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Research article

Spatiotemporal changes in future precipitation of Afghanistan for shared socioeconomic pathways

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A R T I C L E I N F O

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A B S T R A C T

Global warming induces spatially heterogeneous changes in precipitation patterns, highlighting the need to assess these changes at regional scales. This assessment is particularly critical for Afghanistan, where agriculture serves as the primary livelihood for the population. New global climate model (GCM) simulations have recently been released for the recently established shared socioeconomic pathways (SSPs). This requires evaluating projected precipitation changes under these new scenarios and subsequent policy updates. This research employed six GCMs from the CMIP6 to project spatial and temporal precipitation changes across Afghanistan under all SSPs, including SSP1-1.9, SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5. The employed GCMs were bias-corrected using the Global Precipitation Climatological Center's (GPCC) monthly gridded precipitation data with a 1.0° spatial resolution. Subsequently, the climate change factor was calculated to assess precipitation changes for both the near future (2020–2059) and the distant future (2060–2099). The bias-corrected projections' multi-model ensemble (MME) revealed increased precipitation across most of Afghanistan for SSPs with higher emissions scenarios. The bias-corrected simulations showed a substantial increase in summer precipitation of around 50%, projected under SSP1-1.9 in the southwestern region, while a decline of over 50% is projected in the northwestern region until 2100. The annual precipitation in the northwest region was projected to increase up to 15% for SSP1-2.6. SSP2-4.5 showed a projected annual precipitation increase of around 20% in the southwestern and certain eastern regions in the far future.

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Furthermore, a substantial rise of approximately 50% in summer precipitation under SSP3-7.0 is expected in the central and western regions in the far future. However, it is crucial to note that the projected changes exhibit considerable uncertainty among different GCMs.

1. Introduction

The anthropogenic emission of greenhouse gases induces a rise in the Earth's atmospheric temperature, leading to alterations in worldwide precipitation patterns and temperatures, as evidenced by the investigations undertaken by Refs. [1,2]. Similar variations in rainfall and temperature have been documented in regional studies conducted by Refs. [3–6]. The modifications influence several aspects of precipitation, including its frequency, intensity, geographical extent, duration, and timing, as examined in the research conducted by Refs. [7,8]. The alterations have various effects on physical systems and social and economic sectors. Consequently, assessing alterations in precipitation patterns has garnered considerable international recognition within the framework of strategies to mitigate climate change [9–11]. Numerous scholarly investigations have been conducted to analyze modifications in precipitation patterns at the global, regional, and national scales, uncovering significant variations in trends among diverse geographic regions [8,12,13]. The impacts of these modifications vary across different locations due to factors such as the density of the population, the ability to adapt, and the susceptibility of the ecological system [14–16].

Afghanistan, a country that exhibits significant susceptibility to the impacts of climate change, is confronted with escalating temperatures and diminishing levels of precipitation, resulting in an increased occurrence of droughts that are more severe [17,18]. The nation frequently receives rankings indicating its high vulnerability to the consequences of climate change. This vulnerability is primarily attributed to its low capacity to adapt and its heightened susceptibility to alterations in climatic patterns. According to Ref. [19], the country's infrastructure and institutions have suffered considerable harm as a result of an extended armed war. This has led to a pervasive state of poverty and underdevelopment, exacerbating the country's susceptibility to the impacts of climate change. The nation's economy mainly depends on agricultural production, where subsistence farming is crucial. Consequently, several sectors, including water, energy, and agriculture, exhibit heightened vulnerability to the impacts of climate change [20,21]. Afghanistan is prone to frequent and severe weather events, resulting in significant economic damage and the loss of human lives. This underscores its limited ability to adjust to prevailing climatic circumstances [20–22].

Afghanistan, a geographical area with a semiarid to dry climate, experiences a recurring occurrence of drought, as documented by several studies [23–25]. Good natural resource management and climate change adaptation and mitigation techniques cannot be overstated, particularly in regions with a narrow annual precipitation range of 200–400 mm [26]. The scholarly literature has extensively examined the effects of climate change on rural populations that are largely dependent on water, soil, forests, and grazing regions. Notable contributions to this field of research include the works of [23,27–30]. The study undertaken in Afghanistan about climate change projections for adaptation planning and economic development has been restricted, as indicated by studies conducted by Refs. [26,31–35].

Research conducted by Aich et al. (2017) employed reanalysis data and Coordinated Regional Climate Downscaling Experiment (CORDEX)-South Asia simulations to project the climate of Afghanistan. The research primarily examined two scenarios derived from the Coupled Model Intercomparison Projects Phase 5 (CMIP5), Representative Concentration Pathways (RCP) 4.5 and 8.5. Despite considerable uncertainty in the precipitation estimation, the study's findings indicate that the intensification of evapotranspiration has the potential to worsen the already existing water stress in Afghanistan. Sidiqi et al. [26] projected the climate of the Kabul River basin in Afghanistan by utilizing Global Climate Models (GCMs) sourced from the CMIP5 dataset. The research investigation centered on two RCPs, RCP4.5 and RCP8.5. According to their projections, it is anticipated that the mean annual temperature in the basin might potentially rise by 1.8 °C, 3.5 °C, and 4.8 °C in the 2020s, 2050s, and 2080s, respectively. The anticipated increase in mean annual precipitation will likely change monthly precipitation patterns across the river basin by 2100 under both scenarios. Azizi and Asaoka [32] investigated the climatic conditions in the northeastern region of Afghanistan. This investigation involved the utilization of CMIP5 GCMs and the application of RCPs. Ahmed et al. [36] showed multimodal ensemble (MME) of CMIP5 GCMs indicating increase in precipitation ranging from − 12.68% to 6.31%, − 9.61%–3.45%, − 8.70%–9.15%, and − 9.40% to 5.47% under RCP2.6, RCP4.5, RCP6.0, and RCP8.5 scenarios, respectively, in northern regions of Pakistan. Rahimi et al. [37] found annual precipitation in Iran bordering Afghanistan is projected to decrease by −5.41% (2041–2070) for RCP4.5 and −9.5% for RCP8.5. Furthermore, results of a study conducted in China revealed a decrease in precipitation up to 14% and 17% under RC4.5 and RCP8.5, respectively in the period of 2021–2060. It also projected a higher decrease in the period of 2061–2100 in comparison to 2021–2060 [38]. Ali et al. [39] depicted highest decrease in winter precipitation up to 70% was found in southern and western regions of Pakistan in the period of 2020–2039 for RCP2.6. They also projected a higher decrease in winter precipitation until end of 21st century." The objective of this study was to evaluate the impacts of climate change on the spatial patterns of snow distribution and river flows within the western Hindukush-Himalaya area. The research findings revealed alterations in the origins of streams located at elevated altitudes within the Hindukush Mountains, leading to fluctuations in water allocation further downstream. These investigations emphasize the pressing requirement for additional research endeavors and strategic initiatives to adequately tackle the difficulties arising from the changing precipitation patterns in the area.

Scientists utilize mathematical equations of the fundamental physical principles to simulate air circulation and global climate events [40–42]. Numerous climate research institutions have developed diverse GCMs to improve their precision and spatial resolution by integrating novel physical mechanisms and reliable data. The Intergovernmental Panel on Climate Change (IPCC) oversees the coordination of these updates, facilitated by the Coupled Model Intercomparison Project (CMIP). The most recent GCMs iteration is CMIP6, which incorporates a broader spectrum of experimental scenarios. The trials encompass novel prospective situations referred to as SSPs. The formulation of these SSPs is predicated on distinct socioeconomic assumptions, as demonstrated by the works of [43–45].

Most prior studies have utilized the CMIP5 model to conduct climate projections in Afghanistan for RCPs. Several recent studies have employed the CMIP6 model to carry out climate projections for Afghanistan's SSPs [33–35]. However, the scope of these investigations was quite narrow. Farhat et al. [35] employed just the SSP2-4.5 and SSP5-8.5 in their analysis. SSP1-1.9 and SSP1-2.6 hold significant relevance in the context of the Paris Agreement and the continuous endeavors aimed at mitigating greenhouse gas emissions. The aforementioned scenarios are in accordance with the objective of the Paris Agreement, which aims to restrict the increase in global temperatures to 1.5 °C. The attainment of this objective is seen as aspirational [46,47]. The SSP1-1.9 represents a mitigation approach designed to limit global warming to below 1.9 °C by the conclusion of the 21st century. On the other hand, the SSP1-2.6 is a trajectory with low emissions that has been formulated to limit the increase in global temperature to below 2.6 °C [48]. The significance of these situations has escalated due to the recognition by governments and researchers of the urgent necessity to augment climate action and pursue more ambitious reductions in greenhouse gas emissions to avert the most severe repercussions of climate change. Using SSP1-1.9 and SSP1-2.6, in conjunction with higher emission scenarios, inside climate modeling offers decision-makers significant information about the possible advantages and obstacles to attaining the more ambitious climate goals delineated in the Paris Agreement.

The present investigation employed CMIP6 GCMs to project the geographical and temporal fluctuations in precipitation distributions throughout Afghanistan for two forthcoming periods (2020–2059 and 2060–2099) compared to a baseline period (1971–2010). The study examined many SSPs to analyze the effects of global temperature rise on precipitation patterns and their variability. The study included six CMIP6 models to simulate five different SSPs: SSP1-19, SSP1-26, SSP2-45, SSP3-70, and SSP5-85. The aforementioned scenarios contain a spectrum of potential global temperature rises that may occur by the conclusion of the current century, varying in magnitude from modest to significant. The originality of this work is to project annual and seasonal precipitation patterns in Afghanistan for all SSPs, encompassing a spectrum of temperature rises ranging from the least severe (1.5 °C) to the most extreme (business-as-usual) scenarios. The results obtained from this research possess considerable promise in providing valuable insights for formulating adaptation strategies and fostering the establishment of a society in Afghanistan that is robust to climate change impacts.

2. Study area

Afghanistan, located between 29° and 39° N latitude and 60° and 75° E longitude, is a landlocked nation in South-Central Asia. It shares borders with Pakistan to the south and east, Iran to the west, and Turkmenistan, Uzbekistan, and Tajikistan to the north. In the northeast, it borders China. The country boasts a diverse topography featuring imposing mountain ranges, expansive plains, and arid desert regions. Afghanistan's climate varies significantly across its various topographic zones [35]. The climate ranges from dry to semiarid, characterized by high temperatures in the summers and low temperatures in the winters. Fig. 1 illustrates the average annual precipitation across the country, showing a gradual decrease in rainfall from the northeastern region near the Hindukush Mountains to the southern plateau zone. The region with the lowest mean annual precipitation, around 30 mm, is located in the southwestern plateau area. In contrast, the northeastern foothills of the Hindukush Mountains receive the highest precipitation, exceeding 1000 mm. According to Refs. [49,50], there is a gradual increase in the daily mean annual maximum temperature when moving from the northeastern part of the Hindukush Mountains toward the southeastern plateau regions. The lowest areas in the southeastern zone experience the highest mean annual maximum temperatures. In Afghanistan, where a significant portion of the population relies on agriculture, understanding the impact of climate change on precipitation patterns is crucial for implementing sustainable agricultural

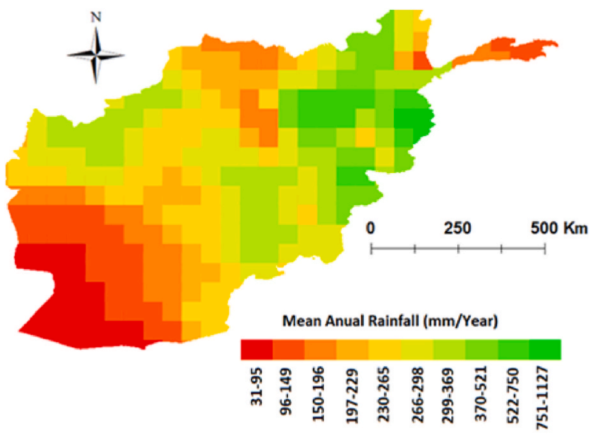

Fig. 1. Geographical distribution of mean annual rainfall (mm/year) in Afghanistan.

practices. The effect of shifting precipitation patterns on crop growing seasons, particularly concerning the reduction of winter snowpack and its impact on wheat production yields, has been identified as a critical concern [18].

3. Data and sources

3.1. CMIP6 datasets

The CMIP6 dataset provides climate variable simulations using updated GCMs for various SSPs [51]. This study used six CMIP6 models, as tabulated in (Table 1), based on the availability of precipitation simulations for all SSPs (SSP1-1.9, SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5) used in this study. Therefore, these specific GCMs were chosen for inclusion in the current investigation. Table 1 presents the names, modeling centers, and resolutions of the selected GCMs.

3.2. Global precipitation climatology centre (GPCC) gridded precipitation

The GPCC precipitation product is a dataset that provides global precipitation data based on a comprehensive analysis of various sources, including rain gauge measurements, satellite data, and other meteorological information [52]. The GPCC is a collaboration between the Deutscher Wetterdienst (German Meteorological Service) and the World Meteorological Organization (WMO). The dataset is available in various spatial and temporal resolutions, allowing researchers and policymakers to access precipitation information at different scales. This study employed $1^\circ \times 1^\circ$ resolution gridded monthly precipitation data for Afghanistan for 1975–2014 as a reference for the downscaling of GCM precipitation. Fig. 1 shows the geographical distribution of the annual mean precipitation of Afghanistan for the period 1975–2014.

4. Methodology

4.1. Procedure

The procedure adhered to established protocols.

i. The methodology used to assess regional and temporal variations in precipitation patterns in Afghanistan across all SSPs consisted of four distinct stages, as outlined below. The following subsections provide a comprehensive explanation of the methodology employed:
ii. Precipitation simulations from the GCMs were adjusted to a standardized resolution of $1.0^\circ \times 1.0^\circ$. Fig. 2 illustrates the spatial coordinates of the grid points.
iii. The delta bias correction method was employed to mitigate bias in GCM precipitation data by comparing it to the GPCC precipitation data.
iv. The Climate Change Factor (CCF) was derived by comparing the historical simulation of GCMs with future projections to assess potential alterations in precipitation patterns.
v. The multi-model ensemble mean (MME) precipitation time data was generated by averaging historical and future estimates from multiple GCMs. CCFs were calculated for the MME to assess variations in precipitation.

4.2. Bilinear interpolation

Bilinear interpolation approximates the value at a given interpolation point by calculating a weighted average of the values at the four closest points on the boundary. The weights used are inverse to the distance between the existing points and the interpolation sites. The interpolation is performed according to formula (1):

$$I_d = (D_a \times D_b \times D_c \times D_d) / (a + b + c + d) \tag{1}$$

Table 1
A comprehensive list of the CMIP6 climate models used.

No	Modelling Centre	Model	Reference	Resolution (Lon × Lat)
1	Canadian Centre for Climate Modelling and Analysis, Canada	CanESM3	Swart et al. (2019)	2.8° × 2.8°
2	EC-Earth-Consortium, Europe	EC-Earth3-Veg	Wyser et al. (2019)	0.7° × 0.7°
3	Geophysical Fluid Dynamics Laboratory, National Oceanic and Atmospheric Administration, USA	GFDL-ESM4	Held et al. (2019)	1.3° × 1°
4	Institut Pierre-Simon Laplace, Sorbonne Université, France	IPSL-CM6A-LR	Olivier et al. (2018)	2.5° × 1.3°
5	Atmosphere and Ocean Research Institute, The University of Tokyo, Japan	MIROC6	Tatebe et al. (2019)	1.4° × 1.4°
6	The Meteorological Research Institute, Japan	MRI-ESM2-0	Yukimoto et al. (2019)	2.8 × 2.8

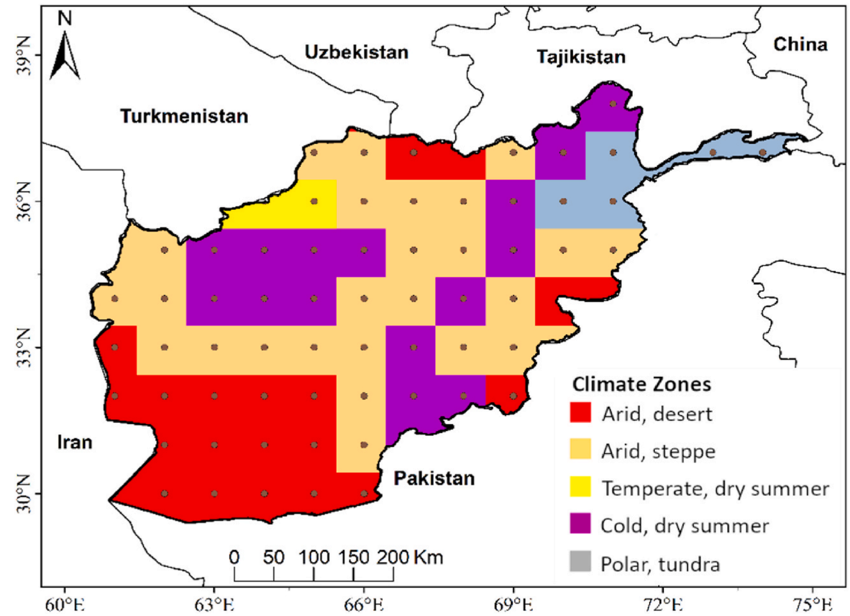

Fig. 2. The geographical position of Afghanistan in south-central Asia and the grid points used for the precipitation projection.

The interpolated value (I_d) is determined based on the values of the adjacent grid points (D_a, D_b, D_c, and D_d), representing the left, right, top, and bottom values, respectively. The corresponding distances from the interpolation point are denoted as a, b, c, and d. This approach has been observed in several studies on the impacts of climate change [53–57].

4.3. Bias correction

Various bias correction techniques have been developed to address bias in GCMs [7,58]. This study aimed to assess average variations in monthly precipitation levels across the geographical region of Afghanistan. Therefore, the mean bias correction technique was used. This approach suggests that monthly data can be adjusted according to the mean bias observed over the reference period [58]. Therefore, the bias is estimated using eq. (2):

$$F_{BC} = P_{GCM} - \overline{F_{REF}} \tag{2}$$

The bias correction factor (F_{BC}) was derived using the GCM simulated precipitation data for the historical period from 1975 to 2014. This factor was determined by comparing the GCM precipitation data (P_{GCM}) with the GPCC precipitation data (F_{REF}) for the same historical period. F_{BC} was used to correct the inherent bias in GCM-simulated precipitation over the projected period from 2020 to 2099. The method is pictorially presented in Fig. 3(a).

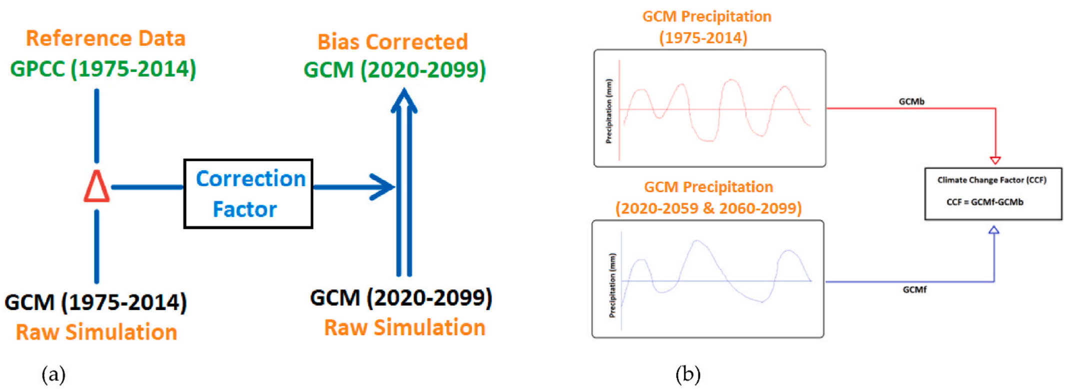

Fig. 3. (a) A schematic diagram illustrating the mean bias correction approach, and (b) the procedure employed to estimate the climatic change factor.

4.4. Climate change factor (CCF)

The CCF was estimated using the bias-corrected GCM simulation. CCF is the difference between projected future precipitation and simulated precipitation for the base period, with both periods of equal duration. The study aims to project potential alterations in precipitation patterns so CCF indicates expected changes relative to the reference period. The study utilizes datasets spanning 40 years, consisting of bias-corrected historical GCM simulations and equivalent datasets for the same period, representing bias-corrected future periods. These datasets are used to calculate CCFs. The methodology used for estimating CCF in this study is depicted in Fig. 3(b).

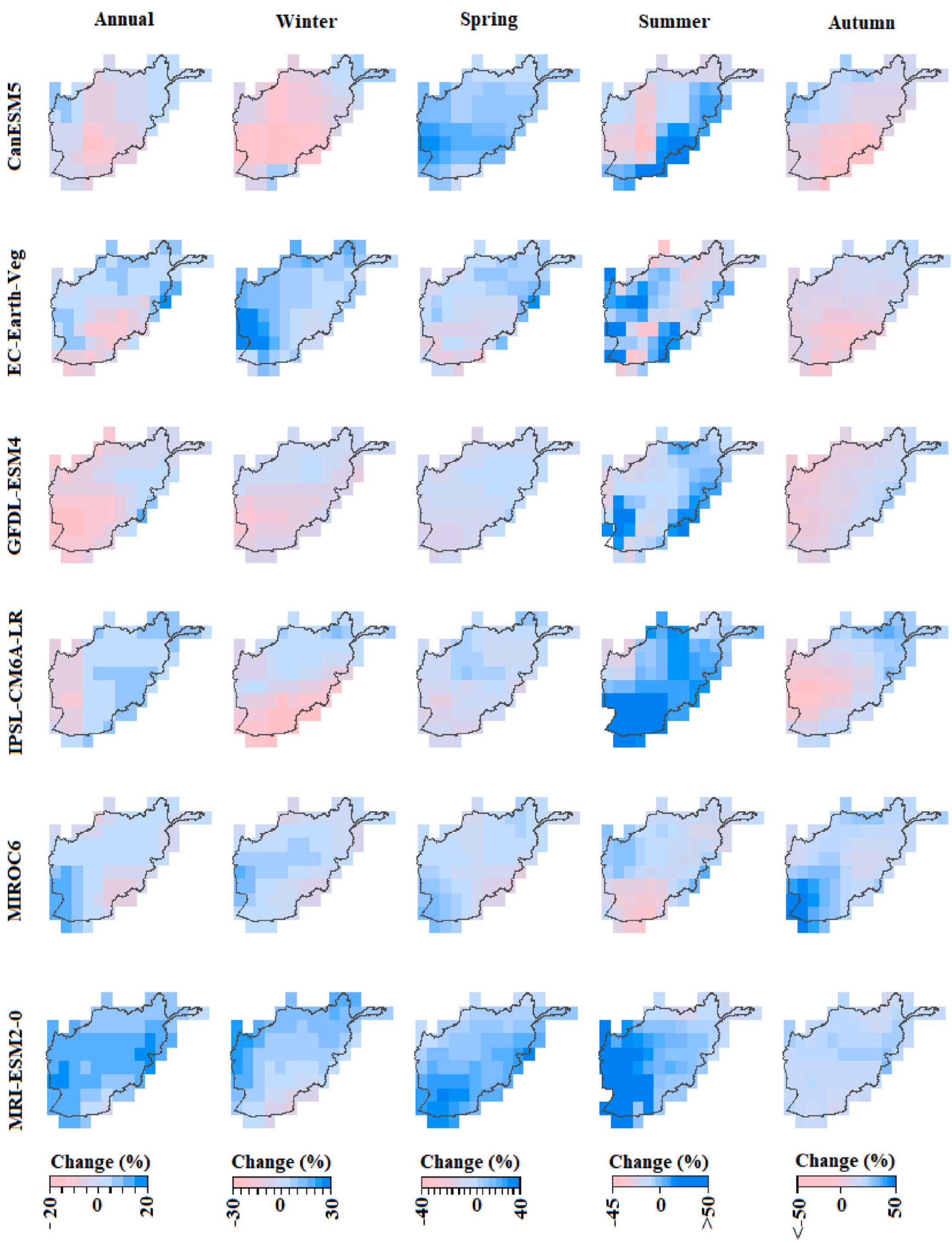

Fig. 4. The spatial distribution of the percentage increases in precipitation projected for 2020–2059, as calculated by the GCMs for SSP1–1.9; first panal: Annul, second panal: Winter, third panal: Spring, fourth panal: Summer, fifth panal: Autumn.

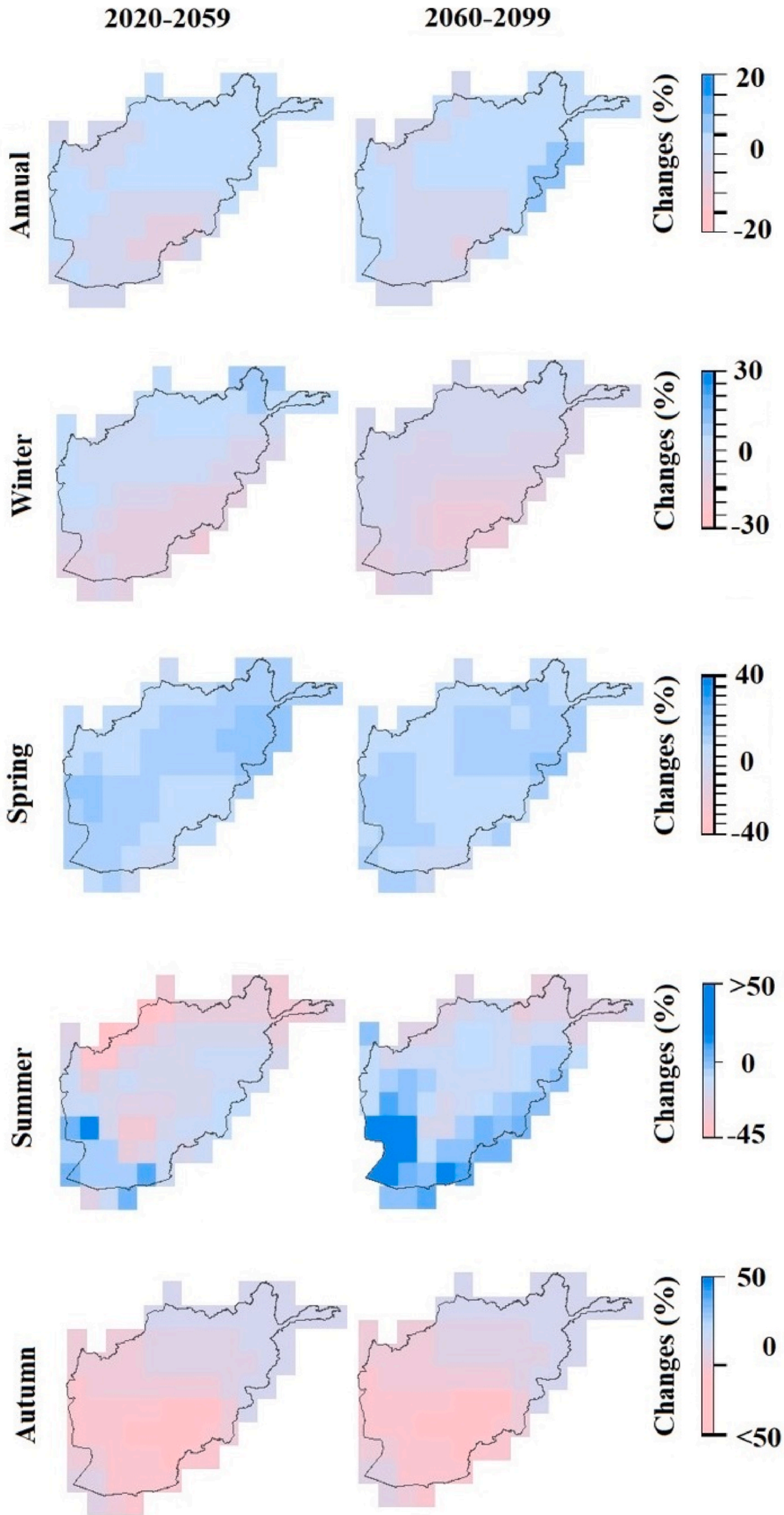

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Fig. 5. The annual and seasonal changes (%) in multi GCM mean precipitation during 2020–2059 (left panal) and 2060–2099 (right panal) for SSP1-1.9.

While CCF methods can be useful for adjusting historical climate data to represent future projections better, they have several limitations. The effectiveness of CCF methods relies heavily on the quality and representativeness of the historical data used to calculate bias factors. Poor quality data can lead to inaccurate bias corrections. The uncertainty in CCF-corrected data based on poor-quality gridded data is difficult to quantify and propagate through subsequent analyses. Besides, applying CCF methods to gridded data often involves averaging bias corrections across large spatial extents, which mask important local variations in bias and lead to inaccurate adjustments in some regions. These drawbacks are handled in this study using GPCC data, which has been found to provide reliable precipitation throughout the globe [52].

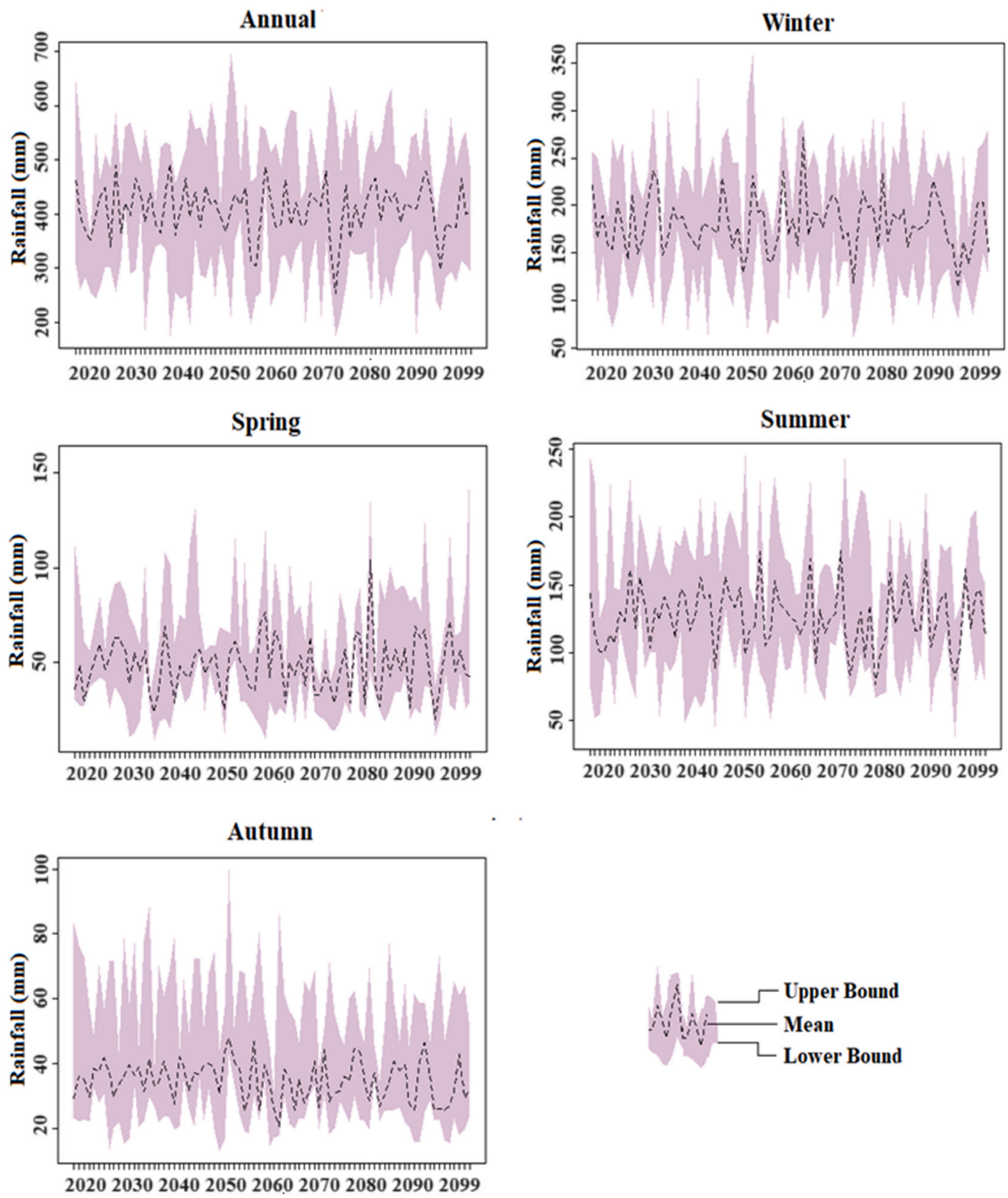

Fig. 6. Projected precipitation series with uncertainty during 2020–2099 for SSP1-1.9 and for all tested seasons: Annul, Winter, Spring, Summer, Autumn.

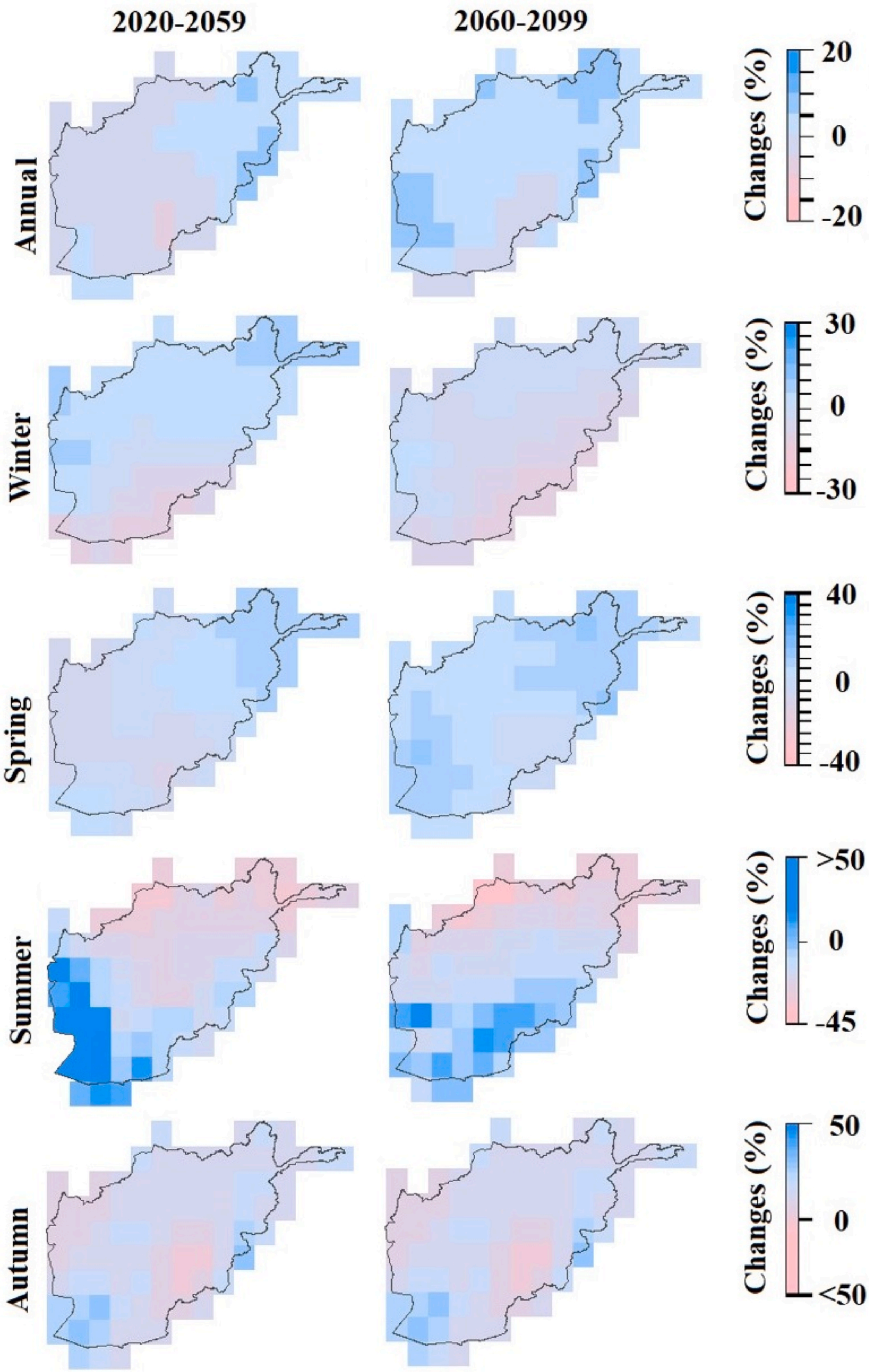

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Fig. 7. The annual and seasonal changes (%) in multi-GCM mean precipitation during 2020–2059 (left panal) and 2060–2099 (right panal) for SSP1-2.6.

4.5. Precipitation projections

Calculating the projected MME precipitation involves aggregating projected precipitation data from various GCMs for distinct SSPs. This study examined variations in mean monthly precipitation in Afghanistan over two distinct future periods: the near future (2020–2059) and the distant future (2060–2099). These periods were compared to the historical period (1971–2010) to evaluate alterations in precipitation patterns.

5. Modeling results

5.1. Precipitation projections

Fig. 4 illustrates the regional distribution of projected changes in annual and seasonal precipitation (%) in Afghanistan for the near future (2020–2059) for SSP-11.9. Significant heterogeneity in anticipated precipitation changes was observed among the GCMs. For example, the MRI-ESM2-0 projected an increase in annual precipitation over most of the nation, while the GFDL-ESM4 model projected a decrease in annual precipitation. Various GCMs have projected increases and decreases in different regions of Afghanistan. Most models indicate an expected increase or no change in annual precipitation in the northeastern region, while a decrease in precipitation is anticipated in the southwestern region, particularly in the southwest. The study revealed a significant inconsistency across the GCM estimates, resulting in the absence of a consistent projection of precipitation increase or reduction for any specific location. Diverse fluctuations in precipitation were noted across various seasons. The most significant disparity in projections was observed during the winter season, which experiences the highest precipitation in most regions in the country. For example, the EC-Earth-Veg model showed a significant increase in winter precipitation over most of the nation. In contrast, the CanESM5 model demonstrated decreased precipitation throughout the country. Most models indicated an expected decrease in winter precipitation in the southwestern region. Expected changes in precipitation patterns include a reduction in spring precipitation in the central area, a decrease in summer precipitation in both the central and northern regions, and a decrease in fall precipitation, specifically in central Afghanistan. Consequently, the GCM projections of annual and seasonal precipitation for various future periods and scenarios were aggregated to create the MME precipitation projections.

5.2. Annual and seasonal precipitation projections for SSP1-1.9

Fig. 5 illustrates the regional distribution of the MME averages of annual and seasonal precipitation variations expressed as percentages for two future periods (2020–2059 and 2060–2099) for SSP 1–1.9. The results indicate notable alterations in yearly precipitation patterns over most of Afghanistan in both future periods for SSP 1–1.9. It is worth noting that there is a projected modest increase in precipitation between 5% and 10% within a restricted region in the northeast during 2020–2059 and 2060–2099. On the other hand, there is an expected reduction in precipitation of around 15% in the southwest.

A noticeable distinction in the regional distribution of winter precipitation alterations is observed between the two scenarios in the immediate future. SSP1-1.9 showed that winter precipitation in the southern areas will experience a reduction of up to 20%. Conversely, a marginal rise in winter precipitation will be in the northern sections in the far-future period. In contrast, spring precipitation exhibited an overall increase over the whole nation, with somewhat greater increments expected in the far future compared to the near future.

Significant alterations are anticipated in summer precipitation. A substantial increase of around 50% is expected in the southwest, while a decline of over 50% in the northwest. Notably, Afghanistan typically experiences modest summer precipitation; hence, the substantial variations observed during this season may not significantly influence the overall annual precipitation.

The study's findings suggest that there would likely be an increase in annual and seasonal precipitation in the northwestern region of Afghanistan, which typically experiences higher levels of rainfall. In contrast, there will be a decrease in precipitation in the southwest, which typically receives less rainfall. This implies that under the SSP1-1.9 in Afghanistan, there would be an intensification of wetness in already wet regions, while dry parts would experience an exacerbation of aridity.

Fig. 6 presents the annual and seasonal mean precipitation with uncertainty for 2020–2099. The black dashed line denotes the average precipitation, while the pink band indicates the level of uncertainty. The precipitation projection for the entire Afghanistan is averaged to prepare the graphs. Upon analyzing the annual precipitation time series for SSP119, a slight decrease in precipitation is observed over time. This decreasing trend is also noticeable in winter and spring precipitation. However, a slight increase in summer and autumn precipitation is projected towards 2100.

This study showed considerable uncertainty in the annual and seasonal precipitation projections. This suggests that the future precipitation patterns in Afghanistan are highly uncertain and subject to variability. As a result, the accuracy and reliability of the projections may be affected by multiple factors. These findings underscore the need for further research and modelling to improve our understanding of the factors influencing precipitation variability in Afghanistan. It also highlights the importance of considering the uncertainty in precipitation projections when planning for water resource management, agriculture, and other sectors sensitive to precipitation changes.

5.3. Annual and seasonal precipitation projections for SSP1-2.6

The spatial changes in precipitation for SSP126 are presented in Fig. 7. These figures exhibit similar spatial patterns of changes to those obtained for SSP1-1.9. However, the projected percentage of changes was a bit higher than for SSP1-1.9. For instance, significant changes in annual precipitation were observed in the northwest region of Afghanistan for both future periods, with increases of up to 15% for SSP1-2.6. Similarly, winter precipitation was expected to reduce in the southern regions. However, the decline might be higher for the SSP1-2.6 than for the SSP1-1.9.

Fig. 8 shows the annual and seasonal mean precipitation and the associated uncertainty over the entire duration from 2020 to 2099 under the SSP1-2.6. For the SSP1-1.9, the black dashed line depicts the average precipitation, while the pink band represents the range of uncertainty. The precipitation projection for the entire Afghanistan is averaged to prepare the graphs. Analyzing the annual precipitation time series for the SSP1-2.6 shows a slight decrease over time, similar to the SSP1-1.9. However, the magnitude of the reduction was a bit higher for SSP1-2.6 than for SSP1-1.9. Similar decreasing patterns were observed for winter and summer precipitation, while there was almost no change in spring and autumn precipitation over the century. Notably, a large uncertainty in both annual and seasonal precipitation projections was observed for SSP1-2.6, just as for SSP1-1.9.

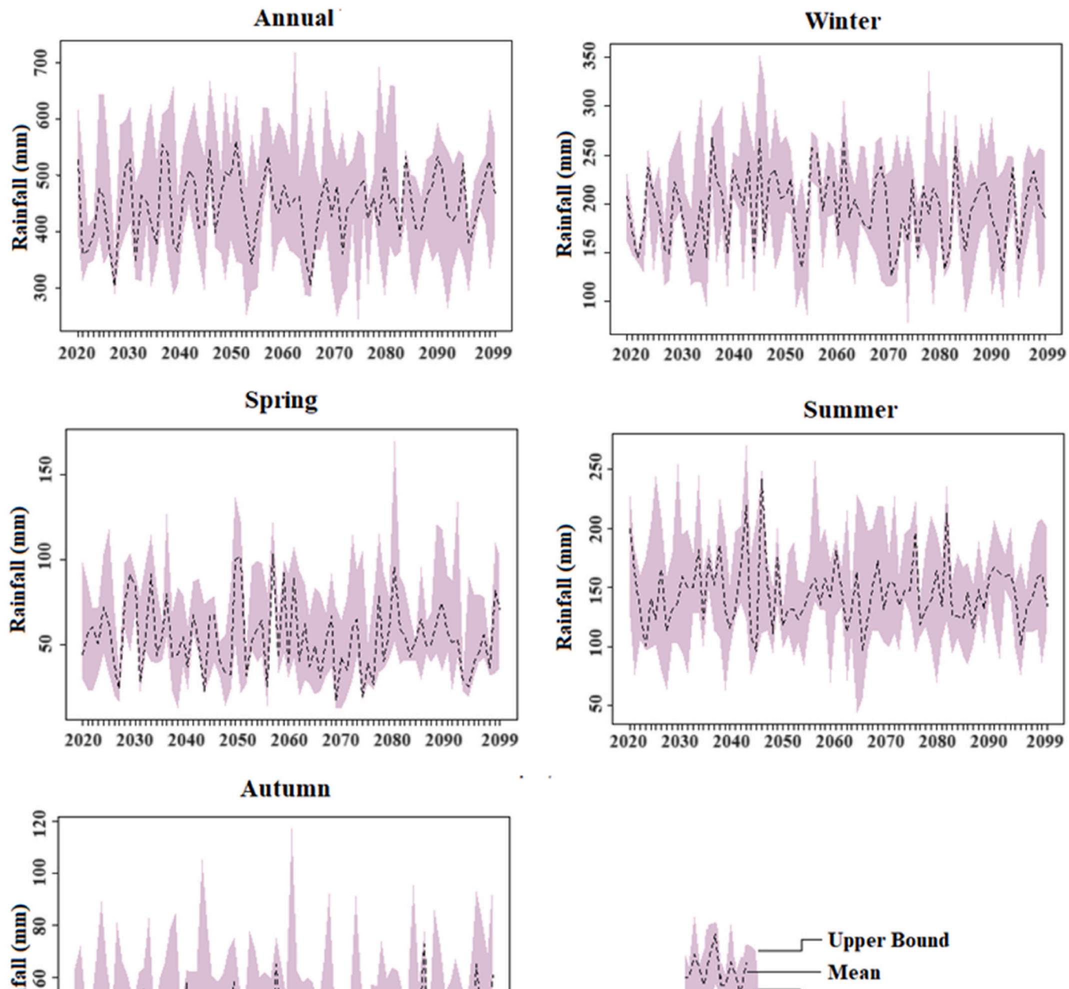


Fig. 8. Projected precipitation series with uncertainty during 2020–2099 for SSP1-2.6 and for all tested seasons: Annul, Winter, Spring, Summer, Autumn.

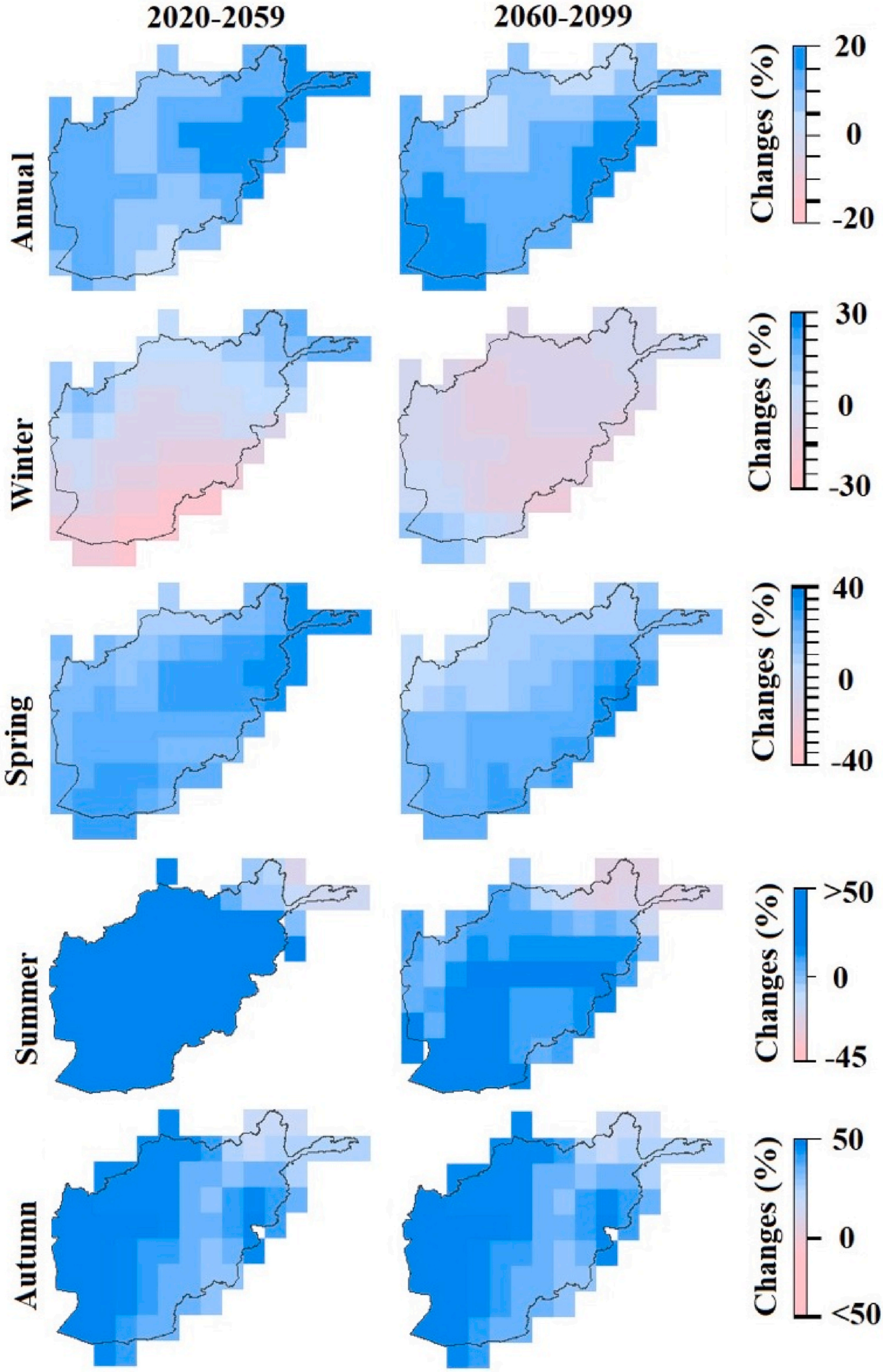


Fig. 9. The annual and seasonal changes (%) in multi-GCM mean precipitation during 2020–2059 (left panal) and 2060–2099 (right panal) for SSP2-4.5.

5.4. Annual and seasonal precipitation projections for other SSPs

The diverse precipitation patterns observed in these scenarios provide valuable insights into the region's susceptibility to the effects of climate change. Therefore, this study assessed the changes in precipitation across all SSPs.

Fig. 9 through 12 illustrate the geographical variations in precipitation patterns corresponding to SSP2-4.5, SSP3-7.0, and SSP5-8.5, respectively. The figures show patterns similar to the geographical variations observed in previous scenarios with lower emissions. However, a significant difference was observed in the expected changes, with much higher percentages for the higher SSPs than the lower ones.

Fig. 9 shows a projected annual precipitation increase of around 20% in the southwestern and certain eastern regions in the far future for SSP2-4.5. Conversely, a precipitation increase of approximately 15% is anticipated in the near future over most of the country. Nevertheless, both upcoming periods suggest a notable decline in winter precipitation, with a potential reduction of up to 30% across most of the territory. The most substantial decrease of 30% is expected in select southern areas within the region. In contrast, there might be around a 20% increase in spring precipitation throughout most of the region during both future times. Furthermore, most of the region will experience significant increases in summer precipitation, exceeding 50%, in the near future for SSP2-4.5. Similarly, the expected changes in fall precipitation indicate a substantial rise of almost 50% in the western regions of the examined area. Fig. 10 presents data regarding the MME mean and the upper and lower limits of projected precipitation over the entire

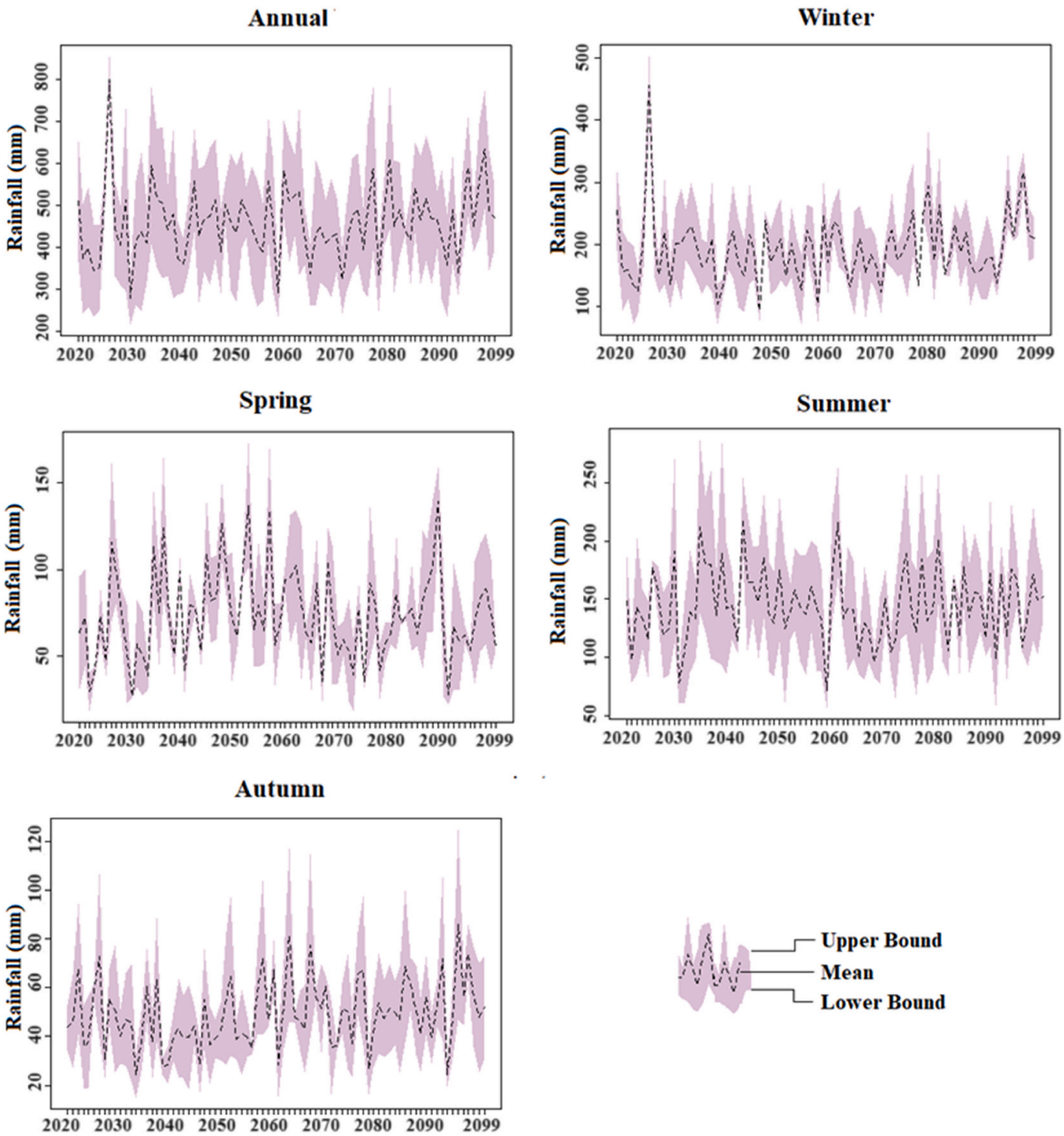
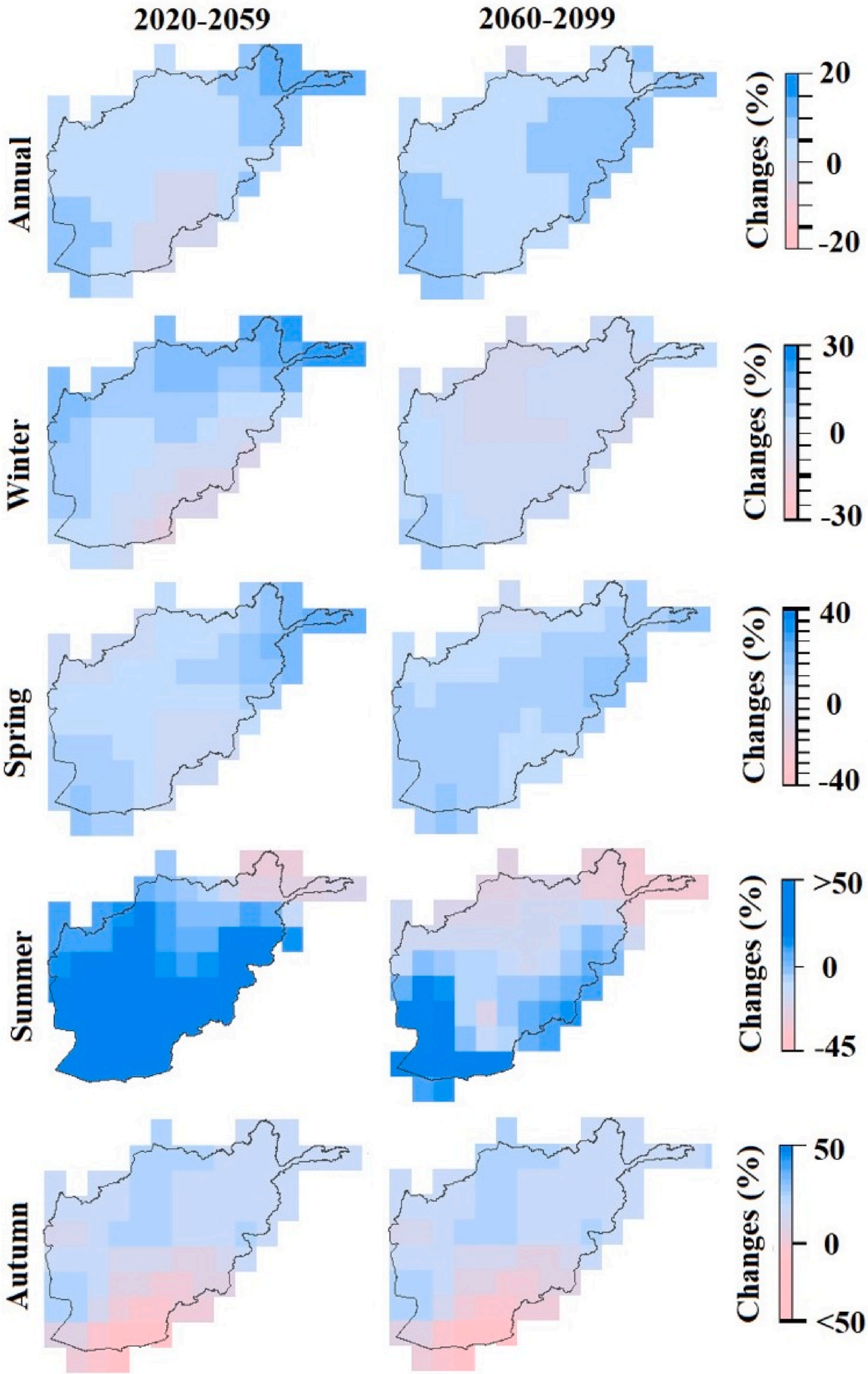


Fig. 10. The projected precipitation series with uncertainty over 2020–2099 for SSP2-4.5 and for all tested seasons: Annul, Winter, Spring, Summer, Autumn.



(caption on next page)

Fig. 11. The annual and seasonal changes (%) in multi-GCM mean precipitation during 2020–2059 (left panal) and 2060–2099 (right panal) for SSP3-7.0.

future period. This data encompasses the annual, winter, spring, summer, and autumn seasons within the context of the SSP245. The findings indicate a significant increase in average precipitation during the early years for both the annual and winter seasons, followed by relatively stable average precipitation until 2100. Similarly, the mean, upper, and lower limits of precipitation during the spring and summer seasons exhibit slight fluctuations within the projected time frame. The fall season shows limited fluctuation in precipitation over the remainder of the 21st century. The spring season showed the narrowest uncertainty band, representing a smaller range between the upper and lower boundaries, with the winter season following a similar pattern.

Fig. 11 displays the anticipated changes in average precipitation, as the mean MME indicates, over different time intervals (2020–2059 and 2060–2099) under the SSP370. The results suggest that a significant portion of Afghanistan will experience an annual precipitation increase of around 20% during the upcoming timeframes. Likewise, there is an anticipated 20% increase in the winter season in the northern and western regions. In the far future, there may be a marginal decline or increase of up to 5% in most of the country. During both periods, the northern regions would experience the most significant increase in spring precipitation, estimated at around 20%. However, a substantial rise of approximately 50% in summer precipitation is expected in the central and western regions

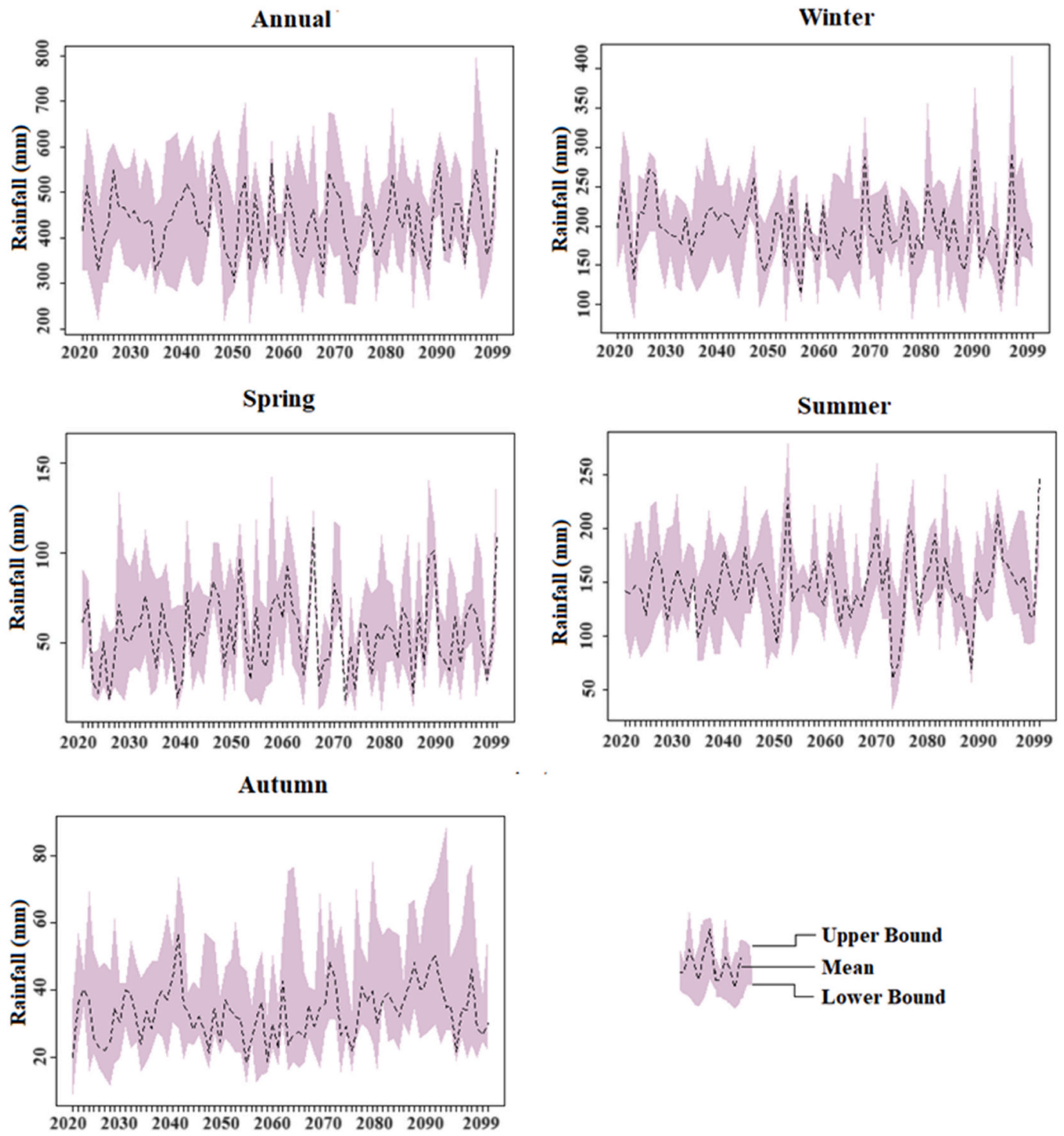


Fig. 12. The projected precipitation series with uncertainty over 2020–2099 for SSP3-7.0 and for all tested seasons: Annul, Winter, Spring, Summer, Autumn.

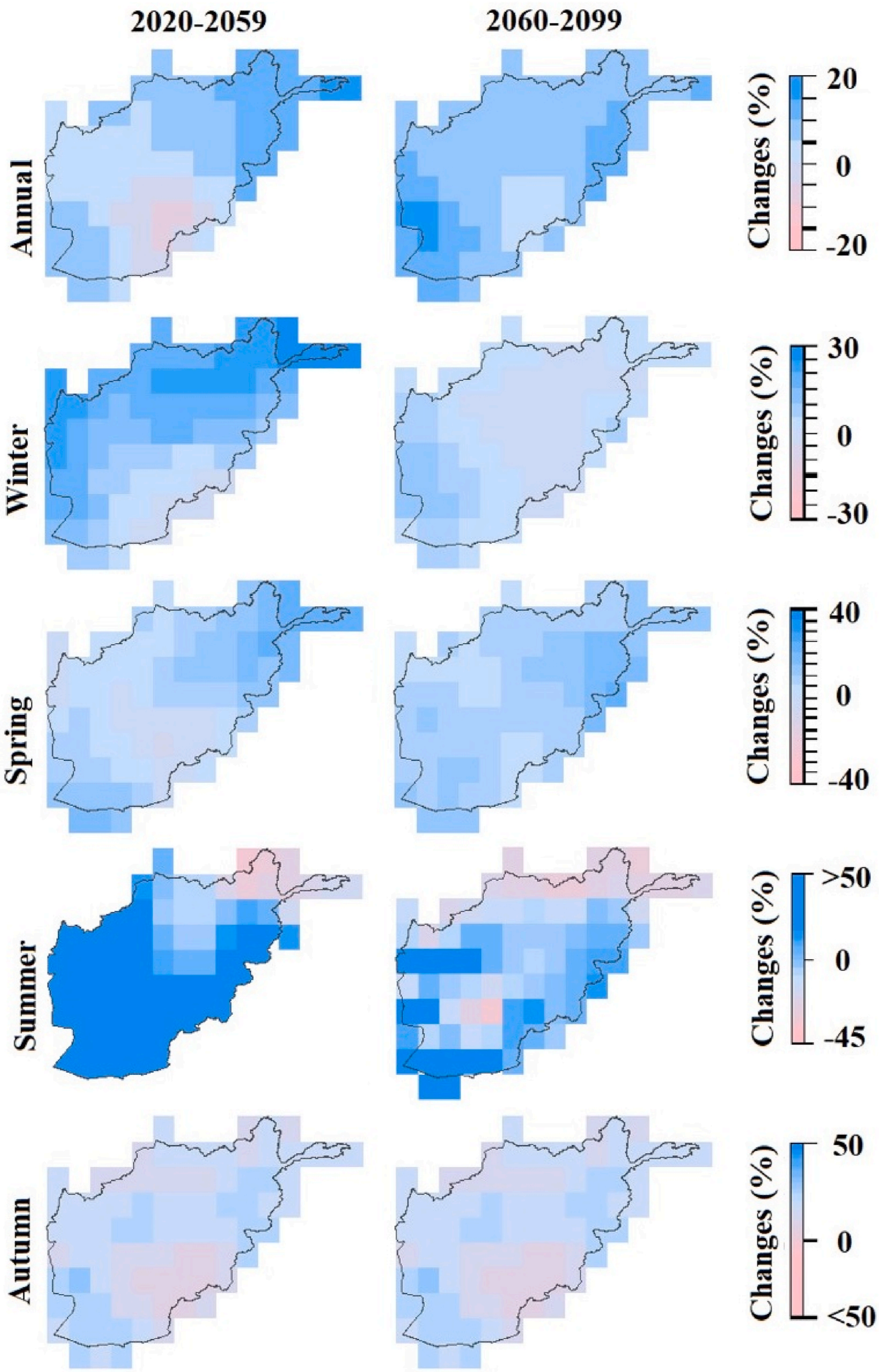


Fig. 13. The annual and seasonal changes (%) in multi-GCM mean precipitation during 2020–2059 (left panal) and 2060–2099 (right panal) for SSP5-8.5.

during summer. In the far future, this increase will be limited to the western areas. Conversely, the southern regions of the research area are expected to see the most significant decrease in fall precipitation, with a projected reduction of up to 25% for both future periods.

Fig. 12 depicts a time series analysis of projected precipitation for both future periods for SSP370. Generally, there is an oscillating trend with modest fluctuations in average precipitation. However, notable uncertainty is associated with the confidence intervals for both the annual and winter periods. In contrast, there is a substantial increase in anticipated precipitation during the spring and summer seasons from 2060 to 2070. Additionally, there is a slight upward and downward trend in projected precipitation in the fall season, extending until the end of the 21st century. The season with the narrowest uncertainty band is summer, followed by spring.

Fig. 13 displays geographical variations in the average MME of precipitation for SSP585. The findings suggest a substantial increase in precipitation, reaching up to 20%, in the northern regions of the research area. The winter season precipitation may experience a considerable rise of 30% in the north, but central areas may see a decrease of up to 10% in the distant future. Furthermore, there is a general increase of around 30% in spring precipitation across most of the region for both futures. In the foreseeable future, the central and western regions are expected to have the most substantial increase in summer precipitation, reaching up to 50%. However, there is a reduction of up to 10% during the fall season in both periods. Fig. 14 presents a time series of precipitation and the associated uncertainty band. The results indicate a progressive increase in average annual precipitation throughout the future. Similarly, estimates for the 21st century suggest a modest increase in average precipitation during winter. Mean precipitation during the spring and

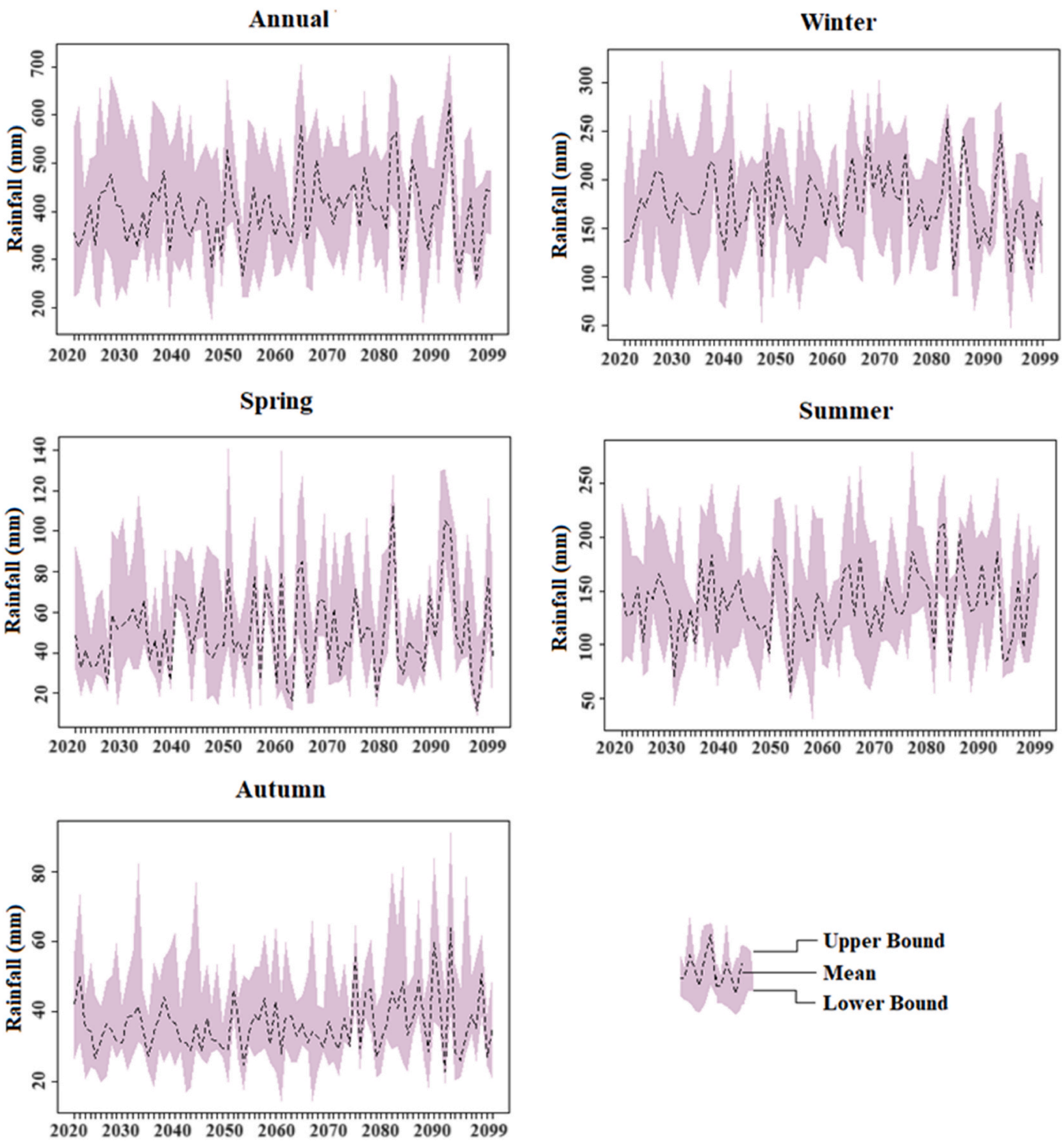


Fig. 14. The projected precipitation with uncertainty over 2020–2099 for SSP5-8.5 and for all tested seasons: Annul, Winter, Spring, Summer, Autumn.

summer seasons shows a slight upward trend until 2050, followed by progressive variability until the end of the 21st century. Notably, the spring season under SSP585 exhibits the least uncertainty compared to other seasons.

In general, the findings suggest an escalating level of precipitation variability as emissions intensity increases. This underscores the significant impact of different emission trajectories on future precipitation patterns in the region. The anticipated increases in precipitation levels under the more ambitious SSPs, particularly SSP5-8.5, indicate the potential for significant alterations in hydrological patterns in the coming years. Examining geographical variability in annual precipitation reveals that the most substantial changes occur in the northwestern region of Afghanistan across all SSPs. This underscores the heightened susceptibility of this region to prospective changes in precipitation trends, highlighting the need for targeted adaptation strategies to address the resulting challenges effectively. However, it is essential to acknowledge the notable uncertainty associated with annual and seasonal precipitation projections for all the low SSPs. Uncertainty in the data emphasizes the importance of cautiously interpreting the results.

6. Discussion

This study examined the spatiotemporal precipitation changes within Afghanistan, considering five SSPs and two distinct future time frames. The MME mean projection of precipitation offers intriguing and insightful trends, shedding light on the evolving climate dynamics in this region. Notably, the findings showcase a distinct contrast between Afghanistan's northeast and southwest areas. The projected increase in annual precipitation in the northeast region emerges as a significant highlight, indicating potential shifts in the region's hydrological cycle. This elevation in precipitation levels in other regions would benefit water resources management, agricultural practices, and overall ecosystem dynamics. It presents opportunities for harnessing increased water availability for sustainable development, including potential benefits for agriculture and livelihoods.

Conversely, the detected decrease in precipitation in the southwest raises concerns about water scarcity and aridity in this already water-stressed region. Such a decline in annual precipitation could exacerbate environmental challenges, impacting agricultural productivity, water supply, and local communities' well-being. This poses a critical challenge to water resource management and necessitates implementing adaptive measures to ensure water security and resilience in the region. The observed spatiotemporal variations in precipitation patterns underscore the necessity of divulging the intricacies of precipitation changes at the regional level. It highlights the necessity of region-specific adaptation strategies, accounting for the divergent impacts of precipitation changes over Afghanistan. Policymakers and stakeholders must take cognizance of these diverse patterns to develop targeted and effective climate adaptation and mitigation plans.

Few studies evaluated the precipitation of Afghanistan for limited SSPs [35,59]. They showed similar precipitation alterations in different Afghanistan regions for various SSPs. Sediqi et al. (2022) showed a large decrease in precipitation by −40% in the southwest of Afghanistan, which agrees with the findings of this study. Studies conducted in Iran [60,61], bordering Afghanistan in the west, also agree with this study's findings. Sediqi et al. (2022) projected significant precipitation increases in the sub-Himalayan northwest, consistent with this study's finding. Studies in the nearby Himalayan regions also revealed increased precipitation [62,63].

Generally, rainfall tends to increase with rising temperatures due to the ability of warmer air to hold more moisture [7,42]. However, there are situations where increased temperature can lead to a decrease in rainfall [64,65]. This phenomenon is mainly attributed to the enhanced evaporation caused by higher temperatures. As temperatures rise, the rate of evaporation from water bodies and the Earth's surface increases. This increased evaporation leads to a greater water vapour flux into the atmosphere, increasing the air moisture content [66]. In regions already characterized by arid or semiarid climates, where water availability is limited, the heightened evaporation can significantly deplete the available moisture, reducing the probability of rainfall incidents [64,66].

The contrasting trends in precipitation between different regions call for region-specific climate adaptation measures. Policymakers and local communities need to develop tailored strategies to address both the excess and scarcity of water in Afghanistan. These strategies should encompass water conservation and storage mechanisms in regions experiencing increasing precipitation while implementing drought-resistant agricultural practices and efficient water allocation systems in regions facing decreasing precipitation [67,68].

The obtained results can help climate change adaptation planning and build a climate-resilient society in Afghanistan, a country facing many environmental challenges [69,70]. As climate change continues to impact the region, understanding the projected changes in precipitation becomes crucial for policymakers and stakeholders to develop effective strategies and policies. The projected changes in precipitation patterns provide critical insights into the future availability of water resources in different regions of Afghanistan. This information can guide decision-makers in developing water management plans that balance water allocation for agriculture, industry, and domestic use. By anticipating potential changes in water availability, policymakers can ensure sustainable and equitable access to this essential resource, thereby safeguarding the livelihoods of millions of Afghan citizens.

Moreover, the study's results offer valuable guidance for the agricultural sector, which forms the backbone of the country's economy [18,71]. Understanding the shifts in precipitation patterns can help farmers adopt climate-smart agricultural practices. This may include promoting drought-resistant crop varieties, implementing efficient irrigation techniques, and adopting sustainable land management practices to mitigate the impacts of changing water availability on crop yields [72]. The projected precipitation changes can also inform Afghanistan's disaster preparedness and response plans. With the likelihood of increased flooding in some regions and intensified aridity in others [73,74], it is essential to strengthen early warning systems and build resilient infrastructure to mitigate climate change risks. By doing so, Afghanistan can reduce the impact of natural disasters on communities and minimize damage to property and infrastructure. Furthermore, the study's findings can enhance Afghan society's overall climate resilience. By understanding how precipitation patterns may evolve in the coming decades, policymakers can integrate climate considerations into various sectors, including urban planning, infrastructure development, and public health. This integrated approach can foster a climate-resilient society that can adapt to the changing climate and withstand future challenges more effectively.

Further research and data collection on precipitation trends is essential to ensure the robustness of the study's projections. Collaborative efforts between local institutions, international organizations, and climate scientists can strengthen Afghanistan's capacity to generate reliable climate data, improving the accuracy of future projections. Moreover, the study highlights the importance of enhancing early warning systems and disaster preparedness measures to tackle potential floods resulting from increased precipitation. Building resilient infrastructure and implementing flood mitigation measures will be crucial to protect communities and reduce the impact of extreme weather events.

7. Conclusion

The primary objective of this study was to examine the spatiotemporal variations in precipitation patterns across Afghanistan during five SPPs and two future periods. This study used bilinear interpolation to re-grid GCMs to a standard resolution of $1.0^\circ \times 1.0^\circ$. The delta change method was employed to reduce the biases in GCM simulations for assessing the projected changes in precipitation in the near future (2020–20259) and far future (2060–2099). Furthermore, the MME technique was applied by averaging historical and future estimates from multiple GCMs. The mean precipitation projections derived from MME reveal significant patterns, including an increase in annual precipitation in the northeastern region and a decrease in the southwestern region. The key findings obtained from this study are as follows:

- The areas with high precipitation are likely to experience increased wetness, while locations with low precipitation levels are expected to face heightened aridity.
- The projections suggest a worrisome decline in precipitation during Afghanistan's primary rainy season, particularly in the southwestern region, which traditionally experiences lower levels of rainfall. The decrease in winter precipitation can worsen aridity in many parts of the nation, especially in the already arid and desert areas in the southern regions. This decrease in precipitation could expedite the process of desertification and diminish the availability of dry areas, thus presenting significant environmental challenges.
- The rise in precipitation in the northeastern area raises concerns about the possibility of hydrological catastrophes, particularly flooding. The surplus water from increased rainfall may lead to flooding, threatening communities and infrastructure in the affected areas. Additionally, the amplified precipitation may cause increased river sedimentation, a significant problem in the region, affecting water quality and availability.
- The study highlights the importance of climate-resilient agricultural practices such as efficient irrigation systems, water management practices, and drought-adapted crops in the southwestern regions.

In the future, it is crucial to evaluate changes in precipitation separately for different climatic regions within Afghanistan to gain a more nuanced understanding of localized impacts. Additionally, the projected precipitation data can be used to assess possible changes in hydrological hazards, such as aridity and droughts, which have severe implications for water resources and agriculture. To enhance the accuracy and resolution of projections, downscaling the GCMs projections to a higher spatial resolution can provide more detailed insights into the spatial variability of precipitation changes.

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Data can be provided upon request.

CRediT authorship contribution statement

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Zulfiqar Ali: Writing – original draft, Visualization, Validation, Resources, Formal analysis, Data curation. **Ghaith Falah Ziarh:** Writing – original draft, Validation, Methodology, Investigation, Formal analysis, Data curation. **Mohamad Rajab Houmsi:** Writing – original draft, Visualization, Validation, Resources, Methodology, Formal analysis, Data curation. **Mohd Khairul Idlan bin Muhammad:** Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation. **Il-Moon Chung:** Writing – original draft, Visualization, Validation, Methodology, Investigation, Data curation, Conceptualization. **Sungwon Kim:** Writing – original draft, Visualization, Validation, Formal analysis, Data curation, Conceptualization. **Zaher Mundher Yaseen:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Project administration, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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