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TEMPERATURE AND RAINFALL TRENDS IN QUETTA VALLEY, PAKISTAN: A CMIP6-BASED ANALYSIS OF HISTORICAL AND FUTURE CLIMATE DYNAMICS

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Abstract
The paper explores historic and future climatic patterns of temperature and rainfall in Quetta Valley in Pakistan which is an arid region with a high susceptibility to climate change. As indicated by historical analysis, there exist strong warming patterns in minimum and maximum temperatures with an obvious trend of rising through the period under consideration, along with a small but statistically significant decline of the annual rainfall that is further boosting regional aridity. The ongoing warming is expected to be followed by a further increase in temperature that may reach 8°C in maximum temperatures by the year 2100 according to the high-emission SSP585 scenario. Projections of precipitation indicate uneven patterns that overall have a drier (the potential of lower rainfall than the baseline in SSP585) trend. These results indicate the growing climate fragility of Quetta Valley and the strong need in adaptive practices in water management, agriculture production, and sustainability initiatives.

INTRODUCTION

Climate change is reshaping global weather patterns, with rising temperatures and altering precipitation systems posing severe threats to ecosystems, economies, and human health [1]. Studies show that Earth's surface temperature has increased by about 1.1°C since the pre-industrial era, and warming has risen to 0.20°C per decade since 1982 [2]. At the same time, global precipitation is expected to increase by 1-2% per degree of warming, but its pattern is not homogeneous, leading to wetter in some areas and drier in others [3]. These changes have a profound impact on water access, food security, and socioeconomic stability, particularly in at-risk communities.

South Asia, being densely populated with an agrarian economy, is most exposed to the impacts of climate change. South Asia has experienced an increase in temperature in the past century by about 0.75°C, along with increased variability of monsoon precipitation and increased frequency of extreme weather events such as heatwaves, floods, and droughts [4]. The Intergovernmental Panel on Climate Change (IPCC) recognizes that South Asia is faced with increased surface air temperatures, particularly at nighttime, and increased variability of monsoon behavior, interfering with agriculture production and water supply systems [5]. Climate change has very serious implications for the livelihoods of millions, especially in rural rain-fed agriculture-based societies.

Pakistan's climate is primarily arid to semi-arid, with the summer monsoon contributing for around 50-60% of total annual rainfall which is critical for agriculture and water supplies. A 36-year analysis in Punjab (1979-2014) shows an increase in hot days, warm nights, and heavy precipitation events [6]. Despite producing less than 1% of global greenhouse gas emissions, Pakistan is among the top ten most climate-affected countries, ranking 8th in the 2021 Germanwatch Climate Risk Index [7]. In recent decades, temperatures have risen by 0.78-1.5°C over the global average. These changes, together with extreme events like heatwaves, floods, and droughts, pose serious dangers to agriculture—which employs around 43% of the population [6].

The problem of the arid climate and inadequate water supply is especially susceptible in the province of Balochistan in Pakistan. The province is characterized by wide temperature variations and erratic rainfall which when combined lead to such issues as desertification and water scarcity [8]. Heatwaves have become more frequent and cities like Turbat had experienced a temperature as high as 52°C in 2017 [9]. It is also characterized by the clear pattern changes in the rainfall, whereby less rainfall causes the drought to be worse and the flash floods that followed are destructive in nature [10].

Quetta Valley, the provincial capital of Balochistan, is an important case study for investigating these climate dynamics. It is at an altitude of 1,680 meters and it has a cold semi-arid climate with extreme seasonal temperature variation, between -18.3°C in winter to 42°C in summer [11]. The highest temperature rose by an average of 0.28°C per decade over 1961 to 2019, and the annual precipitation declined by approximately 2.94 mm [11, 12]. Such climatic changes are compromising the water sources and agricultural output of Quetta and its urban infrastructure.

Previous research has established the foundation for understanding climate variability in the Quetta Valley. For instance, one study [11] examined daily climatic extremes from 1961 to 2019 and found strong warming trends, as well as falling precipitation, both of which worsen water stress in the region. Another study [12] examined climate change-induced drought hazards in Balochistan, highlighting the province's susceptibility to decreased rainfall and rising temperatures. Both studies used statistical tools like the Mann-Kendall test to confirm climatic trends and focused on the socioeconomic repercussions of climate change for local populations.

In spite of these, there is a critical research gap as to how temperature and precipitation analysis through application of modern climate models can be used to forecast future scenarios in the case of Quetta Valley. While the present study is helpful, such information tends to focus on regional trends or single climate parameters in isolation. Synthesis analysis that brings together past and future data for precipitation and temperature, using advanced models such as the Coupled Model Intercomparison Project Phase 6 (CMIP6), is necessary to advance knowledge of Quetta's climatic path and inform adaptation interventions accordingly.

This paper seeks to fill the research gap by examining the past and the future trends of temperature and precipitation in the Quetta Valley. Namely, its three main aims are to examine the past trends of temperature and rainfall based on the observed climate data of the period between 1961 and 2019, to model the future changes of these variables under different Shared Socioeconomic Pathways (SSPs) using the Coupled Model Intercomparison Project Phase 6 (CMIP6) models, and to evaluate possible future impacts on the water resources and agricultural development of the region. The research will give a comprehensive image of the evolving climate of the region and the possible impact on significant socioeconomic areas by incorporating historical records and future projections.

2. Study area description

The research focuses on the Quetta city in Baluchistan province in Pakistan, located at 30°13′29.496″ N and 66°59′18.51″ E. According to the 2017 census, Quetta covers 3,447 square kilometers (

Figure 1) and has a population of 2.2 million. It is the capital of Baluchistan and borders Afghanistan to the west. It has an arid climate, with cold winters and brief, warm summers. Rainfall in the city averages 100mm per year. Extreme events occurred in 2017 (386.219mm) and 2019 (492.472mm). In contrast, the lowest amount of precipitation recorded was 169.374mm in 2021. Summer temperatures in Quetta are warm, averaging between 24 and 26 °C, while winter temperatures falls below freezing and average between 4 and 7 °C [13].

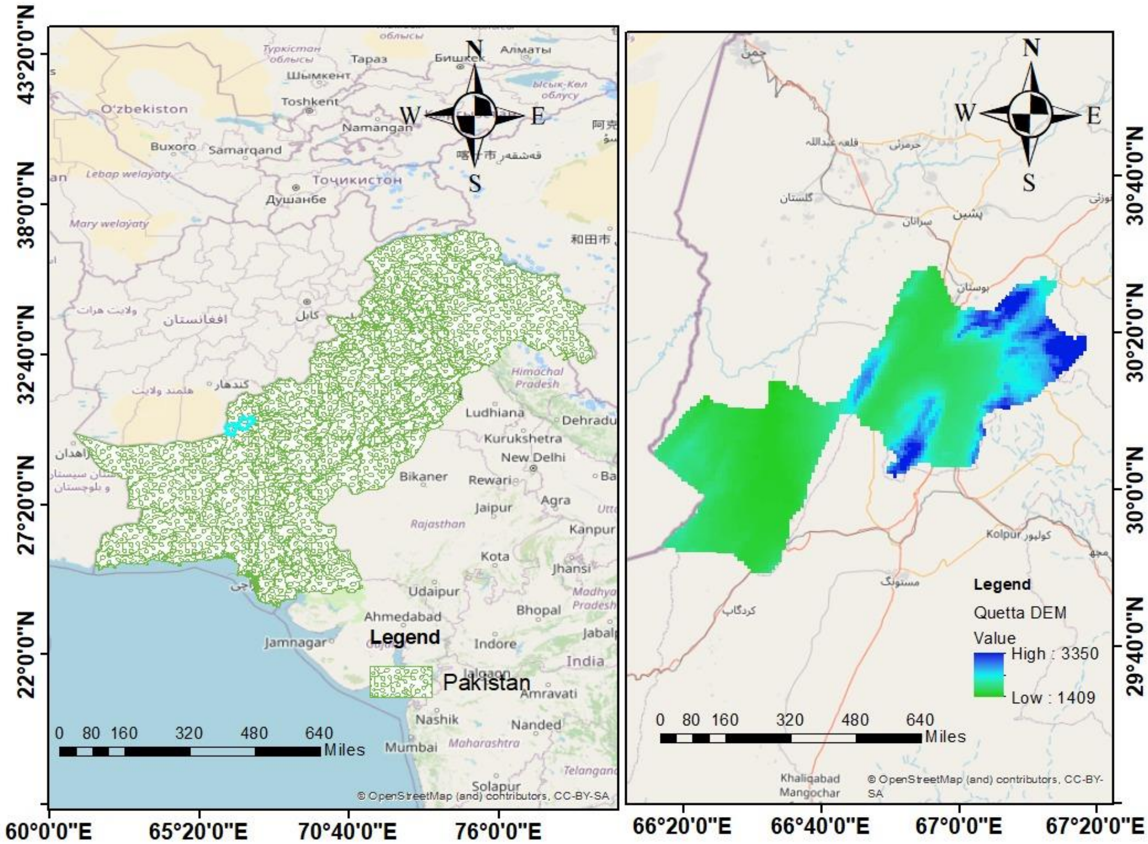

Figure 1 | Location of the study area showing Quetta District within Pakistan.

3. Data collection

Pakistan is a data-scarce country where data availability is a big challenge. Precipitation and mean temperature data were obtained from the Pakistan Meteorological Department. Temperature maximum and temperature minimum data was sourced from online sources namely Global Precipitation Climatology Centre (GPCC) website (https://www.psl.noaa.gov), Prediction of Worldwide Energy Resources - National Aeronautics and Space Administration (POWER NASA) (https://power.larc.nasa.gov/), National Oceanic and Atmospheric Administration - Climate Prediction Center (NOAA CPC) (https://www.cpc.ncep.noaa.gov), Climate Hazards Group Infrared Precipitation with Stations (CHIRPS) website (https://www.chc.ucsb.edu/data/chirps3), Climate Forecast System Reanalysis (CFSR) (https://www.ncei.noaa.gov) and ECMWF Reanalysis v5 (ERA5) (https://climate.copernicus.eu). The observed and online source data is visualized via
Figure 2.

In this study, daily temperature maximum, temperature minimum and precipitation data from 8 Global Climate Models (GCMs) namely Nor-ESM2-MM (Norway), CMCC-ESM2, CNRM-CM6-1 (France), EC-Earth3-Veg-LR (Europe), INM-CM4-8 (Russia), INM-CM5-0, MIROC6 (Japan) and MRI-

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ESM-2-0 were retrieved from the Coupled Model Intercomparison Project Phase 6 (CMIP6) repository. This study employed a comprehensive selection process to identify the most relevant scenarios for capturing a range of potential future climate conditions [14]. The Shared Socioeconomic Pathways (SSP) scenarios SSP 585 and SSP 245, representing high-emission and moderate-emission pathways respectively, as outlined by the Intergovernmental Panel on Climate Change (IPCC), were utilized [15]. These Shared Socioeconomic Pathways (SSPs) were chosen to represent a range of possible future climate trajectories extending through the end of the twenty-first century (2020-2100), allowing for a comprehensive assessment of projected temperature and precipitation trends under various greenhouse gas emission scenarios.

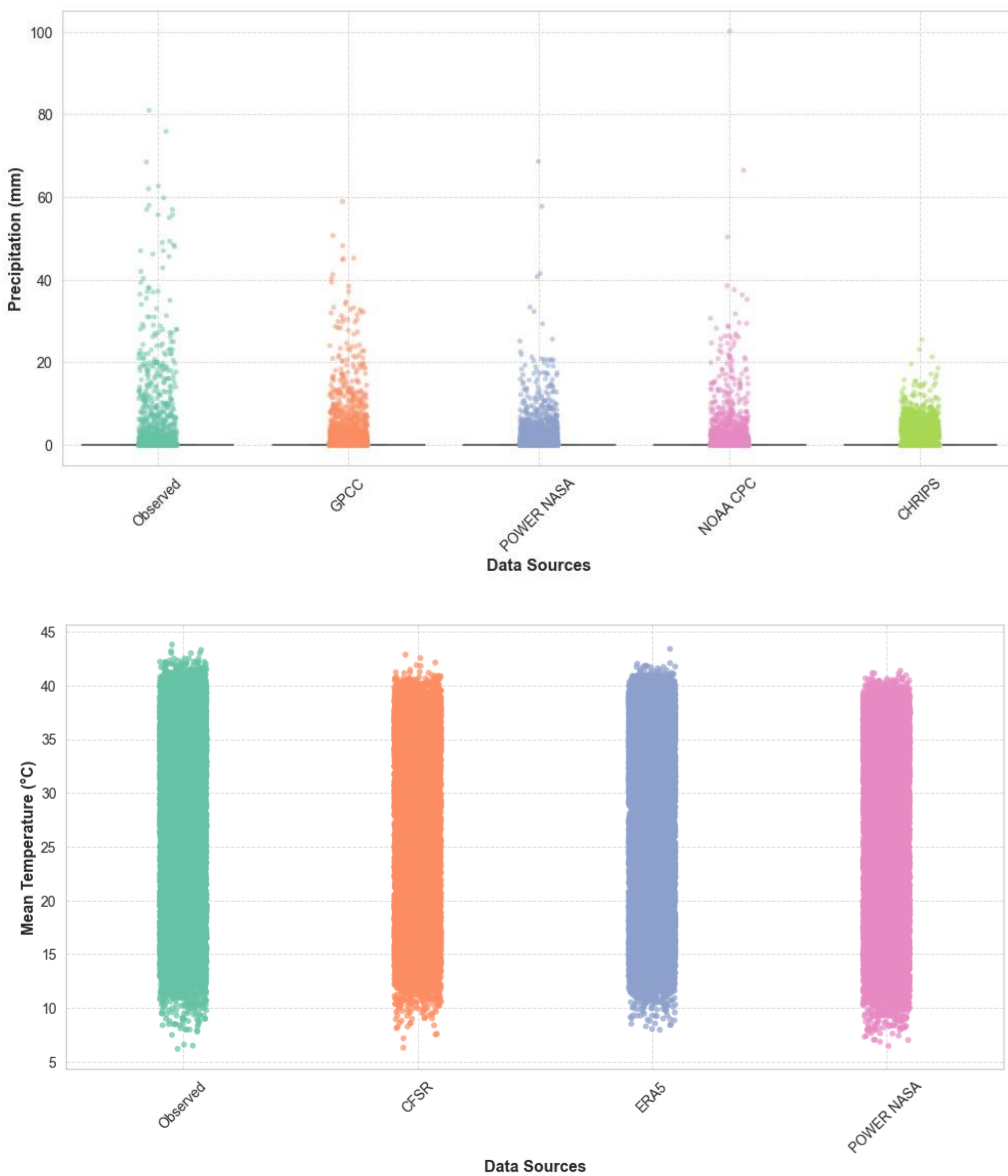


Figure 2|Intercomparison of observed and online data sources

4. Methodology

The methodology of the current project is depicted by **Error! Reference source not found.**. Firstly, climatic data was pretreated. Secondly, anomaly, trend analysis was estimated.

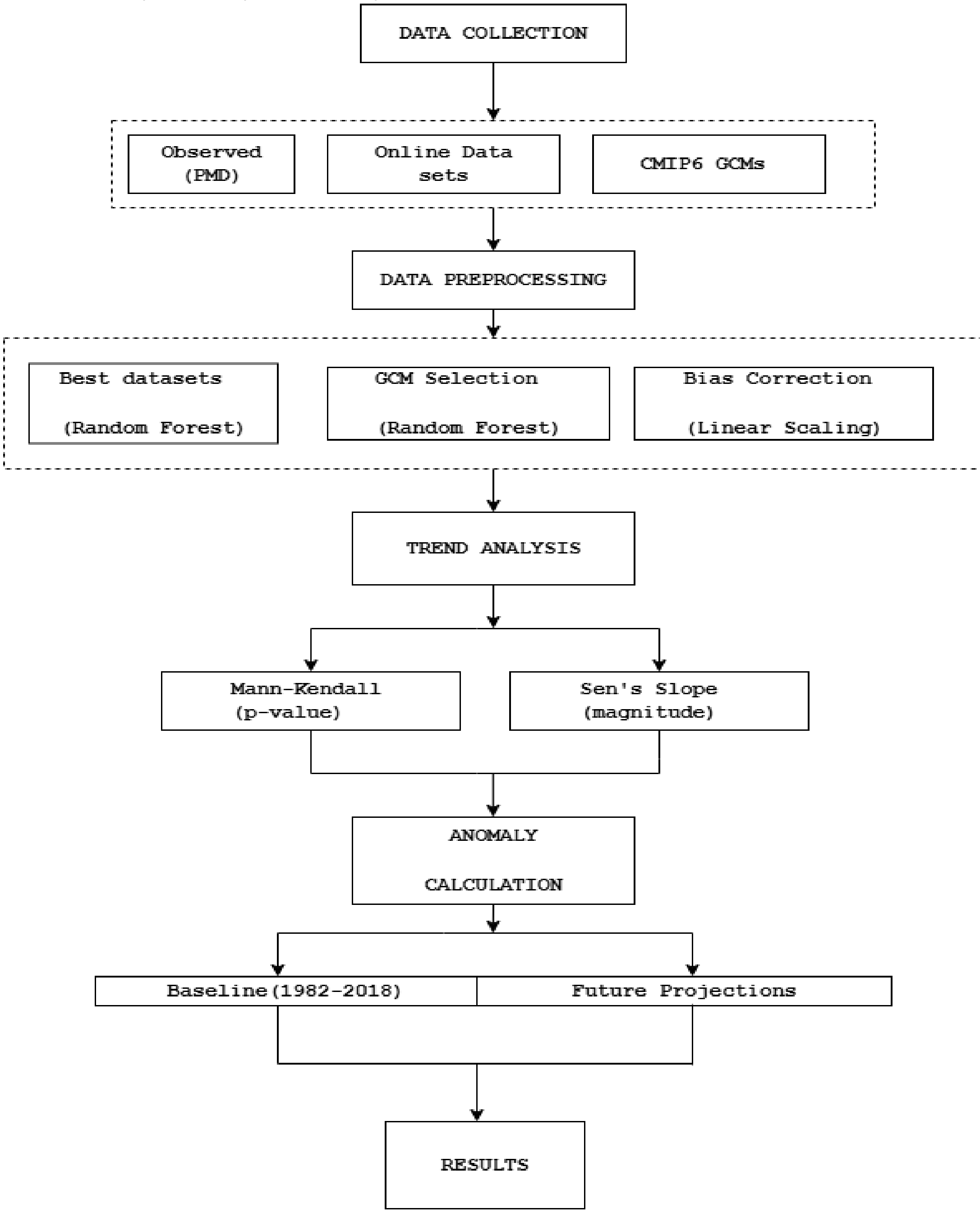


Figure 3|Flow chart of methodology

4.1 Data pretreatment

Pakistan is a data scarce country where data availability is a big challenge [16]. Precipitation and average temperature was observed and obtained through Pakistan Meteorological Department. Temperature maximum and temperature minimum data was obtained online. Since the performance of these datasets in various regions varied, there was need to determine the relative performance of these datasets in replicating the observed climatic patterns in Quetta. To this end, Random Forest (RF) machine learning algorithm was used to identify the most pertinent datasets [17]. Random Forest algorithm measured the predictive skill of every online dataset by training it to predict observed values of PMD using overlapping time series. The model has calculated feature importance scores on each dataset, which are the relative importance of each input variable to the predictive performance of the ensemble model. The greater the feature importance the more it correlates to the observed data and the more explanatory power it possesses. The most credible sources of temperature and precipitation were chosen to be analyzed using these rankings. The same process was used in the selection of the most appropriate Global Climate Models (GCMs) in the CMIP6 ensemble. Eight GCMs were first taken into consideration and the RF algorithm was applied to identify the models that best matched observed climatology in the region of Quetta. Such data-based selection method guaranteed that only the most talented GCMs were kept to perform the bias correction and future projection analysis, thereby increasing the robustness of the past and future climate assessment. Such a demanding procedure of pretreatment, which incorporates the use of observed records, feature selection via machine learning, and multi-source validation, made sure that the most representative and precise datasets were utilized in the analysis of temperature and precipitation trends in the study area.

4.2 Trend analysis

The Mann–Kendall (MK) test is commonly used to identify monotonic trends in climate data [18]. It has advantages for hydro-meteorological time series, where outliers and missing values are often found. This non-parametric test measures monotonic trends in time series data without assuming a linear trend or a normal distribution. The MK test is used to perceive statistically significant decreasing or increasing trends in long-term temporal data. The MK trend test is based on two hypotheses: one is null (H_0) and the other is the alternative (H_1) hypothesis. The H_0 expresses the existence of no trend while H_1 elucidates a significant rising or declining trend in precipitation or temperature data. On the basis of 5% significance level, if p-value is <0.05, then the alternative hypothesis is accepted which signifies the presence of a trend in the data and if the p-value is >0.05, the H_0 will be accepted that denotes the absence of a trend in the data. The equation is as follows:

$$S = \sum_{t=1}^{n-1} \sum_{j=i+1}^{n} \text{sign}(Xj - Xi)$$

where n is the numbers of data points, X_j and X_i are annual values in years j and i, j > 1 and Sign (X_j – X_i) is estimated using the below equation:

$$\text{Sign}(Xj - Xi) = \begin{cases} -1 \text{ for } (Xj - Xi) < 0 \\ \ \ 0 \text{ for } (Xj - Xi) = 0 \\ +1 \text{ for } (Xj - Xi) > 0 \end{cases}$$

Sen's slope is used to compute the trend magnitude in long-term temporal data. Sen's slope is considered better to detect the linear relationship as it is not affected by outliers in the data. In this study, Sen's slope is used to compute the trend magnitude in temperature and precipitation. The following equation is used to estimate each individual slope (Q_i):

$$Qi = \frac{Yj - Yi}{j - 1}$$

where i = 1 to n − 1, j = 2 to n, Yj and Yi are data values at time j and i (j > i), respectively [19].

5 Results:

5.1 Data preprocessing

Feature importance scores are numerical values that help in selecting the most relevant features for the model. Higher scores signify greater importance, meaning the feature has a larger impact on the model's predictions. These scores can guide the selection of relevant online data sources for further analysis, ensuring that the data collected has a strong relationship with the observed data. In this project, Random Forest model was used to compute feature importance scores for the online data sources. For precipitation, the feature importance score of GPCC is higher in comparison to the remaining online data sources as obvious from Figure 4. For temperature, POWER NASA feature importance score overweighs the remaining online data sources as obvious from Figure 4. The aforementioned models were used where observed meteorological data is not available.

Figure 4|Online data sources selection for (a) precipitation and (b) temperature

5.2 Meteorological Forcing

One of the most popular statistical procedures is bias correction of the result of General Circulation Models (GCMs). Such GCMs are sophisticated models of simulating agents that are designed on sophisticated mathematical bases. These models are made to replicate natural processes of the earth concerning atmospheric, oceanic and land surfaces. Although they are very detailed, they do have challenges and are subject to inaccurate results. To deal with this, a bias correction procedure is used where the simulated outputs are modified through comparing it with observed datasets. The change makes the model more applicable to reality and hence makes the results more credible when it comes to their application in making decisions and assessing the potential effects. The statistical downscaling techniques detect and establish statistical relationship between measurement and GCM outputs. They are simpler, less time-consuming and they need less processing capability than dynamic down-scaling. They are, therefore, widely applied in climatic and hydrological research. This research included an application of bias correction, which is based on the Linear Scaling technique, whereby adjustments were carried out in multiplicative and additive corrections. The approach is appreciated in its simplicity and effectiveness, and it preserves dominant trends and variability in the GCM data. Also, to find out the significance of various GCMs, a Random Forest algorithm scrapped. Figure 5 shows that CNRM-CM6-1 (France) scored the highest among all the eight assessed models and it was most important.

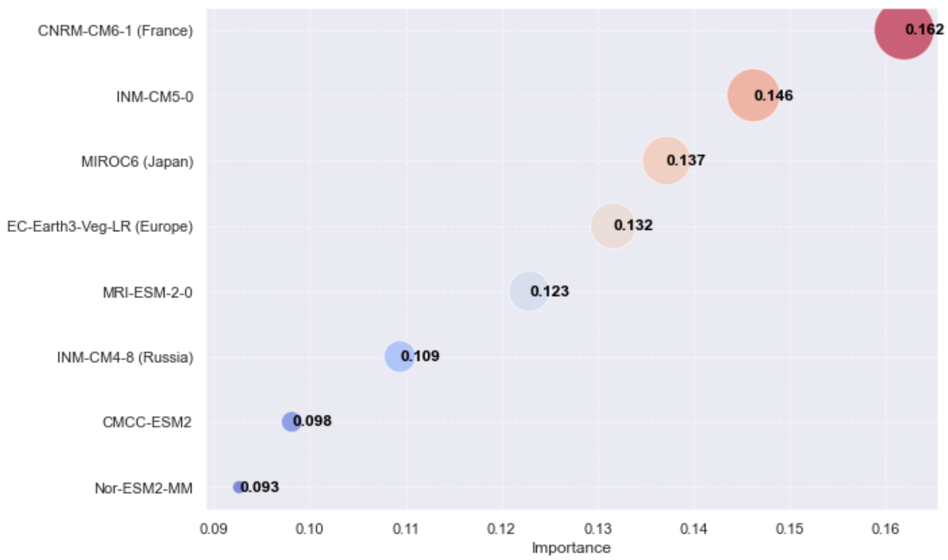
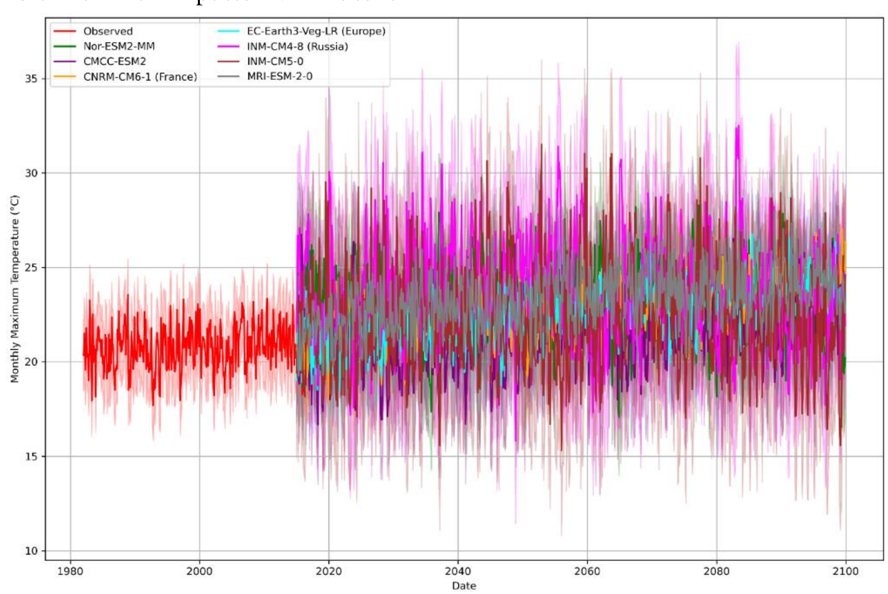


Figure 5 | GCM selection

5.3 Climate conditions

Fluctuations in temperature minimum, maximum and precipitation under the SSP245 and SSP585 scenarios is depicted by Figure 6, Figure 7 and Figure 8 . In comparison to historical, both temperature minimum and maximum is higher under both SSP scenarios. Generally, the observed and future precipitation exhibit similar pattern. Future precipitation has rare spikes which may turn blessing into disaster. This depicts persistent hot and dry conditions in Quetta, indicating a trend that could have significant implications for the local community. Such prolonged weather patterns emphasize the need for effective water adaptation strategies in the region.



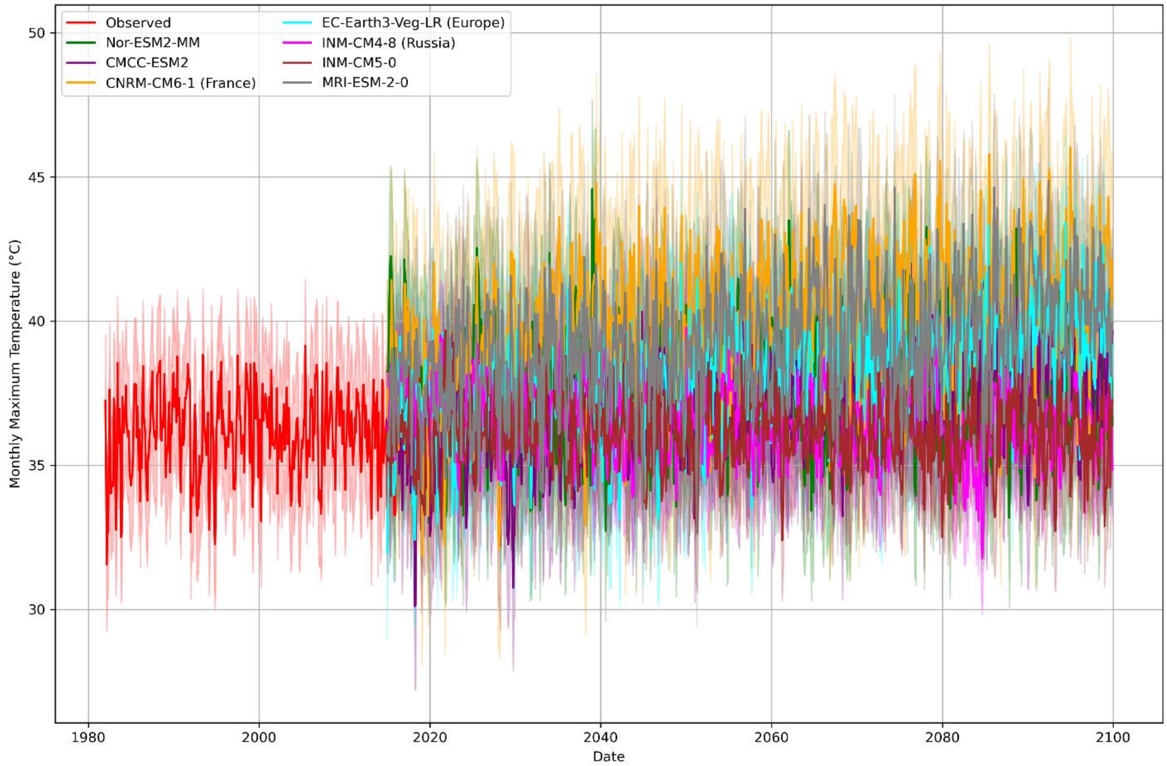
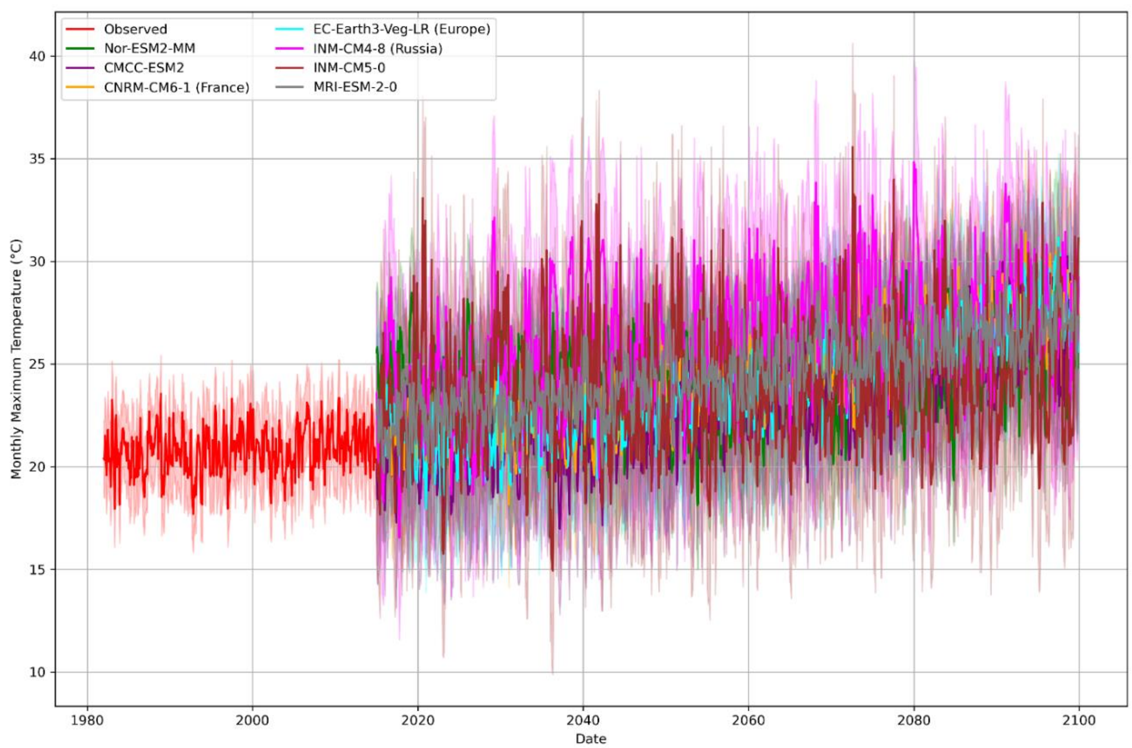


Figure 6|Fluctuations in temperature minimum and maximum under the SSP585 scenario



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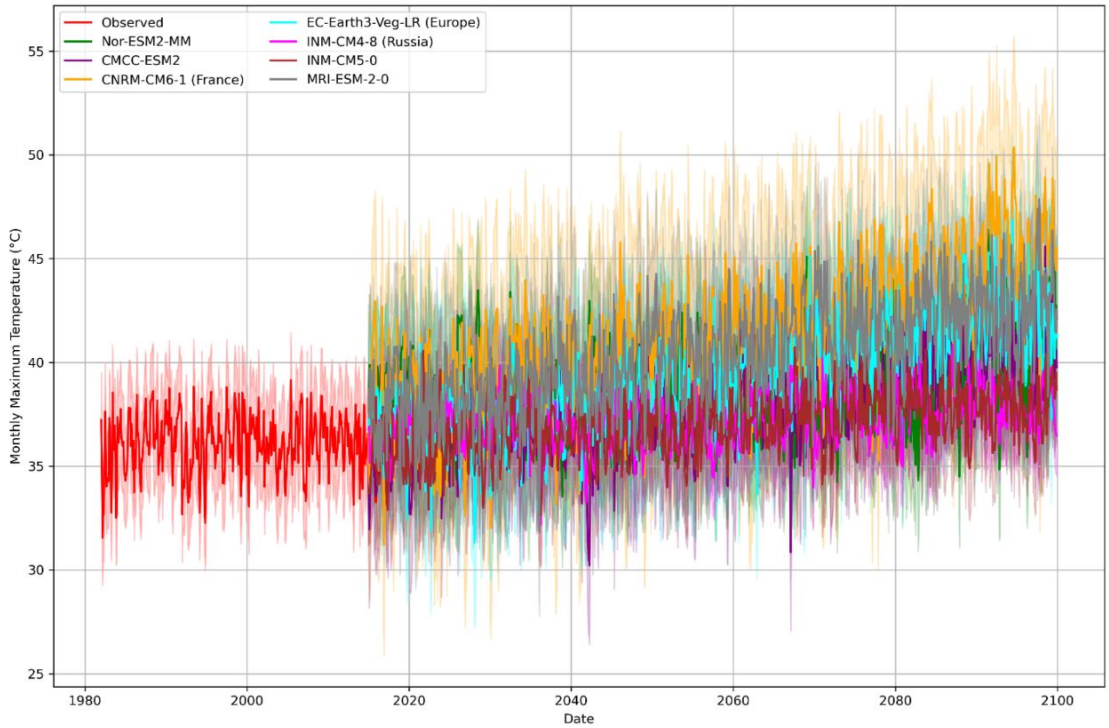
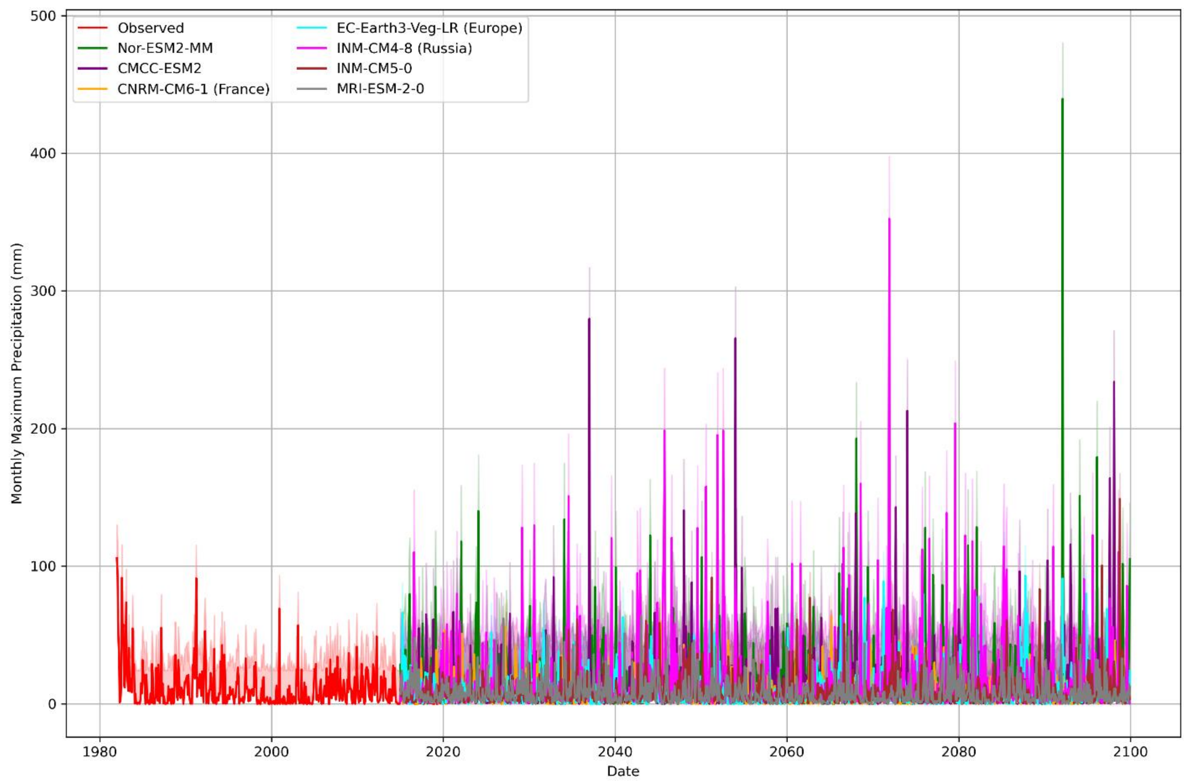


Figure 7|Fluctuations in temperature minimum and maximum under the SSP245 scenario



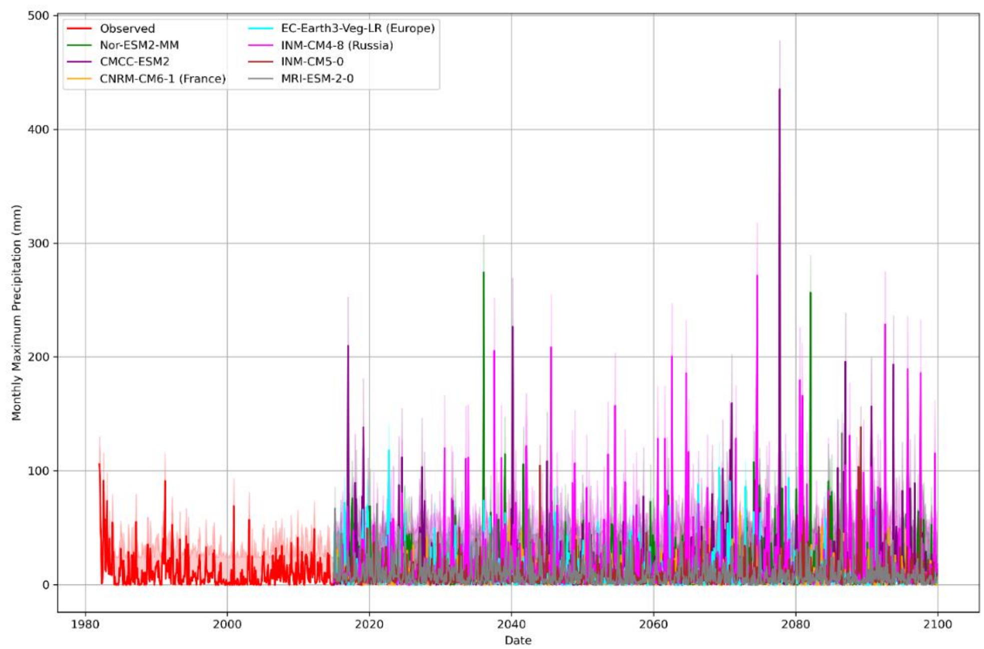
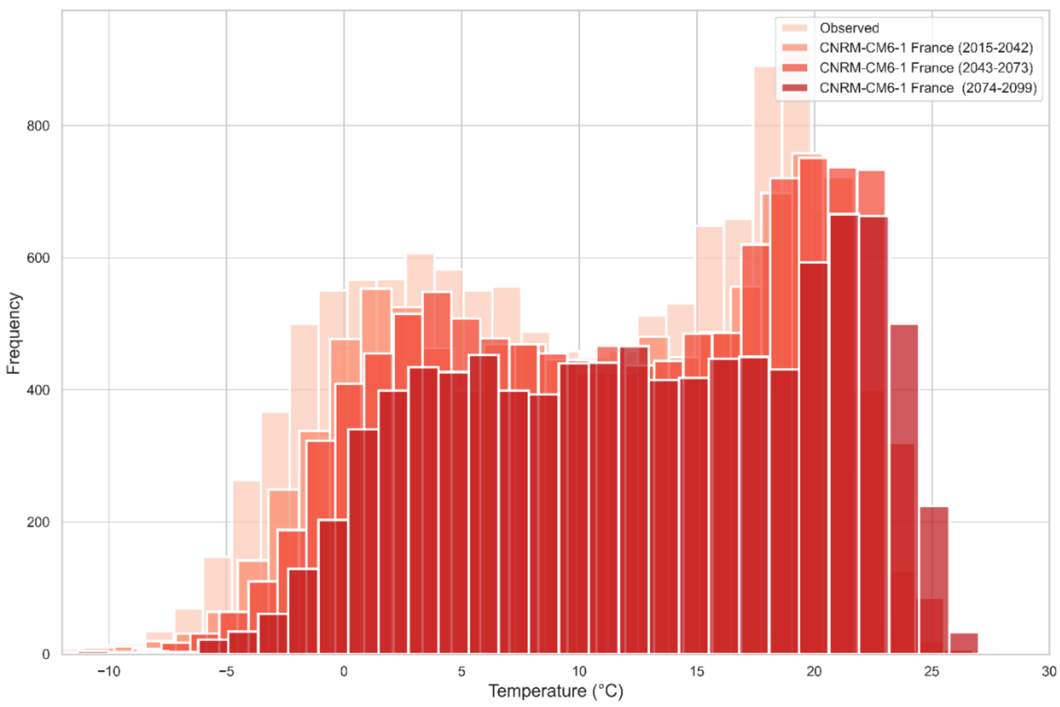


Figure 8|Fluctuations in precipitation under the SSP245 and SSP585 scenarios

To assess shift in both temperature minimum and maximum based on SSP245 and SSP585 scenarios, the future data was split into 27 years' time period. Observed data was used as baseline to assess any shift in temperature for the aforementioned 3 time periods. It is worth notable that there is right shift in temperature for all SSP scenarios as obvious from Figure 9 and Figure 10. Moreover, the magnitude of shift in far future temperature is comparatively higher in comparison to near and mid future. This suggests that temperature will increase in Quetta in future. This trend indicates a significant warming pattern for the region, which could have various implications for the local community.



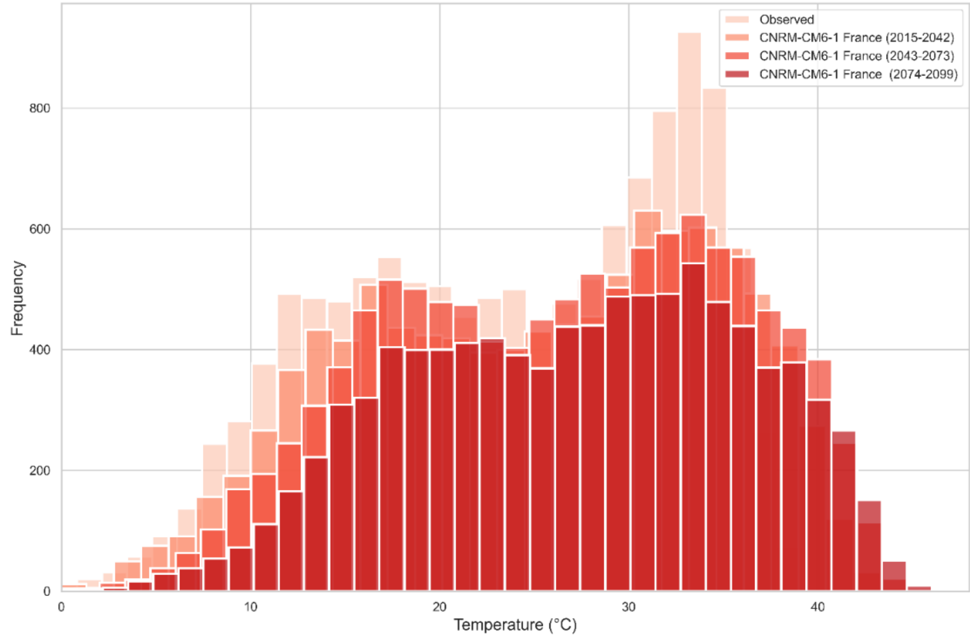
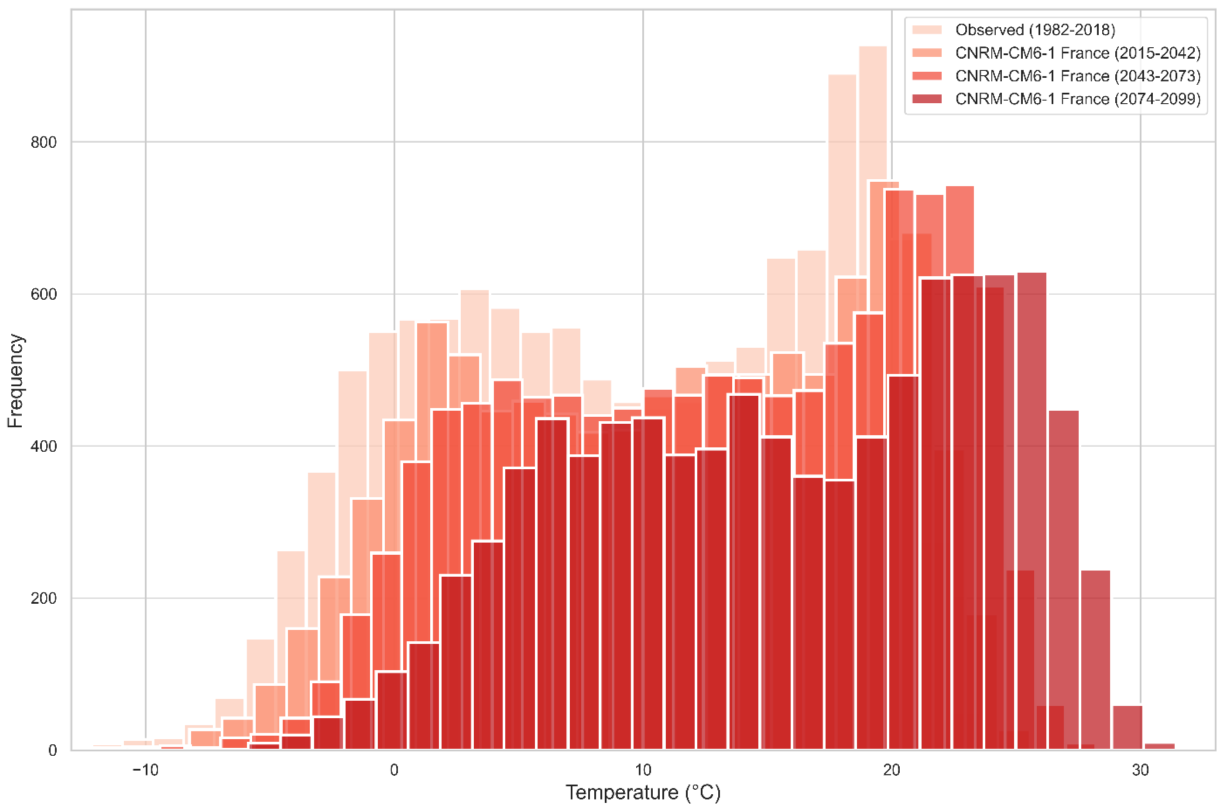


Figure 9|Frequency of occurrence for Tmin and Tmax for various time periods based on SSP245



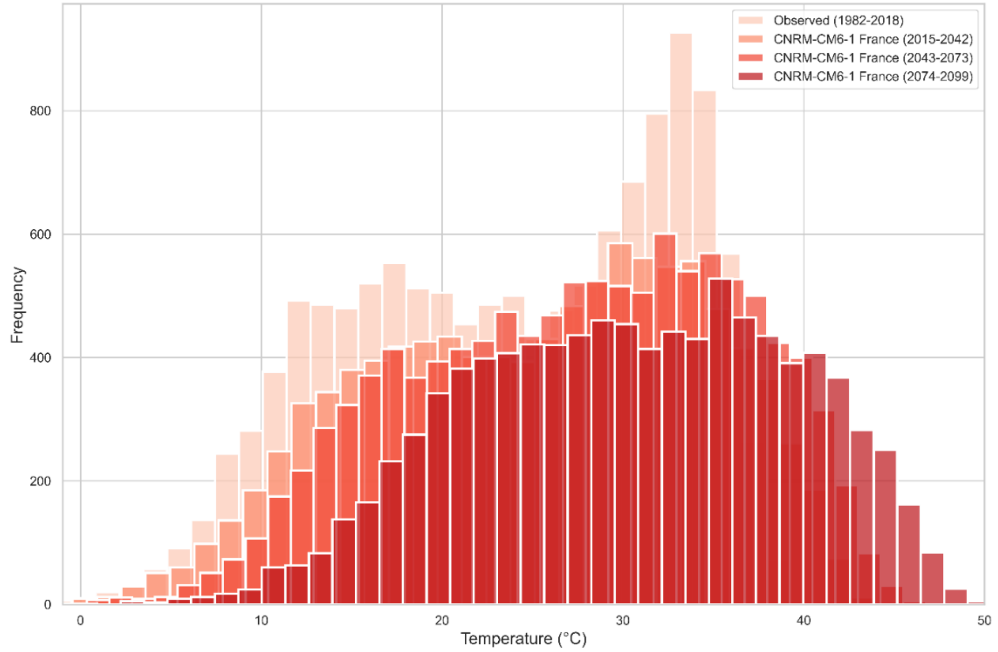


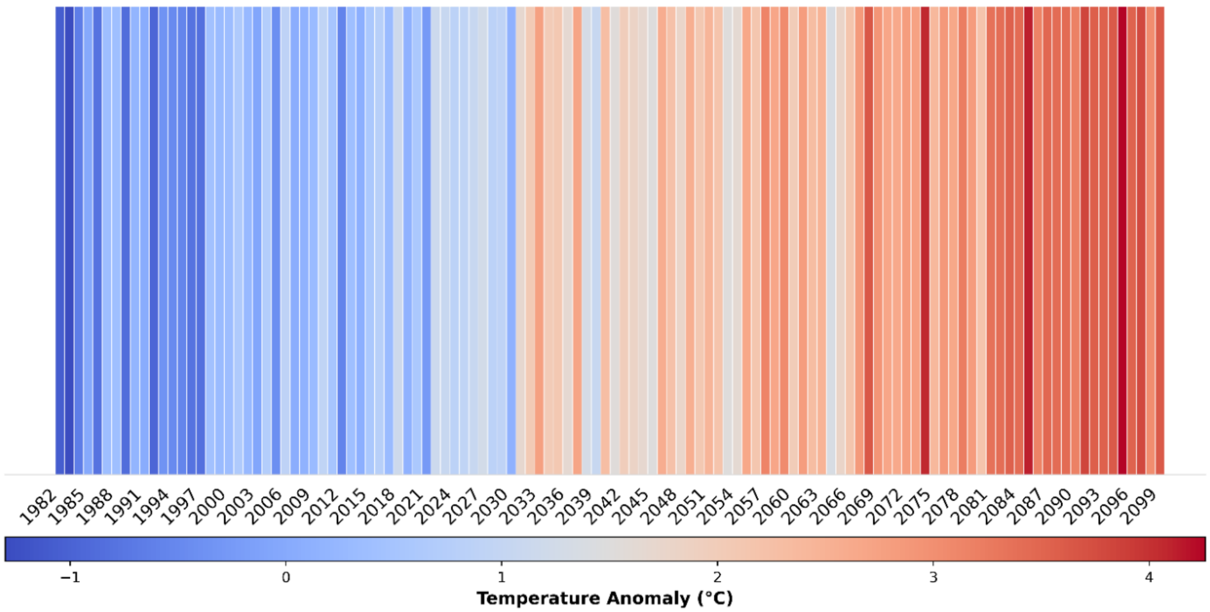
Figure 10|Frequency of occurrence for Tmin and Tmax for various time periods based on SSP585 scenario

Anomaly in climate — past, present and future — always need to be understood in the context of the naturally occurring variability. In this project, anomaly was estimated using the below mentioned equation:

Anomaly = annual mean future precipitation/temperature – baseline mean precipitation/temperautre

In this project baseline period was seleced from 1982 to 2018. The anomaly in temperature minimum and maximum under SSP245 ranges between -1 to 4^{o}C, and -1 to 8^{o}C respectively as obvious from Figure 11. Similarly, the anomaly in temperature minimum and maximum under SSP585 ranges between -2 to 5^{o}C, and -2 to 8^{o}C respectively as obvious from Figure 11. The findings of the current project shows that anomaly of SSP585 is higher than SSP245 for both temperature minimum and maximium. The above discussion indicates that Quetta district is likely to experience a hotter climate in the future compared to baseline period.

For precipitation, anomaly was estimated for both SSP scenerios. The anomaly in both SSP245 and SSP585 ranges between -0.5 to 2mm as demonstrated by Figure 12. It's worth noting that the anomaly of SSP245 and SSP585 is approximately similar. The Figure 12 shows uneven changes in future precipitation. Moreover, it is also notable that future precipitation is lower than baseline period especially in SSP585. The aforediscussion shows that Quetta district is likely to experience a dry climate in the future compared to baseline period.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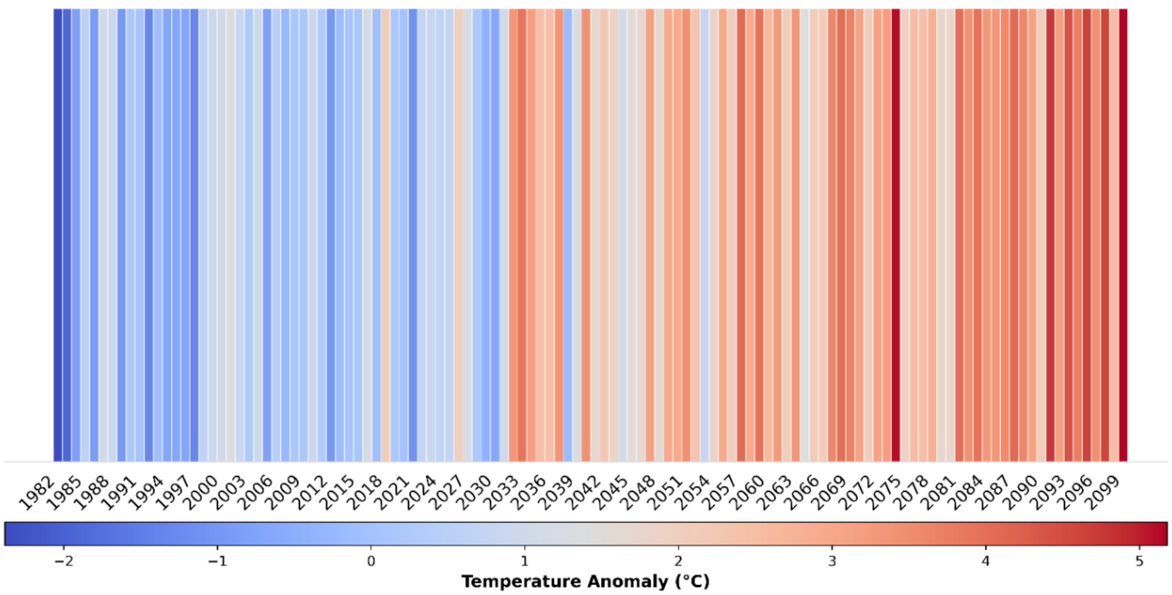
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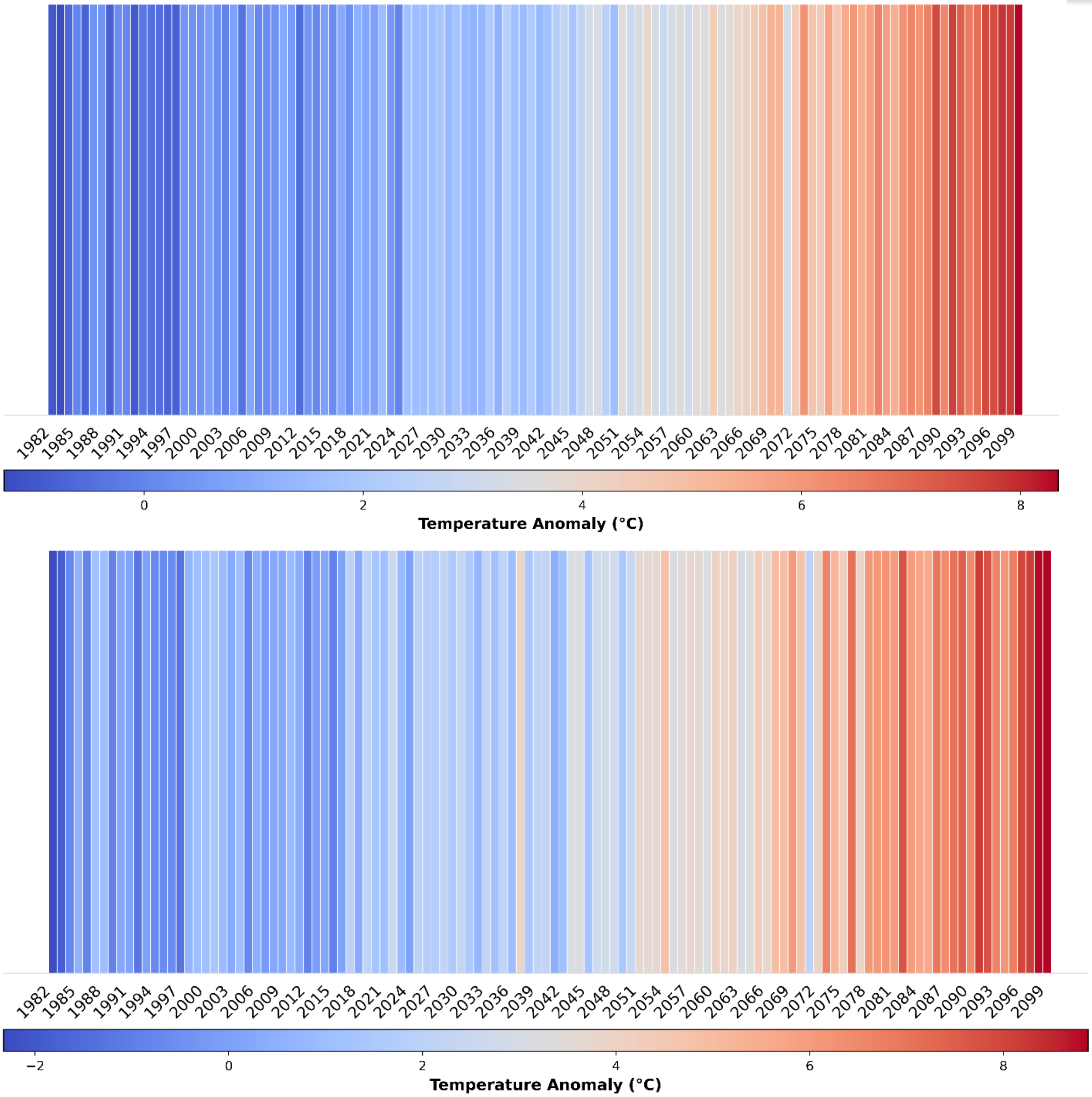
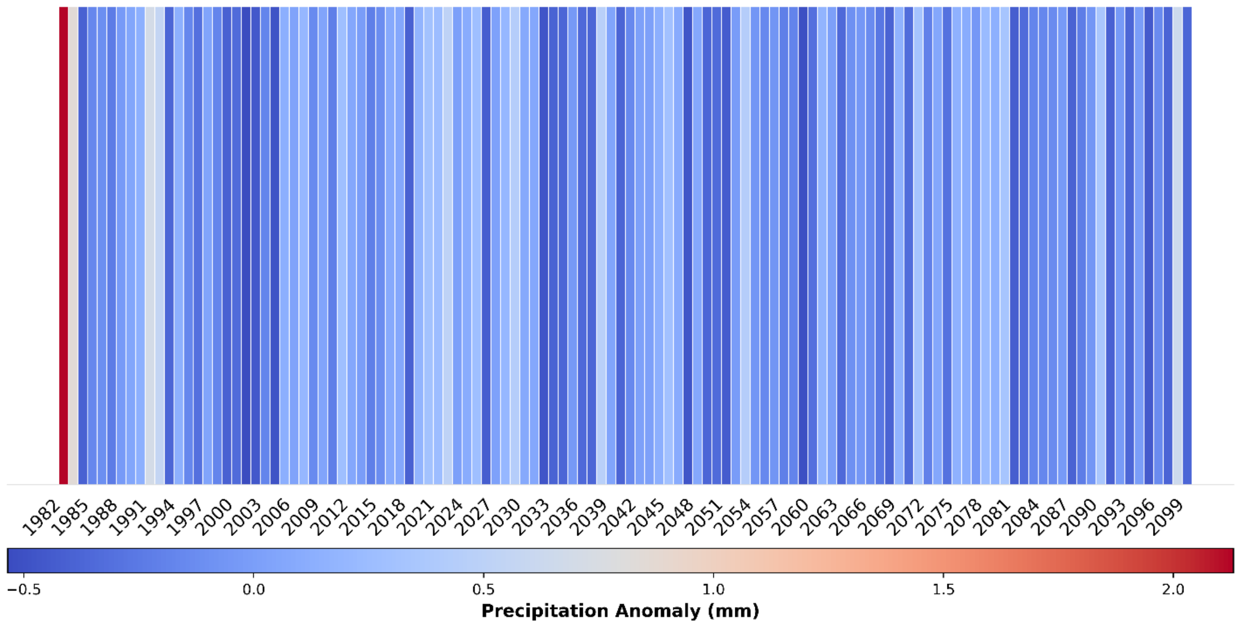


Figure 11|Anomalies in minimum and maximum temperatures under the SSP245 and SSP585 scenarios



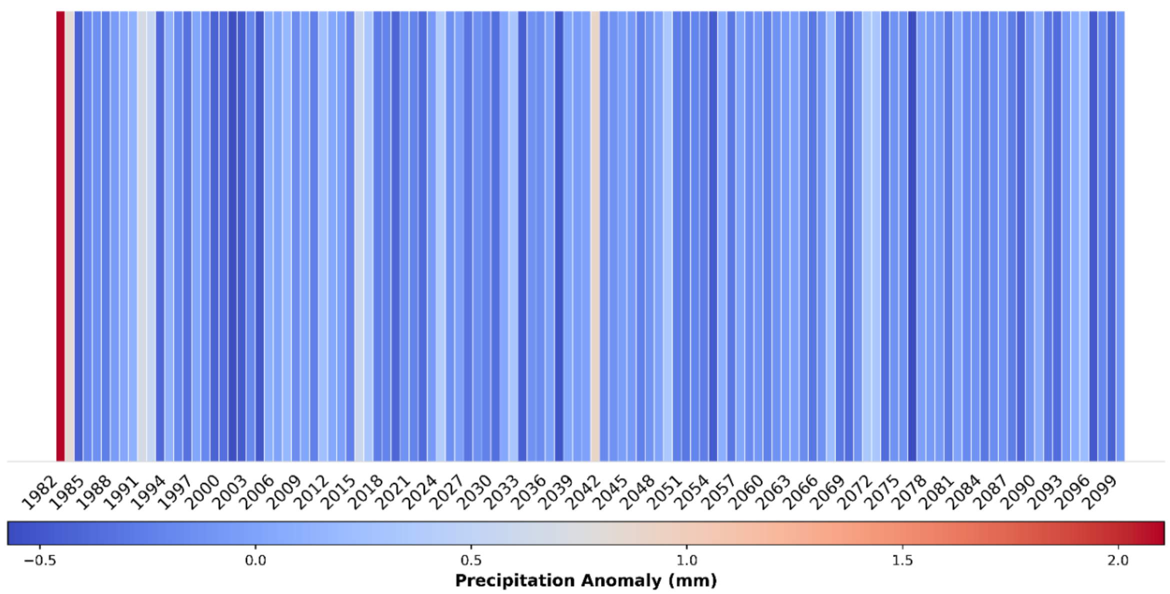


Figure 12|Anomaly in precipitation under (a) SSP245 and (b) SSP585 scenarios.

5.4 Trend of meteorological parameters

Trend analysis of meteorological parameters involves examining historical and future data to identify patterns and changes over time in various meteorological variables. This analysis helps to understand the behavior and long-term alteration in climate. By analyzing trends in meteorological parameters, climatologists and policymakers can make informed decisions to mitigate the impacts of climate change.

Table *1* clearly shows significant increasing trends in both minimum and maximum temperatures under SSP245 and SSP585. It is notable that historical and future temperature showed increasing trend. This gives an idea that temperature will enhance in future in Quetta district. In contrast, observed precipitation showed decreasing while SSP245 and SSP585 showed increasing trend. These findings suggest that the project area will observe hot and wet climate in future. Based on these findings, climatologists, hydrologists, and policymakers can develop informed adaptation strategies for hot and wet climates.

Table 1|Trend analysis of meteorological parameters

Station	Observed/SSP scenario	P value	Tau	Sen slope	Trend
Quetta	Observed (Tmax)	0.0000000014	0.0346	0.00011	Significant
	Observed (Tmin)	0.00000000056	0.0355	0.0001	Significant
	SSP 245 (Tmax)	1.033e-67	0.0657	0.00010	Significant
	SSP 245 (Tmin)	2.439e-97	0.079	0.00010	Significant
	SSP 585 (Tmax)	0.0000000	0.147	0.000237	Significant
	SSP 585 (Tmin)	0.0000000	0.175	0.00024	Significant
	Observed (Precipitation)	0.000000045	0.037	0.000046	Significant
	SSP 245 (Precipitation)	0.0094	-0.0117	-0.0000055	Significant
	SSP 585 (Precipitation)	0.000013	-0.019	-0.0000043	Significant

6 Discussion:

This study presents strong evidence of climate changes in Quetta with significant increases in temperature and a statistically significant decrease in the level of precipitation annually. The Mann-Kendall trend test, applied to observed data, supports a negative trend in precipitation, indicating a progressive change toward drier conditions. While seasonal changes persist, the long-term pattern shows an overall trend of rising aridity.

The analysis of temperature records shows a strong warming trend in both observed records and projections using CMIP6 models. In looking at the SSP5-8.5 scenario, the projection is that the high temperatures will rise by more than 8°C over historical means, suggesting an amplified threat of heat-related impacts in the next decades.

The findings of this study are supported by previous studies. Research [11] reported a significant increase in warm temperature extremes over the past sixty years, while research [20] projected a regional temperature rise of +0.025 °C/annum. Precipitation shows a moderate but consistent decrease in the range of −2.94 mm/year, depicting a trend towards a progressively hotter and drier climate in southwestern Pakistan. The Sixth Assessment Report of the IPCC also projects South Asia to warm at a faster rate than the global average, along with reductions in winter and spring precipitations and a rise in evapotranspiration. These climatic changes are projected to increase stress in arid and semi-arid regions, endangering agricultural yields, recharging groundwater, and urban water supplies in already water-scarce regions [5].

Consistent with our results, Study[21] found significant decreases in rainfall over Balochistan and Pakistan, and it affirmatively stated that Quetta exhibits a similar trend toward increasing aridity. Local patterns of precipitation, However, high seasonal variability continues to characterize local precipitation patterns.

The cumulative impacts of increasing temperatures and decreasing or uncertain precipitation worsen increasing exposures for agriculture, water supplies, and urban infrastructure in this already climate-stressed region. These alterations heighten the necessity of adaptive planning, such as water-saving agriculture, climate-resilient infrastructure, and sustainable natural resource management.

7 Conclusion:

Climate change is a global problem with far-reaching effects across various sectors. Climate change is a cause of human life loss and has wide-ranging social, environmental, and economic effects. In the context of the present study, the minimum and maximum temperature anomalies under the SSP2-4.5 scenario are observed to range from −1 °C to 4 °C and −1 °C to 8 °C, respectively. On the other hand, the SSP5-8.5 scenario reveals temperature anomalies in minimum and maximum temperatures ranging from −2 °C to 5 °C and −2 °C to 8 °C, respectively. Both the scenarios reveal precipitation anomalies ranging from −0.5 mm to 2 mm. To conclude, temperature

reveals a well-defined increasing trend, whereas precipitation reveals a declining trend.
The projected rise in temperature and variability in the rainfall regime pose critical challenges to water management, irrigation, and urban livability in this arid and resource-scarce region. Climate-resilient policy interventions must highlight climate resilience through the promotion of water-saving practices, climate-resilient city planning, and adaptive agriculture practices. As Quetta is already witnessing rising temperatures and uneven rainfall, proactive adaptation planning will need to be implemented to safeguard the region's environmental and socio-economic fabric.

Highlights:

• The multi-model CMIP6 projections of SSP245 and SSP585 were used to evaluate future conditions in Quetta Valley in terms of temperature and rainfall.

• The historical trend analysis based on Mann-Kendall and Sen slope showed that it was much warmer in the minimum and maximum temperature and there was a negative decline in the annual precipitation.

• Warming is expected to be dramatic; maximum temperature anomalies up to 8°C in 2100, SSP585 and precipitation anomalies predicting drier conditions.

• The study reveals that there is an urgent necessity to implement climate adaptation strategies like watershed management and sustainable agriculture when addressing the issue of the increasing aridity and heat stress in the Quetta Valley.

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