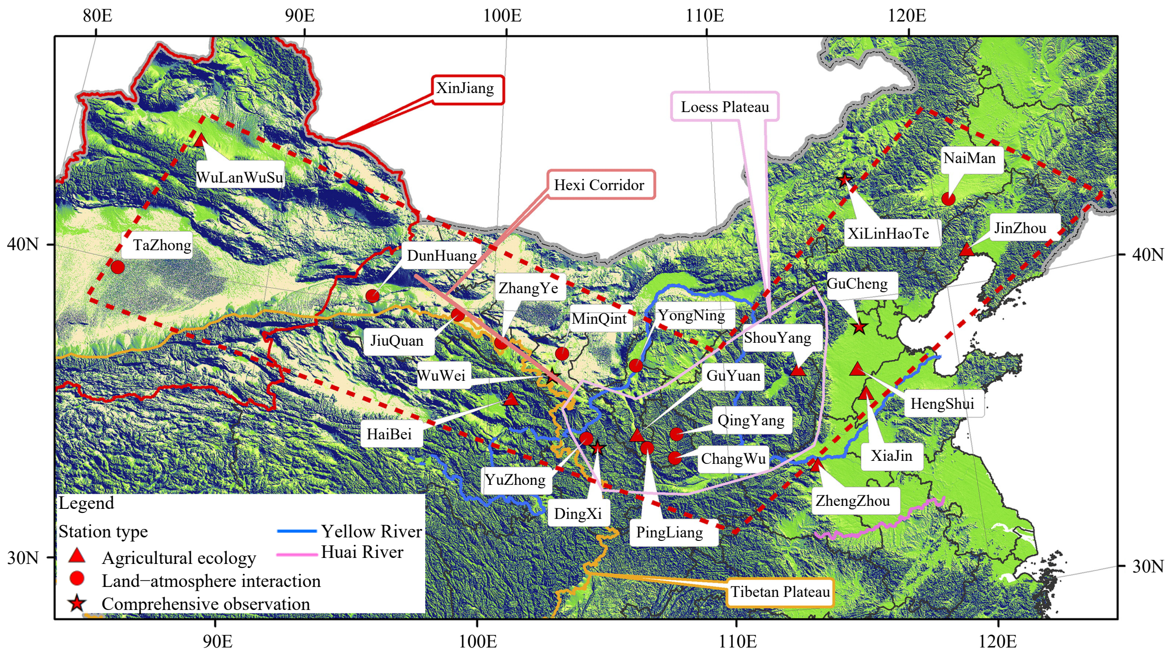

Fig. 3. Station network layout of the field observational experiment DroughtEX China 2015 for drought meteorological scientific research (from Li et al., 2019).

meteorology, agriculture, hydrology, and droughts, as well as the technologies concerning drought mitigation such as accurate monitoring, risk assessment, and early warning (Li et al., 2017, 2019).

2.3 *Drought related risks*

In the early 1980s, the international community began to explore the risks associated with natural hazards. Scientists studying catastrophes discussed the factors that lead to natural hazards and the interaction among them, based on system theory and risk management knowledge (Burton et al., 1993; Blaikie et al., 1994). The research on drought hazard risk in China started in the early 21st century and revolves around the mechanism, assessment, and features of drought hazard risk in China. Since then, the following scientific achievements have been made.

A new concept on the formation mechanism of drought hazard risk is proposed. The theories on the formation of drought hazard risk include primarily the “two-factor theory,” “three-factor theory,” and “four-factor theory” (Zhang et al., 2013). The Intergovernmental Panel on Climate Change (IPCC) takes hazard risk as a function of hazard-inducing factors, exposure, and vulnerability (IPCC, 2014). Zhang Q. et al. (2017a) introduced the influence of climate change and human activities based on the mechanism of formation of hazards. Considering the sensitivity of the environment, a novel drought hazard formation conceptual model was proposed (Fig. 4). This new model could comprehensively and objectively describe the formation mechanism of drought hazard risk, reflecting its variability and dynamic process. The characteristics of drought hazard risk generated by this model are more scientific and close to the nature of drought hazard risk.

Drought risk assessment in terms of risk factors and probability analysis of hazard loss and the risk mechanism is carried out. The method for assessing drought hazard risk forms the basis of risk assessment. Three methods are most commonly used at present: assessment based on risk factors, assessment based on the probability analysis of hazard loss, and assessment based on risk mechanism (Yin, 2012). The first method is a risk assessment system centered around factors influencing the risk. It focuses on the selection, optimization, and weighing factor calculation for hazard risk indices. It is comprehensive and flexible, but only applies to qualitative analysis and is strongly subjective (Huang et al., 2014; Murthy et al., 2015; Wang et al., 2015; Zhang et al., 2015b; Thomas et al., 2016). In the second method, drought risk models are constructed based on the probability analysis of hazard loss, and assessment is performed with these models. Statistics are used to analyze the actual data from past drought events and identify the pattern in the development and evolution of drought, thus predicting and evaluating the risk of future drought events (Zhang and Wang, 2011; Belayneh et al., 2014; Wang W. X. et al., 2014; Wang Y. et al., 2017). The third method, i.e., the physical model-based risk assess-

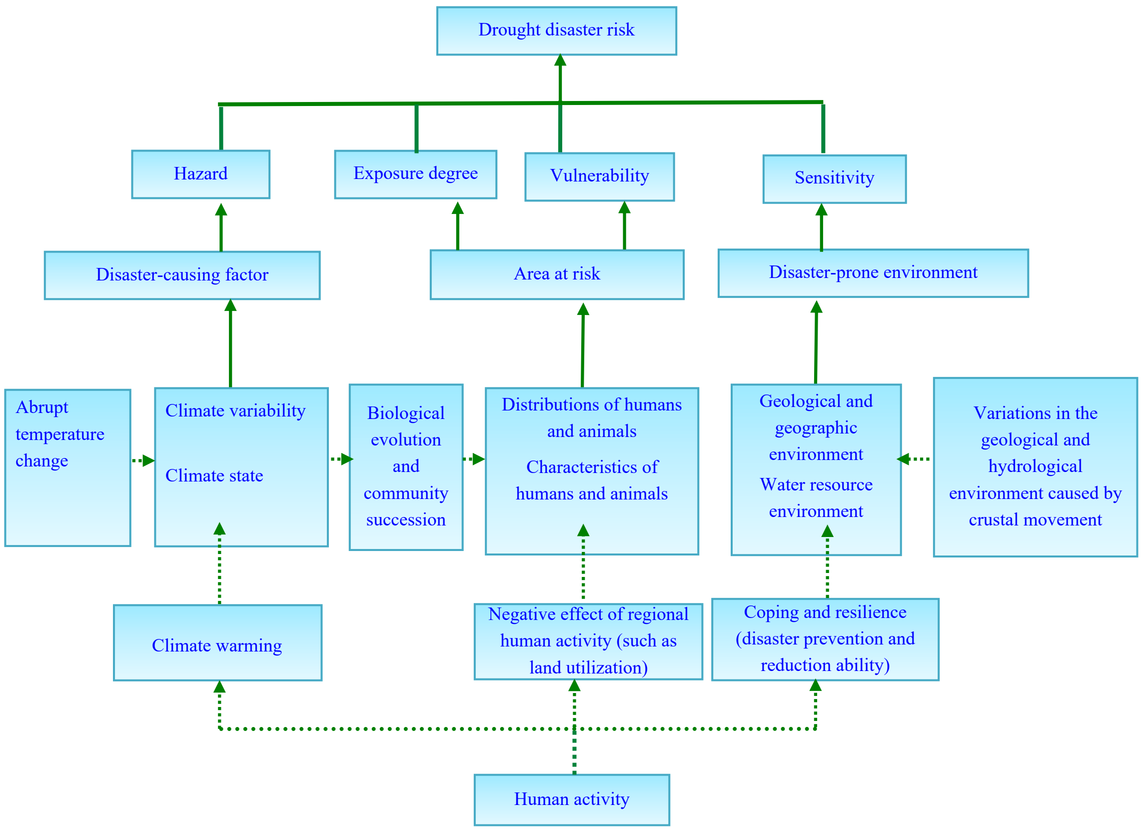

Fig. 4. A conceptual model for the formation mechanism of drought disaster risks (Zhang et al., 2017a).

ment attempts to simulate and model the natural hazard process and conduct analysis and assessment on this basis. This falls into the category of hazard prediction and simulation, which is the simulation and modeling of the hazard-forming process caused by the hazard-inducing factors by means of computing platforms such as a distributed hydrological model and crop growth model. Adverse consequences of each scenario are quantitatively and systematically analyzed to yield the hazard risk of the hazard-affected body under various meteorological hazards. This method is able to describe in detail the feedback mechanism among the factors of a hazard system, but suffers from the difficulty in setting up boundary conditions for simulation and modeling, as many parameters needed are not readily available. Thus, it is generally better suited for the refined analysis and assessment of hazard risk in small or key regions (Wang et al., 2012; Yu C. Q. et al., 2014; Yue et al., 2015).

The risk of drought hazard is mainly high in the north and low in the south in China (Fei et al., 2014), and it is significantly intensified with climate warming. Zhang et al. (2017a) studied the drought hazard risk in southern China and found that high-risk severe drought areas are mainly concentrated in Southwest China. Affected by climate change, the formation and development process of drought hazard become more complex (Neelin et al., 2006; Lu et al., 2007; Kam and Sheffield, 2016). The fluctuation range of global agricultural yield and the uncertainty in food supply will increase. Previous observation and simulation results show that climate change has had a negative impact on the yield of major food crops in many regions, with a small positive impact generally seen in high-latitude regions (Wheeler and Von Braun, 2013; Myers et al., 2017; Liu L. T. et al., 2018; Yao et al., 2018). As a result, some new features have emerged in the formation of drought hazard and in drought hazard itself (Zhang et al., 2014; Qin, 2015; Cheng et al., 2016). With climate warming, the risk, frequency, intensity, and area of drought hazard have increased; and areas with high drought risk have expanded significantly (Zhang et al., 2017a). Further, the area with high drought hazard risk has expanded to the central part of North China, the western part of Northeast China, and the eastern part of Inner Mongolia, but contracted in the western part of Northwest China (Liao and Zhang, 2017). Su et al. (2018) found that under the sustainable development approach of global warming by 1.5°C, China's drought loss would be 10 times higher than that in 1986–2005 and 3 times higher than that in 2006–2015, and the drought risk would increase significantly (Fig. 5). The drought risk for wheat increases substantially in China under the RCP8.5 scenario. A higher risk of drought is seen in Gansu Province as a result of global warming (Wang Y. et al., 2017; Yue et al., 2018).

2.4 *Flash drought*

Flash drought is a short-term drought event that develops rapidly in association with a high-temperature heat wave. It occurs suddenly with fast development and high intensity, posing a serious threat to crop yield and water supply. This type of events has attracted much attention in the study of climate change. Currently, there is no widespread consensus on the definition of flash drought. Some have suggested that flash drought should be defined as a drought event where soil moisture in the plough layer turns abnormally low within half a month due to precipitation shortage, high-temperature heat waves, or human activities (Mo and Lettenmaier, 2015; Sun et al., 2015; Otkin et al., 2018). Compared with traditional drought that develops slowly, flash drought occurs quickly, which has a serious impact on the economy and has higher requirements in terms of its monitoring and prediction. At the known scales, flash drought only occurs in the case of meteorological drought, but does not necessarily occur in the cases of other types of drought. The research on flash drought started after 2010 in China. Since then, the following scientific results have been obtained.

Two major types of flash drought are found in China. Type I flash drought is largely driven by high temperature and is accompanied by increased evapotranspiration and a decrease in soil moisture. Type II flash drought is primarily caused by a high level of water deficit, which leads to rapid drying of soil and weakened evapotranspiration (Mo and Lettenmaier, 2015; Wang et al., 2016; Wang P. Y. et al., 2017). Type I flash droughts mostly occur in humid and semi-humid regions of China (Fig. 6a). South China thus experiences a high incidence of such flash droughts. The average frequency is 12–18 events per decade, and each event lasts for 6–7 days. North and Northeast China rank the second in terms of the occurrence of this type of flash drought. The average frequency is 3–9 events per decade, and each event lasts for 5 days. Type II flash drought is more common in semi-arid regions, such as North China (Fig. 6b), occurring on average 9–15 times per decade and lasting for 7–8 days each time. During the growing season (April–September), the frequency of type I flash drought in South China is 2–3 times that in North China, occurring mostly in July. The frequency of type II flash drought in North China is double that in South China, occurring mostly in late spring and early summer. For the past few decades, both types of flash droughts have shown a significant increase in frequency (Wang et al., 2016; Zhang Y. Q. et al., 2017, 2018; Wang and Yuan, 2018). During 1979–2010, the number of type I flash drought increased by 129%, and the number of type II flash drought increased by 59% (Wang and Yuan, 2018). Generally speaking, anomalous anticyclonic circulation provides favorable conditions for flash drought, but the distribution of these two types of flash droughts is very different due to regional variations in climate, vegetation, and soil conditions. Due to the abundance in water vapor in South China, evapotranspiration is largely dictated by energy. A rise in temperature leads effectively to rapid increases in evapotranspiration, which explains the higher likelihood of type I flash drought in humid regions such as southern China. About 15% of flash droughts occur at the outbreak of seasonal drought. On the contrary, the long-term shortage in water supply in North China is more likely to cause rapid decreases in soil moisture dur-

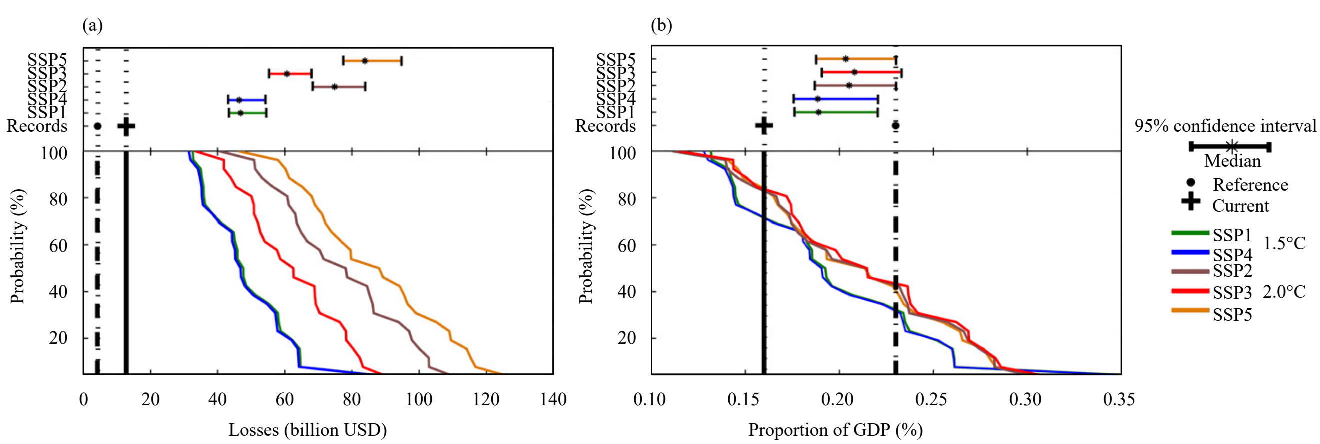

Fig. 5. (a) Drought loss and (b) its share of GDP in China under 1.5 and 2.0°C global warming scenarios (Su et al., 2018).

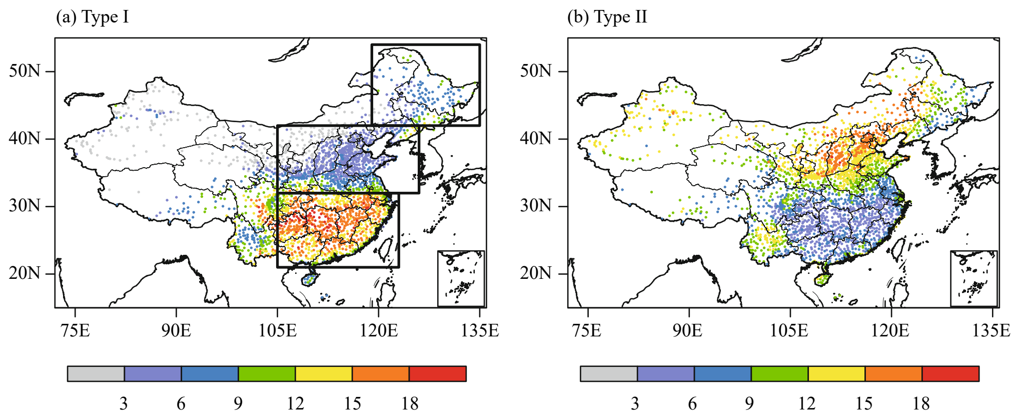

Fig. 6. Frequency (events per decade) of the two types of flash drought during the growing season (April–September) of 1979–2010: (a) Type I and (b) Type II (from Wang and Yuan, 2018).

ing periods of reduced precipitation, resulting in type II flash sudden drought. Flash drought in this region is more likely to occur at the outbreak and during the recovery of seasonal drought (Zhang X. et al., 2018).

The increase in flash droughts is largely caused by the aggravation of long-term global warming (a contribution of 50.1%), and to a less extent by a drop in soil moisture and an increase in evapotranspiration (contributions of 37.7% and 13.8%, respectively; Wang et al., 2016). In general, the humid and semi-humid regions of China are abundant in moisture. Evapotranspiration in these places is controlled predominantly by energy. High temperature leads to readily increased evapotranspiration and rapidly dries the soil. A quick reduction in soil moisture is generally noticed about 10 days prior to the onset of type I flash drought. In arid and semi-arid regions, due to limited availability of surface water and vegetation coverage, soil water deficit results in decreased evapotranspiration and the rise of surface temperature. Soil moisture drops rapidly, leading to type II flash drought. In typical cases, a deficit in the soil moisture content is already observed 10 days before the outbreak of type II flash drought. If rainfall shortage is still experienced after type II flash drought, seasonal drought may occur (Zhang Y. Q. et al., 2017; Wang and Yuan, 2018).

Both similarities and significant differences exist between flash drought and traditional persistent drought (Table 1). The similarities are: (1) climate features, i.e., climate anomalies are observed in both cases; (2) meteorological requirement, i.e., precipitation shortage; (3) spatial scale, i.e., both could happen at local, regional, intercontinental, and even the global scale; (4) the same land–atmosphere interplay and evolution of such an interplay, which is the transformation from being energy-constrained to water-constrained; (5) both are very destructive and difficult to monitor and forecast. Their main differences are: (1) the difference in the speed of development, as flash drought develops rapidly, and traditional drought develops slowly; (2) they occur at different frequencies, with the former occurring less frequently than the latter; (3) they take place across different timescales. Flash drought generally starts and ends in the same season, while traditional drought could last for months, years, and even decades; (4) they are dominated by different factors. Flash drought is caused by the anomaly in multiple meteorological parameters, while traditional drought is typically caused by a precipitation shortage; (5) the two have different times of high occurrence. Flash drought happens mainly in spring and summer, while traditional drought could happen all year round; (6) they are also different in their region of high occurrence. The former mainly occurs in farmland or areas with dense vegetation, while the latter could occur in any region; (7) they cause different degrees of aridness. Flash drought generally results in severe or extreme aridness, while traditional drought could be mild, severe, or extreme in degree; (8) the types of drought involved are different. The former is dominated by meteorological, agricultural, and ecological droughts, while the latter could take on the form of meteorological, agricultural, ecological, hydrological, and socioeconomic droughts; (9) they have different modes of influence. Flash drought is severe in its impact and is highly destructive. Traditional drought, however, is deep and far-reaching in its influence; (10) the formation characteristics of the two are different. The former is marked by sudden and unexpected occurrences, which make it hard to prevent. The latter is well-concealed and often detected only at the late stage; (11) the two are monitored by using different factors. Flash drought is monitored by evapotranspiration, vapor pressure deficit, the balance between water supply and demand, and temperature. Traditional drought is monitored

Table 1. Comparison between flash drought and traditional drought

Property		Flash drought	Traditional drought
Differences	Speed of development	Rapid	Slow
	Frequency of occurrence	Infrequent	Frequent
	Timescale	Intraseasonal	On the scale of months, years, and decades
	Dominating factor	Anomaly in multiple meteorological factors	Shortage in precipitation
	Time of high occurrence	Spring and summer	Entire year
	Region of high occurrence	Farmland or areas with dense vegetation	Any region
	Degree of aridness	Severe or extreme	Mild to extreme
	Type of drought involved	Mainly meteorological drought, agricultural drought, and ecological drought	Meteorological drought, agricultural drought, ecological drought, hydrological drought, and socioeconomic drought
	Mode of influence	Severe impact, highly destructive	Deep and far-reaching influence
	Prevention difficulty	Sudden and hard to prevent	Well-concealed, often detected only at a late stage
	Factors monitored	Evapotranspiration, vapor pressure deficit, the balance between water supply and demand	Precipitation and temperature
	Early sign	Rapid increase in evapotranspiration followed by decrease and weakening of this activity	Evapotranspiration is low and shows no significant change
Similarities	Climate feature	Climate anomaly	
	Meteorological requirement	Precipitation shortage	
	Spatial range	Local, regional, intercontinental, and even global scale	
	Land–atmosphere interplay and its evolution	From energy-constrained to water-constrained	
	Degree of hazard	Highly destructive	
	Monitoring and forecasting	High level of difficulty	

chiefly by precipitation; (12) they also show different signs at the early stage. Flash drought is characterized by a rapid increase in evapotranspiration and a subsequent decrease and weakening of this activity. Traditional drought shows low evapotranspiration that does not change significantly.

3. Scientific issues in and prospects for drought research

Since 1949, China has made great progress in understanding the formation mechanisms of drought, the spatiotemporal variations of drought, and the risk assessment of drought hazards. However, there are still challenges in research of China's droughts. For example, there is a lack of comprehensive scientific field experiments that target and support drought research; a lack of deep understanding of the multi-factor synergism and multi-scale effects of drought formation; a lack of research on the effects of land–atmosphere interactions on drought formation; and a lack of drought identification, monitoring, and prediction techniques related to flash droughts. Moreover, there is insufficient understanding of the transform and inconsistency between meteorological, agricultural, ecological, and hydrological droughts, and little attention has been paid to the key impact period of droughts in drought impact assessment models. In addition, the influences of drought on climate change are poorly understood, and the scientific rigor of the drought risk assessment model needs to be improved. However, the rapid advancement of observation technology and the continuous enrichment of multi-source data and reanalysis datasets, coupled with the continuous development of numerical climate simulations, offer potential solutions to these problems. In the future, drought research is expected to make new breakthroughs in some key scientific areas.

Although some scientific observational experiments related to droughts have been carried out internationally, many of the experiments have insufficient long-term, multi-factor, and systematic observation of land–atmosphere energy, moisture, and mass cycles. At present, a project called "Mechanism of Drought Induced Hazards in Northern China" has built a comprehensive system of observations and experiments for drought meteorology in northern China, forming a geographically V-shaped observation network from Xinjiang to central Northwest China and then to northern China. Continuous observations have been performed to investigate the mechanism of land–atmosphere interactions, drought induced hazard formation and resolution processes, and improvement of drought indices to better capture drought occurrence and development in these areas. New results have been obtained regarding the physical mechanism of drought formation and development of a physical conceptual model for major droughts, an agricultural drought risk assessment model, and risk zoning of droughts (Li et al., 2017, 2019). However, the observational experiments and climate simulation studies are insufficient. There are drought-prone zones in northern China, particularly on the fringe of China's monsoon areas; and the areas in southwestern China experience an increasing frequency of severe droughts (Huang et al., 2012; Qian and Zhang, 2012; Han et al., 2014, 2019). It is necessary to conduct comprehensive scientific experiments on droughts in these areas. Furthermore, in-depth analysis on the dynamic and thermodynamic evolution of droughts is also needed in order to elucidate the occurrence and development of droughts.

The formation and development of droughts in China is uniquely complex. Not only are these affected by both the monsoon and the westerly flows, but in the monsoon system itself there are different influences, such as those from the East Asian and Indian monsoons. In addition, the anomalous heat caused by snow cover and vegetation changes over the TP and the interactions of the regional land–atmosphere coupled system also need to be considered. The mechanism of drought formation and development cannot be understood if only a single factor or a few factors is considered. Moreover, drought events are featured with multiple timescales (Zhang Y. Q. et al., 2017), which include regular seasonal droughts and irregular yearly or interannual droughts. Therefore, a drought prediction system that can simultaneously consider these aspects should be established to improve the ability in monitoring and predicting major drought events.

Additionally, droughts have significant asymmetric characteristics. As the actual surface evapotranspiration is constrained by the evaporation potential, the drought development process is generally slow. In addition, there is theoretically no limit for precipitation, and a heavy rainfall event may end the drought and cause floods instead, which poses difficulties in predicting the completion of droughts (Feng et al., 2012). It is necessary to strengthen the understanding of drought completion so as to improve predictive ability.

Previous studies emphasize the role of atmospheric circulation in the formation of droughts, while the effects of land–atmosphere interaction have been more or less neglected. Even when the effects are considered, this has been only from the perspective of land surface forcing, which might be the main reason of the low accuracy of current drought predictions. Moreover, studies have shown (e.g., Seneviratne et al., 2006) that in the climate transition zones and drought-prone areas, the coupling of land surface processes and the atmosphere is important, and the contribution of land–atmosphere interaction to droughts is basically equal to, and sometime even exceeds, the contribution of atmospheric circulation. Additionally, the coupling between land surface heat, moisture, and physiological ecology plays a critical role in transmitting drought signals and causing hazards. It is important to connect meteorological droughts with agricultural, ecological, and hydrological droughts. Methods such as numerical simulation, observational experiments, remote sensing inversion, and theoretical research should be combined to systematically analyze the dynamics, heat, and moisture characteristics of the land surface process, the atmospheric boundary layer, and their coupling (Zhang et al., 1997, 2012b; Zhang and Zhao, 1999; Zhang Q. et al., 2017c), to lead to improvement of regional drought prediction models and drought monitoring and prediction techniques.

In the past, the drought monitoring and prediction techniques were established based on traditional slow-changing drought events (Tadesse and Wardlow, 2007; Brown et al., 2008; Zou and Zhang, 2008). Such techniques targeted seasonal or yearly drought predictions and required relatively longer monitoring intervals. In recent years, frequent occurrences of flash droughts have been observed (Zhao et al., 2012; Wang et al., 2016; Wang and Yuan, 2018), which exert a great impact on society and economy (Otkin et al., 2016, 2018). This has resulted in higher requirements for the monitoring, identification, and prediction, such as at hourly or weekly monitoring intervals. By using a combination of multi-source observations, models, and simulation data, a drought monitoring index that can be released at weekly intervals should be developed, and climate prediction methods that combine drought dynamics and statistics should be established to achieve accurate and timely identification, monitoring, and prediction of flash droughts.

When there is an accumulated shortage of atmospheric precipitation, there will be meteorological droughts and a chain transmission process from meteorological droughts to agricultural droughts, hydrological droughts, ecological droughts, and social economic droughts. For example, in agricultural droughts or ecological droughts, the transmission process is from soil drought to crop (or vegetation) physiological drought, crop (or vegetation) ecological drought, reduction in crop economic output (or deterioration of vegetation condition), and decline in agricultural (ecological) benefits. However, this process of transmission does not necessarily occur, and the transmission happens only when the previous drought indicator reaches a certain threshold. For instance, if the droughts are blocked before they are passed to the crop physiological droughts, they will not cause damage to the crop, and there will be no hazard. There is a certain inconsistency between meteorological, agricultural, ecological, and hydrological droughts. From the scientific perspective, the index for meteorological, agricultural, ecological, and hydrological drought only reflects the different development stages of droughts. In order to achieve consistent monitoring of the droughts, it is necessary to fully understand the relationship between meteorological, agricultural, ecological, hydrological, and social droughts and reveal the patterns of transmission and threshold criteria. It is also important to fully monitor the occurrence and development of droughts and provide early warning at each transmission.

In analyzing the development of drought, the effects of regional crop differences at different growth stages should be considered proportionally to accurately analyze and evaluate the development trend or degree of impact of agricultural droughts. Currently, the understanding of the key impact period of crops and the effects of drought on different crop growth stages is poorly understood. It is necessary to analyze the sensitivity of different types of crops or vegetation in different regions to drought; to study the weighted distribution of the effects of droughts on different crops or vegetation types in different regions; and to establish comprehensive drought monitoring indicators that combine drought monitoring indexes with the weighted distribution of the effects.

Many factors have complex responses to global warming, and they respond to global warming directly or indirectly. Precipitation, the most important factor in the formation of droughts, is an obvious example. Precipitation does not necessarily vary along with temperature change, but instead, responds to global warming differently in different regions and in different time periods. At the same time, the response of surface evapotranspiration to global warming is also greatly affected by climate and environmental background, and the response in some regions can be the opposite to the response in other regions (Zhang Q. et al., 2018). Moreover, in the process of drought formation and development, the interactions and feedback between temperature, evaporation, humidity, and precipitation are not simple linear processes. Therefore, it is not easy to accurately predict the development trend of droughts or evaluate the response of droughts in the context of global warming. It is necessary to fully elucidate the complexity of the drought response to global warming, systematically understand the effects of global warming on various factors in the formation of droughts, and reveal the impact mechanism of global warming on drought formation.

At present, drought risk is affected by many factors, such as drought-inducing factors, sensitivity to the hazard-breeding environment, and vulnerability and exposure of hazard-affected bodies, and the effects are dynamic and nonlinear. Due to the lack of understanding of the hazard-breeding environment and the socioeconomic attributes of the hazard-affected bodies, as well as limited data information, it is still difficult to scientifically assess drought risk. The danger of drought-inducing factors is often used to represent the drought risk. Even though the hazard-breeding environment and the hazard-affected bodies are considered, only a certain degree of impact of the two factors is shown. Global warming will not only aggravate the danger of drought-inducing factors, but also continually adjust the vulnerability of the hazard-affected bodies and the sensitivity of the hazard-breeding environment. For example, the transition of the hazard-breeding environment from meteorological drought to hydrological drought, agricultural drought, and ecological drought is accelerating, and thus it is necessary to develop a drought risk model that includes factors reflecting the impact of global warming.

For management of drought hazard risks, a scientific and effective drought risk management system with associated technology, mechanisms, and policies should be established (Zhang et al., 2015a; Zhang Q. et al., 2017b). Drought hazard risk management is an internationally recognized scientific strategy (Fisher et al., 1995; Ma, 2007; Zhang et al., 2015a; Zhang H. L. et al, 2016; Zhang Q., 2016; McNeeley et al., 2016). This requires that professional institutions establish accurate predictions for future drought risk and that administrative forces effectively implement policies and strategies for drought prevention, allowing for drought management to be implemented in a systematic manner.

4. Summary

Since the founding of the People's Republic of China, the drought research in China has made significant progress in understanding the spatiotemporal distribution, the formation mechanisms, the impact characteristics of droughts, as well as the characteristics of drought risks and flash droughts. Drought research no longer focuses on precipitation only, but instead is closely connected with other topics, such as changes in climatic factors, global change, the ecological environment and social economy, and sustainable development. It has become a key multi- and cross-disciplinary subject with international focus. However, drought research in China still faces many challenges. Drought formation in China is unique, and global warming and rapid social changes have further aggravated the complexity of this issue. Thus, further research and resource investment are needed, development in drought research should be accelerated, and some priority scientific issues need to be resolved.

At present, extensive social needs and rapid technological advancement will certainly accelerate the development of drought science and technology. The dependence of socioeconomic development on drought prevention and mitigation has increased, and the impact of global climate change on droughts has become increasingly prominent. These present many new scientific issues and bigger challenges for drought science research. On the contrary, the increased investment in science and technology as a result of socioeconomic development, the continuous improvement of China's comprehensive meteorological observation system, and the continuous development of satellite remote sensing technology and atmospheric numerical simulation technology have provided better opportunities for drought science research. Additionally, there is increasing scope for achieving breakthroughs and solving key scientific issues in the field of drought meteorology.

Research on drought hazard is of great theoretical and practical nature. It must follow a chain-style scientific-driven approach: identify key scientific problems related to drought, carry out scientific experiments, perform theoretical and technological research, and develop associated operational/business applications.

Moreover, based on our understanding of the characteristics and formation mechanisms of droughts, new advances in drought monitoring, prediction, and risk assessment techniques should be made. Drought prevention technologies that can simultaneously consider the characteristics of flash droughts and traditional droughts should be established, and the characteristics of droughts in different regions should be explored. The field of drought meteorology in China should be modernized.

With the rapid development of modern satellite remote sensing and earth observation systems in recent years, the ability of remote sensing to distinguish droughts has improved. Fundamental sciences, such as mathematics and physics, and numerical simulation techniques, together with application technologies such as big data plus intelligent technology, have been constantly improved. Based on the latest big data and data mining techniques, visible light remote sensing data and microwave remote sensing data could be used to establish a high-resolution remote sensing drought monitoring system. This system should include and integrate multiple disciplines, such as meteorological data, geographic information, underlying surface conditions, vegetation characteristics, soil types, land use, and plant physiological and ecological data, so as to provide strong scientific data support for drought research.

China's national-level drought meteorological observation and experiment network is improving. A series of major scientific projects has been established based on the "China Drought Science and Experimental Research" as the blueprint. The projects, such as "Mechanism of Drought Hazards in Northern China," aim at solving major drought-related issues, such as the formation mechanism of droughts, patterns of change, drought transformation process, multi-scale drought monitoring and early warning technologies, and the characteristics of drought risks.

In the long term, the prevention of natural hazards, including droughts, is a prioritized topic in public security as stated in the National Medium- and Long-Term Plan for Science and Technology Development (2006–2020). Drought prevention and mitigation are key for managing natural hazards and climate change. Therefore, the long-term development of drought science in China should focus on the frontiers in international drought research, and consider the demand for drought technologies. Moreover, scientific avenues for drought research in China should be explored; the direction of drought science in China should be clarified; and key scientific issues should be targeted. These include comprehensive drought investigations and experiments in drought-prone areas, as well as assessments of 1) the multi-factor and multi-scale effects of drought formation; 2) the effects of land–atmosphere interaction; 3) the identification, monitoring, and prediction of flash droughts; 4) the transmission and inconsistency between various types of droughts; 5) the role of key impact periods on agricultural drought development; 6) the complexity of the response of droughts to global warming; 7) the drought risks; and 8) the realization of risk management concepts. A series of major scientific research projects on droughts should be carried out to promote the scientific and technological innovation of drought science in China to match that of international levels.

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