BAMS Article

Discussion on Major Drought Issues in the Northern Drought-Prone Belt in China

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ABSTRACT: In northern China, the transition zone affected by summer monsoon and its neighboring areas frequently experience drought events. Especially since the twenty-first century, the number of major drought events in this region has significantly increased, making it a notable drought-prone area known as the northern drought-prone belt (NDPB). Till now, major drought events in this area have profoundly impacted China's historical progress and socioeconomic development. In fact, similar drought-prone belts are common in other monsoon transition zones globally, making it highly relevant and scientifically valuable to study the major drought issues in this region. Therefore, we discuss the major drought issues in the NDPB for the first time, comprehensively analyze the basic characteristics of the NDPB, systematically review the main stages of drought research in northern China, and identify scientific challenges currently faced in major drought research in the NDPB. Based on this and in line with the current forefront of Earth system science research, we outline five research directions and their basic approaches, including scientific experimental research focusing on major droughts in the NDPB, the impact of multifactor atmospheric circulation interactions on major drought formation, mechanisms promoting major drought development through the land–atmosphere coupling, the synergistic mechanisms of the atmospheric circulation and land–atmosphere coupling on major droughts, and fine monitoring technology and prediction methods for the full-chain progression of major droughts that have multifactor collaborative impacts. This research work holds significant scientific reference value for promoting innovative breakthroughs in the theory of major drought formation and monitoring and prediction techniques in northern China.

SIGNIFICANCE STATEMENT: Since the twenty-first century, the northern China drought-prone belt has seen a significant increase in severe and extreme drought events. However, there has never been a dedicated discussion on the major drought issues in this unique region. Our manuscript is the first to propose the scientific concept of the northern China drought-prone belt. By understanding the basic characteristics of this region's climate and environment and identifying the main scientific challenges encountered in major drought research, we suggest several key research directions and fundamental approaches. This work offers new insights into future in-depth studies on mechanisms behind major drought occurrences in northern China and methods for their monitoring and prediction.

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1. Introduction

Drought is a pervasive natural disaster characterized by its high frequency, long duration, extensive coverage, and significant economic losses, making it one of the most destructive natural disasters globally (Dai 2011; Belayneh et al. 2014). It directly affects the balance between supply and demand and causes severe damage to agricultural production, natural environments, and socioeconomic sectors (Andreadis and Lettenmaier 2006; Mishra and Singh 2010; Jenkins et al. 2021). Historically, major drought events have been closely associated with the rise and fall of civilizations and changes in dynasties, and in modern times, economic losses from droughts account for one-third of the total losses from all natural disasters (Qin et al. 2015).

In the context of climate warming, the extremity and spatiotemporal variability in global precipitation have further intensified, while water budget processes such as Earth surface evapotranspiration (evaporation) have undergone significant changes (Zhang et al. 2019a). The frequency and intensity of drought disasters are increasing, and their characteristics and patterns are becoming more complex and unpredictable. This exacerbates drought risks, increasing vulnerability in agriculture, ecology, and water resources (Zhang et al. 2019c) and posing a growing threat to human production and livelihoods (Murray and Ebi 2012; Van Loon et al. 2016). From 1964 to 2007 alone, global food production decreased by an average of 10.1% owing to drought (Lesk et al. 2016), and annual economic losses surged from an average of USD 17.33 billion (1980–2009) to USD 23.125 billion (2010–17), far exceeding those from other natural disasters (Wilhite 2000; Su et al. 2018). Moreover, recent studies suggest that extreme weather events such as droughts will further intensify owing to climate warming (Held and Soden 2006; Liang et al. 2008; Orlowsky and Seneviratne 2013). Therefore, organizations such as the World Meteorological Organization and the Food and Agriculture Organization of the United Nations (FAO) prioritize drought research. Unless otherwise specified in this article, the drought events mentioned refer to meteorological droughts; major drought events are defined as meteorological drought events if the meteorological drought composite index (MCI) reaches severe and extreme drought levels according to the National Standard of the People's Republic of China "Meteorological Drought Grade" (GB/T 20481-2017). Here, MCI considers the comprehensive effects of monthly scale evapotranspiration and effective precipitation at 2-month, seasonal, and semiannual scales, applicable for monitoring and assessing meteorological drought on a daily basis during the crop growing season (Zhang et al. 2020a). When $-2.0 < \text{MCI} \le -1.5$, it is classified as severe drought, and when $\text{MCI} \le -2.0$, it is classified as extraordinary drought, with major drought being the situation where $\text{MCI} \le -1.5$.

China ranks among the countries experiencing the highest frequency and most profound impact of drought disasters globally. Extensive droughts persistently occur, affecting approximately 61% of the total land area and accounting for 34% of all losses from natural disasters (Zhang et al. 2020b). Annually, an average of 20.9 hm^2 of crops are affected by drought, leading to a reduction in grain yield ranging from several million to over 30 million tons, equivalent to the grain demand of a medium-sized country. The direct economic losses caused by drought disasters amount to around 44 billion RMB per year (He et al. 2011; Xu et al. 2015; Su et al. 2018). Since the 1950s, with the exacerbation of climate warming, both the degree and frequency of drought disasters in China have increased, and the affected areas have significantly expanded (Li et al. 2015). This trend includes a notable expansion in the overall drought-affected area (Fig. 1). In particular, since the beginning of the twenty-first century, there has been a significant increase in major drought events, with the area affected by major droughts increasing by 3.72% every 10 years (Yu et al. 2014; Wang and Zhang 2011). For example, the large-scale drought disaster event in Yunnan Province, China, from November 2009 to March 2010 threatened nearly 10 million residents with drinking water shortages (Lü et al. 2012). Drought disasters pose a serious threat to China's food security, ecology, and water resources. They have become one of the critical factors constraining the high-quality development of China's current socioeconomy and the construction of an ecological civilization. Therefore, the Scientific and Technological Innovation Plan for the "14th Five-Year Plan" of China has listed technological innovation in drought prevention and mitigation as a key research area. Enhancing drought prevention and mitigation technologies has become a major task in national disaster prevention, mitigation, and climate change response initiatives.

Moreover, the spatial distribution of drought disasters in China is highly specific (He et al. 2016; Jia et al. 2018; Bai et al. 2019; Han et al. 2020; Wen and Chen 2023). Owing to its location in the monsoon climate zone, China has a unique transitional zone between the areas of summer monsoon influence and those that are not, known as the summer monsoon's northern boundary swinging zone. This zone extends from the southwest corner of China through northwestern, central, and northern China to northeastern China. The uncertainty of summer monsoon activity in this transitional belt and its surrounding area results in significant spatiotemporal variability in precipitation, making it extremely prone to drought disasters, thus becoming a prominent area for drought disasters (Wang and Zhang 2011). Studies have shown that against the backdrop of climate warming, the response of land surface evapotranspiration in this region to climate warming is more significant, leading to further increases in the frequency and intensity of droughts. Furthermore, the northern regions of this drought-prone area exhibit more prominent characteristics than the southern regions (Ma and Fu 2007; Han et al. 2019), attracting widespread attention and concern from various

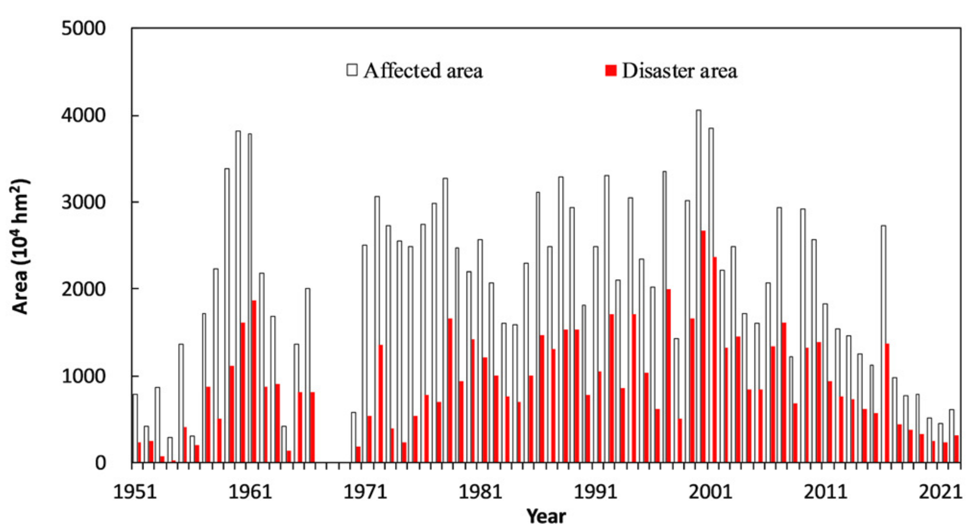

Fig. 1. Variations in areas affected and damaged by droughts in China from 1951 to 2022. [Data are obtained from the National Bureau of Statistics of China (https://data.stats.gov.cn/index.htm)].

sectors of society (Fu and Ma 2008; Qian et al. 2012). Therefore, we define this region as the "northern drought-prone belt" (NDPB).

The NDPB is located between China's agricultural and pastoral regions and the areas with scarce surface water resources. Agriculture, ecology, and water resources in this belt are extremely vulnerable, and socioeconomic development is highly sensitive to droughts. The major drought from 1637 to 1643, which contributed to the downfall of the Ming Dynasty, occurred in this region. Even under the overall trend of warming and humidification (Zhang and Wang 2022), severe early summer droughts and consecutive droughts in midsummer still occurred in 2021. As one of the world's largest agricultural regions, the NDPB's drought patterns provide essential insights into how climate change affects food security in monsoon-influenced semiarid regions. Therefore, the NDPB remains the region that is most severely affected by drought disasters in China and where ecological protection and high-quality development in the Yellow River basin are most constrained by droughts. The region's unique geographical location at the edge of the East Asian monsoon system makes it an ideal natural laboratory for studying how climate change influences the monsoon system and drought mechanisms in climate transition zones. This helps understand similar monsoon–arid transition zones worldwide. The strong land–atmosphere coupling characteristics observed in this region offer valuable case studies for understanding how global warming affects soil moisture–atmosphere feedback processes, which is crucial for improving global climate models. Long-term drought monitoring in the NDPB helps validate and improve climate change projection models, particularly in simulating extreme climate events in monsoon-influenced semiarid regions. Nevertheless, there has never been a specific focus on discussing drought issues in this particular area, severely hindering the improvement of drought disaster prevention and mitigation technologies in northern China.

In light of the above, this paper aims to focus on the major drought issues in the NDPB, providing insights into some of the major scientific issues faced by research on major droughts in this region. By understanding the basic characteristics of the climate environment in the NDPB and reviewing the research progress on major droughts in China, the paper proposes several key research directions and their basic approaches. The primary scientific theme is the synergistic effect of atmospheric circulation and land–atmosphere coupling on major droughts in the NDPB of China. This research provides scientific references for in-depth studies on the occurrence and development mechanisms of major droughts in northern China, as well as their monitoring and prediction methods.

2. Basic characteristics of the NDPB in China

Geographically, the NDPB roughly covers a vast area extending from the east part of northwestern China and the western part of central China to most parts of northern China and the central and western parts of northeastern China. This region is roughly distributed around "Hu's line," a geographical boundary line extending from Heihe in Heilongjiang Province to Tengchong in Yunnan Province (Hu 1935), running in the northeast–southwest direction and was first proposed by Mr. Huanyong Hu, a renowned Chinese geographer. Situated at the northern boundary swinging zone of the East Asian summer monsoon and an active area for northern wind flow (Fig. 2), the NDPB's climatic conditions are significantly influenced by the activity of the summer monsoon and disturbances in mid- and high-latitude atmospheric circulation systems. Consequently, precipitation in this region is highly variable, with significant interannual and interdecadal fluctuations. Lengthy periods without precipitation are common, making the area particularly susceptible to meteorological droughts (Tang et al. 2007; Zhang et al. 2016a, 2019c).

In the NDPB, the seasonal variation characteristics of droughts and floods are primarily controlled by the advance and retreat process of the summer monsoon, while the interannual and interdecadal fluctuations, along with changes in the intensity of the summer monsoon, create a fundamental climatic pattern characterized by alternating droughts and floods. The multiple time-scale superposition effects or abrupt processes of anomalous summer monsoon changes are fundamental drivers of significant drought events. For instance, major shifts in the Asian summer monsoon in 1965 and 1980 resulted in severe drought disasters in the region (Yang et al. 2005; Li et al. 2013; Q. Zhang et al. 2003). Furthermore, the northward-shifted airflow featuring the "ridge-front, trough-back" pattern within mid- and high-latitude circulation systems intermittently resides over the area, leading to prolonged moisture deficits in northern China and, ultimately, extreme droughts.

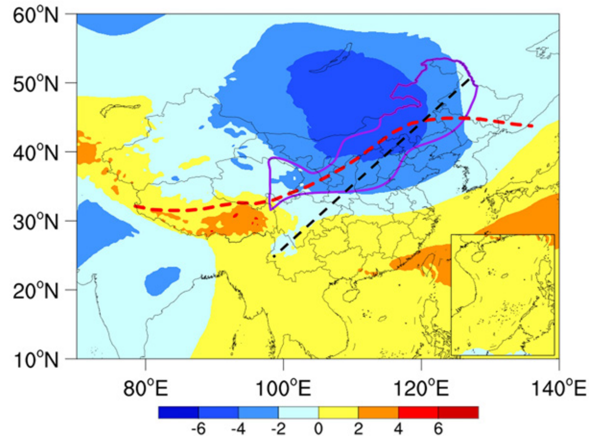

Fig. 2. Composite map of the average distribution of north wind intensity during major drought events in the NDPB from 1951 to 2020. The determination of drought events and their levels is based on the national standard of the People's Republic of China, Meteorological Drought Classification (GB/T 20481-2017), with data sourced from the ERA5 reanalysis data and station observation data. Coloring represents 500-hPa meridional wind speed (m s^{-1}), with cool colors indicating north winds and warm colors denoting south winds. The purple line area represents the NDPB, the red line indicates the long-term average northern edge influenced by summer monsoon, and the dotted black line is Hu's line.

Statistics show that the NDPB has experienced frequent and major droughts over the years, highlighting a notable drought problem. The region's average annual drought days generally exceed 40, with some areas experiencing more than 60 days. The frequency of drought events in most areas exceeds 30%, significantly higher than the national average. It is noteworthy that severe and extreme drought events predominantly occur in the NDPB region (Fig. 3) (Wang et al. 2011; Liao and Zhang 2017).

Major drought events in the NDPB are characterized by their devastating impact, long duration, and extensive coverage, frequently resulting in widespread crop failures and severe famines. Historically, social unrest in northern China has been closely linked to major

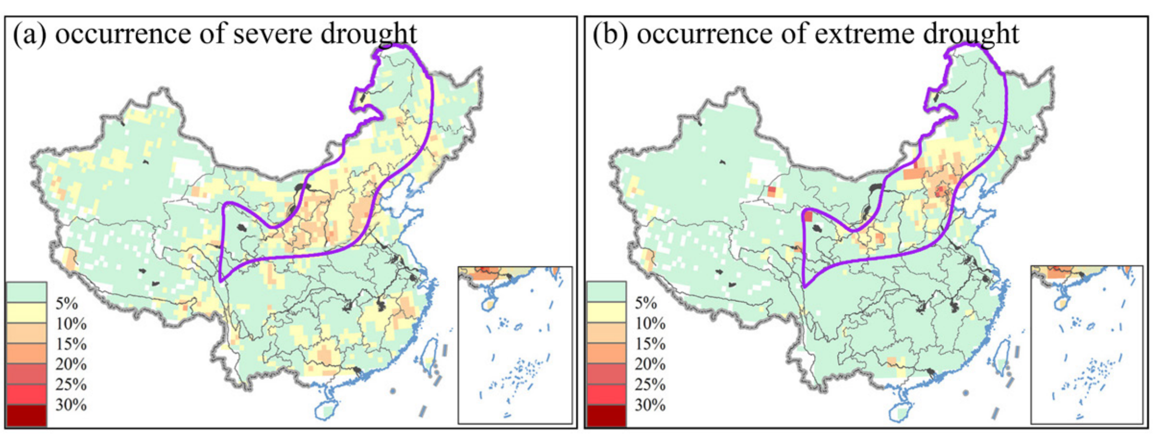

Fig. 3. Frequency of (a) severe drought and (b) extreme drought in China from 1961 to 2009 (revised from Han et al. 2020). The frequency of drought occurrence is the ratio of the number of months with different levels of drought to the total number of months in the statistical period, and the purple line area denotes the NDPB.

droughts in the NDPB. During the Ming and Qing Dynasty periods, the NDPB experienced frequent and severe droughts, with multiple major drought events lasting more than 3 years and affecting more than four provinces. A particularly notable example was a 7-yr-long drought that occurred during Emperor Chongzhen's reign (1637–43, Ming Dynasty period). This severe drought affected most of northern China, resulting in barren lands stretching thousands of miles, dried-up rivers, exhausted wells and springs, withered crops, and complete harvest failures. The situation was so dire that there were even instances of cannibalism. The resulting famine became a trigger for peasant uprisings, which, combined with internal troubles and external threats, led to the fall of the Ming Dynasty. The "Guangxu major drought" that spanned from 1874 to 1879 caused approximately 13 million deaths in provinces, including Shanxi, Henan, Hebei, and Shandong, making it the deadliest recorded drought event before the twentieth century (Chen 1991). This event triggered significant social changes, forcing large numbers of Shanxi residents to migrate north to Inner Mongolia, while famine victims from Hebei and Shandong fled to the grain-rich northeast China. These mass migrations of disaster victims in modern Chinese history, known as "Zou Xikou" (going through the western pass) and "Chuang Guandong" (venturing into Northeast China), continued until the early twentieth century.

Additionally, the region shows significant spatial variability in climatic environment and land surface characteristics. Summer monsoon precipitation decreases rapidly from 900 mm at the southern boundary to 100 mm at the northern boundary, with a gradient of approximately 200 mm $(100\,\text{km})^{-1}$. Simultaneously, the Bowen ratio, a comprehensive land surface water–heat parameter, increases sharply from 1.0 to 6.0, with a gradient of about 1.3 $(100\,\text{km})^{-1}$. This makes it the area with the most significant spatial gradient changes in China for both precipitation and the Bowen ratio. Moreover, potential land surface evaporation in the region is high, reaching up to 1500 mm annually, about 4 times the average annual precipitation. The dryness index ranges from 0.2 to 0.5, indicating a continental arid climate. This significant spatial variation in precipitation results in large spatial changes in ecological vegetation, with interspersed deserts, sparse vegetation, natural grasslands, shrub forests, and farmland, making it the most typical ecological transitional zone in China.

The region responds significantly to global warming, with faster temperature increases and more intense land surface evapotranspiration, leading to increased drought frequency and intensity (Fu and Ma 2008; Qian et al. 2012; Huang et al. 2017). In particular, drought frequencies in Inner Mongolia, northeastern China, and northwestern China have increased by 75%, 66%, and 64%, respectively, since 1980 compared to earlier periods. The areas experiencing significant increases in drought frequency are precisely located within this region (Huang et al. 2016; Zhang 2018) (Fig. 4). Notably, the research by Lu et al. (2023) indicates that under a temperature rise of 2°C, the region's drought frequency will exceed 1.5 months $(\text{yr})^{-1}$, exhibiting a clear increasing trend far above the national average.

This region shows strong land–atmosphere coupling, with land–atmosphere interaction processes significantly influenced by monsoon climate dynamics (Li et al. 2012; Zeng et al. 2016; Liu 2023). The frequent turnover of land-cover types results in significant spatiotemporal variations in the land surface characteristics, such as soil temperature, soil moisture, vegetation cover, and runoff (Li and Ma 2015; Li et al. 2017). The pronounced horizontal spatial changes in land surface characteristics lead to significant spatial gradients in land surface water–heat exchange, atmospheric boundary layer transport, and atmospheric boundary layer thickness. These notable gradients inevitably influence atmospheric motion processes and may even induce local atmospheric circulation (Zhang et al. 2017a), thereby impacting the formation and development of droughts.

The region is also under the synergistic effects of several atmospheric circulation factors. The formation of major droughts is clearly impacted by the synergistic influence of the

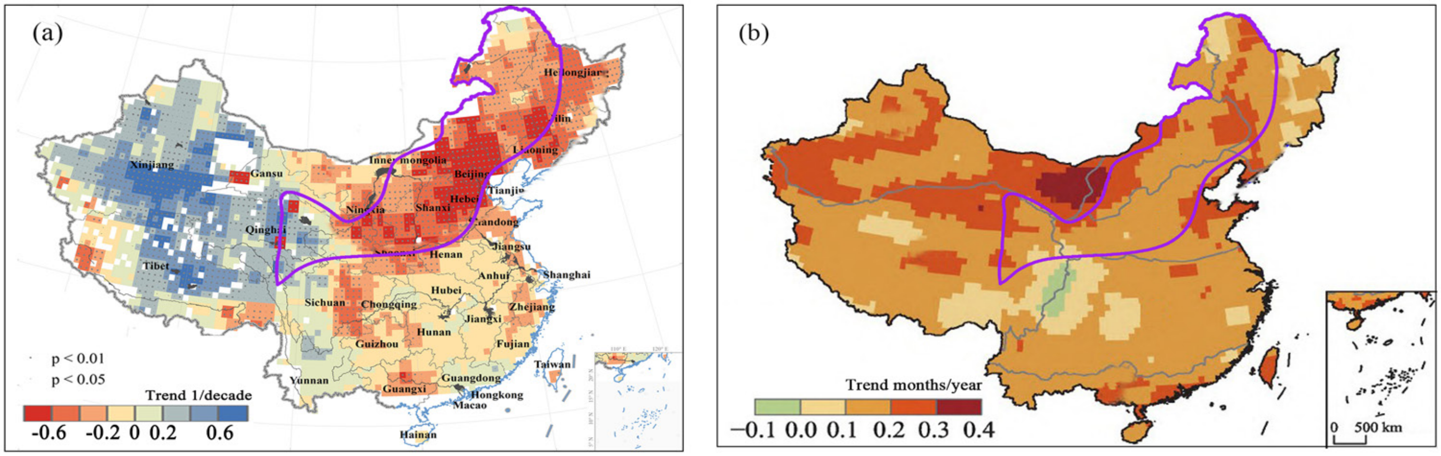

Fig. 4. Distribution of drought trends in China during 1950–2009, where drought events are identified based on (a) self-calibrated Palmer drought intensity index (Han et al. 2020) and (b) distribution of changes in drought frequency in China during 2015–2100 under a 2°C warming scenario (Lu et al. 2023), where drought events are identified based on standardized precipitation evapotranspiration index (SPEI). Purple solid areas represent the NDPB.

westerly circulation, Asian monsoon, and Tibetan Plateau monsoon. It is closely associated with the overlapping or merging of the westerly belt high pressure ridge and subtropical high, as well as the synergy of dynamic divergence and negative vorticity increase caused by the plateau terrain (Yang et al. 2005). Moreover, the frequent convergence of summer cold and dry northwest airflow and warm and moist southward airflow activates mesoscale weather processes, manifesting a distinct dynamic nature of the climate in this region (Huang et al. 2009).

More importantly, the region represents a terrain transitional zone in China, characterized by several features: a terrain transition from high plateaus to plain basins, an interweaving belt between agricultural land and grasslands, a spatial overlap of semiarid, ecological fragile zones, and a crucial belt for desertification and southward and eastward shifting of sandification. The socioeconomic development in this region is highly sensitive to drought (Wang and Zhang 2011; Yue et al. 2015). Furthermore, many species in the region are on the brink of collapse, where slight climate changes or human disturbances could lead to systemic failures, making it a focal point for the impacts of global climate change (Zhang et al. 2009a). Additionally, the region is located within China's primary rain-fed agricultural area, underscoring its strategic role in food security.

It is noteworthy that similar drought-prone belts may also be prevalent in monsoon transition zones globally, such as western North America, southwestern South America, northern Australia, and southern Africa (Stahle et al. 2007; Cui et al. 2021; King et al. 2020; Verhoeven et al. 2022). However, while the NDPB shares similarities with these regions in terms of drought characteristics and driving mechanisms, there are also significant differences. Taking the U.S. Great Plains and northern Australia as two typical drought-prone regions, for example, both the NDPB and the Great Plains are situated in monsoon-to-arid transition zones, exhibiting high precipitation variability and being significantly influenced by atmospheric circulation and land–atmosphere coupling (Stahle et al. 2007). Droughts in both regions are associated with mid-to-high latitude circulation anomalies, and global warming has intensified their frequency and severity (Zeng et al. 2021). Similarly, northern Australia's drought region displays precipitation instability, with strong land–atmosphere coupling characteristics akin to those of the NDPB (Yuan et al. 2023). These commonalities suggest that droughts in monsoon transition zones are collectively regulated by multiscale climate systems. However, the differences are more pronounced. Droughts in the Great Plains are primarily driven by the Pacific decadal oscillation (PDO) and La Niña, exhibiting strong interannual variability (McCabe et al. 2004), whereas the NDPB shows lower interannual variability, modulated by monsoon oscillations and the thermal effects of the Tibetan Plateau (Yang et al. 2005). Northern Australia's droughts are dominated by El Niño–Southern Oscillation (ENSO) and the Indian Ocean dipole (IOD), with interannual fluctuations exceeding those of the NDPB (King et al. 2020; Reddy et al. 2022). Furthermore, the NDPB's complex terrain (transitioning from plateaus to plains) and heightened ecological vulnerability amplify the impacts of drought on agriculture and water resources (Zhang et al. 2020b). In contrast, the Great Plains feature flat terrain, while northern Australia has sparse vegetation, resulting in distinct socioeconomic impact patterns from drought. These differences position the NDPB as a unique laboratory for studying mechanisms in monsoon transition zones, offering insights not only for drought prevention and mitigation in China but also as a reference for similar regions worldwide.

3. Research progress on major droughts in northern China

The issue of drought is exceedingly complex, involving numerous factors that often include superposed, interrelated, coupled, and synergistic effects influencing its formation and development. While minor droughts may result from a single dominant factor, major drought events typically arise from the synergistic linkage of multiple factors and the superposition of multiple scales. Thoroughly understanding the causes and development of development is, therefore, a challenging task. Consequently, the study of drought in northern China has undergone a lengthy process of continuous development and gradual deepening.

a. Stage of statistical investigation on drought disasters and distribution characteristics. China has long recognized the importance of major drought issues. Since its founding, the country has organized specialized investigations into major drought disasters (Hsiao et al. 1964), beginning with the documentation of significant drought events and analyzing their performance characteristics and hazards. With the improvement of observational networks and detection methods, research on the temporal and spatial distribution patterns and causes of droughts has gradually expanded (Wang and Zhao 1979; Xu and Zhang 1983; Tao and Zhang 1998; Luo 2005; Zou and Zhang 2008). Consequently, the study of droughts has progressed from a qualitative and descriptive understanding to a quantitative analysis of their objective characteristics and theoretical explanations of their causes.

b. Research on the role of mid- and high-latitude atmospheric circulation systems in drought formation. Owing to the frequent occurrence of drought disasters in northern China, particularly the prolonged 6-yr drought from 1978 to 1983 (Huang et al. 1999), early Chinese drought research primarily focused on this region. Studies on drought formation mechanisms emphasized the trough–ridge movement and perturbations in mid- and high-latitude atmospheric circulation systems and the distribution of synoptic fields.

Initially, research suggested (Bai et al. 1988) that when the 500-hPa circulation field in midlatitudes featured a Xinjiang high pressure ridge, a deep East Asian trough, and strong north winds, with positive anomalies over Xinjiang and negative anomalies over the Sea of Japan—forming a "positive west and negative east" pattern—northwestern China was generally prone to drought. Subsequent studies further identified (Yatagai and Yasunari 1998; Qian et al. 2001) that drought years in northwestern China during summer often featured a specific atmospheric pattern: "upper-level western-type South Asian high combined with a lower-level Xinjiang high pressure ridge or an eastward-extending Iranian high pressure system over the Qinghai–Tibet Plateau" pattern. Additionally, Luo (2005) found that positive anomalies in northwestern China and negative anomalies near the East Asian coast created a dipole-type thermal forcing anomaly, leading to summer droughts in eastern northwestern China. For the northern China region, Shen et al. (2012) determined that in summer drought years, when mid- to high-latitude regions were dominated by meridional circulation, northern China experienced a "high west, low east" circulation pattern. This pattern, controlled by anomalous northerly airflow and the descending airflow of the Baikal high pressure ridge, hindered summer precipitation, thus making drought events more likely (Fig. 5). Furthermore, studies found that the stability and persistence of a deep, thick, warm high pressure system in midlatitude East Asia, combined with strong subsidence in the upper atmosphere leading to air adiabatic heating and increased sensible heat near the surface, resulted in sustained temperature rises. The nonadiabatic forcing from the underlying surface and the strengthening of the continental warm high pressure system created a positive feedback process, exacerbating summer droughts in northern China (Wei et al. 2003; Q. Zhang et al. 2003).

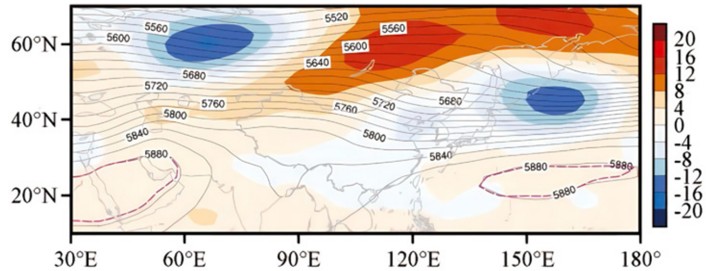

Fig. 5. Composite distribution of 500-hPa geopotential height field (gpm) during years of below-normal precipitation in northern China from May to August during 1981–2019. Contours represent the height field, shading represents the geopotential height anomaly field, and the purple dashed line indicates the climatological position of the subtropical high.

c. Research on the role of the summer monsoon and subtropical highs in drought formation. As research on droughts in northern China deepened, the academic community found that the seasonal variations, east–west oscillations, and north–south movements of the East Asian summer monsoon and the western Pacific subtropical high significantly impact drought formation and development in northern China. Consequently, attention shifted to the properties of air masses originating from the ocean, the transport of warm and moist air flows, and the distribution characteristics of monsoon activities and the subtropical high. Studies indicated (Q. Zhang et al. 2003) that when the East Asian summer monsoon is weak and the western Pacific subtropical high is positioned southward, summer precipitation in northern China decreases, which is a primary cause of drought events in this region. Other research found (Qian et al. 2001; Ding et al. 2003; Zhang et al. 2019b) that when the ridge line of the western Pacific subtropical high shifts southward, the rain belt located 8–9° of latitude north of the ridge also moves southward. This positioning causes the rain belt to settle south of eastern northwestern China, preventing it from reaching eastern northwestern China and leading to drought. Additionally, research suggested (Wei and Zhang 2009; Zeng and Yuan 2021) that when the western Pacific subtropical high is southward and weak in summer, the enhanced Mongolian high hinders the transport of cold air from high latitudes to northeastern China, resulting in reduced summer precipitation and increased drought. Furthermore, studies (Huang et al. 2007; Zhang and Zhou 2015) pointed out that northeastern China, characterized by a temperate continental monsoon climate, frequently experiences droughts owing to monsoon climate instability. Other studies (Lian et al. 2010; Qian and Zhou 2014) revealed that during weak East Asian summer monsoons, the persistent Baikal blocking high weakens the westerlies and hampers moisture transport from the Bay of Bengal, reducing precipitation and making summer droughts more likely in northeastern China. Additionally, researchers (Ding and Li 2016) noted that northern China, influenced by the overlapping effects of two subsystems of the East Asian monsoon—tropical and subtropical monsoons and affected by the westerly circulation and the Qinghai–Tibet Plateau monsoon, exhibits significant regional complexity in drought occurrence and development.

d. Research on the impact of climate warming on drought. With intensifying climate warming, its impact on drought has garnered increasing attention. Observational and modeling results (Held and Soden 2006; Chou et al. 2009) indicate that climate warming leads to the "wet getting wetter and dry getting drier" or the "rich getting richer" phenomenon. This means that tropical and midlatitude regions, which are relatively wet, will become wetter, while arid and semiarid regions in the subtropics will become drier, exacerbating global drought. Research (Zarch et al. 2015) suggests a pronounced trend of increasing drought in severely arid regions globally compared to a decreasing trend. Semiarid, semihumid, and humid regions are becoming slightly drier. Notably, studies (Han et al. 2021; Giorgi et al. 2011) found that since the abrupt temperature rise observed in the 1990s (Table 1), the intensity, frequency, and duration of droughts in China have increased. Northern China and parts of northwestern China are experiencing more frequent and major droughts, corroborated by data on the number of light rain days and precipitation amounts (Yan and Yang 2000). Global warming has led to the significant warming of the Eurasian continent, increasing lower-tropospheric baroclinicity and ultimately contributing to enhanced anticyclonic anomalies in the NDPB, potentially leading to increased consecutive dry days and persistent summer extreme droughts (Zhang et al. 2018). Based on the CMIP5 and CMIP6 simulation results, by the mid-twenty-first century, under the RCP4.5 scenario, the drought duration, frequency, and intensity are expected to increase in most parts of northern China, with the drought intensity in most areas in the NDPB being projected to increase by more than 10 times compared to the baseline period (1976–2005) (Zeng et al. 2021). As the drought intensity and affected areas increase, drought-related losses are expected to surge dramatically. Compared to the baseline period, drought-related losses are projected to increase by 10 times at the 1.5°C warming level, representing nearly a 3-fold increase relative to the 2006–15 period (Su et al. 2018). At the 2.0°C warming level, population exposure to extreme drought risk will increase by approximately 17%, with the NDPB region showing the most prominent increase (Chen and Sun 2019).

Giannini (2010) outlined two possible mechanisms by which global warming could affect drought. First, increased greenhouse gas emissions lead to higher net surface radiation, enhancing potential land surface evaporation and directly causing drought. Second, global warming increases moist static energy in the upper atmosphere, affecting vertical atmospheric stability and indirectly causing drought. Global warming also leads to a more uneven precipitation distribution, with increased precipitation observed in tropical and high-latitude regions and decreased precipitation in midlatitude regions, increasing the probability of droughts in midlatitude areas such as northern China. Held and Soden (2006) found that global warming significantly increases the spatial heterogeneity of Earth's

Table 1. Comparison of drought intensity, occurrence frequency (%), and duration (month) before and after climate warming in China and North China during 1961–2014 (Han et al. 2021). Drought intensity is characterized by the comprehensive meteorological drought index, occurrence frequency is the regional average of the proportion of drought years to total years, and duration is the average number of drought months per year. The Mann–Kendall mutation analysis method was used to evaluate the temperature change trend. Based on the intersection of the forward (UF) curve and backward (UB) curve, it was found that China's annual average temperature suddenly rose after the early 1990s. Therefore, 1961–90 was defined as before temperature warming and after that was defined as after temperature warming.

	Before warming			After warming		
	Intensity	Frequency	Duration	Intensity	Frequency	Duration
North China	−0.98	32.8	10.32	−1.08	35.9	10.70
China	−0.87	28.0	10.91	−0.98	31.8	11.0

surface net water flux (precipitation P minus evaporation E). This heterogeneity is mainly attributed to the uneven distribution of average and transient atmospheric moisture transport. In the wettest tropical regions, the convergence of trade winds and moisture leads to positive $P - E$, while in arid regions, moisture divergence caused by trade winds, stationary waves, and transient eddies results in significant negative $P - E$. Therefore, although a warmer atmosphere will hold more moisture, water moisture transport is enhanced even when the circulation remains constant. Under these hypotheses, the overall distribution of $P - E$ will remain unchanged but with more extreme values, making wet regions wetter and dry regions, like northern China, drier. Additionally, under global warming, the increase in global temperatures is unevenly distributed. Since 1960, approximately 88% of the world has experienced significant warming trends, with over 98% of arid regions seeing a rise in temperatures (Zarch et al. 2015). This may be explained by higher trends in potential evapotranspiration in these regions, further accelerating drought development and intensifying drought intensity.

e. Research on the role of SST anomalies in drought formation. With the occurrence of the El Niño phenomenon, the impact of sea surface temperature (SST) anomalies on major droughts in China has garnered significant attention. Unlike atmospheric movements, SST changes are slower and more persistent, with anomaly signals transmitted to the atmosphere through ocean–atmosphere interactions. This leads to abnormal atmospheric circulation, influencing droughts in northern China (McCabe et al. 2004; Wu et al. 2008). Recent studies (Qian and Zhou 2014; Han et al. 2015; Du et al. 2020) have shown that circulation anomalies caused by SST can significantly impact drought events. Decadal SST signals from different ocean basins may affect droughts in different regions. In particular, the SSTs of the Pacific, Atlantic, and Indian Oceans have a significant impact on droughts in northern China. Research also indicated (Li et al. 2000; Wu et al. 2008) a significant negative correlation between the SST of the equatorial central and eastern Pacific during autumn and spring droughts in northwestern China the following year. Lower SST anomalies, indicative of La Niña phenomena, often result in droughts in northwestern China in the following spring. Furthermore, SST distributions featuring negative anomalies in the North and west Pacific and positive anomalies in the equatorial central and eastern Pacific during summer hinder the development of the western Pacific subtropical high. This makes it challenging for warm and moist airflows from the periphery of the subtropical high to reach northwestern China, rendering the region prone to summer droughts. Other studies (C. J. Zhang et al. 2003; Zhang and Zhou 2015) found that El Niño phenomena significantly impact autumn droughts in eastern northwestern China. A strong El Niño in autumn correlates with higher temperatures and reduced precipitation, increasing the likelihood of droughts. Additionally, Hurrell (1996) suggested that changes in North Atlantic SST could partly explain the occurrence and development of droughts in northern China. Fu and Zeng (2005) pointed out that an abnormal North Atlantic Oscillation (NAO) in the previous season could affect drought occurrences in northern and northeastern China in the current season. When the NAO is in a positive (or negative) phase, the frequency of droughts (or floods) in eastern northern China during summer is exceedingly high. Particularly since the 1970s, when the NAO was in a high positive phase, there was reduced rainfall and major droughts across most parts of northern China (Fig. 6).

SST anomalies and atmospheric circulation anomalies interact in ways that significantly impact major droughts in northern China (Si and Ding 2016). Various studies (Deng et al. 2009; Qian and Zhou 2014) have shown that the phases of the PDO or interdecadal Pacific oscillation significantly affect these droughts. During the positive phase of the PDO, warm SST anomalies in the equatorial central and eastern Pacific increase the sensible heat flux from the ocean to the atmosphere, heating the entire tropical troposphere. Meanwhile, the

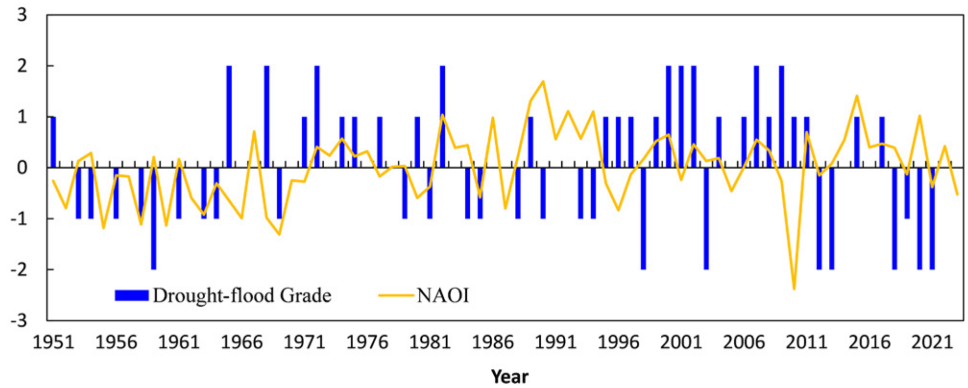

Fig. 6. Temporal variations of drought-flood indices (bar) in the NDPB region from 1951 to 2023, along with the NAO index (NAOI) (yellow solid line). The calculation method for the drought-flood grades refers to the Chinese Academy of Meteorological Sciences (1981), where −2, −1, 0, 1, and 2 represent drought, moderate drought, normal, moderate flood, and flood, respectively. The NAOI is defined as the difference in the zonally averaged standardized monthly sea level pressure in the North Atlantic region between 35° and 65°N from 80°W to 30°E. This paper uses the annual average values, and the data are sourced from the National Oceanic and Atmospheric Administration website (https://psl.noaa.gov/data).

midlatitude troposphere in the Northern Hemisphere undergoes anomalous cooling, which alters the meridional temperature gradient in the North Pacific and surrounding areas. This anomaly results in abnormal northwesterly winds in northern China, weakening the East Asian summer monsoon and preventing the northward advance of tropical moisture and rain belts, thus causing drought conditions. Additionally, research has found (Wang et al. 2009; Sheng et al. 2021; Yang et al. 2017) that different oceanic modes dominate droughts on different time scales. The "drought and flood" in China distribution pattern in China is influenced by the Atlantic multidecadal oscillation (AMO), while the PDO primarily drives interdecadal changes in the "south flood, north drought" precipitation pattern. The AMO further modulates this effect.

f. Research on the relationship between land–atmosphere interactions and drought. Land–atmosphere interactions are crucial in the climate system's response to external forcings. The exchange of matter, energy, and momentum between the land and the atmosphere significantly impacts regional droughts, a topic that has gained attention only recently. The Global Land–Atmosphere Coupling Experiment (GLACE) demonstrated that reduced soil moisture significantly exacerbates soil and atmospheric drought through land–atmosphere interaction processes, such as feedback involving surface temperature, relative humidity, and precipitation (Berg et al. 2016; Zhou et al. 2019). Since the late twentieth century, China has conducted significant land–atmosphere interaction observational experiments, such as the Heihe River Basin Field Experiment (HEIFE), the Inner Mongolia Semi-arid Grassland soil–vegetation–atmosphere Interaction (IMGRASS), the Atmosphere–land Interaction Experiment in Arid Region of Northwest China (NWC–ALIEX), and the Land Surface Processes in Chinese Loess Plateau (LOPEX). These observational studies have provided preliminary insights into the impact of land–atmosphere interactions on drought in northern China (Hu and Gao 1994; Lü et al. 2005; Zhang et al. 2005, 2009b; R. Huang et al. 2013).

Current research indicates that the impact of land–atmosphere interactions on drought can be categorized into two main types. The first type involves rapid feedback processes: land surface processes are influenced by factors such as solar radiation, atmospheric dynamics, physical and chemical properties, temporal variations, spatial variability, and human activities. Changes in these land surface processes can lead to reduced (or increased) local convective activity and precipitation, thereby causing drought (or flooding) events

(Segal et al. 1995; Pielke 2001; Liu et al. 2022). Meanwhile, dry soil leads to reduced evapotranspiration, possibly further decreasing atmospheric humidity and increasing vapor pressure deficit, resulting in reduced precipitation and corresponding drought (Hirschi et al. 2011; Berg et al. 2016). Once a drought event occurs, negative soil moisture anomalies further disrupt land–atmosphere coupling, potentially sustaining soil moisture deficits for weeks to months. A persistent, strong, sensible heat flux can heat the lower atmosphere, create high temperatures, and further reduce the evapotranspiration and atmospheric moisture content, thereby intensifying drought (Roundy et al. 2013; Miralles et al. 2014; Zhou et al. 2019).

The second type of feedback process involves slower mechanisms where anomalies in land–atmosphere coupling can slowly affect local atmospheric circulation through "memory effects" or impact downstream atmospheric circulation through long-distance transmission (Fig. 7). For instance, some studies (Li et al. 2018; Wang et al. 2019; Du et al. 2022) suggest that the disappearance of Barents Sea ice in spring may increase snow depth in western Eurasia, triggering a polar-Eurasian teleconnection pattern. Concurrently, intense warming in Europe and the Caspian Sea can enhance anticyclonic circulation anomalies over the Tibetan Plateau, which subsequently affect the downstream droughts in northeastern China during July–August through long-distance interactions. Additionally, other studies (Zhang and Zuo 2011) revealed that late spring wet soil anomalies in northern China could weaken the thermal contrast between land and sea during summer. This weakening reduces the strength of the East Asian summer monsoon, leading to decreased precipitation and increased drought events. Furthermore, Zhou and Huang (2008) and Zhou et al. (2009) found that since the mid-1970s, significant increases in spring land–atmosphere temperature differences in northwestern arid regions have intensified spring sensible heat flux and abnormal rising airflows. These changes create downward flow anomalies and interdecadal anticyclonic abnormal circulation patterns over northern China, thereby reducing summer precipitation in the region (Fig. 8).

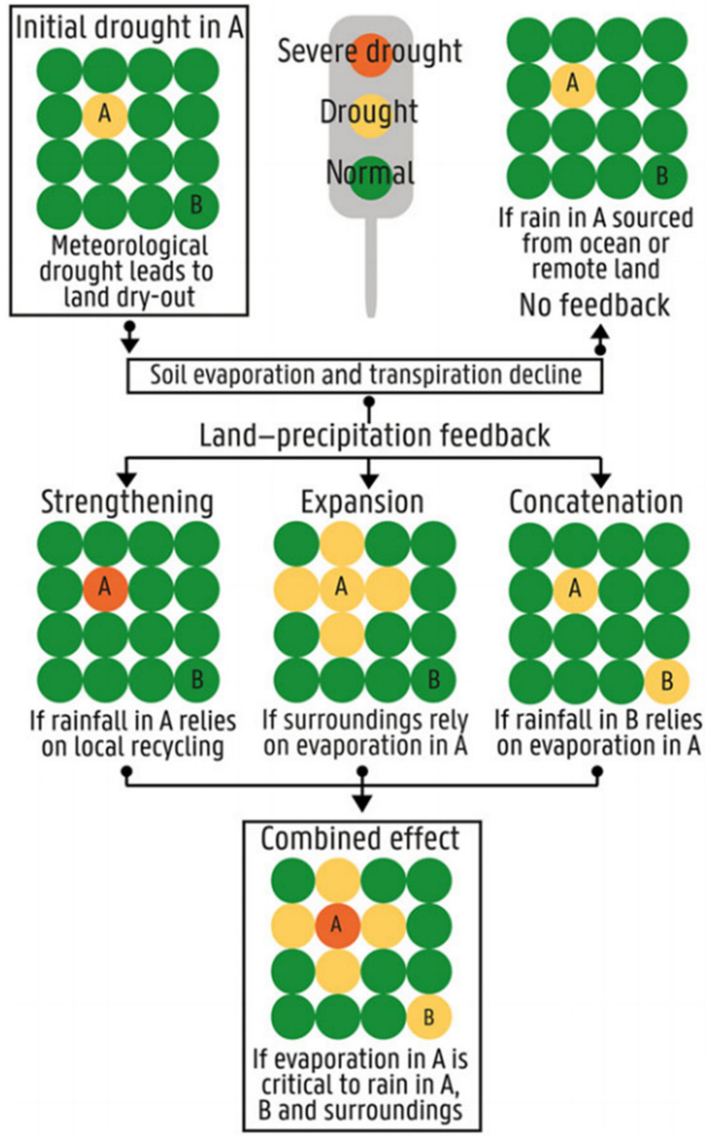

Fig. 7. Schematic of the self-intensification and self-propagation of drought events (Miralles et al. 2019). Local and teleconnected land feedback may aid in the intensification and propagation (expansion and concatenation) of meteorological droughts.

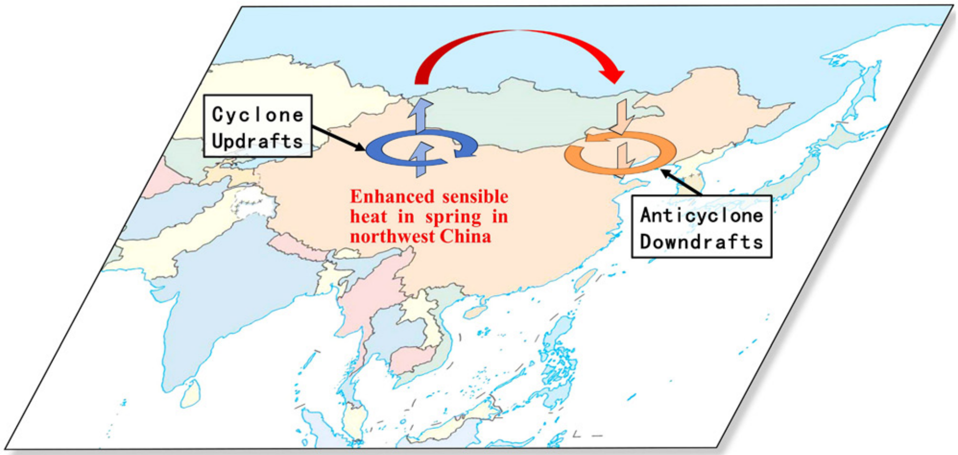

Fig. 8. Schematic map of the impact of intensified spring sensible heat in the arid area of northwest China on summertime precipitation in North China (revised from J. Huang et al. 2013).

g. Understanding the mechanisms of drought from the perspective of the East Asian climate system. Ye and Huang (1996) first proposed the concept of the East Asian climate system, suggesting that droughts in China are linked to various components of this system. Huang et al. (2003) also argued that the formation and development of droughts in China are primarily driven by chain reactions caused by anomalies in certain aspects of the East Asian climate system. Zeng et al. (2019) specifically investigated the severe drought in northeast China in 2017, attributing it to the synergistic effects of atmospheric circulation anomalies and land–atmosphere coupling anomalies (Fig. 9). Their research pointed out a strong positive phase of the Arctic Oscillation in the spring as the initial trigger for the drought. This was followed by anomalous anticyclonic circulation over southern Baikal during the summer, which strengthened the Baikal high pressure ridge and caused subsidence, thereby weakening moisture transport from the south. Meanwhile, the land–atmosphere coupling state in northeast China shifted from wet coupling (occurs under the conditions of sufficient soil moisture and can mitigate drought development through evaporation–precipitation feedback processes that regulate the water balance) in spring to dry coupling (occurs under the conditions of soil moisture deficit and may intensify drought intensity) in summer. This shift increased surface sensible heat, reduced cloud cover, and weakened longwave absorption. This caused anomalous nonadiabatic heating in the lower atmosphere and cooling in the upper atmosphere, resulting in negative anomalies in lower-level potential vorticity. These conditions ultimately caused prolonged extreme drought events in northeast China.

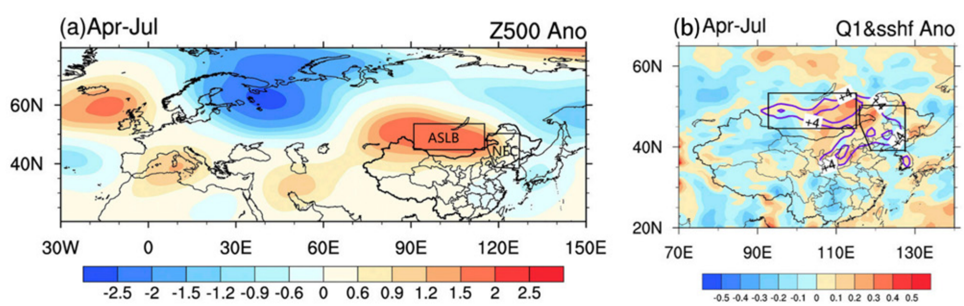

Fig. 9. Composite analysis of atmospheric circulation and land surface processes during seven persistent drought events in northeast China (revised from Zeng et al. 2019). (a) Abnormal geopotential height (shaded; dagpm; ASLB represents Lake Baikal); (b) abnormal nonadiabatic heating Q1 (shaded; K day^{-1}), and surface sensible heating (contour; W m^{-2}).

4. Major scientific issues facing the study of major droughts in the NDPB

First, there is an urgent for a thematic study focusing on the major drought issues in the unique NDPB region. This region covers a vast area in eastern northwest China, western central China, western northern China, and central–western northeast China. It is a typical ecologically sensitive zone and a major rain-fed agricultural area, playing a crucial role in food security and ecological protection (Wang and Zhang 2011). Climatically, this region experiences more active atmospheric circulation, greater uncertainty in monsoon activities, and a significant influence of westerly circulation, the East Asian monsoon, and the plateau monsoon. The role of atmospheric circulation in drought formation is complex. Additionally, the region exhibits tight and strong land–atmosphere coupling, where land surface energy, moisture, and ecological physiological factors exert profound influences through multipath and multiprocess coupling. Moreover, the formation and development of drought disasters in this region involve not only complex climatic dynamics but also multiscale moisture and energy cycle mechanisms (Zhang and Zhou 2015). This makes the NDPB an extremely unique and scientifically significant region for studying major droughts. However, there are currently few dedicated studies on the detailed dynamic characteristics, formation mechanisms, monitoring, and forecasting methods for major droughts in this region. Notably, almost no major national projects have focused on this issue.

Second, there is a unique contribution of land–atmosphere interactions to major droughts in the NDPB. Previous drought research has predominantly focused on atmospheric circulation factors, often neglecting the impact of land–atmosphere interactions. Even when land–atmosphere interactions are involved, they are usually approached from the perspective of land surface forcing. This oversight might be one of the main reasons for the current low accuracy in drought monitoring and prediction (Zhou et al. 2019). Studies have indicated that in climate transition zones and areas prone to frequent droughts, the degree of land–atmosphere coupling is significantly stronger, and the multiscale characteristics of land–atmosphere coupling are more pronounced (Seneviratne et al. 2006; Liu et al. 2022). The contribution of land–atmosphere interactions to drought formation and development can sometimes be comparable to or even exceed that of atmospheric circulation. Moreover, the temperature–evaporation–humidity–precipitation feedback between land and atmosphere during drought formation and development is not a simple linear relationship but often manifests as a complex multilevel, multipath cross-coupling process. Some land surface elements exhibit both positive and negative feedback processes (Fig. 10), and their coupling characteristics can change with variations in land surface features and atmospheric background conditions. Furthermore, the pronounced land–atmosphere coupling in this region notably accelerates the pace of drought development compared to other areas (Wang et al. 2021; Zeng and Yuan 2021). In the region, the feedback relationships between land surface thermal, moisture, and physiological–ecological processes play a critical role in drought signal transmission and disaster processes. This coupling is an important physical link that connects meteorological droughts with agricultural, ecological, and hydrological droughts (Zhang et al. 2017b). In other words, the land–atmosphere coupling process reflects the sensitivity of the drought-prone environment and determines the disaster process of meteorological drought, playing a unique role in drought formation and development. However, it is evident that this issue is not given sufficient attention in many current studies on major droughts.

Third, the issues related to the multifactor synergistic action and multiscale superposition effects in major drought formation in the NDPB are critical. Current studies often focus on specific circulation influencing factors or specific spatiotemporal scales to understand drought formation and development mechanisms. This approach often results in significant errors in drought prediction methods based on such scientific understanding. The formation and development of major droughts in northern China are influenced by a combination of monsoon and

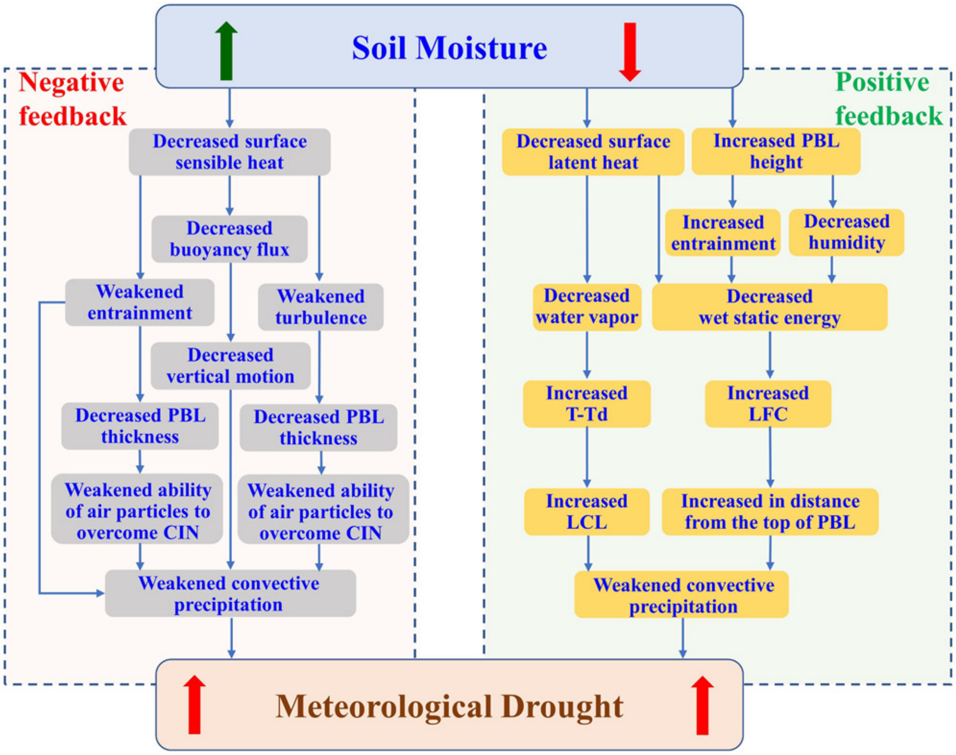

Fig. 10. Schematic diagram of the positive (negative) feedback mechanism between drought and soil moisture. The planetary boundary layer (PBL) is the lowest part of the atmosphere affected by Earth's surface; convective inhibition (CIN) represents the energy barrier to convection; LFC is the height where air parcels become buoyant; and lifting condensation level (LCL) is the height where condensation begins. The *T* – Td is the temperature–dewpoint difference.

westerly circulations, as well as the individual and synergistic effects of different branches of the monsoon system, such as the East Asian monsoon and the Indian monsoon. Additionally, interactions exist between meridional and zonal atmospheric circulations, the associative effects of the subtropical high and the South Asian high "moving toward" or "moving away from" each other, and the seesaw effect between westerly and monsoon circulations (Zhang et al. 2019b; Du et al. 2020). There are also interactions between mid–high-latitude and low-latitude circulation systems. In summary, multifactor linkage in atmospheric circulation is quite prominent in this region (Fig. 11). From the perspective of land–atmosphere interactions, both local thermal and moisture contributions and nonlocal thermal anomalies caused by the large topography of the Tibetan Plateau and changes in snow cover and vegetation must be considered. Moreover, the influence of SST anomalies in key ocean areas such as the Pacific warm pool and the remote correlations of global sensitive region land surface processes play a role (Huang et al. 2017). Notably, drought events exhibit characteristics of multiple time scales, ranging from 10 days to decades or even longer. Major droughts

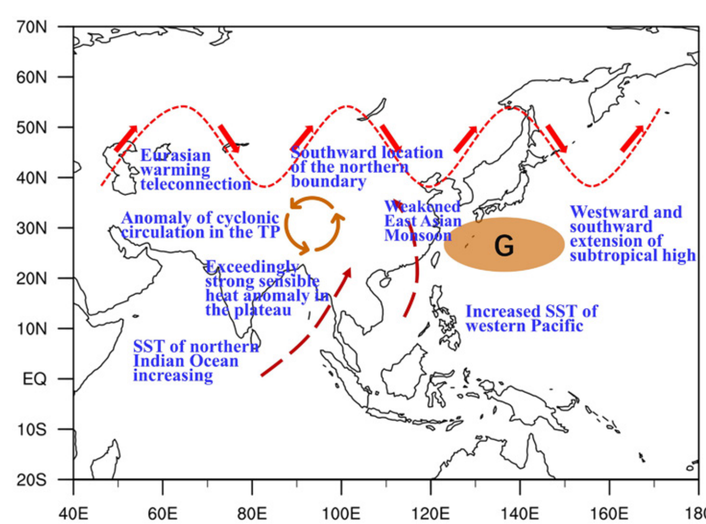

Fig. 11. Schematic diagram of multifactor linkage in atmospheric circulation.

often form through the superposition or transformation of multiple time scales (Zhang et al. 2017b). For example, the severe drought event that affected most of the NDPB region in the winter of 2008 was mainly caused by the synergistic effects and multiscale superposition of multiple factors, such as the southward shift of the subtropical high, the weakening of the Indo–Burma trough, higher surface temperatures on the Qinghai–Tibet Plateau, and SST anomalies, like ENSO and La Niña events (Gao and Yang 2009). Therefore, thoroughly studying the multifactor synergistic actions and multiple time-scale superposition and transformation effects of drought formation is essential to grasp their laws and characteristics. However, current research in this area remains quite weak.

Fourth, the progressive development characteristics of drought need to be addressed. Present understanding of the drought process is often limited to certain stages or processes. Drought monitoring and prediction often focus on a specific aspect of drought, lacking a systematic scientific understanding of the entire process. Consequently, different conclusions or monitoring results often arise for the same drought event. In fact, the occurrence and development of drought disasters are not immediate but a progressive process (Zhang et al. 2016b). Under cumulative precipitation deficits, meteorological drought inevitably occurs, followed by a chain reaction: "meteorological drought → agricultural drought → ecological drought → hydrological drought → socioeconomic drought." Significant transmission processes are within hydrological, agricultural, ecological, and socioeconomic droughts (Fig. 12). For example, within agricultural or ecological droughts, there is a finer transmission process: soil drought → crop (or natural vegetation) physiological drought → crop (or natural vegetation) ecological drought → economic yield reduction (or vegetation degradation) → reduced agricultural (or ecological) benefits. Nevertheless, these transmission processes do not necessarily occur automatically; they are often conditional and constrained by thresholds. From the perspectives of both drought monitoring and disaster reduction, it is essential to thoroughly understand the process characteristics of the progressive development of drought disasters. However, current scientific understanding of this issue remains very limited.

Fifth, the issue of temporal sensitivity of drought impact on agriculture or ecology is crucial. Traditionally, the development state of agricultural or ecological drought is assessed using changes in specific drought indices or elements. This approach often leads to inaccurate or erroneous judgments because it overlooks the sensitivity of drought impacts on agriculture

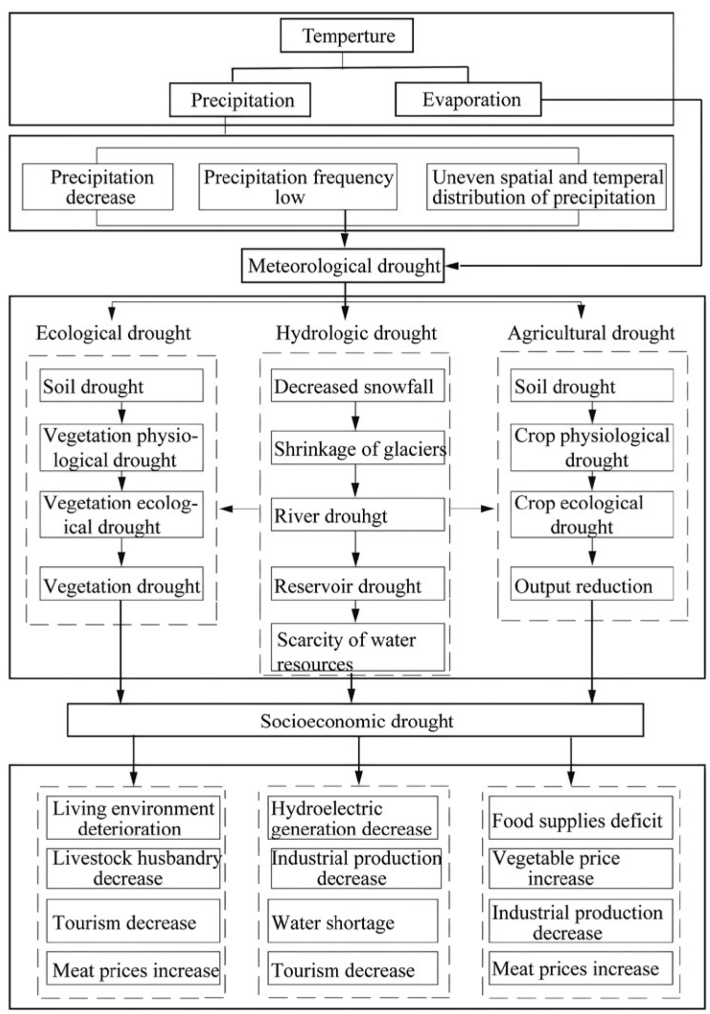

Fig. 12. Schematic diagram of the progressive development process of drought disasters (Zhang et al. 2016b).

or ecology. This sensitivity is mainly attributed to distinct water demands of crops or natural vegetation at different growth stages and varying water consumption under different climatic conditions. In other words, the sensitivity of crops to drought indices or impact elements varies greatly across different growth stages, seasons, or regions. During the peak water demand period, which is critical for crop growth, crops are highly sensitive to drought intensity. Conversely, during noncritical periods, the water demand of crops is much lower or even minimal, making the impact of drought intensity on crop growth less significant and, in some cases, even having the opposite effect. Therefore, when analyzing drought development or assessing drought impacts, it is crucial first to understand the dynamic variation law in sensitivity or impact weight coefficients for specific regions and crops (or ecosystems) during their growth stages and accurately judge the development trend or impact degree of agricultural (or ecological) drought. However, current knowledge about the distribution characteristics of critical drought impact periods or the dynamic variation in sensitivity for crops (or ecosystems) remains very limited. Furthermore, different climatic environments and crop (or ecological) types exhibit significant differences in drought impact weight distribution, which can even change to some extent with climate warming (Zhang et al. 2020a). Given these complexities, an in-depth understanding of how drought impacts plant physiological and ecological responses throughout different growth stages, seasons, and climatic environments is crucial for understanding agricultural (or ecological) drought. However, research progress on this issue is still relatively slow.

Sixth, the complexity of major droughts' response to climate warming must be addressed. The complexity arises because almost all factors affecting drought formation and development respond to climate warming, often triggering chain reactions. Additionally, the response process of many factors to climate warming can be multifaceted, occurring through different pathways and exhibiting multiple modes, both direct and indirect (Fig. 13). For instance, the response of precipitation to climate change, a primary factor influencing drought formation, is one of the clearest examples. Recent research has found (Byrne and O'Gorman 2015) that the response of precipitation to climate warming is highly complex and does not exhibit a straightforward trend with temperature changes. Instead, it shows distinct response characteristics in different regions and periods. Some international studies even suggest that with climate warming, dry areas will become drier and wet areas wetter. Similarly, the response of drought-controlling factors such as surface evapotranspiration to climate warming is significantly influenced by climatic and environmental backgrounds, demonstrating opposite response characteristics in different regions (Zhang 2018). Additionally, affected by climate

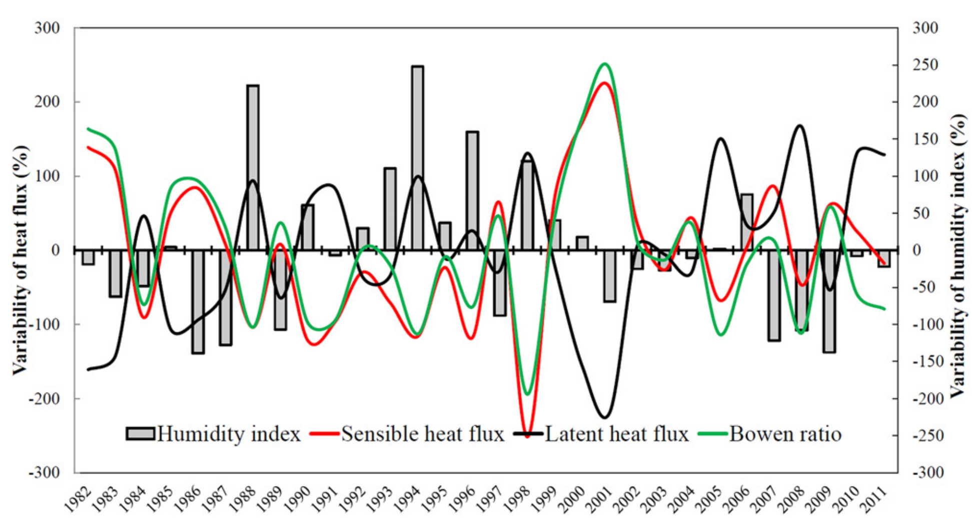

Fig. 13. Time evolution of the moisture index, sensible heat flux, latent heat flux, and Bowen's ratio of the NDPB (Zeng 2020).

warming, the feedback amplification effect of land–atmosphere interactions may intensify drought intensity and speed up drought development in certain regions (Berg et al. 2016). Thus, current research results may only reflect the response of drought to climate warming under certain conditions or in particular ways. To accurately understand the development patterns of climate warming, it is essential to fully recognize the complexity of these responses and systematically understand how climate warming affects various drought-controlling factors. Achieving this goal requires further research in the future.

5. Major research directions and preliminary approaches for major droughts in the NDPB

Based on major scientific challenges identified in studying major droughts in the NDPB and the authors' understanding of current frontier directions in climate system science research, five major directions and approaches for studying major droughts in the NDPB are preliminarily proposed.

First, conducting specialized scientific observation experiments focusing on major droughts in the NDPB is essential. Previous research has led to the establishment of a "comprehensive drought meteorological observation and test system" and a "land–atmosphere interaction observation and test network in the summer monsoon transition zone" in the NDPB and its surrounding areas (Fig. 14). These efforts have enhanced our capability to observe the "+"-shaped land–atmosphere interactions of summer monsoon across the northern region and the "V"-shaped major droughts covering extensive drought-prone areas from northwestern and central to northern China. We have conducted scientific observational experiments and studies on the land–atmosphere coupling characteristics and drought events in the NDPB region (Zhang et al. 2005, 2009b; J. Huang et al. 2013; Zhang and Zhou 2015). Moving forward, existing scientific observations and test conditions can be fully utilized to integrate the +-shaped land–atmosphere interaction observation and test network with the V-shaped drought scientific observation network. This will enable systematic and scientific observation tests focusing on land–atmosphere interaction processes and major drought processes during the formation and development of major drought events in the NDPB. We will conduct a detailed analysis of the dynamic process characteristics and formation mechanisms of these droughts to gain an in-depth understanding of their dynamic characteristics and development patterns in the region. To achieve this, we will utilize advanced data from ERA, GLDAS, China's newly developed land surface data assimilation system (CLDAS), China reanalysis data (CRA), multisource satellite data, conventional meteorological observation data, and drought disaster data.

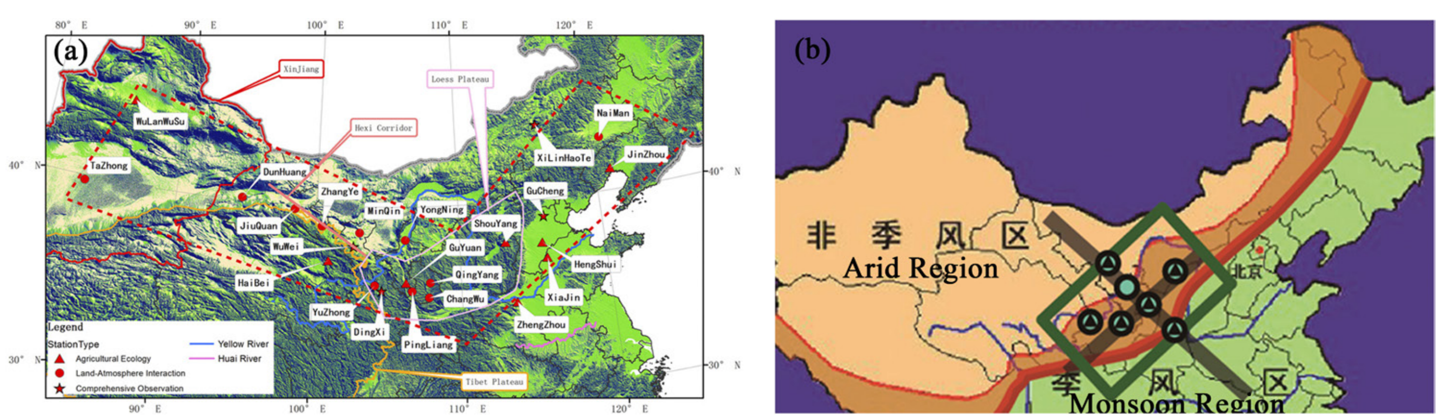

Fig. 14. Distribution diagram of (a) a drought observation system and (b) a land–atmosphere interaction observation system located in the research area (Zhang et al. 2020b).

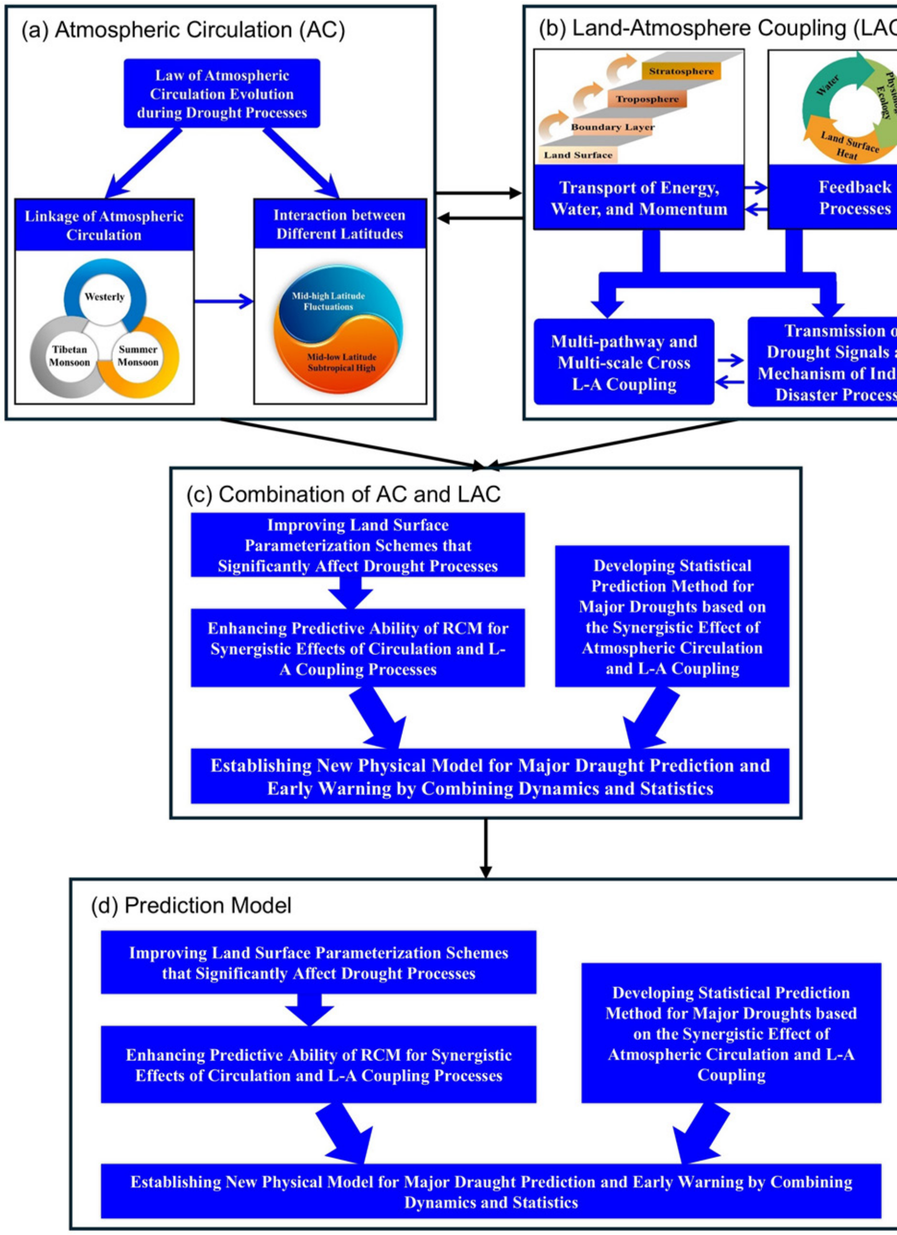

Fig. 15. Schematic diagram for the main scientific issues and technical approaches of the NDPB major drought research. (a) The multifactor interaction laws of atmospheric circulation during major droughts, (b) the characteristics of multiscale and multiprocess land–atmosphere coupling and their effects on the major drought process, (c) the mechanisms of the synergistic effects of land–atmosphere coupling and atmospheric circulation on major drought processes, and (d) the development of a new physical model for major drought prediction.

Second, examining the multifactor synergistic linkage and multiscale superposition effects in atmospheric circulation and their impact on major droughts in the NDPB is critical. This involves analyzing the interaction between the westerly circulation, monsoon circulation, and the branches of the monsoon system (East Asian monsoon and Indian monsoon) and their combined impact on major droughts in the NDPB (Fig. 15a). Specifically, focus on five typical synergistic influence mechanisms of atmospheric circulation: 1) synergistic linkage of atmospheric circulation systems from different developmental orientations: this includes the interaction between the westerly belt system and the Asian monsoon system; 2) synergistic linkage of atmospheric circulation systems at different impact scales: this considers the superposition effects among the westerly belt system, Asian monsoon system, and the Tibetan Plateau monsoon system; 3) synergistic linkage of atmospheric circulation systems at different dimensions: this involves analyzing the combined impact between meridional and zonal circulation systems; 4) synergistic linkage of atmospheric circulation systems at different altitude levels: this involves exploring the moving toward and moving away from interactions between the lower-tropospheric subtropical high and the upper-tropospheric South Asian high; and 5) linkage of atmospheric circulation systems at different latitudes: this involves examining the interactions between mid–high latitude longwave trough–ridge activities and low-latitude tropical cyclones. Additionally, it requires analyzing how major atmospheric circulation responses to climate warming, such as the poleward expansion of the Hadley circulation, the poleward shift of the westerly jet, and the weakening of the Northern Hemisphere polar vortex, influence the formation and development of major droughts in the NDPB.

It also requires exploring the multiple time-scale superposition (or conversion) effects of drought formation by analyzing the multiscale characteristics of drought events ranging from 10 days to decades or even longer. Investigating the dominant factors in atmospheric circulation and the superposition features of multiscale droughts, such as seasonal droughts and abnormal interannual or decadal droughts, is also essential in addition to studying atmospheric circulation conditions under which seasonal drought anomalies develop into longer-term droughts. Generally, multiscale influencing factors corresponding to droughts of different scales differ (Fig. 16): seasonal droughts in China's NDPB are primarily associated with summer monsoon activity, plateau heating, and the annual cycle of solar radiation; interannual droughts correspond mainly to ENSO cycles and interannual variations in the summer monsoon, westerly circulation, and plateau heating; decadal droughts relate mainly to the interdecadal variations in the summer monsoon and westerly circulation, as well as the PDO and AO phases; multidecadal droughts are linked mainly to multi-interannual oscillations in the summer monsoon and westerly circulation, as well as the AO and NAO phases; and the long-term trend of drought intensification corresponds to global warming. Therefore, it is possible to delve further into the multiple time-scale superposition (or conversion) effects of drought formation by studying the impact characteristics

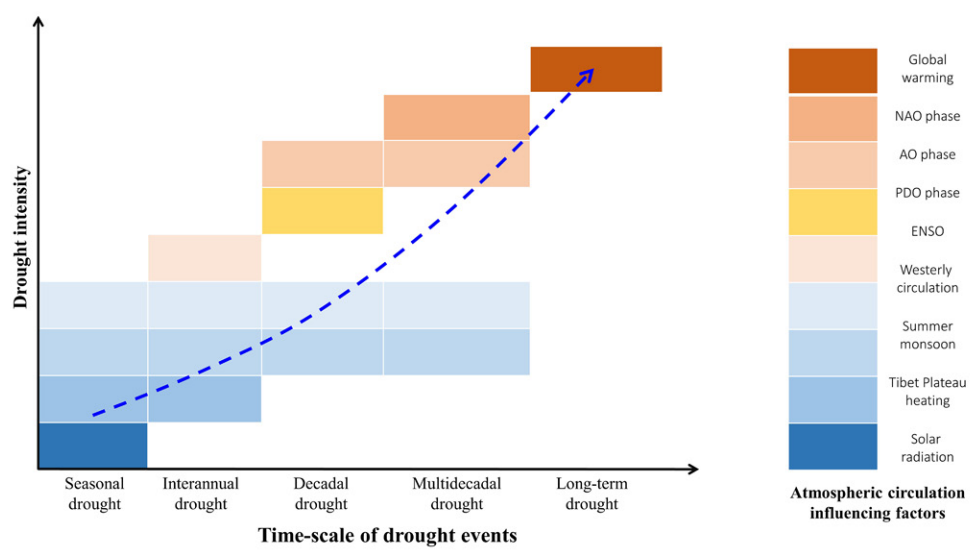

Fig. 16. Schematic of intensity and main influencing factors at different time scales of drought events. The horizontal axis represents the time scale of drought events, the vertical axis denotes the intensity of drought events, and filled rectangular blocks indicate atmospheric circulation factors affecting drought events, with the meaning of different colored blocks shown in the legend on the right. Rectangular blocks corresponding to different time scales represent the main atmospheric circulation factors affecting that type of drought event, and the thick blue dashed line denotes the intensity of drought events at different time scales.

of different atmospheric circulation factors or oceanic modes on drought formation and development at different time scales.

Third, examining the characteristics of land–atmosphere multiprocess coupling in the NDPB against the backdrop of climate warming and their promotion mechanisms for the development of major droughts is important. By analyzing observations and test data as well as conducting sensitivity experiments in land–atmosphere coupled numerical simulations, it is practical to investigate the processes of energy, moisture, and kinetic energy exchange and transport from soil → vegetation → the boundary layer → the troposphere → the stratosphere during major drought events in the NDPB. Delving into the multilevel, multipathway, multiscale, and multiprocess coupling characteristics between land and atmosphere; exploring the action mechanism of the feedback processes among land surface thermal, moisture, physiological, and ecological factors in the land–atmosphere coupling process for the transmission of drought signals and the process of drought-induced disasters; and revealing the nonlinear effects of the coupling processes among land surface temperature, evaporation, humidity, and precipitation on drought formation and development are critical. Moreover, for major drought events in the NDPB, it is essential to systematically analyze the response characteristics of water and energy cycle processes among the atmosphere, soil, and vegetation against atmospheric circulation factors such as the westerly jet and monsoon under climate warming. It is also essential to study the chain effects of land–atmosphere interactions through responses to climate warming on drought formation and development, as well as explore the impact mechanisms of climate warming on key drought control factors and reveal the characteristics of land–atmosphere multiprocess coupling in this context and the promotion mechanisms for major drought development (Fig. 15b).

In particular, to explore the impact mechanisms of land–atmosphere coupling on major droughts in the NDPB, it is imperative to consider different perspectives such as spatial scale, temporal scale, and physical processes. For the land–atmosphere coupling at different spatial scales, from a physical perspective, this includes microscale, local small scale, and regional scale; from an observational technology perspective, it encompasses ground observation footprint scale, satellite pixel scale, and model grid scale. Regarding temporal scales, at the diurnal scale, there is coupling between the land surface radiation balance and boundary layer clouds through land surface energy processes; at the seasonal scale, coupling occurs between the soil temperature, moisture, and boundary layer clouds and land surface radiation balance through land surface evapotranspiration; and at the interannual scale, coupling occurs between the solar radiation and vegetation through land surface radiation balance and aerosol processes.

Land–atmosphere coupling involves different physical processes and is more complex, requiring an understanding of both positive and negative feedback mechanisms (Fig. 17). Positive feedback processes may include 1) drought intensification → reduced surface latent heat → decreased atmospheric water vapor → increased dewpoint spread → reduced precipitation → further drought intensification and 2) drought intensification → thickening of the boundary layer and enhanced entrainment at the boundary layer top → decreased atmospheric water vapor and reduced moist static energy → level of free convection (LFC) → LFC further away from the boundary layer top → reduced precipitation → further drought intensification. Negative feedback processes may include two different mechanisms: 1) drought intensification → increased surface sensible heat → enhanced vertical motion over heterogeneous surfaces → increased precipitation → drought mitigation; and 2) drought intensification → increased surface sensible heat → enhanced atmospheric turbulence and entrainment at the boundary layer top → thickening of the boundary layer → boundary layer top closer to LFC → increased precipitation → drought mitigation.

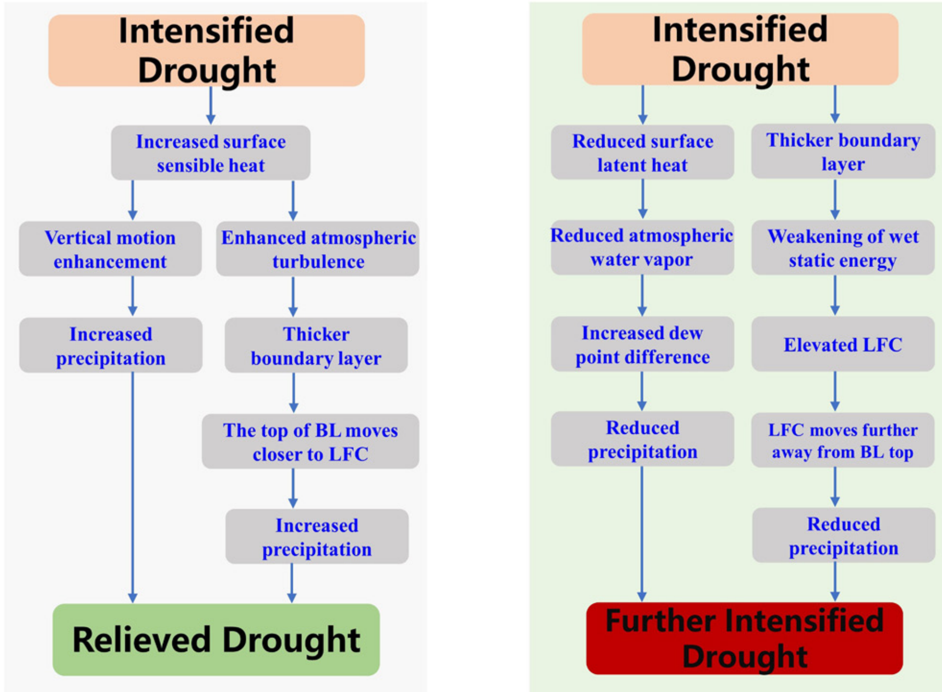

Fig. 17. Schematic diagram of land–atmosphere multiprocess interaction [(left) positive feedback and (right) negative feedback].

Fourth, investigating the synergy mechanism of atmospheric circulation and land–atmosphere coupling on major droughts in the NDPB is pivotal. This involves analyzing the ratio and matching relationships of the multiple physical elements that contribute to major drought events in the NDPB, such as dynamic, energy, and moisture conditions. Their response characteristics to changes in atmospheric circulation and land surface processes need to be thoroughly researched. Key areas of investigation include 1) the interaction mechanisms between local atmospheric circulation controlled by land–atmosphere coupling and large-scale circulation backgrounds, 2) the dynamic and thermal structures of typical drought circulation patterns under different land surface physical conditions and their climatic dynamic characteristics during the evolution process (Fig. 15c), 3) analyzing different combinations of multilevel and multipathway land–atmosphere coupling with multifactor and multiscale atmospheric circulation to explore the main characteristics of drought formation and development under different combinations, and 4) studying how the influence of atmospheric circulation on major drought changes under different intensities of land–atmosphere coupling.

Four typical synergistic modes of atmospheric circulation and land–atmosphere coupling can be mainly selected to compare and analyze the impact patterns of mutual synergy on major droughts in the NDPB. These modes include normal land–atmosphere coupling with normal atmospheric circulation, normal land–atmosphere coupling with abnormal atmospheric circulation, normal atmospheric circulation with abnormal land–atmosphere coupling level, and abnormal land–atmosphere coupling level with abnormal atmospheric circulation. Additionally, the synergistic combinations of different circulation factor anomalies and land–atmosphere coupling levels can be further subdivided for detailed analysis. Numerical models can serve as a basis for designing sensitivity tests of land surface processes and atmospheric circulation coupling under different conditions. These include no land surface processes with atmospheric circulation (namely, using lower boundary forcing instead of a land surface process model), single land surface physical quantities with atmospheric circulation coupling, partial single land surface physical quantities with atmospheric circulation coupling, and all land surface physical quantities with atmospheric circulation coupling.

Fifth, developing the whole-chain refined monitoring techniques for major drought progressive processes and predictive methods for multifactor synergistic effects in the NDPB is important. By analyzing the "whole-chain" transmission and development characteristics of significant agricultural and ecological drought events under varying climatic and environmental conditions, we can better understand the progression from meteorological drought to soil drought → crop (or natural vegetation) physiological drought → crop (or natural vegetation) ecological drought → crop yield (or vegetation biomass) decline → agricultural (ecological) benefit reduction. Developing drought monitoring indices requires considering the effects of climate warming and the sensitivity of different plant growth stages. It also involves revealing the mechanisms by which drought control factors at different scales influence drought formation and development. This approach aims to establish monitoring methods for major droughts that simultaneously consider drought impact sensitivity, progressive development characteristics, and multiscale drought variation patterns. Predictive methods for major droughts focus on understanding the relationships between drought occurrence and development in the NDPB, atmospheric circulation factors, and land–atmosphere coupling elements. This entails developing predictive methods that consider multifactor rhythms, improving key land surface parameterization relationships affecting drought formation and development, such as moisture processes and their physiological and ecological coupling. Additionally, it involves enhancing the capability of climate-coupled models to simulate the synergistic effects of atmospheric circulation and land–atmosphere coupling on major droughts and ultimately establishing a dynamic and statistically combined prediction method for major droughts in the NDPB (Fig. 15d).

6. Conclusions

Currently, major drought issues are closely related to global change, ecological environment, socioeconomic factors, and sustainable development, making them a prominent international interdisciplinary research hotspot. With the intensification of global climate warming and the increasing sensitivity of various social sectors to drought impacts, the complexity of major drought issues has further increased, posing significant theoretical and technical challenges for research on major droughts.

The NDPB is the most prominent drought-prone region in China, yet its emergence is not coincidental. This study introduces the scientific framework of the NDPB, providing a comprehensive analysis of its fundamental characteristics, the evolution of drought research, and the key scientific challenges ahead. Its formation involves both significant regional factors and certain global factors, essentially representing an extreme regional state in the evolution of the global climate system. Situated at the periphery of the Asian monsoon, the NDPB experiences droughts primarily driven by the synergistic interplay of land–atmosphere coupling and multifactor atmospheric circulation. With the intensification of climate warming, the drought characteristics of the NDPB may become more pronounced owing to the more significant response of precipitation and temperature variations to climate warming in this region, as well as more active interactions among Earth's systems.

A historical review of drought research in northern China reveals a progression from statistical assessments to investigations of atmospheric circulation and land–atmosphere interactions, yet focused studies on the NDPB remain limited. Despite some progress in major droughts in the NDPB, there is considerable inconsistency, primarily owing to the long-chain progression of major droughts. Future efforts should focus on understanding the rules of drought progression chains to develop comprehensive drought monitoring methodologies that can govern the whole chain of drought progression processes. High uncertainty in major drought prediction is attributed to an insufficient understanding of the complex formation mechanisms. To address these gaps, this study proposes key research priorities: conducting targeted field experiments to enhance understanding of the NDPB land–atmosphere interaction dynamics, quantifying the effects of multifactor synergies and multiscale interactions to refine drought prediction accuracy, developing full-chain monitoring technologies to elucidate drought transmission from meteorological to ecological impacts, and evaluating the multifaceted drought responses under climate warming to inform adaptive management strategies. These research avenues promise to drive theoretical advancements in the NDPB drought studies while offering valuable insights for drought mitigation in monsoon transition zones globally.

In recent years, China's advancements in meteorological satellite remote sensing technology and atmospheric numerical simulation technology have been significant. The meteorological big data analysis and new technologies like artificial intelligence are also witnessing fast development. China's comprehensive meteorological observation system has become increasingly complete, and the field scientific experiment system has gradually matured. The China Meteorological Administration's atmospheric/land surface reanalysis datasets and land surface data assimilation systems (CRA and CLDAS) have also achieved initial success, providing a solid foundation for studying major droughts in the NDPB. In the future, it is essential to adhere to the principle that "scientific research should not only be at the international forefront but also address key socioeconomic development arenas, advancing society and the economy." Efforts should focus on the fundamental theories and core technologies of major droughts in the NDPB, promoting interdisciplinary and technological integration in drought research and fostering deep cooperation between departments and internationally. Mobilizing research efforts and resource investments in drought studies will create a strong collaborative force, aiming for new breakthroughs in understanding the formation mechanisms and developing effective prediction methods for major droughts in the NDPB.

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