CIVIL ENGINEERING | RESEARCH ARTICLE

Spatio-temporal analysis of temperature projections based on representative concentration pathways for Satluj River Basin, India

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Abstract: A spatio-temporal analysis of representative concentration pathways (RCPs)-based projections of surface air temperatures under different combinations of global circulation models (GCMs) and RCPs for Satluj River Basin has been presented. The projections of temperature anomalies have been obtained for several meteorological stations in the basin using 16 different combinations of emission scenarios and global climate models (GCMs). For each combination, the projections of temperature anomalies have been analysed for two future time periods centred at 2030 and 2050. The results of the analysis conducted herein clearly indicate that the temperature will rise for all the future time scales with the maximum increase being projected under RCP8.5 compared to the baseline 1986–2005. However, there is large inter-model variability in the projections of temperature anomalies under different RCPs. Under RCP 8.5, the average temperature in Satluj basin is projected to rise by around 4°C by mid of the twenty-first century. The projections of temperature anomalies analysed herein could be potentially used for the evaluation of hydrological impacts of climate change in Satluj River Basin—a key basin in the Himalayan region from the view point of global warming.

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PUBLIC INTEREST STATEMENT

The analysis of projected temperature changes in Satluj River Basin clearly indicates substantial warming under all the combinations of GCMs and RCPs considered in this research. With temperature changes, the hydrological cycle is likely to be disturbed. This would lead to changes in average and extreme rainfall in the basin, ultimately resulting in greater number of floods in the basin. The projected increase in temperature, both in the short and the long term, would have serious implications for the operating strategies being currently followed by the reservoir managers at Bhakra. The availability of water at Bhakra would be impacted, thus impacting the livelihoods of the inhabitants of the basin.
1. Introduction

The trajectories of greenhouse gas emissions emanating from socio-economic changes will describe how climate will change in future. Climate changes mainly depend on various factors which include socio-economic changes, technological changes, energy and land use, greenhouse gases emission and air pollutants. These factors are provided as inputs in climate models that are often employed for the evaluation of climate change impacts. Effective comparisons of model projections can only be made only if common scenarios are used in various studies of model results. In 2007, the IPCC superseded the Special Report on Emission Scenarios (SRES) by representative concentration pathways (RCPs). Consequently, the scenarios based on Special Report on Emission Scenarios (IPCC, 2000) have been replaced by representative concentration pathways (RCPs)—the latest iteration of the scenario process used in the IPCC Assessment Report Five (AR5) (IPCC, 2013).

The present research describes the spatio-temporal analysis of projections of temperature departures under different combinations of global circulation models (GCMs) and RCPs for several meteorological stations in Satluj River Basin—a key basin in the Himalayan region. Being a mountainous basin, Satluj is considered highly vulnerable to the impacts of global warming. The intent behind the present research is to create a dataset of temperature projections under plausible scenarios of climate change in the basin. The dataset of the projections of temperature, and the analysis presented herein can be potentially utilized for hydrological modelling in the basin, thus providing an impetus for climate change modelling efforts in the basin. Temperature projections have been obtained for two future time scales, that is, 2020–2039 and 2040–2059 for 16 different combinations of GCMs and RCPs.

Numerous studies have been undertaken by researchers to analyse temperature projections in different parts of the world. The majority of studies conducted so far have utilized temperature projections based upon the scenarios described in the Special Report on Emission Scenarios of IPCC (IPCC, 2000). The analysis of temperature projections is generally based on the outputs derived from a chosen set of GCMs developed by different modelling centres around the world. The development of these GCMs has been described by several researchers. For example, Wu et al. (2013) describes the GCM developed by Beijing Climate Centre (BCC_CSM1.1). Gent et al. (2011) describes the fourth version of the Community Climate System Model (CCSM4). The CCSM4 is
a general circulation climate model consisting of atmosphere, land, ocean, and sea ice components and exchange of energy. The model developed by the Geophysical Fluid Dynamics Laboratory (GFDL) has been extensively described by Donner et al. (2011). The details of the model developed by Commonwealth Scientific Industrial Research (CSIRO-Mk3.0) can be found in the work of Collier et al. (2011). The goal of CSIRO-MK3 is to address complex physical processes, and coupling between the troposphere and stratosphere. He designed a model to ensure that it had acceptable configuration for participation in climate model intercomparison project 5 (CMIP5). The major objective of the model was to simulate present-day and preindustrial climates with a reasonable degree of accuracy.

Sharif (2015) presented an analysis of surface air temperatures over Saudi Arabia region under three emissions scenarios (SRES A2, A1B, and B1) using Climate Wizard Tool. The Projection of temperature anomalies were obtained using a set of four GCMs. Among the four models considered by the author, the CCSM4 model projected the maximum increase in average temperature, whereas CSIRO-Mk3.0 model projected the minimum increase. Using Hadley Centre’s high-resolution model, Kulkarni et al. (2013) predicted possible impacts of a warmer climate on the Hindkush Himalayan region. Rajbandhari et al. (2014) utilised projections from climate models developed by Hadley Centre, United Kingdom for the assessment of climate change impacts over Indus basin. Graham et al. (2007) made an assessment of climate change impacts on hydrology in Northern Europe using a number of RCMs and an offline hydrological model. Cannon et al. (2016) describes the effect of tropical forcing on extreme winter precipitation in the western Himalayan. Another study in Upper Indus basin made by Lutz et al. (2016) underlined the large uncertainty associated with the future availability of water.

Khattak et al. (2011) evaluated trends in streamflow data on major rivers in the Upper Indus River basin. Sharif et al. (2010) evaluated trends in several extreme flow measures at different hydrometeorological stations located in Satluj River Basin. The study by Khattak et al. (2011) in the Upper Indus River basin indicated an increasing trend in winter maximum temperature, with the trend slopes of 1.79, 1.66, and 1.20°C per 39 years for the upper, middle, and lower regions of the basin. Hamid et al. (2014) analysed observed temperature data at eight meteorological stations in Satluj basin. Six stations exhibited increasing trends in annual average maximum temperature with two being statistically significant. Other similar studies in the Satluj River Basin include Goyal and Khan (2017), P Singh and Jain (2002), Shukla et al. (2017), and Jha et al. (2019).

Possible changes in future inflows in the Qu River basin of China were investigated by Gao et al. (2020) using RCP projections. The authors concluded that the effect of RCP uncertainty becomes more pronounced, particularly for low flows. Xuan et al. (2020) used adjusted rain-gauge data to evaluate the performance of APHRODITE dataset. Choudhary and Dimri (2017) estimated probable changes in monsoonal precipitation in the Himalayan region for several combinations of RCPs and future time slices using the data from Coordinated Regional Climate Downscaling Experiment-South Asia (CORDEX) project. A similar study done by Dimri et al. (2018) using the CORDEX-South Asia dataset indicated an increasing trend in diurnal temperature range (DTR) with highest magnitude observed under RCP8.5. Ehsani et al. (2017) analysed the change in precipitation patterns due to rise in surface temperature. Due to change in precipitation pattern the frequency of floods and droughts was found to increase. Due to climate change excessive melting of ice, and retreating snow cover are some of the hydrological changes observed globally. Kothawale and Singh (2017) investigated linear trends of surface and tropospheric temperature of five selected isobaric levels for the period 1971–2015 across India. The study by the authors projected an increase in surface temperature of 0.74°C for the region with latitude greater than 22° N, and an increase of 0.80°C for region with latitude less than 22° N. Radhakrishnan et al. (2017) estimated the trend of the annual and seasonal mean rainfall and temperature of India for duration 1901–2014 using linear regression and Mann–Kendall test. The results indicated a negative trend for rainfall, whereas the temperature showed a positive trend.
Nordhaus (2007) stressed the need for immediate action by different countries to reduce the concentration of greenhouse gas emissions in order to counteract the adverse impacts of climate change. The work of New et al. (2001) emphasized that the inherent drawbacks in the estimation of precipitation on the surface of the earth from surface gauge stations. The authors proposed that use of merged gauge–satellite datasets for the estimation of precipitation on the surface of the earth. Wang et al. (2019) concluded that a 4°C increase in global temperature compared to the pre-industrial levels could have devastating impact on many aspects of the natural environment. The results of this also indicate possibility of extremes events. Vishal Singh and Goyal (2017) developed a modified curve number (CN) method to simulate streamflow and water yield at sub-catchment scale using SWAT—a process-based spatially semi-distributed hydrological model.

Ross et al. (2018) analysed the temperature pattern for pre-monsoon, monsoon, and post-monsoon for seven decades. He compared decadal temperature of 2000s with 1950s and found a consistent pattern of warming over northwestern and southern India. Rahman et al. (2018) investigated climate change impact on yield of crop in Pakistan using 29 general circulation models (GCMs) under high and moderate representative concentration pathway (RCP) scenarios (4.5 and 8.5) at near-term (2010–2039) and mid-century (2040–2069) time spans. Zheng et al. (2018) analysed future climate and runoff projections for the South Asia region under the RCP8.5 scenario with climate change informed by 42 CMIP5 GCMs. The change in runoff is driven mainly by the change in precipitation, by higher temperature and potential evaporation. The paper also investigates the uncertainties of the projection due to scaling methods and selection of GCMs.

2. Study area
The Satluj River originates beyond Indian borders in the southern slopes of the Kailash mountain near Mansarovar lake in Tibet at an elevation of about 4,572 m. The Satluj is one of the major rivers of the Indus system, and is one of the largest five rivers which flow in Himachal Pradesh. The river Indus rises from the Tibetan plateau and enters the Himalayas in Ladakh. In India Satluj river enters from Shipkila situated in Himachal Pradesh and flows in the South-Westerly direction. The length of the river is approximately about 1,448 km. The Satluj basin lies between 30°N and 33° N latitudes, and 76°E and 83°E longitudes. From Himachal Pradesh the Satluj river enters into plain region at Bhakra located in Punjab. India’s highest gravity dam is located at Bhakra in Punjab province of India. The total catchment area upstream of Bhakra dam is 56,980 km². The Bhakra is a concrete dam with a height of 167.64 m above the river bed. Govindisagar—the reservoir formed by the Bhakra Dam, has an area of 168.35 km². The gross storage capacity of the Bhakra dam is 9621 million cum and live storage capacity is 7191 million cum. The average rainfall in this catchment is about 875 mm.

3. Climate change knowledge portal (CCKP)
The climate change knowledge portal (https://sdwebx.worldbank.org/climateportal) is an interactive website containing historical and projected data under an ensemble of climate change scenarios. The CCKP portal has been created by the World Bank in collaboration with Global Facility for Disaster Reduction and Recovery. Girvetz et al. (2009) described how maps, graphs, and tables can be generated using CCKP. Climate related data through CCKP can be easily accessed by policy makers and development practitioners. Information regarding climate change at various geographical locations around the globe can easily be retrieved using this tool. The raw model information is derived from the Earth System Grid distribution of CMIP 5 (Coupled Model Intercomparison Project Phase 5) as described by Taylor et al. (2012). The CCKP contains data from a total of 16 most widely used GCMs as well as ensemble median of the data to improve the reliability of climate simulations obtained through multiple models. The baseline (1986–2005) data have been produced by the Climatic Research Unit (CRU) of University of East Anglia (UEA).

4. Methodology
The projections of temperature for different regions of the world are available on CCKP for different combinations of RCPs, GCMs, and future time periods. Four RCPs for which the temperature anomalies as well as the mean data is available include RCP2.6, RCP4.5, RCP6.0, and RCP8.5. The
RCPs have been described in detail by Van Vuuren et al. (2011). The first step in the methodology employed herein was to select a combination of climate variables, RCP, GCM, and a future time period for which the temperature anomalies are required. The next step is to select the geographical location at which the data is required. In our case, the temperature anomalies were obtained for seven different geographical locations, each corresponding to a meteorological station in the basin. The desired region is selected on CCKP portal and thereafter geographical coordinates of the location of interest are specified along with the required GCM, RCP, and time scale. The climate data for the geographical locations of interest in the Satluj River Basin was then obtained from the CCKP.

Models used in this study under CMIP5 are bcc.csm1-1, CCSM4,CSIRO-MK3-6-0, and GFDL-CM3. The set of models used in this work has been developed by modelling centres in China, USA, Australia and Germany. Once the temperature anomalies have been obtained for different combinations of the RCP, GCM, and future time periods, the statistical analysis was conducted using R-package—an open source software environment for statistical computing and graphics (R Core Team, 2014). The temperature anomaly data at each location of interest was obtained from the CCKP for a total of 16 different combinations of RCPs and GCMs. For each combination and each location, temperature anomalies were obtained for two future time periods; 2020–2039 and 2040–2059. Both the maximum and minimum values of projected temperature anomalies as well as the range of projections under each combination were extracted from the projected data using R-package. The projected data has been presented through tables as well as barplots. Although the analysis of temperature anomalies has been carried out at all seven locations, but the results at Bhakra station only have been presented.

5. Results and discussion
The analysis of temperature projections for 2020–39 and 2040–59 under RCP2.6, RCP4.5, RCP6, RCP8.5 at 7 different locations in Satluj River Basin for various models is presented in the following sections. The details of the GCMs used in this research are presented in Table 1.

6. Model bcc-csm1-1
Table 2 and 3 shows the projections of temperature anomalies at different stations under all four RCPs for two future periods; 2020–2039 and 2040–2059. It can be seen from Table 3 that for RCP 2.6 and time period 2020–39, the anomalies in the temperature range between 0.17°C to 1.66°C. For RCP2.6 and for the time period 2040–59, the temperature anomalies range from 0.29°C to 1.47°C. For the 2040–59 time period, as expected the temperature anomalies under RCP2.6 are, in general, higher than for the 2020–2039 period. It appears that the GCMs do not take into account the technological advancements and subsequent reduction in emissions that are expected to occur by the end of mid-century. The projections of temperature anomalies are, therefore, on the higher side. The projected anomalies for the months of April and May were higher than in the winter season. Under RCP4.5, the anomalies in

| S. no | Model name     | Modelling centre                  | Main reference                  |
|-------|----------------|-----------------------------------|---------------------------------|
| 1     | bcc-csm1-1     | Beijing Climate Centre, China     | Wu et al. (2013)                |
| 2     | CCSM4          | National Centre for Atmospheric Research, USA | Gent et al. (2011)            |
| 3     | CSIRO-Mk3-6-0  | Commonwealth Scientific and Industrial Research, Australia | Rotstayn et al. (2012)          |
| 4     | GFDL-CM3       | Geophysical Fluid Dynamics Laboratory, USA | Donner et al. (2011)           |
temperature ranged between 0.19°C to 1.85°C for the 2020–39 period. For the 2040–59 period, the temperature anomalies were found to be in the range of 0.21°C to 2.36°C. For RCP6, the temperature anomalies for the 2020–39 period ranged from −0.3°C to 1.46°C. The temperature anomaly of −0.3°C was shown by the model for the February and March. This particular anomaly of −0.3°C shall not be considered.

Table 2. Details of stations used

| S. no | Station | Latitude | Longitude |
|-------|---------|----------|-----------|
|       |         | Degree   | Minute    | Second   | Degree | Minute | Second |
| 1     | Bhakra  | 31       | 24        | 56       | 76     | 26     | 5      |
| 2     | Berthin | 31       | 25        | 11       | 76     | 38     | 55     |
| 3     | Kasol   | 31       | 30        | 0        | 77     | 19     | 0      |
| 4     | Kaza    | 32       | 13        | 25       | 78     | 4      | 11     |
| 5     | Kalpa   | 31       | 32        | 0        | 78     | 15     | 0      |
| 6     | Kahu    | 31       | 12        | 43       | 76     | 46     | 52     |
| 7     | Rampur  | 31       | 26        | 24       | 77     | 37     | 40     |

Table 3. Range of temperature anomalies under bcc-csm1-1

| S. no | Station | RCPs | 2020–2039 | 2040–2059 |
|-------|---------|------|------------|-----------|
|       |         |      | 2020–2039  | 2040–2059 |
| 1     | Bhakra  | 2.6  | 0.3        | 1.64      | 0.3      | 1.4     |
|       |         | 4.5  | 0.19       | 1.52      | 0.21     | 2.31    |
|       |         | 6    | −0.3       | 1.26      | 0.16     | 2.79    |
|       |         | 8.5  | 0.8        | 1.94      | 1.06     | 2.61    |
| 2     | Berthin | 2.6  | 0.29       | 1.63      | 0.3      | 1.24    |
|       |         | 4.5  | 0.19       | 1.68      | 0.29     | 2.26    |
|       |         | 6    | 0.22       | 1.29      | 0.22     | 2.71    |
|       |         | 8.5  | 0.52       | 1.93      | 1.22     | 2.67    |
| 3     | Kasol   | 2.6  | 0.22       | 1.66      | 0.31     | 1.47    |
|       |         | 4.5  | 0.19       | 1.68      | 0.29     | 2.26    |
|       |         | 6    | 0.22       | 1.3       | 0.22     | 2.71    |
|       |         | 8.5  | 0.52       | 1.93      | 1.22     | 3.43    |
| 4     | Kaza    | 2.6  | 0.17       | 1.66      | 0.31     | 1.46    |
|       |         | 4.5  | 0.25       | 1.85      | 0.47     | 2.36    |
|       |         | 6    | 0.13       | 1.46      | 0.32     | 2.7     |
|       |         | 8.5  | 0.69       | 2.1       | 1.58     | 3.54    |
| 5     | Kalpa   | 2.6  | 0.17       | 1.66      | 0.31     | 1.46    |
|       |         | 4.5  | 0.25       | 1.85      | 0.47     | 2.36    |
|       |         | 6    | 0.13       | 1.46      | 0.32     | 2.7     |
|       |         | 8.5  | 0.69       | 2.1       | 1.58     | 3.54    |
| 6     | Kahu    | 2.6  | 0.29       | 1.63      | 0.3      | 1.24    |
|       |         | 4.5  | 0.19       | 1.68      | 0.29     | 2.26    |
|       |         | 6    | 0.22       | 1.29      | 0.22     | 2.71    |
|       |         | 8.5  | 0.52       | 1.93      | 1.22     | 2.67    |
| 7     | Rampur  | 2.6  | 0.25       | 1.62      | 0.29     | 1.4     |
|       |         | 4.5  | 0.2       | 1.73      | 0.37     | 2.22    |
|       |         | 6    | 0.13       | 1.32      | 0.28     | 2.64    |
|       |         | 8.5  | 0.55       | 1.93      | 1.39     | 3.45    |
in decision making process as it is highly unlikely that the temperature trend will show a downward trend under RCP4.5, which is a moderately high emission scenario. As expected, the temperature anomalies for the 2040–59 period ranged from 0.16°C to 2.79°C. Under RCP8.5—the most extreme emission scenario—the temperature anomalies for the 2020–39 time period ranged from 0.52°C to 2.1°C. A projected increase of 2°C can be considered to be significantly higher, and could have important implications for many aspects of the natural environment around the year 2030. The projections of temperature anomalies for Bhakra station are shown in Figure 1. It can be seen from Figure 2 that the projections of temperature anomalies under RCP8.5 are the highest, whereas the lowest temperature anomalies have been projected under RCP2.6. This pattern of temperature projections is similar for both the future periods, that is, 2020–2039 and 2040–2059. However, the magnitude of temperature projections for the 2040–2059 period are higher than for the 2020–2039 period. Under RCP8.5, the projections in temperature are of the order of 3.5°C for the 2040-2059 period compared to around 2°C for the 2020–2039 period. These projections of temperature would be required as an input to models used for impact assessment Table 4 and 6.

| S. no. | Station | RCPs | 2020–2039 | 2040–2059 |
|--------|---------|------|-----------|-----------|
| 1      | Bhakra  | 2.6  | 0.16      | 1.79      |
|        |         | 4.5  | 0.12      | 1.17      |
|        |         | 6    | 0.6       | 1.91      |
|        |         | 8.5  | 0.72      | 1.56      |
| 2      | Berthin | 2.6  | 0.28      | 1.98      |
|        |         | 4.5  | 0.56      | 1.44      |
|        |         | 6    | 0.92      | 2.2       |
|        |         | 8.5  | 0.93      | 1.82      |
| 3      | Kasol   | 2.6  | 0.28      | 1.98      |
|        |         | 4.5  | 0.81      | 1.77      |
|        |         | 6    | 0.92      | 2.2       |
|        |         | 8.5  | 1.04      | 1.92      |
| 4      | Kaza    | 2.6  | 0.47      | 2.13      |
|        |         | 4.5  | 0.88      | 2.02      |
|        |         | 6    | 0.71      | 1.87      |
|        |         | 8.5  | 1.03      | 2.02      |
| 5      | Kalpa   | 2.6  | 0.47      | 2.13      |
|        |         | 4.5  | 0.88      | 2.02      |
|        |         | 6    | 0.8       | 1.87      |
|        |         | 8.5  | 1.03      | 2.02      |
| 6      | Kahu    | 2.6  | 0.28      | 1.98      |
|        |         | 4.5  | 0.56      | 1.44      |
|        |         | 6    | 0.92      | 2.2       |
|        |         | 8.5  | 0.93      | 1.82      |
| 7      | Rampur  | 2.6  | 0.35      | 2.2       |
|        |         | 4.5  | 0.77      | 1.72      |
|        |         | 6    | 0.89      | 2.32      |
|        |         | 8.5  | 1.12      | 1.85      |

Table 4. Range of temperature anomalies under CCSM4
7. Model CCSM4
Under RCP2.6, the projections of temperature anomalies for the 2020–2039 period ranges from 0.16°C to 2.2°C, whereas the corresponding values for the 2040–59 period range from 0.56°C to 2.24°C. There are clear indications of higher temperature anomalies for the 2040-2059 period. Under RCP4.5, the anomalies in temperature were found to vary between 0.12°C to 2.02°C, whereas the anomalies for the 2040-59 period ranged from 0.36°C to 2.31°C. A comparison of temperature anomalies under RCP 4.5 with those projected under RCP2.6 indicate similar magnitude of warming. The difference in the values of projected temperature anomalies obtained under these two emission scenarios was found to be negligible. Under RCP2.6, the projected anomalies in temperature ranged from 0.6°C to 2.32°C for the 2020–39 period. For duration 2040-59, temperature anomaly ranged from 0.4°C to 2.54°C. There was only a slight increase in the projected temperature anomalies under RCP6 for the 2040-2059 period compared to the 2020–2039 period. The negligible increase in projected temperature anomalies for the 2040–59 period indicates a level of stabilization in emissions by the year 2050 under RCP6.0. Under RCP8.5, the temperature anomalies for the 2020–39 period ranged from 0.72°C to 2.02°C. There was, however, some increase in temperature anomalies projections for the 2040-59 period.
with the lowest and highest temperature increases of 1.03°C to 3.22°C, respectively. Under RCP8.5, anomalies in the temperature for the 2020–2039 period ranged from 0.72°C to 2.02°C, whereas the corresponding values for the 2040–2059 period were 1.03°C and 3.22°C. The analysis of output from the CCSM4 model clearly indicates that the variability among the projections under different emission scenarios is not significantly large. Under RCP2.6, RCP4.5 and RCP 6, the model projected similar increase in temperature for both the periods of analysis considered herein. The projections under RCP8.5 were, however, significantly higher than the other three emission scenarios. Figure 3 shows the temperature anomalies at Bhakra as projected by the CCSM4 model under different emission scenarios. The bar plots in Figure 3 show a comparison of projections of temperature anomalies at Bhakra for both the time periods considered herein. It can be seen from Figure 3 that under RCP2.6, the temperature anomaly for the 2020–2039 period is minimum (0.54°C) for the month of December, and maximum (1.79°C) for the month of May. For the 2040–2059 period, the minimum and maximum projected temperature anomalies are slightly higher than for the 2020–2039 period. Under RCP4.5, RCP6.0 and RCP8.0, the maximum temperature anomalies were observed in the month of May. This clearly indicates that Bhakra is likely to experience greater warming in the summer months compared to winter months, with the maximum warming expected mostly in the month of May.

### Table 6. Range of temperature anomalies under GFDL-CM3

| S. no. | Station | RCPs | 2020–2039 | 2040–2059 |
|--------|---------|------|-----------|-----------|
| 1      | Bhakra  | 2.6  | 0.8       | 2.13      |
|        |         | 4.5  | 0.46      | 1.96      |
|        |         | 6    | 0.25      | 1.76      |
|        |         | 8.5  | -0.19     | 1.44      |
| 2      | Berthin | 2.6  | 1.2       | 2.72      |
|        |         | 4.5  | 1.13      | 2.55      |
|        |         | 6    | 0.46      | 2.34      |
|        |         | 8.5  | 0.04      | 2.33      |
| 3      | Kasol   | 2.6  | 1.29      | 3.18      |
|        |         | 4.5  | 1.23      | 3.16      |
|        |         | 6    | 0.69      | 2.63      |
|        |         | 8.5  | 0.27      | 2.89      |
| 4      | Kaza    | 2.6  | 1.29      | 3.18      |
|        |         | 4.5  | 1.23      | 3.16      |
|        |         | 6    | 0.69      | 2.63      |
|        |         | 8.5  | 0.27      | 2.89      |
| 5      | Kalpa   | 2.6  | 1.29      | 3.18      |
|        |         | 4.5  | 1.23      | 3.16      |
|        |         | 6    | 0.69      | 2.63      |
|        |         | 8.5  | 0.27      | 2.89      |
| 6      | Kahu    | 2.6  | 1.2       | 2.72      |
|        |         | 4.5  | 1.13      | 2.55      |
|        |         | 6    | 0.46      | 2.34      |
|        |         | 8.5  | 0.04      | 2.33      |
| 7      | Rampur  | 2.6  | 1.43      | 3.51      |
|        |         | 4.5  | 1.41      | 3.53      |
|        |         | 6    | 0.76      | 3.13      |
|        |         | 8.5  | 0.42      | 3.28      |
8. Model CISRO-MK3-6-0

Under RCP2.6, the projections of temperatures for the 2020–39 period were found to be in the range of 1.07 °C to 2.24°C. For 2040–59, the temperature anomalies were projected to vary between 1.25°C to 3.08°C. Thus, there is an increase in the maximum value of projected temperature anomalies of the order of 0.8°C for the 2040–2059 period compared to 2020–2039 period. Under RCP4.5, the model projects an increase of temperature of 0.9°C to 2.12°C for the 2020–2039 period, whereas the projected increase for the 2040–2059 varies from 1.95°C to 3.33°C. The magnitude of projections under RCP4.5 is similar to the projections under RCP2.6. Both the emission scenarios project a maximum rise of around 3°C for the 2040–2059, thus indicating negligible differences in the magnitude of projections by the model under these scenarios. Under RCP6.0, the projected temperature anomalies for the 2020–2039 period ranged from 0.37°C to 1.44°C. For the 2040–2059 time period, the temperature is projected to rise by 1.2°C to 2.2 °C. This is on expected lines as under all emission scenarios, the temperature projections are higher for 2040–2059 period compared to the 2020–2039 period. Under RCP 8.5, the temperature anomalies for the 2020–2039 period were found to be in the range of 1.08°C to 1.86°C, whereas for the 2040–59 period, the temperature anomalies ranged from 1.67°C to 3.24°C. The analysis of projections clearly indicated that the temperature anomalies are the highest under RCP8.5, which is the most extreme scenario. At Bhakra station, the CSIRO Mk3.6.0 model projects highest temperature increase (2.75°C) under RCP2.6 in the month of February, which is in contrast to projections made by CCSM4 model that projected highest increase in the month of May. The model projects a maximum increase in temperature in the month of February under RCP4.5 and RCP6.0. Under RCP8.6, the model projected maximum increase in temperature (3.24°C) for the month of January. The results from Figure 4 clearly
indicate that the CISRO-MK3-6-0 model projects the highest increase in temperature for the winter months, and not summer months as was the case with CCSM4 model.

9. Model GFDL-CM3

The projections of temperature anomalies under different emission scenarios and for the 2020–2039 and 2040–2059 periods made by GFDL-CM3 model were also analysed. Relatively high temperature anomalies ranging from 0.8°C to 3.51°C were projected by the model under RCP2.6 for the 2020–2039 period. For the 2040–59 period, the corresponding values of temperature projections under RCP2.6 were only slightly higher (1.02°C to 3.93°C) than the 2020–39 period. A similar pattern of temperature projections was observed under RCP4.5 and RCP6.0. Under RCP4.5, the projected anomalies in temperature for the 2020–39 period ranged between 0.46°C to 3.53°C. For the 2040–2059 period, the increase in temperature was projected to be between 0.78°C to 3.95°C, which is only slightly higher than that for the 2020–2039 period. Under RCP6.0, the anomalies in temperature projections for the 2020–2039 period ranged from 0.25°C to 3.13°C, whereas the corresponding values for the 2040–2059 period were 0.58°C to 3.71°C. It can be seen that the temperature anomalies under RCP6.0 for the 2040–2059 period were only slightly higher than for the 2020–2039 period. The analysis indicated that the model projected a relatively higher increase in temperature compared to other models under all emission scenarios. At Bhakra, the temperature anomalies under all the emission scenarios and both the time periods were the highest for the summer months (May, June, July), except under RCP2.6 for the 2020–2039 period. For this combination of emission scenario and time period, the highest projections were for the month of January. Under RCP8.5, Bhakra is likely to experience the highest increase in temperature. For the 2020–2039 period, an increase in temperature of 1.82°C for the month of May is likely at Bhakra under RCP8.5. Figure 5 shows that a relatively high temperature
anomaly of 4.06°C for the 2040–2059 period is expected under RCP8.5 at Bhakra in the month of July.

10. Conclusions
The analysis of projected temperature anomalies clearly indicates substantial warming under all the combinations of GCMs and RCPs considered in this research. There is, however, a high inter-model variability in the projections of temperature anomalies for both the periods of analysis, that is, 2020–2039 and 2040–2059. But all the models considered in this research indicate positive temperature anomalies over the Satluj region for both the future time period considered in this research, regardless of emission scenarios. The key findings of the research are:

(1) As expected, RCP8.5 projects the highest increase in temperature for both the future periods and all the models considered in this research.
(2) The average temperature increase over the Satluj basin by the mid of the twenty-first century under RCP8.5 is projected to be between 3°C to 4°C.
(3) By the end of 2030 it is projected that the average annual temperature will rise by around 1.5°C to 2°C.
(4) Abrupt changes in hydrological cycle could lead to increase in the magnitude as well as frequency of extreme events in the basin.
The projected increase in temperature, both in the short and the long term, could have serious implications for the agricultural production in the basin.

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