

Effect of changes in climate variables on hydrological regime of Chenab basin, western Himalaya

Sonia Grover, Shresth Tayal, Richa Sharma and Stein Beldring

ABSTRACT

In high altitude, scarcely gauged basins, climate change impact assessment on river discharge is important for sustainable management of water resources. These basins are sources for irrigation and hydropower generation in the region. Expected changes in precipitation and temperature can affect the basin's hydrological regime which will have consequential impacts on the dependent sectors. For quantifying the impacts of major climatic variables on hydrological processes, this paper examined bias-corrected GCM outputs coupled with a hydrological model – HBV for Chenab basin. Trend analysis shows that precipitation would decrease after the short-term period and temperature is expected to increase throughout the century. Simulated river discharge is expected to increase throughout the 21st century under both RCP 4.5 and RCP 8.5 scenarios. It is also observed that there would be a shift in seasonal discharge patterns with increased pre- and post-monsoon contributions. Increase in snow and ice melt contribution to the overall discharge is also expected and would range between 50 and 59% until 2100. This study concluded that expected increase in discharge volume coupled with shift in seasonal discharge pattern would impact the basin water management and thus it is important to consider the impact of climate change on the hydrological regimes of basins.

Key words | Chenab basin, climate change, HBV model, hydrological processes, snow-melt runoff

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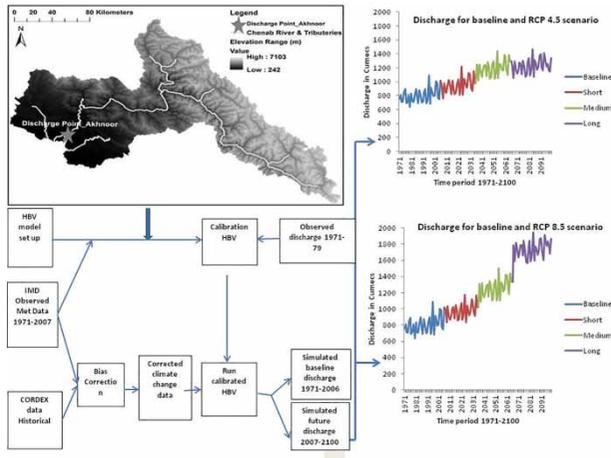
HIGHLIGHTS

- Paper deals with the ungauged basin originating from the Himalayas and assesses shifts in seasonal discharge patterns which highlights increased pre- and post- monsoon contributions in annual discharge.
- Output from the study is important for the data scarce Himalayan region and for better planning and management of water resources.

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GRAPHICAL ABSTRACT



INTRODUCTION

Increasing surface temperature and variable precipitation patterns are likely to occur over the next century and the impacts of climate change are of major concern worldwide (Bajracharya *et al.* 2018). Representative Concentration Pathways (RCP) scenarios defined by the Intergovernmental Panel on Climate Change, based on the Coupled Model Intercomparison Project (CMIP5) (van Vuuren *et al.* 2011) suggest a rise of over 2 °C by the end of the century for global surface temperature. For the Himalayan region, which has many transboundary rivers fed by snow and glacier melt, climate change projections indicate significant warming compared to other parts of the world (Bhadwal *et al.* 2019). Some studies have reported spatial variation in the rate of warming and precipitation dynamics within the Himalayas (Immerzeel *et al.* 2010; Pandey 2016). This has been linked to the melt characteristics of the glaciers in the region and thus to the water availability (Harper & Humphrey 2003; Käab *et al.* 2012; Pritchard 2017). Basins which have a significant contribution from snow and ice melt are more vulnerable to an increase in surface temperature (Jeelani *et al.* 2012) and these changes will impact the hydrological regime by affecting the timing and volume of river discharge in the region (Uprety *et al.* 2019). The Indus basin, one of the most important transboundary basins of the region, has significant discharge contribution from

snow and ice melt. With the warming trend, the Indus basin in particular is more vulnerable to climate change (Shrestha *et al.* 2019). It is thus imperative to understand the potential impacts of climate change on the hydrological regime of the basins in the Himalayan region for sustainable water resources management. Especially, the Indus basin, which sustains the lives of millions of people, requires proper planning and management of water resources with due consideration of climate change (Lutz *et al.* 2014).

In this context, a study analyzed the CMIP5 global climate model and reported an increase in maximum and minimum temperature in the Indus basin region, under both RCP 4.5 and RCP 8.5 scenarios for the time period of the 2030s and 2070s with respect to the baseline period of 1971–2005 (Gebre & Ludwig 2014). In this study, the multimodal results of average monthly maximum temperature ranges from 1 °C to 7 °C indicating an increasing trend for both the periods under both RCP scenarios. A similar pattern was observed for minimum temperature. Another study by Su *et al.* (2016) analyzed CMIP5 outputs for three RCPs – 2.6, 4.5, and 8.5 for mid and late century and suggested increasing temperature in a consistent manner over the entire basin. Under the RCP 2.6, RCP 4.5, and RCP 8.5 scenarios, in the mid-21st century, annual mean temperature will increase by 1.21 °C, 1.93 °C, and 2.71 °C, respectively.

Precipitation projection is more variable than temperature. A study by Huang *et al.* (2017) reported that the trend for annual precipitation over the entire basin, except some parts in the north and south, is decreasing for the three RCPs scenarios (RCP 2.6, RCP 4.5, and RCP 8.5). A study by Gebre & Ludwig (2014) reports that during summer precipitation will increase and in winter precipitation will decrease under both RCP 4.5 and 8.5 scenarios for the time period of the 2030s and 2070s with respect to the baseline period of 1971–2005.

For assessing the hydrological response to changing climate, downscaled future climate projections are used in a hydrological model (Zheng *et al.* 2018). There are numerous studies reported in Nepal & Shrestha (2015) that used climate models to estimate likely changes in precipitation and temperature in the basins which would affect hydrological regimes in the coming years. These studies are important for sustainable management and utilization of water resources (Anjum *et al.* 2019). Also, it is important to understand the expected changes in the hydrological regime of the basin, which is the source of hydropower production, because any alteration in the hydrological regime will have immediate consequences for the hydropower projects (Schaeffli 2015).

This study aims to assess the impacts of climate change on the hydrological regime of Chenab basin which is one of the westward flowing tributaries of the Indus basin. To achieve this objective, we used the semi-distributed Hydrologiska Byråns Vattenbalansavdelning (HBV) hydrological model forced with bias-corrected downscaled CORDEX data for the South Asia domain using the IPCC scenarios RCP 4.5 and 8.5. The model simulations were used to estimate discharge for Chenab basin for short- (2007–2035), mid- (2036–2065), and long-term (2066–2100) future scenarios. This paper also investigates the trends of bias-corrected projected temperature and precipitation changes in the future and simulated changes in snow and ice melt contribution to the basin.

DATA AND METHOD

Study area

Chenab River is one of the five main rivers of the great Indus system and is formed by the merging of two streams, the

Chandra and the Bhaga at Tandi, and traverses through the state of Himachal Pradesh before passing through the state of Jammu and Kashmir. The Chenab basin is located between 30°N and 34°N and 74°E and 78°E (Jain *et al.* 2007) expanding over an area of around 27,195 square kilometers, of which 10% of the total catchment area is covered by glaciers (Figure 1). Around 1,000 large and small glaciers drain into the Chenab River (Grover *et al.* 2020). The basin elevation ranges from <1,500 m to >6,000 m. Snow and ice constitute important components of the hydrological system of this basin. Akhnoor is the last drainage point of the basin in India before it enters Pakistan. The upper half of the basin is located between the middle Himalayan range (Zanskar and Pir Panjal), which is characterized by a number of glaciers and receives precipitation at a modest rate in winter. The lower reaches of the basin are located between the lower Himalayan range (Pir Panjal and Dhauladhar) and receive high precipitation and have short winters (Grover *et al.* 2020). Due to altitudinal variation, lower valleys experience hot and moist tropical conditions, and with the elevation range of 1,500–2,000 m the temperature becomes cooler and then progressively colder at higher elevations. The basin has significant hydropower generation potential compared to other basins, with the union territory of Jammu and Kashmir having an estimated potential around 11,283 MW (Sharma & Thakur 2017). With changing climate, a rise in temperature and variation in precipitation pattern are anticipated that are expected to impact the hydrological system of this basin. This could pose a potential threat to maintaining the consistent flow in the river, which in turn would affect the hydropower development projects in the basin.

Baseline observations and CORDEX data

Coordinated Regional climate Downscaling Experiment (CORDEX) data developed in support of the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC AR5) is a widely used dataset for climate change studies. It comprises dynamically downscaled climate scenarios for the South Asia region derived from the ten models for which daily scenarios were produced and distributed under CMIP5. The outputs provided by atmosphere-ocean coupled general circulation models (AOGCMs) are

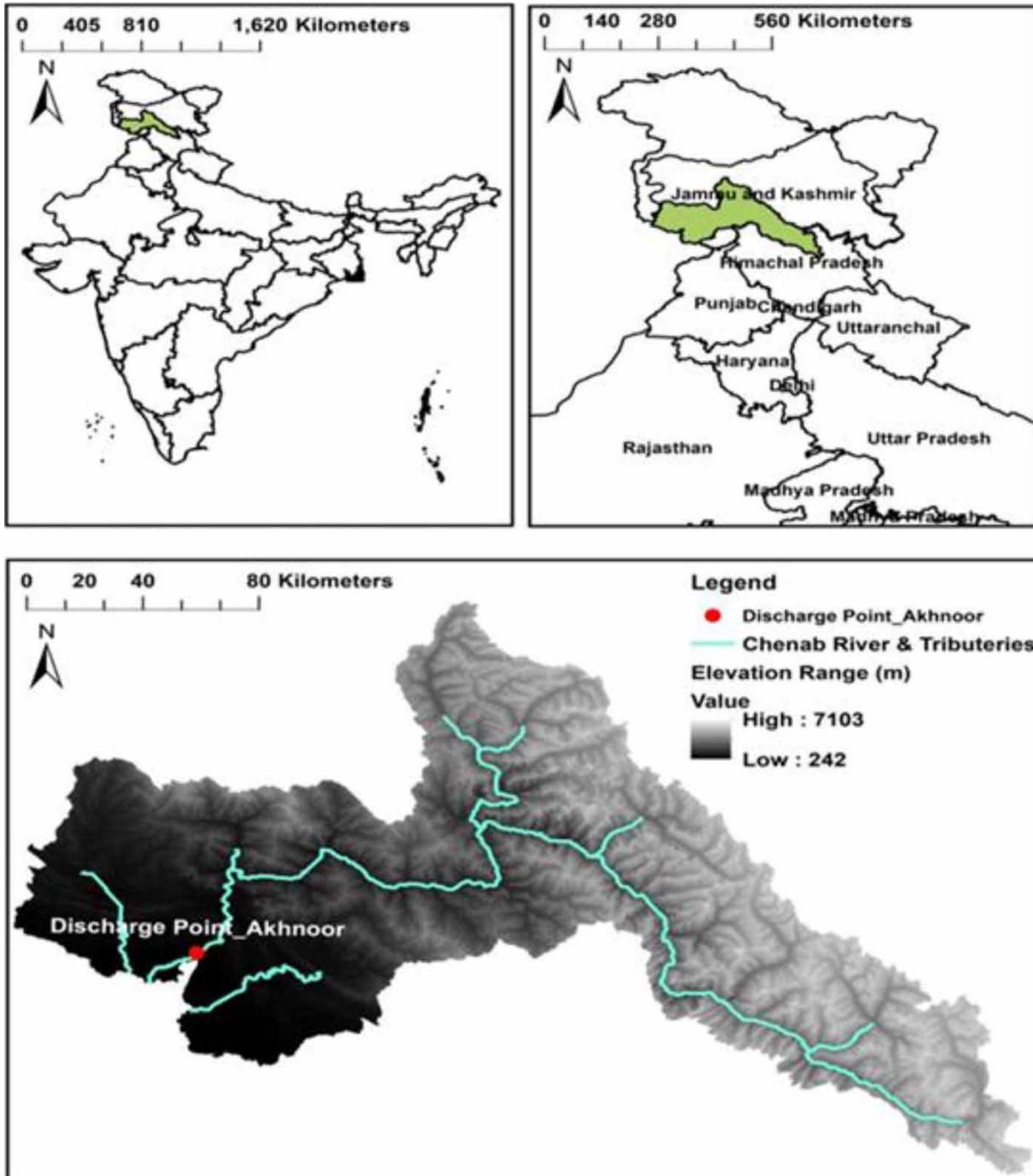


Figure 1 | Location of the study area.

used as lateral boundary condition for high resolution limited area regional climate models (RCMs). Dynamical downscaling is hence applied to provide physically consistent spatiotemporal variations of climatic parameters at smaller

spatial scales resolving the topographical details, coastlines, and land-surface heterogeneities. This makes these datasets more useful for impact assessment studies and in decision-making for adaptation (Flato *et al.* 2013).

The baseline or historical CORDEX data for the period 1971–2005 and future data for the period 2006–2100 are used for this study. CORDEX data for South Asia domain (WAS44i) for two experiments, RCP 4.5 (medium stabilization scenario) and RCP 8.5 (high baseline emission scenario), were procured for two variables – daily precipitation and daily average temperature. The procured datasets (historical and future projections) were processed in R software, clipped to the region of interest (study area basin boundary) and converted to ASCII format to be used as input for the HBV model.

For the bias correction method, baseline observation data obtained from the Indian Meteorological Department (IMD) have been used. They are gridded data interpolated at 1° latitude by 1° longitude and the interpolation is based on the scheme proposed by Shepard in 1968 in which interpolated values are computed from a weighted sum of observations (Rajeevan *et al.* 2006). These data are available from 1971 to 2005 for daily precipitation and temperature: (https://imd pune.gov.in/Clim_Pred_LRF_New/Gridded_Data_Download.html).

Bias correction

Bias correction methods are commonly used for climate model data which are used in hydrological modeling to remove the chances of unrealistic simulations (Wörner *et al.* 2019). Various types of downscaling approaches are available under both statistical and dynamical techniques. Empirical downscaling methods are the most used statistical approaches because of their ease of implementation (Chen *et al.* 2013). Change factor is a simple and popular procedure for the bias correction method (Diaz-Nieto & Wilby 2005). This is a simple downscaling method using the average values of observations and predictions. Change factor is widely used due to its simplified approach where average change factor is scaled to each day. There are limitations attached to this bias correction method as well. However, studies indicate that all bias correction methods are able to reduce biasness to some extent, with variable performances depending on the location of basin and choice of method (Luo *et al.* 2018).

In the current study, the change-factor method, the most commonly used method for bias correction, has been applied. This method estimates the change coefficient by indicating the difference between future predictions and

baseline observations and adjusts the baseline observations using this coefficient to reflect a future climate.

In this study, the change factor for precipitation and temperature was estimated using Equations (1) and (2), respectively, and used to scale the daily observed precipitation and temperature data from IMD to produce future climate time series:

$$\text{Daily adjusted precipitation} = P_{obs,d} \times \frac{P_{GCM,fur,m}}{P_{GCM,ref,m}} \quad (1)$$

$$\text{Daily adjusted temperature} = T_{obs,d} + (T_{GCM,fur,m} - T_{GCM,ref,m}) \quad (2)$$

where $P_{obs,d}$ is observed daily data procured from IMD; $P_{GCM,fur,m}$ is monthly mean precipitation output from GCM for the future and $P_{GCM,ref,m}$ is monthly mean precipitation output from GCM for the historical or reference period. $T_{obs,d}$ is the observed daily temperature for the base years from IMD, $T_{GCM,fur,m}$ is the monthly mean temperature of the GCM outputs for the future years, $T_{GCM,ref,m}$ is the monthly mean temperature of the GCM outputs for the historical or reference period.

Hydrological model for assessment

A spatially distributed version of the HBV model was used to simulate the baseline and future runoff. HBV is a distributed hydrological model that works on gridded scale at a daily time step with limited input data requirement. HBV is a conceptual model, and has three main routines for soil, snow, and groundwater responses. For details on this model, Bergström (1992) and Beldring *et al.* (2003) can be referred to. For simulating runoff, the model requires inputs such as digital elevation model (DEM), landuse land cover information, meteorological data, and information on snow and ice cover. In this study, the 90-m resolution digital elevation model data acquired from the Shuttle Radar Topography Mission (SRTM) (<https://earth-explorer.usgs.gov/>), landuse land cover information sourced from Global Land Cover 2000 database, European Commission, Joint Research Centre, 2003, meteorological data from Indian Meteorological Department in the form of gridded data for daily precipitation and daily average temperature, and ice thickness and ice fraction data from

Huss data series (Huss & Farinotti 2012) were used. For simulating future runoff, bias-corrected meteorological data were used in place of observed meteorological data series.

The discharge was simulated for three time periods, short-term (2007–2035); medium-term (2036–2065), and long-term (2066–2100). For each time series, respective meteorological data series were used as input for simulation.

Calibration was done using parameter estimation and optimization package (PEST) software and observed runoff available for the period 1971–79 was used. For selection of the most optimized parameter set, two benchmarks were set – Nash–Sutcliffe efficiency (NSE) >0.75 and bias in the range –0.05 to +0.05. Further, an optimized parameter set was used for simulating the baseline scenario from 1971 to 2007. NSE of the simulated discharge was estimated to be 80% with bias as –0.05. The annual average discharge simulated at Akhnoor discharge station for the period of 1971–2007 was around 805 m³/s. Owing to lack of data, validation was not undertaken.

CLIMATE CHANGE AND FUTURE PROJECTIONS

A preliminary trend analysis of the CORDEX (2006–2100) average temperature and precipitation projections for RCP 4.5 and RCP 8.5 were analyzed by linear trend line plotting and are presented in Figure 2(a) and 2(b), respectively. Increasing trend for temperature under both future scenarios

is noted. However, trends for precipitation appear to be weakly negative. For detailed investigation of the trends, the Mann–Kendall (MK) test was employed and Sen's slope was estimated for the climate scenarios under the two RCPs.

The MK test is widely used for the analysis of trend in climatologic and in hydrologic time series (Khaled 2008). Since the test is a non-parametric one, it does not require the data to be normally distributed. In addition, the test is even suitable for inhomogeneous time series as it is less sensitive to abrupt breaks. The null hypothesis (H_0) for this test is that there is no trend (the data are independent and randomly ordered), tested against the alternative hypothesis (H_1), which assumes that there is a trend.

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^n \text{sign}(T_j - T_i)$$

$$\text{Sign}(T_j - T_i) = \begin{cases} 1 & \text{if } T_j - T_i > 0 \\ 0 & \text{if } T_j - T_i = 0 \\ -1 & \text{if } T_j - T_i < 0 \end{cases}$$

where T_j and T_i are the annual values in years j and i , $j > i$, respectively.

For $n \geq 10$, the statistic S is approximately normally distributed and the test statistic Z_s is calculated to measure the significance of the trend. If p -value is less than the significance level α (alpha) = 0.05, H_0 is rejected and the result is said to be statistically significant with the presence of a trend in the time series. If the p -value is

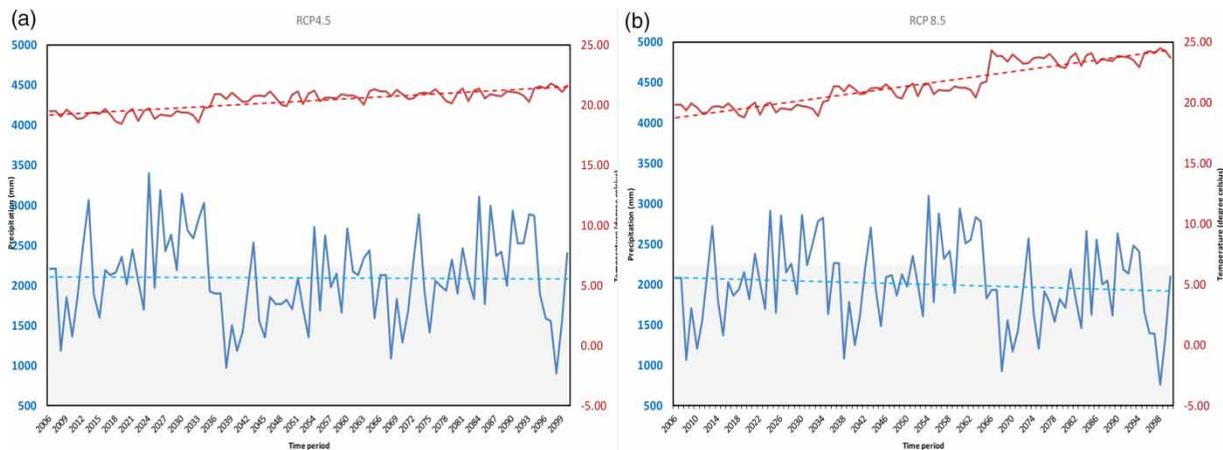


Figure 2 | (a) Temperature (top) and precipitation (bottom) trends under RCP 4.5. (b) Temperature (top) and precipitation (bottom) trends under RCP 8.5.

>0.05 , H_0 is accepted indicating that no trend was detected.

To further estimate the magnitude of the trend, Sen's slope estimator was used. Sen's slope is a non-parametric method that is not much affected by gross data errors and outliers. The Sen's slope (β) is calculated as the median of all the slopes estimated between all the successive data points time series (x) as:

$$\beta = \text{median} \left[\frac{\Delta y}{\Delta t} \right]$$

where Δy is the change in climate variable due to the change in time, Δt between two subsequent observations.

The MK test results (Table 1) show that trends of future temperature projections are significant at 95% confidence interval for mid- and long-term time periods under both RCP 4.5 and RCP 8.5 scenarios. The p -values for these time periods under RCP 4.5 and RCP 8.5 are <0.05 , rejecting the null hypothesis, which means the trends under these scenarios are significant. The high positive values of MK test statistic (S) indicate that there is an increasing temperature trend for the medium- and long-term series. Based on the Sen's slope values, the

average rate of increase in temperature under RCP 4.5 is projected to be $0.036^\circ\text{C}/\text{year}$ for mid-term and $0.024^\circ\text{C}/\text{year}$ for long-term time periods. The projected rates for RCP 8.5 are $0.039^\circ\text{C}/\text{year}$ for mid-term and $0.058^\circ\text{C}/\text{year}$ for long-term periods.

Table 2 presents the trends for precipitation under RCP 4.5 and 8.5 for short-, mid- and long-term time periods. Precipitation trends for the short-term time period under both RCPs are significant with p -values less than 0.05. Positive value of test statistic, S, indicate increasing trends; however, relatively smaller values indicate that the trend is not very strong. In the short-term period, the precipitation is projected to increase at a rate of $33.6\text{ mm}/\text{year}$ for RCP 4.5 and $30.3\text{ mm}/\text{year}$ for RCP 8.5. The trend for mid-term RCP 8.5 is also observed to be significant with positive z and S values. The rate of increase for precipitation until 2065 is projected to be very small ($8.87\text{ mm}/\text{year}$).

CORDEX data indicated significant trends for average temperature for mid- and long-term projections, while for precipitation the trends were significant mainly for short-term projections, which means that in the long run, the basin is expected to have a higher temperature but no

Table 1 | Mann-Kendall results for temperature projections

	RCP 4.5			RCP 8.5		
	Short-term	Mid-term	Long-term	Short-term	Mid-term	Long-term
p -value (95% CI)	0.6683	1.657×10^{-9}	$<2.2 \times 10^{-16}$	0.6683	1.725×10^{-9}	$<2.2 \times 10^{-16}$
z -value	0.4285	6.0283	8.2993	0.4285	6.0218	10.064
S-value	2.500	946.00	2,582.0	2.500	945.00	3,131.0
Sen's slope	0.0038	0.0361	0.0244	0.00375	0.0386	0.0582

Table 2 | Mann-Kendall results for precipitation projections

	RCP 4.5			RCP 8.5		
	Short-term	Mid-term	Long-term	Short-term	Mid-term	Long-term
p -value (95% CI)	0.008715	0.4403	0.9513	0.01072	0.01563	0.3942
z -value	2.623	-0.77176	-0.061088	2.5517	2.4173	-0.85201
S-value	148.00	-122.00	-20	144.00	380.00	-266.0
Sen's slope	33.6125	-3.6775	-0.1469	30.3133	8.8703	-1.8098

significant change in precipitation. Further, the rate of increase in temperature is higher under RCP 8.5 as compared to RCP 4.5.

Percentage changes in seasonal precipitation and temperature with respect to baseline precipitation and temperature for both the RCP scenarios are presented in Figures 3(a), 3(b), 4(a) and 4(b). Precipitation change under RCP 4.5 shows that precipitation in the short-term period will increase with respect to baseline with maximum increase in monsoon season, followed by post-monsoon months. In the medium-term period, increase in precipitation is only for the post-monsoon period. Long-term precipitation trend shows an increase in pre-monsoon and significant increase in post-monsoon seasons. Under the RCP 8.5 scenario, an increase in precipitation is projected to be primarily in the post-monsoon months of September–December, throughout the century.

Percentage change in temperature for RCP 4.5 shows that the maximum percentage increase is expected in the winter season for all time periods. While for RCP 8.5, except for the short-term period where maximum increase is in the monsoon season, maximum percentage increase is in the winter season for the other two time periods.

Precipitation shows a varying trend of increase and decrease throughout the century for different seasons, while temperature exhibits an increasing trend throughout the century. These findings are validated by some of the earlier studies done in the region like that by Rajbhandari *et al.* (2015) over the Indus basin, which reports non-uniform change in overall precipitation with high spatial variability showing an increase in precipitation over the upper Indus basin and decrease over the lower Indus basin and more warming in the upper part than the lower basin. Lutz *et al.* (2016) reported that in the Upper Indus basin, an ensemble of selected GCMs indicates a marginal increase

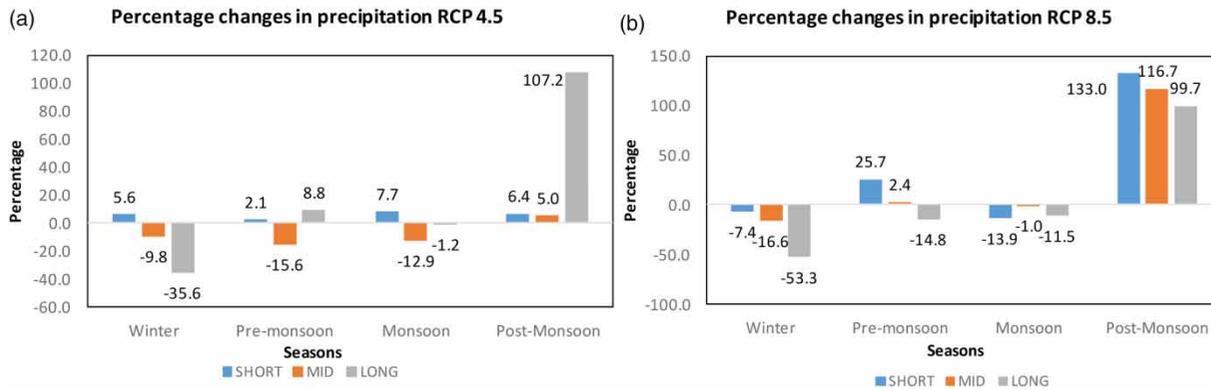


Figure 3 | (a) Percentage change in seasonal precipitation with respect to baseline for RCP 4.5. (b) Percentage change in seasonal precipitation with respect to baseline for RCP 8.5.

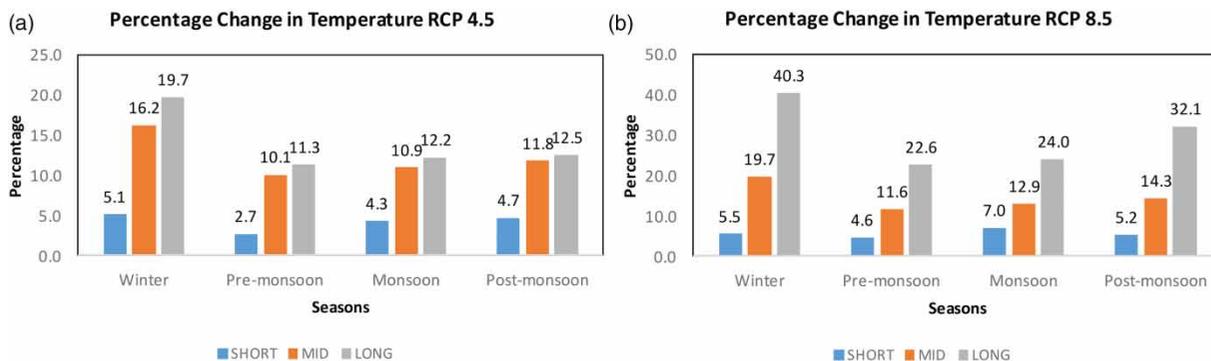


Figure 4 | (a) Percentage change in seasonal temperature with respect to baseline for RCP 4.5. (b) Percentage change in seasonal temperature with respect to baseline for RCP 8.5.

in precipitation and consistent warming. A study over the Jhelum basin, one of the main tributaries of the Indus basin, reports that under RCP 4.5, precipitation is expected to decrease and under RCP 8.5, precipitation is expected to increase (Jasrotia *et al.* 2021). Another study for the HKH region in Afghanistan used eight GCMs to get future temperature and precipitation under RCP 4.5 and RCP 8.5 scenarios and, as per the analysis, temperature is expected to rise and precipitation is expected to decline in future (Azizi & Asaoka 2020). Thus, the projections for precipitation in the region are highly variable in terms of spatial, temporal, and climate change scenarios; while consistent warming is indicated in almost all the studies over the region.

CLIMATE CHANGE IMPACT ON WATER

The simulated discharge under both RCP 4.5 and RCP 8.5 scenarios (Figure 5(a) and 5(b)) indicates an increasing trend compared to the baseline period for all the future time horizons – short-, medium- and long-term. Under RCP 4.5, percentage increase in discharge is projected to be 17, 48, and 53% for short-, medium-, and long-term periods, respectively. Similarly, percentage increase in discharge under RCP 8.5 is projected to be 21, 55, and 115% for short-, medium-, and long-term periods, respectively. The results indicate that the discharge in Chenab River by

mid-century will be around 1.5 times the present discharge under RCP 4.5. However, the rate of increase stabilizes thereafter until the end of the century, while the discharge in Chenab River will be almost double its present value by the end of the century under RCP 8.5.

Correlation of discharge, temperature, and precipitation data (Figure 6(a)–6(d)) indicates that initial increase in discharge could be attributed to the increase in precipitation until mid-century under both RCP 4.5 and RCP 8.5. On the other hand, a similar correlation is not noticeable for the increase in discharge in the second half of the century. Precipitation is projected to decline in the latter half under both scenarios, which does not support the discharge simulation showing an increasing trend for the corresponding period. However, a significant increase in temperature is projected during the second half of the century which will be more pronounced under RCP 8.5 as compared to RCP 4.5. This supports the view that increase in discharge during the second half of the century may be due to significant increase in melting of glaciers in the basin, corresponding with the increase in temperature. Moreover, higher increase in temperature under RCP 8.5 also correlates with the higher increase in discharge under these scenarios towards the end of the century.

Results for Chenab basin showing an increase in discharge until the end of the century are in contrast to the results for some other snow- and ice-fed basins across the world. It has been shown by Huss *et al.* (2008), Bajracharya

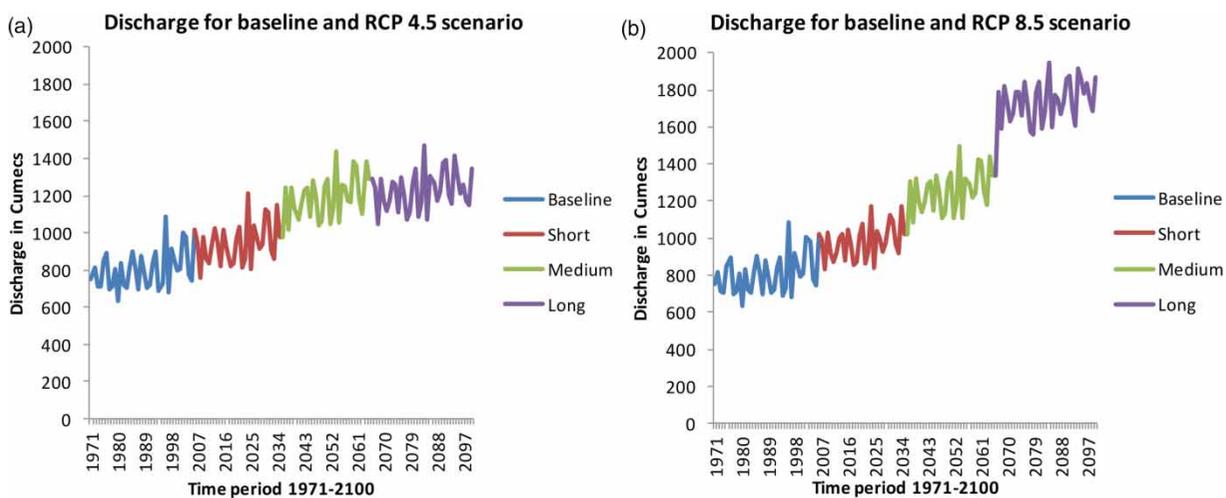


Figure 5 | (a) Simulated baseline discharge (1971–2006) and simulated future discharge 2007–2100 under RCP 4.5. (b) Simulated baseline discharge (1971–2006) and simulated future discharge 2007–2100 under RCP 8.5.

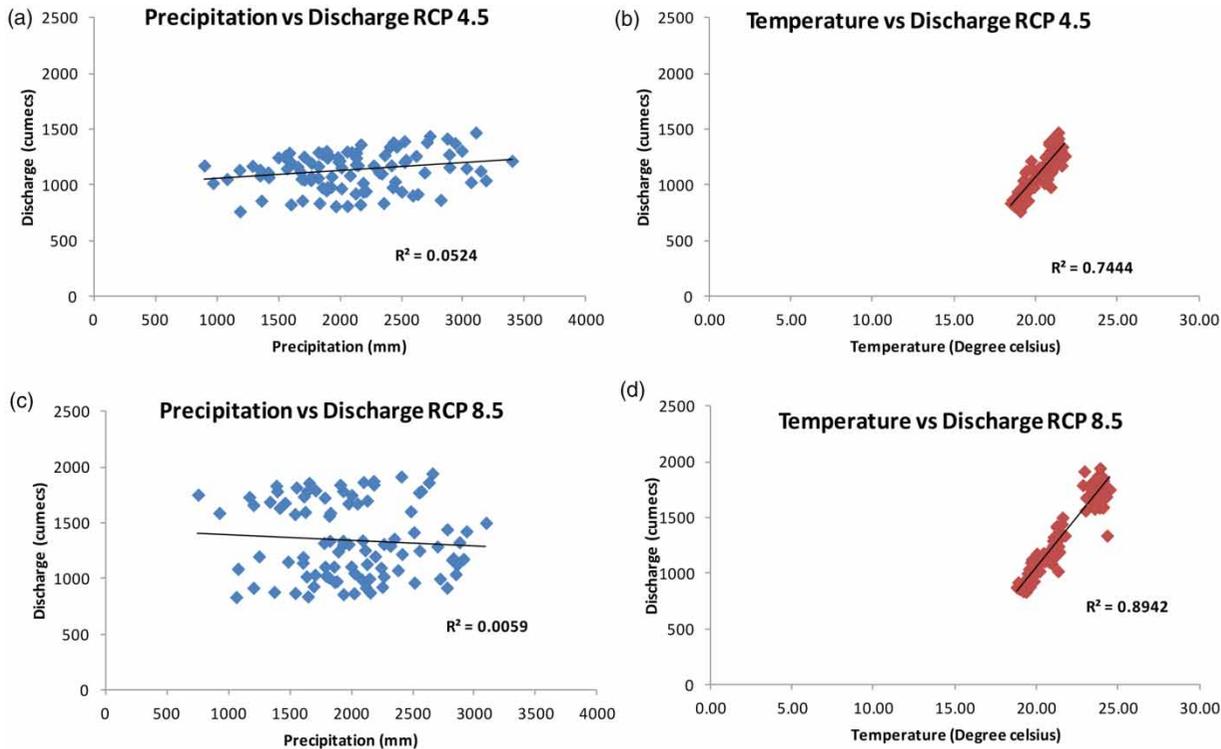


Figure 6 | (a) Correlation between precipitation and discharge under RCP 4.5. (b) Correlation between temperature and discharge under RCP 4.5. (c) Correlation between precipitation and discharge under RCP 8.5. (d) Correlation between temperature and discharge under RCP 8.5.

et al. (2018), Immerzeel *et al.* (2010), and Laghari *et al.* (2012) that initially there will be an increase in annual runoff, followed by a period of stabilization and a drop below the present runoff levels.

Seasonal contribution

For seasonal understanding, the year was split into four seasons: winter (December–March), pre-monsoon (April–June), monsoon (July–September), and post-monsoon (October–November). To understand the seasonal variation of discharge, monthly averages of simulated discharge for the projection period of 2007–2100 under both the RCP scenarios were computed and presented in Figure 7(a) and 7(b). The amplitude of hydrograph under both the RCP scenarios and for all time series is greater for future simulated discharge as compared to the simulated baseline discharge. The simulated future discharge at the outlet of the basin is expected to increase significantly throughout the century, with monsoon season continuing to be the peak discharge period.

Projected precipitation for monsoon season indicates a majorly decreasing trend for all the time series for both the RCPs (except short-term in RCP 4.5), but an increase in volume of monsoon discharge is observed, which can be attributed to the increased contribution from snow and ice melt. This is further supported by the projected increase in temperature in all time series. Projected temperature increase for the monsoon season with respect to the baseline is expected to be in the range of 4–12% for RCP 4.5 and 7–24% for RCP 8.5.

Figure 8(a) and 8(b) indicate that the seasonal contribution to annual discharge in the basin will increase for pre-monsoon (April–May) and post-monsoon months (October–November). Simultaneously, a progressive decline in monsoon contribution to discharge is also observed from baseline to long-term time period. It is interesting to note that the decrease in proportional contribution during the monsoon period is compensated by the increase in other seasons, more prominently during the pre-monsoon season under RCP 4.5 and during the post-monsoon season under RCP 8.5. This indicates a shift in seasonal discharge pattern for the river with decreasing significance of monsoon

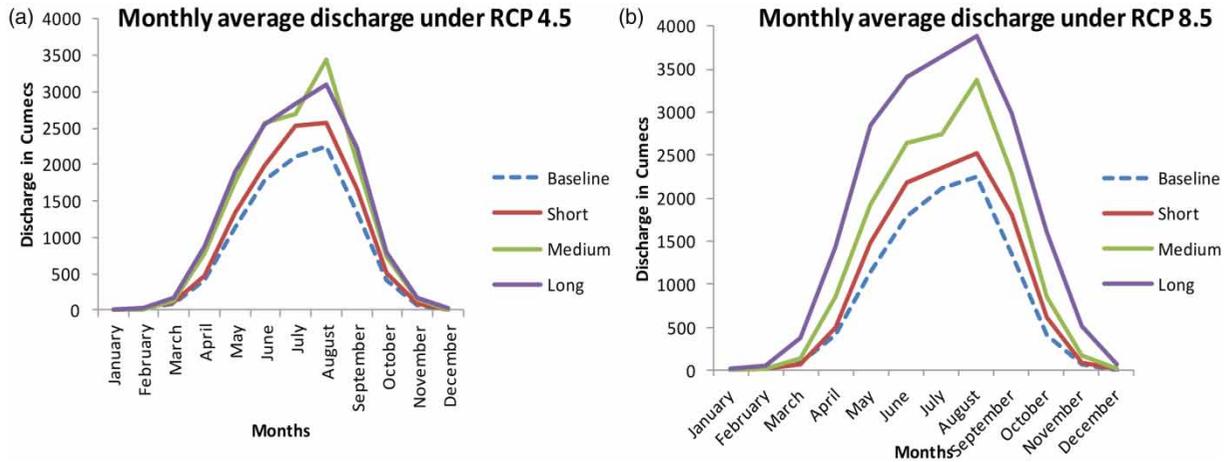


Figure 7 | (a) Monthly average discharge under RCP 4.5 from 2007 to 2100. (b) Monthly average discharge under RCP 8.5 from 2007 to 2100.

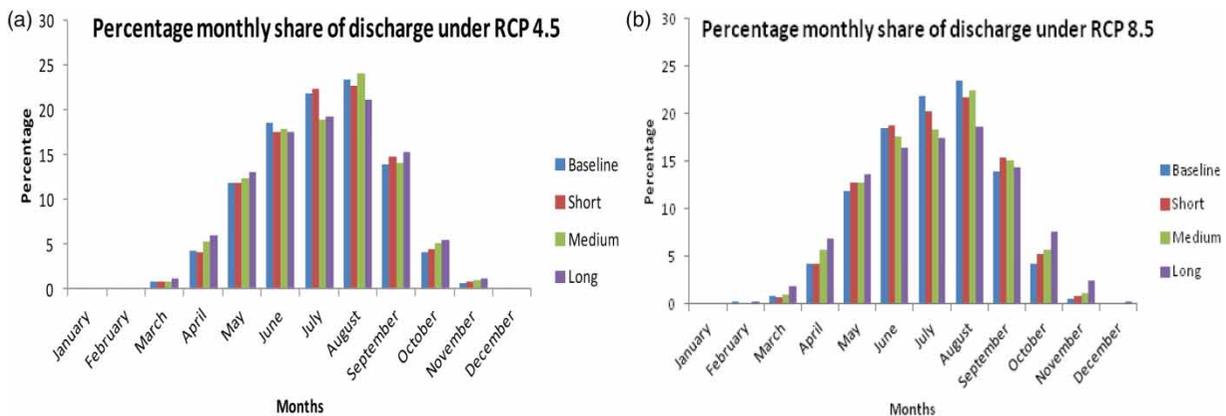


Figure 8 | (a) Percentage monthly share of discharge under RCP 4.5 from 2007 to 2100. (b) Percentage monthly share of discharge under RCP 8.5 from 2007 to 2100.

rainfall and increasing prominence of snow/ice melting in the basin by the end of the century. A study by Anjum *et al.* (2019) also indicates that a shift in seasonal discharge is expected with an increase in the flow expected during low-flow months and a decrease during high-flow months, as simulated under both RCPs.

While the pre-monsoon contribution is mostly in the form of snow and ice melt, with the increasing temperatures the contribution from this important source is expected to increase. The post-monsoon discharge mainly comprises the contribution from base-flow (Grover *et al.* 2020) and with the increase in glacier melt due to increased temperatures, base-flow is expected to increase as a majority of glacier melt runoff percolates to the groundwater. Another reason for an increase in post-monsoon runoff is increase in precipitation during the post-monsoon season. A study

by Azmat *et al.* (2018) also corroborates that the precipitation-runoff during pre-monsoon and winter seasons would increase over Jhelum basin (part of Upper Indus basin) because of the rise in temperature.

Snow and ice melt contribution

Snow and ice melt contribution forms a significant part of the basin and to understand the changes in their contribution for different time periods, monthly averages of snow and ice melt contribution were computed for future time periods under both the RCP scenarios. Figure 9(a) and 9(b) present the monthly average contribution of snow and ice melt and it is observed that snow and ice melt contribution is expected to increase in the future compared to the baseline period. Under RCP 4.5, the maximum snow and ice melt

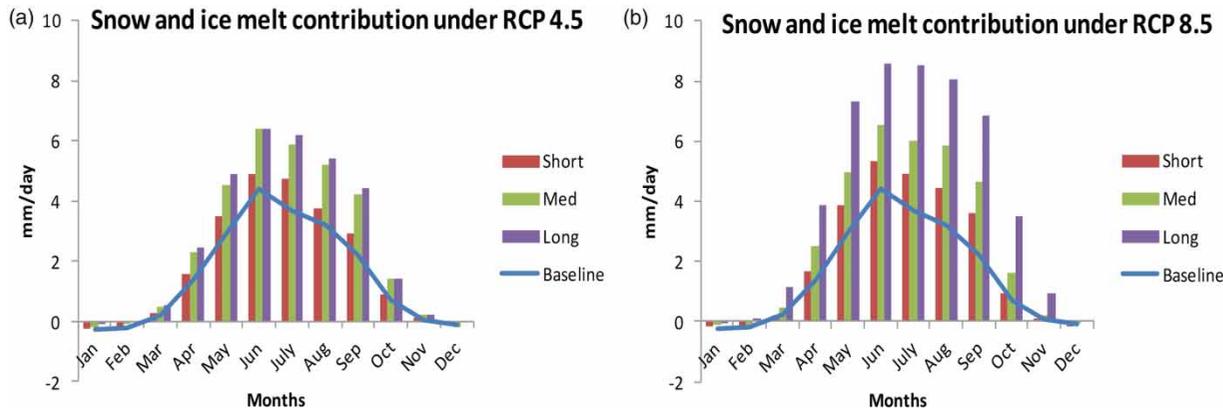


Figure 9 | (a) Monthly snow and ice melt contribution simulated under RCP 4.5. (b) Monthly snow and ice melt contribution simulated under RCP 8.5.

contribution is expected during 2031–2065 and is around 56% of the annual discharge, and remains within this range until the end of the century. The contribution during the short time series is around 50%, which is almost equivalent to the baseline period. Under RCP 8.5, snow and ice melt contribution increases from baseline to short- and medium-term periods to 54–55%, but reaches its peak contribution of 59% of annual discharge towards the end of the century.

Overall, by the end of the century, snow and ice melt contribution is significantly higher as compared to the baseline period. It is important to highlight that the percentage increase in snow and ice melt contribution during post-monsoon (October–November) and winter months (December–March) is expected to be very high. This corresponds to higher percentage increase in projected temperature during these seasons with respect to baseline for both the RCPs. A study on Jhelum, Pakistan also indicates that winter snow melt increases during mid-term and long-term future projections (Azmat *et al.* 2018).

Increasing melt contribution in winter months not accompanied by an equivalent increase in snowfall also signifies that net snow accumulation in the basin may be approaching towards a net ablation scenario during the winter period by the end of the century.

CONCLUSIONS

This study assessed the impact of climate variables (temperature and precipitation) on major hydrological components

(discharge, snow and ice melt contribution, seasonal discharge) in the high altitude, scarcely gauged Chenab basin in India, by examining bias-corrected GCM outputs coupled with a hydrological model. The trend analysis results of projected climatic variables show that precipitation is largely expected to decrease after the short-term period while temperature is expected to increase throughout the century, over the basin.

Hydrological simulation under climate change scenarios for both RCP 4.5 and RCP 8.5 scenarios indicates increasing discharge compared to the baseline period throughout the 21st century; however, discharge attains its peak by mid century under RCP 4.5 but continues to rise until the end of the century under RCP 8.5. A shift in seasonal discharge pattern is also observed with increased pre- and post-monsoon contributions in annual discharge. Further, an increase in temperature also indicates a consequential impact on snow and ice cover of the basin, resulting in their increased contribution to the Chenab River flows throughout the century. Increase in discharge volume as well as its shifting seasonality might have an impact on the basin water management, irrigation, reservoirs, and hydropower projects. An increase in water could present a threat of flooding in low-lying areas and this needs to be managed in advance by creating storage reservoirs. Hydropower projects need to be better prepared for climate change-induced variability in discharge pattern and associated events such as flooding to keep their economic feasibility viable. Run-of-river projects operating and planned over Chenab basin are also vulnerable to variation in discharge, especially increase/shifts in peak flows. Thus, hydrological

simulations under climate change scenarios provide valuable information about future discharge patterns which are useful to prepare well in terms of water management.

CONFLICT OF INTEREST

We wish to confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

DATA AVAILABILITY STATEMENT

All relevant data are available from https://www.imdpune.gov.in/Clim_Pred_LRF_New/Gridded_Data_Download.html
<https://climate4impact.eu/impactportal/data/esgfsearch.jsp>
<https://earthexplorer.usgs.gov/>

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