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ORIGINAL PAPER

Future precipitation extremes over base Himalayan Uttarakhand region: analysis using the statistically downscaled, bias-corrected high-resolution NEX-GDDP datasets

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Abstract

The Himalayan region of Uttarakhand, India, has witnessed floods and landslides, and more extremes are likely in the future. This study examined the projected changes in precipitation extremes by using state-of-the-art, high-resolution (0.25° × 0.25°) statistically downscaled NASA Earth Exchange Global Daily Downscaled Projections (NEX-GDDP) during southwest monsoon season (June to September) under the RCP 4.5 and RCP 8.5 scenarios. The spatial variations of mean precipitation, as well as the extremes obtained from the multi-model mean (MMM) from NEX-GDDP simulations, were compared with Asian Precipitation-Highly-Resolved Observational Data Integration Towards Evaluation of Water Resources (APHRODITE) observational data for the baseline period (1976–2005). For the future climate, the monsoon precipitation over the Uttarakhand region may increase by ~13% and ~16% under the RCP 4.5 and RCP 8.5 emission scenarios, respectively, in the near future (2021–2050) and may further increase by 23% and 36% in the far future (2070–2099). The different extreme precipitation indices analyzed show an increase with the exception of consecutive dry days (CDDs) over Uttarakhand, both in the near future and in the far future, under both scenarios. The RCP 4.5 and RCP 8.5 scenarios exhibited a noticeable increase in the highest 1-day rainfall (by 1.4 mm decade^{-1} and 3.3 mm decade^{-1}) and in the highest 5-day rainfall (by 2.7 mm decade^{-1} and 7 mm decade^{-1}), along with the extreme R95P precipitation days (by 11% and 22%), and consecutive wet days become more frequent during monsoon season, respectively. The study findings highlight the need for considering more extreme rains in base Himalayan climate resiliency planning.

Keywords NASA downscaled projections · Emission scenarios · Precipitation extremes · Indian summer monsoon · Uttarakhand

1 Introduction

Rapid changes in the current climatic condition have become alarming, having an impact on a global scale. The projected changes in these extreme climate events affect the water resources, natural ecosystems, and economy in the future (IPCC 2013). Recent studies concluded that, as a result of global warming, there are significant signs of more frequent extreme precipitation events (Alexander et al. 2006; Goswami et al. 2006; Min et al. 2011; Trenberth 2011; Field et al. 2012; Donat et al. 2016; Kulkarni et al. 2020; Rao et al. 2020). It is evident that with an increase in temperature, global warming increases the capacity of the atmosphere to hold moisture (Trenberth et al. 2003). This increase in rainfall intensity is primarily due to moisture convergence and the thermodynamic effect of the Clausius-Clapeyron relationship (Kunkel et al. 2013). According to several studies, global warming is causing

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extreme precipitation events to increase in various regions (Choi et al. 2009; Caesar et al. 2011; Tan et al. 2017; Forestieri et al. 2018; Rao et al. 2020). In recent decades, an increase in heavy precipitation events and flood frequency over many parts of the world has also been observed (World Meteorological Organization 2011). Nonetheless, there exist uncertainties in the future projections of precipitation extremes (Knutti 2008; Chen et al. 2014) due to the very complex nature of the earth climate system, which is not well understood in the regional and global models (Zhou and Chen 2015; Jiang et al. 2016).

Rainfall variability, both spatial and temporal, is crucial for India's agriculture, hydrology, and water resources. The Indian subcontinent receives 80% rain during the southwest (SW) monsoon, i.e., between June and September (JJAS) (Ghosh et al. 2009). The low-pressure systems and depressions moving towards the northwest direction and the monsoon trough shifting to Himalayan foothills also contribute to rainfall in this season. Seasonal variation of Inter-Tropical Convergence Zone (ITCZ) over the monsoon region is an indication of reversal wind, which plays a crucial role in the development of the Indian summer monsoon (Gadgil 2003). Reports of substantial variations in precipitation at a finer scale have been reported by Ghosh et al. (2009). There has been an increase in rainfall from 1901 to 1964, followed by a decreasing trend from 1965 to 1980 in the Indian Himalayan region (Basistha et al. 2009). The western Himalayan region observed a considerable increase in extreme weather events in the recent 30–40 years (International Disaster Database; http://www.emdat.be). According to Sen Roy and Balling (2004), the rainfall intensity has increased between 1910 and 2000 in some parts of the Western Himalayas, particularly in Uttarakhand. It may be attributed to increased global warming in recent periods (Wang et al. 2012). In recent years, India has faced extreme precipitation events resulting in the loss of lives and damage to agriculture and infrastructure. Extreme rainfall (both high and low), particularly during the monsoon season in India, can cause major disasters such as increasing drought conditions (Kumar et al. 2013), flash floods in many regions (Guhathakurta et al. 2011), and soil erosion (Martınez-Casasnovas et al. 2002). Landslides are another primary concern associated with extreme rainfall events over the mountainous region. The Uttarakhand State has been exposed to landslides and mudslides during the monsoon season and mainly due to the intense rainfall activity over the region (Rajesh et al. 2016; Chawla et al. 2018, cross references). Individual case studies revealed that these intense rainfall episodes are mainly due to the individual or cumulative effect of organized mesoscale convective systems and large-scale monsoonal features such as depressions from Bay of Bengal and Arabian Sea, mid-tropospheric cyclones (MTCs), and offshore troughs/vortices (Sikka and Gadgil 1980; Fasullo and Webster 2003; Rajesh et al. 2016). Generally, the landslides are exacerbated during the monsoon season due to (i) increased pore water pressure, (ii) greater weight of the rock mass, (iii) decreased frictional forces, etc. Among all, the intense rainfall appears to be one of the important factors along with the Himalayan geology (Gupta and Uniyal 2012). Kirschbaum et al. (2020) reported that extreme rainfall from short cloudbursts to prolonged rainfall of several days to weeks is the most significant trigger of landslides. Uttarakhand, an Indian Himalayan state, is prone to these extreme events and witnessed climate change impacts (Dore 2005; Kumar et al. 2010). The Uttarakhand flash flood which occurred in 2013 resulted in the deaths of 6000 people and a loss of 3.8 billion USD (Rapidly Assessing Flood Damage in Uttarakhand, India 2014).

Very few studies have concentrated on the rainfall trend analysis over the Himalayan region. Although research studies encapsulate the present and future spatial rainfall variations over Uttarakhand during the monsoon season (Banerjee et al. 2020), no studies have been done to understand the future projections of extreme rainfall events using high-resolution downscaled datasets. Previous studies showed the absence of Himalayan region rainfall data due to a lack of rain gauge observatories and Doppler radar observations (Basistha et al. 2009; Singh and Mal 2014). All these factors are attributed to the vulnerabilities associated with the impact of climate change. Thus, there was a need for a study that could better understand the future climate extreme events over the state of Uttarakhand for better climate preparedness and avoid the catastrophic damages of climate change. The global climate models (GCMs) have proven an excellent source for projecting the climate status for the future. Under a warming period, high-resolution modeling or downscaling of GCMs can capture future extremes and rainfall variability (Kumar et al. 2011; Rao et al. 2014). Several studies have admitted and did a step-forward method to reduce the uncertainties in the rainfall projections by weighting the CMIP5 and CMIP6 models (Brunner et al. 2020; Kolusu et al. 2021; Siderius et al. 2021). In our study, we have emphasized the use of a statistically downscaled, bias-corrected, high-resolution NASA Earth Exchange Global Daily Downscaled Projections (NEX-GDDP) dataset developed by the National Aeronautics and Space Administration (NASA) by using the Coupled Model Intercomparison Project Phase 5 (CMIP5) models (Thrasher et al. 2012). Section 2 of the article explains the study area of Uttarakhand and the data and methods, followed by the Section 3 on results and discussion. Section 4 of the article deals with a concluding remark.

2 Area, data, and methods

The current study considers the Uttarakhand State to offer a better understanding of the varying rainfall patterns in the region (Fig. 1). Uttarakhand, previously known as Uttaranchal, is one of the northern states in India. The state lies between the latitudes of 28° N to 31.5° N and the longitudes of 77.5° E to 81.4° E. This state is located in the foothills of Himalayas and is mainly a hilly state. The Uttarakhand State has a total geographical area of 51,125 km^2, of which 93% are mountains, in which 65% are covered by forest, glaciers are at the high elevation regions and coolest weather, and dense forest is at lower elevations (Banerjee et al. 2020). This state is abundant in natural resources like glaciers, lush forests, perennial rivers, and snow-capped mountain peaks that can also be found across the state. The Uttarakhand State receives 80% rainfall in the SW monsoon season, and the annual average rainfall is 1494.7 mm (Banerjee et al. 2020).

NEX-GDDP dataset provides a suite of 20 statistically downscaled models from a set of CMIP5 models for two scenarios: representative concentration pathway (RCP) 4.5 and RCP 8.5. This data was used to generate future climate projections (Wood et al. 2004; Thrasher et al. 2013). More information is available at https://cds.nccs.nasa.gov/nex-gddp/. The bias correction and spatial disaggregation (BCSD) statistical downscaling method has been applied to generate these data products (Wood et al. 2004). Statistical downscaling is advantageous over dynamical downscaling as it uses low system resources and can be used over a region of any scale (Fowler et al. 2007; Kulkarni et al. 2020; Rao et al. 2020). The NEX-GDDP provides three climate variables: daily precipitation, maximum temperature, and minimum temperature (Table 1). However, we have used precipitation as the only parameter for this study. The historical runs are available for 1950–2005, while the projections are for 2006–2100. These datasets provide global, high-resolution, bias-corrected climate projections. The present study examines the future changes in precipitation extremes over Uttarakhand in two time periods: the near future (2021–2050) and the far future (2070–2099). The future precipitation extremes have been estimated concerning the baseline period (1976–2005). These high-resolution climate projections can also be helpful to comprehend processes that are sensitive to finer scales and the impact of local topography on climate conditions.

As a first step, the NEX-GDDP model output is evaluated against high-resolution gridded precipitation data (0.25° × 0.25°) from Asian Precipitation-Highly-Resolved Observational Data Integration Towards Evaluation of Water Resources (APHRODITE) for the baseline period for monthly means, seasonal means, and extreme precipitation indices. The APHRODITE data have been widely used for trend and extreme analysis of rainfall in several regions, including India (Palazzi et al. 2013; Iqbal and Athar 2018; Kim et al. 2019; Banerjee et al. 2020). The APHRODITE precipitation has been demonstrated for its better consistency with station data over India (Pai et al. 2014; Prakash et al. 2015; Kishore et al. 2016; Bandyopadhyay et al. 2018). APHRODITE data has achieved a strong correlation of 0.99 and less root mean square difference of 0.82 mm day^{-1} against IMD gridded rainfall of 0.25° × 0.25° resolution in the monsoon season (Pai et al. 2014).

The extreme precipitation indices examined in this study include (i) simple daily intensity index (SDII), (ii) very wet days (R95P), (iii) highest 1-day precipitation (RX1DAY), (iv) highest 5-day precipitation (RX5DAY), (v) consecutive wet days (CWDs), and (vi) consecutive dry days (CDDs) as shown in Table 2. These indices are widely used to investigate extremes in observations and

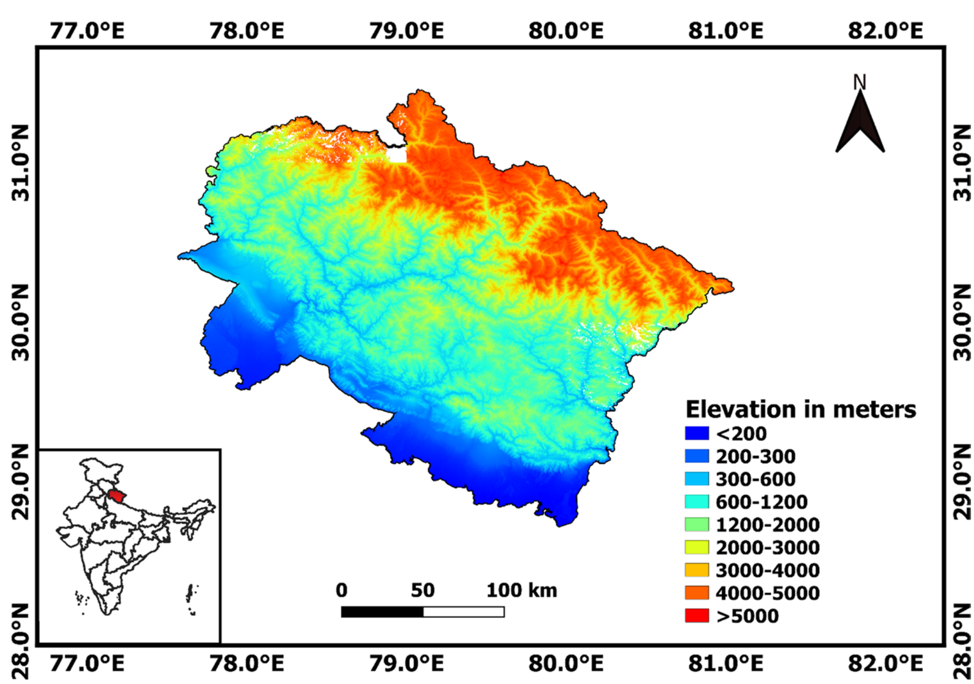


Fig. 1 Topography map of Uttarakhand State, India, the study region

Table 1 List of NEX-GDDP models used in this study (source: Thrasher et al. 2012)

Model	Institute
ACCESS1-0	Commonwealth Scientific and Industrial Research Organization (CSIRO) and Bureau of Meteorology (BOM), Australia
BCC-CSM1-1	Beijing Climate Center, China Meteorological Administration, China
BNU-ESM	Beijing Normal University, China
CanESM2	Canadian Centre for Climate Modelling and Analysis, Canada
CCSM4	National Center for Atmospheric Research, USA
CESM1/CAM5	National Center for Atmospheric Research, USA
CNRM-CM5	Centre National de Recherches Meteorologiques, France
CSIRO-Mk3-6-0	Commonwealth Scientific and Industrial Research Organization, Australia
GFDL-ESM2G	NOAA Geophysical Fluid Dynamics Laboratory, USA
GFDL-ESM2M	NOAA Geophysical Fluid Dynamics Laboratory, USA
INM-CM4	Institute for Numerical Mathematics, Russia
IPSL-CM5A-LR	Institut Pierre-Simon Laplace, France
IPSL-CM5A-MR	Institut Pierre-Simon Laplace, France
MIROC-ESM	Atmosphere and Ocean Research Institute (The University of Tokyo), National Institute for Environ-mental Studies, and Japan Agency for Marine-Earth Science and Technology, Japan
MIROC-ESM-CHEM	Atmosphere and Ocean Research Institute (The University of Tokyo), National Institute for Environ-mental Studies, and Japan Agency for Marine-Earth Science and Technology, Japan
MIROC5	Atmosphere and Ocean Research Institute (The University of Tokyo), National Institute for Environ-mental Studies, and Japan Agency for Marine-Earth Science and Technology, Japan
MPI-ESM-LR	Max Planck Institute for Meteorology, Germany
MPI-ESM-MR	Max Planck Institute for Meteorology, Germany
MRI-CGCM3	Meteorological Research Institute, Japan
NorESM1-M	Norwegian Climate Centre, Norway

future projections in various GCMs (Donat et al. 2013; Kulkarni et al. 2020; Rao et al. 2020). These indices have also been used to assess the future projections of Uttarakhand precipitation.

3 Results and discussion

3.1 Evaluation of NEX-GDDP models

To understand the fidelity of the model simulations, we have examined the annual cycles in the precipitation (mm day^{-1}) over the Uttarakhand State from 1976 to 2005, as shown in Figure 2. Figure 2 represents monthly mean precipitation from the APHRODITE (black line) and multi-model mean (MMM) (red line). Red shading denotes precipitation variability (± standard deviation) among the 20 models. The gray shade marks the monsoon season (JJAS). The visual inspection shows that the model simulations could reasonably capture the seasonal rainfall. The mean monthly precipitation patterns obtained from the MMM are the same as that of APHRODITE. The maximum peak exhibited by APHRODITE is 9.7 mm day^{-1} in July and lowest of 0.3 mm day^{-1} in November, whereas the MMM peaked in August (7.9 mm day^{-1}) and a minimum of 0.06 mm day^{-1} in November. The variability in the MMM precipitation increases with rainfall quantity. Overall, It can conclude that the MMM can capture the monthly mean precipitation over the Uttarakhand State.

Table 2 List of extreme climate indices analyzed in the study

Indices	Description	Units
Simple Daily Intensity Index (SDII)	The ratio of seasonal total precipitation to the number of wet days (≥ 1 mm)	mm/day
Very wet days (R95P)	Total precipitation from days with rainfall ≥ 95th percentile	mm
Highest 1-day precipitation (RX1DAY)	Seasonal maximum 1-day precipitation	mm
Highest 5-day precipitation (RX5DAY)	Seasonal maximum consecutive 5-day precipitation	mm
Consecutive Wet Days (CWD)	Maximum number of consecutive days when precipitation > 1 mm	Days
Consecutive Dry Days (CDD)	Maximum number of consecutive days when precipitation < 1 mm	Days

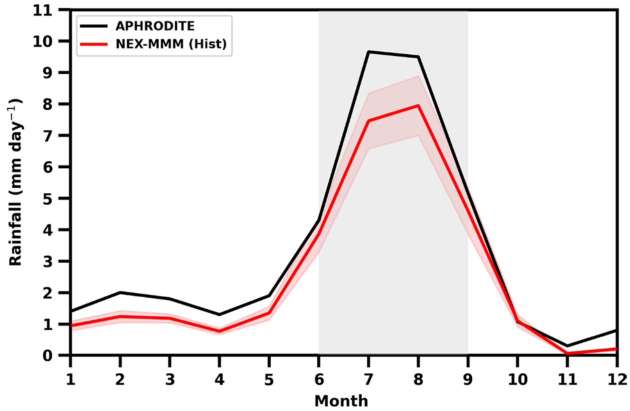


Fig. 2 Annual cycle of monthly precipitation (mm day^{-1}) over Uttarakhand during 1976–2005 from APHRODITE (black) and NEX-GDDP MMM (red line). Red-colored shading denotes ± standard deviation of 20 NEX-GDDP models. Gray-shaded region denotes the SW monsoon season (JJAS)

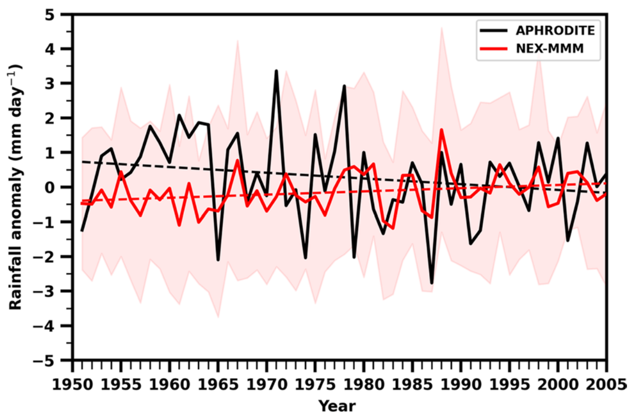


Fig. 3 Inter-annual variability of SW monsoon rainfall over Uttarakhand during 1951–2005 from APHRODITE (black) and NEX-GDDP MMM (red line). Red-colored shading denotes ± standard deviation of 20 NEX-GDDP models

Figure 3 shows the SW monsoon mean precipitation anomalies from APHRODITE and MMM over Uttarakhand (area averaged) from 1951 to 2005. Interestingly, the SW monsoon rainfall has been decreasing (slightly negative trend −0.0166 mm day^{-1}) in APHRODITE and increasing in MMM (0.0093 mm day^{-1}). Both these trends are statistically significant at 90% confidence level. It also indicates that the rainfall has been more variable in APHRODITE in recent years, unlike in MMM. Note that the MMM shows relatively wet period (excess rainfall) in the recent years compared to the APHRODITE. The SW monsoon season mean precipitation obtained by individual models and MMM has been compared with APHRODITE over the Uttarakhand region from 1976 to 2005 (Fig. 4). The mean bias of MMM for the same area is shown in Fig. 4w. The APHRODITE reveals north-south variability in the precipitation over Uttarakhand. The southern part of the state receives higher rainfall (> 7 mm day^{-1}) than the northern part (< 4 mm day^{-1}) (Fig. 4v). The observed precipitation patterns were replicated in the individual models showing consistent north-south rainfall patterns. However, minute variations (about −2 to −3 mm day^{-1}) were observed in the precipitation amount. The mean bias of MMM (Fig. 4w) shows slightly dry bias in the study region, except the extreme northern part where the wet bias of 2–3 mm day^{-1} is noticed (Fig. 4w).

Figure 5 compares the monsoon rainfall and its variability over Uttarakhand from individual model, MMM, and observed data during 1976–2005. The mean and ± 2 standard deviations of the observed rainfall are shown in blue and dotted lines. The black dot indicates the individual model's mean precipitation, and the right and left limits indicate the standard deviation. The mean observed precipitation is 7.2 mm day^{-1}. The mean rainfall values obtained by the individual models and the MMM are more or less close to the observed mean rainfall and lie within the limit of observed rainfall variability (Fig. 5). The seasonal mean precipitation is less than the observed, showing dry bias, as seen in Fig. 4. Note that the individual model variability is also close to the observed. Thus the bias-corrected models could be able to provide the rainfall over Uttarakhand reasonably well. Figure 6 shows the contribution of the monsoon rainfall to the annual rainfall of Uttarakhand as obtained from APHRODITE and MMM. As revealed from MMM, southern parts of Uttarakhand receive about 75–90%, and northern parts receive 60–70% of the annual rainfall (Fig. 6b). On the other hand, most of the Uttarakhand region receives ~ 75% of the annual rainfall in the monsoon season.

Figure 7 exhibits the spatial distribution of precipitation extremes (refer to Table 2) such as SDII, R95P, RX1 DAY, RX5 DAY, CWD, and CDD between MMM and APHRODITE from 1976 to 2005. The SDII is high in the southern part compared to the northern part of the Uttarakhand region (Fig. 7a, b). Though the APHRODITE and MMM showed similar precipitation intensity patterns, the MMM slightly overestimated intense precipitation over the Uttarakhand State. From Fig. 7c and d, there is a southeast-northwest pattern in extreme precipitation days (R95P) in observation and model. The southeast parts receive extreme precipitation for ~ 3.5 days (3 days), while the northwest region receives extreme precipitation for 2.5 days (3 days), respectively, in MMM (observation). Overall, the extreme precipitation days are captured reasonably well in MMM compared with observation (Fig. 7c, d). Moreover, the spatial pattern of extreme rainfall in 1 day (RX1DAY; Fig. 7e, f) and in 5 days (RX5DAY; Fig. 7g, h) shows a similar pattern. The highest and lowest magnitude of precipitation occurred in the south and northern parts of Uttarakhand, as seen in seasonal rainfall. Note that the south-north patterns observed in R95P, RX1DAY, and RX5DAY are expected to contribute highly to the monsoon season precipitation. Comparing RX1DAY and

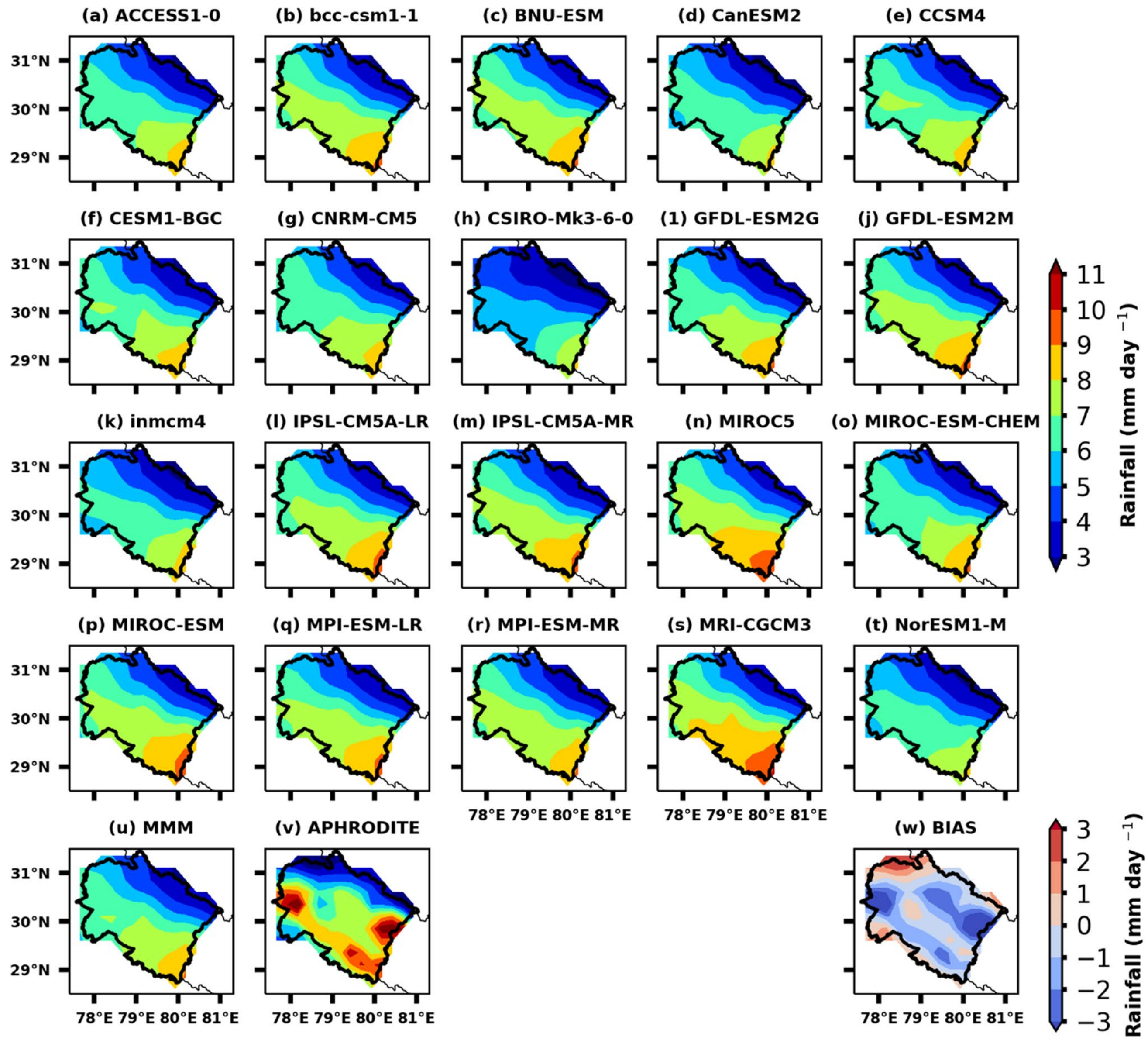


Fig. 4 Spatial distribution of SW monsoon mean rainfall from NEX-GDDP's 20 individual model simulations (**a**–**t**), MMM (**u**), APHRODITE (**v**), and the bias of MMM against APHRODITE for the period 1976–2005 (**w**)

RX5DAY indices reveals that the model highly overestimates the extreme precipitation in 5-day period than the 1-day extreme (Fig. 7e–h). The CWD also exhibits a similar pattern between APHRODITE and MMM over the Uttarakhand region. However, the MMM is slightly underestimated in the central parts and overestimated in the northern parts (Fig. 7i, j). The analysis of consecutive dry days indicates that the CDD is more in northwest parts and less in southwest parts (Fig. 7k, l). The MMM captured the spatial distribution of CWD and CDD during the monsoon period reasonably well, and the characteristics are quite the opposite of each other. These results are consistent with Kim et al. (2019) and demonstrated that the APHRODITE dataset captures the intense precipitation well in the South Asian regions. Overall, the precipitation extremes in MMM, thus in the individual simulations, are consistent with APHRODITE.

The above analyses conclude the better performance of NEX-GDDP downscaled models in capturing seasonal, monthly, and precipitation extremes over the Uttarakhand region. Thus, the analyses build up substantial confidence in using these products for future projections.

3.2 Projected changes in seasonal mean rainfall

This section mainly focuses on the future changes in mean seasonal rainfall over Uttarakhand under two emission scenarios (RCP 4.5 and RCP 8.5) for the near future

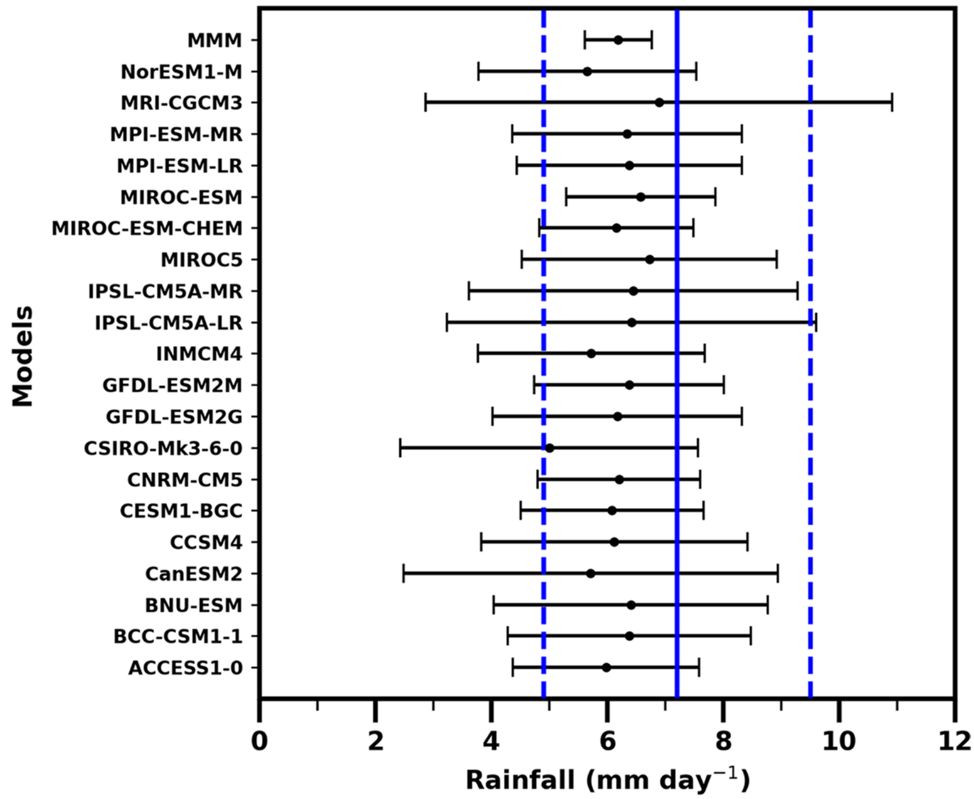


Fig. 5 Evolution of SW monsoon rainfall by NEX-GDDP's individual models and MMM during 1976–2005. The blue line shows the observed mean rainfall. Blue dashed line shows ±2 standard deviation of observed rainfall. Black dots are mean rainfall of individual model

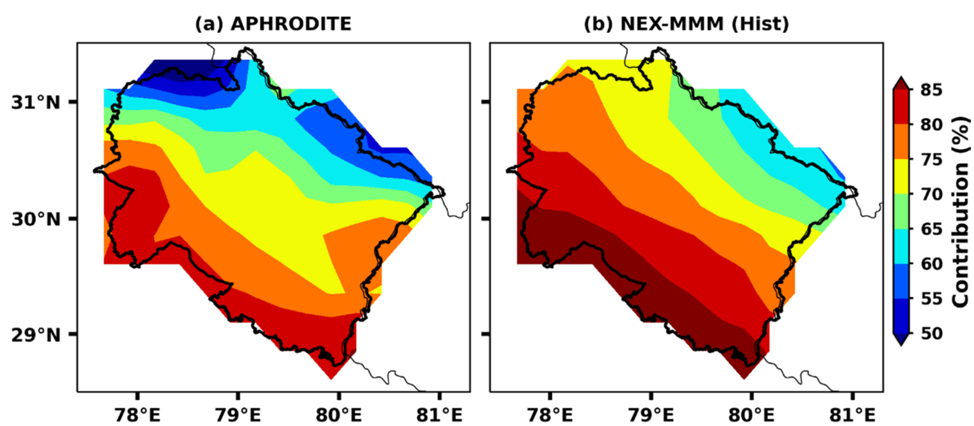


Fig. 6 The contribution of the SW monsoon rainfall to the annual rainfall from **a** APHRODITE and **b** NEX-MMM

(2021–2050) and far future (2070–2099). Figure 8 provides the percentage of projected changes in seasonal mean rainfall from the near future to the far future concerning the baseline period.

Results indicate both RCP 4.5 and RCP 8.5 scenarios show a notable and consistent increase in the near future and far future. An increase of 13% (16%) under the RCP 4.5 (RCP 8.5) scenario was observed in the near future from the MMM. In contrast, the rainfall has substantially increased by 23% (36%) in RCP 4.5 (RCP 8.5) in the far future compared with the precipitation in the baseline period from the MMM. Few individual models show decreasing rainfall activity in both RCP 4.5 and RCP 8.5 scenarios. However, most models show higher precipitation activity in the near- and far-future periods. The increase in precipitation extremes in the global warming conditions could be the reason for the overall increase in future rainfall and is consistent with the earlier studies (Kulkarni et al. 2020; Rao et al. 2020). Under the effects of global warming, the South Asian summer monsoon is expected to have more precipitation but weakening of circulation (Ueda et al. 2006; Sun et al. 2010). The increased water vapor content in the atmosphere and atmospheric moisture convergence in the region of South Asia is thought to be the cause of the increasing precipitation (Douville et al. 2000; Ueda et al. 2006; May 2004).

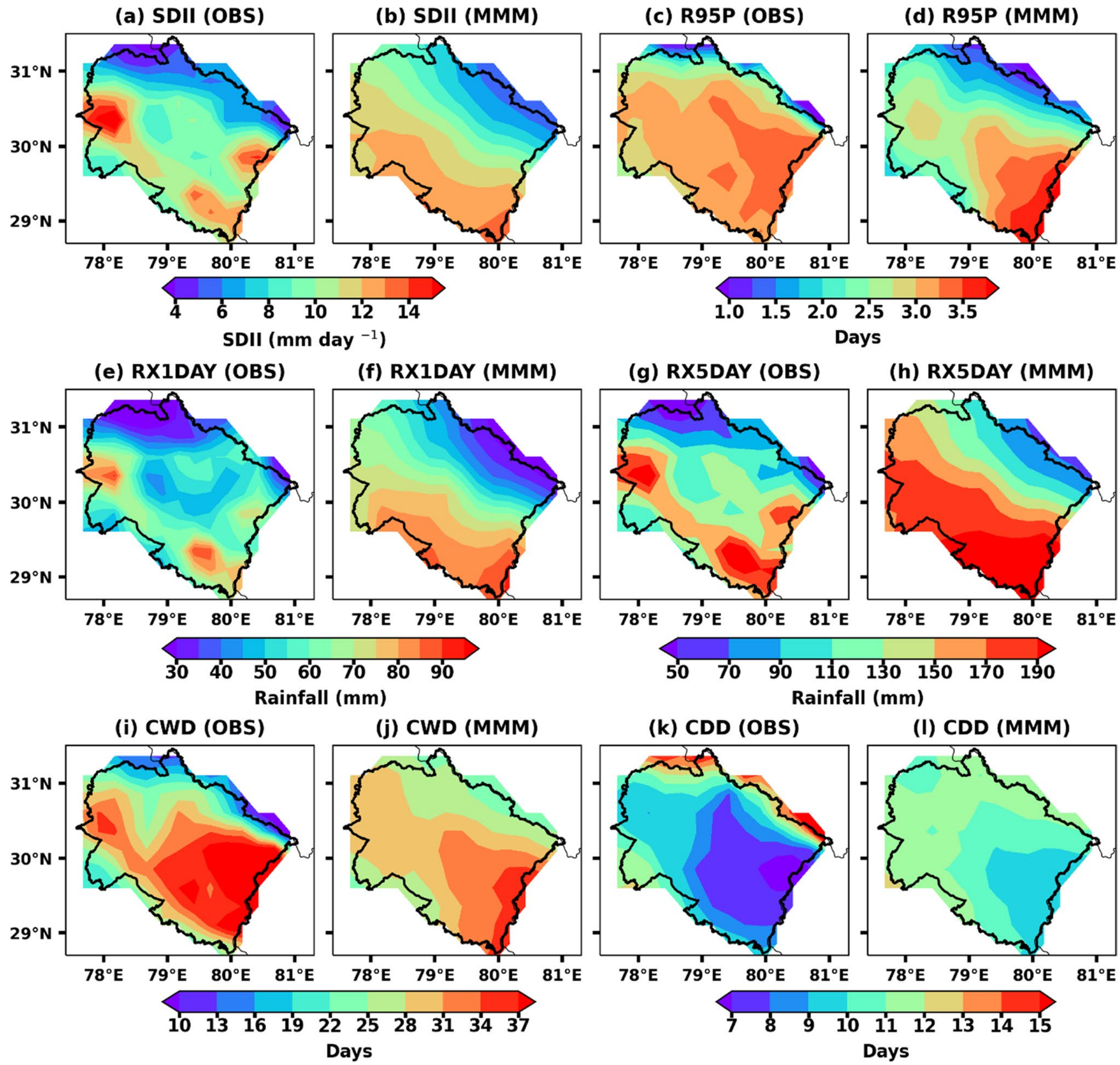


Fig. 7 Comparison of precipitation extremes in terms of SDII (**a**, **b**), R95P (**c**, **d**), RX1DAY (**e**, **f**), RX5DAY (**g**, **h**), CWD (**i**, **j**), and CDD (**k**, **l**). The APHRODITE (OBS) and MMM products have been used in this analysis for the period 1976–2005

The spatial distribution of projected precipitation (%) changes from the MMM is presented for the near future and far future with reference to the model baseline period (Fig. 9). Figure 9a and b shows an increase in the near future of about 10% in the RCP 4.5 scenario and 18% in the RCP 8.5 scenario. At the same time, it may increase by 21% and 42% in the far future from RCP 4.5 and RCP 8.5 scenarios, respectively (Fig. 9c, d). A substantial increase in rainfall percentage has been noticed in the high emission scenario (RCP 8.5) to the end of the twenty-first century (Fig. 9d). The projected changes in precipitation vary across Uttarakhand, but overall, a significant increase in the future rainfall is noticed. The spatial analysis further reveals that maximum precipitation change may be seen in the northern parts of Uttarakhand under lower and higher emission scenarios to the end of the century. Sharma et al. (2015) also presented increasing rainfall patterns of Uttarakhand in the future using multiple linear regression analysis and artificial neural networks.

3.3 Future changes of precipitation extremes

SDII is the intensity of the daily rainfall received over the region. The inter-annual variability in SDII under the RCP

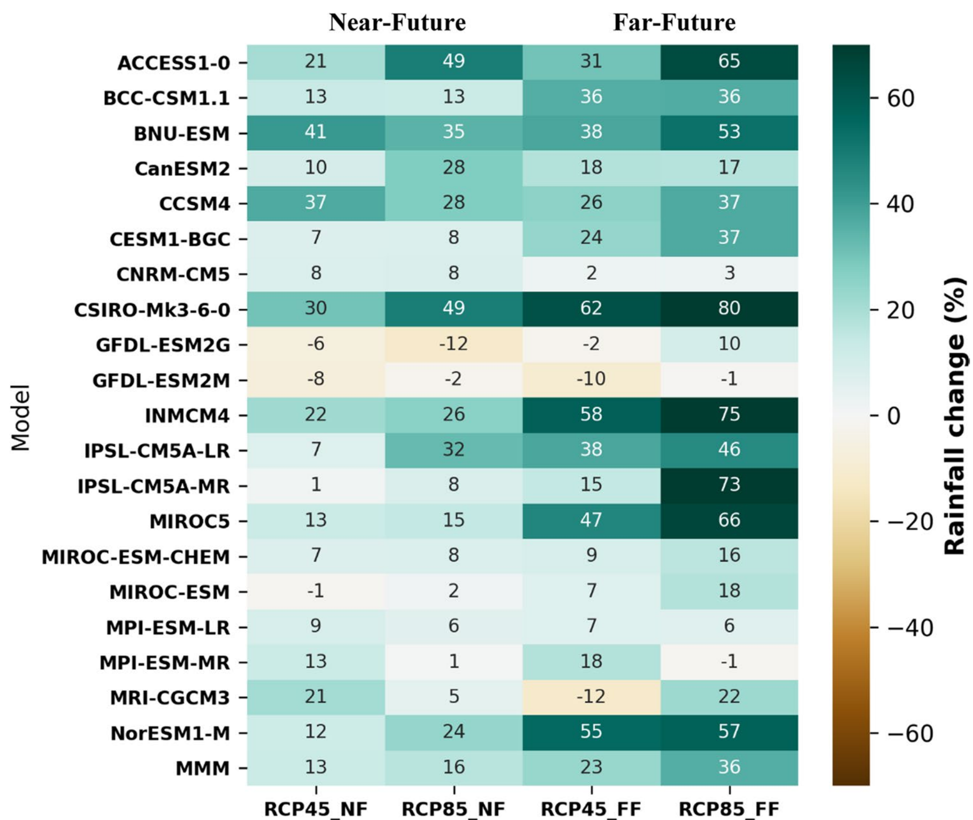


Fig. 8 Projected changes (%) in the SW monsoon rainfall over Uttarakhand. NF refers to near future (2021–2050), FF refers to far future (2070–2099), with respect to the baseline period of 1976–2005 under the RCP 4.5 and RCP 8.5 scenarios

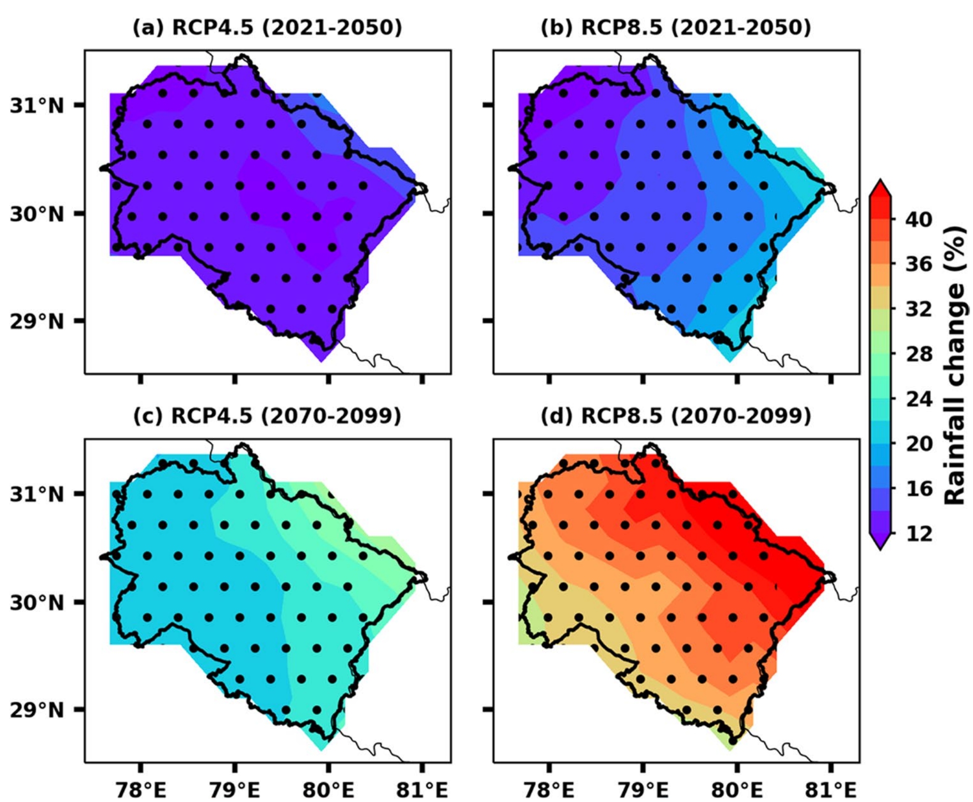


Fig. 9 **a**–**d** Projected changes in the MMM of rainfall in the near future (2021–2050) and far future (2070–2099) under the RCP 4.5 and RCP 8.5 scenarios relative to 1976–2005. The black dots represent regions of 90% significance level

4.5 and RCP 8.5 scenarios from 1976 to 2099 is shown in Fig. 10. The variability of the MMM is compared with APHRODITE rainfall for the baseline period. The MMM is overestimated compared to observation throughout 1976–2005, and it shows a wet bias of 1 mm day^{-1} compared with the observation. There is no trend from observed data and MMM from 1976 to 2005 with comparable patterns and tendencies. However, MMM showed an increase in the trend of 0.5 mm decade^{-1} (99.9% significance level) and 0.9 mm decade^{-1} (99.9% significance level) prominently under the RCP 4.5 and RCP 8.5 scenarios, respectively. The SDII increases in the RCP 4.5 and RCP 8.5 emission scenarios indicate wet days with intense precipitation in the future. A general rise in SDII suggests the likelihood of fewer rainy days with heavy rains in most parts of the globe (Kostopoulou and Jones 2005; Kulkarni et al. 2020; Rao et al. 2020). On a global scale, the observed intensity of daily heavy precipitation events has increased. This could be because, with each 1 °C increase in temperature, the water holding capacity of air increases by about 7%, resulting in more water vapor in the atmosphere (Trenberth 2011).

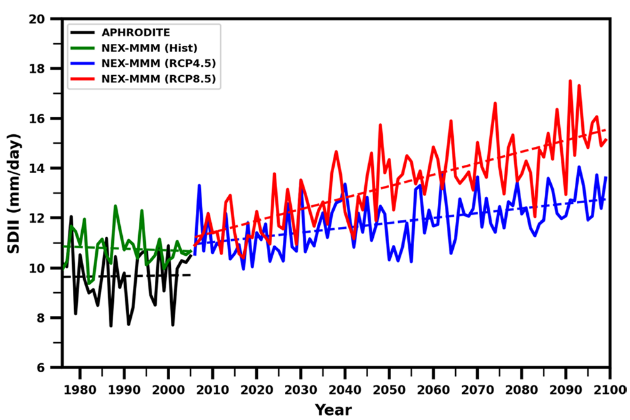
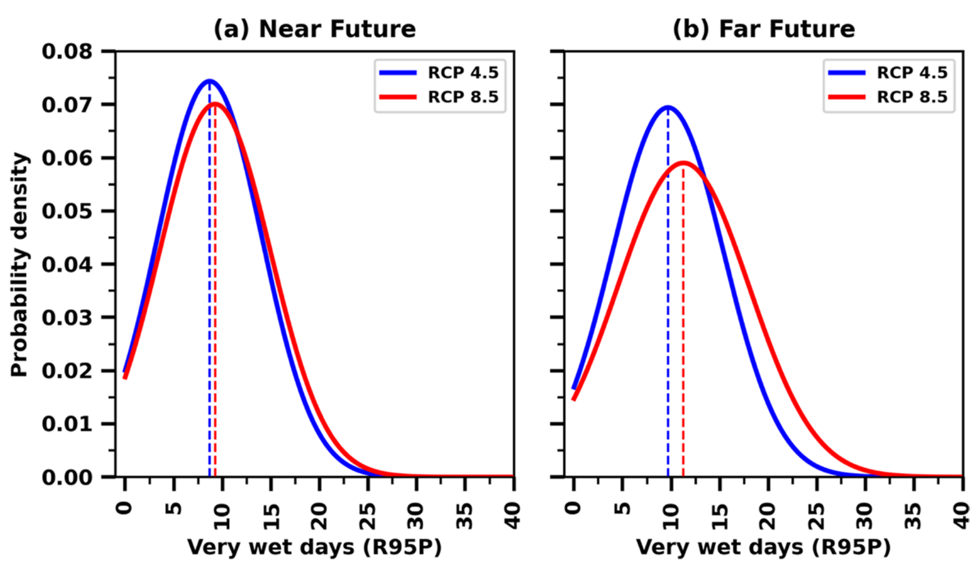


Fig. 10 Inter-annual variability in Simple daily intensity index (SDII) over Uttarakhand State from 1976 to 2099

The probability density functions (PDFs) of very wet days (R95P) under the RCP 4.5 and RCP 8.5 scenarios have been computed over Uttarakhand for the near future and far future. The curve's peak shifts more towards the right in the RCP 8.5 scenario than that in the RCP 4.5 scenario, which can be seen clearly in Fig. 11a and b. There is an increase in very wet days with a marked shift of ~11% in the RCP 4.5 scenario and ~22% in the RCP 8.5 scenario from the near future to the far future. This shift can be correlated with the increase in the planet's radiative forcing. The right tail of the PDFs being elongated in the far future suggests a higher chance of extreme events occurring at the end of the present century. Extreme precipitation intensity rises faster than mean precipitation with global mean surface temperature (Kharin et al. 2013). The SDII and R95P future projections suggest that the Uttarakhand region can experience more wet days with intense rainfall.

Figure 12 shows the relative projections in the highest 1-day (RX1DAY) and 5-day (RX5DAY) precipitation in the Uttarakhand State. The solid lines represent the MMM of RX1DAY and RX5DAY, and the shaded regions indicate the individual model's standard deviation. Results show an increase in RX1DAY and RX5DAY rainfall from the middle of the twenty-first century. RX1DAY increases by 1.4 mm decade^{-1} and 3.3 mm decade^{-1} under the RCP 4.5 and RCP 8.5 scenarios. However, the RX5DAY precipitation increases by 2.7 mm decade^{-1} and 7 mm decade^{-1} under the RCP 4.5 and RCP 8.5 scenarios. Increasing extreme precipitation intensity is expected to be the primary cause of total precipitation increase. The twenty-first century projected intense rainfall, RX1DAY, and RX5DAY consistently, indicating increased precipitation over the Uttarakhand region.

Fig. 11 Probability distribution function of very wet days. **a** Near future. **b** Far future. Blue (red) lines indicate RCP 4.5 (RCP 8.5)



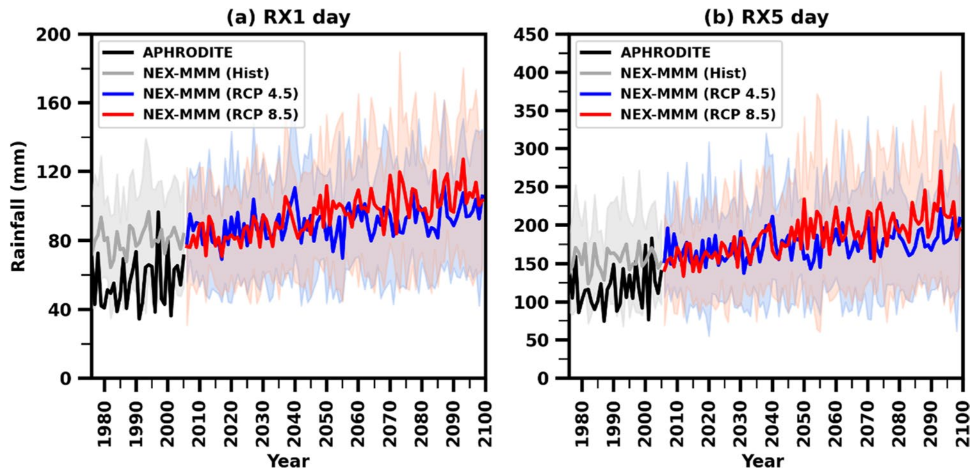


Fig. 12 Future projections of **a** RX1DAY and **b** RX5DAY (area averaged over Uttarakhand State). Solid lines show the MMM, and shaded regions indicate the range of the standard deviation between the models

Thus, future flood risk is expected to grow with extreme precipitation (Gu et al. 2018).

The number of CWDs measures the wet conditions in a given area. The near- and far-future CWD changes for both the emission scenarios are given in Fig. 13. The 90% significance level is represented with black dots. The northern parts of Uttarakhand show an increase in CWDs in the far future under both scenarios, as evident from the MMM (Fig. 13c, d), whereas in the near-future period, the northern parts could experience more CWDs than the southern parts (Fig. 13a, b). There are notable changes in CWDs from RCP 8.5 to RCP 4.5 scenarios in the near and far future. The spatial gradient in CWDs in the far future is relatively higher than that in the near future in both emission scenarios. Figure 13 infers an overall increase in CWDs, leading to severe floods and landslides. The number of CDDs is an index to understand the dry conditions. The changes in CDD percentage in the near and far future under the RCP 4.5 and RCP 8.5 scenarios respective to the baseline period have been represented in Fig. 14. A decrease in CDDs was noticed in many parts of the Uttarakhand both in near (around 5%) and far future (> 6%) under both emission scenarios. Under the RCP 4.5 and RCP 8.5 scenarios, CWD increased while CDD decreased, increasing total rainfall, reducing drought

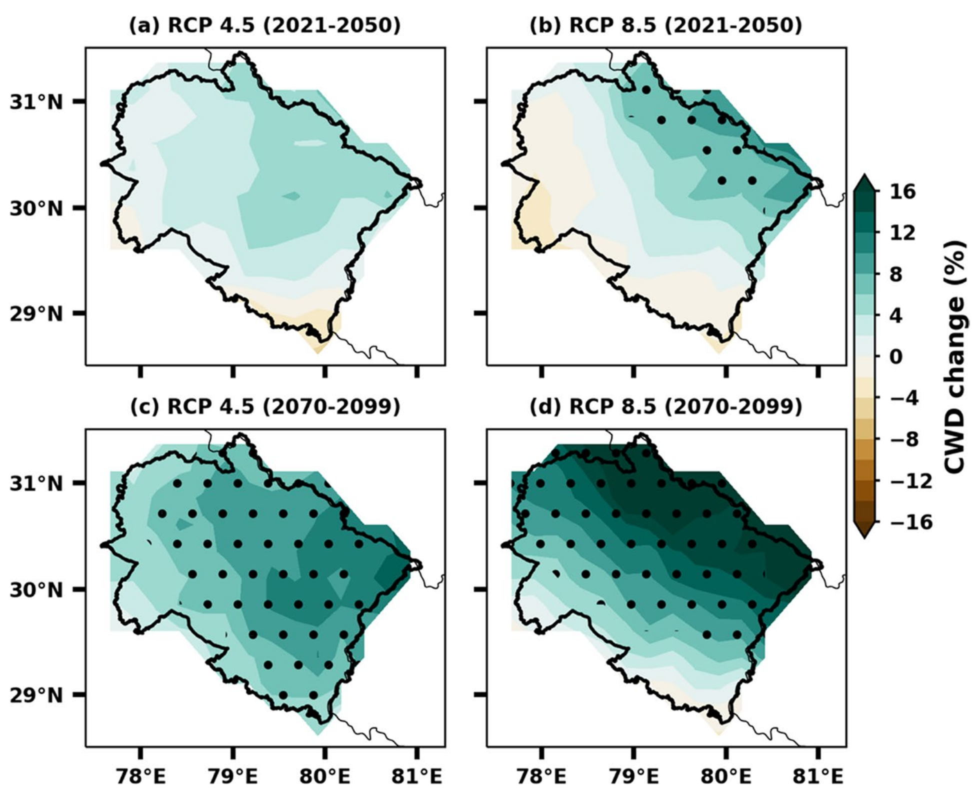


Fig. 13 **a**–**d** Future changes in the MMM of CWD in the near future (2021–2050) and far future (2070–2099) under the RCP 4.5 and RCP 8.5 scenarios relative to the baseline period of 1976–2005. The black dots represent regions of 90% significance level

occurrence, and extending wet spell duration over the Uttarakhand State.

A recent study by Dikshit et al. (2020) reveals that the Himalayan region is vulnerable to 15% of all rainfall-induced landslides. It is well known that most of the landslides in this area are caused mainly by extreme rainfall events (Dubey et al. 2005; Kanungo and Sharma 2014; Dikshit and Satyam 2018). The above analysis consistently demonstrated that the precipitation would be more intense with more rainy days over the Uttarakhand region. Further, most of the rainfall over this region is mainly from the low-pressure systems and depressions formed over the Bay of Bengal, which are moving northwestward (Rajesh et al. 2016; Nandargi et al. 2016; Chawla et al. 2018). Rainfall over this region can also be associated with the northward shift of the monsoon trough towards the Himalayan foothills (Nandargi et al. 2016). The orography effect is critical for rainfall activity in the Uttarakhand State (refer to Fig. 1). Also, the increase in rainfall is primarily due to moisture convergence and the thermodynamic effect of the Clausius-Clapeyron relationship (Rajesh et al. 2016).

4 Summary and conclusions

The NEX-GDDP MMM shows an increase in rainfall over Uttarakhand in the near future, and it is likely to increase further towards the end of the twenty-first century. We noticed from Fig. 5 that most of the individual models capture the seasonal mean rainfall well over Uttarakhand. The values obtained by the models are close to the observed rainfall. The analysis reveals that the mean rainfall observed is 7.2 mm day^{-1}, with a standard deviation (SD) of 1.1 mm day^{-1}. NEX-GDDP MMM simulations reproduce the extreme precipitation characteristics with marginal overestimates over Uttarakhand. The study results are consistent with those of Banerjee et al. (2020).

Projected change in mean rainfall infers a modest increase in precipitation in the near future and a considerable increase in the far future. Most models show unanimity changes of precipitation extremes in the future projections of Uttarakhand rainfall during the monsoon season towards the end of the century. A study by Kulkarni et al. (2020) also reported that rainfall in India is increasing in the future due to the response of global warming. The change in rainfall in the northern parts of Uttarakhand is relatively higher than that in the southern parts of the state. An increase in monsoon precipitation may be connected to an increase in extreme precipitation events arising from the intensified Arabian Sea moisture transport into the Indian landmass towards the Himalayan foothills (Roxy et al. 2017). The increasing trend in SDII under warming conditions shows increasing rainfall intensity over Uttarakhand under both scenarios (RCP 4.5 and RCP 8.5). The increase in very wet days (R95P) indicates an increase in total rainfall over Uttarakhand in the near and

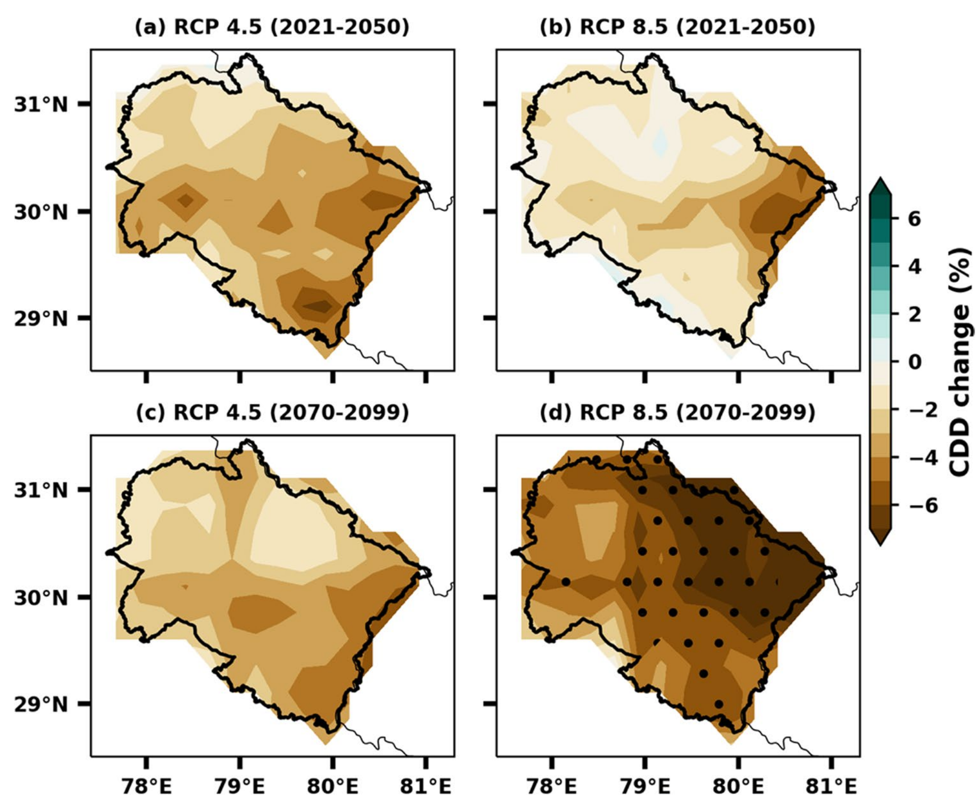


Fig. 14 **a–d** Future changes in the MMM of CDD in the near future (2021–2050) and far future (2070–2099) under the RCP 4.5 and RCP 8.5 scenarios relative to the baseline period of 1976–2005. The black dots represent regions of 90% significance level

far future is majorly due to the frequency of extreme precipitation events which has increased due to global warming (Kulkarni et al. 2020).

Most models show increased precipitation over the Uttarakhand State in the future under the RCP 4.5 and RCP 8.5 scenarios (Fig. 8). Earlier studies also demonstrated the increasing trends in projected precipitation over most tropical regions, including Indian landmass in the twenty-first century (Kulkarni et al. 2020). RX1DAY and RX5DAY precipitations under the RCP 8.5 scenario increase more than those under the RCP 4.5 scenario. This could be the reason for intense downpours occurring over the Uttarakhand region.

The decrease of CDD in the Uttarakhand State indicates that the state will see a shorter duration of dry spells in the future. The CDD is notably decreasing in the far future (2070–2099) under the RCP 8.5 scenario. Although this might seem to be beneficial for agriculture and water resources management, an increase in CWD can lead to natural hazards such as flash floods and landslides on the contrary. An increase in CWD in both the near future and far future is a cause for concern as Uttarakhand is already prone to flooding and landslides.

According to this study, the mean and extreme precipitation events over Uttarakhand during the SW monsoon season would change in the future. Future projections for six climate indices have been discussed and will help in understanding the extreme precipitation events that are likely to happen over Uttarakhand in the future. In the future, the intensity of precipitation and the extreme event frequency in Uttarakhand are likely to increase under global warming conditions.

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Data availability The data that support the findings of this study are freely available from the website (source is given in the data methodology). The software/programs related to the study may be available from the corresponding author upon reasonable request.

Declarations

Ethics approval and consent to participate No ethical issues are involved in this paper. The authors gave their consent to participate.

Consent for publication The authors gave their consent for publication.

Competing interests The authors declare no competing interests.

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