Postprint: Analysis of Climate Change Characteristics in Afghanistan from 1951 to 2020

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Abstract

Based on the latest CRU TS V4.05 gridded dataset, this study systematically analyzes the spatiotemporal variation characteristics of climate elements in Afghanistan from 1951 to 2020. The results show:

(1) From southwest to northeast, Afghanistan comprises extremely arid, arid, arid-semi-humid, and humid climate zones. Annual mean temperature and potential evapotranspiration decrease from the Sistan Basin in the southwest to the Wakhan Corridor in the northeast, while annual precipitation exhibits a spatially increasing distribution.

(2) Over the past 70 years, annual and seasonal mean temperatures in Afghanistan have shown a consistent increase across the entire region, with a greater warming rate in the west than in the east, and the most significant warming magnitude occurring in spring. Precipitation in Afghanistan exhibits large regional and seasonal differences; annual precipitation shows a weak decreasing trend [-0.43 mm · (10a)-1], spatially displaying a "decrease-increase-decrease" pattern from southwest to northeast. Precipitation in winter and spring, the concentrated rainfall seasons, shows a decreasing trend.

(3) Potential evapotranspiration in Afghanistan is substantial, showing a significant increase from 1951 to 2020 [5.59 mm · (10a)-1]. However, its spatial variation is opposite to that of precipitation: annual potential evapotranspiration in the central Hindu Kush mountains shows a decreasing trend. Potential evapotranspiration increases in spring, summer, and autumn, but decreases in winter.

(4) Over the past 70 years, the Aridity Index (AI) indicates that the dry-wet climate change trend in Afghanistan is not significant, dominated by interannual variability. Spatially, the extremely arid Sistan Basin in southwestern Afghanistan has experienced intensified drought, the central Hindu

Kush mountains have undergone "warm-wet" changes, while the Wakhan Corridor region with the most concentrated precipitation shows "warm-dry" changes. The mean AI in spring shows the largest decrease, exacerbating the risk of periodic drought. Since the 21st century, Afghanistan has experienced a period of climatic warm-wet changes, with slightly increased temperature, sharply increased precipitation, and significantly decreased potential evapotranspiration, particularly pronounced in spring. These changes will pose challenges to agricultural production, cryosphere risks, and water resource management in the region.

Full Text

Spatiotemporal Characteristics of Climate Change in Afghanistan from 1951 to 2020

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Abstract

Based on the latest CRU TS V4.05 gridded dataset, this study systematically analyzes the spatiotemporal characteristics of climate change in Afghanistan from 1951 to 2020. The results indicate that Afghanistan' s climate zones are distributed from southwest to northeast as extremely arid, arid, semi-arid, semi-humid, and humid regions. The annual mean temperature and potential evapotranspiration decrease from the Sistan Basin in the southwest toward the Wakhan Corridor in the northeast, while annual precipitation shows an increasing gradient in the same direction. Both annual and seasonal average temperatures exhibit a consistent warming trend across the entire region, with greater warming rates in the west than in the east, and the most pronounced warming occurring in spring. Precipitation displays strong spatial heterogeneity and large seasonal differences, with a slight decreasing trend of -0.43 mm · (10a)^-1 at the national scale and a spatial pattern of "decrease-increase-decrease" from southwest to northeast. Precipitation is concentrated in winter and spring, both showing decreasing trends. Potential evapotranspiration (PET) is generally high across Afghanistan, with a significant increasing trend of 5.59 mm · (10a)^-1, though the central Hindu Kush region shows decreasing PET. Seasonally, PET increased in spring, summer, and autumn but decreased in winter. The aridity index (AI) reveals that Afghanistan' s climate change is dominated by interannual variability without a significant long-term trend. Spatially, the extremely arid Sistan Basin in the southwest has experienced intensified drought, the central Hindu Kush region has undergone "warming-wetting" changes, while the precipitation-rich Wakhan Corridor has become "warming-drying." The significant decrease in spring AI has exacerbated the risk of periodic drought. Since the 21st century, Afghanistan has experienced a period of warming-wetting climate characterized by slight temperature increases, sharp precipitation increases, and significant PET decreases, particularly pronounced in spring. These changes pose significant challenges to agricultural production, cryospheric stability, and water resource management in the region.

Keywords: Afghanistan; warming-wetting; aridity index; Sistan Basin; Wakhan Corridor

1. Introduction

Climate change represents a critical global issue of international concern. It not only alters the temporal and spatial distribution of water resources but also increases the frequency of extreme climate events such as floods and droughts, thereby disrupting natural ecosystems and exerting profound impacts on economic development and human livelihoods. Consequently, climate change plays a crucial role in regional, national, and global sustainable development. The Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report indicates that the global climate system is undergoing rapid and widespread changes, with anthropogenic climate change significantly altering the global water cycle since the mid-20th century.

Afghanistan, a landlocked country in Central and Western Asia, faces constraints on socioeconomic and agricultural development due to its unique geopolitical situation and harsh climate conditions. The country' s complex topography extends from high mountains in the northeast to plateaus and highlands in the southwest, with the Hindu Kush Mountains representing the largest mountain range. Previous studies have identified this region as experiencing significant warming. Afghanistan' s northern and southwestern regions are characterized by arid and desert climates. The Sistan Basin in southwestern Afghanistan is one of the world' s most arid regions, comprising the Helmand River basin, Hamoun wetlands, and terminal lakes. The Helmand River originates from the Hindu Kush Mountains and replenishes downstream wetlands and highly saline terminal lakes. The Hamoun wetlands serve as an oasis in Afghanistan' s southwestern desert region, supporting a large population that depends on them for daily water supply and agricultural irrigation, while also facing pressure from unstable upstream water supply and water disputes with neighboring countries.

Recent research has begun to address climate change in Afghanistan. Rehana et al. analyzed precipitation and temperature variations across Afghanistan and its agricultural-climatic zones from 1951-2015 using the APHRODITE high-resolution daily Asian land precipitation gridded dataset, revealing a "warming-drying" trend in northern, northeastern, and western Afghanistan, while southern, southwestern, and eastern regions experienced "warming-wetting" changes. Aliyar et al., also using APHRODITE data, found significant decreasing precipitation trends in northeastern and southwestern Afghanistan since 1951, with increasing dry spell duration, particularly pronounced in spring. Spring precipitation reductions affect spring crop production, especially in northeastern Afghanistan where arable land accounts for 43.2% of the total area. Conversely, summer precipitation has increased in central, eastern, and southern Afghanistan, with increasing frequency of heavy and extreme precipitation events. Climate change characterized by warming, along with extreme events such as droughts, dust storms, heavy snow, and extreme cold, poses enormous challenges to Afghanistan' s ecology, agriculture, economy, biodiversity, public health, and food security.

Dry-wet climate changes significantly impact regional water cycles and ecosystems, affecting agricultural production, economic development, and social stability. Drought represents one of Afghanistan' s primary meteorological disasters. Qutbudin et al. demonstrated that drought intensity and frequency increased in Afghanistan from 1951-2015. During rice and corn growing seasons (July-October), rising temperatures caused decreases in the Standardized Precipitation Evapotranspiration Index (SPEI) in northwestern and southwestern Afghanistan. During barley growing seasons (November-April), warming and precipitation reduction led to decreased SPEI values. As global warming continues, Afghanistan' s dry-wet climate patterns have changed. This study employs the latest high-resolution monthly climate gridded dataset (CRU TS V4.05) to comprehensively analyze Afghanistan's average climate change characteristics and dry-wet variations, providing a scientific basis for social, economic, agricultural, and ecological development in Afghanistan.

1.1 Study Area Overview

Afghanistan is a landlocked country located in the southern part of Central Asia' s arid region, geographically positioned between 29°35 -38°40 N and 60°31 -75°E. It borders Turkmenistan, Uzbekistan, and Tajikistan to the north; Iran to the west; China via the narrow Wakhan Corridor to the northeast; and Pakistan to the southeast. The terrain is characterized by low elevation in the southwest and high elevation in the east (Fig. 1). The northern and southwestern regions consist primarily of plains, while the central to northeastern areas are mountainous, with plateaus and mountains covering 80% of the country' s territory. The Hindu Kush Mountains extend from northeast to southwest, with an average elevation exceeding 5000 m. The eastern Hindu Kush represents the westernmost boundary of the Asian monsoon region, while the western Hindu Kush marks the eastern boundary of Mediterranean climate influence. The Sistan Basin in southwestern Afghanistan is one of the world' s most arid regions, frequently experiencing extreme drought and dust storm events.

1.2 Data Sources and Processing

Observational data were obtained from the Global Historical Climatology Network Monthly (GHCN-M V4.0) dataset developed by the National Climatic

Data Center (NCDC). This dataset represents the most comprehensive global climate data product in terms of station coverage and temporal-spatial range, widely applied in global and regional climate change research. Afghanistan has 29 precipitation observation stations. After conducting temporal consistency checks to ensure data stability and homogeneity, 10 stations were selected for analysis (Table 1). The data cover the period 1951-2020, with seasons defined as spring (March-May), summer (June-August), autumn (September-November), and winter (December-February).

The study employs the latest global monthly climate gridded dataset (CRU TS V4.05) reconstructed by the Climatic Research Unit at the University of East Anglia, covering 1951-2020 with a spatial resolution of 0.5°$×$0.5°. Potential evapotranspiration was calculated using the Penman-Monteith method recommended by the Food and Agriculture Organization of the United Nations (FAO). Previous studies have demonstrated that CRU TS data exhibit high resolution, complete coverage, and good agreement with observational data. Yan et al. analyzed climate characteristics in the Pan-Central Asian arid region using CRU data, confirming its reliability in data-scarce regions. Chen et al. and Yu et al. also validated the applicability of CRU data in Central Asia and the China-Pakistan Economic Corridor, respectively, showing high correlation coefficients with ground observations.

To validate CRU TS data reliability in Afghanistan, bilinear interpolation was used to extract gridded values corresponding to station locations (Table 1). Linear regression and Pearson correlation coefficients served as evaluation metrics, with higher R^2 values indicating better linear fit. Comparison between observed and interpolated temperature data yielded a correlation coefficient of 0.98, indicating strong correlation and a linear regression coefficient of 0.96, confirming high reliability and suitability for climate change analysis.

The aridity index (AI) characterizes climate dry-wet conditions and is widely applied in global and regional climate studies, defined as AI = PRE/PET, where PRE represents precipitation and PET represents potential evapotranspiration. According to the United Nations Environment Programme (UNEP) classification, dry-wet climates are categorized into five types: extreme arid ($AI<0.05$), arid ($0.05 \leq AI<0.2$), semi-arid ($0.2 \leq AI<0.5$), semi-humid ($0.5 \leq AI<0.65$), and humid ($AI>0.65$). Climate trend analysis employed linear trend estimation and significance testing methods.

2. Results and Analysis

2.1 Average Temperature Change Characteristics

The annual temperature cycle in Afghanistan shows distinct seasonal differences, with a "single-peak" distribution (Fig. 2a). The maximum monthly average temperature occurs in July (25.7°C), while the minimum occurs in January (3.6°C). The spatial distribution of annual average temperature decreases from the northwest, southwest, and southeast toward the northeast (Fig. 2b), with southwestern temperatures exceeding 18.8°C, central regions above 12.1°C, and Hindu Kush mountain areas below 7°C, particularly the Wakhan Corridor where annual average temperature is below 0°C.

From 1951-2020, the national average temperature showed a significant increasing trend at a rate of 0.22°C·(10a)^-1 ($p<0.01$) (Fig. 2c,d). Since the 21st century, the warming rate has been 0.48°C·(10a)^-1. Spatially, the entire country exhibited significant warming ($p<0.05$), with decreasing magnitude from west to east. Western plains showed warming rates exceeding 0.3°C·(10a)^-1.

Seasonal temperature variations show similar patterns (Fig. 3). All four seasons display warming trends with rates of 0.29°C·(10a)^-1 for spring, 0.23°C·(10a)^-1 for summer, 0.22°C·(10a)^-1 for autumn, and 0.12°C·(10a)^-1 for winter (all $p<0.05$). Spring shows the greatest warming magnitude, while winter shows the smallest. Since the 21st century, summer and winter warming rates have reached 0.48°C·(10a)^-1 and 0.16°C·(10a)^-1, respectively ($p<0.01$). Spatially, spring, summer, and autumn show significant warming across the entire country, while winter exhibits significant warming in the northeast and southwest but less pronounced warming in the central region.

2.2 Precipitation Change Characteristics

Atmospheric precipitation constitutes a crucial water resource in Afghanistan. Precipitation shows uneven seasonal distribution with a "double-peak" pattern (Fig. 4a). Spring precipitation accounts for 43.2% of annual total, winter 40.5%, while summer and autumn contribute only 11.4% and 4.9%, respectively. The maximum monthly precipitation occurs in March (63.4 mm), while the minimum occurs in September (3.6 mm).

The spatial distribution of annual precipitation increases from southwest to northeast (Fig. 4b). The national average shows a slight decreasing trend of -0.43 mm·(10a)^-1 (not significant) (Fig. 4c). Spatially, precipitation trends show a "decrease-increase-decrease" pattern from southwest to northeast, with decreasing trends in southwestern and northeastern regions (-2.1 mm·(10a)^-1) and increasing trends in the central mountainous region (Fig. 4d).

Seasonal precipitation patterns reveal large spatial and temporal differences (Fig. 5). Spring precipitation has decreased at -0.68 mm·(10a)^-1, particularly in the north where the decreasing rate reaches -2 mm·(10a)^-1, affecting spring crop production in northeastern Afghanistan where arable land accounts for 43.2% of the national total. Winter precipitation shows the most significant decrease at -1.24 mm·(10a)^-1 ($p<0.05$). Conversely, summer and autumn precipitation have increased at rates of 0.74 mm·(10a)^-1 and 0.11 mm·(10a)^-1, respectively.

2.3 Potential Evapotranspiration Change Characteristics

Potential evapotranspiration significantly influences regional climate, ecology, and water resource allocation. The annual cycle of PET in Afghanistan shows a "single-peak" distribution, with the maximum in July (224.5 mm) and minimum in January (29.7 mm) (Fig. 6a). Spatially, annual PET is high across the country, decreasing from southwest to northeast with increasing elevation (Fig. 6b). The national average PET shows a significant increasing trend of 5.59 mm · (10a)^-1 ($p<0.01$) (Fig. 6c), though the central Hindu Kush region exhibits decreasing PET.

Seasonal PET patterns show significant increases in spring (0.84 mm · (10a)^-1), summer (0.87 mm · (10a)^-1), and autumn (0.26 mm · (10a)^-1), all significant at $p<0.05$, with spring showing the largest increase (Fig. 7). Winter PET shows a decreasing trend of -0.1 mm · (10a)^-1. Spatially, spring and summer PET increased across the entire country, with significant increases in western regions ($p<0.05$). Autumn PET increased slightly in the southwest and decreased in the northeast, while winter PET decreased across most of the country.

2.4 Aridity Index (AI) Change Characteristics

The annual cycle of AI shows distinct seasonal differences, with lower values in spring and winter (wetter conditions) and higher values in summer and autumn (drier conditions) (Fig. 8a). According to UNEP classification, southwestern Afghanistan is arid, the central region is semi-arid, the western part of the northeast is semi-humid, and the eastern part of the northeast is humid (Fig. 8b).

The national average AI shows a slight increasing trend (wetting) of 0.04 · (10a)^-1 ($p<0.05$) (Fig. 8c). Spatially, the AI trend shows a "decrease-increase-decrease" pattern from southwest to northeast, indicating intensified drought in the southwestern arid region, wetting in the central semi-humid region, and drying in the northeastern humid region (Fig. 8d).

Seasonal AI variations reveal complex patterns (Fig. 9). Spring AI shows a decreasing trend of -0.01 · (10a)^-1, indicating "warming-drying" conditions, particularly in the northeast. Summer AI shows a decreasing trend of -0.004 · (10a)^-1, with drying in the west and wetting in the east. Autumn AI shows an increasing trend of 0.027 · (10a)^-1, indicating wetting tendencies across the country. Winter AI shows the most significant increase at 0.041 · (10a)^-1 ($p<0.05$), with a "decrease-increase-decrease" pattern from southwest to northeast. Since the 21st century, spring AI has increased significantly at 0.13 · (10a)^-1, while changes in other seasons have been less pronounced.

3. Conclusions

Based on the latest CRU TS V4.05 monthly climate dataset, this study provides a comprehensive analysis of climate change in Afghanistan from 1951-2020, yielding the following main conclusions:

The spatial distribution of annual mean temperature and potential evapotranspiration decreases from the Sistan Basin in the southwest toward the Wakhan

Corridor in the northeast, while annual precipitation increases in the same direction. The Wakhan Corridor in the northeast represents the coldest and most precipitation-concentrated alpine region of Afghanistan. Over the past 70 years, Afghanistan has experienced consistent and significant warming across the entire country, with a slight decreasing trend in annual precipitation and a significant increasing trend in potential evapotranspiration. Precipitation changes show large spatial heterogeneity, decreasing in the southwest and northeast while increasing in the central mountainous region.

Since the 21st century, climate characteristics have changed markedly, showing slight temperature increases, significant precipitation increases, and slight PET decreases. Seasonally, all four seasons have warmed significantly, with greater warming in the west than east and the strongest warming in spring. Precipitation decreased in spring and winter but increased in summer and autumn. Spring precipitation reductions mainly occurred in the north, while winter precipitation showed a "decrease-increase-decrease" pattern from southwest to northeast. PET increased in spring, summer, and autumn but decreased slightly in winter.

The spatial heterogeneity of AI changes is pronounced, with a pattern similar to the annual average: "drying-wetting-drying" from southwest to northeast. The central Hindu Kush region shows wetting trends. Spring AI decreased across the country, indicating "warming-drying" conditions, while summer AI decreased in the west and increased in the east. Autumn AI increased, showing wetting tendencies, and winter AI increased significantly with a "decrease-increase-decrease" spatial pattern. Since the 21st century, annual AI has increased significantly, consistent across spring, autumn, and winter, but showing drying trends in summer.

The "warming-drying" trend in the Sistan Basin will continue to pose challenges for agricultural production and transboundary water resource coordination. The "warming-wetting"trend in the central Hindu Kush region may accelerate snow and ice melt, triggering cryospheric hazards such as ice avalanches and glacier retreat, posing risks to mountain environments and downstream river systems. This study provides a foundation for understanding climate change in Afghanistan, though further research is needed on extreme events, mechanisms behind the sharp spring precipitation increase since the 21st century, and potential impacts on water resources and ecological environments in neighboring Xinjiang, China.

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