Pak. J. Engg. Appl. Sci. Vol. 33 July, 2025 (p. 50–69)

CMIP6-Based Climate Projections and Trends for Exploring Adaptations and Policies in Pakistan

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Abstract

Pakistan is largely dependent on agriculture; climate change induces considerable complexities for its anthropogenic systems, requiring detailed climate projections at fine spatio-temporal scales. This study employs bias-corrected daily climate data based on 13 CMIP6 General Circulation Models (GCMs), which were validated against CRU TS4. 03 datasets to comparatively assess past and projected climate conditions among SSP245 and SSP585 pathways. For two cropping season (Rabi, and Kharif) temperature and precipitation trends were investigated for Pakistan's main agricultural provinces, Punjab and Sindh. Mann-Kendall and Sen's slope tests were employed to investigate temperature and precipitation variations over time and space. Our CMIP6 based results reproduces reliable historical data both spatially and temporally, supporting its use in regional climate impact studies. At national scale, Tmin increase more than Tmax. In SSP585, Tmin is projected to increase by 5.22°C, while Tmax is expected to rise by 4.02°C, by 2100. Precipitation too has a more or less steady upward trend by 28% and 53% under SSP245 and SSP585, respectively. Summer and winter temperatures increase strongly in Punjab. Tmin is likely to rise between 1.6°C–4.8°C by 2100 across the different scenarios. Summer precipitation rises moderately under SSP245 at around 20–40% and increases steeply up to 100% under SSP585. In Sindh, both summer and winter temperature increases follow similar trends; summer Tmax can reach up to 4°C in SSP585. Precipitation in Sindh may increase as much as 187% during the summer season in late century. Under SSP585, projections of increasing temperatures indicate growing trends of heat stress across Pakistan, which is impactful for agricultural productivity and water resource management. The research highlights Punjab's increased temperature variability from interactions with westerly systems and Sindh's steady rise in warming, associated with enhanced monsoons. These findings underscore the importance of high-resolution climate models in formulating evidence-based adaptation plans. Major recommendations encompass heat-resilient crop species, improved irrigation infrastructure, and early warning systems. These are critical measures to protect food security and threats from climate change to Pakistan's agriculture and water sectors.

Keywords: Climate projections; temperature trends; precipitation variability; agricultural adaptation; spatio-temporal analysis

1. Introduction

Climate change poses profound challenges to agriculture and water resources, particularly in countries like Pakistan, where these sectors are deeply intertwined with the national economy and livelihoods [1]. Pakistan's reliance on climate-sensitive cropping seasons, Kharif (summer) and Rabi (winter), renders it vulnerable to changing temperature and precipitation patterns. Punjab and Sindh, as the major wheat- and rice-producing provinces, are at the heart of the nation's food security. Understanding climate change impacts at a high spatial and temporal resolution is critical for effective adaptation and policy planning to mitigate risks associated with rising temperatures, altered precipitation patterns, and increasing frequency of extreme weather events. Punjab, known as the "breadbasket of Pakistan," produces over 75% of the country's wheat and rice, ensuring a steady supply of staple crops for domestic consumption and export. Sindh contributes significantly to rice production, second only to Punjab, while also being a major source of sugarcane and cotton. Both provinces are heavily dependent on the Indus River system for irrigation, making them particularly vulnerable to climatic variability and water scarcity. Changes in temperature and precipitation patterns, such as increased heat stress during the Rabi season or reduced rainfall in Kharif, can significantly disrupt crop yields and compromise water resource availability. Recent studies highlight that climate-driven changes in hydrology and agricultural productivity are already evident, with far-reaching implications for food security [2], [3][4], [5]. Thus, understanding regional climate dynamics is crucial for safeguarding the agricultural productivity and water security of these provinces, which are linchpins of the national economy.

This study aims to generate high-resolution climate projections for Pakistan using bias-corrected data from 13 General Circulation Models (GCMs) of the CMIP6 framework focusing Tmin, Tmax, Tmean, and precipitation gradients across the country, with detailed analyses for Punjab and Sindh. These provinces are crucial to Pakistan's food security, contributing significantly to the production of staple crops like wheat and rice. Seasonal and annual climate trends are assessed under SSP245 and SSP585 socioeconomic pathways for historical (1974–2014) and future (2020–2060 and 2061–2100) periods. High-resolution projections provide a robust foundation for assessing localized climate impacts, offering actionable insights into agricultural risks, water resource challenges, and regional vulnerabilities.

The significance of high-resolution climate projections lies in their ability to capture fine-scale spatial and temporal variations that are often obscured in coarser datasets [6]. These projections are particularly important for regions like Pakistan, where diverse topographies and microclimates amplify localized climate impacts. Studies have demonstrated that finer-scale models improve the accuracy of impact assessments for agriculture, water resources, and public health [7]–[9]. Moreover, they enhance our understanding of how regional climate responses differ within a broader national context, informing more effective adaptation strategies.

The integration of Representative Concentration Pathways (RCPs) and Shared Socioeconomic Pathways (SSPs) in climate modeling further strengthens the applicability of these projections for policy development. RCPs account for varying levels of greenhouse gas emissions, while SSPs incorporate socioeconomic trends such as population growth, urbanization, and economic development, providing a multidimensional framework for scenario analysis. Recent advancements in bias correction techniques have significantly improved the reliability of GCM outputs for regional studies [10], [11].

In Pakistan, high-resolution projections have revealed critical vulnerabilities, including increasing heat stress, declining water availability, and heightened risks to crop yields under high-emission scenarios [4], [12]. The study examines the impacts of climate change on wheat and rice production in Punjab and Sindh, offering a scientific foundation for region-specific adaptation strategies to enhance agricultural resilience and safeguard food and water resources.

This study provides CMIP6 projections to analyze future climatic variations across Pakistan, providing actionable insights for impact assessments, adaptation strategies, and policy guidelines. It emphasizes adaptive governance, resource management, and forward-looking policies to mitigate climate risks and ensure sustainable development.

2. Materials and Methods

2.1 Study area

Pakistan's geography is characterized by three major zones: the northern highlands, the Indus River plain, and the Balochistan Plateau. Among these, the Indus River plain, encompassing the Punjab and Sindh provinces, forms the backbone of the country's agriculture and food production.

This study focuses on assessing spatial precipitation and temperature gradients and estimating future seasonal climate changes from the northern highlands to the southern plains of Pakistan. (Fig1). Particular attention is given to Punjab and Sindh provinces, which are critical contributors to Pakistan's food security due to their significant agricultural productivity.

Punjab province lies between 27°N to 34°N latitude and 69°E to 75°E longitude. The climate in central and southern Punjab is predominantly dry semi-arid agro-climatic. Punjab is the largest wheat-producing region in Pakistan, contributing approximately 75% of the nation's total wheat production. Additionally, the province accounts for over 50% of the country's total agricultural output. Based on geographical boundaries, water availability, and cropping patterns, Punjab is divided into four regions: Northern, Central, Southern, and Western [13]. The Northern region, being mountainous, has limited cultivable land, whereas the Central, Southern, and Western regions comprise the fertile plains that support extensive agricultural activity.

Sindh is the third-largest province of Pakistan, geographically stretching about 579 km from north to south and averaging 281 km from east to west. The Thar Desert in the east, the Kirthar Mountains in the west, and the Arabian Sea to the south border it. The central area features a fertile

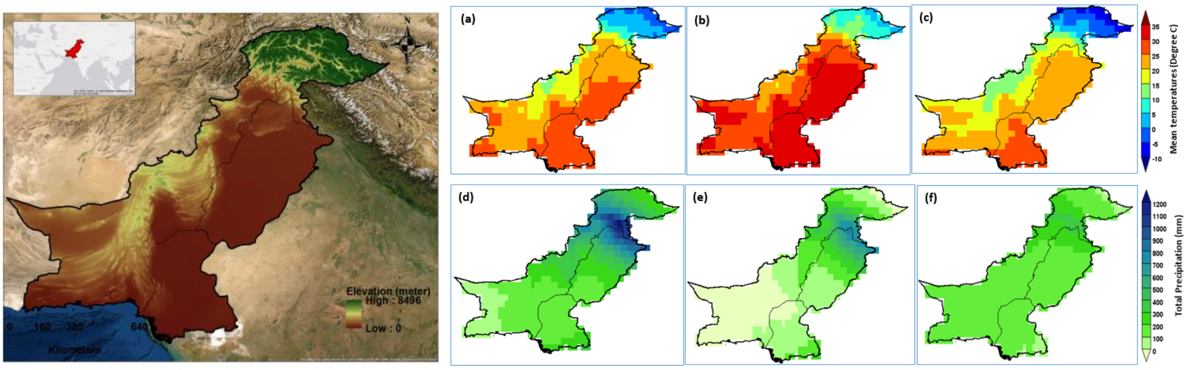

Fig 1: The geographical map of the study area (61–78◦ E and 23–37.5◦ N) shows the elevation (m) of the whole country with the two major crop-producing provinces of Pakistan i.e., Punjab and Sind in the first panel. Lower panels show the mean temperature (Degree C) and total precipitation (mm) at Annual (January – December) (a, d), summer (April – September) (b, e) and winter (October – March) (c, f) scale during control period 1974–2014. The spatial maps have been prepared using temperature and precipitation climatology computed using the re-gridded CRU datasets for the period 1974-2014

plain irrigated by the Indus River. Sindh ranks second in wheat production nationally, with cultivated areas in lower Sindh benefiting from the irrigated plains and fertile alluvial soils deposited by the Indus River.

Pakistan's diverse physiographic features and elevation variations result in significant differences in temperature and precipitation regimes from north to south. Punjab's annual mean temperature ranges from −2°C to 45°C, with summer peaks reaching up to 50°C and winter lows dropping to −10°C. Sindh experiences even more extreme temperatures, with highs frequently exceeding 46°C between May and August and minimum average temperatures of around 2°C during winter. These climatic conditions significantly influence provincial agriculture, underscoring the importance of analyzing future climate trends for adaptive planning.

2.2 Data Acquisition

The CMIP6 framework, an advanced iteration of the previous CMIP5, has been developed to address the growing needs of the scientific community, enhancing several of the shortcomings identified in its predecessor [14]. Recently, CMIP6 General Circulation Models (GCMs) have become integral to climate research worldwide. In this study, we utilized historical (1974–2014) and future (2020–2100) simulations from the latest CMIP6 dataset to assess future drought conditions in South Asia. Specifically, the study analyzes monthly climatological parameters including precipitation, maximum temperature, and minimum temperature for the periods 1974–2014 and 2020–2100.

To ensure comprehensive data coverage, 13 GCMs from the CMIP6 archive were selected (as shown in Table 1). These 13 models are the only ones that currently provide all the necessary parameters across four common SSP-RCP scenarios: SSP1-2.6 (low emission, low societal vulnerability), SSP2-4.5 (intermediate emission, intermediate societal vulnerability), SSP3-7.0 (high societal vulnerability, medium-to-high emissions), and SSP5-8.5 (high emissions with high mitigation but low adaptation challenges) [15]. These scenarios are used to project different levels of climate change and vulnerability across the region.

For this study, we utilized daily climate data, including precipitation, maximum, and minimum temperatures at a 0.25° spatial resolution, for both historical (1951–2014) and future (2015–2100) periods over Pakistan, as provided by Mishra et al. (2020). The mean temperature was calculated as the average of the maximum and minimum temperatures. Bias-corrected, downscaled datasets from 13 GCMs of CMIP6 were used for two emission scenarios, SSP245 and SSP585 (Table 1). The daily bias-corrected data were downloaded in compressed format from Zenodo (https://doi.org/10.5281/zenodo.3987736, 2020), and subsequently converted from compressed to gridded format using the R tool.

The Multi-Model Ensemble Mean (MMEM) was then created by averaging the data from the 13 GCMs for annual (January–December) and seasonal (summer: April–September, winter: October–March) periods. The resulting bias-corrected projections from CMIP6-GCMs provide a valuable tool for climate change impact assessments in South Asia and hydrological studies of sub-continental river basins.

The study combines quantitative projections of socio-economic and emission data to estimate climate changes across various spatial and temporal scales. To estimate accurate future climate projections and trends using GCM's data, firstly the GCMs' capability in reproducing climatological variables during the control period is tested which provides a confident basis for future climate projections [16].

The monthly mean observational data of temperature (maximum, minimum) and precipitation from the Climate Research Unit (CRU TS 4.03) has been used in the study data to analyze climatology over Pakistan at Annual and seasonal scales as presented in Fig 2. The CRU datasets is used to estimate CMIP6 GCM models' performance during the base period (1974-2014) [12], [17]. The CRU data has been widely used by the scientific community to evaluate the GCM's performance globally [12][18].

Table 1: Bias-corrected, downscaled datasets from 13 GCMs of CMIP6 for two emission scenarios, SSP245 and SSP585

S. No.	CMIP6 Model name	Institute	Model's raw Spatial resolution Lat X Long (degree)	Re-gridded resolution used Lat X Long (degree)	Temporal resolution	Ref.
1	ACCESS-CM2	Commonwealth Scientific and Industrial Research Organization (CSIRO) and ACCESS (Australian Research Council Centre of Excellence for Climate System Science, Australia	1.25 X 1.875	0.25 x 0.25	Daily	[19]Mishra V., et al., (2020)
2	ACCESS-ESM1-5	Commonwealth Scientific and Industrial Research Organization (CSIRO) and ACCESS (Australian Research Council Centre of Excellence for Climate System Science, Australia	1.25 X 1.875	0.25 x 0.25	Daily	[19]
3	BCC-CSM2-MR	Beijing Climate Center, China Meteorological Administration (BCC)	1.1215 X 1.125	0.25 x 0.25	Daily	[19]
4	CanESM5	Canadian Centre for Climate Modelling and Analysis (CCCMA), Victoria, Canada	2.7906 X 2.8125	0.25 x 0.25	Daily	[19]
5	EC-Earth3	EC-Earth Consortium (EC), Europe	0.7018 X 0.703125	0.25 x 0.25	Daily	[19]
6	EC-Earth3-Veg	European Consortium (EC), Europe	0.7018 X 0.703125	0.25 x 0.25	Daily	[19]
7	INM-CM4-8	Institute for Numerical Mathematics, Russian Academy of Science, Russia	1.5 X 2	0.25 x 0.25	Daily	[19]
8	INM-CM5-0	Institute of Numerical Mathematics of the Russian Academy of Sciences	1.5 X 2	0.25 x 0.25	Daily	[19]
9	MPI-ESM1-2-HR	Max Planck Institute for Meteorology (MPI-M), Germany	0.9351 X 0.9375	0.25 x 0.25	Daily	[19]

10	MPI-ESM1-2-LR	Max Planck Institute for Meteorology (MPI-M), Germany	1.8653 X 1.875	0.25 x 0.25	Daily	[19]
11	MRI-ESM2-0	Meteorological Research Institute, Ibaraki, Japan	1.1215 X 1.125	0.25 x 0.25	Daily	[19]
12	NorESM2-LM	Norwegian Climate Service Centre, Norway	1.8947 X 2.5	0.25 x 0.25	Daily	[19]
13	NorESM2-MM	Norwegian Climate Service Centre, Norway	0.9424 X 1.25	0.25 x 0.25	Daily	[19]

3. Analysis

To estimate the CMIP6 models performance over whole Pakistan during the historical period (1951–2014) against the CRU datasets, we used Taylor diagram (Fig 2). The Taylor diagrams provide a graphical representation of how closely models data resemble the observation both spatially and temporally [20]. The model reliability skills are quantified in terms of their correlation with observations, their centered root mean square (RMS) difference and the standard deviation. The Taylor analysis is broadly known by the scientists and researchers to reproduce the base period climatology for carrying out future analysis with more confidence [16][21]. The CMIP6 models performance against observation data have been computed by estimating the root mean square error (RMSE), and correlation coefficient (r).

$$r\,(O, M) = \frac{\sum_{k=1}^{n}(O_i - \overline{O_i}) \times (M_i - \overline{M_i})}{\sqrt{\sum_{i=1}^{n}(O_i - \overline{O_i}))^2 \times \sum_{k=1}^{n}(M_i - \overline{M_i}))^2}}$$

$$RMSE = \sqrt{\frac{1}{n}\sum\nolimits_{k=1}^{n}(M_i - O_i)^2}$$

Where M is CMIP6 model and O is observational values, i refer to observational and modelled data where n is the length of data.

In order to estimate spatial and temporal trends in the climate data, the Modified Mann-Kendall (MMK) trend and Sen's Slope test is applied. The Mann Kendall trend estimator is a non-parametric statistical test [22], [23] widely used to estimate the monotonic trends of time series with unknown distribution of the data as it is less sensitive to outliers and missing values in data [24]–[26]. The magnitude of the trend was estimated using a non-parametric Theil−Sen's (TS) slope method [27]. Trend test statics S is defined as:

$$S = \sum_{i=1}^{n-1}\sum_{j=i+1}^{n} sgn(x_j - x_i)$$

where x1, x2...xn represent n data points, xj represents the data point at jth time. Positive S indicates an increasing trend while low S value exhibits decreasing trends, i.e.:

$$sgn(x_j - x_i) = \begin{Bmatrix} for\ (x_j - x_i) > 0 \\ for(x_j - x_i) = 0 \\ for(x_j - x_i) < 0 \end{Bmatrix}$$

where xj and xi represent the time series observations, and n is length of the time series. The statistical significance of the trends i.e. the probability (p-value) associated with the Mann-Kendall statistics was estimated at three different significance levels i.e. $p < 0.001$ or 99.9% confidence level (***), $p < 0.01$ or 99% confidence level (**), $p < 0.05$ or 95% confidence level (*).

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This study uses bias-corrected downscaled CMIP6 data from 13 GCMs, evaluated against observational data at basin, country, and annual scales. [19]. Considering our study objective, we

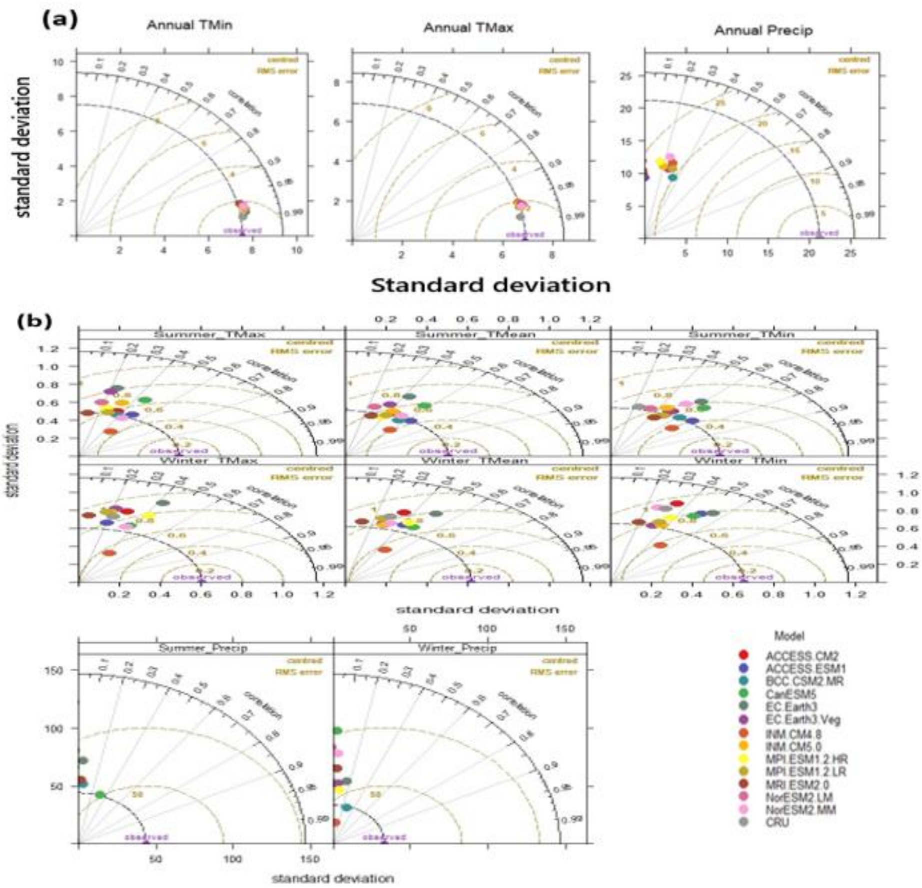

Fig 2 (a) Taylor diagrams of Mean Annual Temperature minimum (Degree C), Mean Annual Temperature maximum (Degree C) and Annual Total Precipitation (mm). (b) Taylor diagram of Tmax, Tmean, Tmin and precip during summer and winter seasons against observational climate data from the Climate Research Unit (CRU) across whole Pakistan for the period of 1951–2014.

have tested the CMIP6 models' skills to reproduce the historical climatology (1951-2014) at seasonal scale over Pakistan against the CRU observations.

The Taylor Diagrams [20] are used for the qualitative analysis of temperature and precipitation, to investigate the inter-annual variations in correlation, standard deviation and RMSE of the observation data and CMIP6 model over whole Pakistan at seasonal (i.e., summer and winter) scale for the period 1974–2014. The Taylor diagram shows the CMIP6 model skills to reproduce the historical climatology over Pakistan against observation at seasonal scale. Fig 2 sows the correlation coefficient, RMS difference and the standard deviation of the seasonal maximum, minimum temperature and precipitation with respect to the CRU data. All GCM's temperatures show strong significant correlation with CRU temperature both for summer and winter season with the highest correlation of 0.98 multi-model ensemble (MME) with observation. All CMIP6 models including MME are able to capture the spatial variability to a good extent as evident from their closer standard deviations to that of CRU. However, in the case of seasonal precipitation comparison, all models show poor performance by estimating smaller correlations, higher RMSE and standard deviation values with respect to the observation data.

4. Results

Our result section will be mainly focusing on estimating the Temperature and Precipitation Climatology over Pakistan and at province level. Here we presented some spatial maps which shows temperature and precipitation gradients in the country. Next, we showed projected changes in temperature and precipitation. Then maps of biases in climate data at different spatial and temporal scale at annual and seasonal scales are presented.

4.1 Temperature and Precipitation Projections over Pakistan

Fig 3 shows the projected changes (2020 – 2100) in maximum, minimum, mean temperatures (degree C) and precipitation (%) over whole

Pakistan under two emission scenarios i.e., SSP245 and SSp585 in continuation of historical period starting from 1951.

Long-term climate projections show that under both emissions scenarios (i.e., SSP2 and SSP5) revealed a strong and continuous increase in the temperature (maximum, minimum, and mean) and precipitation at annual scale over whole Pakistan for the period (1951-2100). The largest increase in both temperature and precipitation projections are associated with the high-emission scenario (SSP585). In case of temperature, all of three temperature variable projections show large divergence after 2050's mainly associates with the projected increase in radiative forcing and socio-economic factors. There is large spread in the warming of individual models as revealed from the uncertainty range of the measurement spread.

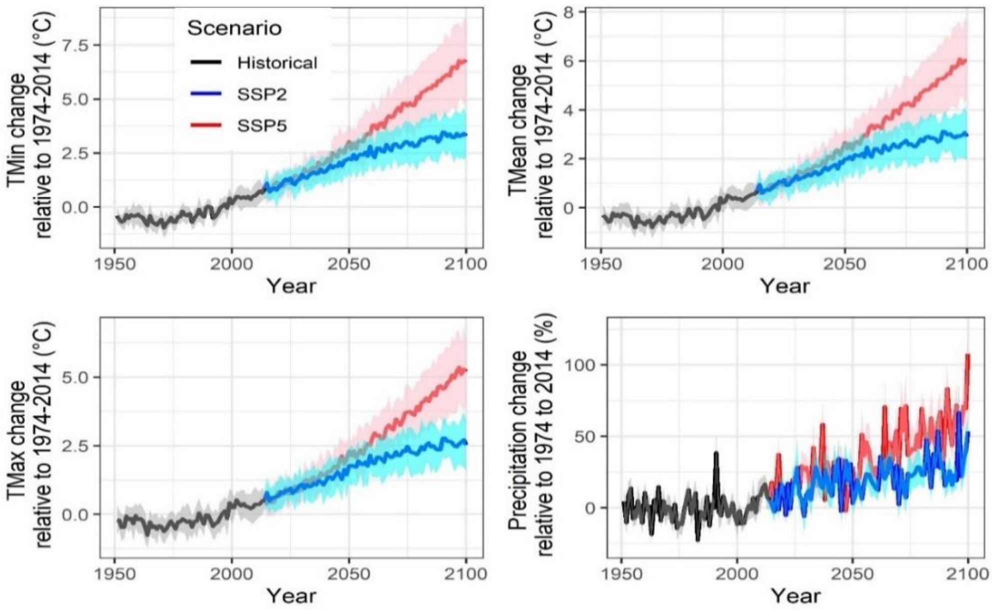

Fig 3 shows the long-term trends, inter-annual variations and uncertainty range of the 13 GCM's CMIP6 models data along with multi-model ensemble mean (MMEM). The climate data of temperature and precipitation has been plotted at annual scale over whole Pakistan using two selected emission scenarios for period (1951 -2100). The MMEM data is plotted with the dark lines (i.e., black during control period (1974 -2014) and blue (SSP245) and red (SSP585) line for future period (2020 – 2100). The shaded areas around MMEM data both in historic (1951 – 2014) and future periods show the spread of individual CMIP6 models. However, for precipitation change expressed as percentage, the ribbon is standard error not the standard deviation

Table 2: Mean annual projected changes in temperature (Degree C) and precipitation (%) over whole Pakistan during period (2020 – 2100) under two emission scenarios (i.e., SSP245 and SSP585)

		ssp245		ssp585	
		DeltaF1	DeltaF2	DeltaF1	DeltaF2
Tmax (Degree C)	Mean	1.31	2.37	1.55	4.02
	Min	0.93	1.84	0.92	3.04
	Max	1.71	2.82	2.18	4.99
Tmin (Degree C)	Mean	1.77	3.04	2.12	5.22
	Min	1.42	2.64	1.30	4.11
	Max	2.26	3.63	2.71	6.24
Tmean (Degree C)	Mean	1.54	2.71	1.84	4.62
	Min	1.17	2.26	1.11	3.60
	Max	1.94	3.19	2.42	5.61
Precip (%)	Mean	17%	28%	24%	53%
	Min	-18%	-7%	0%	9%
	Max	48%	74%	64%	93%

The projected changes (2020 – 2100) in mean annual temperatures and precipitation relative to the control period (1974 – 2014) are given in Table 2. The largest change in the temperature and precipitation are observed at the end of the century. For temperatures, all three variables show a range of temperature increase from 1.30 – 5.20 for F1 (2020-2060) and F2 (2061-2100) under two emission scenarios. The largest change in temperature is observed for mean annual minimum temperatures during F2 where it shows an increase of 1.70 during F1 with SSP245 emission scenario and 5.20 during F2 when projected with SSP585 emission scenario.

However, the rate of increase in maximum mean annual temperature is less when compared with minimum and mean annual temperatures. The minimum temperatures are crucial to understand and analyze, as can have serious implications for agriculture production in the country.

In case of mean and minimum annual mean temperatures, the temperature is projected to increase by 1.70 to 5.20 and 1.50 to 4.60 under 2 emission scenarios respectively. In case of precipitation, all 13 CMIP6 GCM's models and MEM show a significant increase in annual mean precipitation under both selected emission scenarios. SSP245 emission scenario shows a 17 – 28 % increase in the annual mean precipitation over whole Pakistan with larger increase at the end of the current century. However, this increase in precipitation increases almost doubled under SSP585 emission scenario (24 % during F1 period (2020 – 2060) and 53% during F2 (2061 – 2100). The precipitation projections and the spread of individual GCMs are almost same during period (2020 – 2050) but diverges away largely by the end of current century with the largest increase in case of SSP585 emission scenario.

4.2 GCMs model mean annual cycles (seasonality) during historical period

To estimate the CMIP6 GCM's model skills in representing seasonality, we have compared the mean seasonal cycles of temperature (maximum, minimum and mean) and precipitation against observation over whole Pakistan during the control period (1974-2014). The projected seasonal cycle of the GCM's has also been analyzed in future under two emission scenarios (i.e., SSP245 and SSP585) for the periods 2020 – 2100 as shown in Fig 4.

The Fig 4 reveals that all GCM's model are capable to well capture the temperature seasonality and display a bell-shaped distribution of temperature over years with the highest temperature i.e., 39 0C (Tmax) and 26 0C (Tmin) during months summer (April – September) and lowest temperature (i.e., 15 0C (Tmax) and 5 0C (Tmin)) during winter months (October – March).

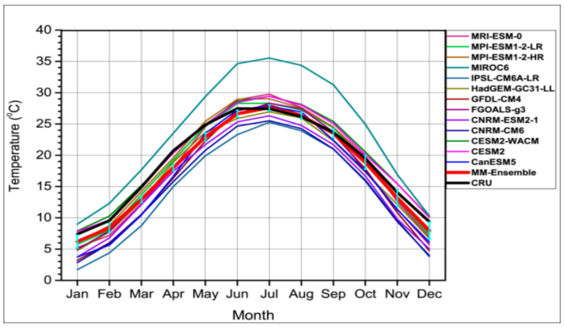

Fig 4: a) Mean seasonal cycle of individual 13 CMIP6 GCM's, multi model ensemble mean (MMEM) and observational (CRU) datasets over whole Pakistan during the control period (1974 – 2014)

The bell-shapes mean seasonal temperature distribution of multi-model ensemble mean (MMEM) is in good agreement with the observational cycle. There is less difference between individual 13 GCM's temperature ranges as shown by uncertainty spread. The 13 GCM model show under (over) estimation only during summer months (i.e., May – September). Whereas, the models are in good agreement in reproducing winter months mean monthly values. This analysis revealed that there is a linear and continuous increase in the temperatures by the end of current century with the largest increase estimated under RCP8.5 emission scenarios.

The precipitation patterns show large variations throughout the study period as shown by the varied amplitude by all GCM's. However, the MMEM are able to capture the mean seasonal precipitation patterns when compared with the observation. The MME shows largest total monthly precipitation during months June – August which coincides with the monsoon precipitation patterns in the study area.

This analysis confirms that the bias corrected method i.e., Empirical Quantile Mapping (EQM) as applied by Vimal Mishra [19] remained a successful statistical approach to remove the biases from the latest CMIP6 model projections and by capturing the monsoon precipitation signals in the region.

Based on the individual CMIP6 GCM's and MME satisfactory representational of mean seasonal cycle of temperature and precipitation results, this data is further used in our study to estimate and analyze the seasonal and province-specific climate projections and changes in future.

Our hypothesis is that the season and province-specific climate projections will give detailed information on climate projections that can be used to estimate the future water and food projections in the country. The bias-corrected season and province-specific temperature (maximum and minimum) and precipitation changes can be used to estimate the location-specific impacts on water resources and crop growth cycle and production.

4.3 Spatial Distribution of Seasonal Temperature and Precipitation during Control Period (1974-2014)

Our spatial and seasonal analysis of control period as simulated by MMEM revealed that there are large variations in temperature distributions between seasons and locations (i.e., North to South).

The highest temperatures are recorded during summer months ranging from -10 °C to 35 °C throughout the Pakistan with the highest mean seasonal temperature observed in the Punjab and Sindh provinces (mostly > 35 °C). In winter, the temperature drops substantially in the range of 10 °C to 30 °C maximum with the highest temperatures in the Southeastern (Sindh) belt of Pakistan. There is large temperature gradient in the country as we move from North hill to the South of Pakistan and between seasons.

Similarly, there is large variation in the precipitation distribution both in space and time in the country.

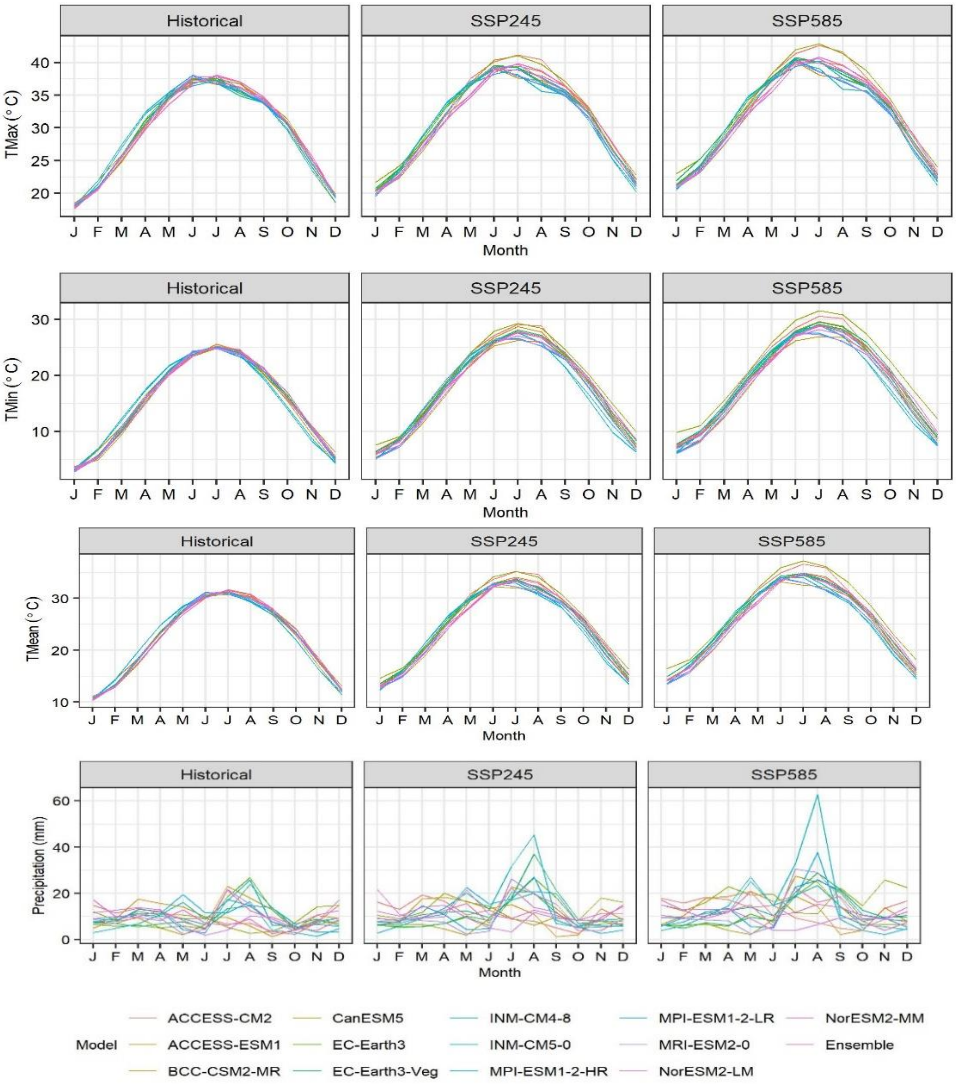

Fig 4: b) Mean seasonal cycle of individual 13 CMIP6 GCM's for Tmax, Tmin, Tmean and precip over whole Pakistan during the control period (1974 – 2014)

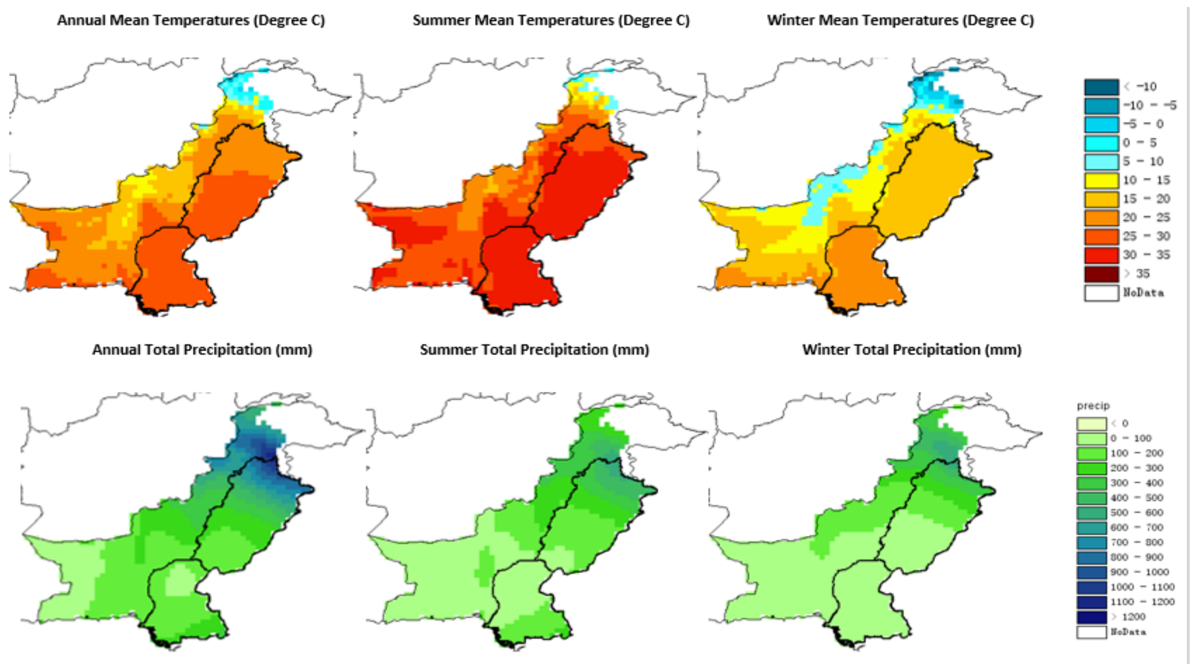

Fig 5: Spatial (North – South) distribution of temperature (upper panel) and precipitation (lower panels) patterns at annual and seasonal (summer and winter) scales during the control period 1974-2014 under CMIP6 SSP245 emission scenarios

The large amount of rain received in the northern mountainous region of Pakistan and reduces gradually as we move toward the plain areas. The precipitation patterns are almost equally distributed in different seasons in Pakistan with a larger share of rains during summer months received under monsoon oscillations. However, during winter, large amount of rain obtained due to westerlies, which cause to fall most of the rain as snow. Pakistan receives ~ 1200 mm annual total precipitation with the larger precipitation during summer months in Punjab followed by Sindh.

4.4 Future Changes in Spatial Distribution of Seasonal Temperature and Precipitation

Fig 6 shows spatial (North to South) and seasonal (summer and winter) distribution of future changes in temperature and precipitation during two selected periods i.e., F1 (2020 – 2060) and F2 (2061 – 2100) over whole Pakistan. The future changes in temperature and precipitation has been estimated with respect to the control duration (1974 – 2014) under two emission scenarios i.e., SSP245 and SSP585.During winter, largest temperature increase is observed in minimum temperatures (night time temperatures) which can have serious and adverse implications on winter crops phenological development and production.

The spatial analysis shows a consistent increase in temperature, particularly in summer, ranging from 0.01°C to 0.11°C per year for mean temperatures. The greatest temperature changes occur in the western regions under the SSP585 scenario during the F2 period. For SSP245, the largest change is observed in the northern high mountains during the F1 period. These trends are consistent across all temperature variables (maximum, minimum, and mean) during both seasons.

However, under SSP585 emission scenario, the large temperature changes observed during second half of the century (F2) with the largest variations in the northern and southwestern parts of the country during both seasons.

Our statistical results revealed that larger change in temperature data is occurring in higher values with the largest change in summer season in the North and Southwestern belt of Pakistan under SSP585 emission scenario.

In case of precipitation, both positive and negative change is observed. A positive and continuous change in precipitation is observe during summer season. A large and positive change during summer season is witnessed where up to 6mm increase in precipitation is observed by the end of current century in the eastern parts of Punjab and Sindh provinces under SSP585 emission scenarios. Under extreme climate emission scenario, a negative change (decrease of 0.74 mm/ year) is also revealed during summer season in the

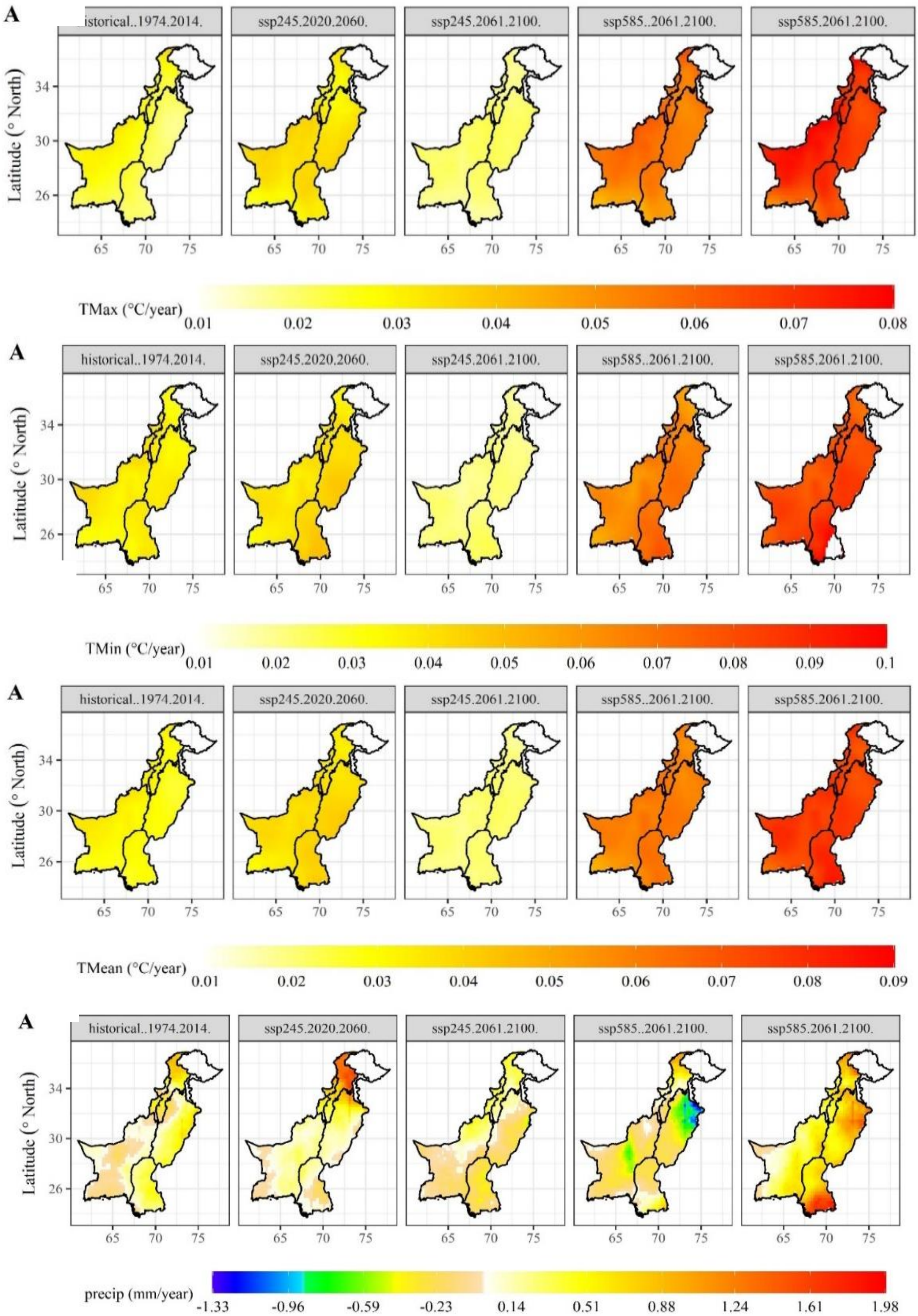

Fig. 6: Spatial (North to South) and seasonal (summer) distribution of future changes in temperature (Tmax, Tmin and Tmean) and precipitation during two selected periods i.e., F1 (2020 – 2060) and F2 (2061 – 2100) over whole Pakistan. The future changes in temperature and precipitation estimated with respect to the control duration (1974 – 2014) under two emission scenarios i.e., SSP245 and SSP585

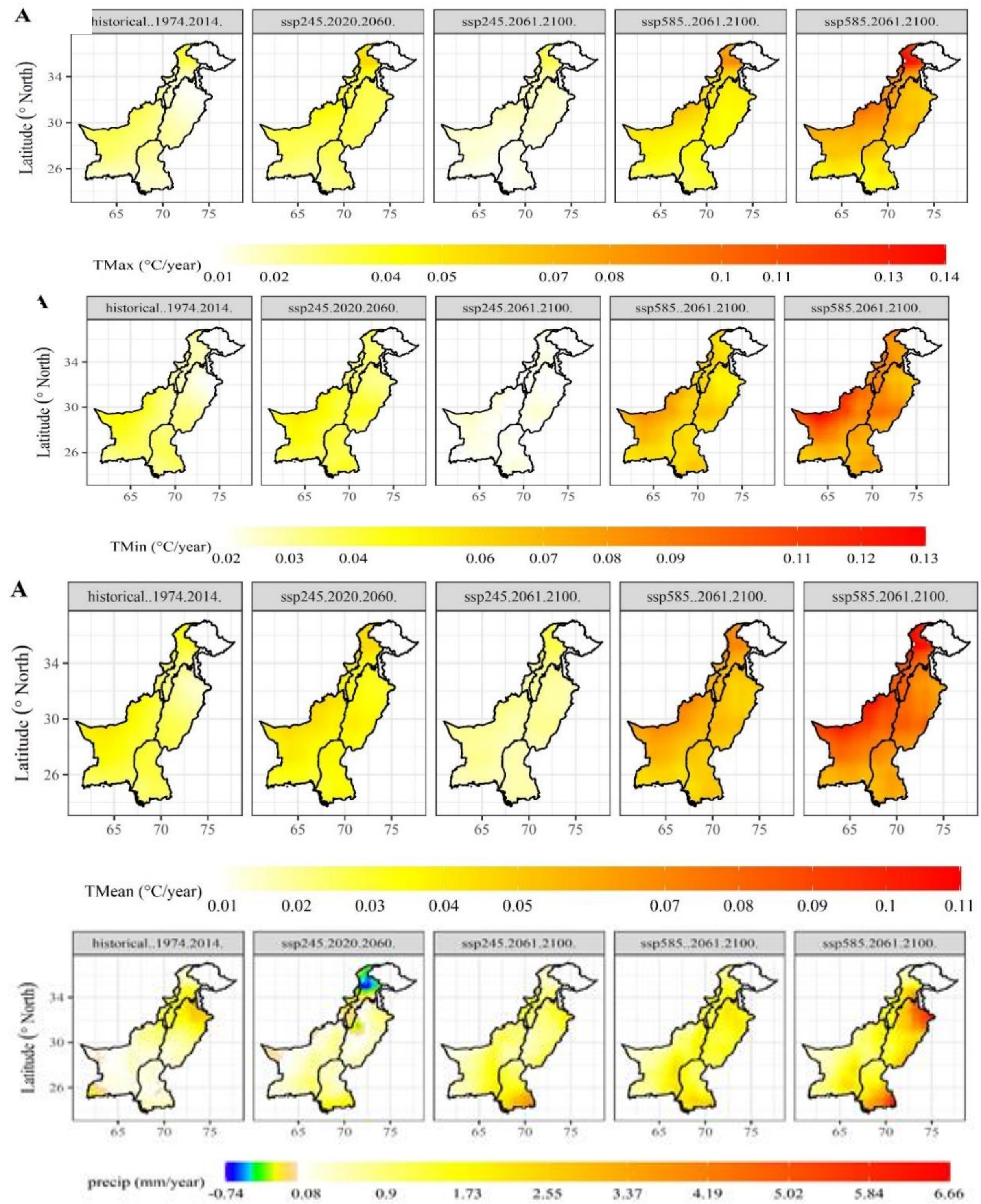

Fig. 7: Spatial (North to South) and seasonal (winter) distribution of future changes in temperature (Tmax, Tmin and Tmean) and precipitation during two selected periods i.e., F1 (2020 – 2060) and F2 (2061 – 2100) over whole Pakistan. The future changes in temperature and precipitation estimated with respect to the control duration (1974 – 2014) under two emission scenarios i.e., SSP245 and SSP585

Northern region of Pakistan during F1 period. However, during winter, a large (1.98 mm/ year) and a positive change in precipitation is observed in the Northern mountainous of Pakistan during F1 period under SSP245 emission scenario.

This change is reduced in the second half of the century and drops to 1mm/ year in Southern parts of the country. Entire different winter precipitation change projections are observed under SSP585 emission scenario i.e., a large negative change (1.33 mm/year) is observed in Northern

Punjab during F1 with a positive change (1.98 mm/year) in Southern Sindh during F2 period.

In case of temperature, largest and significant changes are observed in the western parts of the country during both seasons. However, for precipitation, largest change is observed in the eastern part of the country with a significant change in summer as influenced by the shifts in monsoon patterns in the country.

In case of both temperature and precipitation, a significant and continuous change is observed during both seasons and periods under both emission scenarios. This significant change in seasonal temperature and precipitation can have a visible and devastating impacts on water and food security of the country.

4.5 Projected Changes in Seasonal Temperature and Precipitation over provinces

The projected changes in temperature and precipitation are diverse in seasons and locations when compared under different emission scenarios Fig. 8.

Seasonal and Emission Scenario Variations Notably, summer (AMJJAS) and winter (ONDJFM) seasons show significant warming under both the SSP245 (moderate emissions) and SSP585 (high emissions) scenarios relative to the historical baseline (1974–2014). For the summer months, the projected warming is around 2°C under SSP245 and just above 2.5°C under SSP585 during the period 2020–2060. The warming trend is further compounded in the 2061–2100 period, with increases of approximately 3°C for the SSP245 scenario, while the SSP585 scenario yields even higher increases of more than 4°C, portraying the critical role of high-emission pathways in future climate projections. Similar trends operate during winter months, albeit with slightly lower levels of warming, under SSP245.

Winter temperatures are projected to increase approximately 1.5°C for 2020–2060 under the SSP245 scenario and by 2°C under the SSP585 scenario. In the future period (2061–2100), warming under SSP245 is projected to be about +2.5°C and for SSP585 over +4°C, which highlights the role of emissions in driving winter temperature rises.

There have also been significant changes in precipitation patterns particularly during the summer months. Summer precipitation over this

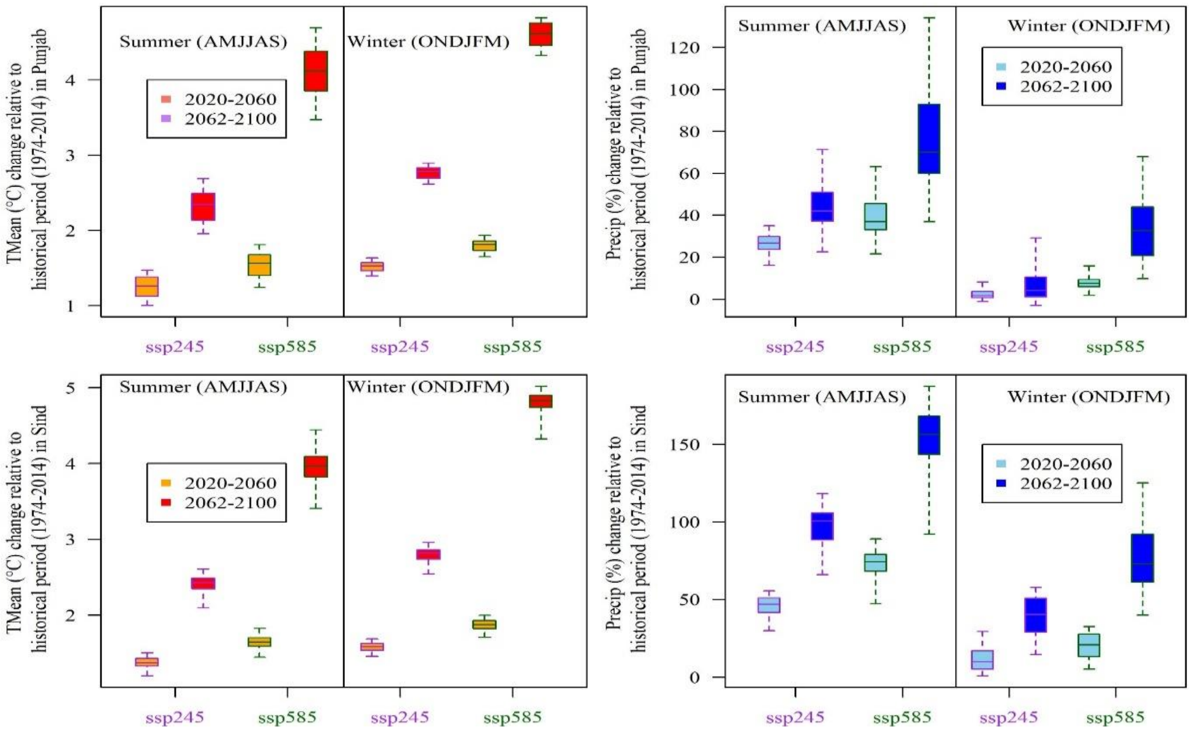

Fig. 8: Box and whisker plots for projected changes in seasonal temperature and precipitation over Punjab (upper panels) and Sindh (lower panels) provinces of Pakistan under two emission scenarios i.e., SSP245 and SSP585. The boxes show the interquartile range, horizontal lines represent the median and the whiskers show the maximum/minimum value of the lower/upper quartile

period is projected to increase by approximately 20% under SSP245 and 40% under SSP585. This upward trend becomes more marked in the 2061–2100 period, as SSP585 scenarios suggest an increase of around 80%, while projections for SSP245 level off between 20–30%. Changes in winter precipitation are much more variable, and the relative increases are much smaller than for summer. For 2020–2060, a slight increase of approximately 5% (SSP245) and 10% (SSP585) is expected. For 2061–2100, SSP245 still indicates moderate increases (10%), but SSP585 predicts a much larger rise of 40%.

Sindh Province is predicted to experience servant increases in temperature and precipitation by 2050, under two scenarios of greenhouse gas emissions (SSP245: moderate emissions; SSP585: high emissions). All of these projections are observed against the historical record from 1974–2014, for 2 seasons (summer (Apr-Sep) and winter (Oct-Mar)) over 2 future timeframes: 2020–2060 and 2061–2100.

They also project significant warming in both summer and winter seasons. The projected rise for summer of the 2020–2060 period amounts to around 2°C under SSP245 and just above 2.5°C under SSP585. This warming continued in the 2061–2100 period, with temperatures rising by approximately 3°C in SSP245 and by more than 4°C in SSP585. Winter temperatures show a similar trend over 2020–2060, with differences of about 1.5°C (SSP245) and just over 2°C (SSP585), moving to around 2.5°C (SSP245) and close to 4°C (SSP585) for 2061–2100. The result are in line with other studies showing progressive temperature rises in Sindh.

It is especially marked during the summer season when precipitation patterns have also changed significantly. Under SSP245, summer precipitation is expected to rise by about 20–30% for 2021–2060, and by 50–60% under SSP585. Forecasts for the period 2061–2100 show even more significant increases, with about a 40% increase under SSP245 and over 100% under SSP585, indicating the possibility of summer rainfall doubling under high emission scenarios. Changes in winter precipitation are more modest relative, but still appreciable, with increases (SSP245) of approximately 10% and (SSP585) ~20% for the period 2021–2060, increasing to projected changes (SSP245) of 20% and (SSP585) 50–60% for (2061–2100). These projections are in line with studies that have found erratic precipitation patterns and rising frequency of extreme events in the region.

Our season-specific results of future changes in climate data revealed a large variation in temperature and precipitation ranges when compared between two provinces. We observed that, large temperature change (increase) is observed during winter season in both provinces with the largest temperature increase i.e., 1.6 0C to 2.9 0C in F1 and F2 in case of SSP245 emission scenario and 1.9 0C to 4.8 0C in F1 and F2 respectively under SSP585 emission scenario in Punjab. The largest temperature positive change is witnessed in Sindh province in F2 under SSP585 emission scenario in winter. Deviation from mean/Inert-annual variations (uncertainty) is large in Punjab as compare to Sindh province in case of temperatures. In case of precipitation, there is large diversity in change between seasons and provinces. For example, large future change in precipitation is observed in summer season in both provinces with largest positive change observed in Sindh province. Our scenario-specific results revealed that there is a linear increase in the future (i.e., change in F2 is large as compare to F1 in both provinces) with the largest positive change (increase) is observed in F2 (2061-2100) 187% as estimated under SSSP585 emission scenario.

The uncertainty ranges observed in seasons and provinces are large in case of precipitation and this is not consistent over space and time.

5. Discussion

5.1 Temperature and Precipitation Projections over Pakistan

Figure shows that there are substantial trends in the temperature and precipitation projected over Pakistan for both SSP245 and SSP585 scenarios for the period of the year 2020–2100. Annual mean maximum (Tmax), minimum (Tmin), and mean (Tmean) temperatures show a linear increase, which is more pronounced under the highest-emission scenario (SSP585). This agrees with previous studies showing that escalated warming trends occur in the case of more intense radiative forcing under SSP585 [28], [29]. Of particular significance is the increase of Tmin projections, specifically within the F2 period (2061–2100), which may particularly drive agricultural impacts and nighttime cooling needs.

Likewise, the global projections of annual precipitation show a noticeable increase, particularly after 2050, where more divergences in predictions are also seen. Under SSP245, precipitation is projected to increase by 17–28%, whereas SSP585 predicts a more pronounced increase of 24–53%, highlighting the role high-emission scenarios have on hydrological extremes. In contrast, the spread in model projections for the mid-century onward illustrates uncertainties in regional estimates of precipitation, reflecting recent studies [16], [30].

The findings highlight the urgency of addressing future climatic impacts on Pakistan's water resources and agriculture given the fact of pronounced warming and a potential increase in extreme precipitation events. The findings align with broader regional studies, further emphasizing the importance of mitigation efforts to curb high-emission pathways and adapt to inevitable climatic changes.

5.2 GCMs model mean annual cycles (seasonality) during historical period

Assessment of mean annual cycle of Temperature and Precipitation from CMIP6 General Circulation Models (GCMs): Implications for future Climate projections over Pakistan The analysis of historical periods (1974–2014) demonstrates good agreement for GCMs, especially for MMEM, with respect to temperature seasonality and the reproduction of some observational data patterns. The bell-shaped temperature distribution having maxima (39°C for Tmax and 26°C for Tmin) in summer and minima (15°C for Tmax and 5°C for Tmin) in winter is also consistent with observations from climatology.

Though individual GCMs exhibit moderate underestimation in summer months (May–September), MMEM minimizes biases and represents the linear increase in temperatures under both SSP245 and SSP585 emission scenarios. The strong performance of MMEM is in line with results reported in Aryal [28] and Mehta [31], noted the potential of ensembles (of which the mean is one example) to outperform examples by canceling out inherent biases.

Precipitation seasonality, though is more variable, as GCMs struggle to accurately simulate precipitation patterns, especially in monsoon-dominated areas. This variability notwithstanding, the MMEM captures the observed monsoon precipitation peaks (June–August) quite well. The bias-correction method, Empirical Quantile Mapping (EQM), is particularly successful at correcting the model biases and improving the model projections of monsoon precipitation, which is consistent with the previous studies by Mishra [19] and Mondal [16]. As such, EQM is more reliable for policy and planning, ensuring that the projected precipitation is consistent with historical observations.

Models using SSP245 and SSP585, such as the CMIP6 models, predict linear and continuous increases in temperatures, emphasizing the importance of mitigation and adaptation strategies for populations at risk. This intensity of warming, particularly during summer months, under the SSP585 scenario will lead to increased heat stress, which creates significant threats to agriculture, water availability, and public health. The MMEM's ability to replicate these trends can support its continued use in future climate impact assessments.

The appropriately scaling applications of GCMs and MMEM to predict province and season specific climate changes, is a logical extension of their demonstration (and skillful) representation of in-situ climate. Bias-corrected models at the provincial level can offer sounder insights of water and food system impacts at this location-specific level. These projections are critical in estimation of future crop cycle along with water demand where Pakistan's overall agricultural, lands are more reliant on seasonal precipitation as suggested by Sanjay [21] and Aryal [28].

We conclude that capacity of CMIP6 models and MMEM have in reproducing historical and projecting seasonal cycles of temperature and precipitation underpins detailed, regional climate projections. These findings underscore the need for national adaptation strategies integrating these datasets to inform policy responses to the multiple impacts of climate change on water resources, food security, and disaster risk management.

5.3 Spatial Distribution of Seasonal Temperature and Precipitation during Control Period (1974-2014)

During the control period (1974–2014), temporal and spatial analysis show that Pakistan has significant variability in temperature and precipitation, confirming that Pakistan is climatically a diverse country. The hottest summers (+35 °C) are experienced in the Punjab and Sindh provinces, whereas winters with −10 °C are recorded in the northern mountainous areas and can reach 30 °C in the southeastern plains. Precipitation patterns also exhibit a north-south gradient, with the northern areas receiving considerable rainfall from monsoonal oscillation and westerly systems, while much lower precipitation occurs for the southern plains. This is consistent with the work of Archer and Fowler [32] and Ali [33], where they characterized the intricate interplay between topography and regional climatic drivers in influencing the climate of Pakistan.

Climate projections under SSP245 and SSP585 models for the future indicate warming across Pakistan with substantial increases over time, especially for summer temperatures, which indicate maximum increasing rates. By 2100 and under SSP585, the mean summer temperatures may increase by up to 0.11°C year-1 with the northern and southwestern regions being the most affected. For CMIP6 projected scenarios, these findings are consistent with higher warming rates for the high-emission scenarios at the global scale [34]. The significant increase in winter minimum temperatures in northern latitudes may drive accelerated retreat of glaciers in the Karakoram and Himalayan ranges and may contribute to shifts in seasonal water flows and glacial-fed river systems [4], [35]. Trends in precipitation are perhaps positive as well as negative and are again geographically and seasonally specific. Under both climate scenarios (SSP585), significant increases in summer rainfall in eastern Punjab and Sindh (up to 6 mm year−1) and up to 0.74 mm year−1 decrease in northern Pakistan are projected for the earlier period (2020–2060). The trends in winter precipitation vary considerably in that the north's precipitation is positive in SSP245 for the first half of the century but declines in Punjab and increases in Sindh by the second half also in the extreme SSP585. The precipitation trends are consistent with those of Abbas [4] and Ashfaq [36] the impact of monsoonal variability and westerly disturbances on hydrological cycles over Pakistan.

These climatic changes will has important consequences for water resources management and disaster risk reduction. Examples include increased monsoonal rainfall in the south contributing to urban flooding in mega cities such as Karachi, while decreased winter precipitation in the north threatens reservoir recharge and hydropower generation. Adaptive approaches such as enhanced urban planning, water storage infrastructure, and ecosystem-based flood management will be essential. Future work utilizing high-resolution regional climate models and socio-economic vulnerability assessments will lead to actionable insights for decision makers [29], [35].

5.4 Projected Changes in Seasonal Temperature and Precipitation over provinces

Under various emission scenarios, there is considerable spatial and temporal variation in the projected seasonal changes in temperature and precipitation between Punjab and Sindh. This warming is most prominent for the winter season, where the increase is in the range of 1.6°C to 2.9°C (SSP245) and 1.9°C to 4.8°C (SSP585) in the F1 (2020–2060) and F2 (2061–2100) periods in the Punjab region. Sindh shows even greater warming in F2 for SSP585, indicating a general warming across the regions. South Asia has also been characterized as a climate hotspot, under high-emission scenarios, in other recent studies with similar trends [37], [38]. Winter warming, especially minimum temperatures, can affect the two main crop-producing seasons like wheat in Punjab and can change thermal comfort indices in Sindh and other areas.

Inter-annual variations are higher in Punjab than in Sindh, including temperature variability. This is in accordance with findings made by [12], who traced this variability to the interaction of westerly systems with the complex northern topography. The temperatures in Sindh, which has relatively uniform terrain and dry climatic conditions, are more consistent in their projections. These trends imply a need for focused adaptation measures for Punjab with the development of new heat-tolerant crop varieties, whereas Sindh may need strategies to deal with sustained frequent heat stress.

Summer becomes the most critical season concerning precipitation with significant increases expected under SSP585, especially in Sindh, with up to 187% rise in precipitation F2 (2061–2100) expected. This is in line with studies that have linked these raises to enhancing monsoon systems [39], [40]. In addition to higher precipitation, it could help resolve water scarcity in Sindh, but it also raises the issue of urban flooding and waterlogging in low-lying places like Karachi. In contrast, Punjab has significant inter-annual variability in precipitation, indicating the influence of both monsoon and middle-latitude westerly systems. Fluctuations in precipitation create dilemmas for water resource development, as reported by Tahir [41].

Uncertainty about precipitation projections is particularly large, related to local meteorological processes and global climate drivers. These uncertainties are in agreement with the results from the IPCC [34] and Ahmed [6]3) note the challenges of predicting regional precipitation transitions because of the stochastic nature of atmospheric circulation. Tackling these uncertainties will necessitate context-appropriate climate models and new hydrological management strategies, especially in agriculture and urban water systems.

In Punjab, rising minimum winter temperatures (Tmin) are narrowing the thermal window required for optimal wheat growth, increasing the risk of yield declines. These findings align with global warming projections and highlight the vulnerability of wheat crops during critical growth stages [42], [43]. Additionally, altered precipitation patterns may exacerbated water availability challenges, leading to reduced crop yields and grain quality deterioration. In contrast, south eastern Sindh is expected to face increasing maximum temperatures (Tmax) and declining precipitation levels which together intensify heat stress and water scarcity, posing severe risks to rice productivity [43], [44]. These dual stresses, combined with the increasing frequency of extreme climate events, highlight the regional variability of climate impacts and the need for localized adaptation measures.

6. Conclusions

This study reveals significant spatio-temporal changes in temperature (Tmax, Tmin) and precipitation patterns across Punjab and Sindh under SSP245 and SSP585 emission scenarios. Rising minimum temperatures (Tmin) during the winter in Punjab threaten the thermal window for optimal wheat growth, potentially leading the yield reductions. Meanwhile, increasing maximum temperatures (Tmax) and declining precipitation in southeastern Sindh exacerbate heat stress and water scarcity, which could severely impact rice production. The observed climatic shifts are expected to disrupt both crop yields and water availability, presenting serious challenges to Pakistan's food security.

At the national level, the increase in Tmin exceeds that of Tmax. Under SSP585, Tmin is projected to rise by 5.22°C, compared to a 4.02°C increase in Tmax by 2100. Precipitation shows a relatively steady upward trend, with increases of 28% and 53% projected under SSP245 and SSP585, respectively. In Punjab, both summer and winter temperatures are expected to rise significantly, with Tmin likely to increase by 1.6°C to 4.8°C across various scenarios by 2100. Summer precipitation is projected to increase moderately under SSP245, ranging from 20% to 40%, and more sharply under SSP585, potentially reaching up to 100%. In Sindh, summer and winter temperature trends are similar, with summer Tmax potentially rising by as much as 4°C under SSP585. Summer precipitation in Sindh could see an extraordinary increase, potentially reaching 187% by 2100 under SSP585

These findings underscore the critical need for region-specific adaptation strategies to address the diverse climatic impacts across different provinces. the use of CMIP6 climate models and robust statistical methods such as (Mann-Kendall trend tests) enhances the reliability of these projections. The results serve as a foundation for devising climate resilient agricultural practices and inform evidence-based policymaking to reduce vulnerability in agriculture-dependent regions. These insights are vital for the development of long-term strategies to build resilience against climate-induced risks in Pakistan's agricultural sector.

7. Recommendations

To mitigate the risks posed by spatio-temporal climatic changes and ensure sustainable agricultural productivity, the following recommendations emphasize the need for high-resolution, location-specific climate risk assessments and their implications for the agriculture sector:

1. Conduct seasonal to sub-seasonal climate risk assessments using high-resolution climate models (e.g., CMIP6) tailored to specific agricultural zones.
2. Develop heat-resistant crop varieties and adjust planting schedules in Punjab; promote drought tolerant rice and water-saving practices in Sindh
3. Encourage crop diversification, precision agriculture, and climate-resilient cultivars.
4. Invest in efficient irrigation and rainwater harvesting.
5. Use climate data for evidence-based policies and early warning systems.
6. Offer comprehensive training support to farming communities on climate-resilient agricultural practices and available financial mechanisms.

8. Acknowledgment

The authors are thankful to all who contributed to this paper. They declare that there are no conflicts of interest regarding the publication of this manuscript.

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