



Evaluating climate change for the early 21st century in the Potwar Region of Pakistan using CMIP6 simulations

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Abstract

The warming climate is influencing patterns of natural variability. The impact of global climate change is uncertain, and its assessment is challenging. The Intergovernmental Panel on Climate Change (IPCC) predicted in its sixth assessment report (AR6) that a threshold of 1.5 °C above pre-industrial levels will be reached by the mid-21st century, beyond which current systems will not be supported or sufficient. This research aims to investigate the change in future climate in the Potwar region of Pakistan for early century (by 2039). The study employs both in-situ data and outputs from three Global Climate Models (GCMs) – INM-CM5-0, MIROC6, and NorESM2-MM – under the Coupled Model Inter-comparison Project-6 (CMIP6) project to examine the future climate scenario for the study region. The socio-economic pathway SSP2-4.5 scenario is used for future projections along with baseline data from 1980 to 2010. The CMIP6 data is down-scaled, to bridge the gap between the coarse-scale outputs of GCMs and the local-scale climate information required for decision-making and planning in the Potwar region, by utilizing delta method for Islamabad, Murree, and Jhelum stations of the region using SD-GCM. Our results show that expected temperature rise for early century is ranging from 0.3 to 1 °C, with an average change of +0.6 °C in case of maximum average surface temperature (Tasmax), and +0.7 °C in case of minimum average surface temperature (Tasmin) for Potwar region. The effect on rainfall average is uncertain with more variability and changes in the timing and intensity of rainfall events. The ensemble mean value can be estimated as +0.4 mm in case of rainfall. The investigation helps to study the effects of climate change and provides a basis for impact assessment, as well as the development of adaptative strategies to mitigate unwelcome changes. The research on climate change in the Potwar region of Pakistan is of significant importance due to the potential impacts it can have on various sectors, including agriculture, water resources, and human health as the study provides valuable insights into the finer-scale climate change in the Potwar region, which can be used to inform decision-making processes and policy formulation for sustainable development in the area.

Keywords Climate Change · CMIP6 · Global climate models · Shared Socio-economic pathways · Meteorology · Potwar

Introduction

Climate change is a significant alteration in natural systems worldwide, but changes in the patterns of natural variability could have more severe and drastic effects on Pakistan (Ali et al. 2019). Pakistan lies in a temperate zone and is highly vulnerable to the negative effects of climate change. Its climate is highly variable, with 66% of the region exhibiting an arid-type climate (Rashid and Rasul 2011). Increasing temperature in most parts of the country could decrease the Standardized Precipitation Evapotranspiration Index (SPEI) values and thus increase the frequency of droughts (Ullah et al. 2021b).

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Pakistan is a developing country with limited financial and technical resources to address the challenges of climate change. Climate change is expected to increase vulnerability globally, particularly in Pakistan (Ahmad et al. 2015; Nasim et al. 2016; Rahman et al. 2018) due to extreme weather events, changes in precipitation patterns, and rising temperatures, among other factors. (IPCC, 2014; IPCC 2023). Ullah et al. (2023a) provided insights into the physical mechanisms behind the changing climate over the Punjab region of Pakistan, including the impact of precipitation, temperature, and soil moisture levels. In another study Ullah et al. (2023b) described a nonlinear relationship between flood timing, duration, and intensity, indicating the influence of flood events on dryness/wetness conditions. Climate change involves long-term changes, including rising temperatures, increasing greenhouse gas emissions and carbon dioxide concentrations, as well as non-uniform and cyclical distribution of precipitation (Ullah et al. 2018a). The increasing dryness/wetness in the regions can be attributed to long-term drying trends, particularly in arid and semi-arid regions (Ullah et al. 2022c). The primary cause behind the upward trend in surface temperature is the increasing concentration of greenhouse gases in the environment, which ultimately enhances the greenhouse effect.

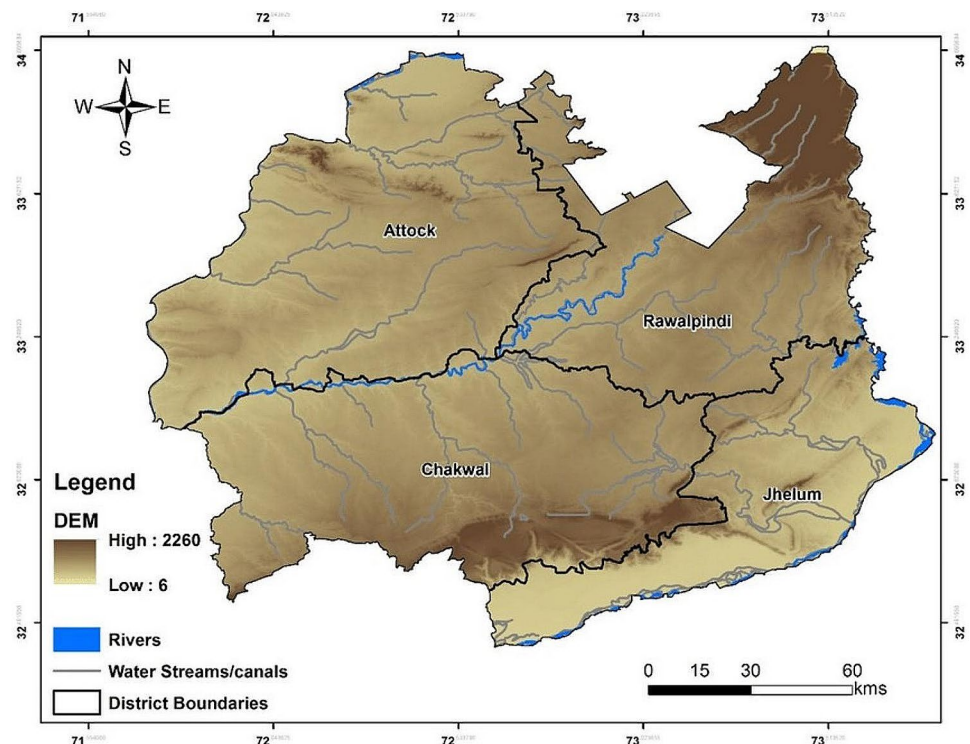
Water vapor is the largest contributor to the greenhouse effect due to its abundance. The atmosphere's capacity to hold water vapor depends on temperature - as temperature increases, the concentration of water vapor in the atmosphere also increases, contributing to global warming.

However, there are other factors that affect the flow of water vapor in the atmosphere, so there is no direct human activity that contributes to its concentration. Changes and shifts in natural climate variability, such as monsoons, can have dire effects on human societies that have become accustomed to or dependent on specific long-term temperature, wind, and precipitation patterns. Hydroclimate extremes caused by global warming have impacted the hydrological cycle globally (Ullah et al. 2022b). Pakistan also has experienced severe weather events in recent years (see, for instance, Basit et al. 2012; Siddiqua et al. 2019). The Potwar region of Pakistan, shown in Fig. 1, extends from 32.5°N to 34.0°N latitude and 72°E to 74°E longitude (Chaudhry and Rasul, 2004) and experiences a range of semi-arid to humid climates (Ghazala and Mahmood, 2009).

Inter-annual rainfall variability from 1991 to 2008 for the Potwar region by Rashid and Rasool (2011) is shown in Fig. 2, which helps in rainfall pattern assessment. A significant variation can be seen in rainfall patterns over this 18-year period, which can have a serious impact on the region's agricultural practices and sustainability. Since crop growth in this area relies heavily on precipitation distribution (Rashid and Rasool, 2011).

Future impact assessments by using projected climate change scenarios are essential to estimate climate change and its effects (Rahman et al. 2018). Scientists and researchers used the representative concentration pathways (RCPs) in GCMs to simulate climate change and its impact under these scenarios. RCPs helped to understand how our climate

Fig. 1 Location map of the Potwar region in Pakistan (Ullah et al., 2018b)



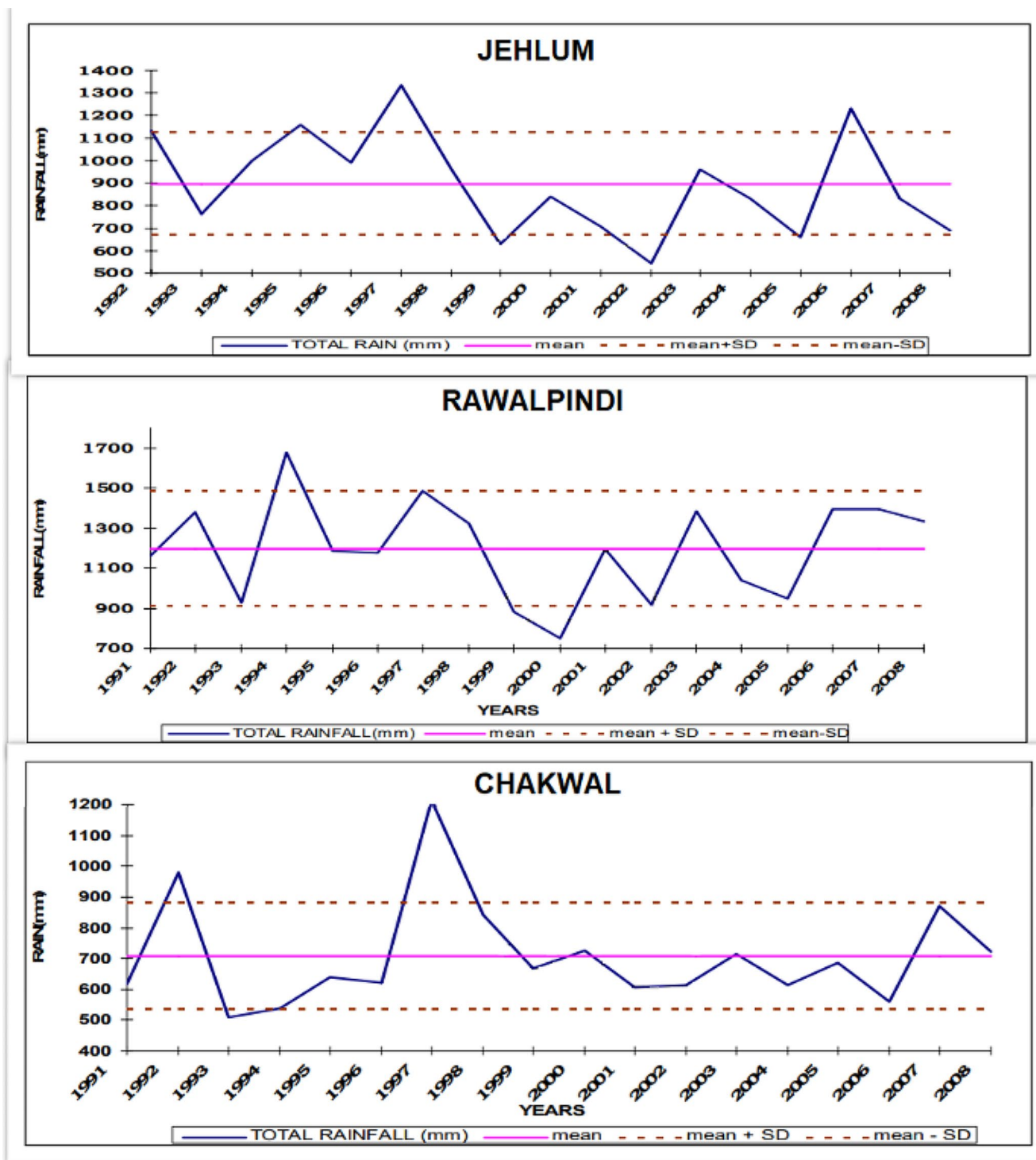


Fig. 2 Inter-annual rainfall variability in ‘mm’ for Potwar region of Pakistan from 1991–2008

be changed in the future. The RCPs were used as the basis for the report’s conclusions in the 2014 IPCC 5th assessment report. RCPs fix the emissions pathways and resultant radiative forcing. The RCPs try to capture future trends. They make predictions about future changes in greenhouse gas concentrations in the atmosphere due to human

activities. The radiative forcing of the four RCPs ranges from very high concentrations (RCP 8.5) to very low future concentrations (RCP 2.6). The values of RCP (2.6, 4.5, 6.0, and 8.5) represent radiative forcing by the end of 2100. In phase 6 of Coupled Model Intercomparison Project (CMIP6), which is a major international effort to improve

climate modelling and provide updated projections of future climate change, an improved version of projected climate change scenarios is introduced. These alternative scenarios are directly relevant to societal concerns and will provide multi-model climate projections in an advanced manner. RCP 4.5 with alternative SSPs is illustrated by O'Neill et al. (2016) in Fig. 3 in the form of an SSP forcing scenario matrix. CMIP6 climate projections are not only advanced due to updated versions of climate models, but because of the shared socioeconomic pathway (SSPs), updated version of integrated assessment models (IAMs), and data on recent emissions trends (O'Neill et al. 2016). For example, SSP2-4.5 is one of the Intergovernmental Panel on Climate Change's (IPCC) Shared Socioeconomic Pathways (SSPs). It represents a world in which global population peaks in the mid-century and then declines, renewable energy sources are developed moderately, and international cooperation to address climate change is moderate. The "4.5" in the scenario name refers to the radiative forcing level (in watts per square metre) associated with the scenario by 2100, which is roughly equivalent to maintaining atmospheric CO₂ concentrations at around 540 parts per million.

Verma et al. (2023) provided hydrological insights for the India region. The study concludes that the CMIP6 ensemble offers a lower margin of uncertainty for future climate projections and better credibility for hydrological effect

analysis as compared to CMIP5. Martel et al. (2022) recommended to update studies performed using CMIP5 with the CMIP6 ensemble as CMIP6 provide a narrower band of uncertainty. Another study (Li et al. 2021) compares the latest 6th phase (CMIP6) versus the 5th phase (CMIP5) of the Coupled Model Intercomparison Project for precipitation simulation and conclude that performance of CMIP6 increases or decreases regionally.

Using observational data from the Climate Prediction Center (CPC) and validating CMIP6, it has been indicated that warming in regions can contribute to dryness and it is important to understand climate interaction under physical mechanism for adaptation strategies (Iyakaremye et al. 2021). The increase in compound drought and heatwave (CDHW) events worldwide, particularly in South Asia, under CMIP6 identify vulnerable areas more likely to experience frequent and severe CDHW events due to climate change (Ullah et al. 2023c).

Studies have shown that countries are not only affected by regional climate change but also by changes in competitiveness caused by climate change (Calzadilla et al. 2010). Ullah et al. (2022a) examines the projected heat stress and associated socioeconomic exposure across South Asia using different socioeconomic pathways and climate models of CMIP6, finding that though the region has the potential for widespread changes to Wet bulb globe temperature (WBGT)

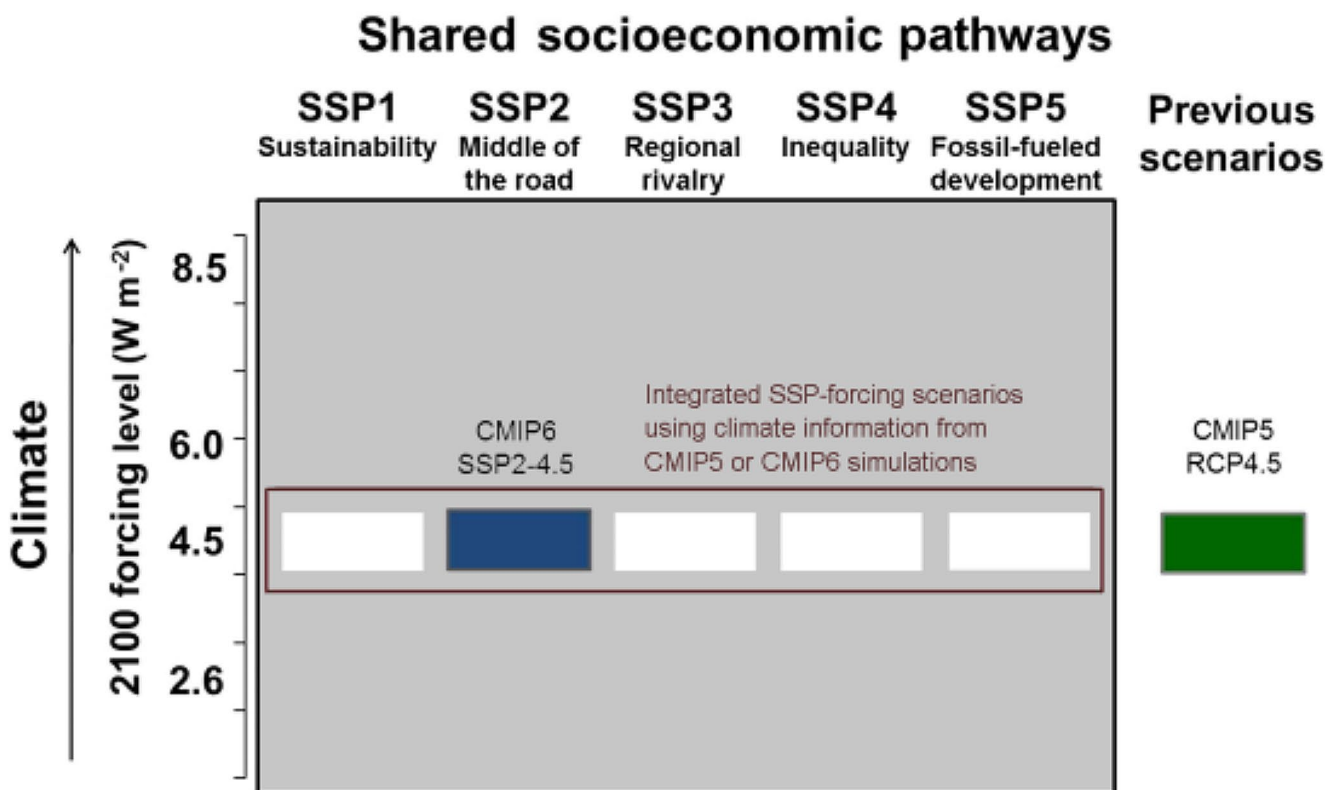


Fig. 3 Relationship between SSPs CMIP6 vs. RCPs CMIP5 (O'Neill et al. 2016)

of 6.5 °C (which can exceed the theoretical limits of human tolerance) but the projected changes in exposure are mainly due to the interaction effect, and the climate influence is more dominant than the population. The skilful seasonal climate predictions can help reduce risk (Jha et al., 2019) by introducing adaptations against climate change (Naqvi et al. 2019). Therefore, it is crucial to assess the potential impacts of climate change in advance. A little investigative effort is done to study the effects of climate change in the Potwar region of Pakistan for the early 21st century (2039) using CMIP6 simulations and in-situ data. The research focuses on examining the future climate scenarios for the study region by utilizing three Global Climate Models (GCMs). The study also aims to provide a basis for impact assessment and the development of adaptive strategies to mitigate unwelcome changes caused by climate change in the Potwar region. The research is significant as it contributes to the understanding of climate change patterns and their potential impacts on the Potwar region of Pakistan. The assessment of future climate scenarios can help policymakers and stakeholders in the Potwar region to make informed decisions and develop adaptive strategies to address the potential challenges posed by climate change. The findings of the study can be useful in various sectors, such as applied meteorology, agrometeorology, and biometeorology, for developing mitigation strategies and assessing the finer-scale climate change in the region.

Data and GCMs of the study

There are several platforms to access the Coupled Model Intercomparison Project (CMIP) phase 6. Many experiments are performed in 6th phase of this project i.e., CMIP6, that include Scenarios (ScenarioMIP), Impacts (CORDEX, VIACS AB), Ocean/land/ice (OMIP, FAFMIP/LS3MIP/SIMIP, ISMAIP6), Regional phenomena (GMMIP, HighResMIP), Clouds/circulation (CFMIP, DynVarMIP), Palaeo (PMIP), Characterizing forcing (RFMIP, DAMIP, VolMIP), Chemistry/aerosols (AerChemMIP), Carbon cycle (C4MIP), Land use (LUMIP), Geo-engineering (GeoMIP), and, Decadal prediction (DCPP) (Simpkins 2017). Since, ScenarioMIP offers a collection of future scenarios that represent various socioeconomic pathways and emission trajectories, ScenarioMIP data under CMIP6 was accessed via Copernicus (DOI: <https://doi.org/10.24381/cds.c866074c>) for experiment SSP2-4.5.

It is common practice in climate research to select a subset of GCMs for analysis, considering computational limitations and the need to capture a reasonable range of climate projections and uncertainties. For instance, John et al. (2022) quantifying the model response uncertainty

for CMIP6, Doi and Kim (2022) exploring uncertainties of CMIP6 for future projections over CMIP5 and Jin et al. (2024) while evaluating uncertainties in projections of DSL under CMIP6 recommends to use more than one model for projections. Since, there are numerous General Circulation Models (GCMs) used in climate science research, each with its own set of advantages and disadvantages. As a result, ranking models in a straightforward manner can be difficult. However, several studies have compared various GCMs and evaluated their performance in various ways. Several studies have emphasised MIROC6's strengths as a GCM for simulating regional climate patterns and phenomena. Watanabe et al. (2019) describe MIROC6's comprehensive representation of the Earth System as well as its high spatial and temporal resolution. Akimoto et al. (2019) assess MIROC6's performance in simulating regional climate patterns in East Asia. Oki et al. (2019) discuss the water cycle representation in MIROC6 and its applications for water resource management. MIROC6's features make it a valuable tool for studying climate change impacts in Pakistan's Potwar region, where water resource management and agricultural productivity are critical. The INM-CM5-0 is a cutting-edge General Circulation Model (GCM) that has been used in a wide range of climate science studies. According to Kajtar et al. (2018), the model does a good job of simulating the variability and trends of temperature and precipitation over time. Takemura et al. (2019) emphasise the model's ability to simulate aerosol-cloud interactions and their climate impacts. Wu et al. (2018) discuss the model's role in forecasting future monsoon rainfall changes over China. Finally, Malik et al. (2020) use INM-CM5-0 to project future changes in temperature and precipitation over Pakistan's Potwar region under various greenhouse gas scenarios, indicating that the model is a useful tool for assessing the region's climate change impacts. The NorESM2-MM is also a General Circulation Model (GCM) that is widely used in climate science research. According to Bao et al. (2019), the model's performance in simulating the variability and trends in temperature and precipitation over time is comparable to that of other cutting-edge GCMs. Furthermore, Hwang et al. (2019) highlight the model's ability to simulate the effects of climate change on East Asian water resources. Meanwhile, Fuglestedt et al. (2018) discuss how the model represents carbon cycle feedbacks and how this affects future climate change scenarios. Ullah et al. (2021a) use NorESM2-MM to forecast future temperature and precipitation changes over Pakistan's Potwar region, implying that the model is a useful tool for assessing the effects of climate change on the region.

Methodology

Based on GCMs performance in previous studies, availability of data, and relevance to the Potwar region of Pakistan three GCMs, INM-CM5-0, MIROC6, and NorESM2-MM, were selected. It allows for a reasonable representation of the range of climate projections and uncertainties associated with different modeling approaches.

The historical and SSP2-4.5 experiment daily data for three variables, namely precipitation (pr), maximum near-surface air temperature (Tasmax), and minimum near-surface air temperature (Tasmin), was downloaded for the Potwar region of Pakistan from three selected Global Climate Models (GCMs) i.e., INM-CM5-0 (Russia), MIROC6 (Japan), and NorESM2-MM (Norway). The data files available were in the form of computer numerical control (CNC).

In-situ data for the stated three stations of the Potwar region was obtained from Climate Data Processing Center (CDPC) of Pakistan Meteorological Department (PMD). Since, Coupled Model Intercomparison Project (CMIP), is a multi-model effort aimed at improving our understanding of past, present, and future climate change; and GCMs are evaluated by the CMIP project based on their ability to reproduce observed climate variability and trends, as well as their ability to simulate future climate projections. Therefore, using historical data, a common approach is used in this study to compare the models' ability to simulate past climate conditions. The in-situ historical (1981–2010) rainfall and temperature data is used to downscale the CMIP6 historical data for the same period. Also, along with historical data, future data (2015–2039) under SSP2-4.5 is also downscaled, as downscaling eliminates the gap between coarse-scale climate data and fine-scale climate data.

A tool, Statistical Downscaling of Global Circulation Model (SD-GCM) was used to downscale the CMIP6 data, developed by Agrimetsoft (2021). SD-GCM software provides a unique option to evaluate the performance of the CMIP5/CMIP6 model by comparing it to observational data over a common time period. For evaluation, the observational data is presented in Excel file format whereas the model's historical data in NetCDF format. The evaluation process uses six efficiency criteria to measure model accuracy including Pearson correlation coefficient, Nash-Sutcliffe efficiency, Spearman correlation coefficient, root mean square error (RSME), D (protocol index) and Mean Absolute Error (MAE). By utilizing these criteria, performance of methodological models can be effectively analysed and measured based on the observed data. This tool has been used in several studies to provide high-resolution climate data for specific locations. Hu et al. (2014), for example, used SD-GCM to downscale GCM output and generate high-resolution temperature and precipitation data

for China. The authors discovered that SD-GCM provided more accurate information than traditional downscaling methods, and that the tool was especially helpful in areas with complex terrain. In another study, Park et al. (2015) used SD-GCM to generate high-resolution temperature and precipitation data for South Korea. The authors found that SD-GCM provided more accurate information than other downscaling methods and was useful in predicting extreme events such as heatwaves and heavy rainfall.

There are many methods of statistical downscaling. In SD-GCM, three models are available including, the delta method (Schaake et al. 1996), quantile mapping (Panofsky and Briar, 1968), and empirical quantile mapping (Boe et al., 2007). In this study, delta method is used under SD-GCM. Many studies have used the Delta method to statistically downscale CMIP6 outputs, for example, Khan et al. (2021) used the Delta method to downscale future temperature and precipitation projections from the CORDEX South Asia dataset to a finer resolution over Pakistan in a recent study. Moreover, Dessu and Melesse (2013) used the Delta method to statistically downscale precipitation from CMIP5 Global Climate Models (GCMs) outputs to a finer scale over the Abay River Basin in Ethiopia. Some potential limitations of delta method may include assumption regarding relationship between the observed and GCM data as constant over time, which may not always hold true. Moreover, it may contain potential biases in downscaled data by not capturing fine-scale spatial variability for which SD-GCM cater for. The uncertainties of downscaled data are also dependent upon uncertainties of the GCMs which are improved in CMIP6.

For this study, following Eqs. (1–3) are adopted and deltas are calculated as follows:

$$\Delta_{mean} = mean_{observed} - mean_{GCM} \quad (1)$$

$$\Delta_{std} = \frac{std_{observed}}{std_{GCM}} \quad (2)$$

where, $mean_{observed}$ and $std_{observed}$ are the mean and standard deviation of the observed precipitation, respectively, and $mean_{GCM}$ and std_{GCM} are the mean and standard deviation of the GCM precipitation.

GCM precipitation data downscaling:

$$downscaled_{pr} = (GCM_{pr} + \Delta_{mean}) \times \Delta_{std} \quad (3)$$

where, GCM_{pr} represents the original GCM precipitation data and $downscaled_{pr}$ represents the downscaled precipitation data. In this equation, delta mean is applied to the GCM precipitation data to shift its mean to match the observed precipitation. The adjusted GCM precipitation

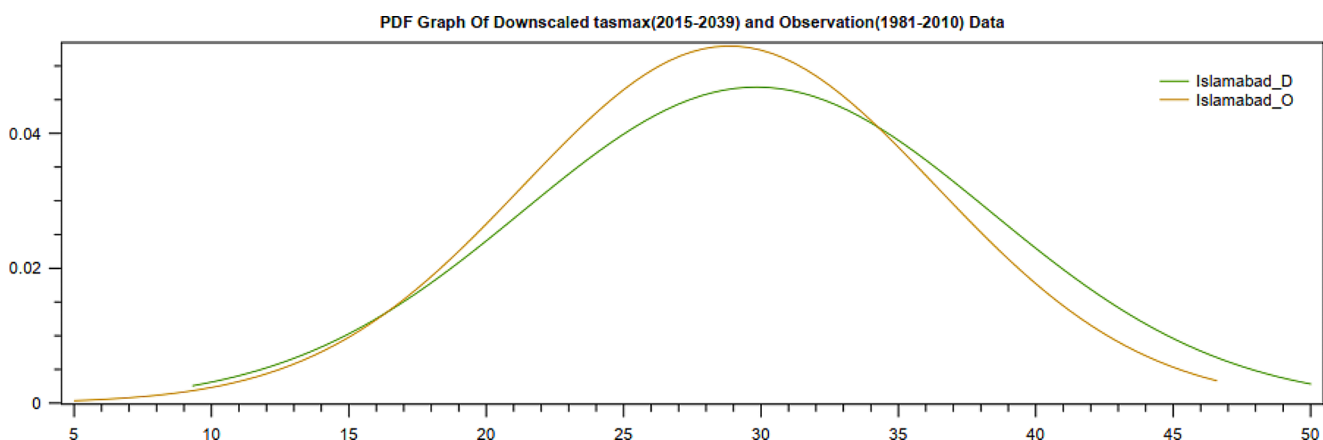


Fig. 4 PDF graph of historical in-situ and downscaled CMIP6 projections for Tasmax under SSP2-4.5 for Islamabad station (Islamabad_D means downscaled data and Islamabad_O means observed/insitu data)

data is then multiplied by the scaling factor or “delta” for the standard deviation, to scale its variability to match that of the observed precipitation. The above equations have been used by SD-GCM for precipitation as well as for temperature.

Foregoing above, the delta model was selected for all GCMs to downscale the selected three variables i.e., Tasmax, Tasmin, and pr. A probability density function (PDF) graph is shown in Fig. 4, just as an example, to show how closer downscaling was done in the case of Islamabad station. The variable, in this case, is Tasmax and the GCM is NorESM2-MM. The graph illustrates how closely the downscaling was performed.

Similarly, downscaling was done station-wise for all GCMs and variables, one by one, to get all data in XML-based files. Finally, the data was then plotted using Microsoft Excel to evaluate climate change in the region for the early 21st century. Additionally, another source of data/image provided by the NOAA/OAR/ESRL PSL, Boulder, Colorado, USA, is used to assess the trends and behaviours of climatic variables such as temperature and precipitation.

Results and discussion

The climatology of the Potwar region for three stations i.e., Islamabad, Jhelum, and Murree is plotted for three selected GCMs, which are discussed earlier. Considering the nature of research i.e., Climate Change, it is important to acknowledge some potential limitations. This investigation relies on outputs from Global Climate Models (GCMs) under the CMIP6 project, which have inherent uncertainties and limitations in simulating regional climate patterns. It only focuses on the Potwar region of Pakistan, and the findings may not be directly applicable to other regions. Further, it primarily examines only temperature and precipitation

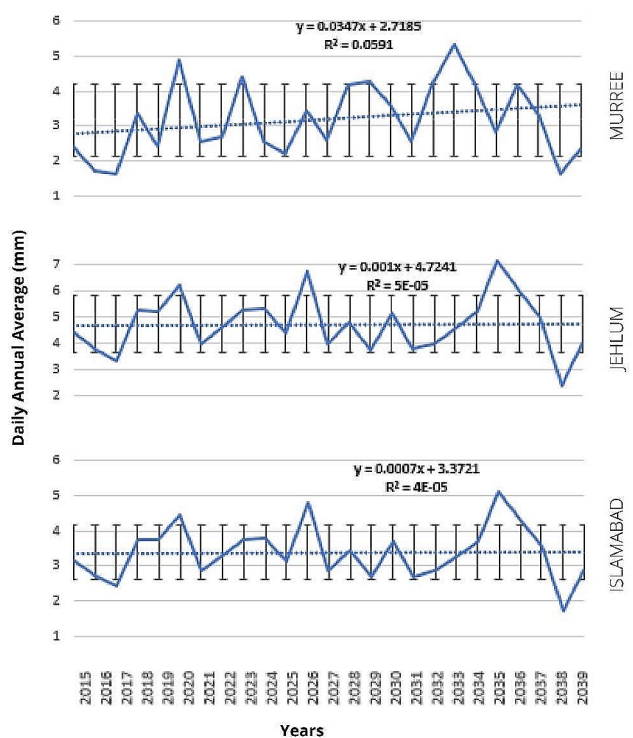


Fig. 5 Early century SSP2-4.5 CMIP6 projections for precipitation ‘pr’ under Russian GCM INM-CM5-0 for Potwar, Pakistan

changes. Based on changes in precipitation, and minimum and maximum air surface temperature for the early century, results are discussed below.

Precipitation

Based on the daily annual average, future projections under experiment SSP2-4.5, in case of precipitation, are shown in Figs. 5 and 6, and 7 for Russian (INM-CM5-0), Japanese

(MIROC6), and Norwegian (NorESM2-MM) global climate models respectively.

In the case of the Russian model, a clear increasing trend is observed for precipitation at station Murree as compared to the other two stations, as shown in Fig. 5. The other two stations are showing daily annual average precipitation which shows almost no change or slight decrease in precipitation average over time.

The change in precipitation at Murree is estimated around 0.9 mm. For rainfall it will be 0.7 mm if multiplied by the factor 0.81. The factor of 0.81 assumes that, on average, about 81% of precipitation in India falls as rain and the remaining 19% falls as snow (Kothyari et al. 2005). For mean value it is estimated as 0.2 mm in the region.

Japanese model i.e., MIROC6 under SSP2-4.5 experiment, shows slight increasing trends for all stations, but in fact this slight increment over 25-year span will not overcome the drought period observed during the years 2035–2037 in Fig. 6. It can be estimated that a 0.81 mm increase in rainfall may occur over the quarter century at Jhelum, 0.6 mm at Islamabad, and 0.2 mm at Murree. The average for all these stations is estimated as 0.5 mm. The precipitation peak at all station may be observed for the year ~2029 under GCM MIROC6.

The Norwegian GCM shows almost similar trends as shown by MIROC6 with an average change of +0.3 mm rainfall as shown in Fig. 7.

The ensemble mean value can be estimated as +0.4 mm in case of rainfall. However, it is just a projection by models which is uncertain, and many other factors can affect the variability like human activity, natural variability etc. The drought period is also observed for the years 2032–33 with more precipitation in 2037–38, in case of NorESM2-MM.

Rainfall projections for the early part of the century are uncertain, but the most likely scenario predicts an increase or decrease in mean annual precipitation in the Potwar region, as shown in Figs. 5, 6 and 7, with more variability and changes in the timing and intensity of rainfall events. This could have an impact on water availability and management in the region.

According to Ahmad et al. (2021), precipitation is increasing in the Indus basin. They attribute this trend to the impact of global climate change, which has caused changes in the behaviour of the Indian Ocean Dipole and the El Nio Southern Oscillation (ENSO). These climate modes have the potential to influence regional climate variability, including precipitation patterns.

One possible explanation is that higher temperatures increase evaporation, increasing atmospheric moisture content and precipitation. Changes in land use and land cover are another possible explanation for the increasing trend of rainfall. As the region's urbanisation and deforestation

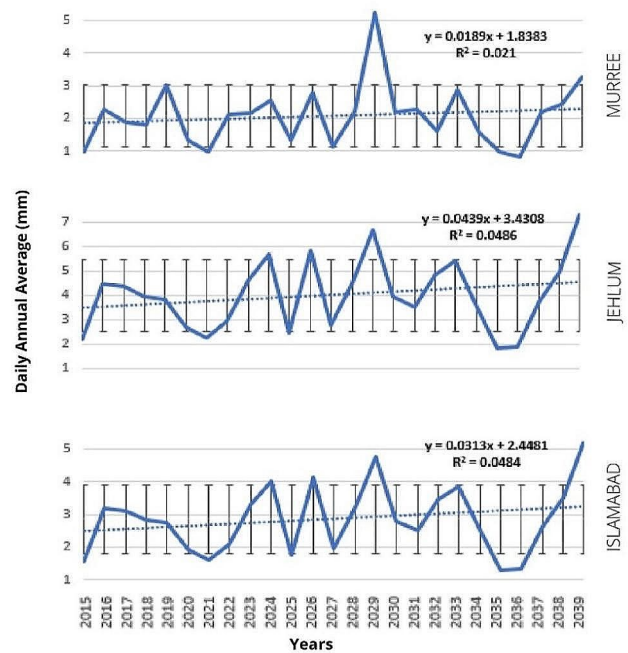


Fig. 6 Early century SSP2-4.5 CMIP6 projections for precipitation 'pr' under Japanese GCM MIROC6

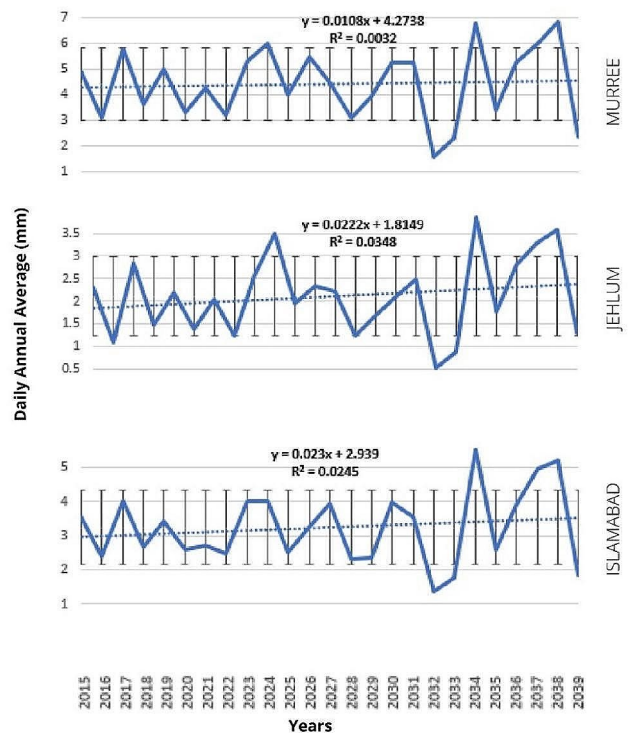


Fig. 7 Early century SSP2-4.5 CMIP6 projections for precipitation 'pr' under Norwegian GCM NorESM2-MM

continue to expand, these changes can alter local weather patterns, resulting in increased rainfall in some areas. While there is no definitive explanation for the slight increasing trend of rainfall in the Potwar region, it is likely that a combination of factors, such as changes in the hydrological cycle, atmospheric circulation patterns, and land use/land cover, are contributing to this trend.

It is also possible that selected GCMs may be showing a slight increasing trend of rainfall in the Potwar region may be due to capturing different aspects of regional climate variability than other models, as GCMs can capture various aspects of the climate system, including temperature and precipitation patterns, atmospheric circulation, oceanic circulation, and land surface processes etc. Another possibility is that there may be some variability in the response of the climate system to the SSP2-4.5 scenario across different regions and timescales. In conclusion, it's important to understand that these are model projections and there is still some uncertainty in the exact changes in rainfall that may occur in the region.

Air surface temperature (maximum)

Air surface temperature T_{max} is plotted for the early century using downscaled CMIP6 data of the SSP2-4.5 experiment. Figure 8 corresponds to the Russian global climate model (INM-CM5-0). Figures 9 and 10 also show the daily annual average of T_{max} like Fig. 8 but for Japanese (MIROC6) and Norwegian (NorESM2-MM) GCM respectively.

In Fig. 8, temperature change is observed as +0.5 °C over the time at two stations, except Jhelum, which is showing +0.25 °C change. It may be because of more transportation/movement in these cities i.e., Islamabad and Murree. As both stations are tourist spots. Islamabad and Rawalpindi both are so close that they make giant concrete structures which also enhances the greenhouse gases in the form of CO₂ emissions from concrete.

The temperature drops in recent years i.e., ~ 2020, is observed at all stations, which may be due to Covid-19, as human activity was restricted, and energy use was limited in all sectors including the transportation sector. Such temperature drops observed in recent years could have short-term impacts on local climate patterns and ecosystems. However, it is important to note that these temperature drops are likely temporary and do not necessarily indicate a long-term trend in global climate change.

The GCM INM-CM5-0 estimates that average increase in temperature by 2039, in case of tasmax will be about 0.3 °C based on daily annual average under SSP2-4.5 scenario.

In Fig. 9, MIROC6 depicts the peak in daily annual average temperature for the years 2034-37. It may be due

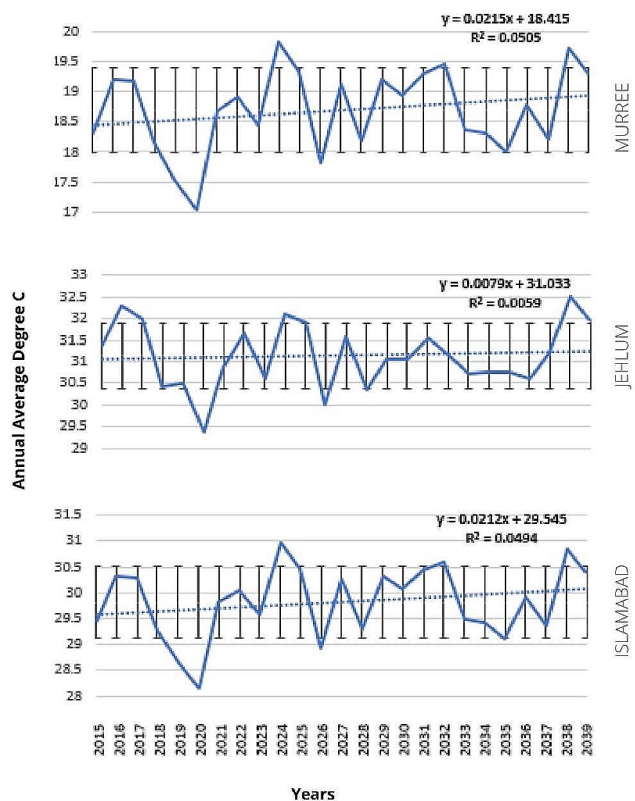


Fig. 8 Early century SSP2-4.5 CMIP6 projections for maximum temperature ‘T_{max}’ under Russian GCM INM-CM5-0

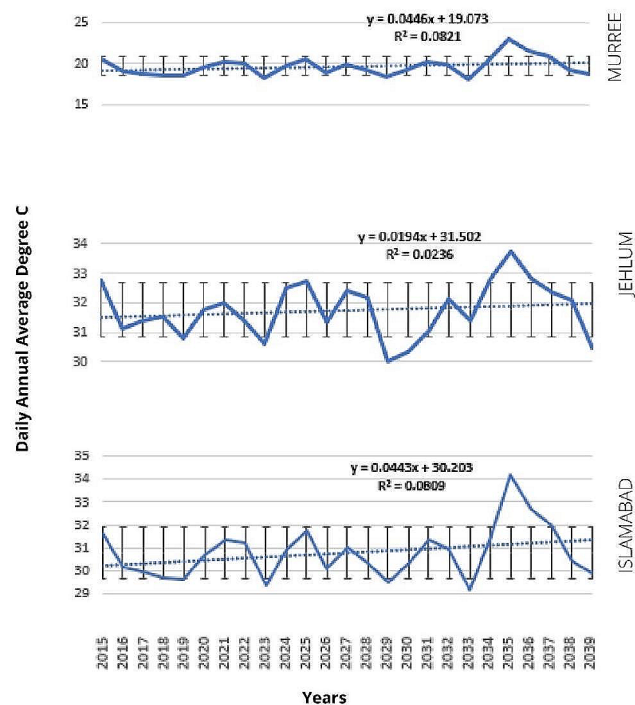
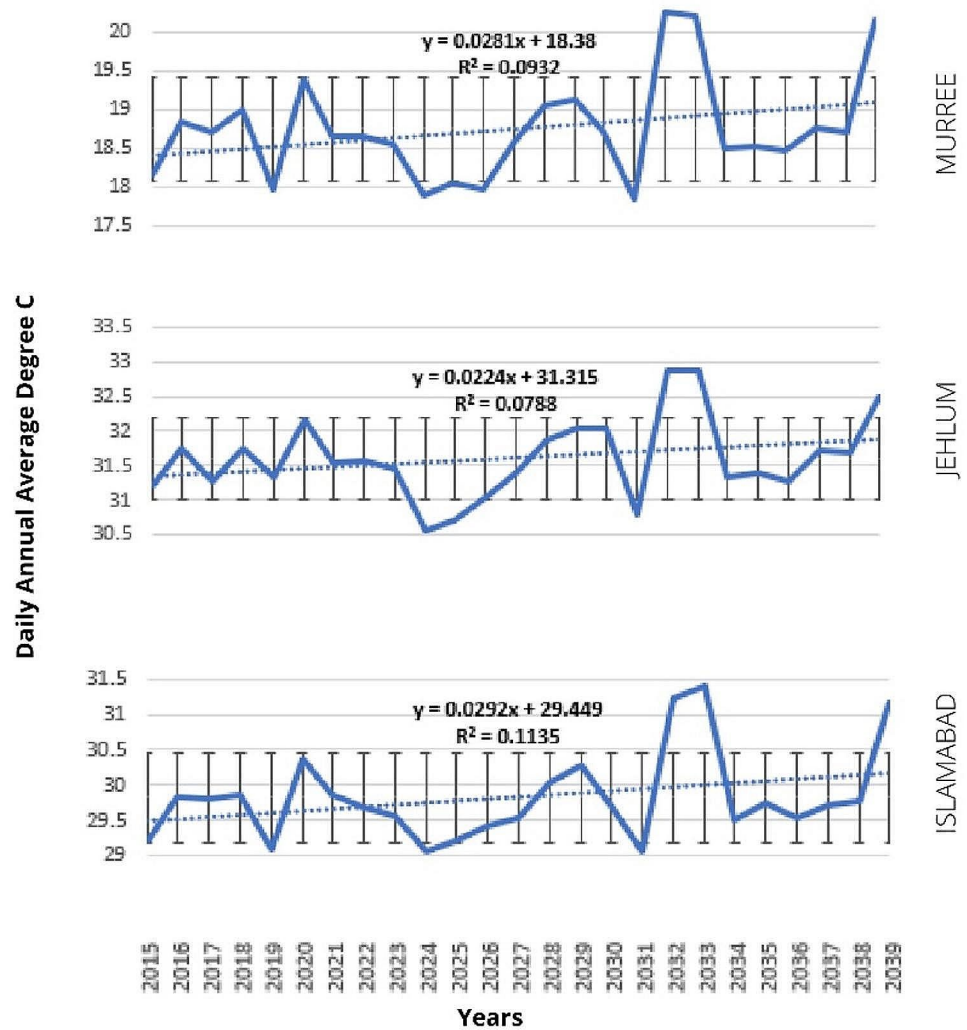


Fig. 9 Early century SSP2-4.5 CMIP6 projections for maximum temperature ‘T_{max}’ under Japanese GCM MIROC6

Fig. 10 Early century SSP2-4.5 CMIP6 projections for maximum temperature ‘Tasmax’ under Norwegian GCM NorESM2-MM



to several reasons. Droughts observed in preceding years i.e., 2032-33, in Fig. 7, under NorESM2-MM could be one of the possible reasons, resulting increase in temperature. However, possible reasons to increase in temperature are discussed in succeeding paragraphs. Here, it can also be correlated with Fig. 6 where droughts are reflected in these years (2034-37). Droughts observed in 2032-33 may result in less evaporation in these years and affect the rains in coming years i.e., drought period 2034-37. So, decrease in rainfall will ultimately increase the temperature. The daily annual average change in Tasmax under MIROC6 may be estimated as $+0.9^{\circ}\text{C}$.

In Fig. 10, peaks in daily annual average temperature are observed during the years 2032-33 which can also be correlated with droughts observed in these years, in Fig. 7, under same GCM i.e., NorESM2-MM. The same temperature peaks over these years i.e., 2032-33 are observed, for the same GCM, in the case of Tasmin also, shown in Fig. 13.

The estimated average increase for all stations under this GCM is $+0.6^{\circ}\text{C}$.

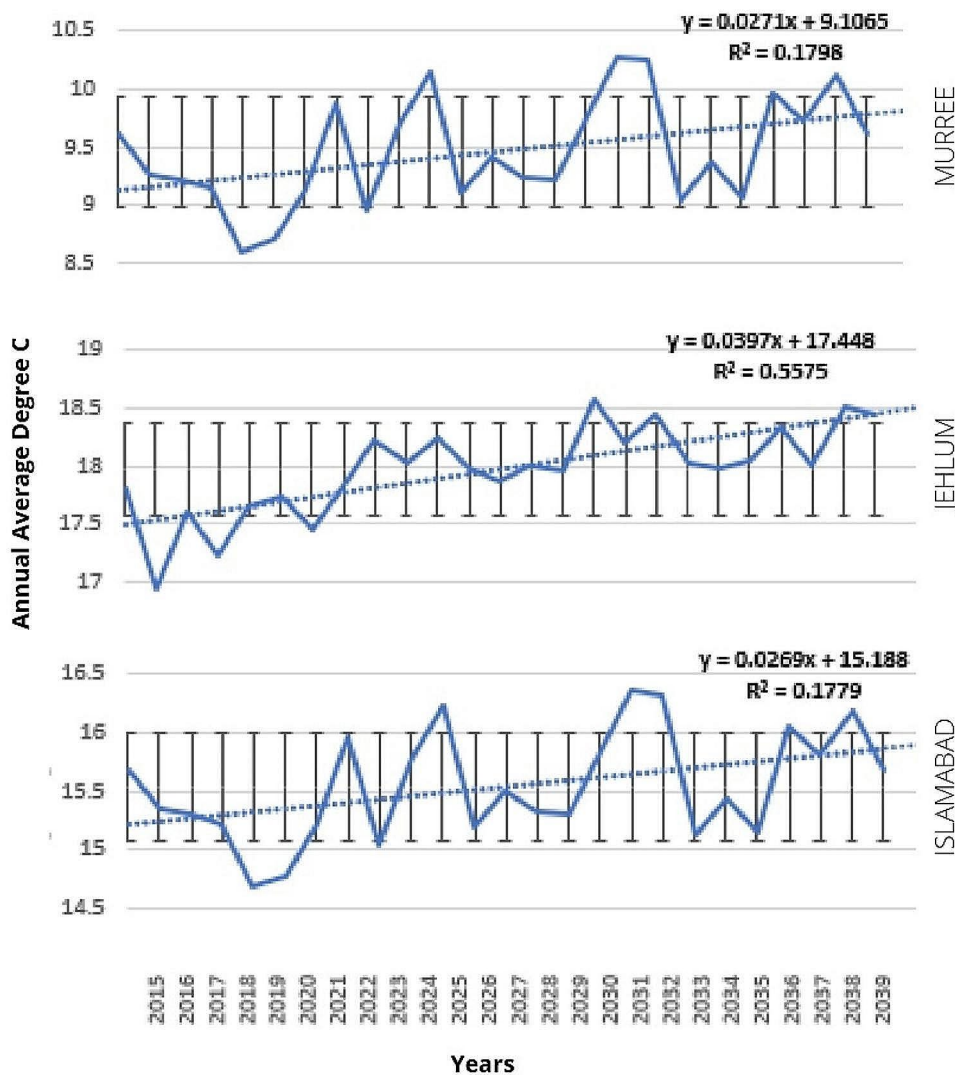
The ensemble mean change in Tasmax is estimated as 0.6°C which is expected in early century under socio-economic pathway SSP2-4.5.

Air surface temperature (minimum)

Air surface temperature Tasmin is also plotted for the early century using downscaled CMIP6 data of the SSP2-4.5 experiment. Figure 11 corresponds to the Russian global climate model (INM-CM5-0). Figures 12 and 13 also show the daily annual average of Tasmin like Fig. 11 but for Japanese (MIROC6) and Norwegian (NorESM2-MM) GCM respectively.

It is observed that air surface temperature (minimum) over time is increasing. The average increase by 2039 is estimated as 0.9°C for all stations in the case of INM-CM5-0, as shown in Fig. 11. Low temperature period is observed

Fig. 11 Early century SSP2-4.5 CMIP6 projections for minimum temperature ‘Tasmin’ under Rus-sain GCM INM-CM5-0



during Covid-19 period as it is also observed in the case of Tasmax under same GCM.

It is also observed that temperature drops for the years around 2034-36 under GCM INM-CM5-0. The observation is not only true for Tasmin but for Tasmax as well. The possible reason may include the higher rate of precipitation in the same years as the peaks are observed in Fig. 5 for the same GCM. During the years 2030-31 rise in temperatures is expected as obvious in the Fig. 11. The same is true in case of Tasmax. These periods are also showing less precipitation under same GCM.

In case of Tasmin under MIROC6, Fig. 12, the average temperature change for mentioned stations is +1 °C during the early century. Temperature with relatively higher values during the years 2034-37 is in line with the trend for Tasmax under the same GCM. The reasons, discussed in Tasmax under MIROC6 GCM, are possibly affecting the Tasmin.

also. These perturbations require special attention during studies corresponding to applied meteorology. As many processes depend upon one another resulting a very complex phenomenon, which can only be mitigated by some special adaptative strategies.

In Fig. 13, Norwegian GCM not only reflects temperature peaks for Tasmin but also has been observed in the case of Tasmax for the same years. The daily annual average mean rise is expected to be 0.4 °C. The ensemble value for Tasmin is estimated as 0.7 °C.

As mentioned in materials and methods, data and images provided by NOAA are also used for benchmarking and to further reinforce the results of this study. The coordinates used for Potwar region are 73.9E, 34.15 N, 71.1 W, 32.16 S at web portal of physical science laboratory (PSL) of NOAA. The anomaly in rainfall patterns (contours) and temperature (shading) is shown in Fig. 14, which is generated for GCM INM-CM5-0 as well as for GCM MIROC6.

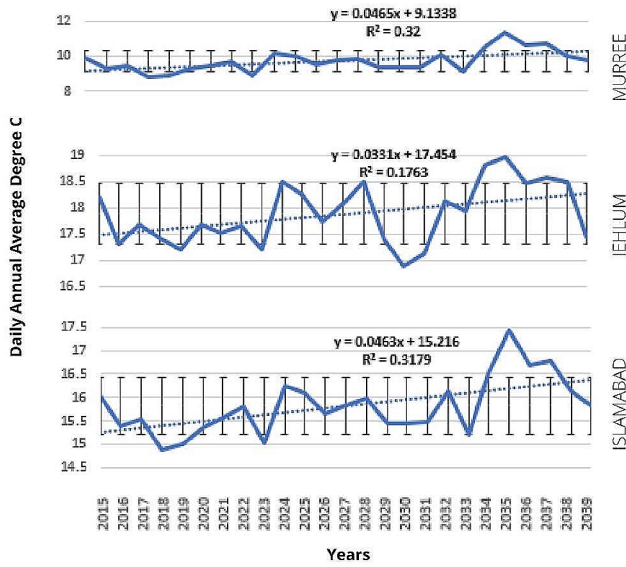
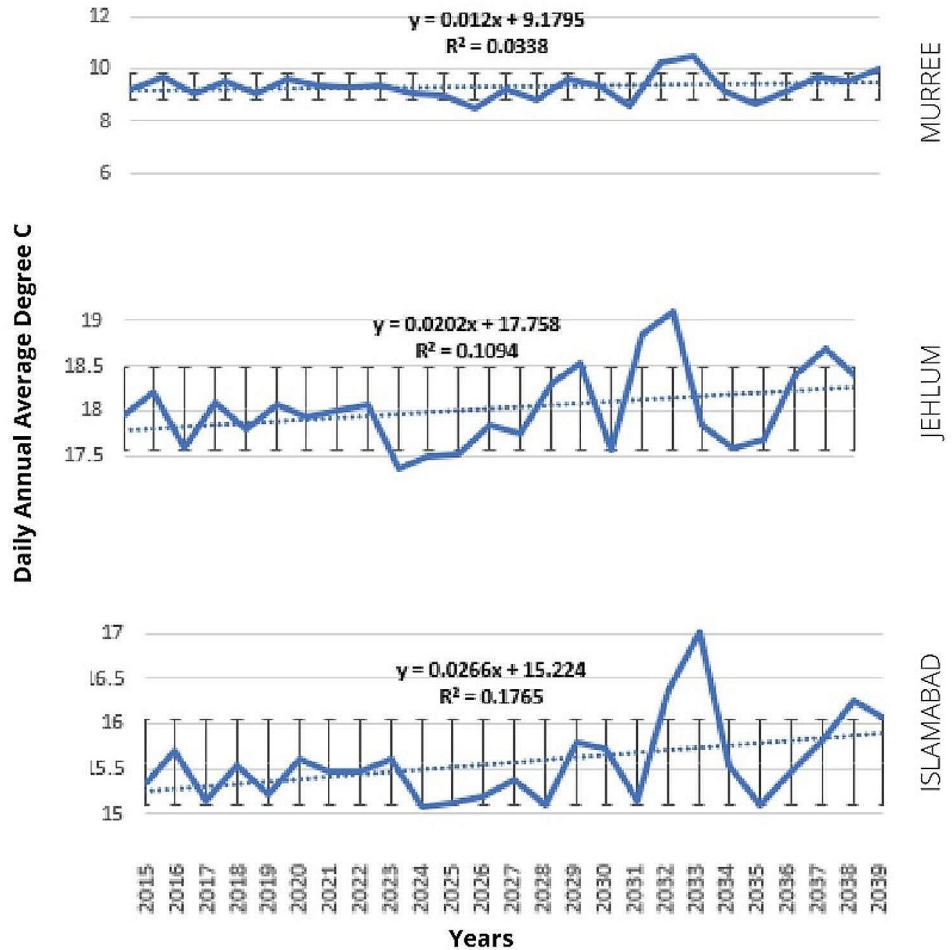


Fig. 12 Early century SSP2-4.5 CMIP6 projections for minimum temperature ‘Tasmin’ under Japanese GCM MIROC6

Fig. 13 Early century SSP2-4.5 CMIP6 projections for minimum temperature ‘Tasmin’ under Norwegian GCM NorESM2-MM



From this Figure it is evident that temperature rise and rainfall uncertainties are real in early century.

From Fig. 14 i.e., in case of MIROC6, Potwar region of Pakistan may experience a decrease in rainfall in the coming decades. On the other hand, anomaly under Russian model is showing increase in precipitation in some areas. There may be many reasons for this, but some possible reasons are discussed here to support the assessment made in this study.

The increase in temperature, which is evident from all previous Figures, due to climate change may cause increased evaporation and transpiration, leading to a decrease in available water in the region by reducing soil moisture and increase the risk of drought. Higher temperatures can also exacerbate the impacts of heatwaves and other extreme weather events, which can have negative impacts on agriculture and human health. A study by Hussain et al. (2019) found that in the Potwar region, there was a significant negative correlation between temperature and rainfall, suggesting that as temperature increases, rainfall tends to decrease.

Further to this, changes in atmospheric circulation patterns due to climate change can also affect rainfall patterns

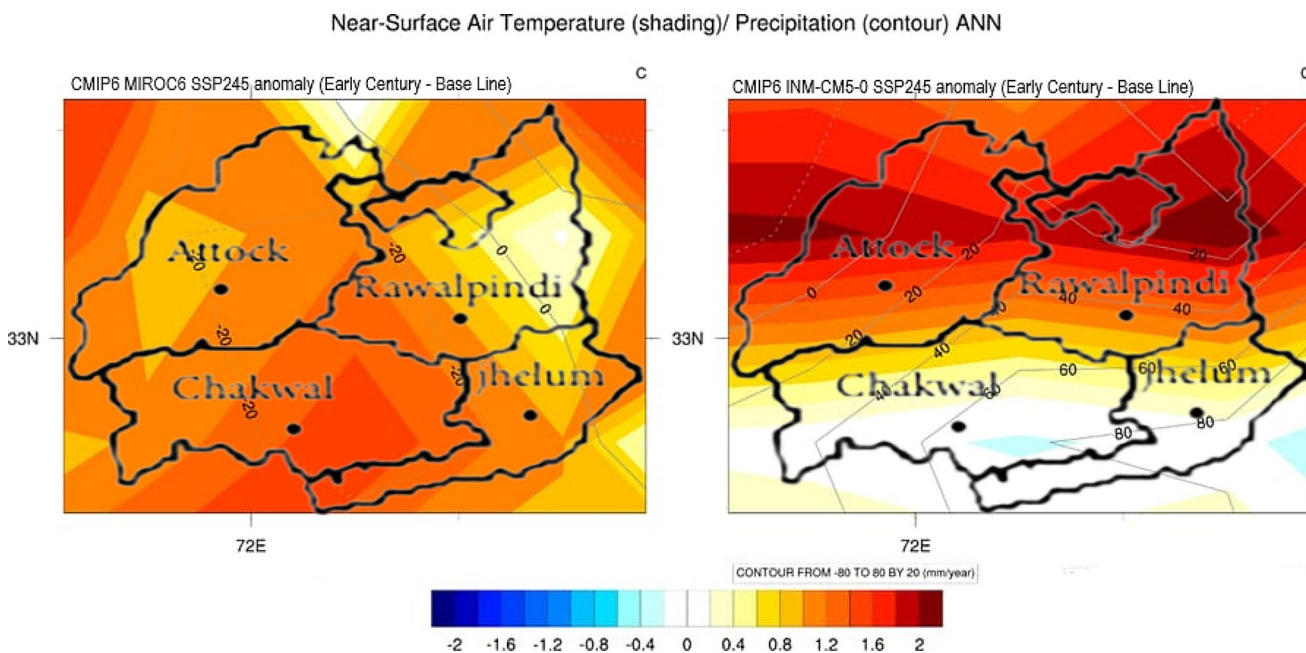


Fig. 14 Early Century CMIP6 SSP2-4.5 anomaly for Japanese (left) and Russian (right) GCMs by PSL NOAA

in the region. This decrease in rainfall could be linked to changes in the Indian Ocean Dipole (IOD) and El Niño-Southern Oscillation (ENSO) patterns, which are two major sources of interannual variability in regional rainfall. Studies have shown that a positive IOD phase is associated with below-normal rainfall in the Potwar region, while El Niño events can lead to above-normal rainfall. Under the SSP2-4.5 scenario, it's possible that these patterns may shift, resulting in a decrease in overall rainfall. Mahmood et al. (2019) states that the Potwar region of Pakistan may experience a decrease in summer monsoon rainfall due to changes in the Indian Ocean Dipole and El Niño Southern Oscillation.

Moreover, land-use change, such as deforestation and urbanization, can also affect rainfall patterns by altering the local climate. A study regarding land-use changes in the Potwar region by Ali et al. (2017) found that it has led to a decrease in rainfall, especially during the monsoon season.

As the increase in temperature is observed in this study, there may be several possible reasons for the temperature increase in the Potwar region including increased GHG emissions; urbanization, as the region is experiencing rapid urbanization, which could be contributing to the increase in temperature due to the urban heat island effect; land use change, as the region is undergoing land use change, with forests and natural vegetation being converted into agricultural and urban areas, which could be contributing to the increase in temperature; changes in atmospheric circulation patterns, such as increased frequency and intensity of heatwaves, could be contributing to the increase in temperature,

and; feedback loops, such as the loss of ice and snow cover in nearby mountain ranges, could be contributing to the increase in temperature by reducing the amount of sunlight reflected back into the space. It's important to note that these factors are not mutually exclusive and could be acting in combination to cause the temperature increase.

Effectiveness and efficiency of GCMs

To know about effective and efficient GCM for this study, station-wise Taylor diagrams are plotted and shown in Figs. 15 and 16, and 17 for Islamabad, Jhelum, and Murree stations respectively. In the case of temperature, the index of agreement in respect of all GCMs is good for all stations.

The Pearson correlation coefficient is not good in the case of precipitation. Somehow, the index of agreement is better for Murree and Islamabad stations, in the case of Norwegian GCM (NorESM2-MM), whereas for Jhelum, Russian GCM has shown better results.

Implications of climate change and detail forward for planning

As the results of this study demonstrate, projected changes in temperature and precipitation in the Potwar region that can have serious consequences for the region's climate and ecosystems. Therefore, we briefly discuss the expected impacts and the need for adaptive strategies.

The study predicts a temperature rise of 0.3 to 1.0 °Celsius in the Potwar region by 2039. Moreover, it is worth

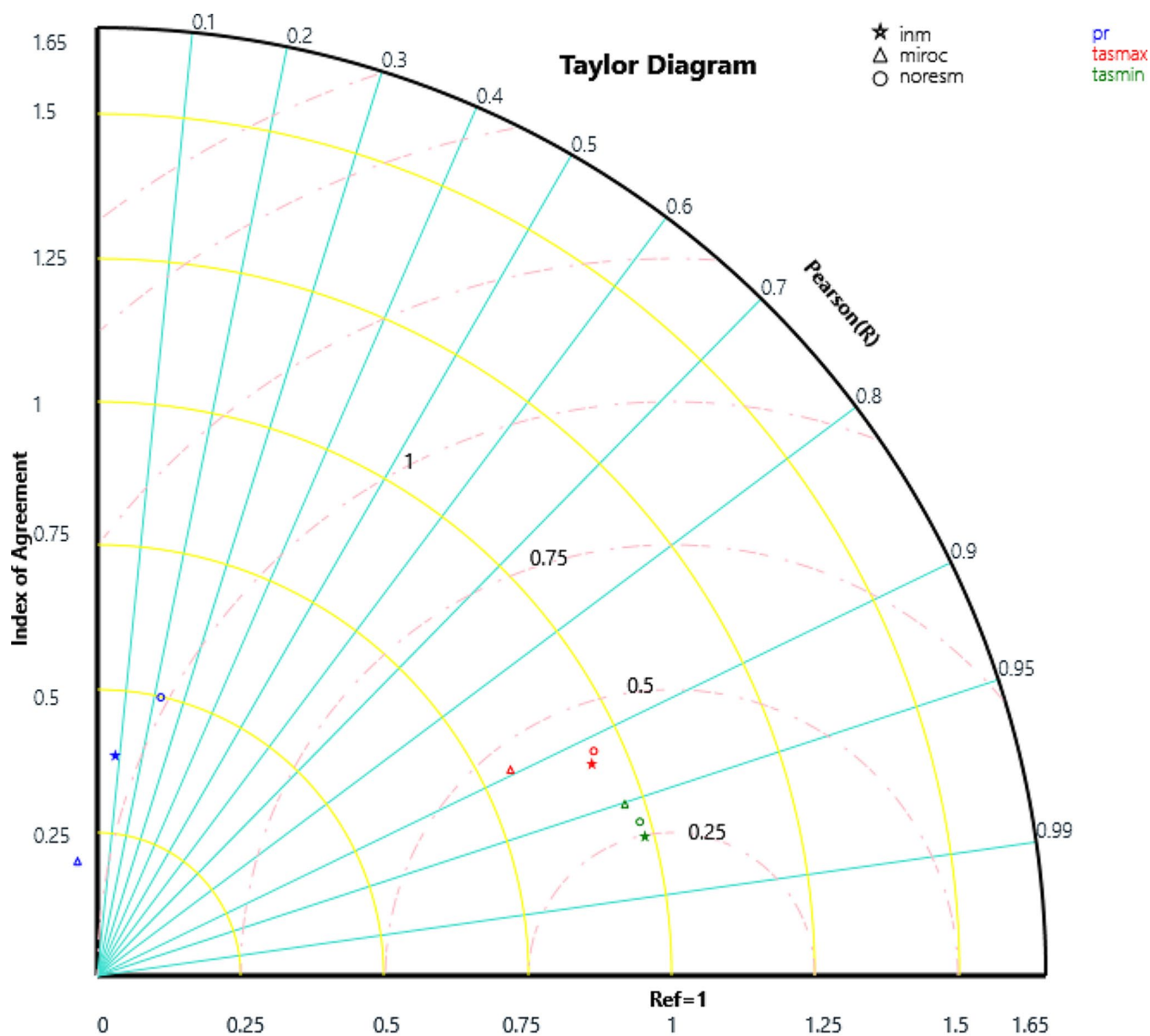


Fig. 15 Index of agreement among three GCMs (INM-CM5-0, MIROC6, and NorESM2-MM) for Islamabad station

noting that the temperature rises asymmetrically, with the Tasmin temperature rising significantly more than the Tasmax. This phenomenon can be attributed to a variety of factors, including changes in cloud cover, humidity, wind patterns and urbanization. Elevated levels of Tasmin may increase nighttime heat stress in humans and animals. This has direct implications for health and productivity, requiring adaptive measures and increased awareness to address potential adverse effects. In addition, energy demand for night-time cooling is expected to increase, highlighting the importance of energy-saving practices in mitigating global warming trends. Urban areas affected by the heat island effect have become the focus of implementing strategies to combat rising nighttime temperatures.

Also, the study highlights the uncertainty in predicting changes in average rainfall in the Potwar region. Expected changes and fluctuations in the timing and intensity of rainfall create challenges for water management, agriculture and overall ecosystem stability. The average rainfall change is estimated at +0.4 mm, indicating a slight increase, but this change introduces a layer of complexity. A careful understanding of how these changes affect local hydrological cycles, water availability, and ecosystem resilience is needed.

In light of these expected changes, the need for adaptation strategies and impact assessments becomes clear. The Potwar region must proactively deal with potential negative consequences associated with changes in temperature and

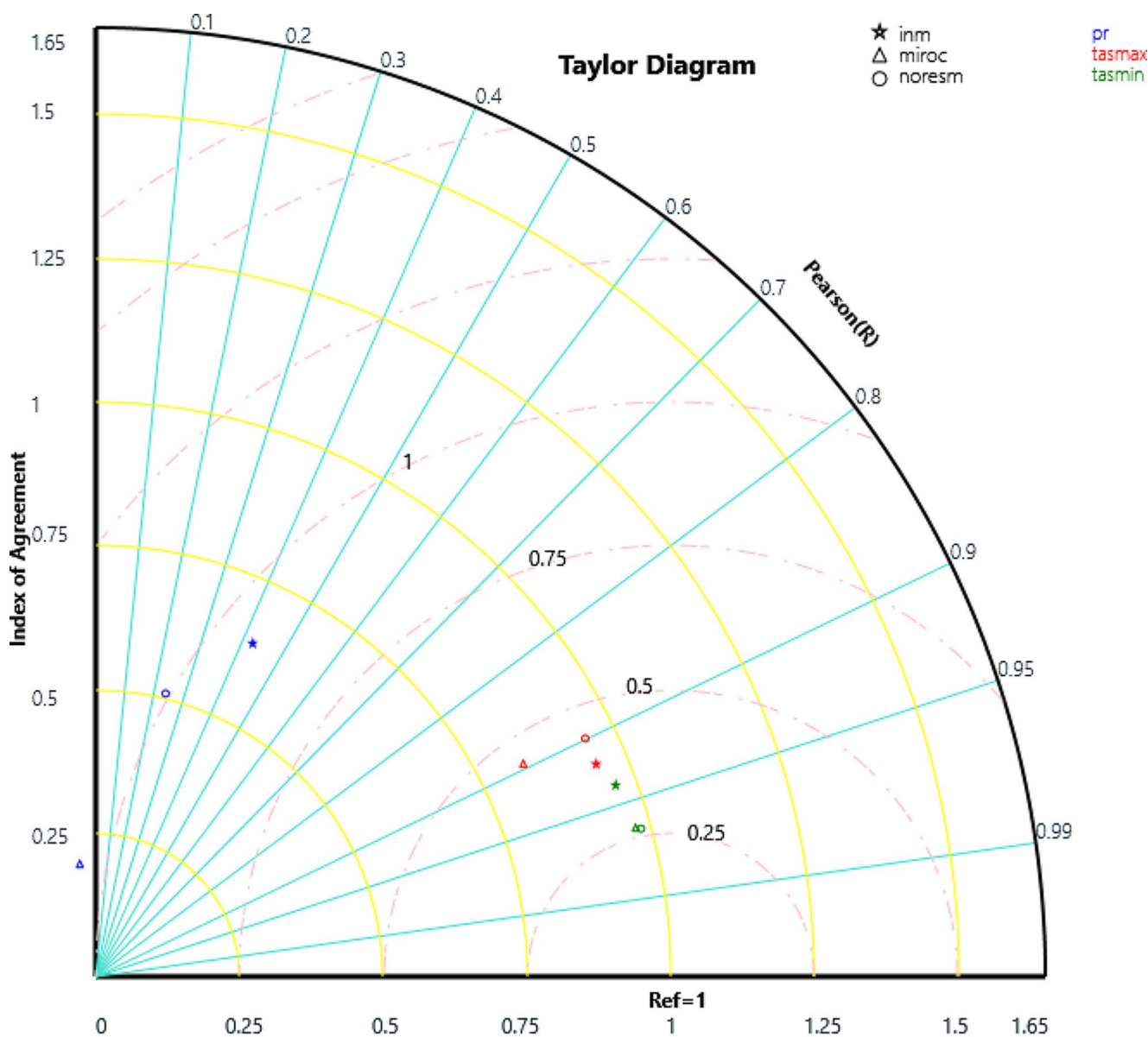


Fig. 16 Index of agreement among three GCMs (INM-CM5-0, MIROC6, and NorESM2-MM) for Jhelum station

precipitation. Adaptation measures may include developing sustainable water management practices, implementing heat stress mitigation strategies, and promoting energy saving technologies.

Furthermore, the results of this study can serve as a basis for impact assessment and development of adaptation strategies tailored to the nuances of the Potwar region. By gaining a comprehensive understanding of expected changes, stakeholders can work to increase the resilience of sectors such as agriculture, water supply and urban planning.

Overall, projected changes in temperature and precipitation highlight the urgent need to address the impacts of climate change in this region. This research is an important tool to guide informed decision-making and proactive

measures to promote a resilient and sustainable future for the region.

Conclusion

The Potwar region of Pakistan is expected to experience changes in its weather patterns by 2039. The study used CMIP6 moderate socio-economic pathway SSP2-4.5 scenario and in-situ data for the baseline period of 1981–2010. To conclude, this investigation can be summarized as follows;

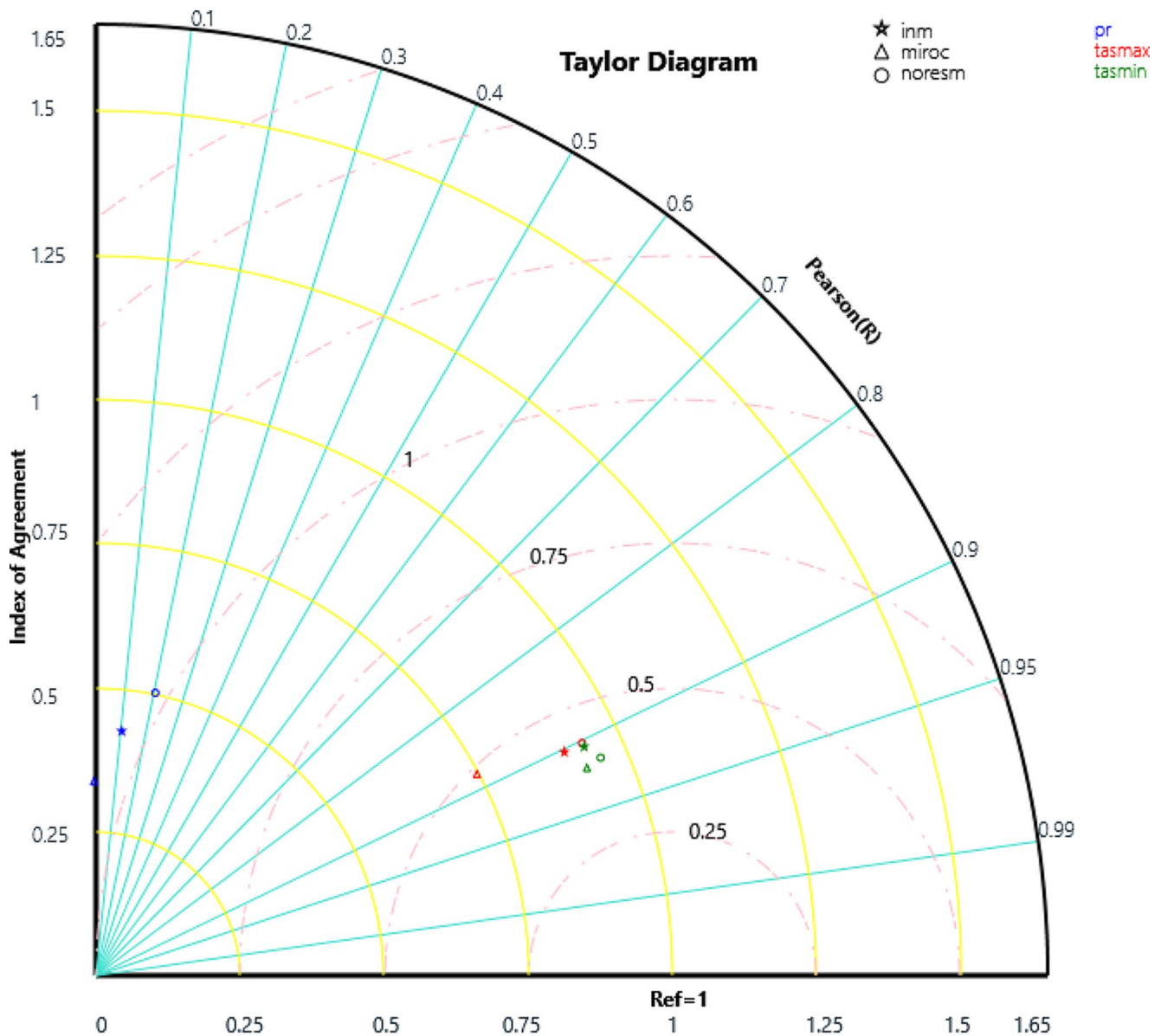


Fig. 17 Index of agreement among three GCMs (INM-CM5-0, MIROC6, and NorESM2-MM) for Murree station

- The study utilizes both in-situ data and outputs from three Global Climate Models (GCMs) - INM-CM5-0, MIROC6, and NorESM2-MM - under the CMIP6 project to examine future climate scenarios for the Potwar region of Pakistan.
- The CMIP6 data is downscaled using SD-GCM (delta method) for specific stations in the region, namely Islamabad, Murree, and Jhelum.
- The study assesses the change in future climate in the Potwar region by 2039, focusing on temperature rise and rainfall patterns.
- The expected temperature rise ranges from 0.3 to 1.0 °C, with an average change of +0.6 °C in Tasmax and +0.7 °C in Tasmin for the Potwar region.
- The impact on rainfall average is uncertain, with more variability and changes in the timing and intensity of rainfall events. The ensemble mean value for rainfall change is estimated as +0.4 mm.
- The research aims to provide a basis for impact assessment and the development of adaptive strategies to mitigate the potential adverse effects of climate change in the Potwar region.

The projected temperature and rainfall changes highlight the need for adaptive strategies and impact assessments to mitigate the potential negative consequences and develop sustainable approaches for the Potwar region.

Navigating the next steps

Future research could explore the broader spatial extent and assess the regional variability of climate by considering following;

- Other climate variables and their interactions could also be considered to provide a more comprehensive understanding of climate change impacts.
- Incorporating socio-economic factors and their influence on climate change vulnerability and adaptation strategies could enhance the practical implications.
- Long-term monitoring and data collection efforts are crucial to validate and refine the model projections and improve the accuracy of future climate predictions.
- Collaborative research efforts and interdisciplinary approaches can further enhance the understanding of climate change impacts and facilitate the development of effective mitigation and adaptation strategies for the region.

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Author contributions Interest in studying climate and environment led the authors to conduct this research. M.T. prepared the methodology and wrote the original manuscript. H.B. helped with the computational part.

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Data availability The data used for this study is open-source data and it is available at climate data store of Copernicus <https://cds.climate.copernicus.eu/>.

Declarations

Competing interests The authors declare no competing interests.

Conflicts of interest/Competing interests Authors have no competing interests as defined by Springer, or other interests that might be perceived to influence the results and/or discussion reported in this paper.

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