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• REVIEW •

Advances in Research on Climate Change and Its Effects on the Arid and Semi-Arid Regions of China over the Past Century

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ABSTRACT

Arid and semi-arid regions constitute approximately one-third of the total land area in China and are vulnerable to the effects of global climate change. Over the past century, a large number of studies have investigated regional climate change and its impacts. However, the conclusions are inconsistent due to differing research perspectives, and this has highlighted the urgent need to obtain systematic, scientific knowledge through review and synthesis. This study, based on a survey of all available literature, reviews the evolution of regional climate change and its effects in the arid and semi-arid regions of China over the last century. The present review examines three aspects of the surveyed previous studies: data, methods, and subjects, and then summarizes essential scientific findings into four subject areas: the origin and expansion of arid and semi-arid regions, the characteristics of climate change in these areas, the drivers of climate change in arid and semi-arid zones, and the consequences of climate change in such environments. Finally, six key directions for future research on climate change and its effects on the arid and semi-arid regions of China are proposed.

Key words: climate change, impact, progress and prospects, arid and semi-arid regions of China

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1. Introduction

Arid and semi-arid areas across the globe are considered to be climate change-sensitive and ecologically fragile regions and are uniquely positioned in the global climate system (Xu et al., 2016; Chen, 2021). Over one-third of the total land in China is classified as arid and semi-arid (Fig. 1), and climate change has substantially affected the ecological and natural environment, water resources, and social and economic development in these regions. Therefore, a series of major national strategies, such as the "West China Development" and the "Belt and Road" initiatives have been implemented. Climate change and its effects on the arid and semi-arid areas of China have been a concern to all sectors of society and it is an important scientific issue that the government and the science community are working hard to solve (Zhu, 1972; Xu, 1997; Zhang et al., 2000, 2019a, 2021a; Ding and Wang, 2001; Huang et al., 2013; Guan et al., 2019; Zhang Q. et al., 2022; Li Z. Y. et al., 2024).

Researchers have investigated climate change in the arid and semi-arid areas of China over the last 100 years.

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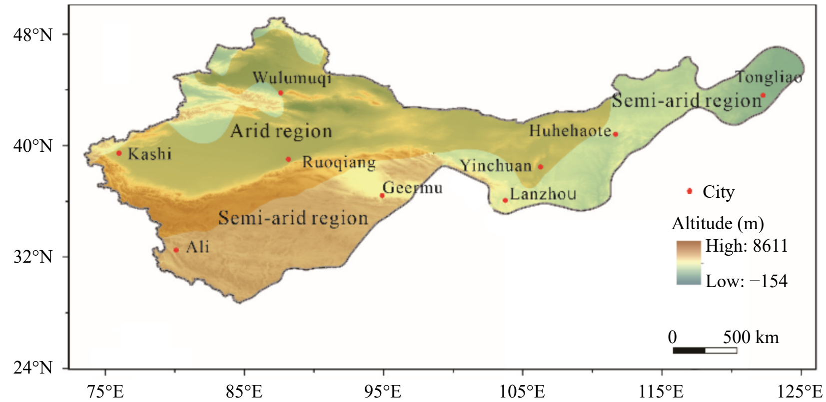

Fig. 1. Distribution of the arid and semi-arid regions in China (Zhu et al., 2023).

The progressive improvement in observational instruments, ongoing refinements to technical methodologies, and shifting focal points have led to the continual evolution of research data, methods, and subjects (Zhu, 1972; Wang, 1993; Zhang, 1996; Sun, 1997; Xu, 1997; Zhang et al., 2012, 2019b; Huang et al., 2013, 2016; Yao et al., 2022). This has led to the emergence of several relatively distinct phases and the depth of the investigations has progressively intensified as the research data, methodologies, and subjects have evolved. Furthermore, perspectives have been consistently modified and scientific comprehension has been enhanced (Li et al., 2015; Huang et al., 2019; Zhang et al., 2021b, 2023a; Yao et al., 2022; Ding et al., 2023). Nonetheless, a single study is inherently biased and constrained. Therefore, synthesis and induction methodologies need to be used to obtain a systematic and comprehensive scientific understanding and to establish a scientific consensus that will advance the innovative development of research into solid knowledge on regional climate change and its impacts.

This study systematically reviews research processes, summarizes advances, consolidates the scientific consensus, and derives insights into future research directions by integrating literature on climate change and its effects on the arid and semi-arid regions of China over the past century. This review is a crucial reference that can be used to comprehensively advance research into regional climate change and its consequences.

2. Research progress on climate change and its impacts on arid and semi-arid regions

Research on climate change and its effects on the arid and semi-arid regions of China has consistently advanced over the last century. It can be categorized into several developmental phases, each exhibiting unique attributes concerning study data, objectives, and methodologies.

2.1 *Development of the research data*

2.1.1 *Research based on the available literature*

Before the 1950s, the absence of observational data meant that climate change in the arid and semi-arid regions of China was predominantly assessed using literature analyses. Many studies concentrated on climate change, floods, and droughts within historical contexts (Zhu, 1925; Tu and Zhang, 1944) and the study of historical documents proliferated after the revolution. Li (1955) summarized cold wave phenomena, noting their frequency, intensity, and extensive reach during winter, and Zhu (1972) showed that a regional phenological difference of 4 days corresponded to the impact of a one-degree latitude variation and utilized this metric to estimate temperatures in the arid and semi-arid regions of China during the Middle Ages (476 AD–1453 AD).

2.1.2 *Research based on instrumental data*

Since the 1950s, the academic community has used limited observational data to preliminarily investigate climate change in the arid and semi-arid regions (Bai and Xu, 1988; Gao, 1989). Advances in meteorological observation instruments and the aggregation of meteorological data have allowed researchers to progressively utilize observational data in their studies. Xu (1997) and Sun (1997) performed a systematic analysis of regional climate change; Li et al. (1997) studied regional summer precipitation in the northwest; Shi et al. (2002) reported that there had been a transition from warm and dry to warm and humid conditions in the arid northwestern region; and Zhang et al. (2021b) identified new warming and humidification characteristics in Northwest China.

2.1.3 *Research relies on scientific field observations*

Since the late 1980s, China has conducted a succession of extensive land surface process experiments, including the "Heihe Area Land–Atmosphere Interaction Observation Experiment" (Hu and Gao, 1994), the "Land–Atmosphere Interaction Experiment in the Arid

Area of Northwest China" (Zhang et al., 2005), and the "Loess Plateau Land Surface Process Experiment" (Zhang et al., 2012). The experimental data from these studies show how land surface processes in arid and semi-arid regions affect climate change (Zhang et al., 2014; Yue et al., 2015). The progressive establishment of several long-term scientific experimental observation stations at the beginning of the 21st century yielded more systematic and standardized observational data and Zhang et al. (2014) used data from the Semi-Arid Climate and Environment Observation Station (SACOL) (Huang et al., 2008) to investigate the correlation between the regional land surface energy balance and climatic factors.

2.1.4 *Research dominated by multi-source data*

At the beginning of the 21st century, multi-source data, including reanalysis and satellite remote sensing data, began to be used in climate change research and augmented the existing data concerning climate change in the arid and semi-arid regions of China. These new datasets included extensive grid data from the NCEP/NCAR in the United States, the Climatic Research Unit (CRU) data from the University of East Anglia in the United Kingdom, first generation land surface reanalysis data from China (CRA40/Land), and fifth generation atmospheric reanalysis data from ECMWF (ERA5). Additionally, satellite remote sensing data, such as the Normalized Difference Vegetation Index (NDVI) and the Leaf Area Index (LAI), have also been extensively utilized to broaden the scope of research (Luo et al., 2003; Sun et al., 2021; Li J. Z. et al., 2024). In recent years, the utilization of multi-source data has elevated the research data conditions to a new level.

2.2 *Development of research methods*

2.2.1 *Research based on qualitative analysis*

Before the 1950s, most conclusions were based on qualitative data and in 1981, the Chinese Academy of Meteorological Sciences (1981) used historical data to create a qualitative map depicting the drought and flood distribution from 1947 to 1979. In addition, pollen, ice core, and other proxy data analyses revealed a warm phase in the dry region of northwest China. However, the extent of the temperature increase relative to today varied. For example, the temperature difference between the warm period and today reported by Shi (1992) was more significant than that reported by Wang and Gong (2000) and it remains a challenge to ascertain whose conclusion is more precise.

2.2.2 *Research based on climate statistical diagnosis*

Besides statistical analysis, climate statistical diagnosis also requires a sequence of scientific conclusions. Statistical diagnosis improves the quantitative analysis of climate change characteristics and allows scientific assessments of their causes (Wang, 1993). Climatic statistical analysis and diagnostics are intricately intertwined in current scientific research. The progressive accumulation of observational data since the 1980s has allowed researchers to employ statistical diagnostic methods, including empirical orthogonal decomposition, wavelet analysis, and mutation detection, to elucidate the characteristics of regional climate change (Shi et al., 2002; Huang et al., 2012; Zhang et al., 2021a).

2.2.3 *Research based on climate dynamics analysis*

Climate dynamics analysis is an important approach for investigating climate change because they diagnose and evaluate the climate dynamics system and its link with climate change, and can be used to investigate the dynamic mechanisms underlying climate change. The climate dynamics systems most pertinent to the climate in the arid and semi-arid regions of China are primarily based on the temperature conditions associated with the underlying surface of the Qinghai–Xizang Plateau (QXP), atmospheric circulation patterns, and the western Pacific subtropical high-pressure system. Previous studes have indicated that anomalous latent heating of the QXP induces alterations in the Qinghai–Xizang high pressure, the western Pacific subtropical high, the Asian monsoon, and the mid- to high-latitude circulation of Eurasia, and these changes subsequently impact regional climate change (Luo et al., 2003; Wei et al., 2021b; Yu et al., 2022).

2.2.4 *Research based on a combination of climate statistics and climate numerical simulation*

The rapid development of computer technology since the 1980s, statistical methods, and numerical predictions (Luo and Li, 2014; Zhang M. Q. et al., 2022) has significantly improved the simulation performance of climate models. Improvements in statistical diagnosis and numerical simulation, particularly when combined with statistical analyses and the numerical simulation of climate prediction (Huang et al., 1993; Su et al., 2023), have improved climate prediction ability in the arid and semi-arid areas of China (Yang et al., 2024). Furthermore, in-depth regional climate change research has also been undertaken by combining diagnostic analyses with continuously developing numerical methods and these new techniques have become powerful research tools (Zhao et al., 2014; Yang Y. F. et al., 2019; Wang et al., 2021).

2.3 *Development associated with research subjects*

2.3.1 *Research focused on essential climate elements*

Temperature and precipitation are the fundamental meteorological variables that indicate climate change. Climate change investigations in the arid and semi-arid regions of China predominantly utilized instrumental temperature and precipitation data (Ma, 2007) and Zhai and Zou (2005) employed low-resolution temperature and precipitation data to investigate regional warming and moisture level changes, respectively. Furthermore, researchers have recently employed high-resolution temperature and precipitation data to systematically examine regional warming and moisture level changes (Zhang et al., 2021b; Zhu et al., 2023).

2.3.2 *Research based on potential evapotranspiration*

Potential evapotranspiration is an important indicator of climate change. The growing focus on climate variability, specifically on dryness and wetness, has led to the extensive use of potential evapotranspiration when researching climate change in the arid and semi-arid regions of China (Huang et al., 2013; Ren et al., 2022). The three primary approaches for determining potential evapotranspiration are the Thornthwaite (Yang et al., 2012), Penman–Monteith (Allen et al., 1998), and the Holdridge methods (Zhang C. J. et al., 2016). The Penman–Monteith approach is endorsed by the Food and Agriculture Organization of the United Nations and is the method that is most extensively utilized at present. Many scientists in China have investigated alterations in regional dryness and wetness through the lens of potential evapotranspiration and have reported a number of significant conclusions (Zhang C. J. et al., 2016; Zhang H. L. et al., 2016; Ren et al., 2022).

2.3.3 *Research based on extreme weather and climate*

At the start of this century, the changes in severe climate events became increasingly important and the examination of climate change in the arid and semi-arid regions of China was no exception. Initially, most scientists employed the absolute threshold of conventional meteorology to quantify exceptional events (Yang et al., 2005, 2006). However, the climatic variations across regions mean that using a singular absolute criterion lacks scientific validity. Subsequently, scientists established a threshold for extreme climate events using the percentile technique and investigated climate change in the arid and semi-arid regions of China (Yang et al., 2007, 2008; Wang et al., 2008). In particular, drought and sandstorms have attracted considerable interest because they are the most important extreme events in the region (Ma, 2007; Li et al., 2022).

2.3.4 *Research on multiple spheres of the climate system*

The climate system comprises the atmosphere, hydrosphere, cryosphere, lithosphere, and biosphere, all of which are integral to climate change. Oceanic influences on climate change in the arid and semi-arid regions of China are particularly significant (Guan et al., 2019; Zhou et al., 2024). Soil moisture contributes to climate change through its impacts on surface energy and the water balance and their subsequent effects on atmospheric sensible and latent heat, surface albedo, and heat capacity (Zhang Q. et al., 2016a; Gao et al., 2023; Jiang et al., 2023). Arctic sea ice (Wu, 2018) and snow on the QXP (Che et al., 2019) also strongly influence regional climate change.

3. Primary understanding about climate change in and its impacts on arid and semi-arid regions

Over the past century, research on climate change and its impacts across the arid and semi-arid areas of China has gradually deepened and a large number of important results have been reported. The leading scientific conclusions are summarized based on the following aspects.

3.1 *Causes of the formation, expansion, and contraction of the arid and semi-arid areas*

3.1.1 *Hadley circulation as the main reason for the expansion and contraction*

The Hadley, Ferrel, and polar circulations are the principal circulations associated with the yearly, winter, and summer mean circumpolar circulations in the Southern and Northern Hemispheres. Despite being situated in the mid-latitudes of the Northern Hemisphere, the arid and semi-arid regions of China are positioned within the descending zone of the Hadley circulation and are influenced by the QXP. Consequently, the region exhibits arid climatic traits throughout the year (Yan et al., 2019) and this is the primary factor contributing to the formation of arid and semi-arid zones in China.

3.1.2 *Distance from the ocean and control by the "westerly wind mode"*

The arid and semi-arid regions of China are located a long way from the ocean and are influenced by the westerly circulation throughout the year. However, the water vapor supplied to the region by the westerly circulation is constrained (Wang, 1997; Qian et al., 1998). Chen et al. (2023) reported that the arid areas of central Asia exhibit a "westerly mode" that markedly contrasts with monsoon regions at the millennium–centenary–interdecadal timescale of the current interglacial epoch (Fig. 2). The external force driving the climate system operates at the suborbital scale and the primary determinant of the "westerly mode" on a century-to-decadal scale is predominantly governed by the internal variability of the climate system (Chen et al., 2019).

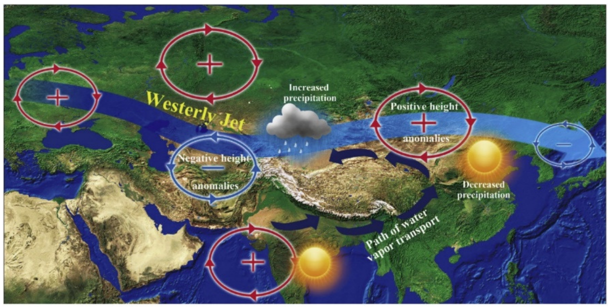

Fig. 2. Schematic diagram showing the formation mechanism for the "westerly wind mode" from the centennial to decadal timescale (Chen et al., 2019).

3.1.3 *Uplift provided by the QXP*

The Qinghai–Xizang Plateau is crucial to the development of arid and semi-arid regions in China (Wang, 1997; Qian et al., 1998). The QXP obstructs the flow of warm, humid air from the Indian Ocean to inland Asia. This results in descending air currents on the northern flank of the plateau, which contribute to a dry climate in the Asia interior (An et al., 2006; Luo et al., 2024). Consequently, the elevation of the QXP plays a significant role in the development of arid and semi-arid regions in China (Wu et al., 2012; Tang et al., 2013; Liu et al., 2015; Luo et al., 2023).

3.1.4 *Semi-arid areas have expanded since 1950s*

The semi-arid regions in China have expanded since the 1950s (Li et al., 2015; Jiang et al., 2017; Huang et al., 2019; Wei et al., 2019; Gao et al., 2020), predominantly in the eastern portion of the semi-arid zone (Li et al., 2015). However, there have been many contradictory reports about arid regions and how they have changed. Huang et al. (2019) reported that there had been little change in the area covered by arid regions; Jiang et al. (2017) reported that the area covered by arid regions fluctuated; and Gao et al. (2020) suggested that the area covered by arid regions had considerably decreased. The discrepancies in research findings may be attributed to the duration of the study and their delineation of the arid zone.

3.2 ***Main characteristics of climate change in the arid and semi-arid regions of China***

3.2.1 *Two cold–dry periods and two warm–wet periods identified at the millennial scale*

The temperature fluctuations across the arid and semi-arid regions of China over the last 2000 years can be categorized into four distinct phases: two cold periods from 0 to 600 AD and from 1350 to 1850 AD and two warm periods from 600 to 1400 AD and since 1850 AD (Zhu, 1972; Zheng and Wang, 2005). Despite unique regional variations in arid and humid transitions, warm intervals often align with moist phases, whereas cold intervals correspond to arid phases. Consequently, the climatic fluctuations in cold and warm periods and dry and wet conditions over the past 2000 years can be broadly categorized into four phases: the cold and dry phase from the Eastern Han Dynasty to the Southern and Northern Dynasties, the warm and wet phase during the Sui, Tang, and Song Dynasties, the subsequent cold and dry phase from the Ming and Qing Dynasties, and the warm–wet phase from 1800 AD to the present day (Hao et al., 2020).

3.2.2 *Consistent warming trends, dry and wet fluctuations, and regional differences*

The arid and semi-arid areas in China have undergone some of the most pronounced global warming over the last century (Ji et al., 2014; Huang et al., 2016). Precipitation slightly increased from the early 1900s until the 1940s, followed by a substantial decline by the late 1970s. Then there was a precipitation resurgence at the beginning of the 2000s that had considerable amplitude (Cong et al., 2017). Regionally, the arid and semi-arid west experienced rain fluctuations up to 1960, followed by a considerable increase in precipitation post-1960. However, the climate in the central region cycled between dry and wet phases, with wet phases prevailing over dry phases from the 1920s to the 1980s. Over the last three decades, the arid phase has exceeded the duration of the humid phase (Zhang et al., 2023a). The eastern region experienced aridity from the early 1900s to the 1940s, followed by increased precipitation from the 1940s to the 1970s. Then it transitioned from wet to dry in the late 1970s (Huang, 2006; Xu and Wei, 2006).

3.2.3 *Precipitation fluctuations over past half-century*

Between 1971 and 2019, the warming rates in the arid and semi-arid regions of China were 0.399°C decade^{-1} and 0.371°C decade^{-1}, respectively (Zhu et al., 2023). Warming intensified in the 1980s but then decelerated in most areas after 1998. There was another progressive increase in the past decade or so, but there were seasonal variations (Ran et al., 2014; Yan et al., 2021). The arid and semi-arid western regions showed a distinct upward trend in precipitation (Zhang Q. et al., 2022), whereas the middle and eastern areas showed a downward trend where there were reductions in both precipitation and the frequency of rainy days (Zhang et al., 2019a).

3.2.4 *Warming and humidification since 2000s*

Temperature variations in the arid and semi-arid regions of China have mirrored global trends since the beginning of the 21st century. The temperature increase rate decelerated in the 2000s and then accelerated and since 2013, the temperature anomaly has increased by 0.5°C (Yao et al., 2022; Zhu et al., 2023). Precipitation was predominantly low before 2000, but has risen markedly since the beginning of the 21st century (Ma et al., 2018, 2020) and has been relatively high since 2010 (Fig. 3). The trends observed in the western arid and semi-arid regions during the 1980s showed that warmth and humidity had intensified towards the east and that the regions had significantly expanded (Zhang et al., 2021b; Ding et al., 2023).

3.2.5 *Greater warming in China*

Similar to other arid and semi-arid regions, the arid and semi-arid zones in China are significant elements of the global landscape. Huang et al. (2012) noted that global land temperatures have increased since 1900, beginning in the high latitudes of the Northern Hemisphere and in subtropical areas. The subtropical regions of the Southern Hemisphere began warming, whereas the tropics underwent both cooling and warming phases. From 1900 to the present, the areas experiencing the most rapid cumulative warming have had precipitation levels between 200 and 500 mm (Fig. 4). In particular winter temperatures in the midlatitudes of the Northern Hemisphere have risen by 1.89°C (Table 1). Consequently, the arid and semi-arid regions in China have experienced some of the largest temperature increases over the past century (Ji et al., 2014).

3.2.6 *Changes in land surface moisture and energy*

The surface evapotranspiration response to increasing temperatures in the semi-arid areas of China varies markedly with precipitation levels. There is no regional response to yearly rainfalls of 200–400 mm, whereas wetter regions show a positive response and drier regions have a negative response (Zhang et al., 2018, 2019b). These responses are generally universal, but the level of the response differs across regions. Furthermore, climate warming has led to a marked rise in pan evaporation in the semi-arid regions of China and this rise shows an inverse "evaporation paradox" that diverges significantly from other regions (Zhang Q. et al., 2016b; Yang Z. S. et al., 2019) (Fig. 5). This phenomenon is primarily associated with reductions in low cloud cover and increases in wind speed and solar radiation. The gradient variations for latent heat and sensible heat fluxes in the semi-arid regions of China have markedly increased and exhibit mutation characteristics, with the mutation in sensible heat being more pronounced than that of latent heat flux (Zeng et al., 2016).

3.3 *Main factors driving climate change in the arid and semi-arid regions*

3.3.1 *Increased greenhouse gases*

Greenhouse gas emissions are the primary driver of global warming and arid and semi-arid regions in China are similarly affected (Zhang et al., 2021b, 2023a). Furthermore, the reduced heat capacities of the atmosphere and soil in arid and semi-arid regions amplify the impact of greenhouse gases. Greenhouse gases elevate surface temperatures, increase ground evapotranspiration, and enhance the precipitation recycling rate by increasing air moisture content. The precipitation recycling rate in the western arid and semi-arid regions rises 6%–8% from October to March (Kang et al., 2005). Greenhouse gases and aerosol emissions increase mountain snow and glacier melting, resulting in a better conversion of solid water to liquid water. This extra water is added to the local water cycle and increases the precipitation recycling rate (Zhang et al., 2023b).

3.3.2 *Oxygen cycle*

Historically, the significance of oxygen was overlooked when assessing climate warming. A reduction in atmospheric oxygen (Huang et al., 2018; Han et al., 2021, 2022; Li et al., 2021; Wei et al., 2021a) leads to in-

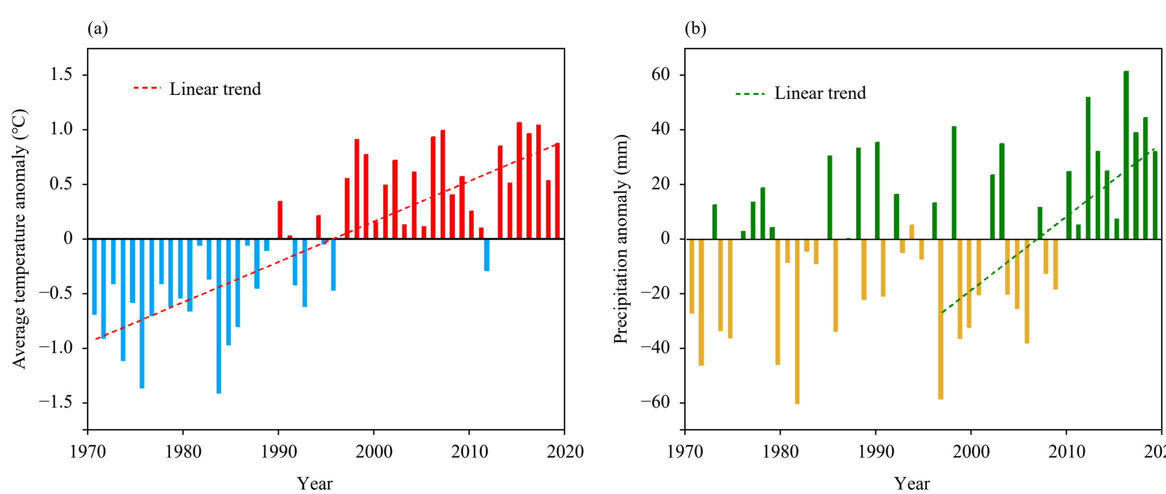

Fig. 3. Changes in (a) temperature and (b) precipitation in the arid and semi-arid regions of China over the past half century (Zhu et al., 2023).

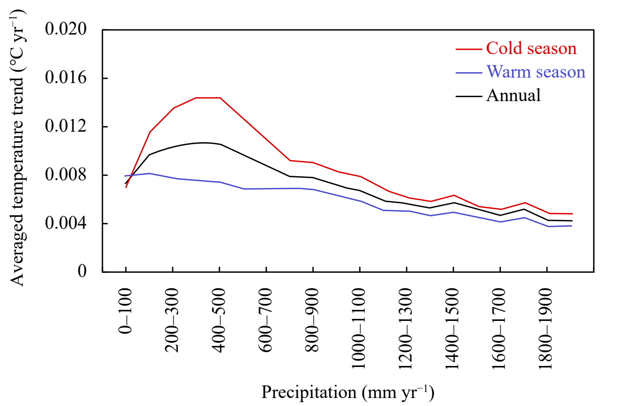

Fig. 4. Temperature variations under different precipitation types and different seasons (Huang et al., 2012).

Table 1. Temperature variation amplitude (°C) in different regions

	Global	Northern Hemisphere	20°–60°N	Europe	Asia	North America
Annual	1.13	1.23	1.33	1.18	1.51	1.19
Cold season	1.53	1.72	1.89	1.41	2.42	1.50
Warm season	0.79	0.81	0.85	0.95	0.68	1.06

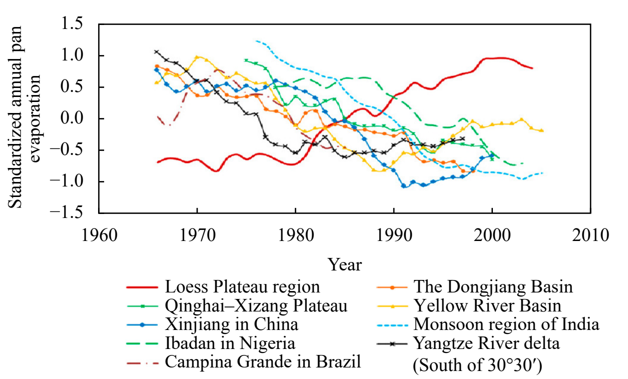

Fig. 5. Evaporation change trends in different regions of the world (Zhang H. L. et al., 2016).

creases in atmospheric radiation, which will elevate surface temperatures and significantly alter the climate system (Poulsen et al., 2015; Han et al., 2021, 2022). Under low oxygen conditions, the frequency of shortwave scattering by air molecules from the sun decreases, resulting in increased shortwave radiation at the surface. This increases the surface temperature and subsequently accelerates surface water circulation, which alters the precipitation and evaporation rates. Aridification occurs when the potential evaporation rate exceeds precipitation. In the high emission climate change scenario (RCP8.5), the oxygen cycle escalates with rising temperature, precipitation, and potential evaporation. Unsustainable oxygen production and consumption will increase the likelihood that dry ecosystems will be destroyed (Fig. 6).

3.3.3 *Atmospheric circulation*

The current humidification of the arid and semi-arid regions in China may be due to the multifaceted and multiscale impacts of atmospheric circulation, with primary influencing elements varying across different temporal scales (Zhang et al., 2023b). There are notable differences among humid climate regions (Zhang H. L. et al., 2016) and the Asian monsoon and westerly anomalies significantly influence multiscale climatic variations. In the 1980s, the intensification of westerly zonal circulation may have increased precipitation in the western arid and semi-arid regions (Gong et al., 2023). The Silk Road, Eurasia, North America, and Pacific teleconnection wave trains have contributed to the rise in regional winter precipitation since the 1990s (Ren et al., 2024). In addition, the meridional displacement of the subtropical westerly jet induces anomalous vertical and advective vorticities, which can increase regional precipitation (Zhang et al., 2021a, 2023b).

3.3.4 *Ocean processes*

The ocean remains a crucial source of water vapor even though the arid and semi-arid regions in China are far from the coast. The westerly belt causes water vapor from the Atlantic to penetrate the western boundary of the arid and semi-arid regions. The thermal disparity between the ocean and land can initiate monsoon activities, which affect the climate in arid and semi-arid areas (Zhang et al., 2023b). Oceans significantly influence global atmospheric circulation and affect the climate in arid and semi-arid regions (Huang, 2006; Cheng et al., 2024). Alterations to Pacific water temperatures can influence the severity and location of the westerly belt. An increase in sea temperatures leads to an intensification of the westerly belt, which then conveys greater amounts of water vapor to arid and semi-arid regions. In summary, anomalous sea temperatures can disrupt the westerly and monsoon circulations. These changes then affect the local region and climate (Ding et al., 2022; Wu et al., 2022; Wei and Yu, 2024).

3.3.5 *Land surface processes*

The ongoing expansion of human development and the exploitation of natural resources has resulted in land-use alterations and these influence climate change via land–atmosphere interactions (Zhang et al., 2023b). In recent years, land utilization changes in the arid and semi-arid regions have resulted in an increase in the amount of cultivated land and degraded grasslands and a decrease in forestland. These alterations will influence climate change via terrestrial surface processes. The extension of cultivated land will enhance soil water evaporation, increase air humidity, and influence precipitation.

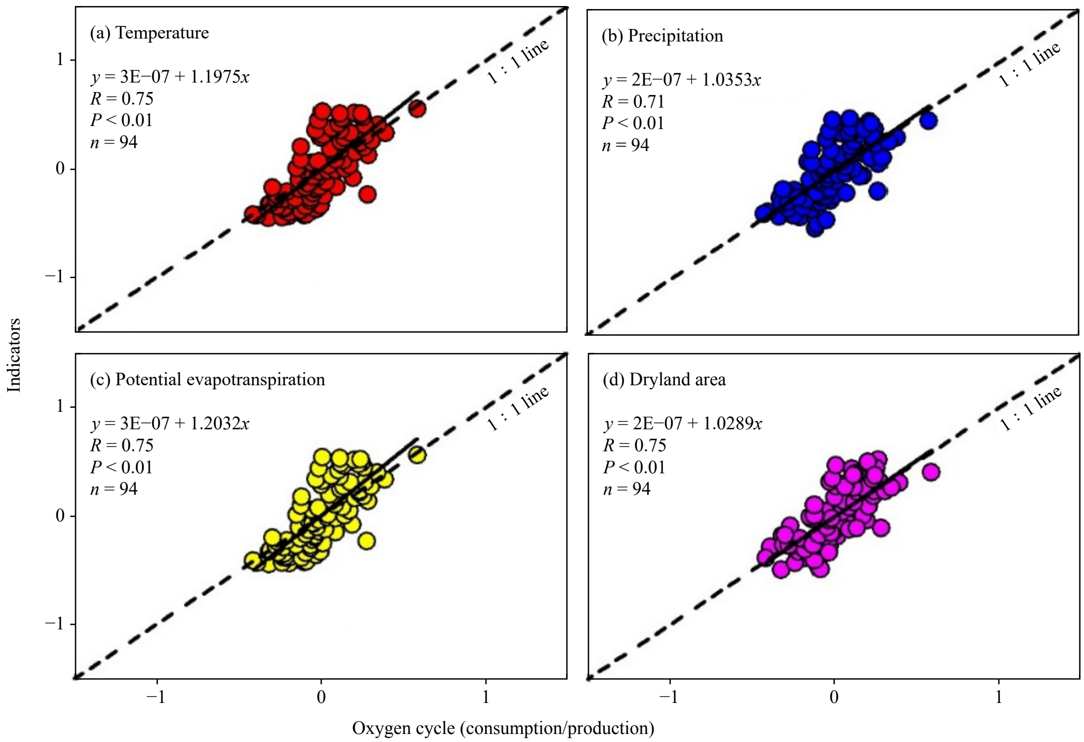

Fig. 6. Relationship between the oxygen cycle and climate effect in arid and semi-arid regions of China (Han et al., 2021).

Grassland degradation will decrease vegetation cover, increase soil erosion and desertification, and affect the surface energy balance and hydrological cycle. Deforestation will reduce the carbon sink capacity, increase greenhouse gas emissions, and intensify climate change (Zhang et al., 2023b; Zhu et al., 2023). Consequently, terrestrial surface processes exert a substantial influence on regional climate change.

3.4 *Impacts of climate change in the arid and semi-arid regions of China*

3.4.1 *Impact on terrestrial vegetation*

Climate change has a profound impact on terrestrial vegetation, with temperature and precipitation serving as the primary influencing factors. Vegetation changes in the arid and semi-arid regions of China are positively correlated with temperature and precipitation. Regional warming and increased humidity promote vegetation growth, as indicated by increasing NDVI in Fig. 7, but there are distinct regional variations. For instance, the warmth and moisture in this century enhanced vegetation coverage in the Hexi Corridor between 2000 and 2015, whereas the Loess Plateau, encompassing Gansu Longdong, Longzhong, and northern Shaanxi, suffered considerable vegetation degradation from 1982 to 2000; however, vegetation cover significantly improved between 2001 and 2018 (Writing Committee of Northwest Regional Climate Change Assessment Report, 2021).

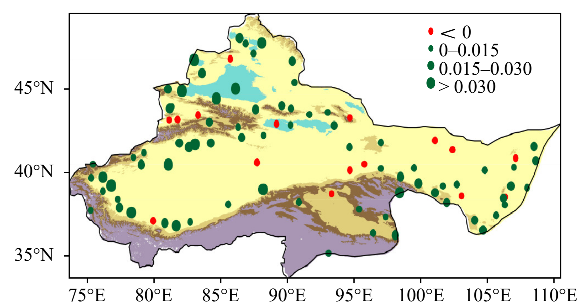

Fig. 7. NDVI changes in the arid region of Northwest China during 1981–2015 (Zhang et al., 2021a).

The warming and the increased precipitation experienced by most arid and semi-arid regions have led to ecological enhancement, but changing the long-term arid climate conditions in the short term is challenging.

3.4.2 *Impact on water resources*

A significant proportion of the river flow in the arid and semi-arid regions of China originates from glacier and snow melting. Alterations in glacier extent substantially influence terrestrial water storage and fluvial discharge. Climate warming decreased the area of inland glaciers in Tarim, China, by 3.3% between 1960 and 2001, the area covered by glaciers in the Qilian Mountains, China, dropped by 20.9% between 1956 and 2010, and runoff into the Urumqi River rose by 70% between

1993 and 2017 compared to the period 1959 to 1992. Since 1961, annual runoff into the Shule River has increased at a rate of 3.3 m^3 (10 yr s)$^{-1}$, while the Heihe River has experienced an increase of 2.0 m^3 (10 yr s)$^{-1}$, the Yarkant River 0.73 m^3 (10 yr s)$^{-1}$, and the Maras River 1.37 m^3 (10 yr s)$^{-1}$ as shown in Fig. 8 (Writing Committee of Xinjiang Regional Climate Change Assessment Report, 2021). These results suggest that climate change significantly affects regional water resources (Huang et al., 2017). This may present various opportunities. For example, increased precipitation and temporary glacier meltwater may enhance the flow of inland rivers. However, significant concerns have emerged, including the increased vulnerability of water resources and increased degradation of the biological environment (Gong et al., 2023; Ren et al., 2024).

3.4.3 *Impact on soil carbon*

Soil carbon is an important indicator of the services and functions provided by terrestrial ecosystems; it is crucial for the healthy development of ecosystems, and is one of the key elements affected by climate change (Ma et al., 2018; Chen et al., 2023; Fu and Ma, 2023). Since the beginning of this century, regional warming and the rise in humidity have increased carbon transfer from vegetation to soil via litter decomposition (Jiang et al., 2017). When additional carbon is introduced into the soil, it amalgamates with soil mineral particles to create aggregates of varying sizes, thereby safeguarding and enhancing soil carbon accumulation, which promotes soil fertility (Han et al., 2021, 2022). Climatic change may decrease soil carbon sequestration and increase the likelihood of carbon emissions into the atmosphere, which may impact regional and global carbon cycles and cause further climate change.

3.4.4 *Impact on agriculture*

Climate warming has led to an increase in the availability of light, heat, water, and carbon resources in the arid and semi-arid regions of China and these increases have expanded the potential agricultural planting area and increased yields. The cotton cultivation area in northern and southern Xinjiang has expanded (Writing Committee of Xinjiang Regional Climate Change Assessment Report, 2021); the boundary for winter wheat planting in Gansu has moved westward and northward to varying extents, with the Hexi region advancing northward by 130–180 km and westward by 80–170 km; the Gannan Plateau has expanded northward by 80–140 km and westward by 40–150 km; and the northern boundary for winter rapeseed cultivation in Gansu has shifted northward by an average of 40–300 km. Simultaneously, the yield per unit area of spring wheat in Hexi, Gansu, has risen by 3.18 kg hm^{-2}, while potato and corn yields have increased by 9.60 and 13.08 kg hm^{-2}, respectively (Li et al., 2010; Bao and Zhou, 2017).

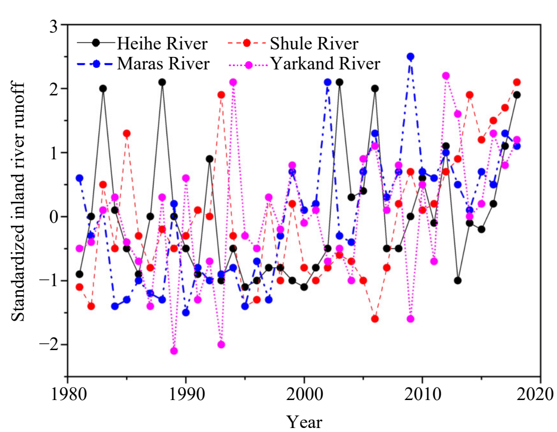

Fig. 8. Inland river runoff changes in the arid region of Northwest China during 1980–2020 (Zhang et al., 2023a).

3.4.5 *Impact on ecosystems*

Climate change alters regional ecological environments, which can shift the distribution and populations of some species (Ma et al., 2018; Fu and Ma, 2023). Species that show robust regional adaptability will broaden their distribution range, whereas those with low adaptability will experience survival challenges, population decline, or even potential extinction. The survival of certain rare and endangered species that depend on specific climatic conditions is jeopardized by climate change. Climate change may alter interspecies connections and potentially disrupt certain food chains and webs (Ma and Fu, 2005; Cong et al., 2017; Fu and Ma, 2023). For instance, decreases in specific flora may reduce the population of fauna that depend on them, which will impact the entire ecosystem equilibrium. Climate change affects regional species (Hu et al., 2018; Zhang et al., 2023a) and this can potentially lead to significant difficulties, including reductions in ecosystem stability and biodiversity (Guo, 2017; Zhang et al., 2023b).

4. Prospects

Over the past century, research on climate change in the arid and semi-arid regions of China has produced significant results about spatiotemporal distributions, formation mechanisms, attribution, and its impacts and a critical scientific consensus has developed. However, there are still many scientific issues that need to be addressed.

4.1 *A regional high-resolution scientific data base*

There are insufficient meteorological monitoring stations in the arid and semi-arid areas and this has led to considerable gaps in the datasets. Furthermore, discrepancies in multi-source meteorological data across spatial and temporal dimensions have impeded understanding about climate change. Therefore, more meteorological monitoring stations are required in the arid and semi-arid regions. In addition, integrating existing ground observations, satellite remote sensing, reanalysis data, and data assimilation technology can enhance the consistency and accuracy of the meteorological data. This data can then be used to create a high-resolution scientific dataset that will provide more reliable and scientifically robust support for comprehensive research on regional climate change.

4.2 *Responses of land–atmosphere coupled system to external forcing*

Various factors, including anthropogenic activities, internal variability, and external forcing, influence climate change in arid and semi-arid regions. Assessing the relative impact of multiple causes on climate change is crucial. Consequently, future research should focus on the roles played by internal variability, external forcing, and anthropogenic activities, their detection, and their attributions. High-quality multi-source data should be used to elucidate the regional disparities in land–atmosphere coupled system responses to external forcing and clarify the mechanisms underlying regional climate change and the correlations and differences among regions.

4.3 *Response of water cycle to a wetter regional climate*

The conclusions regarding the tendency towards climate humidification in the arid and semi-arid regions of China since the beginning of this century are derived from alterations in precipitation. However, it is not clear how regional surface water balances have changed. Consequently, improving the high-resolution climate and hydrological models must be prioritized. These improvements should increase the accuracy of water cycle process simulations, enhance model predictive capabilities, accurately assess actual surface evapotranspiration and runoff, and identify changes in the surface water balance. The data from these models will provide enhanced scientific support for regional water resource management.

4.4 *Regional extreme weather and climate events*

Climate warming increases the frequency and severity of extreme regional weather and climate events. Currently, research is concentrated on the alterations to and effects of the overall climate condition. The evolving legislation regarding extreme weather and climate events in China lacks clarity and the impact mechanisms are ambiguous. The current climate models have significant uncertainty levels when forecasting extreme occurrences. Consequently, future efforts should focus on enhancing the detection and attribution analysis of extreme weather and climate events and this research should be integrated with a coupled model comparison strategy to investigate potential future alterations in these phenomena. This approach would provide a scientific foundation for regional meteorological disaster prevention and mitigation.

4.5 *Multi-sphere interactions*

Regional climate change research has previously focused on conventional climate elements, such as temperature and precipitation. There has been little in-depth research on the changes in multi-sphere climate system components, such as surface radiation balance, sensible and latent heat, soil moisture, snow cover, freeze–thawing, and other land surface moisture and energy factors. Therefore, multi-spheric coupled climate system models and field-based scientific experimental observation station networks at different temporal and spatial scales should be developed to improve the comprehensive simulation capabilities of climate models for various sphere elements. The results should increase understanding about the interactions between various sphere elements, thereby improving knowledge about the laws and mechanisms associated with multi-sphere changes in the regional climate system and the ability to predict them.

4.6 *Different regional responses to climate change*

Atmospheric drought and land surface drought are not always linked. The transfer from atmospheric drought to land surface drought is conditional and not guaranteed. Certain studies have suggested that regional atmospheric drought is increasing due to climate change (Huang et al., 2019) and other studies have reported that the importance of land surface drought is decreasing (Berg and McColl, 2021). The changes in atmospheric and land surface drought are inconsistent. Consequently, it is important to comprehensively understand the intrinsic relationship between atmospheric drought and land surface drought, elucidate the transmission laws and mechanisms connecting them, clarify the reasons for the disparities in their responses to climate change, and enhance drought prediction and prevention capabilities.

5. Concluding remarks

The arid and semi-arid regions of China are situated to the west of the "Hu Huanyong Line" (Hu, 1935) (Fig. 9). The climatic conditions result in a scarcity of natural re-

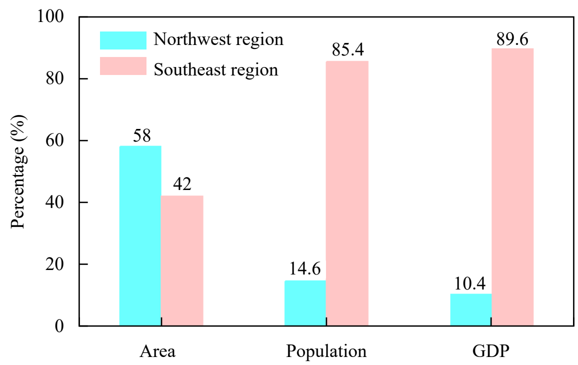

Fig. 9. Comparison of Indicators for the Northwest and Southeast of the Hu Huanyong Line over China in 2023.

sources essential for human subsistence in this region and this has contributed to their historically underdeveloped social and economic status. Less than 8% of the total Chinese population lives in the arid and semi-arid areas, even though they cover one-third of China. This has led to a significant disparity in social and economic growth across China. The primary factor hindering the advancement of high-quality development in China is unbalanced and inadequate development.

To address this issue, equitable development between eastern and western China needs to occur. One way to achieve this is to undertake a comprehensive study on climate change in the arid and semi-arid regions of China and its effects on natural resources. Developing and utilizing natural resources and facilitating cross-regional allocation will address the resource deficiencies in the western region, overcome the natural constraints imposed by the "Hu Huanyong Line", and foster sustainable ecology and high-quality socio–economic development in western China.

The arid and semi-arid regions are not only globally distinctive climate and ecological zones, they are also abundant in wind and solar energy and can become important areas for introducing national strategies, such as the development of the western region of China and the establishment of the "Belt and Road" economic corridor. These two plans are central to the future growth of China. Current scientific advances need to be integrated into the execution of significant national strategies to facilitate the rapid, high-quality development of a region while also understanding the principles and future trajectories of climate change and its implications for ecological security, water security, energy security, and socio–economic development. This approach would provide scientific and technological support for the holistic development of the Chinese nation.

Simultaneously, the arid and semi-arid regions of China are emblematic of global climate change sensitivity and ecological fragility. They are exceptionally distinctive regions because the high-latitude, mid-latitude, and low-latitude circulation systems and the continental circulation system influence their climatic variations. The effects of these atmospheric interactions are more pronounced than in other regions across the globe. There are also significant impacts due to human activities and substantial terrain and thermal variations across the QXP. Consequently, the process by which regional climate change exerts its effects is highly intricate, current comprehension remains rudimentary, and significant scientific questions require further elucidation.

The national climate observatory and observation and research network established in the arid and semi-arid regions of China currently collects multiscale, multi-factor, high-precision data on various aspects of the climate system. This allows a comprehensive analysis of the changes in diverse elements of the climate system in the region and their interrelationships to be undertaken. China should establish a distinct initiative to undertake a thorough scientific inquiry into climate change and its regional impacts. The results from this initiative could be used to undertake extensive and systematic research that addresses critical scientific challenges, elucidates the interplay between climate change, the natural environment, and socio-economic development in the region, and determines how the "Hu Huanyong Line" affects the scientific issues that affect overall growth and development in China. Such a study would robustly support modernization of the nation.

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