BE CIVIL ENGINEERING PROJECT REPORT

CLIMATE PROFILING AND TREND ANALYSIS OF CLIMATIC PARAMETERS IN PAKISTAN

Project submitted in partial fulfillment of requirements for the degree of

BE Civil Engineering

PROJECT ADVISOR Dr. Muhammad Amjad

SUBMITTED BY

PA-55793	**Captain Shabab Haider (Syndicate Leader)**	**(CMS ID. 281084)**
PA-55360	**Captain M. Aqib Khalil**	**(CMS ID. 281071)**
PA-55790	**Captain Rafi Ullah**	**(CMS ID. 281083)**
PA-55667	**Captain Ameer Sultan**	**(CMS ID. 281080)**
PA-55983	**Captain Rao Abdul Mannan**	**(CMS ID. 281089)**
PA-55851	**Captain Atta Ullah Khan**	**(CMS ID. 281087)**

MILITARY COLLEGE OF ENGINEERING

NATIONAL UNIVERSITY OF SCIENCE & TECHNOLOGY

RISALPUR CAMPUS, PAKISTAN (2022)

This is to certify that the

BE Civil Engineering Project entitled

CLIMATE PROFILING AND TREND ANALYSIS OF CLIMATIC PARAMETERS IN PAKISTAN

<u>SUBMITTED BY</u>

PA-55793	**Captain Shabab Haider (Syndicate Leader)**	**(CMS ID. 281084)**
PA-55360	**Captain M. Aqib Khalil**	**(CMS ID. 281071)**
PA-55790	**Captain Rafi Ullah**	**(CMS ID. 281083)**
PA-55667	**Captain Ameer Sultan**	**(CMS ID. 281080)**
PA-55983	**Captain Rao Abdul Mannan**	**(CMS ID. 281089)**
PA-55851	**Captain Atta Ullah Khan**	**(CMS ID. 281087)**

Has been accepted towards the partial fulfilment of requirements for BE Civil Engineering Degree

____

Assistant Professor Dr. Muhammad Amjad

(Project Advisor)

Dedication

Dedicated to our parents who prayed for us since ever and our teachers without whose support this effort would never have been completed.

ACKNOWLEDGEMENT

All thanks and praise to Allah Almighty.

We bow our heads before Almighty Allah for giving us opportunity and resources to complete this research work. There are several individuals whose contributions have been vital for completion of this project. Asst Prof Dr M Amjad, our project advisor, was beacon of guideline and driving force behind this research. He contributed valuable ideas, invaluable guidance and enthusiastic encouragement throughout our research work. Also many thanks to our faculty members and teachers for guiding and helping us whenever it was needed.

Our profound gratitude also goes to Regional Meteorological Department (KPK), Surface water hydrology department (WAPDA) and Pakistan Navy Hydrographic Department for provision of climate data.

All Syndicate members

TABLE OF CONTENTS

LIST OF FIGURES

LISTS OF TABLES

ABSTRACT

Pakistan, a resource stressed country, is considered among the top-ranked countries that are being and going to be adversely affected by climate change impacts. Moreover, Pakistan lacks in resources to properly monitor the climate processes; it has a sparse network of ground-based gauge stations. However, recent technological advancements offer some alternatives to ground-based observations; these alternatives include satellite- and model-based climate datasets. This study first evaluates precipitation and temperature datasets from such a model-based climate dataset (namely ERA5) using data observed at 15 ground-based gauge stations as reference, and then it conducts a comprehensive climate profiling and spatial trend analyses of Pakistan using ERA5. Initial evaluation was conducted at daily and monthly time scales and the results show that ERA5, despite some discrepancies, quite efficiently match the fluctuation patterns of observed data as it showed acceptable values of correlation coefficient (CC) at both daily (precipitation CC: 0.35, temperature CC: 0.96) and monthly (precipitation CC: 0.76, temperature CC: 0.98) time scales. Climate profiling and trend analyses using ERA5 climate data concluded that the annual precipitation in KPK has strong decreasing trends up to 10 mm/year and most regions (including the northern glacial regions) of Pakistan are getting hotter with the spatial trends showing an increase in temperature of above 5 ^{o}C/century. Moreover, most regions of Pakistan are getting drier and hotter due to which there could be increasing frequencies and intensities of extreme events in Pakistan. The findings of this study might be beneficial for various stakeholders / target sectors including researchers investigating climate change impacts, water resource management sectors, and water and power regulatory authorities.

CHAPTER 1

INTRODUCTION

1.1. Background

One of the greatest threats to the earth and its inhabitants is a rapidly changing climate. The primary cause of environmental damage in the universe is global warming. Greenhouse gas emissions from fossil fuel combustion are causing the Earth's average temperature to rise as well as polluting the atmosphere. There are a number of natural disasters that result from climate change, such as flooding and drought. The economy is also affected by this increase in the Earth's temperature. It is projected that the rapid rate of climate change will have significant effects on Pakistan, including decreased agricultural production, water scarcity, increased coastline erosion, and a rise in the frequency of devastating hydrometeorological extremes, such as flooding and coastal erosion. As a result of its geographical location, Pakistan has been named among the top ten countries most impacted by climate change over the past twenty years, according to German Watch (Finance.gov.pk, 2020).

Climate change has become a global issue in the last 2 decades because of its predicted effects on vulnerable regions' environments. Many parts of the world are experiencing an increase in temperature, which is having an impact on the cryosphere and precipitation. Large-scale trends of climate change are causing concern that Pakistan would suffer.

Changing precipitation patterns in space were a major cause of climate change, and they were linked to shifts in the region's atmospheric circulation. Water, agriculture, and disaster management are directly impacted by changes in precipitation patterns. Many natural disasters, such as floods, cyclones, drought, and intense rainfall, are a threat to Pakistan according to the Task Force on Global Warming (2010). (Salma et al., 2012). In addition to its standing in top most affected countries in the world, Pakistan’s socioeconomic conditions also render it a weak and easy target for the disastrous impacts triggered by natural hazards originating from climate changes (Finance.gov.pk, 2020)

1.2. Problem Statement

People in Pakistan are concerned about the immense social, environmental, and economic consequences of climate change. Floods, droughts, and cyclones are all natural disasters that Pakistan is vulnerable to. Combined with vulnerabilities (e.g. poverty, isolation, and poor political decisions), these risks make people more vulnerable to their effects. Variations in cropping and its production as a result of climate changes, will have a direct impact on the poorest areas in the country. It is the dry land areas, including desert and semi-arid regions, that are most sensitive to these changes since they face water problems and high temperatures that are already a great concern there.

The rain gauge network has remained conventional method that has been most commonly used for measuring climate parameters such as temperature and precipitation. However, the density and spatial patterns of the rain gauge networks deviate significantly across the globe. The measurement of precipitation and temperature through station gauges has been considered a reliable and precise method. However, in far-off areas and ocean bodies, the density of these station gauges is relatively scarce thus limiting the availability of gauge data. Weather radar can also be used for measurement of climatic parameters, but it is necessary that the radar systems should be covering the large areas and must be calibrated according to the nature of precipitation. Pakistan, being a resource-stressed country, lacks in monitoring resources for weather and climate processes.

Inclusion of Pakistan in the list of top most affected countries in the world necessitates that it must have a strong and reliable network of ground-based gauge stations to properly monitor the weather and climate processes. Moreover, diverse geo-climatic variability of Pakistan also strongly requires a dense network of observation stations. However, this is unfortunate that Pakistan, mainly due to lack of economic resources, has a sparse network of observation gauge stations that lags behind the required standards both in quantity of gauge stations and quality of data observation. On the other hand, precise and reliable forecast and estimation of precipitation and temperature can help in improving the processing and modelling of water budgeting, water consumption, flood and droughts forecasting, and determining crop water necessities. Periodic changes in magnitude and patterns of precipitation and temperature are significant indicators of climate change. Pakistan, as mentioned earlier, lacks in weather and climate monitoring resources.

Given the sparsity of gauge station-based observation network in Pakistan, gridded (i.e., spatially continuous in nature) datasets originating from satellites and climate models could be considered as potential alternative sources of climate data. However, quantification of error uncertainty in these model- and satellite-based datasets is a pre-requisite before they can be used as potential alternatives to gauges data.

Therefore, the main motives of this study include:

1. Pakistan being among the worst affected countries in the world due to climate change impacts.
2. Lack of ground-based resources for climate monitoring in Pakistan.

1.3 Literature Review

1.3.1 Global Level

` A significant warming trend in temperature and precipitation was observed in the past few decades in entire world in general and Pakistan in particular. Shen et al. (2022) analysed temperature trends using ERA5 in some major countries i.e., Greenland, Ukraine, Russia, New Zealand, South America, Southeast Asia, and Southern Africa from the 1980s to 2019. The results of the study was compared with the existing research. During the period 1981–2019, the global land temperature changed by 0.320°C/10a per year, which is somewhat greater than the previous results.

Sharma et al. (2020) conducted the study in Nepal using ERA5 data set to check the dominant pattern of year-to-year variability of summer precipitation in Nepal during 1987–2015. A deeper understanding of the primary patterns of summers precipitation variability throughout Nepal from 1987-2015 is provided by this research. The findings are profound. According to the annual cycle of precipitation, 80 percent of the precipitation occurs in summer, with the greatest quantity occurring in the central parts of Nepal.

Meng et al. (2021) carried out the study to check the variability of summer atmospheric water cycle over the Tibetan Plateau and its response to the Indo-Pacific Warm Pool using Remote sensing, ERA5 monthly dataset. This shows that the water cycle mechanism of the TP and its main constituents has increased during the last 62 years. Evapotranspiration exhibited a clearly growing trend while total intake and output water vapour decreased. Diana Francis and her colleagues used ERA5 and

ERA-Interim to analyze a summertime convective event that occurred over UAE on September 5, 2017. Temperatures dropped 7°C, wind speeds doubled, and the wind direction shifted from easterly to southerly to westerly within 45 minutes of each other at a meteorological station near the surface of the Earth.

1.3.2.Local level

Bank (2019) has conducted study on mean rise in temperature of south Asian region and has done profiling and found out that a trend of about 0.57°C increase is temperature was observed, in the past century between 1901-2000 in Pakistan. This is less than the mean yearly temperature of 0.75°C in the past century in the South Asia region. A more intense trends of warming, with the temperature of 0.47°C, was configured from 1961 to 2007 in a country. The warmest year recorded was 2004, when the temperature ranges from 0.52°C-1.12°C.

Pomee & Hertig (2021) carried out study on assessing Tmax and Tmin over Pakistan (Indus river basin) for the span of (1976–2005). This discovery shows that water cycle process and main constituents have improved over the last 62 years. Although water vapour intake and emission were decreasing, evapotranspiration was clearly rising. Researchers used ERA5 and ERA-Interim to analyze convective activity over the UAE on September 5, 2017. At a meteorological station close to the surface, temperatures dropped by 7 degrees Celsius, sustained winds increased, and the predominant winds shifted from east to south to southwest in 45 minutes.

Arshad et al. (2021) analyzed weather and climate extremes on climatic diversity regions of Pakistan. In the research, five geographical areas were selected for consideration; "region A, region B, region C, region D, and region E". ERA5 and CFS-2 both revealed that precipitation intensities and severe precipitation occurrences (95th percentile) could be accurately recorded by ERA-5. In contrast to MERRA-2, JRA-55 underestimated precipitation in places with lower annual average precipitation, but ERA5 captured precipitation intensity accurately. In terms of root-mean-square deviation (1.53 mm), the ERA5 closely tracks the rain gauge data.

Ullah et al. (2021) had carried out study for checking large-scale atmospheric circulation patterns associated with extreme monsoon precipitation in Pakistan span between 981-2018. It was shown that exceptional monsoon precipitation occurrences may be traced back to two approaches, namely the "Empirical Orthogonal Function (EOF) and the Percent Normal (PN) indices", both of which were employed in the statistical reanalysis. The results indicated that the leading EOF was responsible for

60% of the variation and portrayed the high floods and drought years.

Tariq et al. (2014) had carried out study over region of Gilgit-Baltistan and checked temperature and precipitation gauge with special focus on analysis of GLOF (Glacial Lake Outburst Flood) for the period from 1994 to 2012. For GLOF occurrences, meteorological data from Pakistani Meteorological Department, Pakistan WAPDA Pakistan, and the National Centre for the Environment Prediction were utilized. The research found that these occurrences followed a brief period of rainfall or a spike in temperature, following which they were analyzed using precise dates and locations. This suggests that the combination of rainfall, temperature rise, and heat waves might increase the likelihood of a glacier lake's outburst.

Dilawar et al. (2021) had conducted study using Up to date ground based observations and analysis was performed on RclimDex software. Study was conducted in Pakistan and this research scrutinize the effect of climate extreme variability in drought changes (i.e., yearly and the seasonal trends) in the AEZs (Agro-ecological zones) . The drought characteristics (frequency, duration, and intensity) were investigated at SPEI timescales (SPEI-1, SPEI-3, SPEI-6, and SPEI-12). Overall, rising trends of SPEI and temperature extremes over the last 40 years were discovered, with distinct temporal patterns over the different AEZs. Temperature indices indicated the increasing trend of warming in all AEZs during the period 1980–2019 in Pakistan. On yearly scale, the mean Tmin increased significantly more than Tmax in all zones. During 1980 to 2019, the trend of intensity and frequency of precipitation in all AEZs throughout Pakistan was lessened.

Ali et al. (2022) had conducted study over Pakistan for period of (1985–2015) using ERA5. Climate extremes might have a negative influence on wheat and wheat cotton harvests in Pakistan's Punjab province. Annual total rainfall and the number of consecutive rainy days in all regions increased, as did the maximum temperature. Study by Saifullah et al. highlighted the Kunhar River Basin in Pakistan's climatic change and human effect on runoff characteristics. ERA5 was used to conduct the analysis, and the results revealed an increasing trend in rainfall.

Rashid et al. (2022) conducted a study of 1981 to 2018 about El Nio–Southern Oscillation teleconnections affected early summer surface air temperature fluctuation across Pakistan. Early summer (May–June), also referred as the (pre-monsoon) period in Pakistan, had the largest SAT anomalies compared to the subsequent monsoon season (July–September). SAT over Pakistan and Nio3.4 SSTs have a

Correlation Coefficient of 0.43.

Dahri et al.(2021) study on Global warming and hydrogeological system of the high-altitude Indus using ERA5, which has shown an increase of 0.6 degrees Celsius over the last 40 years; the median annual air temperature is projected to rise by 0.8 to 5.7 degrees Celsius at the conclusion of this century. Pakistan. Similarly, annual precipitation has decreased by 11.9 percent, although future forecasts are very ambiguous and geographically varying. Forecasters predict a rise in rainfall in the Karakoram area and a decrease in precipitation in other regions, including sections of the W-Himalayan region. Under warm-wet and cold-dry conditions, the Indus Tarbela inflows are expected to grow by 17.0–73.6 percent and 1.2–9.7 percent, respectively, during the months of April through July. For the lower Kabul River basin, seasonal changes are expected to be moderate, with river inflows decreasing somewhat under cold-dry predictions and increasing slightly under warm-wet scenarios.

Jan et al. (2022). In this investigation, we used "CHIRPSv2, MSWEPv2.2, PERSIANN-CDR, and ERA5" data sets. Specifically examined were Spatio-temporal assessments of gridded rainfall, evaporation and transpiration products over Pakistan's Baluchistan Province ERA5 had r values ranging from 0.68 to 0.88, with the majority of stations falling within the 0.68 to 0.80 range.

Mentioned above studies shows that ERA5 data set is well grounded and definitive and assessment carried out based on ERA5 data shows pertinence and accuracy.

1.4. Literature Gap

In Pakistan, change in climate is expected to have wide range impacts, such as: reduced agricultural production, increased inconsistency of water availability, increased coastal losses and sea water intrusion, and enhanced frequency of severe climatic events. Different studies have been performed to foresee the tendencies of climatic parameters in Pakistan and those studies where it has been focused on either station data or gauges data. No zoning and profiling of the regions based on assessment of both gauge station and station data were carried out.

So, in order to fill the gap study is primarily focused on evaluation and ensuring the reliability and precision of various gauge stations data and its comparison with ERA5. During evaluation of both the data's, their relative accurateness has been checked with the aid of a variety of statistical tools. Climatic data obtained from gauge stations shows a stretch in location and predicts the maximum regions of Pakistan. After evaluation and checking the reliability, the climatic profiling of complete Pakistan has been carried out.

Most of the profiling carried out in Pakistan in past involves studies basing on local station data. But this study involves climatic profiling of complete Pakistan basing on data acquired from ERA5, which is reliable and precise as it has been used for several research purposes in different countries. This study is focused on ERA5 reanalysis and its data is applied for climatic profiling and zoning of Pakistan.

1.5. Objectives

Objectives of this study are:

1. Performance evaluation of a climate reanalysis dataset to be considered as a potential alternative to gauge-based observed data
2. Climate profiling, trend analyses, and zoning of climate parameters in Pakistan

1.6. Scope of the study

Given that Pakistan is among the top most countries that are being affected or going to be affected in the future due to the climate change, a comprehensive climate profiling of Pakistan can be useful for disaster risk managers and decision makers related to sectors such as water resources and agriculture. The findings of this study might be beneficial for various stakeholders / target sectors that include the researchers investigating climate change impacts, water resource management sectors and water and power regulatory authorities.

CHAPTER 2

MATERIALS AND METHODS

2.1. Study area

2.1.1 Geology of Pakistan

Pakistan is a large country (796096 sq. kilometers in size) with a composite structure, which replicates its location at the edge of the Eurasian, Indo-Pakistan and Arabian plates Pakistan, positioned in the north-western part of the South Asian subcontinent. It is a geographical mass with a diverse terrain, with immense plains in the Indus basin, a rocky stretch of plateaus in the southwest, and breathtaking highlands in the north with stunning valleys, snow-covered mountains, and glaciers. The Indus basin is home to some of the world's largest plains. The latitude of Pakistan ranges from 24 degrees to 37 degrees north, while the longitude is from 61 degrees to 75 degrees east. Because of its geographical variety, Pakistan is divided into six primary regions: the Northern Hilly Region, the Western Low Mountain ranges Region, the Baluchistan Plateau, the Pothar Highlands, and the Punjab and Sindh fertile plains. From Ladakh all the way up to Chitral and beyond, the Karakoram and Hindu Kush Mountains come together to form an arching chain that runs east to west through the very top of Pakistan. These territories include a portion of the Himalayas, the Karakoram Range, and the Hindukush Mountains.

Large dams like Tarbela and Mangla, as well as important rivers like the Indus river and its tributaries, may be found in Pakistan. Karachi, Rawalpindi, Islamabad, and Peshawar are the major urban centers that fall under the scope of this research. The Potwar Plateau may be found in the middle, which is dry yet cultivable land due to its location. The majority of has a climate that is classified as semiarid, and the annual rainfall totals are lower than 25 centimeters (cm). More than one hundred centimeters of precipitation are often received annually in the northern portion of the belt. At an elevation of 510 meters, the average minimum temperature in Rawalpindi is 14.8 degrees Celsius, while the average maximum temperature is 28.9 degrees Celsius. Temperatures change related to height. The Southern Hazara Range is where you will find the highest elevations in the Potwar region; these ranges often have heights that are more than 1,200 meters above mean sea level. The Indus River Plains and the Jhelum River Plains both have water lines that are lower than 300 meters, hence these areas have the lowest altitude in the region. The heights in the

Potwar Plateau range anywhere from 300 to 600 meters.

A typical desert may be found in the south-eastern section of the Indus plain, which extends from the eastern half of Bahawalpur to the Thar Parkar area in the south. It is very reliant on the quantity of water that may be obtained from a variety of sources. Cholistan is the biggest desert in the Punjab province of Pakistan and may be found on the Pakistani side of the international border with India. The landmass that extends between longitudes 69°52′ to 73°24′ East and latitudes 28°42′ to 29°25′ North has a total size of 26,300 km2 and an elevation of 89 m above mean sea level. It is bounded to the north by the district of Bahawalnagar and to the south by the district of Rahimyar Khan. It stretches from the east to the south of an irrigated track in the district of Bahawalpur. This area has an unusually hot and dry climate, with mean maximum and minimum temperatures of 55 and 27.5 degrees Celsius, respectively, and low and infrequent annual average rainfall of around 160.5 millimeters.The major characteristics of the summer climate include very high temperatures, low relative humidity, a significant degree of evaporation, and intense dust storms.

2.1.2 Climate of Pakistan

Near the Tropic of Cancer, Pakistan is in the temperate zone. Pakistan has four distinct seasons: a warm winter (December to February), a hot spring (March to May), and a rainy autumn. During the spring rainy season (or southwest monsoon) from March to May; the summer rainy season (or southwest monsoon) from June to September; and the waning monsoon season (from October to November). Seasons begin and end at different times depending on where you live. Tropical to mild weather may be seen throughout the year. Dry conditions prevail in the coastal south, where the monsoon season brings adequate rainfall and the dry season brings less, whereas Punjab receives enough of rain and has vast temperature variations between extremes. There has been a statistically significant increase in Punjab's average annual rainfall of 3.23 millimeters per year (p=0.016) in both the summer and autumn seasons.

As little as 10 inches of rain may fall in certain areas of the country, while more than 150 inches might fall in others. These generalizations, however, should not mask the specific distinctions that occur in certain regions. For example, the Arabian Sea coastline is normally mild, but the Karakoram Range and other mountain ranges are usually covered in snow and frozen to the summits. Climbers from across the globe can only make it to the far north for a few weeks each year in May and June since it is so frigid there all year round. To understand Pakistan's climate, it is important to understand how aridity manifests itself in the country's extremes in temperature. In Pakistan, the country is situated on the brink of a monsoon. Forecasts for the amount of precipitation are poor, and the amount of precipitation itself is very erratic.

Due to its geographical location, Sindh is protected from both the southwest monsoon from the Indian Ocean and the northeast receding monsoon, which is redirected towards it by the Himalayan Mountains. Sindh receives an average of 8–9 inches (20–23 centimeters) of rain each year. A daily high of 38 °C (100 °F) may be seen in the city of Islamabad, Pakistan's capital, during the summer months. Nearly 300 millimeters (11.81 in) falls in July and August, which is about half of the year's rainfall. The rest of the year sees just approximately 100 millimeters (3.94 inches) of rain every month. In the spring, hailstorms are prevalent.

Karachi, Pakistan's largest metropolis and industrial center, is more humid than Islamabad, but receives less rain. Only July and August in Karachi get more than 50 millimeters (1.97 inches) of rain, while the rest of the year is very dry. Karachi's temperature ranges from a mean daily low of 13 degrees Celsius (55.4 degrees Fahrenheit) in winter nights to a mean daily high of 34 degrees Celsius (93.2 degrees Fahrenheit) in summer. Even while the summer temperatures aren't as high as they are in Punjab, the heavy humidity is nevertheless a source of concern for the locals. Increases in glacial retreat rates all across the globe have been linked to climate change. Changes in peak runoff and water balance have significant effects on water resources for agriculture, drinking, hydro-based industry, and hydropower. Climate change is to blame for this.

The monsoonal precipitation is ineffective from July through September, when high temperatures increase the amount of water that evaporates from the ground. There is an average of 13 inches (330mm) of rain each year in Peshawar and 37 inches (760mm) in Rawalpindi in the north (950 mm). Since Lahore receives around 20 inches (500 mm) of rain a year and the Indus river corridor gets less than 5 inches (130 mm), the average annual precipitation in the plains reduces from about 20 to 3.5 inches (90 to 90 mm). Precipitation rises significantly to 6 inches (155 mm) in Hyderabad and 8 inches (200 mm) at Karachi when there is a maritime influence. For dry farming, the Potwar Plateau and a portion of the Indus plain in the northeast get adequate rainfall along a 20-inch (500-mm) precipitation line that runs northwest from

Lahore (farming without irrigation).

Temperatures in the Baluchistan plateau are exacerbated by the high altitude of the northern highlands. Sea winds influence the climate along the shore. In the rest of the nation, summer temperatures may reach extremes; in the plains, where the greatest temperatures can exceed (47 °C), the typical temperature in June is 100 °F (38 °C). The hottest temperature in Pakistan was recorded at Jacobabad, Sindh (53 degrees Celsius).

2.1.3 Digital Elevation Map of Pakistan

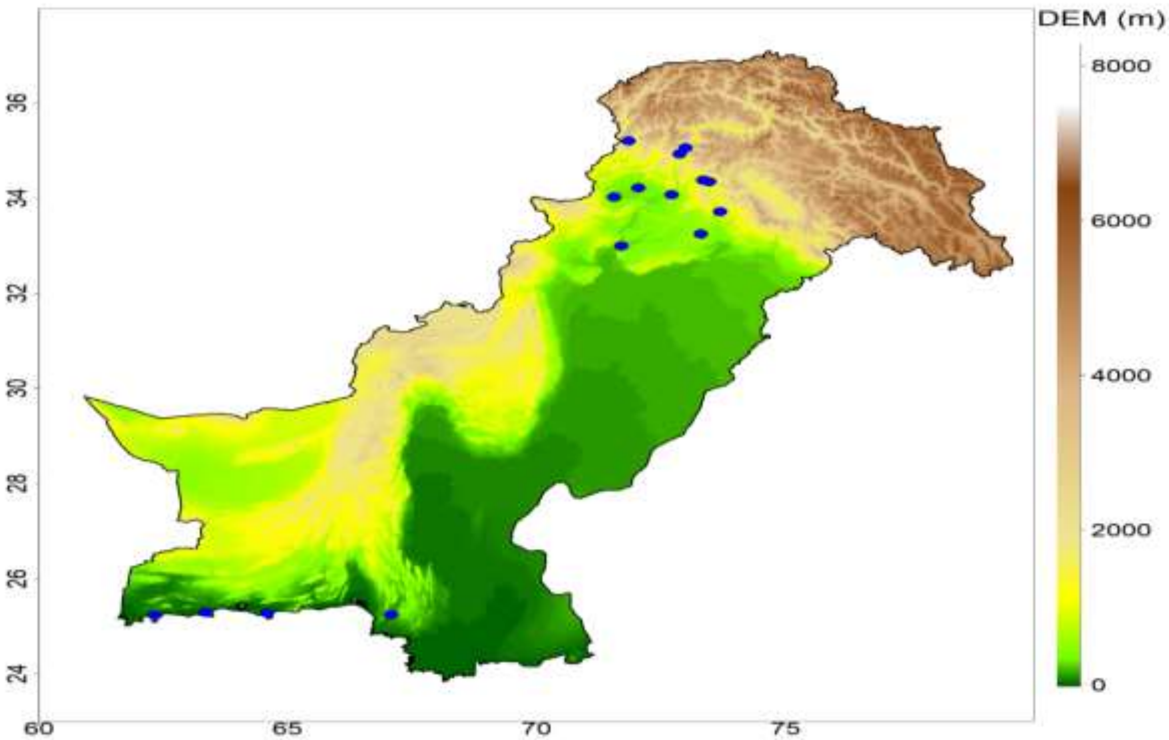

Fig 1: Locations of selected stations plotted over DEM of Pakistan

Figure 1 shows DEM of Pakistan along with the locations of selected (15 in total) stations plotted over the DEM. Three of the 15 stations, namely Pasni, Gawadar, and Ormara, are coastal stations located in south of Balochistan, while another station belonging to Balochistan province is Hub Dam. The remaining 10 out of 11 stations are situated in KPK province having relatively complex topography. Among the selected stations after quality control procedure, only one station (i.e., Gujjar Khan) is situated within the boundary of Punjab. The DEM of Pakistan shows the diverse variability of spatial elevation of different regions. For example, its North comprises of high mountains of Himalaya where the elevations of peaks climb up to more than 8000 meters above mean sea level (MSL). The central and central eastern regions are mostly flatter in nature while there exist ranges of dry mountains in western regions of Balochistan.

2.2. Data Sets

2.2.1. Observed Data

Daily precipitation and temperature data for 31 gauge stations were obtained from Regional Meteorological Department (RMD), KPK, Surface Water Hydrology Department of Water and Power Development Authority (WAPDA), and Pakistan Navy Hydrographic Department. However, several stations were excluded after quality control. The quality control procedure consisted of removing the outliers, removing stations with significant data gaps, the stations having a large number of repeated data entries, and the stations with zero long-term monthly means (i.e., missing data). Finally, data belonging to 15 ground-based gauge stations for 2010-2019 was used in the analyses after the application of the quality control procedure.

Table 2.1 shows the detail for the 15 gauge stations whose data was kept after the quality control procedure. Data sets over different stations in Pakistan were used for evaluation.

Table 2.1. Information on gauge stations in Pakistan

Ser	Station name	Coordinates	Duration
1	Balakot	34° 32’ 49” N , 73° 21’ 21” E	1979-2019
2	Dir	35° 11’ 55” N , 71° 52’ 19” E	1979-2019
3	Pattan	35° 06’ 28” N , 73° 00’ 07” E	2010-2019
4	Peshawar(AP)	34° 01’ 45” N , 71° 31’ 24” E	2010-2019
5	Hub dam	25° 14’ 39” N , 67° 06’ 47” E	2010-2019
6	Massan	31° 19’ 0” N, 72° 11’ 0” E	2010-2019
7	Gawadar	25° 15’ 07” N , 62° 17’ 07” E	2010-2019
8	Ormara	25° 16’ 19” N , 64° 36’ 30” E	2010-2019
9	Pasni	25° 15’ 25” N , 63° 24’ 54” E	2010-2019
10	Besham	34° 54’ 45” N , 72° 52’ 04” E	2010-2019
11	Domel	33° 36’ 12” N , 72° 11’ 16” E	2010-2019
12	Gujjar khan	33° 15’ 35” N , 73° 18’ 12” E	2010-2019
13	Mardan	34° 12’ 20” N , 72° 02’ 22” E	2010-2019
14	Palandri	33° 42’ 52” N , 73° 41’ 15” E	2010-2019
15	Tarbela	34° 7’ 35” N, 72° 48’ 37” E	2010-2019

Balakot's climate is humid subtropical, with hot summers and mild winters. Compared to the rest of the nation, Balakot sees a lot more rain. The largest rain fall in the monsoon seasons (June–August) or in the late winters (February–March) is associated with frontal systems; nonetheless, rainfall is considerable throughout the year. There is an average high temperature of 25.1, a mean low temperature of 12 degrees Celsius, and an average annual rainfall of 1744.6 millimeters. Dir has most of the southern slopes of Khyber Pakhtunkhwa and has a humid subtropical climate. Owing to the city's exposed location, rainfall from frontal cyclones, from the west is heavier than in any other part of the country, their passage, as well as very penetrative monsoonal periods, are usually accompanied by thunderstorms. It has an average high temperature of °C is of 22.6, an average low temperature of °C is 7.8 per year and the average precipitation in mm is 1468.6 per year.

Pattan has an oceanic climate prevailing. There is rainfall during all months of the year. The average annual temperature for Pattan is 23° and there is about 611 mm of rain in a year on average. The climate of Peshawar is classified as warm and temperate. The rainfall in Peshawar is significant, with precipitation even during the driest months. The average temperature is about 22.3 °C. The average precipitation is about 817 mm per year. The general area of the Hub dam is arid and with an average annual rainfall of fewer than 200 millimeters (mm). The trends in temperature of the Massan area show temperature higher than 36 °C during summer. Summers are sweltering, humid and clear and the winters are short, cool, dry, and mostly clear. Over the year, the temperature varies from 42°F to 106°F and is rarely below 37°F or above 112°F. In Gwadar, summers are short, hot, and arid; the winters are short, comfortable, and dry; and it is mostly clear around the year. Its average high temperature is 29.89°C, average low temperature is 21.05°C and average precipitation in mm is 89.8 per year.

In Ormara, the warmest month (with the highest average high temperature) in May with a temperature of 32.8°C. The month with the lowest average high temperature in January with a temperature of 23°C. The month with the highest average low temperature is June (28.5°C). In Pasni, the summers are short, hot, and arid; the winters are short, comfortable, dry, and windy; and it is mostly clear. The temperature typically varies from 58°F to 93°F and is rarely below 52°F or above 98°F.

Pasni does not have significant seasonal variation in the frequency of wet days. The month with the highest precipitation in Pasni is January, with an average rainfall of 0.4 inches. The month with the least rain in Pasni is September, with an average rainfall of 0 inches. In Besham, the daytime temperature stays around 18°C and at night it goes to 7°C. In March on average Besham gets 167.51mm of rainfall and approximately 9 rainy days in a month. During the daytime temperature stays around 40°C and at night it goes to 25°C. In May on average Domel gets 53.10mm of precipitation and approximately 3 rainy days in the month. In Gujar khan temperature hovers around 37°C during the day and at night it feels like 27°C. In August, Gujar Khan gets 175.98mm of rainfall and approximately 7 rainy days in a month. Humidity is close to 52 percent.

In Mardan, the month with the largest precipitation are July, August and March with 530 mm precipitation. Most of the precipitation occurs in July with an average precipitation of 222 mm. The annual precipitation in Mardan is 1067mm. The average annual temperature is 29°C in Mardan. The warmest month of the year is June, with an average temperature of 39°C. Usually, January is the coldest month in Mardan, with an average temperature of 18°C. Palandri has an oceanic climate prevailing. The average annual temperature for Palandri is 29°C degrees and there is about 378mm of rainfall in a year. Tarbela has a moderate climate. There is a lot of rainfall in the summer, and in the winter it gets quite dry again. The average annual temperature for Tarbela is 29°C degrees and there is about 357 mm of rainfall in a year.

2.2.2. ERA5

The modern-era weather forecasting centers are releasing the short-to-medium range weather forecasts that are run on sophisticated computational models multiple times a day. While producing weather forecasts, the models usually are in a continuous evolution regarding the introduction of their updated versions. There is another type of data release that is obtained by keeping the model state constant and the model is run at a relatively coarser resolution for archival data. This type of dataset is called reanalysis data.

The fifth-generation reanalysis data (ERA5) of European ECMWF is based on 4D-Var data assimilation using Cycle 41r2 of the Integrated Forecasting System (IFS) of the European Center of Medium-Range Weather Forecasts (ECMWF). ERA5 benefits from a decade of developments in model physics, core dynamics, and data assimilation relative to its predecessor ERA-Interim (Hersbach et al., 2019). ERA5 features several improvements over ERA-Interim, such as a more recent model and data assimilation system, a higher horizontal resolution, assimilation of substantially more observations (including gauges and ground radars), a near-real-time release of the data, and outputs with a higher resolution ion (Beck et al., 2019). ERA5 hourly data (with a spatial resolution of 0.25) for precipitation and temperature for the period 1979-2018 were obtained from Climate Data Store (CDS) and were converted to daily and monthly data for further processing in this study.

2.3. Methods

2.3.1. Extraction of ERA5 data at Gauge Locations

As the gauge-based observation data is point data in its kind, potential errors have resulted when interpolation techniques are applied to convert the point data into continuous spatial precipitation data (Kidd and Huffman, 2011). Moreover, the spatial representativeness of gauge-based observations (i.e., point) and model-based datasets (i.e., grids) is different. In the studies performing comparisons of such datasets, in general, two different methodologies are commonly used to resolve the spatial scale differences between the gauges data and the products: either the grids of the product data that are closest to the gauge stations are extracted (point-to-grid methodology following Amjad et al., 2020; El Kenawy et al., 2015; Heidinger et al., 2012; Islam et al., 2012) or the station-based observations within the grids of the product data are averaged so that a compatible as well as spatially distributed estimate can be obtained. This study followed the first methodology; that is keeping the original quality of gauges data. Hence, ERA5 data was extracted over point locations of gauge stations for initial evaluation (i.e., the values of ERA5 grids containing respective 15 gauge stations were extracted). Sample R Codes are attached as Appendix A.

2.3.2. Initial Evaluation of ERA5 Data

2.3.2.1. Monthly Time Series

The downloaded original data of ERA5 at hourly scale was converted to daily and monthly time scales for further processing and plotting for comparison. Monthly precipitation and temperature data were plotted as time series. Patterns, trends and fluctuations were observed in monthly time series.

2.3.2.2. Statistical Analysis

On daily and monthly time scales, statistics such as mean, standard deviation, bias, RMSE and correlation coefficient were computed. Monthly variations in precipitation and temperature were investigated by plotting boxplots against individual months of a year. Precipitation intensity-frequency analysis was conducted to investigate the detection ability of ERA5 for precipitation of different intensities

2.3.2.3. Precipitation Spatial Map

Spatial maps of monthly precipitation over locations of gauge stations were plotted to assess the performance of ERA5 compared to observed data. The over and under estimation trends were observed.

2.3.2.4. Climate Profiling

Climate profiling were carried out which shows the decadal variation of both the climate parameters i.e. temperature and precipitation. These variations were plotted and the plots shows the trends investigation in climate parameters. Basing on the results from climate profiling, climate change zones were established.

Equations for Statistics

The statistics were calculated as:

$$\mu_s^o = \frac{1}{t} \sum_{i=1}^{t} P_{s,i}^o \quad (1)$$

$$\mu_s^e = \frac{1}{t} \sum_{i=1}^{t} P_{s,i}^e \quad (2)$$

$$SD_s^o = \sqrt{\frac{1}{t-1} \sum_{i=1}^{t} \left(P_{s,i}^o - \mu_s^o\right)^2} \quad (3)$$

$$SD_s^e = \sqrt{\frac{1}{t-1} \sum_{i=1}^{t} \left(P_{s,i}^e - \mu_s^e\right)^2} \quad (4)$$

$$Bias_s = \mu_s^e - \mu_s^o \quad (5)$$

$$\varepsilon_{s,i} = P_{s,i}^e - P_{s,i}^o \quad (6)$$

$$RMSE_s = \sqrt{\frac{1}{t} \sum_{i=1}^{t} \varepsilon_{s,i}^2} \quad (7)$$

$$CC_s = \frac{\sum_{i=1}^{t} (P_{s,i}^e - \mu_s^e)(P_{s,i}^o - \mu_s^o)}{\sqrt{\sum_{i=1}^{t} (P_{s,i}^e - \mu_s^e)^2} \cdot \sqrt{\sum_{i=1}^{t} (P_{s,i}^o - \mu_s^o)^2}} \quad (8)$$

where subscript s is the station number, t is the total number of days that precipitation datasets are available (e.g., 3650 days for 2010-2019), *i* denotes i^{th} day, *e* denotes ERA5, *o* denotes observed data; ε refers to the error and P denotes precipitation (which could be replaced by T in equations for temperature) in mm/day for daily time scale. All the statistics mentioned above were determined over all stations.

CHAPTER 3

RESULTS AND DISCUSSION

3.1. Initial Evaluation

3.1.1. Monthly Time Series

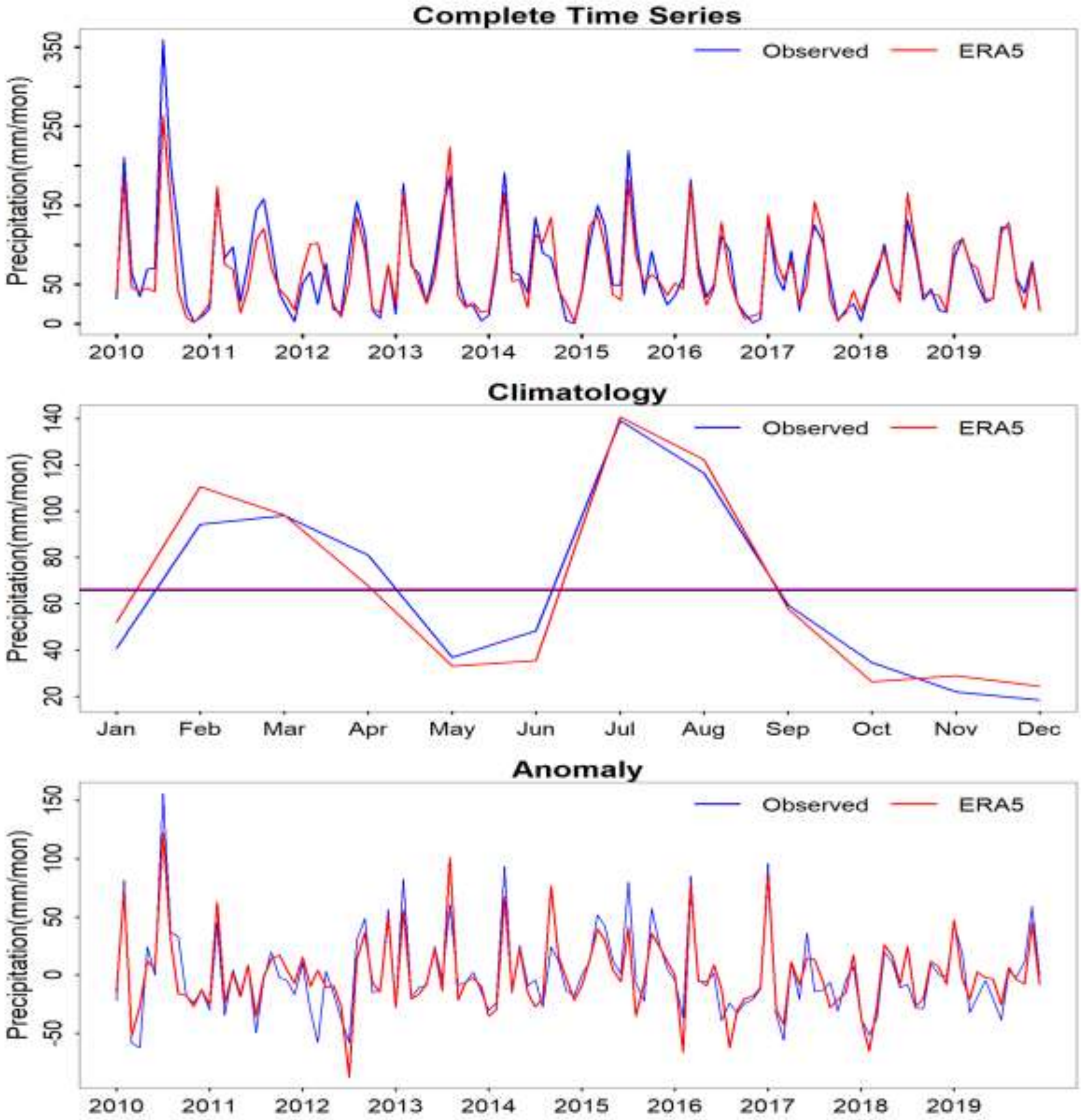

Fig 2: Time series plots (complete time series, climatology, and anomaly) for monthly precipitation for ERA5 and Observed data, averaged over 15 stations

Fig 2 shows time series plots for monthly precipitation for ERA5 and Observed data, averaged over 15 stations during the period of 2010-2019. Fluctuation patterns show similarity for almost all months of duration 2010-2019, which indicates the reliability of ERA5. Patterns are well-matched by ERA5 except a few instances. On average, there are less discrepancies between ERA5 and observed precipitation during some of the summer months. Monthly anomaly is well-matched indicating the potential of ERA5 to be used in flood and drought monitoring studies.

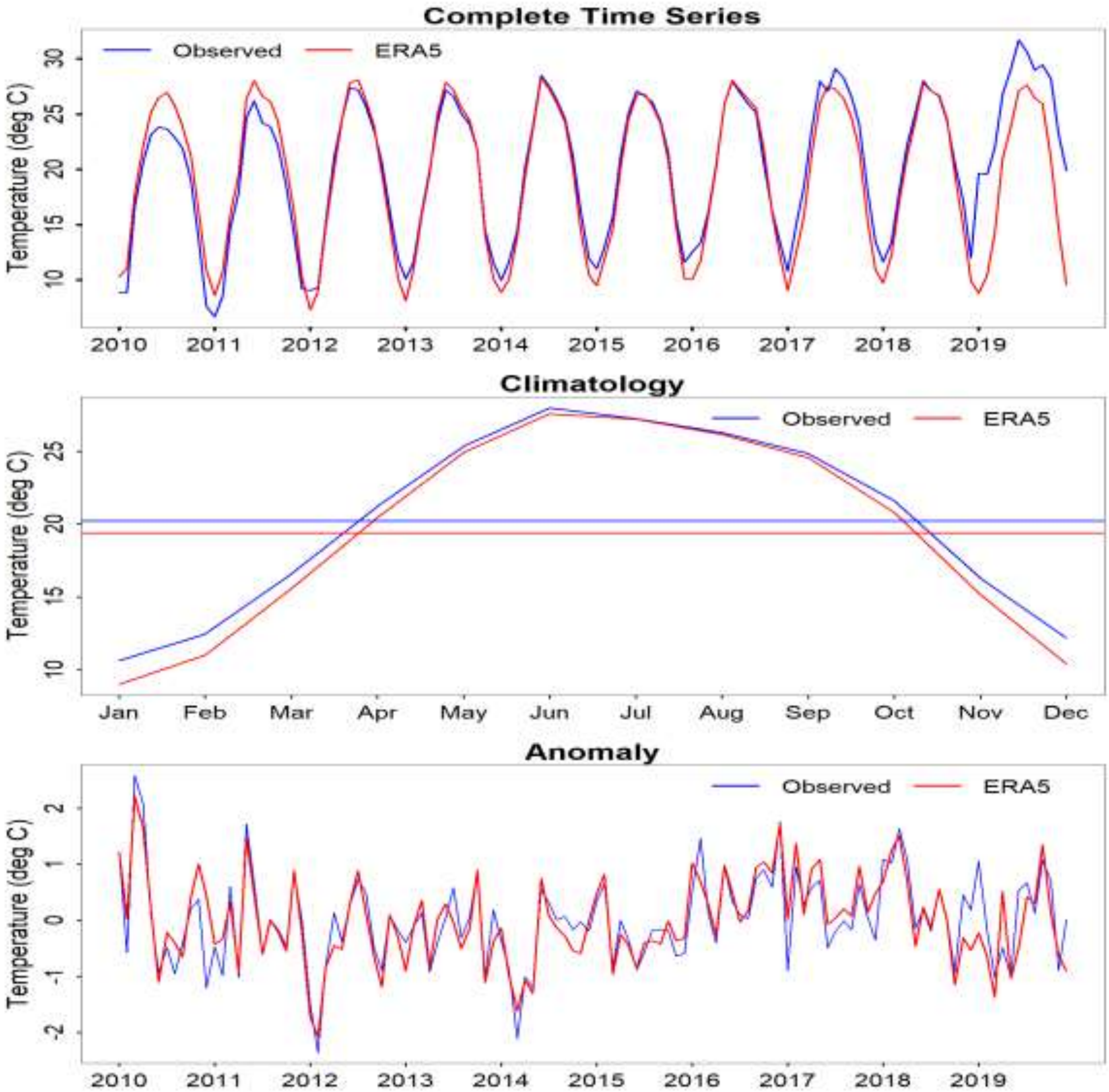

Fig 3: Time series plots (complete time series, climatology, and anomaly) for monthly temperature for ERA5 and Observed data, averaged over 15 stations

Fig 3 shows time series plots for monthly temperature for ERA5 and Observed data, averaged over 15 stations. There are some discrepancies over the peaks of temperature fluctuations. Temperature during winter months is especially underestimated by ERA5.

3.1.2. Statistical Analyses

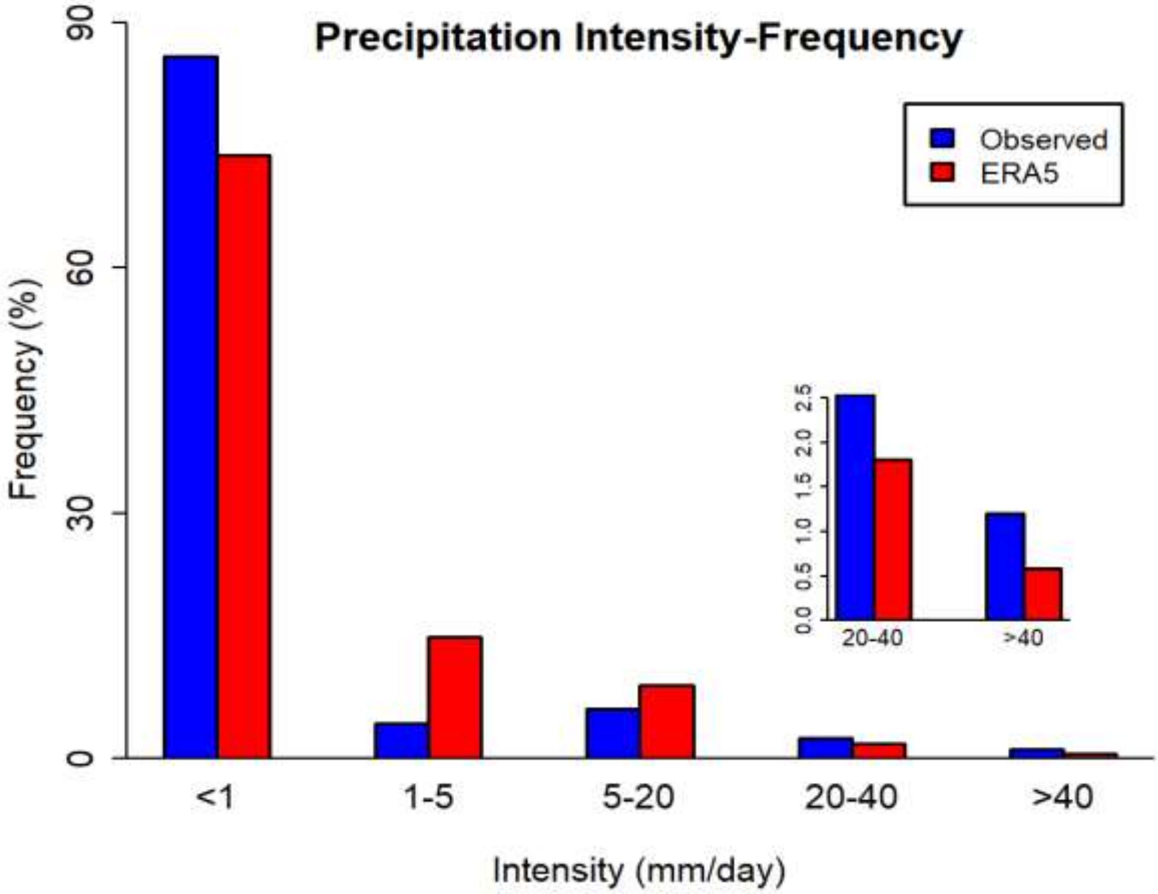

Fig 4: Precipitation intensity-frequency analysis averaged over 15 stations for (2010-2019)

To investigate the performance accuracy of ERA5 in detection of precipitation events of different intensities, precipitation intensity-frequency analysis was conducted. The results in figure 4 show that ERA5 struggles in accurately detecting the precipitation events of very low and very high daily intensities over the selected 15 stations. In literature, researchers have considered a precipitation intensity of < 1 mm/day as a "no precipitation" day (Amjad et al., 2020), while there are examples where the precipitation events of > 40 mm/day were regarded as "violent precipitation" days. Hence, the intensity-frequency analysis conducted under this study depicts that ERA5 underestimates the frequency of "no precipitation" days, while it overestimates the frequency of days with medium precipitation. Similarly, it underestimates "violent precipitation" days. On the other hand, it displays mixed results in detecting low to high intensity precipitation days (Fig 4).

Table 2: Daily and monthly statistics obtained as initial evaluation of precipitation data for 15 stations

Initial Evaluation Statistics for Precipitation									
Time Scale	stations	Period	Statistics						
			Mean		SD		Bias	RMSE	CC
			Obs	ERA5	Obs	ERA5			
Daily	15	2010-2019	2.17	2.18	7.94	6.25	0.01	8.31	0.35
Monthly	15	2010-2019	66.33	66.42	69.32	61.29	0.09	47.11	0.76

On average, a wet bias of 0.01 mm/day (Table 2) can be taken as acceptable performance of ERA5 in catching the mean of observed precipitation over 15 stations by keeping in mind that most of these stations lie in complex topography (Fig 1). However, daily MSE of 8.31 mm is quite a high RMSE that is also a reason of lower value of daily CC with the observed data (0.35). In the literature, it is often observed that model-based precipitation data is not capable of catching the dispersion of observed data. However, EA5 shows good performance in nearly reaching the SD of observed precipitation data. On monthly time scale, EA5 precipitation data displays a promising value of CC (i.e., 0.76) with the observed monthly data (Table 2) while it shows an RMSE of 47.11 mm/month. Again, the monthly precipitation bias in ERA5 is very low which implies that this reanalysis data might be considered as a potential input data to model the flood forecasting in complex topography regions.

Table 3: Daily and monthly statistics obtained as initial evaluation of temperature data over 15 stations

Initial Evaluation Statistics for Temperature									
Time Scale	stations	Period	Statistics						
			Mean (°C)		SD		Bias	RMSE	CC
			Obs	ERA5	Obs	ERA5			
Daily	15	2010-2019	20.3	19.45	6.6	7.04	-0.13	5.87	0.94
Monthly	15	2010-2019	20.30	19.41	6.26	6.76	-0.14	5.33	0.98

ERA5, despite underestimating (Table 3) both daily and monthly mean temperatures over 15 stations, displays excellent values of CC at daily (0.94) and monthly (0.98). On the other hand, SD values of ERA5 daily and monthly temperature are higher than those of the observed data.

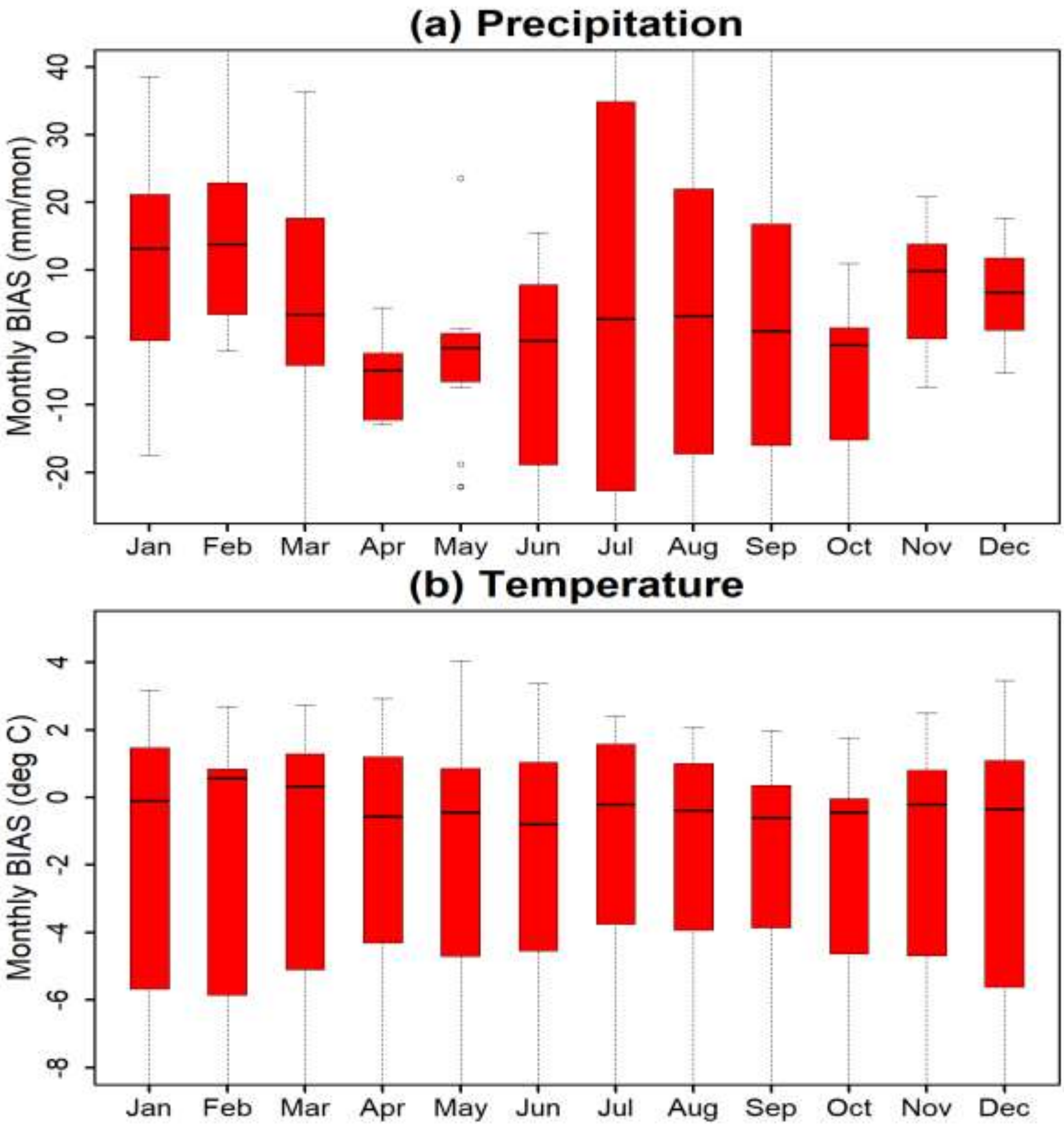

Fig 5: Boxplots for monthly bias in ERA5 precipitation and temperature over individual months of a year for 15 stations

In Figure 5 each boxplot shows spread of monthly bias of ERA5 over 15 stations against each individual month (from Jan – Dec) of a year. The bias boxplots are given separately for precipitation and temperature.

Considering precipitation, the medians of bias are higher during winter months as compared to summer months, while the spread of bias during summer months (especially during Jul-Sep) is higher. For temperature, the spread of boxplots shrinks a bit during summer months.

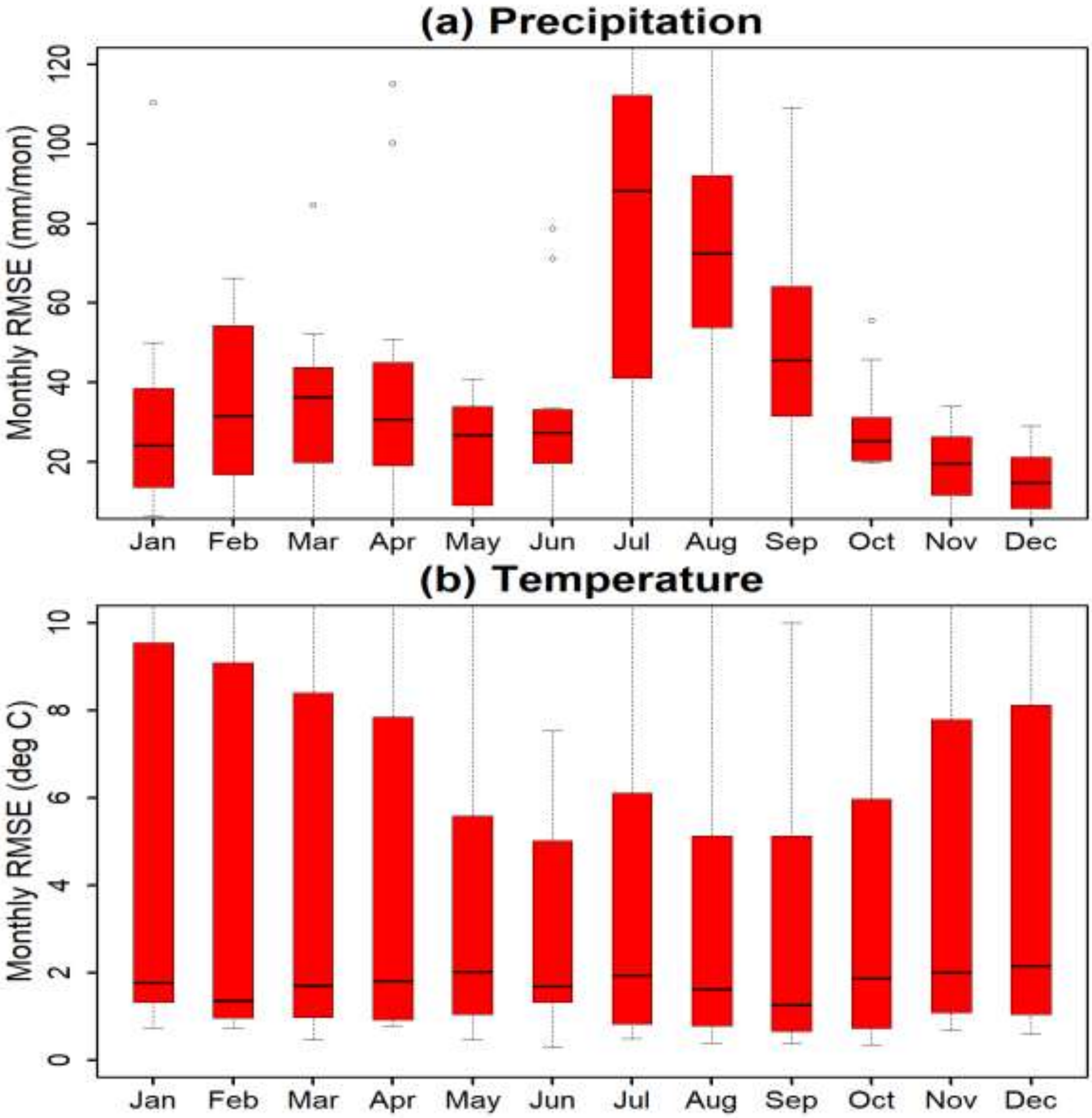

Fig 6: Boxplots for monthly RMSE in ERA5 precipitation and temperature over individual months of a year for 15 stations

Monthly RMSE in ERA5 data becomes obviously higher (Figure 6) during summer months as compared to winter months. This could be attributed towards the large errors model-based datasets suffer from during the convective precipitation events, and such events occur so often during the Monsoon period. The spread of monthly mean temperature RMSE boxplots during summer months follows almost the same pattern as in the case of bias.

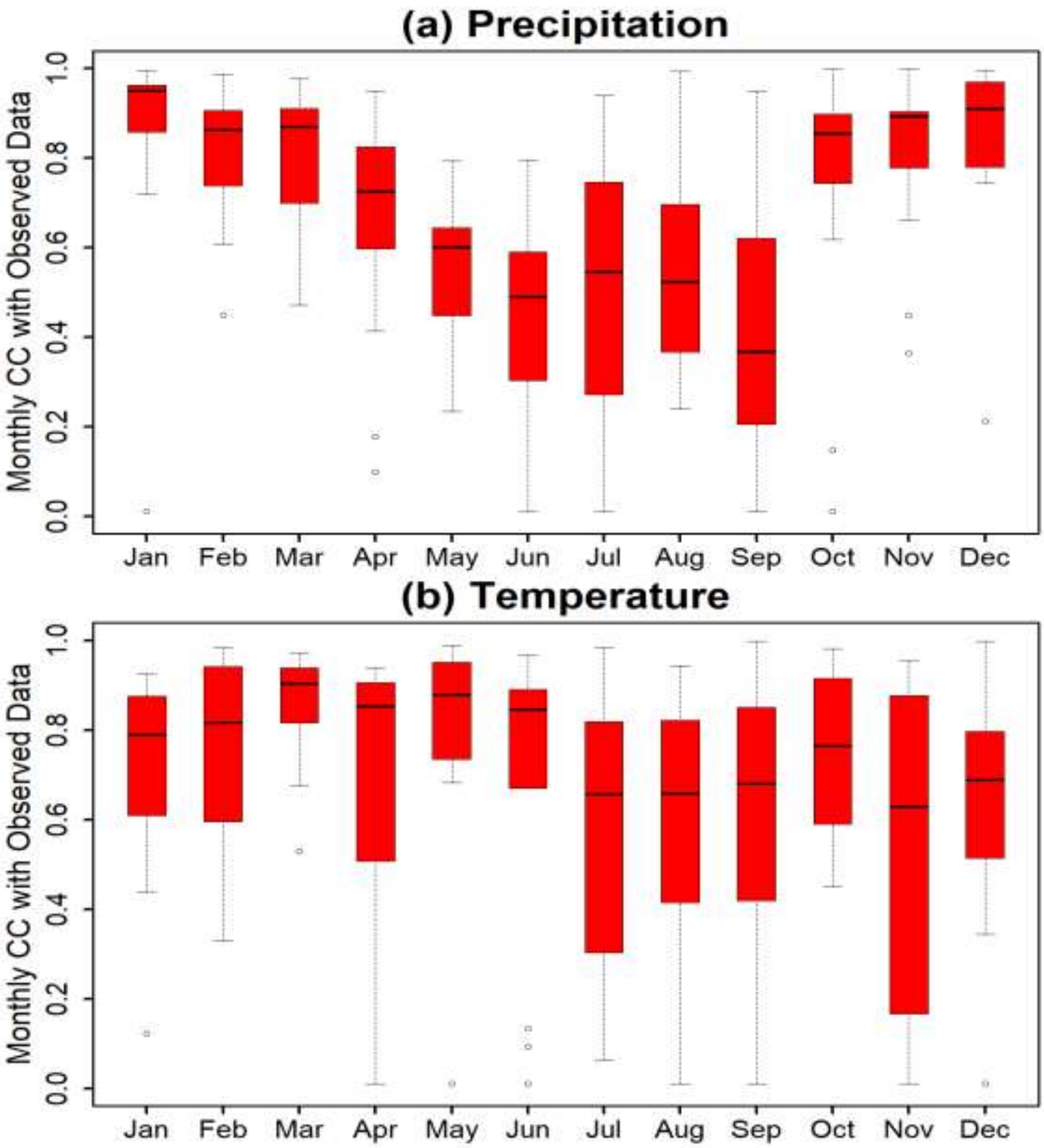

Fig 7: Boxplots for monthly CC between ERA5 and Observed data for precipitation and temperature over individual months of a year for 15 stations

During summer months, values of monthly CC between ERA5 and observed precipitation come up considerably lower than CC during winter months (Fig 7). This again might be because of the violent and diverse nature of Monsoon sequels during summer months. Whereas such uniform and distinguishable pattern is not followed in case of monthly CC between temperature of ERA5 and observed data (Fig 7).

3.1.3. Precipitation Spatial Map

Spatial maps of monthly precipitation over locations of gauge stations were plotted to assess the performance of ERA5 compared to observed data. The over and under estimation trends were observed.

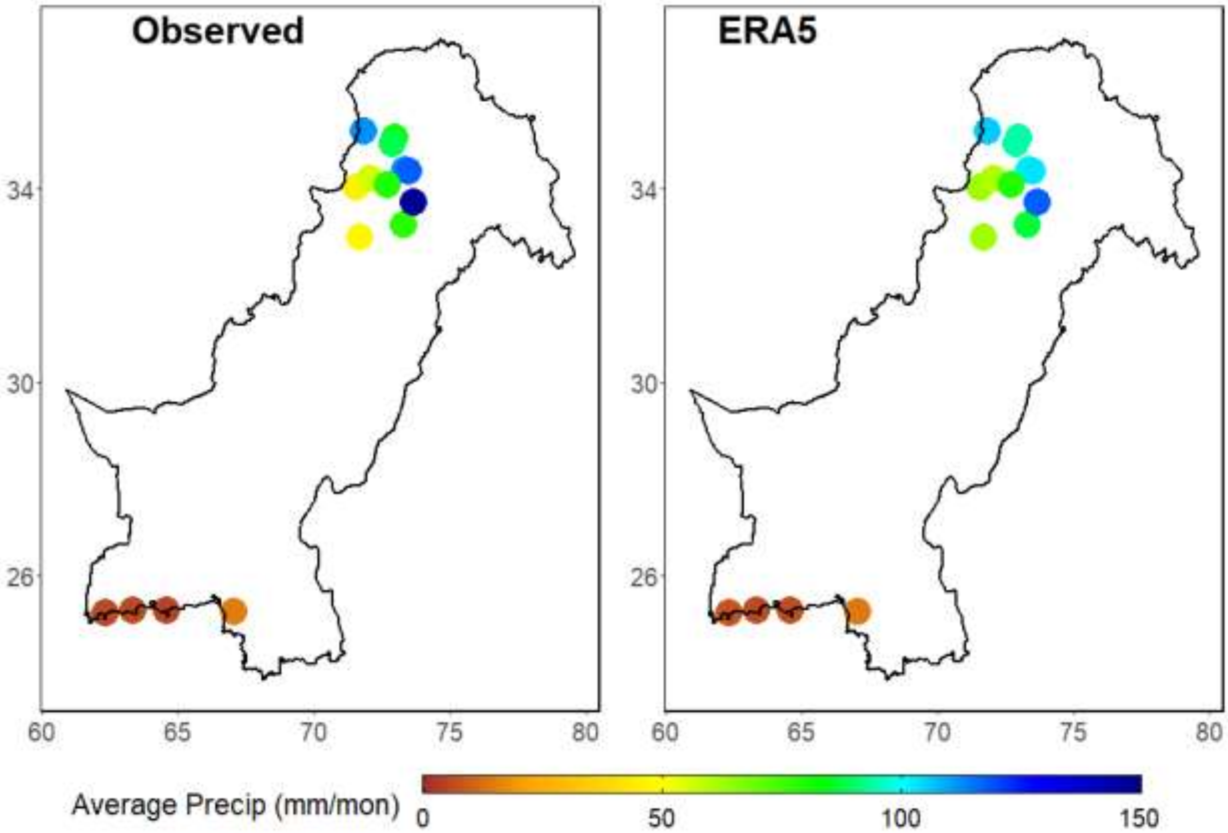

Fig 8: Spatial plots for average monthly precipitation from ERA5 and Observed data over 15 stations

With the help of color-coded circles, Fig 8 depicts the spatial distribution of monthly average precipitation (from both ERA5 and observed data) over the locations of 15 stations. Figure shows that ERA5 tends to overestimate the average monthly observed precipitation over the locations of stations that receive lower amounts of precipitation (i.e., drier stations) while the converse is true for wetter stations; ERA5 tends to underestimate the precipitation there (Figure 8). However, such a tendency is not valid for the case of coastal stations.

3.2. Climate Profiling

3.2.1.Precipitation

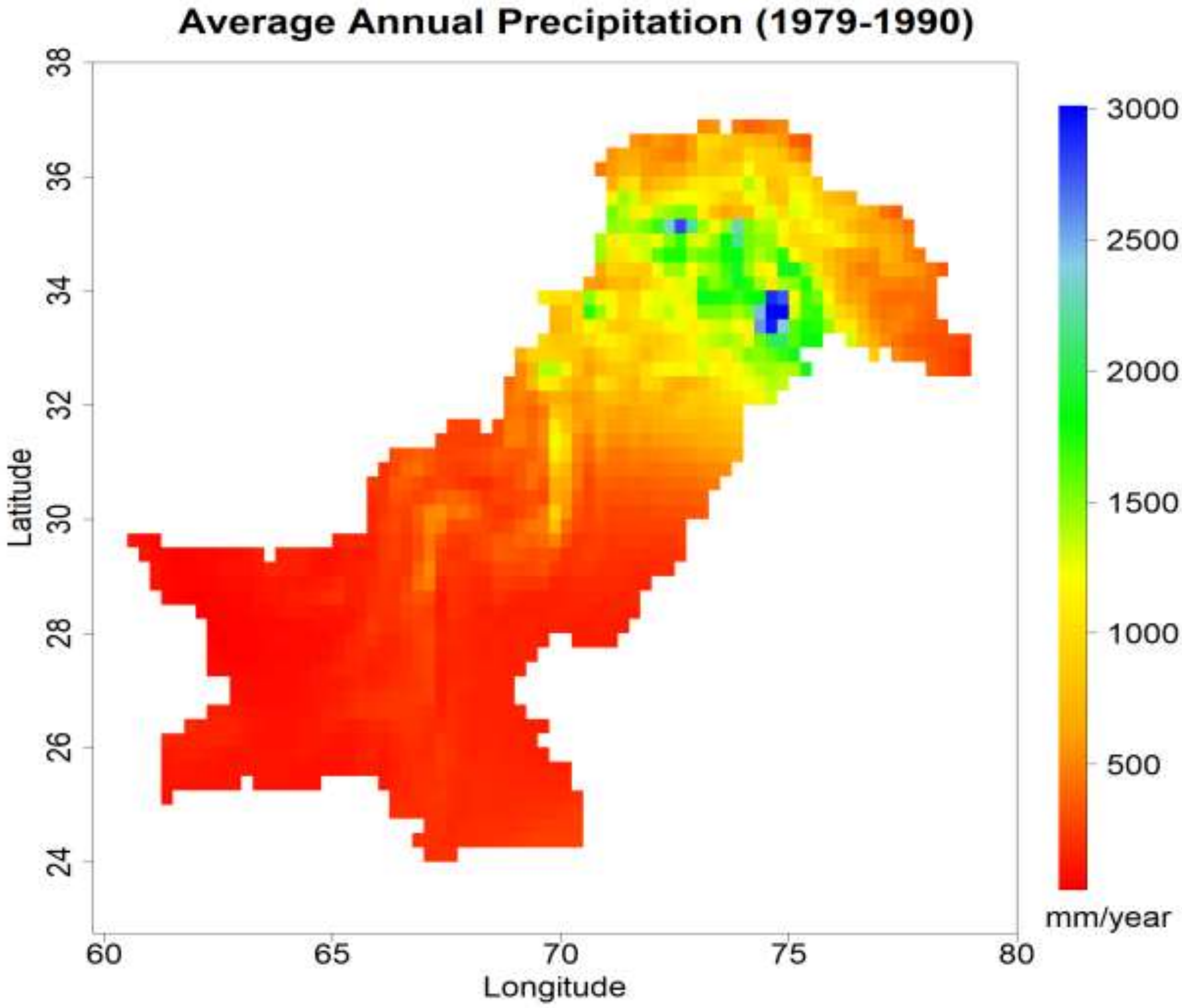

Fig 9: Average annual precipitation for ERA5 over Pakistan during decade 1 (1979-1990)

Figure 9 shows higher precipitation values over most regions of KPK. Southwestern part of Balochistan shows dry regions (i.e., receiving very low amounts of precipitation). Central to southern regions of the country are mostly arid to semi-arid regions, receive lower precipitation.

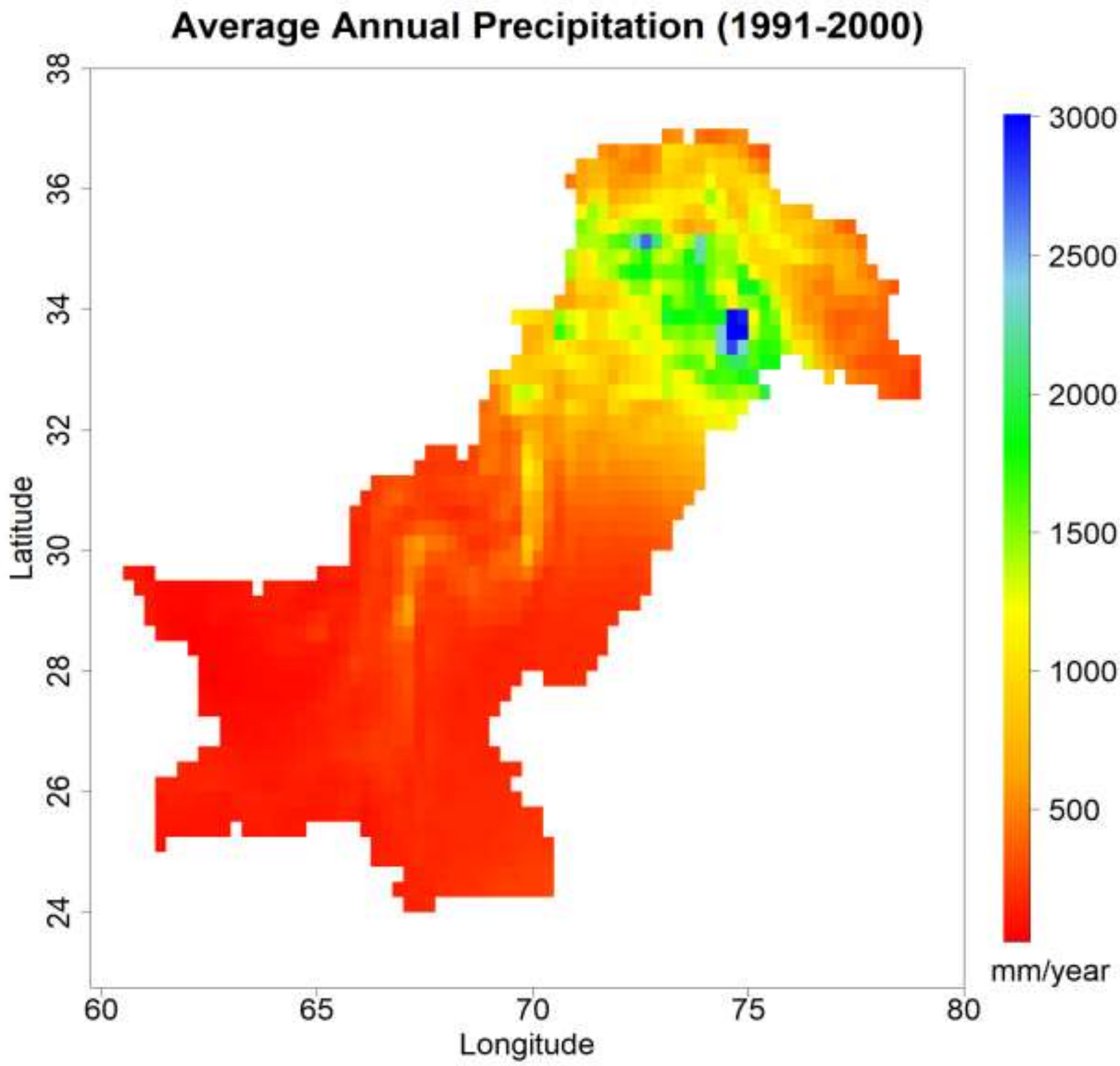

Fig 10: Average annual precipitation for ERA5 over Pakistan during decade 2 (1991-2000)

Minute decade-to-decade changes between the previous and this decade is observed. A further reduction of precipitation events on micro scale level in southern and south western part of the country are observed. Overall trends shows similarity with trends of previous decades.

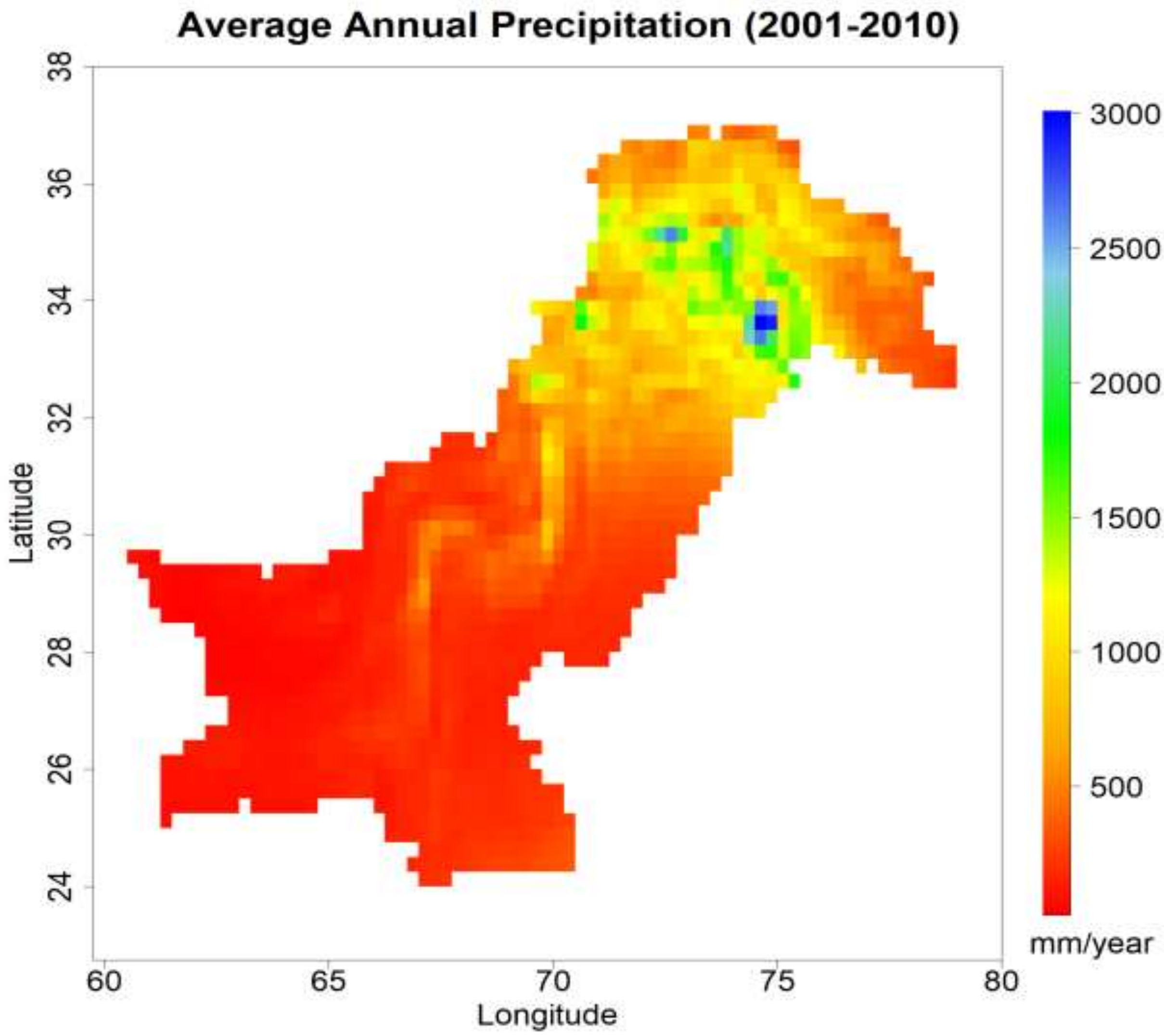

Fig 11: Average annual precipitation for ERA5 over Pakistan during decade 3 (2001-2010)

The above figure 11 shows reduction of precipitation over most part of KPK. KPK receiving lower precipitation in decade 3 as compared to first two decades specially the areas between Kohat and Bannu districts. However the spread of precipitation amounts between 500 and 1200 mm/year is more in this decade. Fig 11 shows an overall decreasing trend of precipitation.

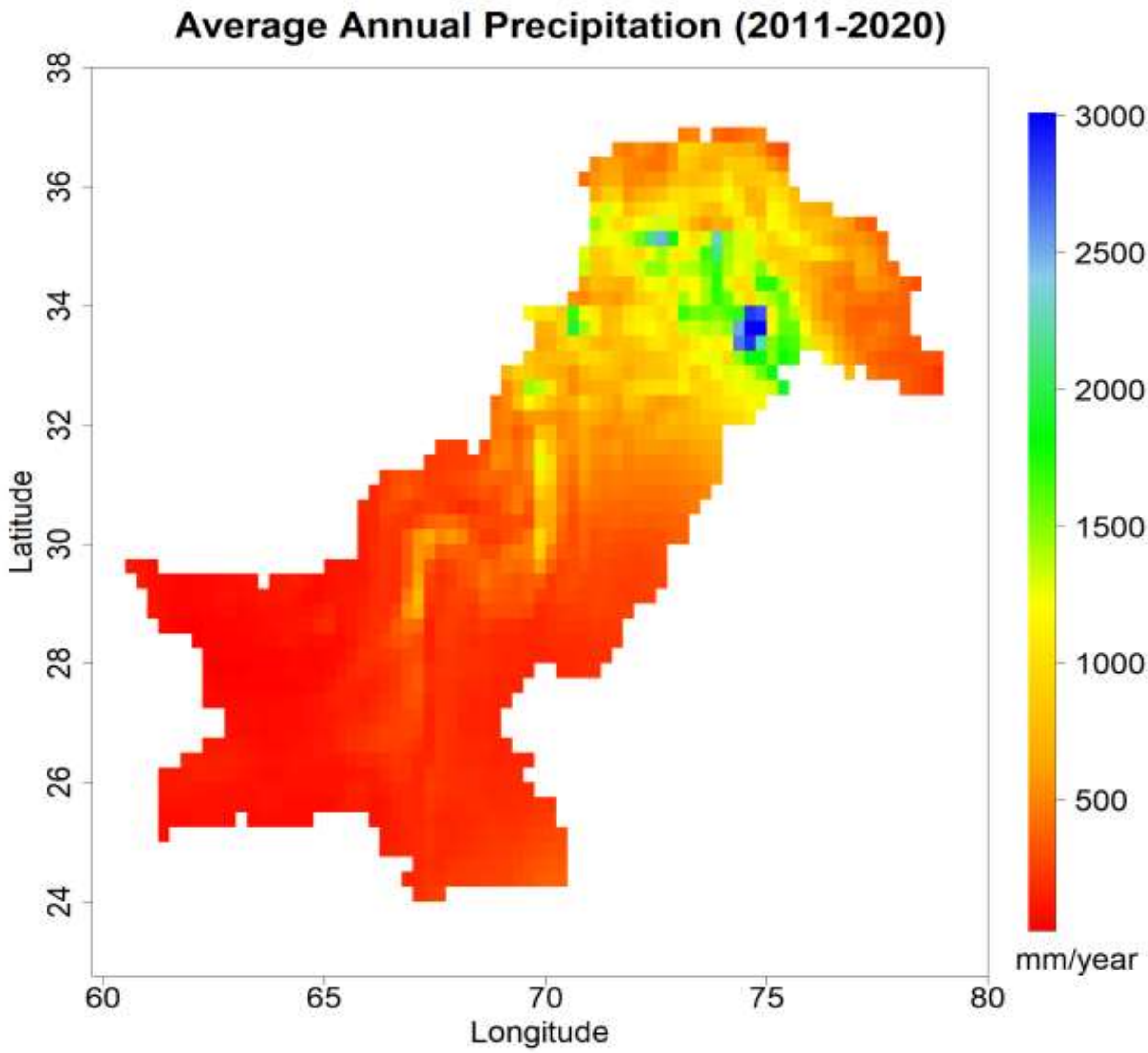

Fig 12: Average annual precipitation for ERA5 over Pakistan during decade 4 (2011-2020)

Trends of higher precipitation appears in central part of the country i.e. Multan etc. The color-coded yellow pixels (receiving low to high precipitation amounts) cover more area in decade 4 as compared to the case of first two decades. On average the KPK and central Punjab has seen a low to high precipitation trends between the decade of (2011 to 2020).

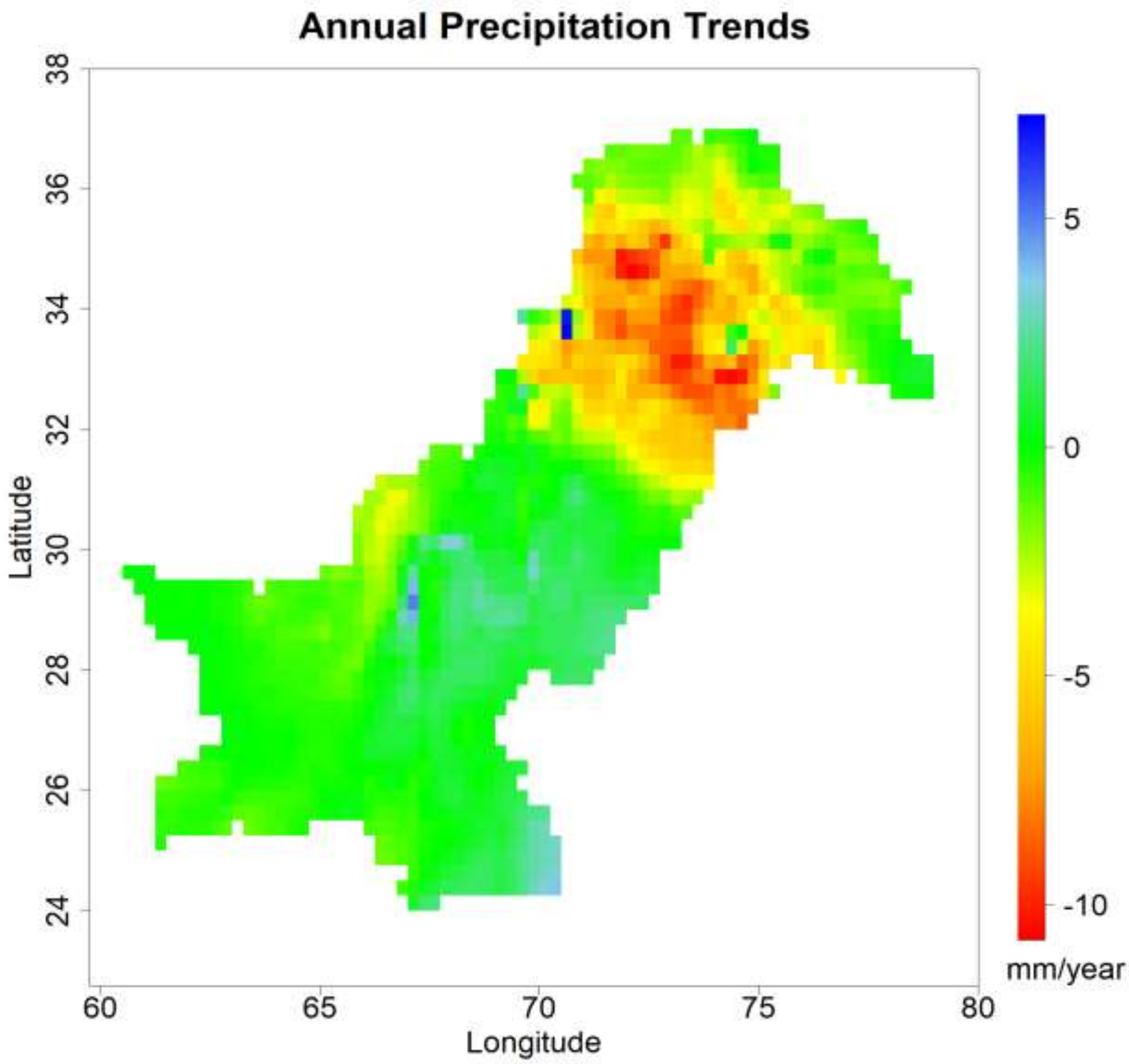

Fig 13: Annual precipitation trends for ERA5 over Pakistan during 1979-2020

Precipitation trends over most of KPK province are negative. There are mixed trends over Balochistan: both positive and negative. But it has more negative precipitation trends over most parts of Balochistan especially its southwestern parts. Few areas in southern and south eastern part of the country shows positive trends in precipitation. Upper Punjab and lower KPK has negative trends.

3.2.2 Temperature

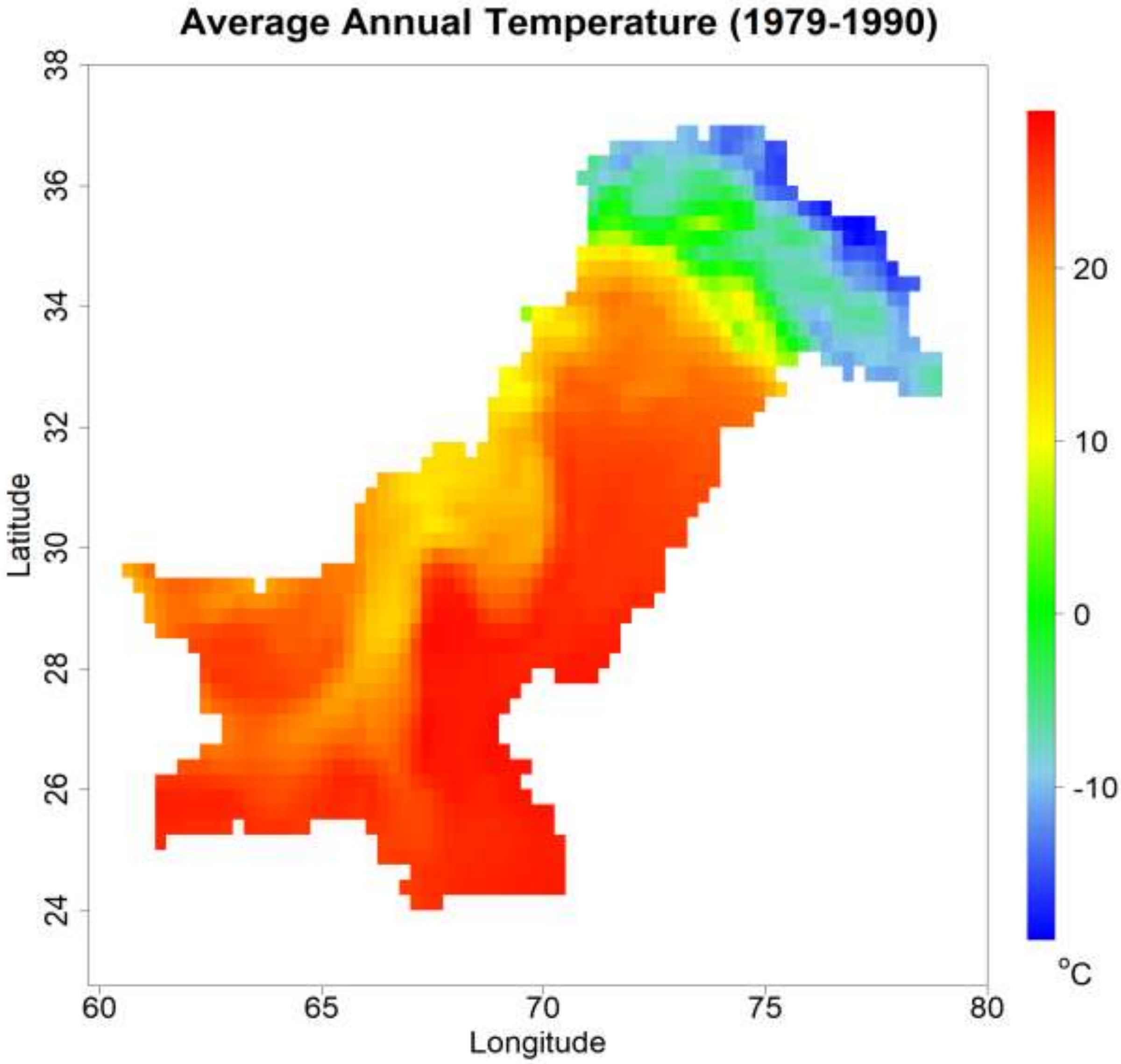

Fig 14: Average annual temperature for ERA5 over Pakistan during decade 1 (1979-1990)

Figure 14 shows lowest temperature values over the Himalaya. Punjab and Balochistan show higher temperature values i.e. >20°C. Upper KPK show temperature values ranging from 0-10°C. Western Punjab and central Balochistan shows the average annual temperature of <20°C.

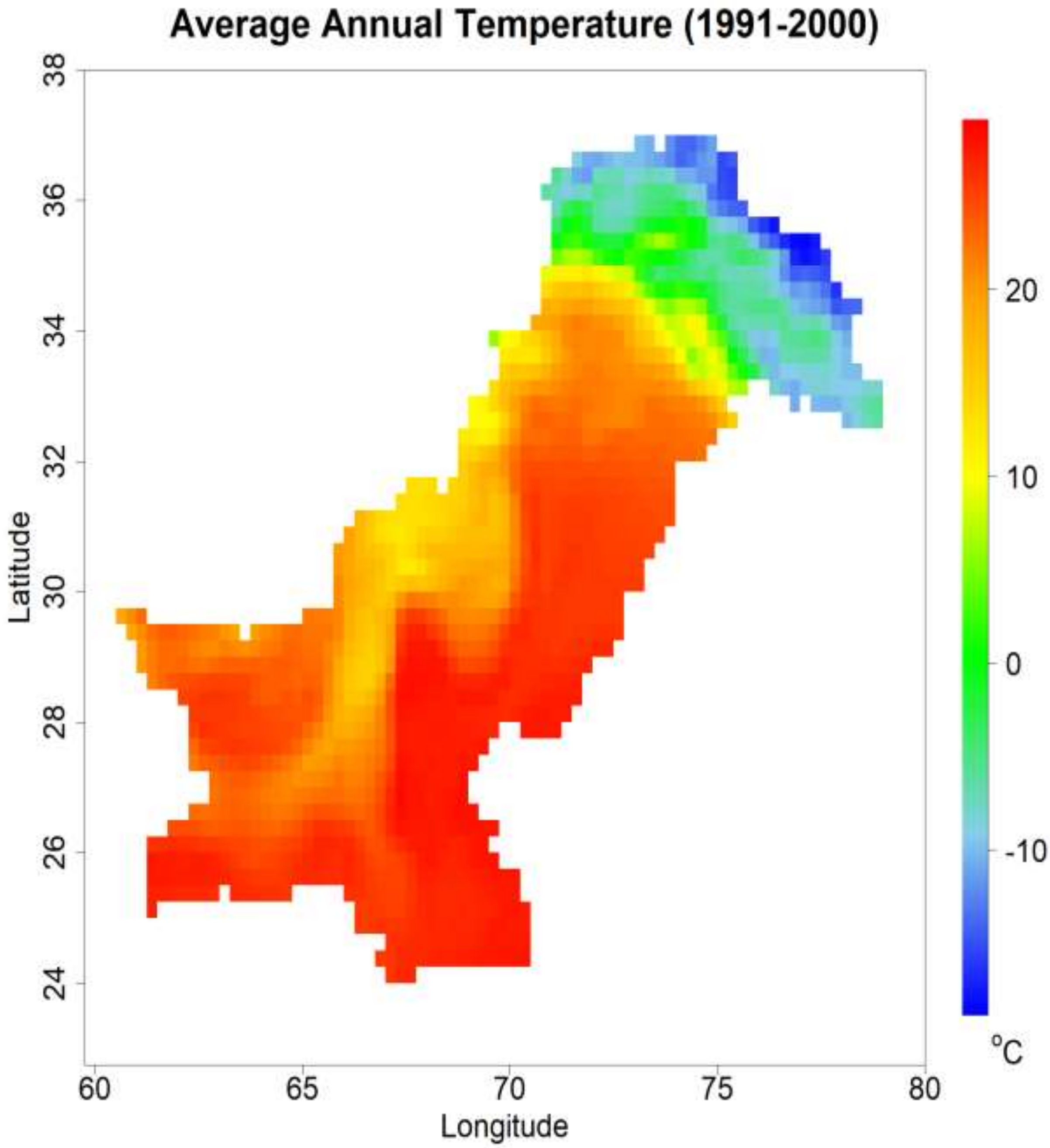

Fig 15: Average annual temperature for ERA5 over Pakistan during decade 2 (1991-2000)

Regions with temperature around 10 °C cover more areas during this decade, clearly showing the rise in temperature in upper Balochistan and KPK. Northern part of the country and himalayas show slight increase in temperature trends over the decade.

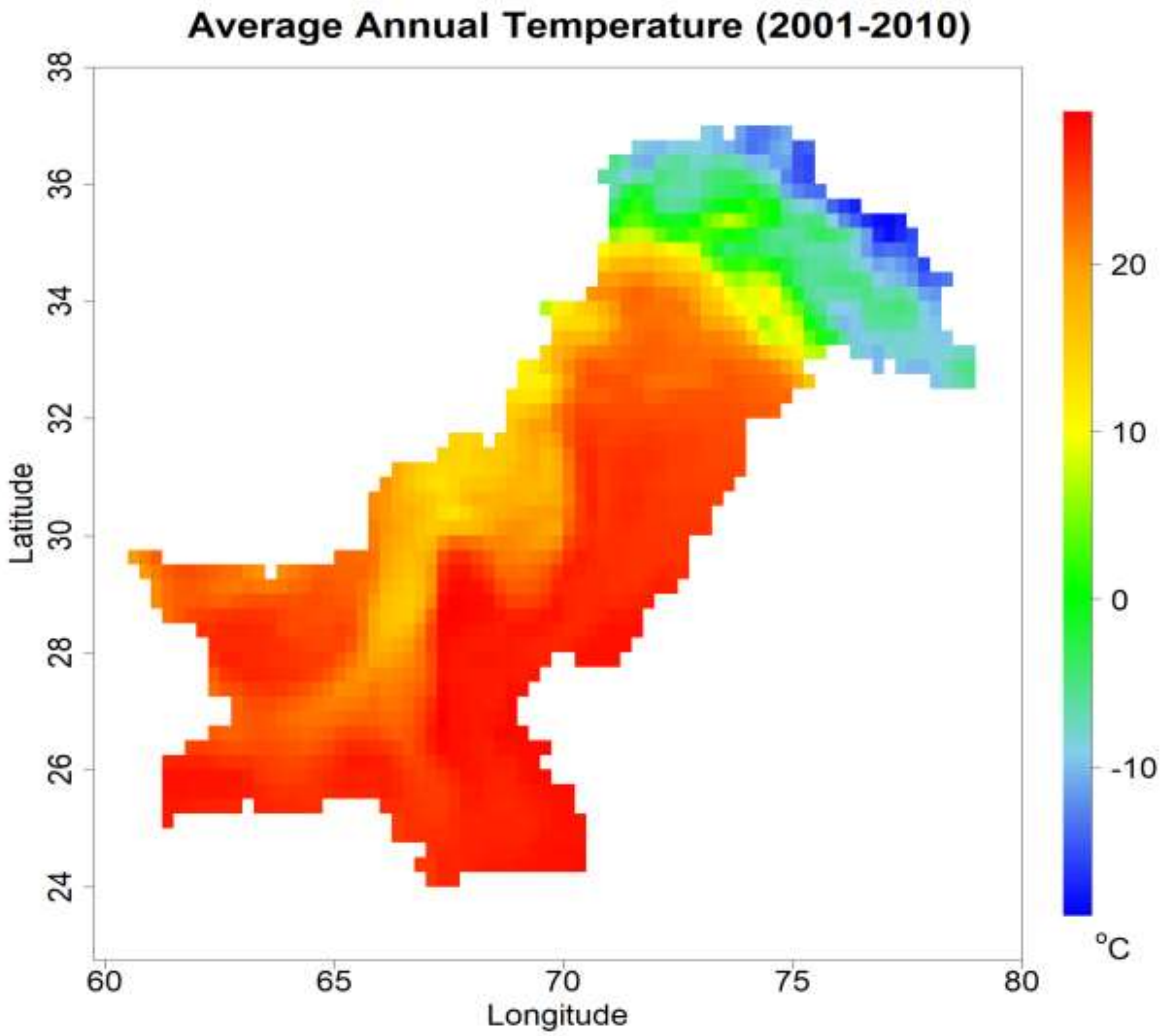

Fig 16: Average annual temperature for ERA5 over Pakistan during decade 3 (2001-2010)

Figure 16 shows an increase trends in temperature in Northern, upper KPK and Western part of KPK province. Average temperature in most part of upper KPK and Northern areas has increased from 0-10ºC in most parts of the region. Southern Balochistan and Punjab in general shows a same trends of higher temperature.

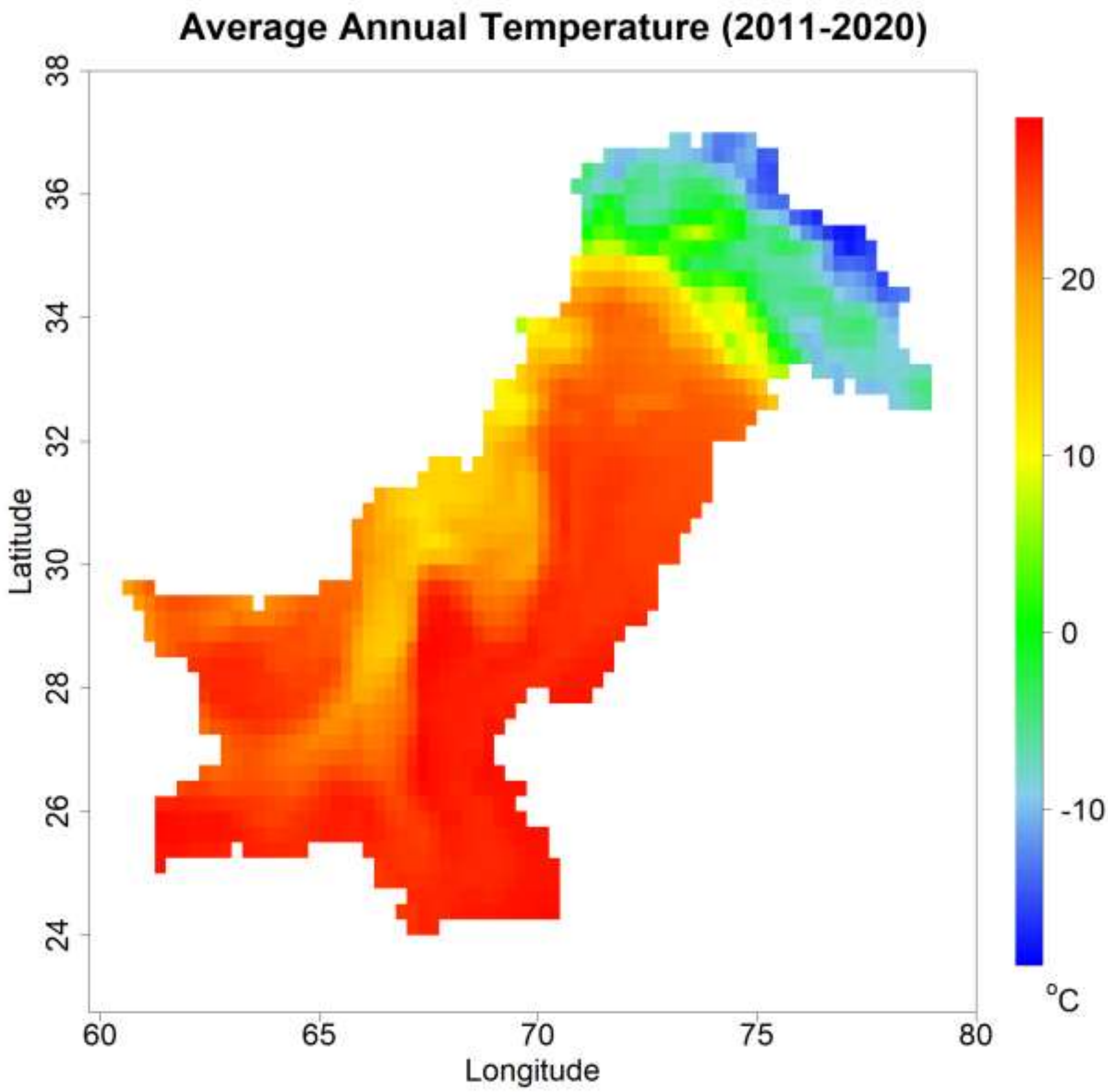

Fig 17: Average annual temperature for ERA5 over Pakistan during decade 4 (2011-2020)

Figure 17 shows further increasing trends in temperature in Himalayas. Color-coded light blue pixels (>-10°C) cover more area in decade 4 as compared to the case of first two decades . Balochistan , KPK and Punjab in general shows a same trends of higher temperature.

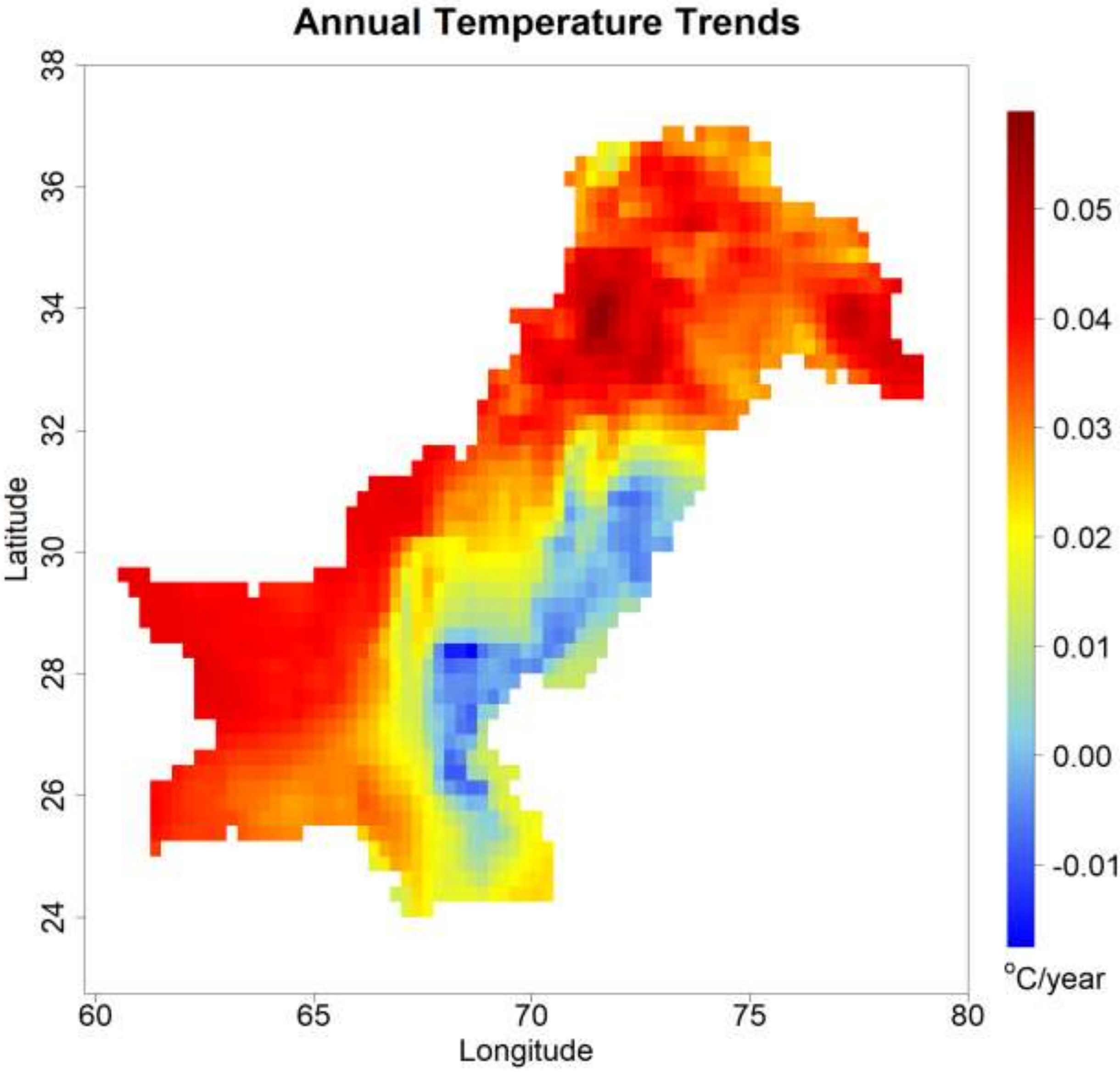

Fig 18: Annual temperature trends for ERA5 over Pakistan during 1979-2020

Rise in temperature by 5°C / century in almost all KPK is alarming as the precipitation trends in this region are also negative, which means this region is getting drier and hotter. Northern glacial regions also observe rise in temperatures which can translate into higher rates of snowmelt, more intense flooding in the downstream regions, and more GLOF events. Southwestern Balochistan is also at risk of further rise in temperatures. Most of the agricultural regions of western Punjab are becoming hotter.

3.2.3 Climate Change Zones

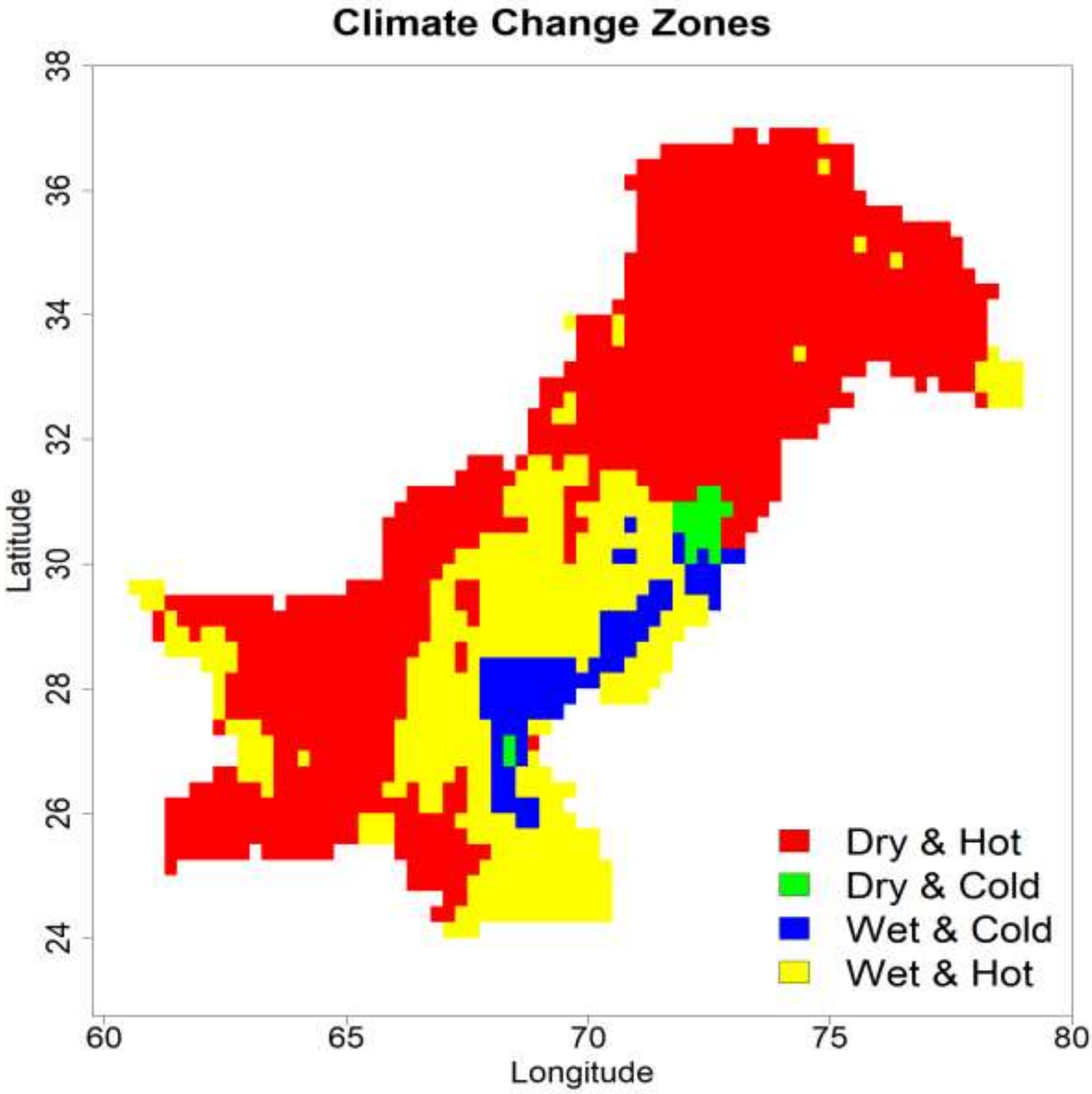

Fig 19: Climate change zones based on annual precipitation and temperature trends for ERA5 over Pakistan during 1979-2020

Above figure 19 shows that almost all the North of Pak is getting drier and hotter which is an alarming situation. Balochistan is getting hotter and drier; which predicts the risk of more frequent and more intense droughts in future. Only some agricultural regions in eastern Punjab lie in the scarce wet & cold zone

CHAPTER 4

CONCLUSIONS AND RECOMMENDATIONS

4.1. Conclusions

1. Considering monthly time series of climate parameters, the fluctuation patterns show similarity between observed and ERA5 data, indicating the reliability of ERA5
2. Monthly observed anomaly time series of climate parameters are well-matched by ERA5, indicating the potential of ERA5 to be used in flood and drought monitoring studies
3. ERA5 monthly precipitation data during monsoon season shows larger RMSE, larger bias and lower correlation with the observed data; this could be attributed towards a well-known fact that model-based precipitation datasets struggle in catching the convective precipitation events during monsoons.
4. On both daily and monthly time scales, the statistical analyses depict ERA5 to be showing low bias; acceptable values of correlation coefficient and RMSE for both the climate parameters
5. The spatial plotting of ERA5 precipitation trends concludes that the annual precipitation amounts received by most parts of KPK have a strong decreasing trends up to 10 mm/year which is quite an alarming situation as this region is also getting increasingly drier
6. Most regions (including the northern glacial regions) of Pakistan are getting hotter with the spatial trends showing an increase in temperature of above 0.05 ^{o}C/year which depicts an increase of 5 ^{o}C/century
7. The study concludes that most regions of Pakistan are among climate change zone of “dry and hot” inferring that they show trends of getting drier and hotter
8. Indication of northern glacial regions and southwestern Balochistan getting hotter and drier is quite an alarming situation for both these regions in the contexts of frequent and extreme flooding due to snowmelt in glacial regions and frequent and intense droughts in southwestern Balochistan

4.2. Recommendations

1. Based on ERA5 closely following the observed monthly fluctuation patterns for both climate parameters, it could be recommended as a potential alternative (especially in flood and drought monitoring) to sparsely installed gauges network in mountainous and hard-to-access regions of Pakistan
2. With reference to the findings of this study, a proactive and well-connected disaster management framework is recommended in the northern glacial regions and southwestern Balochistan to monitor the hydrometeorological extremes at real-time
3. This study utilized ERA5 with a spatial resolution of 25 km to conduct climate profiling and trend analysis of Pakistan. Climate profiling by using climate data products with higher resolution is recommended to be conducted so that the trend analyses could be performed based on data showing more details of climate processes

References

1. Ali, M. A., Hassan, M., Mehmood, M., Kazmi, D. H., Chishtie, F. A., & Shahid, I. (2022). The Potential Impact of Climate Extremes on Cotton and Wheat Crops in Southern Punjab, Pakistan. *Sustainability (Switzerland)*, *14*(3). https://doi.org/10.3390/su14031609

2. Arshad, M., Ma, X., Yin, J., Ullah, W., Liu, M., & Ullah, I. (2021). Performance evaluation of ERA-5, JRA-55, MERRA-2, and CFS-2 reanalysis datasets, over diverse climate regions of Pakistan. *Weather and Climate Extremes*, *33*, 100373. https://doi.org/10.1016/j.wace.2021.100373

3. Bank, A. D. (2019). *Climate Change of Pakistan*.

4. Dahri, Z. H., Ludwig, F., Moors, E., Ahmad, S., Ahmad, B., Ahmad, S., Riaz, M., & Kabat, P. (2021). Climate change and hydrological regime of the high-altitude Indus basin under extreme climate scenarios. *Science of the Total Environment*, *768*(January), 144467. https://doi.org/10.1016/j.scitotenv.2020.144467

6. Dilawar, A., Chen, B., Arshad, A., Guo, L., Ehsan, M. I., Hussain, Y., Kayiranga, A., Measho, S., Zhang, H., Wang, F., Sun, X., & Ge, M. (2021). Towards understanding variability in droughts in response to extreme climate conditions over the different agro-ecological zones of Pakistan. *Sustainability (Switzerland)*, *13*(12). https://doi.org/10.3390/su13126910

7. Finance.gov.pk. (2020). *Climate Change*. http://www.finance.gov.pk/survey/chapter_20/16_Climate_Change.pdf

8. Jan, A., Manuel Baez-Villanueva, O., & Ribbe, L. (2022). *Spatio-temporal Evaluation of Gridded Precipitation and Evapotranspiration Products Over Balochistan Province in Pakistan*.

9. Meng, D., Song, W., Dong, Q., Yin, Z., & Zhao, W. (2021). The variability of summer atmospheric water cycle over the tibetan plateau and its response to the indo-pacific warm pool. *Remote Sensing*, *13*(22). https://doi.org/10.3390/rs13224676

10. Ougahi, J. H., & Mahmood, S. A. (2022). Evaluation of satellite-based and reanalysis precipitation datasets by hydrologic simulation in the Chenab river basin. *Journal of Water and Climate Change*, *13*(3), 1563–1582. https://doi.org/10.2166/wcc.2022.410

11. Pomee, M. S., & Hertig, E. (2021). Temperature projections over the indus river basin of Pakistan using statistical downscaling. *Atmosphere*, *12*(2), 1–32. https://doi.org/10.3390/atmos12020195

12. Rashid, I. U., Abid, M. A., Almazroui, M., Kucharski, F., Hanif, M., Ali, S., & Ismail, M. (2022). Early summer surface air temperature variability over Pakistan and the role of El Niño–Southern Oscillation teleconnections. *International Journal of Climatology*, *January*, 1–17. https://doi.org/10.1002/joc.7560

13. Salma, S., Rehman, S., & Shah, M. a. (2012). Rainfall Trends in Different Climate Zones of Pakistan. *Pakistan Journal of Meteorology*, *9*(17), 37–47. http://www.pmd.gov.pk/rnd/rnd_files/vol8_issue17/4.pdf

14. Sharma, S., Hamal, K., Khadka, N., & Joshi, B. B. (2020). Dominant pattern of year-to-year variability of summer precipitation in Nepal during 1987–2015. *Theoretical and Applied Climatology*, *142*(3–4), 1071–1084. https://doi.org/10.1007/s00704-020-03359-1

15. Shen, B., Song, S., Zhang, L., Wang, Z., Ren, C., & Li, Y. (2022). Temperature trends in some major countries from the 1980s to 2019. *Journal of Geographical Sciences*, *32*(1), 79–100. https://doi.org/10.1007/s11442-022-1937-1

Tariq, S., Mahmood, A., & Rasul, G. (2014). Temperature and Precipitation : GLOF Triggering Indicators in Gilgit-Baltistan , Pakistan. *Pakistan Journal of Meteorology*, *10*(20), 39–56.

16. Ullah, W., Wang, G., Lou, D., Ullah, S., Bhatti, A. S., Ullah, S., Karim, A., Hagan, D. F. T., & Ali, G. (2021). Large-scale atmospheric circulation patterns associated with extreme monsoon precipitation in Pakistan during 1981–2018. *Atmospheric Research*, *253*(November 2020), 105489. https://doi.org/10.1016/j.atmosres.2021.105489

Appendix A

Sample R Codes

1. Loading Required Packages

```
rm(list=ls())              ## removing memory
library(ncdf4)             ## to read nc files
library(fields)            ## to use impage.plot
library(magic)             ## to use impage.plot
library(ggplot2)           ## for ggplot
library(ggpubr)            ## for ggplot
library(pdp)               ## for ggplot
library(maps)              ## for maps
library(rworldmap)         ## to draw world countries
library(shapefiles)        ## ARCGIS SHAPE FILES
library(raster)            ## for raster objects
library(sp)                ## for raster objects
```

2. Giving Path to Input and Output Folders

```
infold_ERA5     =    'D:/FYP/ERA5/ERA5_nc_data/'
outfold_ERA5    =    'D:/FYP/ERA5/ERA5_Rdata/'
infold_G1       =    'C:/Users/Mani/Drive3/00_MCE NUST/03_Final Year
                Projects/2022_OD90/Group1_Shabab/Data/csv/'
infold_G2       =    'C:/Users/Mani/Drive3/00_MCE NUST/03_Final Year
                Projects/2022_OD90/Group2_Haseeb/Data/csv/'
outfold_sta     =    'D:/FYP/Gauges_and_Output/'
figfold         =    'D:/FYP/Results/'
colorfold       =    'C:/Users/Mani/Drive
1/PhD/002_R_Help/R_files_docs/colorbars/'
mapsfold        =    'D:/FYP/Shapes_masks/'
```

3. Reading .netcdf Files and Saving as Rdata Files

```
t1              =       proc.time()[3]
for (year in 1979:2020){                                  ## for loop
nc_file         =       paste0(infold_ERA5,'ERA5_data_',year,'.nc')
nc              =       nc_open(nc_file)
prcp            =       ncvar_get(nc, 'tp') * 1000
dim(prcp)
# [81,61,8760]
nc_close(nc)
if(year%%4!=0){ ### for normal years
prcpD           =       array(NA, dim = c(81,61,365))
for (dd in 1:365){
H1              =       (dd-1)*24+1
H2              =       H1 + 23
HOYlocs         =       H1:H2
prcpD[,,dd]     =       rowMeans(prcp[,,HOYlocs],dims=2, na.rm=T) * 24
}
assign(paste0('prcp_',year),prcpD)
}
if(year%%4==0){ ### for leap years
prcpD           =       array(NA, dim = c(81,61,366))
for (dd in 1:366){
H1              =       (dd-1)*24+1
H2              =       H1 + 23
HOYlocs         =       H1:H2
prcpD[,,dd]     =       rowMeans(prcp[,,HOYlocs],dims=2, na.rm=T) * 24
}
valid_days      =       c(1:59,61:366)
prcpD           =       prcpD[,,valid_days]          ## Removing leap days
assign(paste0('prcp_',year),prcpD)
}
print(paste0(year,' done'))
}
t2              =       proc.time()[3]
```

```
t_taken          =        round((t2-t1)/60,1)
print(paste0(t_taken,' min'))
### 1.5 min                                              ## Time taken to run the code

list_matrix                    =       mget(paste0('prcp_', 1979:2020))
comb                           =       do.call(abind, c(list_matrix, along = 3))
ERA5_d_tp_1979_2020_1          =       comb
dim(ERA5_d_tp_1979_2020_1)     =       c(81,61,15330)
ERA5_d_tp_1979_2020_2          =       comb
dim(ERA5_d_tp_1979_2020_2)     =       c(81,61,365,42)          ## Output
```

4. Removing Outliers and Saving Output as Rdata File

```
ERA5_d_tp_1979_2020_1[ERA5_d_tp_1979_2020_1 > 375]      =      375
ERA5_d_tp_1979_2020_2[ERA5_d_tp_1979_2020_2 > 375]      =      375
info_tp='ERA5 daily total precipitation at 0.25 resolution over box including Pak (59.875-80.125E,22.875-38.125N)'
save(ERA5_d_tp_1979_2020_2,ERA5_d_tp_1979_2020_1,info_tp,
file     =     paste0(outfold_ERA5,'ERA5_daily_tp_1979_2020_Pk.Rdata'))
```

5. Extracting ERA5 Gridded Data over Station Locations

```
load(paste0(outfold_ERA5,'ERA5_daily_tp_1979_2020_Pk.Rdata'))
### ERA5_d_tp_1979_2020_2,ERA5_d_tp_1979_2020_1,info_tp
load(paste0(outfold_ERA5,'ERA5_daily_t2m_1979_2020_Pk.Rdata'))
### ERA5_d_t2m_1979_2020_2,ERA5_d_t2m_1979_2020_1,info_t2m
load(paste0(outfold_sta,'GaugeData_G1_12staKPK_daily_tp_t2m_1979_2020.Rdata'))
### Tmax,Tmin,Tavg,Prcp,station_names,lon,lat,metafile
nsta             =        length(lon)
BOX                       =       c(59.875,80.125,22.875,38.125)          ## bounding box of Pak
pixxy            =        0.25
xloc             =        ceiling( (lon - BOX[1])/pixxy )
yloc             =        ceiling( (BOX[4] - lat)/pixxy )
```

```
ERA5_d_t2m_g1_12sta_1979_2020 =        array(NA, dim = c(nsta,365,42))
ERA5_d_tp_g1_12sta_1979_2020   =        array(NA, dim = c(nsta,365,42))
for (sta in 1:nsta){                                        ## for loop
ERA5_d_t2m_g1_12sta_1979_2020[sta,,]    =
        ERA5_d_t2m_1979_2020_2[xloc[sta],yloc[sta],,]
ERA5_d_tp_g1_12sta_1979_2020 [sta,,]    =        ERA5_d_tp_1979_2020_2
[xloc[sta],yloc[sta],,]
}
##################################################### saving extracted data
lon_g1_12sta            =       lon
lat_g1_12sta            =       lat
sta_names_g1_12sta =       c('Balakot','Bannu','Cherat','Chitral','Dir','Kalam','Lower
Dir','Malam Jabba','Mirkhani','Pattan','Peshawar(AP)','Risalpur')
metafile='ERA5 daily precipitation and avg temperature extracted over locations of 12 KPK
gauge stations for 1979-2020'
save(ERA5_d_t2m_g1_12sta_1979_2020,ERA5_d_tp_g1_12sta_1979_2020,
metafile,lon_g1_12sta,lat_g1_12sta,sta_names_g1_12sta,
file    =       paste0(outfold_sta,'ERA5_d_tp_t2m_g1_12sta_1979_2020.Rdata'))
```

6. Calculating Statistics

```
st_d_tp                         =       st_tp_15sta_2010_2019
e5_d_tp                 =       e5_tp_15sta_2010_2019
dim(st_d_tp)            =       c(15,3650)
dim(e5_d_tp)            =       c(15,3650)
nsta                    =       dim(st_d_tp)[1]
STATS_d_tp              =       array(NA,dim=c(nsta,8))
for(sta in 1:nsta) {                                        ## for loop
STATS_d_tp[sta,1]       =       mean(st_d_tp[sta,],     na.rm = T)
STATS_d_tp[sta,2]       =       mean(e5_d_tp[sta,],     na.rm = T)
STATS_d_tp[sta,3]       =       sd  (st_d_tp[sta,],     na.rm = T)
STATS_d_tp[sta,4]       =       sd  (e5_d_tp[sta,],     na.rm = T)
STATS_d_tp[sta,5]       =       mean(e5_d_tp[sta,],na.rm = T) - mean(st_d_tp[sta,],na.rm = T)
STATS_d_tp[sta,6]       =       sqrt(mean((st_d_tp[sta,] - e5_d_tp[sta,])^2,na.rm = T))
STATS_d_tp[sta,7]       =       sd(e5_d_tp[sta,]-st_d_tp[sta,],na.rm  = T)
if ((STATS_d_tp[sta,3] > 0) && !is.na(STATS_d_tp[sta,3])){
STATS_d_tp[sta,8]       =       cor(st_d_tp[sta,],e5_d_tp[sta,],use='na.or.complete')
```

```
}}
round(colMeans(STATS_d_tp,na.rm=T),2)                    ## Output Stats
```

7. Annual Trends

```
Ptrends          =    array(NA, dim = c(81,61,2))
Ttrends          =    array(NA, dim = c(81,61,2))
for (x in 1:81){
for (y in 1:61){
if(!is.na(Pannual[x,y,1])){
ser1           =    ts(Pannual[x,y,], start=(1979), end=c(2020), frequency=1)
a1             =    c(1:length(ser1))
reg1           =    lm(ser1~a1)
slope1         =    summary(reg1)$coefficients[2, 1]
sig1           =    summary(reg1)$coefficients[2, 4]
Ptrends[x,y,1] =    slope1
Ptrends[x,y,2] =    sig1
}
if(!is.na(Tannual[x,y,1])){
ser2           =    ts(Tannual[x,y,], start=(1979), end=c(2020), frequency=1)
a2             =    c(1:length(ser2))
reg2           =    lm(ser2~a2)
slope2         =    summary(reg2)$coefficients[2, 1]
sig2           =    summary(reg2)$coefficients[2, 4]
Ttrends[x,y,1] =    slope2
Ttrends[x,y,2] =    sig2
}}}
########################################################### saving Trends data
metafile='trends[dimension2 --> slope,significance]. Annual precipitation & temperature trends/slope (mm/year&degC/year) and their significance derived from the data obtained from ERA5 25 km for Pakistan (59.875,80.125,22.875,38.125) for 1979-2020'
save(Ptrends,Ttrends,metafile,
file=paste0(outfold,'ERA5_annual_trends_tpt2m_1979_2020.Rdata'))
```

8. Plotting Annual Trends

```
fig5           =    paste(figfold,'climprof_Annual_precip_trends.png', sep = '')
```

```
cols            =       c('red','orange','yellow','green','sky blue','blue')
mypalette       =       colorRampPalette(cols)(200)                        ## Color Pallette
longitude       =       59.875          + (80.125-59.875)*((1:81)-1)/81
latitude        =       22.875 + (38.125-22.875)*((1:61)-1)/61
tr              =       Ptrends[,,1]
limits          =       range(tr,na.rm=T)
zlim            =       limits

png(filename=fig5,units="px", width = 1800, height = 1800, pointsize = 24)
op <- par(mfrow = c(1,1),pty = "m", mar=c(5,5,2,3), oma=c(1,1,2,1) ) ## [B,L,T,R]
image.plot(longitude, latitude, arev(tr,2),xlab='Longitude',ylab='Latitude',zlim=zlim,
cex.lab=2,cex=2,cex.axis=2,col=mypalette,axis.args = list(cex.axis = 2),legend.width = 2)
title('Annual Precipitation Trends', line=-
0.25,cex=2,cex.main=2.5,font.main=2,col.main='black',outer=TRUE)
text(82,23, expression(paste("mm/year")),cex=2,xpd=NA)
par(op)
dev.off()
```

9. Plotting Station Locations over DEM of Pak

```
load(paste0(outfold,'000_MonthlyData_15sta_tp_t2m_2010_2019.Rdata'))
### lon_15sta,lat_15sta,sta_names_15sta
load(paste(mapsfold,'PkDEM_0.00833.Rdata', sep = ''))
### PkDEM[2400,1800],coords
load(paste(mapsfold,'PK_filter_border_0.008333333.Rdata', sep = ''))
### PKfilter,PKborder
load(paste(colorfold,'mybowDEM_Pk.Rdata', sep = ''))
### mybowDEM, mybowDEM2
PKfilter[PKfilter == 0]         =       NA

longitude1              =       60      + (80-60)*((1:2400)-1)/2400
latitude1               =       23      + (38-23)*((1:1800)-1)/1800
im1                     =       PkDEM
im1[im1 < -1000]        =       NA
im1                     =       im1     *       PKfilter
```

```
zlim = range(im1,na.rm=T)

png(filename=figDEM,units="px", width = 2000, height = 2000, pointsize = 15)
op <- par(mfrow = c(1,1),pty = "m", mar=c(3,6,2,3), oma=c(2,0,1,6) ) ## [B,L,T,R]
image.plot(longitude1, latitude1, arev(im1,2),xlab='',ylab='',zlim=zlim,
cex.lab=3,cex=3,cex.axis=3,col=mybowDEM,axis.args = list(cex.axis = 3),legend.width = 3)
points( PKborder, typ='l', col='black', lwd=3)
points(lon_15sta,lat_15sta,pch=21,col='black',bg='blue',    lwd=1, cex=3.5)
text(81.35,37.75, expression(paste("DEM (m)")),cex=3.5,xpd=NA)
par(op)
dev.off()
```