Spatiotemporal Patterns of Climate Change in the Yellow River Source Region (1960-2019): Postprint

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Abstract

The Yellow River source region is a climate-sensitive area and ecologically vulnerable zone, as well as the primary runoff generation area of the Yellow River, and its climate change issues have attracted considerable attention. Using homogenized temperature and precipitation observation data from the Yellow River source region, this study systematically analyzes the variation characteristics of the regional average climate and extreme climate events over the past 60 years. The results indicate that from 1960 to 2019, the annual mean temperature, mean maximum temperature, and mean minimum temperature in the Yellow River source region exhibited consistent warming trends, with the magnitude of warming being greater in the eastern part than in the western part. The annual mean temperature in the region experienced an abrupt change around 2000, with the post-turning point warming rate reaching 0.61 ℃·(10a) -1, exceeding the warming rate of 0.37 ℃·(10a) -1 for the entire 1960-2019 period. From 1960 to 2019, the annual precipitation in the region showed a weak increasing trend [7.6 mm·(10a) -1], entering a phase of above-normal precipitation after 2003, with the average annual precipitation in the recent decade (2010-2019) reaching 610 mm. Precipitation increased in spring, summer, and winter, while decreasing in autumn; notably, summer and autumn precipitation decreased significantly in the eastern part of the region, exacerbating the risk of periodic drought. In the recent decade, both the average temperature and precipitation in the region reached their highest values in 60 years, indicating an overall warmest and wettest phase. Under the influence of continuous warming and wetting, the average extreme temperature threshold in the Yellow River source region showed a significant increasing trend from 1960 to 2019, while the number of frost days decreased. The annual maximum 3-day precipitation and the number of heavy precipitation days increased, with precipitation intensity strengthening, particularly pronounced in summer, which may pose risks and

challenges to ecological protection and water resource utilization in the source region and even the high-quality development of the entire Yellow River basin.

Full Text

Spatio-temporal characteristics of climate change in the Yellow River source area from 1960 to 2019

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Abstract

The source region of the Yellow River (SRYR) represents a fragile ecological environment sensitive to climate change and serves as the primary runoff-generating area for the Yellow River Basin. Climate change issues in this region have attracted widespread attention. Using homogenized temperature and precipitation observations from the SRYR, this study systematically analyzed changes in average climate and extreme climate events over the past 60 years. From 1960 to 2019, the annual mean temperature, mean maximum temperature, and mean minimum temperature in the SRYR showed consistent warming trends, with greater warming amplitude in the eastern than western parts of the source area. The annual mean temperature underwent an abrupt shift around 2000, after which the warming rate reached 0.61 ℃ $\cdot$ $(10a)^{-1}$, exceeding the 0.37 ℃ $\cdot$ $(10a)^{-1}$ rate observed for the entire period. Annual precipitation exhibited a weak increasing trend [7.6 mm $\cdot$ $(10a)^{-1}$], entering a relatively abundant phase after 2003, with the regional average annual precipitation reaching 610 mm during 2010–2019. Precipitation increased in spring, summer, and winter but decreased in autumn, with significant reductions in summer and autumn precipitation in the eastern SRYR intensifying the risk of periodic drought. Over the past decade, both average temperature and precipitation reached their highest values in 60 years, placing the region in its warmest and wettest stage. Under sustained warming and wetting conditions, the average extreme temperature threshold in the SRYR increased significantly from 1960 to 2019, while frost days decreased. Annual maximum 3-day precipitation and heavy precipitation days increased, with precipitation intensity strengthening, particularly in summer. These changes may pose risks and challenges to ecological protection, water resource utilization in the SRYR, and high-quality development across the entire Yellow River Basin.

Keywords: Yellow River source area; climate change; extreme events; warming-wetting; spatial-temporal pattern

Introduction

The Three-River-Source region, known as the "Water Tower of China," is located on the Tibetan Plateau and constitutes an important ecological security barrier for China and one of Asia' s most sensitive areas to global climate and environmental change [1]. The source region of the Yellow River is a key component of the Three-River-Source, representing the catchment area above the Tangnaihai hydrological station on the Yellow River' s main stream. Characterized by a unique natural ecosystem and abundant natural resources, it features a plateau continental climate and serves as the primary runoff-producing area for the Yellow River [2]. Climate warming has significantly impacted water resources and ecosystems in the SRYR, manifesting as permafrost degradation [3], glacier retreat [4], slowly increasing vegetation coverage [5], generally decreasing river runoff [6], and significant lake expansion with increasing numbers of lakes [7]. Under future scenarios of continued warming, potential ecological risks in the SRYR will intensify [8].

In recent years, climate change in the SRYR has attracted widespread attention from scholars and governments, yielding numerous studies. Hao et al. [9] demonstrated that the SRYR experienced overall warming from 1961 to 2010 at a rate of 0.31 ℃ $\cdot$ $(10a)^{-1}$, with the largest temperature increase in Maqin County and the greatest decrease in Henan County. Yang et al. [10], based on representative meteorological stations in the source region, found that the annual mean maximum temperature first increased and then stabilized, while the warming rate of the annual mean minimum temperature decreased after 2000. Annual precipitation showed a weak overall increase [11], with decreasing heavy precipitation days and increasing annual non-precipitation days in the west but opposite patterns in the east [12]. Annual precipitation and mean temperature exhibited consistent periodicity and phase [13]. While previous studies have yielded meaningful conclusions, most focused on climate change impacts, with relatively few addressing observed climate facts in the SRYR. Many studies used individual stations to represent the entire source region or failed to account for non-homogeneity factors such as station relocations, leading to inconsistent and contradictory results that cannot objectively reflect the spatio-temporal patterns and dynamic changes of climate in the SRYR. Therefore, this study systematically analyzes changes in average climate and extreme climate events over the past 60 years based on homogenized temperature and precipitation observations, aiming to comprehensively understand regional climate change facts, particularly new characteristics since the beginning of this century, and provide scientific support for protecting the "Yellow River Water Tower" and implementing high-quality development projects in the Yellow River Basin.

1.1 Study Area Overview

The SRYR is the primary runoff-producing area in the middle and upper reaches of the Yellow River [14], located in the northeastern Tibetan Plateau (95°50 - 103°28 E, 32°12 -36°48 N). Originating from Maduo and Qumarlêb counties in

Qinghai Province and terminating at the Tangnaihai hydrological station, it flows through Sichuan, Qinghai, and Gansu provinces. The region features a plateau sub-frigid semi-humid semi-arid continental monsoon climate [15]. As a crucial water resource formation area for the Yellow River Basin, the SRYR covers 12.2$\times10^{4}$ km^2, accounting for 16.2% of the Yellow River Basin area (75.2$\times10^{4}$ km^2). Its multi-year average natural runoff is 205.2$\times10^{8}$ m^3 (at Tangnaihai station), representing 35% of the total runoff at Lijin Station (580.0$\times10^{8}$ m^3) [16]. The region features extensive water networks, numerous tributaries, widespread snow cover, glaciers, grasslands, and lakes, as well as large areas of permafrost and seasonal frozen soil. The alpine landscape and climatic environment create a unique water resource system [17] that directly affects water supply security in the middle and lower reaches of the Yellow River.

[Figure 1: see original paper]

1.2 Data and Methods

Homogenized long-term observation data are fundamental to climate change research and crucial for authentic and accurate assessment of regional climate and extreme event changes. The SRYR contains 11 national meteorological stations: Maduo, Maqin, Dari, Jiuzhi, Tongde, Henan, Zêkog, Gêdê, Maqu, Ruoergai, and Hongyuan (Fig. 1). Homogenized monthly temperature and precipitation observation data from 1960 to 2019 were obtained from the National Meteorological Information Center (http://data.cma.cn/) [18]. Among these stations, Tongde relocated from Machang (3289.4 m) to Tongde County seat (3148.2 m) in 2006, and Henan relocated from Kesheng Township (3500.0 m) to Henan County seat (3414.1 m) in 2007, with elevation differences of 141.2 m and 85.9 m, respectively. Comparisons of annual mean temperature series before and after homogenization correction for these two stations are shown in Fig. 2 [Figure 2: see original paper].

Extreme climate indices were adopted from the STARDEX project "Statistical and Regional Dynamical Downscaling of Extremes for European Regions" [19], which developed extreme indices based on daily temperature and precipitation observations. We selected 10 core indices to analyze changes in extreme temperature, precipitation intensity, and frequency (Table 1). Seasons were defined as spring (March–May), summer (June–August), autumn (September–November), and winter (December–February). Climate element change characteristics and trends were analyzed using climate trend analysis, Mann-Kendall tests, and significance testing methods [20].

2.1.1 Long-term Temperature Changes and Characteristics in the SRYR Temperature, as the most fundamental climate element, influences regional runoff by affecting glacier and snow melt, evaporation, and infiltration [21]. From 1960 to 2019, the annual mean temperature in the SRYR showed a significant increasing trend at a rate of 0.37 ℃·$(10a)^{-1}$, passing the significance test. Seasonal mean temperatures also exhibited consistent warming across spring, summer, autumn, and winter. During the 1990s, the mean minimum temperature showed rapid warming, with an increase of 0.81 ℃ compared to the previous decade. At the seasonal scale, extreme temperature warming was most significant in winter, with warming rates of 0.71 ℃ · $(10a)^{-1}$ and 0.56 ℃ · $(10a)^{-1}$ for mean maximum and minimum temperatures, respectively.

The SRYR experienced obvious interdecadal temperature variations from 1960 to 2019, with mean temperatures rising decade by decade (Fig. 3 [Figure 2010: see original paper]). The Mann-Kendall test revealed an abrupt change in 2000, after which the warming rate reached 0.61 ℃ · $(10a)^{-1}$ (Fig. 3 [Figure 2010: see original paper]), 1.15 times faster than before the shift. The 2010s were the warmest decade, with the regional mean temperature 1.5 ℃ higher than in the 1960s. At the seasonal scale, all stations showed consistent warming across seasons, with winter warming rates exceeding 0.70 ℃ · $(10a)^{-1}$ at most stations. These analyses indicate that annual mean temperature, mean maximum temperature, and mean minimum temperature at all stations in the SRYR showed overall consistent increasing trends, with the mean minimum temperature warming rate significantly higher than those of mean temperature and mean maximum temperature.

2.1.2 Spatial Patterns of Temperature Change in the SRYR Spatially (Fig. 4 [Figure 4: see original paper]), the annual mean temperature increase rate across the SRYR from 1960 to 2019 ranged from 0.31 to 0.46 ℃ · $(10a)^{-1}$, with greater warming in the east than west. Zêkog, Dari, Jiuzhi, and Maqu showed warming rates above 0.40 ℃ · $(10a)^{-1}$, while Henan Station recorded the maximum rate of 0.46 ℃ · $(10a)^{-1}$. Mean maximum temperatures generally increased (Fig. 5 [Figure 5: see original paper]), with most areas warming at 0.31 ℃ · $(10a)^{-1}$, except Dari which showed a higher rate of 0.57 ℃ · $(10a)^{-1}$. The spatial distribution of mean minimum temperature trends resembled that of mean temperature, showing an overall east-high, west-low pattern with rates of 0.41 ℃ · $(10a)^{-1}$ and 0.59 ℃ · $(10a)^{-1}$, respectively. Dari showed the smallest warming rate, while Maqu showed the largest.

2.2.1 Precipitation Changes in the SRYR Atmospheric precipitation constitutes an important water resource supplement in the SRYR [22]. From 1960 to 2019, the multi-year average precipitation was 564.9 mm, with regional mean annual precipitation showing a weak increasing trend of 7.6 mm · $(10a)^{-1}$, though not passing significance tests (Fig. 6 [Figure 6: see original paper]). The polynomial fitting curve reveals interdecadal precipitation fluctuations: the 1960s-1970s were dry periods, precipitation increased in the mid-1980s, the late 1990s to early 2000s were relatively dry, and precipitation has fluctuated and increased since 2003. During 2010–2019, regional mean precipitation was 610 mm, 13.5% and 10.9% higher than in the 1960s and 1970s, respectively, representing the most abundant precipitation stage in 60 years.

Seasonal precipitation changes show distinct seasonal differences: spring, summer, and winter precipitation increased, while autumn precipitation decreased slightly by 0.5 mm · $(10a)^{-1}$. Spring showed the most significant increase, passing the 0.05 significance level test. These seasonal differences in precipitation changes are consistent with precipitation characteristics in the Three-River-Source region [23]. Notably, in the recent decade (2010–2019), spring precipitation in the SRYR has been consistently high, averaging 20.7% above the historical mean, making a non-negligible contribution to river flow.

2.2.2 Spatial Patterns of Precipitation Change in the SRYR Spatially, annual precipitation trends show significant regional differences (Fig. 7 [Figure 7: see original paper]), with smaller changes in the east than west. Tongde, Zêkog, Maduo, and Dari in the central and western SRYR showed the most significant increases at rates of 16.8 mm · $(10a)^{-1}$, with Maduo showing the maximum increase. Henan Station showed a decreasing trend of 6.8 mm · $(10a)^{-1}$, while other areas increased at 7.2 mm · $(10a)^{-1}$. Seasonal precipitation is unevenly distributed, accounting for 19.4%, 54.5%, 23.8%, and 2.3% of annual precipitation in spring, summer, autumn, and winter, respectively. Seasonal changes vary: spring precipitation increased consistently across the region at 4.3 mm · $(10a)^{-1}$, with Dari showing the most obvious increase (Fig. 8 [Figure 8: see original paper]). In summer, Henan, Jiuzhi, and Hongyuan in the east decreased by 0.9 mm · $(10a)^{-1}$, while other areas increased, most notably Maduo at 1.2 mm · $(10a)^{-1}$. In autumn, southeastern areas (the main runoff-producing region) showed slight decreases of 4.0 mm · $(10a)^{-1}$, with Maqu showing the most significant reduction, while other areas increased at 4.7 mm · $(10a)^{-1}$, with Zêkog showing the maximum increase. Winter precipitation increased consistently, with Gêdê and Ruoergai showing the most significant increases at 1.8 mm · $(10a)^{-1}$.

2.3 Changes in Extreme Events in the SRYR Climate warming directly affects extreme climate changes, and small changes in extreme weather and climate events can trigger a series of changes in the fragile ecosystem of the Tibetan Plateau [24]. Recent studies on extreme climate in the plateau region indicate that over the past 60 years, extreme low-temperature events have decreased while extreme warm events have become more frequent, with increased frequency of heavy precipitation and flood disasters [25]. These trends are projected to continue in the 21st century [26]. Against this background of warming and wetting, extreme temperature indices in the SRYR have changed significantly. From 1960 to 2019, annual warm night threshold, warm day threshold, cold night threshold, and cold day threshold increased significantly, with cold night threshold increasing most rapidly at 0.92 ℃ · $(10a)^{-1}$. Seasonal extreme temperature thresholds also increased consistently, with greater increases in autumn and winter than spring and summer.

Over the past 60 years, annual frost days in the SRYR decreased significantly at a rate of 8.5 d · $(10a)^{-1}$, passing the significance test, consistent with extreme temperature event changes in the Three-River-Source region [27]. Compared with extreme temperature, extreme precipitation indices show distinct differences at annual and seasonal scales. Both consecutive dry and wet periods decreased by 0.58 $d \cdot (10a)^{-1}$ and 0.35 $d \cdot (10a)^{-1}$, respectively, indicating increased intra-annual precipitation oscillation variability in the SRYR. Annual maximum 3-day precipitation and heavy precipitation days increased, with precipitation intensity showing a significant increasing trend that contributed substantially to the increase in annual precipitation. Notably, summer showed the most significant increases in precipitation intensity and heavy precipitation days (table omitted), with more rainstorm events. The increase in extreme precipitation events and greater precipitation instability may pose safety risks to the Three-River-Source National Park construction, ecological environment protection, and water resource utilization in the SRYR, as well as high-quality development across the Yellow River Basin.

3 Discussion

The SRYR shows a consistent and significant warming trend with asymmetric seasonal warming, as winter warming is significantly higher than summer warming, and the overall warming rate exceeds global and national averages [28]. Since the 21st century, the SRYR has experienced accelerated warming, with the most recent decade representing the warmest and most rapidly warming period. Compared with previous assessments [9,10], our results are generally consistent, but regionally, the recalculated warming rate in the northeastern SRYR (e.g., Henan Station) is significantly higher than published results. Besides slight differences in analysis periods, the use of homogenized temperature data is an important reason for this discrepancy.

Our analysis of long-term precipitation changes and spatial patterns in the SRYR indicates that since the 1980s, precipitation has generally increased with prominent regional and seasonal differences. The increasing precipitation trend [11,12] synchronizes with the warming-wetting trend in Northwest China under global warming [29], particularly significant in the SRYR. Additionally, with continued warming-wetting, extreme temperature and precipitation events have become more frequent and intense. Although increased temperature, snowmelt, and precipitation occurred in the 21st century, river runoff in the SRYR has decreased [6], permafrost has degraded, typical glacier surface elevations have declined, and ecological disasters such as lake overflow and ice avalanches have become frequent, posing safety risks to ecological restoration, environmental protection, and sustainable development.

Climate change is an extremely complex issue. This study only reanalyzed basic temperature and precipitation change characteristics in the SRYR based on long-term homogenized station observations, particularly regional climate facts in the recent decade. However, further systematic observations and research are needed on synergistic changes in other climate elements such as evapotranspiration, their causal mechanisms, and future impacts of climate change on regional and downstream hydrology, water resources, and cryosphere service functions [30].

4 Conclusions

Based on homogenized temperature and precipitation data, this study comprehensively analyzed changes in average climate and extreme climate events in the SRYR, yielding the following main conclusions:

1. From 1960 to 2019, annual and seasonal mean temperatures, mean maximum temperatures, and mean minimum temperatures in the SRYR increased significantly, with the largest increase in mean minimum temperature and most pronounced warming in winter. Warming amplitude in the eastern region was generally greater than in the western region. Since 2000, warming has accelerated, with the most recent decade representing the warmest period in 60 years.

2. From 1960 to 2019, annual precipitation in the SRYR showed an increasing trend, with more precipitation in spring, summer, and winter but a slight decrease in autumn. Regional differences were significant, with the most obvious increases in Tongde, Zêkog, Maduo, and Dari. Precipitation increased consistently across the region in winter and spring, while in summer and autumn, precipitation increased in the west but decreased significantly in the east, increasing the risk of periodic drought. In the most recent decade, the regional mean annual precipitation reached 610 mm, the highest in 60 years, indicating a clear warming-wetting trend.

3. From 1960 to 2019, annual warm night threshold, warm day threshold, cold night threshold, and cold day threshold increased significantly in the SRYR, while frost days decreased significantly. Annual maximum 3-day precipitation and heavy precipitation days increased, with precipitation intensity strengthening, most notably in summer with increased rainstorm frequency. Against the background of warming-wetting, the frequency and intensity of extreme climate events in the SRYR have increased.

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Note: Figure translations are in progress. See original paper for figures.