CLIMATE CHANGE EXTREMES AND RAINFALL VARIABILITY OVER PAKISTAN

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PREFACE

The special report on global warming and impacts on extreme events and rainfall variability over Pakistan under $2°C$ warming above the baseline period $(1971 - 2000)$ is prepared. This report presents the changes in temperature and precipitation distributions in different agro-climate zones of Pakistan, the impact of climate change on urban centers (federal and provincial capitals) and on summer monsoon precipitation in Pakistan. The prime objective of the report is to identify the changes in extreme events and water resource availability in the future warm climate and to aware public regarding greenhouse gas emission, resultant global warning, and imminent threat of climate change, so that sustainable development may be attained by adopting mitigation measures. This report is jointly prepared by Dr. Furrukh Bashir from the Research and Development Division (R&D) of Pakistan Meteorological Department (PMD), Islamabad as Principal Investigator (P.I) and Dr. Uzma Hanif F. C. College. Lahore as Co-P.I. Dr. Furrukh Bashir have analyzed the in-situ observations recorded by PMD and Global Circulation Models (GCM) to identify the potential changes in future warm climate under $2°C$ warming, Dr. Uzma Hanif have evaluated the impact of climate change on society of Pakistan and perception of society regarding climate change to identify which fractions of the society are more vulnerable and which out them are more sensitive to climate change.

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LIST OF ABBREVIATIONS

ACZ	Agro-Climate Zone
AJK	Azad Jammu Kashmir
AR5	Fifth Assessment Report
BCSD	Bias-Correction Spatial Disaggregation
CMIP5	Coupled Model Inter-Comparison Project Phase 5
DTR	Diurnal Temperature Range
GCISC	Global Change Impact Study Centre
GCM	Global Circulation Models
GDDP	Global Daily Downscaled Projections
IIASA	International Institute for Applied System Analysis
IPCC	Intergovernmental Panel on Climate Change
KPK	Khyber-Pakhtunkhwa
m.a.s.l	Meters above Seal Level
NEX	NASA Earth Exchange
PMD	Pakistan Meteorological Department
RCPs	Representative Concentration Pathways
UHI	Urban Heat Island
UNFCCC	United Nations Framework Convention on Climate Change
WMO	World Meteorological Organization
T_N	Minimum Temperature
T_X	Maximum Temperature

CHAPTER 1: EXECUTIVE SUMMARY

Since the comity of world's nations is committed to maintain the global average temperature below $2°C$ above pre-industrial levels and pursuing efforts to limit the temperature increase to $1.5°C$ above pre-industrial levels, therefore, they are pursuing to control the emission of greenhouses gases into the atmosphere under the umbrella of United Nations.

Since the increase in global temperature is unavoidable, and weather and climate extremes that are an inherent part of our weather and climate are expected to change in terms of their frequency, intensity and areal coverage. Extremes of weather and climate can have devastating effects on human society and the environment[1,2]. In order to understand changes in climate and extreme events' variability especially under $2°C$ warmer future climate scenario, this report presents the outlook and change in the distribution of temperature and precipitation in different agro-climate zones, big urban cities (federal and provincial capitals) of Pakistan under future $2°C$ warming scenarios. Since, Pakistan receives a substantial portion of its precipitation in monsoon season, and variability in monsoon rains affects Pakistan in several different ways, therefore, the change in monsoon precipitation under $2°C$ warming scenarios are also analyzed.

As already mentioned, the following report comprises three research studies. The first study evaluates the impact of climate change under $2°C$ warming scenarios on agro-climatic zones of Pakistan. Second describes the changes in extremes events under $2°C$ warming scenarios in major urban centers of Pakistan and third study describes the variability in monsoon precipitation in Pakistan under $2°C$ warming scenarios.

Since population of Pakistan is increasing with an average annual growth rate of 2.87% that is higher than global population growth rate (1.09%), and future warmer period is dominated by cyclic oscillation of prolonged dry spell with short wet periods, therefore, there is a need to provide a sustainable water supply to satisfy its ever-increasing needs in agriculture and for other human purposes. Late winter seasons and spring season are expected to be warmer under future $2°C$ warming scenario. Together with this, the annual frequency of warm and hot days is expected to increase all over the Pakistan.

The soaring temperature in late winter and spring may desiccate the soils and may reduce the amount of soil moisture available to Kharif crops. On the other hand, the Rabi crops are expected to be affected by an increase and shift in monsoon precipitation toward the autumn season that is coupled with an increase in the probability of floods and inundation. On average, the annual amount of precipitation received in Pakistan is likely to increase in future $2°C$ warmer scenarios, except for Balochistan where winter and spring precipitation that delivers snowfall on mountainous areas and recharges groundwater is decreasing. Since the future warmer period is dominated by prolonged dry spells, therefore, short-lived micro to mesoscale convective precipitation is more likely to happen that may generate runoff and localized flood while reducing the amount of effective rainfall available to agriculture and natural vegetation.

Though future warmer period is dominated by prolonged warm and hot spells, however, the analysis suggests that such dry spells are expected to be terminated with intense rainfall events that may drop the temperature. Generally, annual frequency of wet days is expected to decrease in a future warmer period, however, the moderate to heavy intensity rainfall events are expected to increase that corroborates with the above-said statement on increase in short duration microscale convective rainfalls.

Night-time temperature is also expected to increase in a future warmer period, especially in the monsoon season when water vapor concentration is high in the region. The annual frequency of warm nights is increasing all over Pakistan. The effects of increased temperature exhibit a greater impact on grain yield than on vegetative growth because of the increased minimum temperatures. These effects are evident in an increased rate of senescence which reduces the ability of the crop to efficiently fill the grain (in case of grain crops) or fruit (in case of orchards). Observations in controlled environment studies show that maize grain yield is greatly reduced by above normal temperatures during the grain filling period[3]. Temperature effects interact with the soil water status which would suggest that variation in precipitation coupled with warm temperatures would increase the negative effects on grain production.

Another interesting and revealing finding is that the areas that receive greater rainfall than others, are expected to receive more in the future warm climate and wet seasons are expected to be wetter in future warm scenarios. This phenomenon is summed up in an adage by Kevin E. Trenberth as "rich get richer and the poor get poorer"[4] both in terms of spatial and temporal scales.

Though, annual accumulated rainfall of Pakistan is expected to increase generally, however, the annual accumulated rainfall in the province of Balochistan is expected to decrease in future $2°C$ warm period. The main reason is decrease in winter and spring rainfall over its mountains from western disturbances. It can cause a severe shortage of water in groundwater and its availability for agriculture and drinking. In this situation, the policymakers need to pay special attention to Balochistan as its population growth rate is highest all over the Pakistan.

Another interesting feature of future 2^oC warming in Pakistan, as pointed out by GCM, is an increase in precipitation in Gilgit-Baltistan in all season, all over the year. Increase in precipitation is coupled with an increase in cloudiness. These conditions validate the Karakoram Anomaly hypothesis for GB in northern Pakistan. Increase in cloudiness, especially in summer season may halt melting on high altitude and it may decrease the amount of melt water in river[5]. Therefore, glaciers in the Karakoram are expected to survive with positive mass balance in $2°C$ warming scenarios, nevertheless, since they are holding water back therefore inflows in River Indus may decrease. Decrease in snow and glacier melt has got implication for down riparian areas.

The urban city environments are now called “heat islands” since their concrete pavements and lack of vegetation cause them to be warmer than the neighboring natural environment. Urban cities especially megalopolis like Karachi, Lahore, and Islamabad are vulnerable to prolonged heatwaves and to the flooding and inundation, as well. Since concrete-built structures absorb incoming solar radiation than its surrounding natural landscape that results in higher temperatures, moreover, these structures occupy open space that was once helping percolation of incoming precipitation, therefore, moderate precipitation results in flooding and inundation.

Urban centers such as Karachi, Lahore, Islamabad, Peshawar and Quetta and many other cities of the same size are better equipped with educational, health, business, employment, and recreational activities, therefore, people are pulled toward these areas. Such pull migrations result in the higher growth rate of these cities and exponential growth of concrete structures for business centers, housing and connecting roads on the behalf of formerly open spaces and vegetation. As already mentioned that, urban centers are warmer than their surrounding and in-case of occurrence of extreme prolonged temperatures (heatwaves) the elderly, infants and poor fractions of society fell victim to these environmental disasters.

In global warming scenarios, a high increase in minimum temperature is expected as compared to an increase in day time temperature. In large urban built environments, that covers a large area and pavement are higher in ratio than open spaces and vegetation, the case is opposite as we are expecting more increase in maximum (daytime) temperature in comparison to minimum (nighttime) temperatures.

Karachi, being the most densely populated and biggest city of Pakistan is highly vulnerable to climate change and global warming. Since its temperature is maintained by land-sea breeze circulation, therefore, a halt in this circulation can cause severe heatwaves in warm seasons. However, the increase in mean annual temperature of Karachi is less than$2°C$, nevertheless, it is highly vulnerable to the occurrence of frequent heatwaves in dry periods of spring and autumn season and probability of such occurrence is expected to increase in the future. The magnitudes of extreme temperature events are likely to increase along with longevity in their duration in the future warmer period that may risk the health condition of the civic population. Annual accumulated precipitation of Karachi in future warmer period is expected to increase a little, but intensities of the individual rainfall events is expected to increase especially in late monsoon season. Such irregularities may cause a decrease in the amount of effective rainfall.

Similar to Karachi, Lahore is also expected to experience urban center climate change syndrome. The increase in T_x $(2.1°C)$ is higher than that for T_n $(2.0°C)$, which is associated with climate change characteristics in urban settings. Presence of higher and lower extremes in temperature distribution of Lahore indicates the cyclic variability between warmer dry and cooler wet years. March to July months are highly susceptible to extreme events and heatwaves.

This will increase the demand for electricity for air conditioning. Districts governments need to take precautionary actions to save its civic population against prolonged heatwaves, as well. Such precautionary actions may include cold shelters for the public where people without air-conditioning may take refuge. Moreover, it is time to reconsider the provision of electricity, food, and hydrants to big megalopolis like Lahore and Karachi in the light of information on its demand growth.

Monsoon precipitation patterns are expected to be changed in future warm scenarios. Monsoon is likely to deliver more rainfall on northern (Gilgit-Baltistan) and western mountains (Khyber Pakhtunkhwa and Balochistan) and to deliver less rainfall in southern Panjab and south-eastern Sindh. Although, the monsoon is gaining strength in the late season, nevertheless, the increase in south-western Pakistan is not substantial. This increasing (north and west) and decreasing (South-east) pattern will affect the agriculture and socioeconomic of Pakistan. Especially in the south where monsoon is the only rainy season throughout the year, a decrease in monsoon rainfall may cause long term droughts and famine.

CHAPTER 2: INTRODUCTION

During a summit, in Paris in December 2015, organized under the United Nations Framework Convention on Climate Change (UNFCCC), 195 countries adopted the Paris Agreement which includes a long-term temperature goal:

"*Holding the increase in the global average temperature to well below* $2°C$ *above pre-industrial levels and pursuing efforts to limit the temperature increase to* $1.5°C$ *above pre-industrial levels, recognizing that this would significantly reduce the risks and impacts of climate change*;" (Article 2.1.a).

and

"*In order to achieve the long-term temperature goal set out in Article 2, Parties aim to reach global peaking of greenhouse gas emissions as soon as possible, recognizing that peaking will take longer for developing country Parties, and to undertake rapid reductions thereafter in accordance with the best available science, so as to achieve a balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases in the second half of this century, on the basis of equity, and in the context of sustainable development and efforts to eradicate poverty*." (Article4.1)[6].

The Paris Agreement reached in December 2015 under the auspices of the United Nations Framework Convention on Climate Change (UNFCCC) with an explicit intention to "*pursue efforts to limit the global temperature increase to* $1.5°C$ *above pre-industrial level*"[7].

Since the increase in global temperature is unavoidable, and weather and climate extremes that are an inherent part of our weather and climate are expected to change in terms of their frequency, intensity and areal coverage. Extremes of weather and climate can have devastating effects on human society and the environment[1,2].

The extreme events may be defined in several different ways, mainly depending on the need of the user and the objectives of the study. Such extremes may be maxima or minima, or they may be described as rare events, moreover, they may be identified by their enormous magnitude, or they are important due to their socioeconomic implications. In terms of statistics, extreme events are events located in the tail of the distribution. Nevertheless, statistical analysis of extreme events is challenging for several reasons.

As already said, extremes are often characterized by large values (such as outliers) and identification of such events requires robust and resistant statistics. They are often rare events, identified by a small sample of the population coupled with large uncertainty. Such samples may be poorly recorded observations or erroneous values, however, a collection of such values over space and time may provide meaningful information regarding the nature of extreme events. Another, robust measure of extreme events is a statistical analysis of moderate extremes (such as first and third quartile) that can be used to infer the behavior of more extreme events. Whereas small samples in a categorical approach can result in a biased and non-informative asymptotic limit.

Since all nations are unanimously committed to limit the increase in global temperature under $2°C$ above the pre-industrial levels, therefore, it is time to reckon the impact of climate change on distribution, frequency and magnitude under $2°C$ warming.

The most important sector of human socioeconomic life that is vulnerable to climate change in agriculture. Developing countries, such as Pakistan, where extraction of natural resources and agriculture are contributing more in the economy than industry, and subsistence farming is being practiced at large, are more vulnerable to climate change and resultant food security threats. It has been suggested that climate change will change the sowing and harvesting dates in many locations and in some cases a crop may cease to exist in a specific location. The threats to food security in the wake of climate change are mainly because of rising temperatures and change in precipitation patterns. Presently, Pakistan commands the highest ratio of irrigated cropland in the region with four-fifth of its total cropland being currently irrigated and the remainder being rain-fed[8], and such rain-fed areas are more vulnerable to deficiency of water in case of a decrease in precipitation because few alternatives are available to irrigate such areas.

It has been pointed out[8] that in addition to the magnitude and pace of climate change, the stage of growth during which a crop is exposed to drought or heat is important as temperature and seasonal precipitation patterns vary from year-to-year and region-to-region, regardless of long-term trends in climate. Water availability is the most important resource for food production globally. Additionally, variations in genotype, growing period, agricultural practices, meteorological and soil conditions also affect the magnitude of yield from the crop, moreover, phenological development is the most important aspect of climate adaptation to climate shifting. Climate change may alter the rate of phenological development and the amount and distribution of precipitation during the growing season. Therefore, such changes may result in a mismatch between water demand by crops and water availability from precipitation. Climate change may result in changes in the temporal distribution of meteorological variables during the crop growing season. One particular concern is the crop phonological development which is largely determined by temperature and photoperiod, may be out of phase with precipitation and hence water availability during critical periods of grain yield determination[9]. Since, the amount of water vapor in the atmosphere is expected to increase roughly exponentially with increase in temperature, especially when a source with an uninterrupted supply of water is present in ambiance, therefore, it is expected that human-induced global warming is contributing in an increase in heavy precipitation. Changes (increase) in extreme precipitation are projected by the models, however, impacts of future changes in extreme precipitation may be underestimated because models seem to underestimate the observed increase in heavy precipitation with warming.

Since urban centers are full of attractions, such as opportunities for better health care, better educational prospects, and better employment and business potentials all over the globe. Therefore, an exponential increase in urban population and a resultant increase in pavements and concrete built environment can turn these big urban centers highly vulnerable to climate change. Human-induced global warming has a compounded effect on the urban landscape. Keep all these aforementioned impacts of climate on different sectors on human life and Pakistan's economy, the following report is prepared to explain the effect of climate change under 2^oC warming scenarios on agro-climatic zones of Pakistan and on its urban centers and on the variability of monsoon in its different areas.

Chapter 2 provides the rationale of the study. Chapter 3 describes the characteristics of the data that are utilized in the study. Further, it explains the importance of Global Circulation Models (GCMS) for the assessment of future climate change and description of the best GCM data that is available for Pakistan for the monitoring, detection, and attribution of changes in climate extremes in Pakistan. Moreover, it explains the utility of ensemble mean and median over the individual GCM runs and the variables that are analyzed from gridded GCM along with in-*situ* observations collected and recorded by Pakistan Meteorological Department. Chapter 4 explains the methodology to compute GCM ensemble averages of temperature and precipitation for the retrospect and prospect. Moreover, it describes the baseline period (retrospect) that is taken as a standard climate of Pakistan and a future period (prospect) when the mean annual temperature of Pakistan will be increased by$2°C$. Furthermore, it delivers information on climate indices that provides the basis for the evaluation of climate change and the associated change in distribution, frequency, and intensity of extreme events. Methodology to delineate Pakistan into different agro-climate zones is described along with details on the strategy to evaluate the change in future warm climate. In addition to this, methodology to estimate the change in future climate extremes distribution for urban centres of Pakistan and to estimate the change in monsoon precipitation in different regions of Pakistan is explained. Chapter 5 describes the change in future climate extremes under $\mathbf{2°C}$ scenarios in cropping zones of Pakistan. Chapter 6 discusses the impact of climate change in $\mathbf{2°C}$ in major urban cities (federal and provincial capitals) of Pakistan and how the proportion of natural landscape and concrete built pavements is affecting the distribution of temperature and precipitation. Chapter 7 deals with the variability of monsoon in future $2°C$ warming scenarios and how it is affecting socio-economic life in different areas of Pakistan. Chapter 8 accounts for the impact of heatwaves on human health and how heatwaves and climate change is perceived in different areas of Pakistan, keeping the socio-economic, regional and educational background of the public in purview.

CHAPTER 3: DATA

There is a general consensus within the climate community that any change in the frequency or severity of extreme climate events would have profound impacts on nature and society. It is thus very important to analyze extreme events. The monitoring, detection, and attribution of changes in climate extremes usually require fine spatially continuous daily data. The most accurate information (the finest spatiotemporal resolution) regarding future climate is delivered by Global Circulation Models (GCMs). General Circulation Models describe how the air in the atmosphere moves, or circulates, around the globe. They utilize the human collective understanding of the description of the conservation and movement of momentum, energy, and the mass of atmospheric constituents (including water vapor). Along with the transfer of momentum, energy, and mass into and out of the atmosphere from oceans and continents, and the energy incoming to the atmosphere as shortwave radiation from the Sun and outgoing as longwave radiation to deep space. GCMs also describe the evolution of hydrometeorological variables with that of atmospheric constituents (addition of human-induced greenhouse gases and the increase in water vapor due to the increase in temperature). This may require a description of chemical reactions but much more commonly it requires that the phase changes for atmospheric constituents are described, the description of the phase changes of water being the most important need[10].

NASA Earth Exchange (NEX) Global Daily Downscaled Projections (GDDP) dataset (see Table 3) are utilized for the analyses of future extreme events in Pakistan. The NEX-GDDP dataset comprises downscaled climate scenarios for the whole globe, that are derived from the GCM runs conducted under the Coupled Model Inter-Comparison Project Phase 5 (CMIP5)[11] and across two of the four greenhouse gas emissions scenarios known as Representative Concentration Pathways (RCPs)[12]. The CMIP5 GCM runs were developed in support of the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC AR5). This dataset includes downscaled projections from the 21 models and scenarios for which daily scenario was produced and distributed under CMIP5. The purpose of this dataset is to provide a set of global, high resolution (0.25° x 0.25° degree), bias-corrected climate change projections that can be used to evaluate climate change impacts on processes that are sensitive to finer-scale climate gradients and the effects of local topography on climate conditions.

Use of GCM outputs for impact studies is limited for two reasons; firstly, GCMs are of relatively coarse resolution grids (e.g., 10^2 km), which limit their capability to capture features, such as the impact of topography at local scales. Secondly, though GCMs are globally accurate, however, locally they show bias when compared to *in-situ* observations. The NEX-GDDP dataset is bias-corrected using Bias-Correction Spatial Disaggregation (BCSD)[13,14]. BCSD algorithm compares the GCM output with corresponding gridded climate observations over a common time period to adjust future climate projections to maintain consistency with historical observations and the area of interest at a higher spatial resolution.

Each climatic projection of NEX-GDDP includes daily maximum temperature (T_x, °K), daily minimum temperature (T_n, °K) and precipitation (P_r, $Kgm^{-2}s^{-1}$) for the periods from 1950 through 2005 ("Retrospective Run") and from 2006 to 2100 ("Prospective Run"). Over here, we have further computed the ensembles of the 21 downscaled CMIP5 GCMs runs in both RCP 4.5 and 8.5 scenarios, as an ensemble is closer to *in-situ* observations than individual members[15].

The RCPs are named according to the radiative forcing target level for year 2100[16]. The radiative forcing estimates are based on the forcing of greenhouse gases and other forcing relative to pre-industrial values and do not include land use (albedo), dust, or nitrate aerosols forcing. The four IPCC approved RCP scenarios are considered to be representative of the literature and included one mitigation scenarios leading to a very low forcing level (RCP 2.6, not included in this study), two medium stabilization scenarios (RCP 4.5/RCP 6.0) and one very high baseline emission scenarios (RCP 8.5). In AR4 only 6 scenarios imitated the RCP 2.6, therefore, we are not using this RCP for the study. RCP 4.5 was imitated by 118 scenarios and RCP 8.5 (high greenhouse gas concentration levels [17]) was imitated by 40, therefore, both of them are considered for the study. RCP 8.5 was developed using MESSAGE model by the Integrated Assessment Framework by the International Institute for Applied System Analysis (IIASA), Austria[17]. RCP 8.5 is characterized by increasing greenhouse gas emissions over time. The RCP 4.5 was developed by the GCAM modeling team at the Pacific Northwest National Laboratory's Joint Global Change Research Institute (JGCRI) in the United States. It is a stabilization scenario in which total radiative forcing is stabilized shortly after 2100, without overshooting the long-run radiative forcing target level [18–20].

RCPs are not the fully integrated scenarios as they do not incorporate socio-economic, emissions, and climate projects, nevertheless, they are internally consistent sets of projections of the components of radiative forcing. In total, a set of four pathways have produced that lead to radiative forcing levels of 8.5,6, 4.5, and 2.6 W/m^{-2}, by the end of the century.

In addition to ensemble downscaled GCMs scenarios, we have used meteorological observations collected by the Pakistan Meteorological Department. These observations include a time series of daily maximum temperature ($T_x, °C$), minimum temperature ($T_n, °C$) and daily accumulated precipitation (P_r, mm). Most of these time series covers the period of 1960 to 2013, however, some of them are of shorter duration.

CHAPTER 4: METHODOLOGY

GCM Ensemble Averages

One of the simplest ways to utilize a suite of GCMs runs is by computing the ensemble averages[21] at each grid point within a domain. Literature review suggests that the ensemble averages will have a smaller error then the individual ensemble member when compared to *in-situ* observations. This error reduction occurs because high-predictability features that the members agree on are emphasized by the mean, while low-predictability features that the members do not agree on are filtered out or heavily dampened[15]. Median of the maximum and minimum temperatures of the NEX-GDDP downscaled GCM for Pakistan are adopted as ensemble median (see Figure 1, 'a' and 'b' for T_x, and T_n, respectively). A mean value is influenced by outliers and skewed distributions; therefore, we are adopting the median (50^{th} percentile, that is also equal to mean for a normal distribution) for the development of both retrospect and prospect runs of GCMs. On the other hand, for precipitation GCM runs we are adopting mean value of the daily precipitation because precipitation follows an extreme value distribution where the median is presenting extremely low values that do not match with observations, however mean is a better estimation of the collective response of a suit of GCMs (see Figure 1, 'c').

Climate extreme in Pakistan under 2°C of warming

The scientific community has indicated that substantial changes in the earth system would occur if the global mean temperature exceeds the threshold of $2°C$ relative to pre-industrial levels. Since the signing of the Paris Agreement of December 2015[22], there is an international effort to limit global warming well below $2°C$ above pre-industrial levels and to pursue efforts to limit the temperature increase to $1.5°C$ above pre-industrial levels, recognizing that, this would significantly reduce the risks and impacts of climate change. Another important hypothesis in continuation of $2°C$ rise in global warming and change in intensity and frequency of extreme events is the rise of $2°C$ with respect to recent climate and how climatic extremes will shape in such scenario, locally. Therefore, over here we are examining how climate extremes will shape when annual mean temperature of Pakistan will be increased by $2°C$ from a baseline climate (1971-2000) that is before the onset of world warmest years in 21st century[23]. Therefore a $2°C$ warm Pakistan is defined as years under RCP 4.5 and RCP 8.5 scenarios when areal average annual mean temperature of Pakistan is $1.5°C$ to $2.5°C$ higher than that of the baseline period. Figure 2 presents the areal average mean annual temperature of Pakistan for the period of 1950-2099. It is apparent from the figure that areal average mean annual temperature for Pakistan is increasing throughout the 21st century in both RCP 4.5 and RCP 8.5 scenarios. Increase in areal average annual mean temperature in RCP 8.5 is higher than that of RCP 4.5. Areal average mean annual temperature of Pakistan in baseline scenarios is almost 20.25°C (see Figure 2, 'a' grey box), and under RCP 4.5 GCMs ensemble an increase of $2°C$ is expected to happen in the period of ($2027 - 2069$, see Figure 2, 'b' red-blue box, where areal average mean annual temperature anomalies with respect to baseline period are presented), whereas, in RCP 8.5 GCMs ensemble this period is $2027 - 2045$ (see Figure 2, 'b' red box). The duration of the increase in $2°C$ from a baseline period in RCP 8.5 ensemble is way shorter than that of RCP 4.5 ensemble, because, the former is very high emission scenarios, therefore, the higher rise in temperature is expected as compared to later that is a stabilized emission scenario. Similarly, the area average annually cumulative precipitation of Pakistan for both historical and future periods are presented in Figure 3. Future areal average annually cumulative precipitation in Pakistan is increasing with increase in temperature as suggested by Clausius-Clapeyron (C-C) equation, that describes the water-holding capacity of the atmosphere as a function of temperature, and typical values are about 7% change for $1°C$ change in temperature[4].

Climate Indices

There are a number of ways extreme climate events can be defined, such as extreme daily temperatures, extreme daily rainfall amounts, large areas experiencing unusually warm monthly temperatures, or even storm events such as tropical cyclones[24]. Extreme events can also be defined by the impact an event has on society. That impact may involve excessive loss of life, excessive economic or monetary losses, or both.

Since climate extremes can be defined as large areas experiencing unusual climate values over longer periods of time (e.g., large areas experiencing severe drought), one way to investigate trends in climate extremes over time is to develop indices that combine a number of these types of measures. A list of World Meteorological Organization (WMO) approved indices is presented in Appendix-B. These indices are instrumental to detect variation in climate.

Since there is always a mismatch between *in-situ* observations and gridded data, therefore, historical gridded areal averages of temperature and precipitation are not comparable to *in-situ* observations. However, both retrospect and prospect projections are downscaled, and bias-corrected on the same resolution, hence, their areal averages and probability distributions are also comparable to each other.

To analyze the change in nature of the climate extreme with $2°C$ rise in mean annual temperature in agro-climatic zones of Pakistan, we have classified the country into eleven zones. Nine of them are agro-climatic zones based upon an Asian Development Bank study on agricultural growth and rural poverty in Pakistan[25] and other two (i.e., Gilgit-Baltistan and Azad Jammu Kashmir) are based on administration divisions (see Figure 4). The comparison of future climate extremes with baseline period are performed using various WMO approved standard climate indices. Areal average of daily means for the baseline period (365-days cycle) of maximum (T_x, magenta Line and red circle markers) and minimum temperature (T_n , dark blue line and circle markers) are compared with that of RCP 4.5 and RCP 8.5 for each agro-climate zone (see Figure 5 to Figure **15**, 'b'). Since we are computing the areal average of the whole climatic zone that must be not as high as *in-situ* observations recorded at individual stations, nevertheless, their distributions are still comparable, and they will reveal a lot of information regarding nature of change in extreme events. Similarly, daily mean precipitation presenting 365-days annual cycle from bassline period (see Figure 5 to Figure **15**, 'c' blue line) is compared to that of $2°C$ warm Pakistan in both RCP 4.5 and RCP 8.5 scenarios (see Figure 5 to Figure **15**, 'c' red dashed line and yellow dotted line, respectively).

The distribution of temperature and precipitation in baseline and $2°C$ warmer Pakistan are compared though box and whiskers plots that provides a visual presentation of data. A box and whisker plot (boxplot) is a graph that presents information from a five-number summary. It does not show a distribution in as much detail but indicates whether a distribution is skewed and whether there are potential unusual observations (outliers) in the data set. Box and whisker plots are also very useful to compare baseline distribution of temperature and precipitation with that of $2°C$ warmer Pakistan as it compares the spread and overall range of the distributions. In such a plot (see Figure 5 to Figure **15**, 'd' to 'r') the end of the box are the upper and lower quartiles (75^{th} and 25^{th} percentiles of the cumulative distribution function, respectively), so the box spans the interquartile range and delineates the outliers. The whiskers extend to the most extreme data points not considered outliers, and the outliers are plotted individually using the red '+' symbol[26]. Median value (50^{th} percentile) of the distribution is presented by the central bar of the box plot.

We have computed some very informative climates indices that helps to identify the characteristics of extreme events in $2°C$ warmer Pakistan. Theses indices includes;

i) Total count of days where maximum temperature (T_x) is above $25°C$ that also refers to count of summer days in a calendar year,

ii) Total count of days where maximum temperature (T_x) is above$30°C$, in a calendar year, that refers to hot days.

iii) Total count of days where maximum temperature (T_x) is above$35°C$, in a calendar year, that refers to very hot days.

iv) Total count of days where maximum temperature (T_x) is above$40°C$, in a calendar year, that refers to extremely hot days.

v) Total count of nights where minimum temperature (T_n) is above 25$°C$, in a calendar year, that refers to extremely hot nights.

vi) Total count of nights where minimum temperature (T_n) is below 10$°C$, in a calendar year, that refers to cold nights.

vii) Total count of nights where minimum temperature (T_n) is below 5$°C$, in a calendar year, that refers to very cold nights.

viii) Total count of wet days with precipitation (P_r) is greater than 1 mm, in a calendar year.

ix) Total count of days with moderately intense precipitation $(P_r > 5mm)$, in a calendar year.

x) Total count of days with intense precipitation $(P_r > 10mm)$, in a calendar year.

xi) Total count of days with extremely intense precipitation $(P_r > 20mm)$, in a calendar year.

xii) Total count of dry days $(P_r < 1mm)$, in a calendar year.

All these climate indices are presented in Figure 5 to Figure 15 for different agro-climatic zones of Pakistan. In addition to these climate indices, the average precipitation for each Julian day (365-days cycle) from baseline years and warm years is presented (see Figure 5 to Figure 15, 'c'). This reveals seasonal changes in precipitation in warm periods with respect to the baseline period. Furthermore, we have used a single mass curve to present mean daily cumulative precipitation for the baseline period and $2°C$ warm periods for comparison. The mass curve revels long-term sustained trends. The comparison of the mean annual trend of baseline period to $2°C$ warm Pakistan in different agro-climatic zone reveals how precipitation in the different season will be affected (see Figure 5 to Figure 15,'s').

The impact of climate change on the extreme events of different urban centers of Pakistan is also evaluated. The urban built environment of the megalopolis of Karachi, Lahore, Islamabad, Peshawar, and Quetta is growing exponentially and so does their population. Since these urban centers are more vulnerable to climate change and extreme climate hazards than their surrounding natural landscape, therefore, change in extreme events distribution, longevity, and intensity are evaluated for them under $2°C$ warmer scenarios. In addition to the above mentioned indices, the following indices are also analyzed for the urban centers of Pakistan:

i) Change in the magnitude of a maximum of maximum temperature (T_{x_x}).

ii) Change in the magnitude of a minimum of maximum temperature (T_{x_n}).

iii) Change in the magnitude of the maximum of minimum temperature (T_{n_x}).

iv) Change in the magnitude of a minimum of minimum temperature (T_{n_n}).

v) Percentage of days above the 90th percentile of baseline temperature ($\%Days\ T_x > 90p$).

vi) Percentage of days below the 10th percentile of baseline temperature ($\%Days\ T_x > 10p$).

vii) Percentage of days above the 90th percentile of baseline temperature ($\%Days\ T_n > 90p$).

viii) Percentage of days below the 10th percentile of baseline temperature ($\%Days\ T_n > 10p$).

ix) Warm Spell Duration Index.

To evaluate the change in summer monsoon rainfall in Pakistan, the percentage change (%Δ) in monthly and seasonal cumulative precipitation from baseline period to future warmer period (both RCP 4.5 and 8.5 scenarios) is evaluated for whole Pakistan.

CHAPTER 5: FUTURE CLIMATE EXTREMES UNDER $2°C$ SCENARIOS IN CROPPING ZONES OF PAKISTAN

Introduction

The country is divided into 11 agro-climatic zones (see Figure 4), broadly based on physiography, climate, agriculture, land use, water availability, and cropping patterns bounded within common administration boundaries. The main agro-climatic zones of Pakistan are as follows:

i) Rice-Wheat Punjab

ii) Cotton-Wheat Punjab

iii) Low-Intensity Punjab

iv) Barani-Rain Fed Punjab

v) Cotton-Wheat Sindh

vi) Rice-Other Sindh

vii) Khyber-Pakhtunkhwa (KPK)

viii) Balochistan

ix) Mixed-Punjab

x) Gilgit-Baltistan

xi) Azad Jammu Kashmir

Details of the districts in each Agro-Climatic Zone is presented in Table 1.

i. Rice/Wheat Punjab

Rice/Wheat Punjab is comprised of districts of Sialkot, Gujrat, Gujranwala, Sheikhupura, Lahore, Kasur, Narowal, Mandi Bahauddin, and Hafizabad (See Figure 4, Figure 5 and Table 1). The population of this zone is recorded as 35 million in the year2017, whereas it was 23 million in year1998. The annual growth rate of the zone is almost 2.2%.

Rice, Wheat, and Sugarcane are the main crops grown in the zone. The source of irrigation is perennial and non-perennial canals supplemented by tub wells (groundwater abstractions). Rice and Wheat are the major food crops while Rice dominates with an earning as foreign exchange. Besides them, Jawar, Bajra, Mash, Moong, Masoor, Gram, Maize, Tobacco, Oil Seed such as Rape/Mustard, and sunflower are also grown in minor quantities in this zone. Winters are mild, whereas late spring and summers are hot followed by a rainy summer (Monsoon) season that ends in dry autumn. Both historical and future ensemble of GCM runs capture 365 days annual changes in temperature and precipitation very effectively. Rise in spring and summers maximum temperature (Figure 5, Panel '*a*') indicates accumulation of sensible heat with limited precipitation. However, the monsoon season that starts in early July and ends in the middle of September delivers a copious amount of rainfall (as high as 8 mm/day, $\sim 450mm$ for the season, Figure 5, Panel 'c'). Autumn is relatively a dry season, although winters receives rain from western disturbances time to time. Maximum temperature drops in the rainy season and diurnal temperature range (DTR) decreases (See Figure 5, 'a'). With the increase in annually mean areal average temperature of Pakistan by$2°C$, future GCM simulation suggest an increase in both maximum and minimum temperature in all months (see Figure 5, 'd' and 'e'). An increase in the likelihood of extreme events in maximum temperature is expected in spring and autumn seasons (April and November) that are mainly dry. $40°C$ lies almost on the 50th percentile of future GCM Projections in the months of May and June. It indicates the increase in the likelihood of maximum temperature above half of the time. On the other hand, in the month of June, the likelihood of extreme daytime temperature increases if it goes dry.

In the case of minimum temperature, (see Figure 5, 'e') likelihood of an increase in extreme events is higher for the whole year. The future minimum temperature of the summer and winter seasons is significantly higher than the historical baseline period. An annual number of days with maximum temperature above $25°C$ is expected to increase in the future warmer period. In the baseline period, it is almost nine months (~265 days) with a temperature above $25°C$, while in the future it is expected to increase by another ~ 20 days. It indicates that winter are shrinking, and the summer season is expanding. There is a substantial increase (almost a month, see Figure 5, 'h') in annual frequency of hot days i.e. $T_x > 30°C$. Frequency of days above $35°C$ (very hot) and $40°C$ (extremely hot) is expected to increase drastically. Increase in duration is more than two months for former and 1.5 months for later, respectively. Temperature higher than $40°C$ is more likely to prevail in late spring and early summer before the onset of monsoon, and it is marked by extreme events in both historical and future scenarios. Similar to maximum temperatures the night time minimum temperatures are also increasing (see Figure 5, 'k'). On the other hand, the frequency of the cold nights ($T_n < 10°C$) is decreasing by 30 days and very cold night will cease to exist with

$2°C$ increase in mean annual temperature. Annual number of wet days ($P_r > 1mm$) are decreasing in a future warm climate in this agro-climate zone. Whereas, moderate to extreme intensity precipitation events are likely to increase (see Figure 5, 'o' and 'p'). It indicates that in warming world intense precipitation (micro and meso-scale) events are more likely to happen, whereas, large scale and less intense events are less likely to happen in this zone in a future warm climate. Together with this, the annual frequency of dry days is expected to increase in the future warm climate, as well (see Figure 5, 'r'). On the seasonal scale, the precipitation in winter, spring and autumn is decreasing, while monsoon precipitation is increasing in this zone. That indicates a decrease in precipitation from large scale western disturbances and increase in micro and meso-scale precipitation from monsoon with more chances of flooding (see Figure 5, 'f'). Comparison of yearly cumulative precipitation in the baseline period and future warming periods indicates that late winter and spring will turn drier in the warm scenario. Early monsoon will receive less rainfall whereas late monsoon will receive more rainfall dominated by extreme intensity events that may lead to flooding and inundation. Wet summer are expected to lead to wet winters.

With an increase in $2°C$ in mean annual temperature of Pakistan this zone is expected to be warmer. However, the presence of extreme events on the both ends of temperature's probability distribution (above 75^{th} percentile and below 25^{th} percentile) indicates an oscillation of climate between prolonged hot dry and relatively shorter cool wet cycles on inter-annual to inter-decadal scales. Since this region is one of the densely populated agro-climate zone of Pakistan and it provides essential food grains that beefs up the regional food security, therefore, there is a need to device strategies that can ensure water from snow and glacial ice melts in dry seasons. In addition to this, since, late winter and spring are expected to be warmer and dryer, therefore, it may affect sowing of Kharif crops (sown in spring and harvested in autumn) due to limited availability of soil moisture, on the other hand, the Rabi (sown in autumn and harvested in spring) may be affected by an increase in late monsoon precipitation especially if it is causing flood and inundation. Overall, annually cumulative precipitation is expected to increase with higher variability coupled with prolonged dry spells terminated with intermittent short intense rainy periods.

ii. Cotton Wheat Punjab

Cotton-wheat Punjab is comprised of districts of Sahiwal, Pakpatan, Khanewal, Vehari, Multan, Lodhran, Bahawalnagar, Bahawalpur, and Rahim Yar Khan and it covers Sothern part of Punjab that borders with India and province of Sindh (see Figure 6, 'a'). The population of this agro-climatic region has been increased from 7 million (1998) to 9.8 million (2017)[27] with an annual growth rate of around 2.1%. Major crops sown in this region are cotton, wheat, rice, maze, sugar cane and potato on large areas, whereas, oil seeds, pulses and vegetables on small scales. Fruits includes citrus, mangoes and guava. The region is irrigated by canals, and wells and a small portion is depending on rainfall only.

Both maximum and minimum temperature are expected to increase with the rise in $2°C$ in mean annual temperature of Pakistan. This region is predominantly warm throughout the year, as a portion of the region is covered by Cholistan desert that adjoins the Thal desert in its south extending to Sindh, and into India in its east. Daytime temperature exceeds $30°C$ in early spring and within a month it exceeds $40°C$ threshold and stay above it for next three month, till August (see Figure 6, 'd'). Night temperature also remain above $30°C$ in June and July (see Figure 6, 'e'). GCM ensemble in both retrospect and prospect is imitating 365-days annual cycle of change in maximum and minimum temperature and precipitation, very effectively. Winter and spring season's rainfall in this region is very low (not more than trace most of the times), however, it receives a good rainfall in monsoon season that extends to September, sometimes. Amount of cumulative rainfall received in this ACZ is lower than ACZs situated in its north and it is higher than those in its south and west. Winter and spring season's rainfall is already very low in baseline years and they are expected to decrease further in $2°C$ warmed climate, especially in the spring season. Mean monthly accumulated monsoon rainfall is expected to decrease with an increase in extreme intensity events (see Figure 6, 'f'). That indicates that the overall amount of rainfall received is expected to decrease and chances of torrential rainfall events increase in projected $2°C$ warm periods. Such a change in precipitation pattern may decrease the amount of effective rainfall that can be stored in the root zone and can be utilized by the plants. Moreover, such erratic behavior may increase the dependency on irrigation methods, other than natural rainfall.

Annual frequency of summer days ($T_x > 25°C$) is expected to increase from ~290 to ~320 (almost by a month, see Figure 6, 'g') but in warm years it is expected to cover whole year duration. Similarly, the annual frequency of hot days ($T_x > 30°C$) is expected to increase from eight months to around nine months (see Figure 6, 'h') and annual frequency of very hot day ($T_x > 35°C$, see Figure 6, 'i') is expected to increase from ~6 months to ~7 months. Drastic change is expected in extremely hot days (very extreme events, $T_x > 40°C$, see Figure 6, '$\boldsymbol{j}$') where the frequency of occurrence is likely to be increased by 2 folds (i.e., ~60 days/year to greater than 100 days/year). Frequency of nighttime temperature is also expected to increase from 118 $days/year$ to 130 $days/year$ averagely in warm environment (annual number of warmer nights $T_n > 25°C$, see Figure 6, '$\boldsymbol{k}$'). Annual frequency of cold nights is expected to decrease in $2°C$ warmed future period by 20 nights/year averagely ($T_n < 10°C$, see Figure 6, '$\boldsymbol{l}$'), and very cold nights are not expected to occur in the future warm climate (see Figure 6, '$\boldsymbol{m}$'). The annual frequency of wet days are expected to decrease a little (by ~ 5 days), however, variability in the annual frequency of wet days is also decreasing, indicating a sustainable supply of rainfall though for shorter durations ($P_r < 1mm$, see Figure 6, '$\boldsymbol{n}$'). This is complemented by increase in annual frequency of dry days with the higher consistency (see Figure 6, '**r**'). Annual frequency of days with moderate intensity rainfall are expected to increase indicating an increase in the likelihood of extreme events (see Figure 6, '$\boldsymbol{o}$'), however, considering a very dry nature of this region, very extreme events are less likely to happen (see Figure 6, '$\boldsymbol{p}$').

Analysis of mass curves does not indicate strong deviations, especially in RCP 4.5 scenario where higher number of years are available for the analysis as compared to RCP 8.5

scenarios (see Figure 6, 's'). Likelihood of extreme events in the late monsoon may cause unnecessary deluge for sugarcane and rice crop. Downpour may damage standing crops and may risk the growth of weeds that may scale back the yield.

Heat stress affects both yield and quality of vegetables, therefore increase in summer season temperature is catastrophic for the vegetables. That can be avoided by adopting "Agro-Forestry" techniques. In such methods, trees are planted around the field to provide partial shade from scorching Sun.

Vegetables are nutritious as these provide vitamins and anti-oxidants, have low level of sugars and fat. An integrated approach is necessary to save vegetables in such situations. Growing vegetables in the right area is essential. As vegetables require less area, so behind the wall of any building will be helpful in providing shade. We should encourage "Agro-forestry". When there are trees around the field of the vegetable area, it will create a partial shade and also act as shelter belts. It's also important to water plants frequently as evaporation becomes high in summer. Heat becomes the cause of drought stress. Keep in mind that many sun-loving plants, such as tomatoes, also require a lot of water. Water is the key component to healthy plants, especially during the hottest parts of the day.

This ACZ is relatively warmer than its northern counterparts because of its proximity to a desert and, therefore, it is dry as well, as it receives $130mm/year$ annually. In future $2°C$ warm climate the winter and spring are expected to be warmer and drier that will increase the likelihood of convective rainfall on micro-scales especially in late monsoon. Such change in precipitation do not favours the timely availability of moisture in the soil for sowing. Warm duration of the year is expected to be stretched with a substantial increase in the frequency of extremely hot days and warm nights. Whereas, the annual frequency of clod nights will decrease to naught in future $2°C$ warm climate. Since the future climate is drier, therefore, the annual frequency of wet days is decreasing, nevertheless, the chances of moderate intensity rainfall are increasing.

iii. Low-Intensity Punjab

The ACZ of Low-Intensity Punjab includes districts of Dera Ghazi Khan, Rajanpur, Muzaffargarh, Layyah, Mianwali, Bhakkar, and Dera Ismail Khan. The population of the regions has been increased from 2.3 million (1998) to 3.0 million (2017)[27] by an annual growth rate of ~3.28%, that is highest among all the ACZs.

This region is situated on the banks of River Indus, contouring the base of Suliman mountain ranges (see Figure 7, '***a***'). Rivers of Punjab also merge together in the south of this ACZ. The overall climate of this ACZ is normally dry and hot in summer, having little rainfall, but winter is relatively cold. Due to the dry and barren mountains of Koh-Suleman and desert like the soil of the area, heavy windstorms are very much common in the summer. Wheat, Rice, fruits and vegetables are the popular corps in the region.

As already mentioned, the climatology of this ACZ is dominated by high temperatures and due to less rainfall, the soil remains mainly dry that leads to accumulation of available energy into sensible heat instead of latent heat. The daytime temperature in winter is moderate, nights are cold, however, increase in temperature starts in spring and cross threshold of $40°C$ in April and remain high till the end of August (see Figure 7, '***b***'). Diurnal temperature range remains high throughout the year; however, nights are very warm ($T_n > 30°C$) in summer season. Daytime temperature subsides in monsoon season (see Figure 7, '***b***' & '***c***'). Highest variability in daytime temperature is expected in April. It is because April will remain cold if it is rainy elsewise heatwave like satiation may prevails. Similar conditions are valid for May and June as well. Concentration of low temperature extremes indicates immediate relief from very high temperatures from rainfall (see Figure 7, '***d***').

This ACZ is characterized by a very low precipitation in winters (see Figure 7, '***c***'). It receives a little rain (mostly trace i.e. $< 1\ mm$) in late winter and early spring season. Spring and summer are mainly dry before the onset of monsoon. That is the time when temperature is expected to soar up in dry conditions. Monsoon starts in June and lasts till September. The amount of precipitation received in monsoon is less than its northern neighboring ACZs. Autumn season is again very dry and may cause heatwave conditions.

Both maximum and minimum's temperature monthly distribution in baseline period and future $2°C$ warm period is distinguished by low temperate extremes below the 25th percentile (see Figure 7, '***d***' & '***e***'). It is because the ACZ is mainly dry and very warm, however, due to cloudiness and rainfall the temperature subsides. Though, both maximum and minimum temperature are marked with a distinct increase in temperature in $2°C$ warm climate. However, heatwave conditions are expected to be more frequent in spring and autumn, especially if they are dry. Nighttime temperature is expected to be uncomfortable from May to August, especially in dry conditions.

Annually frequency of warms days is expected to increase by $25 - 30$ days in future warmer period (see Figure 7, '***g***'). Similarly, hot days are expect to increase from 225 to 245 (~ 40) days (see Figure 7, '***h***'). Increase in annual frequency of very hot days is expected to be around 20 (see Figure 7, '***i***'). Whereas, extreme hot days ($T_x > 40°C$) are expected to increase from 50 to 90 (~ 40) days (see Figure 7, '***j***'). In baseline period the annual frequency of extreme hot days was little more than 50 days that would be increased to 3 months in the future warmer period. Increase in temperature for such long period is intimidating, as it can affect life seriously. It may damage Rabi crop. Moreover, the demand in energy for air conditioning is expected rise. Annual frequency of warm nights is also expected to increase from 105 days to 135 days (~ one month, see Figure 7, '***k***'). Complementing these conditions, the frequency of cold nights is expected to decrease from 100 to 75 and probability of very cold nights cease to exist in future warmer periods (see Figure 7, '***l***' & '***m***'). A little increase in wet days (decrease in dry days) is expected in future warmer period (see Figure 7, '***n***' & '***r***'). However, probability of intermediately intense precipitation is expected to increase (see Figure 7, '***o***'). Seasonal analysis of precipitation suggest that monthly accumulated precipitation is expected to decrease in spring and monsoon season, however the probability of intense rain is likely to increase (see Figure 7, '***f***'). Such situation may reduce the amount of effective rainfall available to the agriculture. Single mass curve analysis of mean 365-days of baseline and future warmer period suggests that spring precipitation is expected to decrease in future that will cause more dryness and will increase the chances of heatwave conditions, in additions to that monsoon rainfall are shifting toward autumn with decrease in monthly accumulated precipitation and increase in intensity (see Figure 7, '***s***'). Late season intense precipitation may cause flooding as well.

This agro-climate zone is densely populated with higher than average growth rate. High temperatures and relatively low rainfall ($\sim 200 mm/year$) are the dominant characteristics of the ACZ. Spring season is dry and extremely warm, summers are dominated by monsoon and are relatively cooler. Higher concentration of low temperature extreme events ($< 25^{th}$ $percentile$) indicates that this ACZ is expected be dryer and warmer in future warmer period, however, cloudiness and rainfall will bring an immediate relief from heat stress and may cause low temperature (as per temperature distribution of ACZ) incidences. Occurrence of warm, hot, very hot and extremely hot days are expected to increase in future warmer period. Through, annual frequency of wet days is expected to increase with an increase in frequency of intermediately intense rainfall events, but monthly accumulated rainfall of spring and summer is expected to decrease. Monsoon is expected to be more intense toward the end of the season that may cause flooding and inundation in low lying areas. In conclusion, Low Intensity Punjab is expected to be warmer with frequent occurrence of low temperature extremes that are coupled with cloudiness and rain.

iv. Barani-Rain Fed Punjab

Barani-Rain Feb Punjab includes the districts of Attock, Rawalpindi, Islamabad, Chakwal, and Jhelum (see Figure **8**, '***a***'). It lies between the river Jhelum and the River Indus and also called as Potohar Plateau. Geomorphologically, the area can be classified into mountains, hills, rock plains, weathered rock plains, piedmont plains, loess plains, and river plains. The soils of the area have developed from wind and water transported materials consisting of loess, old alluvial deposits. The population of the region has been increased from 7.4 million (1998) to 12 million (2017)[27] in 20 years with an annual growth rate of 3.26% that makes it a rapidly growing area.

Dryland farming is the main land use. Wheat, maize, sorghum, groundnut, gram, mustard, sunflower, and soybean are the major cultivated crops along with livestock rearing as the main component of the rural economy.

Climate of this ACZ is mildly cold in winter and hot in summers when daytime temperatures soars above $40°C$ (see Figure **8**, '***b***'). Temperatures increase rapidly in summer season up the onset of monsoon in the month of June (see Figure **8**, '***b***' and '***c***'), afterwards daytime temperature subsides. Minimum temperatures remain above $0°C$ throughout the year except for very few nights (see Figure **8**, '***e***'). This region receives copious amount of rainfall in both winter and summers as compared to other ACZs of Pakistan (see Figure **8**, 'b'). Western disturbances intercepted by lesser Himalayas in winter season delivers substantial amount of rainfall. On the other hand, in summer season, the two arms of monsoon; i.e., from tail of monsoon from Bay of Bengal and Arabian Sea both converges over here and deliver highest amount of precipitation across the country. The spring is relatively dry season in comparison to winter and summer, whereas autumn is the driest season (see Figure **8**, 'b'). Whenever the summer season is dry, it increases the probability of heatwaves in the season, as soil moisture is not available to consume available energy through evapotranspiration process, therefore, net energy is stored as sensible heat that increase the temperature (especially daytime). Combination of dry and hot is conducive for heatwaves.

Heatwave conditions in April are noticed in the baseline period, however, its likelihood increases in $2°C$ warm future period (see Figure **8**, '***d***'). In addition to that, months of May, June and July are expected to be very hot, especially, if they are dry for extended periods of time. August and September are relatively cooler than their preceding months, however, they are hotter in warmed future projections. Daytime temperature are marked with low temperature extremes all around the year, these are the incidences of cloudy days with relieving temperature after a long dry spell, and they are not damaging in comparison to heat waves, instead, they are comforting (see Figure **8**, '***d***'). Nevertheless, high temperature extremes (>75th percentile) are evident in spring and summer seasons that may cause very uncomfortable conditions for people living especially in urban built environments.

Nighttime temperatures are, sometimes, below $0°C$ in winter season that is not conducive for growing season, whereas they are projected to be above $30°C$ in summer of warm future period that can increase heat stress on human life, especially infants, children and senile portions of the population (see Figure **8**,'***e***').

Comparative analysis of monthly precipitation of baseline period with future warmer period indicates that extreme events in winter precipitation are expected to decrease in this ACZ, whereas, the cumulative monthly spring precipitation is expected to decrease (see Figure **8**, '***f***'). The monthly cumulative precipitation of summer season is expected to increase with an increase in the likelihood of extreme precipitation events, similarly, autumn precipitation is expected to increase both in magnitude and in extreme events.

A decrease in winter precipitation is catastrophic for the fall (Rabi) crops in the region, especially wheat. The decrease in spring precipitation indicates drier period that is usually coupled with soaring temperatures and heat waves. Summer season increase in monthly cumulative precipitation and the likelihood of extreme events indicates the possibility of meso and micro-scale events with torrential rainfall. Such conditions can reduce the number of wet days and torrential rainfall may cause flooding, therefore less effective rainfall is available for the ACZ.

Annual frequency of warm days above different thresholds are expected to increase in warm future climate scenarios (see Figure **8**, '***g***', '***h***', '***i***', '***j***' and '***k***'). It indicates the likelihood of expansion in the summer season by at least a month with the possibility of above $40°C$ for more than 30 days. Furthermore, the annual frequency of very warm nights is expected to increase up to more than three months as compared to one month in the baseline period.

Moreover, the annual frequency of cold nights is substantially decreasing (see Figure **8**, ‘***l***’), and very cold nights ceased to exist (see Figure **8**, ‘***m***’).

As already mentioned that annual frequency of wet days is decreasing and that of dry days is increasing (see Figure **8**, ‘***n***’ and ‘***r***’), with an increase in days with moderately intense precipitation (see Figure **8**, ‘***o***’ and ‘***p***’). Increase in frequency of moderately intense precipitation indicates an increase in the likelihood of micro and meso-scale precipitation events that will reduce the amount of effective rainfall available to the soil. Furthermore, winter and spring season precipitation is projected to decrease till early monsoon, however, late season monsoon is expected to increase with an increase in autumn season rainfall (see Figure **8**, ‘***s***’).

Summarizing this, the population of ACZ of Barani-Rainfed Punjab is growing at a higher annual growth rate than that of country’s average. It is rain-fed plateau in-between two large rivers i.e., Jhelum and Indus with mildly cold winter and hot summers. It receives highest rainfall among all the ACZ of Pakistan. The spring season in this ACZ is warm and vulnerable to heatwaves, especially if it goes dry and it is expected to be warmer and dries in future warmer period. Nevertheless, both day and night temperatures are marked with cold extremes due to cloudiness and rain events. Such extremes are not damaging, rather, they are relieving for such high ambient temperature regime. Warm days are expected to expand by a month in future warmer period. In addition to this, nights are also expected to be warmer that may cause uneasiness for children, elders and ailing person of the society. Wet days are expected to decrease with an increase in the intensity of individual rainfall events. Winter precipitation is expected to decrease in projected warm period, whereas, summer precipitation is expected to increase with an increase in extreme rainfall events. Early monsoon period is getting dry, whereas, late monsoon seasons are getting wet and intense.

v. Cotton-Wheat Sindh

This ACZ is situated in south-eastern Pakistan bordering states of Rajasthan and Gujrat of India, comprising districts of Kahirpur, Nawabshah, Hyderabad, Tharparkar, Nowshehro Feroz, Ghotki, Umerkot, and Sanghar (see Figure **9**, '$\boldsymbol{a}$'). A large fraction of this ACZ is irrigated through the water canal. Population of this ACZ was recorded as 2 million in 1998, whereas, it is increase to 3.2 million in 2017[27] with an annual average growth rate of 2.9% per year that almost equal to that of Pakistan on average (2.81%). Cotton, wheat, sugar cane and rice are the main crops of the region.

The climate of this ACZ is predominantly dry and extremely hot. A record of extreme temperature observation has been set on Monday, April 30, 2018, when $50.2°C$ temperature was observed in Nawabshah by Meteo-France[28], which was the highest temperature ever reliably measured on the planet during April. Similarly, Pakistan Meteorological Department reported $53.5°C$ as Maximum Temperature at Turbat[29], $50.2°C$ at Nawabshah, $50°C$ at Jacobabad and $49°C$ at Larkana on the same date. Extreme dry conditions desiccated soil moisture and all available sun energy accumulated at sensible heat energy and with no partitioning in latent heat, it causes the extreme temperature to happen in the area.

Daytime temperature in this ACZ is above $25°C$, and night temperature is above $5°C$, all around the year (see Figure **9**, '$\boldsymbol{b}$'). In warmed future period, the areal average annual mean temperature is expected to increase $2 - 3°C$, which is warmest among all the agro climatic zones. The annual hydro-meteorological cycle of the ACZ is effectively imitated by the baseline and future climate scenarios (see Figure **9**, '$\boldsymbol{b}$' & '$\boldsymbol{c}$'). All year, expect monsoon that starts in June and ends in September, is dry and extremely hot. Monsoon season have a cooling effect on daytime temperatures all over the Pakistan, however, temperature in this ACZ is so high that monsoon cooling can be observed on nighttime minimum temperatures, as well (see Figure **9**, '$\boldsymbol{b}$'). Monthly accumulated rainfall of monsoon season in this ACZ is not as high as that of rice-Wheat Punjab and Barani Punjab, it is very low and is limited to only one rainy season.

As already mentioned, that it is very warm ACZ where maximum temperature is above $25°C$ nearly all around the year. Summer season in particular is very dry and extremely hot. $40°C$ Threshold is crossed in the month of April that is expected to be crossed in March in warm future climate projections. In the baseline period climate, maximum temperatures stay higher than $40°C$ in May and June for more than 75% of the time, however, it cools down in July with the onset of monsoon rainfall. In future warm climate period, maximum temperature (T_x) is expected to stay higher then $40°C$ from March to October. There is higher probability that it will stay above $45°C$ for 25% of the times in the May and June (see Figure **9**, '***d***'). Similarly, nighttime temperature is above $5°C$ all around the year in baseline period, which are expected t0 be above $10°C$ throughout the year in future warm years (see Figure **9**, '***d***'). Minimum temperature is vulnerable to occurrence of extremes events in future warm climate in winters, however, these extremes are not catastrophic for human life. On the other hand, expected increase above $30°C$ in T_n is expected to cause discomfort from May to August in future warm climate period (see Figure **9**, '***e***').

Monthly cumulative precipitation comparison of baseline period with future warm climate period indicates that future monsoon rainfall is expected to increase in quantity and intensity. Considering the sandy soil conditions of the ACZ the increase in quantity and intensity of monsoon rainfall may increase the likelihood of flooding and decrease in availability of effective rainfall (see Figure **9**, '***f***'). Autumn season rainfall is also expected to increase in quantity and intensity. That indicates likelihood of intense, short lived micro and meso-scale events.

Different indices based on temperature threshold indicates that frequency of warm days are expected to increase in this ACZ as suggested by warmed future climate projections (see Figure **9**, '***g***', '***h***', '***i***', '***j***', '***k***'). Future warmer years are expected to be above $25°C$ all around the year. Furthermore, annual frequency of very hot days and warm nights are expected by increase by a month. On the other hand, annual frequency of colds nights is expected to decrease.

Annual frequency of wet days is expected to increase in future warmer climate (see Figure **9**, '*n*'), and that of dry days is expected to decrease (see Figure **9**, '***r***'). In addition to this, intermediate intensity events are expected to increase (see Figure **9**, '***o***'). Annual mean cumulative precipitation single mass curve analysis of baseline period to that of future warmed climatic projections indicates an increase in monsoon precipitation especially in the months September and October. It is indicative of longevity of monsoon season with increase in its quantity and intensity toward the end of season.

Summarizing the discussion, it can be said that ACZ of Cotton-Wheat Sindh is very dry and extremely hot. World record of extreme temperature in summer has be observed over here. Apart from monsoon season the whole year is very dry, even though, the accumulated monsoon rainfall is less than other ACZs of Pakistan that are situated in its north. Annual frequency of extremely warm days is expected to increase by at least a month in future $2°C$ warm projected scenarios. Furthermore, very warm and stressful nights are expected to increase, as well. Quantity and intensity of monsoon rains are expected to increase, especially in late summers and early autumn season. This will reduce amount of effective rainfall available to Rabi crops. Moreover, short-lived micro-scale rain spells are more likely to occur in a warm ambiance as suggested by future climate change projections.

vi. Rice-Other Sindh

Agro-climatic zone of Rice-Other Sindh is comprised of districts of Jacobabad, Larkana, Dadu, Thatta, Badin, Shikarpur, Karachi (see Table 1). This ACZ strides the lover portions of the river Indus (see Figure **10**, '***a***'). The population of this region grew from 3.6 million (1998) to 5.3 million (2107)[27] in nearly 20 years with mean annual growth rate of 2.2% (see Table 2) that is little less than average mean annual growth rate of all ACZs. Due to proximity of Indus River this ACZ has got a very fertile land. Dominant crops are rice, wheat, sugarcane, barely and pulses and in fruits and vegetables guava, mangoes, oranges, olives, melons, carrots, cucumber, onion and potatoes are prominent.

Though, this region is relatively cooler than Cotton-Wheat Sindh, however, still it is warmer than other ACZ situated in its north. Winters are mild whereas summers are hot (see Figure **10**, '***b***') with a relief in daytime temperature in monsoon season. Nights are relatively warm in this ACZ (see Figure **10**, '***b***'), and the reason is the presence of water vapor due to river Indus and irrigation canals. Though, this ACZ receives rainfall in monsoon season predominantly, however, it also receives a little rainfall in winter as well, as sometimes western disturbances with southward extension approaches this ACZ. However, rainfall received in seasons other than monsoon are not substantial (see Figure **10**, '***c***') and amount of rainfall received in monsoon is little less than Cotton-Wheat Sindh. This ACZ is also vulnerable to a greater increase in temperature when mean annual temperature of the country will increase by $2°C$ in future projections (see Figure **10**, '***b***'). In addition to that, summer monsoon precipitation is expected in increase in early season that is contrary to ACZs in its north, where late season monsoon precipitation is increasing while early season precipitation is decreasing.

Spring season is expected to be very warm under warmed future climate projections. Springs are expected to be warmer than $40°C$ for 50% of the times with increase in probability of $45°C$. Especially month of May is expected to be higher than $40°C$ most of the time (see Figure **10**, '***d***'). Daytime temperature decreases with the onset of monsoon season; however, it is expected to be extremely hot in the absence of cloudiness and rain. Daytime temperature extremes are marked with low temperature extremes (due to cloudiness and precipitation), as well. Which provides relief in very hot summers. Nighttime temperature is marked with high temperature extremes in the late spring and summers (see Figure **10**, '***e***') that may increase the risk of heat stress. Extreme night temperature in spring season can be attributed to advection of warm continental winds from India, whereas, extreme night temperature in summers may be attributed to an increase in vapor pressure before saturation and condensation processes. Minimum temperature of September is marked with low temperature extremes that may attributed to cold fronts and penetration of western disturbances in the southern parts of Pakistan.

Monthly accumulative precipitation and intensity of individual rain events are expected to rise in summer monsoon and autumn in this ACZ as suggested by future warm climate projections (see Figure **10**, '$\boldsymbol{f}$'). Increase in summer monsoon precipitation may have a positive impact on Rabi crops (Rice) of this ACZ, especially when River Indus flows are strictly regulated and a decrease is expected in River Indus Flows due to Karakoram Anomaly[30]. Nevertheless, due to increase in intensity of the monsoon rainfall, short-lived micro-scales events are more likely to happen that may reduce the amount of effective rainfall available to moisten the soil.

Warmed future climate projection suggest that annual frequency of maximum temperature $T_x > 25°C$ (see Figure **10**, '$\boldsymbol{g}$') will be increased to whole year from almost 11 months in baseline scenarios. Similarly annual frequency of warms days is also increased by a month in future warm climate projections (see Figure **10**, '$\boldsymbol{h}$', & '$\boldsymbol{i}$'), especially very hot days $T_x > 40°C$ is expected to increase to 60 days from 15 days in baseline scenario (see Figure **10**, '$\boldsymbol{j}$'). Span of warm nights are expected to increase from 4 months to more than 5 months (see Figure **10**, '$\boldsymbol{k}$') cold nights will virtually cease to exist in projected warm climatic projections (see Figure **10**, '$\boldsymbol{l}$' and '$\boldsymbol{m}$').

Number of wet days is increasing with complementing decrease in number of dry days in future warmed climatic projections as compared to baseline period (see Figure **10**, '$\boldsymbol{n}$' and '$\boldsymbol{r}$'). However, the variability in the number of wet and dry days is far higher in future warmed climatic projections as compared to baseline period. It means that wet years could be exceptional wet and vice versa. Such high variability can place this ACZ in a vulnerable situation alternating between extreme flooding and severe droughts. Due to a greater number of years in RCP 4.5 scenario than that of RCP 8.5 scenarios, there is higher variability in former then latter. Together with this, probability of intermediate intensity precipitation evenest is increasing that is indicative of short-lived micro and meso-scale events (see Figure **10**, '*o*').

Annual cumulative precipitation single mass curve comparison of baseline period to that of future warmed climate scenarios indicates an increase in early season monsoon rainfall that will extend to autumn. There is not much difference in winter and early spring rainfall (see Figure **10**, '*s*') between these two periods.

Summarizing it, this ACZ is situated alongside the banks of River Indus, and a substantial portion of the ACZ is irrigated through canals, therefore, the soil is rich in moisture and vegetation cover is substantial that holds a cooling effect on the thermal regime of the ACZ. Its temperature is cooler then that neighboring relatively dry ACZs. Monsoon is a predominant rainy season, nevertheless, a little rainfall is received in winters, as well. A higher increase in temperature is expected in this ACZ in $2°C$ warm future climate projections than other neighboring ACZs in its north. Spring season is expected to be warmer than any other season. Daytime temperature is expected to be higher than $40°C$ in warmed future climate change projections. Daytime temperatures subside with onset of monsoon, however, in case of dry summers the likelihood to heatwaves is expected to increase in future. In addition to this, warm season are expected to stretch by 2 months in this ACZ. Summer monsoon and autumn monthly cumulative precipitation is expected to increase in warmed future days with increase in intensity of individual events that it indicative of short-lived micro scale events. Such events may reduce the amount of effective rainfall available to soil for agriculture purposes. Moreover, variability of seasonal rainfall is expected to increase in warm future projections that is validating the popular adage "rich get richer and the poor get poorer'[4] in terms of water availability on temporal scale, where wet years are vulnerable to floods and dry years are vulnerable to intense droughts.

vii. Khyber-Pakhtunkhwa

Agro climatic zone of Khyber-Pakhtunkhwa is comprised of all districts excluding Dera Ismail Khan (see Table 2). It can be divided into two geographic regions: mountainous areas in the north (Hindu-Kush) and Trans-Indus plains and minor mountains ranges in the south. It is a diversified region comprised of mountains, plateaus, plains, and river valleys with heterogeneous characteristics. The population of the region has grown from 17.7 million in the year 1998 to 30.5 million in the year 2017 with mean annual growth rate of 3.6% that is above the mean annual population growth rate of all ACZ of Pakistan (2.87%, see Table 2). The main crops of the region are Maize, Rice, Cotton, and Sugarcane in Kahrif (spring) and Wheat, Barly, Tobacco and Sugar Beet in Rabi (fall) along with various variety of fruits and vegetables.

Areal average of daily maximum and minimum temperature from baseline scenarios and future warmed climatic projections has imitated 365-days annual cycle of change in temperature very effectively. However due to diversity of the landscape of KPK the areal means are representing a specific land use, never the less they are presenting the mean characteristics of the region.

The climate of KPK is mainly cold in winter and it is warm in summers (see Figure **11**, 'b'). The mountainous high elevated areas are severely cold in winter with mild warm summers, whereas, plains are mildly cold in winter with hot summers. Such extremes are presented in bar and whiskers plot of maximum and minimum temperature (see Figure **11**, 'd' and 'e'), where extremes below 25th percentiles are presenting thermal regime of cold parts of KPK in extremes above 75th percentile presents the thermal regime of hot parts. Daytime temperature in Winters are extremely cold in elevated northern parts of the this ACZ with below $0°C$ temperature, however it is mild in plains with nearly$15°C$, whereas night time temperature goes below freezing in most of the hilly areas and it is mildly cold in plains. Soaring temperature in spring can be witnessed in both day and nighttime temperatures and summers are hot. Though only in heatwave conditions, that do not persist for a very long time period, the maximum temperate shoots above $40°C$, but in future warmed climatic projections maximum temperature is likely to cross $40°C$ in the month of April and October, whereas there is no precedence of such events in baseline period. Likewise, occurrence of minimum temperature above $30°C$ (uncomfortable nights) is likely to happen in future warm climate projection in duration from May to September, whereas in baseline scenario it is confined to Jun and July temperature (see Figure **11**, 'e').

Annual frequency of warm days are expected to rise by a month in future warmer climate (see Figure **11**, 'g'), and very hot days are expected by rise by more than three months (see Figure **11**, 'h'). The annual frequency of cold nights, on the other hand, is expected to decrease from 195 to 170 with low uncertainty (see Figure **11**, 'l'). Similarly, very cold nights are also expected to decrease by a month (see Figure **11**, 'm').

Annual precipitation pattern is captured effectively by ensemble GCMs projections in both baseline period and future warmed climate (see Figure **11**, 'c'). This ACZ receives rainfall in both winter and summer season. Western disturbances start to deliver rainfall in different parts of the ACZ in December till early spring when it receives the maximum of western disturbances rainfall (see Figure **11**, 'c'). Spring season is relatively dry with minimum rainfall in June. July is market with onset of monsoon rainy season that extends to September, sometimes. Early autumn is also dry. Winter cumulative precipitation is higher then that of Punjab, however, summer monsoon cumulative precipitation is less than that of Punjab. Areal average monthly cumulative precipitation in baseline and future warmed years is compared though Bar and whisker plots at seasonal scales (see Figure **11**, 'f'). It indicates that increase in winter precipitation is expected with increase in intensity of extreme events. It is indicative of occurrence of micro-scale events instead of large-scale precipitation events. In addition to this, increase in intensity of individual events indicates presence convective storm embedded in wester disturbances. Spring season monthly cumulative precipitation is expected to decrease with increase in intensity of individual events. That is again indicative of micro-scale convective precipitation. Decrease in monthly cumulative indicates prolonged dry seasons and whenever it will rain it is expected to be convective storm that may cause localized flooding. Monthly cumulative precipitation of monsoon season is expected to increase with little increase in extreme precipitation events. It indicates more consistent monsoon precipitation in this region as it receives tail of monsoon moisture from both Bay of Bengal and Arabian Sea and increase if one trail of moisture is not strong enough it may receive precipitation from other. Similar to winter, autumn precipitation is expected to increase averagely with an increase in its intensity.

Mean inter-annually cumulative precipitation single mass curve analysis of baseline period with that of future warm year is presented (see Figure **11**,'s'). It indicates increase in winter precipitation, decrease in spring precipitation, and again increase in late monsoon (August to October) and autumn in warmed future years as compared to baseline scenarios.

Summarizing the discussion on ACZ of KPK, which is comprised of a diversified land cover, ranging from lofty mountains in its north and west to river plains in its entre and south. Mean annual growth rate of population in this ACZ is higher than average of other ACZs. Land is fertile and cultivable all around the year. High elevated mountainous areas are severely cold in winter with mildly warm in summers, whereas, winters are mildly cold, and summers are hot in plains. In future warm climate projections, the summers are stretched by two months. Duration of both hot days and very warm nights is expected to increase. Frequency of cold nights is decreasing. This ACZ is moist as it receives precipitation from both western disturbances (in winters) and monsoon (in summers). Future warmed GCM projections suggests that winter precipitation is expected to increase in quantity and intensity, where chances of occurrence of convective precipitation are increasing. Spring season quantitative precipitation is decreasing with increase in likelihood of extreme events that may cause localized flooding. Decrease in spring season precipitation is also indicative of dry conditions that may facilitate the occurrence of heatwave conditions in dry years. Monsoon quantitative precipitation is expected to increase, especially in the late monsoon season, which increase the risk of flooding as soil is already saturated in late monsoon season and it may cause runoff instead of percolation. Such conditions reduce the amount of effective rainfall available to soil for agriculture.

viii. Balochistan

Province of Balochistan is an arid desert and mountainous region in the southwestern of Pakistan. It borders Arabian Sea, Gulf of Oman, Iran, KPK, Punjab and Sindh. The main crops of the region includes wheat, rice, maize, bajra, jawar and barley in limited areas[31]. The population of the province has grown from 6.5 million in 1998 to 12.5 million in 2017[27] with a mean annual growth rate of 4.4% than is higher than any other ACZ of Pakistan.

Due to scarcity of water agricultural activities are very limited. Unlike, Hindukush-Karakoram- Himalaya (HKH), there are no perennial rivers in Balochistan and most of the surface runoff never reaches to Arabian Sea[32]. Most of the rainfall received either accumulates as groundwater or lakes. In case of intense rainfall, the hill torrents cause flooding coupled with land and mudslides.

Comparison of 365-day annual cycle of maximum and minimum temperature in baseline period and future warmer period indicates that both maximum and minimum temperatures are expected to increase, all around the year (see Figure 1,'b'). Though Balochistan is an arid region however the areal average temperature is not as high as in Sindh. The reason behind is mountainous terrain of the province, where temperature at elevated locations is low, nevertheless, at low lying locations temperature is very high. For instance the location of Sibbi is exceptionally warm throughout the province of Balochistan[33]. Maximum temperature in winters is very moderate that it indicative of mild winters. Minimum temperature is sometimes below freezing (see Figure 1,'b'). In spring season, the maximum temperatures soars from $20°C$ to above $40°C$ and it remains high through the summer season till autumn. There is no dominant contribution of monsoon especially at high altitude location, whereas low-lying areas receive precipitation in monsoon season. Similarly, the minimum temperature at follows the same pattern, although, the diurnal temperature range decreases in low-lying regions in monsoon season (see Figure 1,'c'). Amount of Precipitation received in Balochistan is extremely low throughout the year (see Figure 1, 'c'). Western mountainous locations of the Balochistan province receives precipitation mainly in winter season through western disturbances. On the other hand, low-lying areas on the east receives precipitation in monsoon season. The intermittent spring season receives seldom rainfall, and whenever it is dry, the likelihood of extreme heatwaves prevalence will be increased in warmed future climatic projections (see Figure 1, 'd'). The likelihood of heatwaves is expected in autumn (especially in September) in dry years. Though maximum temperature is not as high as Sindh, nevertheless, the minimum temperature are quite high in late from May to September and they are expected to increase in warmed future period (see Figure 1, 'e'). Annual frequency of warm days is increasing (see Figure 1, 'g', 'h' and 'i'), in warm future period in comparison to baseline period, especially occurrence of $T_x > 40°C$ that is non-existent in baseline period is likely to happen in warm future years (see Figure 1, 'j'), similarly $T_n > 25°C$ is unprecedented in baseline that present with a conspicuous magnitude in warm future period years (see Figure 1, 'k'). On the other hand occurrence of cold nights is decrease in warm future period (see Figure 1, 'l' and 'm').

Annual frequency of wet days are expected to decrease in future warmer period, that is a direct contrast to rest of ACZs of Pakistan where they are increasing (see Figure 1, 'n'). The region is extremely dry therefor no events of intermediate resolution has been notice in baseline or future warmer period. Monthly cumulative Precipitation in winter, spring and autumn seasons is expected to decrease in quantity and intensity of individual events is also expected to decrease, as well (see Figure 1, 'f'). Monsoon receiving areas are expected to receive more monthly accumulated precipitation with increase in the intensity of individual events in summer season. Although, monsoon is already a convective precipitation tyupe phenomena, but an increase in the intensity of individual rainfall events indicates likelihood of short lived micro scale phenomenon.

The annual cumulative precipitation single mass curve comparison of mean baseline period to that of mean future warmer period indicates that precipitation is likely to decrease almost all around the year expect in summer season. It has got implication on food security of the region. Mountainous areas of Balochistan receives precipitation from southward extended western disturbances in winter and spring season. A substantial portion of the this winter precipitation is snowfall that serves as a memory and it is available to moisten soil upon melting in spring season and sustains a water supply. A decrease in winter season precipitation may cause wheat crop (rabi) and orchids to fail and may create a famine like situation. On the other hand, monsoon rain is expected to increase with likelihood of short lived microscale rainfall events that may cause flooding. Hill torrents of Balochistan will be more extreme in future warmer period.

In summary, Balochistan is a dry arid region with speedily growing population. Daytime temperature is likely to increase with increase in probability of heatwaves in spring and autumn season. In future warmer period, probability of warm, uneasy, stressful nights is expected to increase with decrease in probability of cold nights. Frequency of wet days is expected to decrease. Winter and spring rainfall over high elevated mountainous areas is expected to decrease and summer monsoon in low-lying areas in east of Balochistan is expected to increase with an increase in high intensity events in warm future period, this can cause an increase in frequency of hill torrents. Whereas, decrease in winter precipitation may affect the food security of the region that would affect other areas of Pakistan as well.

ix. Mixed Punjab

The agro-climatic zone of mixed Punjab is comprised of districts of Sargodha, Khushab, Jhang, Faisalabad, Toba Tek Singh and Okara (see Figure **13**). The population of mixed Punjab is increase from 2.3 million (1998) to 3.2 million (2017) by annual growth rate of 1.8%, though that is lowest among all the agro-climatic zones throughout the Pakistan (see Table 2). Together with fruits and vegetables, the popular corps of the region are wheat and sugarcane in Rabi (fall) season and rice in kharif (spring) season.

Both maximum (T_x) and minimum (T_n) temperatures are increasing with an increase in mean annual temperature of Pakistan by $2°C$ (see Figure **13**, 'b'). Comparison of 365 Julian days mean annual cycle of T_x and T_n in baseline period (1971-2000) to that of warmed climate (RCP 4.5 and 8.5) indicates that both daytime and night temperature are expected to increase as suggested by GCM runs. Nevertheless, annual cycle of $T_x$and $T_n$are fully captured by the future GCM runs. In baseline period, this zone is dominated by mild cold days and cold nights and they will turn more warm with projected increase of $2°C$ temperature (future period). In baseline period, this zone is receiving a meager amount of late winter rainfall ($< 1mm$), mainly from western disturbances, that is expected to decrease in projected warmer years (see Figure **13**, 'c' & 'f'). Spring season in this zone is very dry with extremely less rainfall and soaring temperature ($T_x > 40°C$) as a little of available energy is consumed by latent heat of evaporation and remaining all energy is available sensible heat. In baseline period the mean monthly T_x for the month of May is less than $40°C$, however, in warming scenario it is expected to increase above the threshold of $40°C$ (see Figure **13**,'d'). That will increase the likelihood of extreme heat events in spring season. On the other hand, many of the extreme events are present below 1st quantile indicating presence of not very hot days across the year (see Figure **13**,'d') in both baseline and warmed years. They are probably because of cloudy days, nevertheless, their occurrence is decreasing with increase in temperature in future warmed years. Increase in diurnal temperature range (DTR) in summer season will continue to increase till the onset of summer monsoon in the month of July, afterwards it decreases throughout the rainy season. Monsoon season is very well captured by the GCM runs in both historical and future periods. It starts in mid-June and continues will September. Summer monsoon rainfall is expected to remain same or decrease a little in magnitude, however, it is expected to increase in variability (extreme events) in future warm environment. Likelihood of very hot nights is expected to increase in summer monsoon period in projected warming, moreover, very warm nights will stretch from May to September in comparison to baseline scenarios where it is confined to June-August. Least increase in T_x is observed in autumn season of warm periods (see Figure **13**,'b'), and a little increase in seasonal precipitation with chances of more extreme events is expected (see Figure **13**,'f').

Frequency of warm days ($T_x > 25°C$) per year is expected to increase from 275 to almost ~300 days per year (see Figure **13**,'g'), a similar increase in hot days ($T_x > 30°C$, see Figure **13**,'h'), however, a dominant increase in frequency is witnessed in very hot and extremely hot days, i.e., ~30 days (165 days to ~195 days) for the former and nearly 25 days (45 days to ~ 70 days) for the later (see Figure **13**,'i & j'). It indicates that summer season will stretch by nearly one month and extremely hot summer will also stretch by three weeks. Similarly, frequency of warm nights per year are also increasing by a month (see Figure **13**,'k'). On the other hand, frequency of cold nights is decreasing and very cold nights are virtually non-existent in warmed projections (see Figure **13**,'l & m').

Number of wet days are decreasing in warmed Pakistan with respect to baseline period (see Figure **13**,'n'), however, the moderate intensity events frequency is increasing (see Figure **13**,'o'), whereas extreme intensity ($P_r > 10mm$) that are very few in baseline period are increase in the future (see Figure **13**,'p'). Frequency of dry days is expected to increase and that is complementary to decrease in wet days as already indicated (see Figure **13**,'n & r').

Comparison of precipitation mass curves, of the region, from historical baseline period and warm future periods indicates that late winter and spring precipitation is likely to decrease in magnitude. Monsoon is expected to decrease in early season while an increase is likely by the end of monsoon season followed by an almost unchanged autumn season (see Figure **13**,'s').

With growing population the demand of wheat and rice is expected to increase in coming decades. Though agro-climatic zones of mixed-Punjab is irrigated region. However, the increase in spring temperature coupled with decrease in spring rainfall can cause severe abiotic stress on wheat crop while restraining its crop production, similarly, Rice yield also declines with increase in temperature[34]. Spring planted crops are likely to be affected by the decrease in spring rainfall and increase in its temperature. As this region is irrigated as well, snow-melt water is usually not available for spring period. On the other hand, increase in late monsoon rainfall can facilitate plantation of sugarcane (fall planted crop) as higher temperature and availability of more moisture is suitable for it[35].

Summarizing the discussion on ACZ of Mixed Punjab, the GCM are effectively imitating 365-days annual cycle of change in temperature and precipitation and they indicate an increase in both day and nighttime temperatures in a future $2°C$ warm period. Spring is the warmest season of the year and probability of heatwaves is very high in late spring and summer period in case of dryness. Annual frequency of warm and hot days along with warm uneasy nights is expected to increase with decrease in that of wet days. However, the intensity of individual rainfall events is expected to increase in future warmer period, especially in summer and autumn season. Late winter and spring season cumulative precipitation is likely to decrease in magnitude and monsoon is likely to be weaken in early season, while being strong and intense in late season that may increase the risk of flooding. On the other hand, increase in autumn season rainfall may have a positive effect on fall (Rabi) crops as soil would be more moist (in case there is no flood).

x. Gilgit-Baltistan

Gilgit-Baltistan is taken as an administrative region. It is comprised of districts of Ghanche, Shigar, Kharmang, Skardu, Gilgit, Ghizer, Hunza, Nagar, Diamer and Astore (Figure 14, ‘a’). This regions is comprised of mountain ranges of Karakoram and Himalayas. Some of the world highest mountains belong to this region.

Being highly elevated mountainous region the temperature of the region is cold. Winters are extremely cold with mildly warm summers (see Figure 14, ‘b’), and August is the warmest month. Distribution of temperature of the region are marked with high temperature extreme events in nearly every month (see Figure 14, ‘d’), however, due to elevation the temperature are low therefore these extreme temperature events and heatwaves are not lethal for the people, expect in summer and low-lying areas, such as Gilgit Valley. Maximum temperate (T_x) are expected to increase all around the year in future $2°C$ warm period and highest increase in temperature is expected in summers. Similar trends are witnessed in minimum temperature (T_n) as well (see Figure 14, 'e'). There are not many instances where areal average temperature of the regions is considered as heat weaves, nevertheless, big cities situated in valleys often experience heatwave like conditions for few days in summers. However, number of cold nights are decreasing by around two months (see Figure 14, 'm').

365-days hydrologic cycle is fully imitated by GCM in both baseline and $2°C$ warm future scenarios. This ACZ receives precipitation from western disturbances obstructed by lofty orography in winter and spring, a small fraction of monsoon approaches in summer season, although, autumn is relatively a dry season (see Figure 14, 'c'). The cumulative monthly precipitation in increase all around the year, with increase in intensity of individual rainfall events (see Figure 14, 'f'). This indicates transition of large scale precipitation to meso- and micro-scale short lived convective precipitation. Increase in precipitation in $2°C$ warm future scenario may help to turn the hydrologic mass balance of the catchments positive if less melting of glacier is occurring at high altitude suggested by the hydro meteorological perspective of Karakorum anomaly[36]. Annual frequency of wet days is also expected to increase in future warmer period (see Figure 14, 'n'). Moreover, rainfall events of moderate intensity are likely to increase in warm future scenario (see Figure 14, 'o'). The single mass curve analysis of mean annual cumulative precipitation in baseline and future warmer period scenarios indicates that precipitation is likely to increase in all seasons in warm future periods (see Figure 14, 's').

ACZ of Gilgit-Baltistan is comprised of mountains, valleys and plateaus, it is host to some of world tallest mountains and largest glaciers, as well. The winters over here are extremely cold, whereas, summers are mildly warm. Low-lying valleys are vulnerable to heatwave in $2°C$ warm future period since both day and nighttime temperatures are expected to increase.

Though, very high temperature events are not fully presented in areal averages of temperature on regional scale, nevertheless, frequency of cold nights is decreasing and region is expected to be warmer in future warmer period. Although, winter and early spring will remain below freezing even if the temperature increases. Change in precipitation in future warmer period is positive throughout the year. Though, distribution of precipitation events indicates an increase in changes of convective and short-lived micro and meso-scale precipitation. An increase in precipitation across the year may turn the mass balance of the glaciers in the region, positive, especially when summer monsoon will approach to high elevation[36] and high elevated location are perennially below $0°C$ and precipitation accumulates in the form of snow.

xi. Azad Jammu Kashmir

The agro-climate zone of Azad Jammu Kashmir (AJK) is taken as an administrative division. It is comprised of ten districts; namely Mirpur, Kotli, Bhimber, Poonch, Haveli, Bagh, Sudhanoti, Muzaffarabad, Jhelum Valley, and Neelam Valley. This ACZ is a mountainous region predominantly that encompasses the power part of the Himalaya. Agriculture is main source of mean of production. Low-lying areas are densely populated and they grow crops like wheat, maize, barley and millet, whereas the high elevated locations are sparsely populate and they rely mainly on forestry and livestock, nevertheless, they grow potato, maize and wheat.

Temperature of the ACZ of AJK is mildly cold in winters and moderately warm in summers, nevertheless, low-lying areas are vulnerable to high temperature and heatwaves in summers. Comparison of Areal average maximum and minimum temperature of the region in baseline period and future $2°C$ warm period indicates that averagely temperature is expected to increase in future warm years, with higher increase in summers (see Figure **15**, 'b'). DTR is expected to increase in spring period, especially in case of low precipitation. Annual frequency of warm days are expected to increase in warm future period (see Figure **15**, 'g' and 'h'). Counts of days when $T_x > 30°C$ are almost non-existent in baseline period, however, they are more than a month in future period. Although, very hot days and very warm nights are not traced in future warm scenarios. Another indicator of future warming in AJK is decrease in cold nights (see Figure **15**, 'l' and 'm').

AJK receives precipitation in winter through interception of western disturbances by Himalayan Mountains and in summer through monsoon as gradual northward increase in elevation allows monsoon moisture to rise on the mountain range with substantial downpour. For this reason amount of precipitation received in monsoon is greater than that of winters (see Figure **15**, 'c'). 365-day annual cycle of precipitation is effectively imitated by GCM runs in both baseline and future warmer period. Monthly cumulative precipitation analysis on seasonal scales indicates a decrease in winter and spring precipitation, but an increase in summer and autumn precipitation, although, the intensity of individual events is expected to increase in all seasons (see Figure **15**, 'f'). Decrease in winter and spring cumulative precipitation has got a negative effect on annual frequency of wet days as it is expected to decrease in future warmer period (see Figure **15**, 'n' and 'r'). Analysis of annual frequency of days with $P_r > 5mm$ and $P_r > 10mm$ also suggests an increase in rainfall events with moderate and heavy precipitation (see Figure **15**, 'o' and 'p'). In addition to this, comparison of cumulative precipitation single mass curve of baseline period to future warmer period is also indicative of decrease in winter and spring precipitation up to monsoon season. However, it is expected to increase in late monsoon with higher intensity till autumn. Such conditions are more likely to generate flooding in late monsoon and early autumn season. That is the time when snow and glaciated ice is also melting and torrential rainfall on top of ice melting may cause flood in downstream areas and it may also damage the hydropower generation plants and affect the water reservoirs such as Mangla Dam on River Jhelum.

Conclusions

In $2°C$ future warming period the temperature of Pakistan is expected to increase with variability in its different agro-climate zones. In Rice/Wheat Punjab presence of extreme events on the both tails of temperature's probability distribution (above 75th percentile and below 25th percentile) indicates an oscillation of climate between prolonged hot dry and relatively shorter cool wet cycles on inter-annual to inter-decadal scales. Since, this regions is one of the densely populated agro-climate zone of Pakistan and it provides essential food grains that beefs up the regional food security, therefore, there is need to device strategies that can ensure sustained water availability from snow and glacial ice melts in dry seasons. In addition to this, since, late winter and spring are expected to be warmer and dryer, therefore, it may affect sowing of Kharif crops (sown in spring and harvested in autumn) due to limited availability of soil moisture, on the other hand, the Rabi (sown in autumn and harvested in spring) may be affected by an increase in late season monsoon precipitation especially if it is causing flood and inundation. Overall, annually cumulative precipitation is expected to increase with higher variability coupled with prolonged dry spells terminated with intermittent short intense rainy periods.

ACZ of Cotton Wheat Punjab is warmer than other ACZ in Punjab as it is in close proximity of a desert. It is dry and receives little rainfall. In future $2°C$ warm climate the winter and spring are expected to be warmer and drier that will increase the likelihood of convective rainfall on micro-scales especially in late monsoon. Such change in precipitation do not favours timely availability of moisture in the soil for sowing. Warm duration of the year is expected to be stretched with a substantial increase in frequency of extremely hot days and warm nights. Whereas, annual frequency of clod nights will decrease to naught in future $2°C$ warm climate. Since future climate is drier, therefore, annual frequency of wet days is decreasing, nevertheless, the chances of moderate intensity rainfall are increasing.

ACZ of Low Intensity Punjab is densely populated with higher than average growth rate. High temperatures and relatively low rainfall ($\sim 200mm/year$) are its dominant characteristics. Spring season is dry and extremely warm, summers are dominated by monsoon and are relatively cooler. Higher concentration of low temperature extreme events indicates that this ACZ is expected be dryer and warmer in future warmer period with frequency occurrence of very hot days, however, cloudiness and rainfall will bring an immediate relief from heat stress and may cause a decrease in temperature. Annual frequency of wet days is expected to increase with an increase in frequency of intermediately intense rainfall events but monthly accumulated rainfall of spring and summer is expected to decrease. Monsoon is expected to be more intense toward the end of the season with increased likelihood of flooding and inundation in low lying areas. In conclusion, Low Intensity Punjab is expected to be warmer with frequent occurrence of low temperature extremes that are coupled with cloudiness and rain.

The population of ACZ of Barani-Rainfed Punjab is growing at a higher annual growth rate than that of country's average. It receives highest rainfall among all the ACZ of Pakistan. The spring season in this ACZ is warm and vulnerable to heatwaves, especially if it goes dry and it is expected to be warmer and dries in future warmer period. Nevertheless, both day and night temperatures are marked with cold extremes due to cloudiness and rainy events. Warm and hot period of the years are expected to be stretched in future warmer period. Wet days are expected to decrease with an increase in the intensity of individual rainfall events. Winter precipitation is expected to decrease in projected warm period, whereas, summer precipitation is expected to increase with an increase in extreme rainfall events. Early monsoon period are getting dry, whereas, late monsoon seasons are getting wet and intense.

ACZ of Cotton-Wheat Sindh is very dry and extremely hot and the hottest period of summers is expected to expand in length coupled with increase in annual frequency of very warm nights. It receives rainfall only in monsoon season. Quantity and intensity of monsoon rains are expected to increase, especially in late summers and early autumn season with dominance of short-lived micro-scale rainfall events. This will reduce amount of effective rainfall available to Rabi crops.

A large portion of Rice-Other Sindh is irrigated through river Indus. Its temperature is cooler then that neighboring relatively dry ACZs. Monsoon is a dominating rainy season, nevertheless, a little rainfall is received in winters, as well. In comparison to ACZs in its north a higher increase in temperature is expected under $2°C$ warmer future projections. Warm seasons is expected to be prolonged with frequency occurrence of heatwaves, especially in prolonged dry conditions. Summer monsoon is expected to increase in quantity and it is expected to prolong toward autumn. Probability of short-lived micro scale events is expected to increase. Moreover, variability of seasonal rainfall is expected to increase in warm future projections that is validating the popular adage "rich get richer and the poor get poorer'[4] in terms of water availability on temporal scale, where wet years are vulnerable to floods and dry years are vulnerable to intense droughts.

ACZ of Khyber-Pakhtunkhwa is comprised of diversified land cover ranging from lofty mountains in its north and west to river plains in its entre and south. High elevated mountainous areas are severely cold in winter with mildly warm in summers, whereas, winters are mildly cold and summers are hot in plains. In future warm climate projections, the summers are stretched by two months. Duration of both hot days and very warm nights is expected to increase, along with decreasing frequency of cold nights. This ACZ is moist as it receives precipitation from both western disturbances (in winters) and monsoon (in summers). Future warmed GCM projections suggests that winter precipitation is expected to increase in quantity and intensity, where chances of occurrence of convective precipitation are increasing. Spring season quantitative precipitation is decreasing with increase in likelihood of extreme events that may cause localized flooding. Decrease in spring season precipitation is also indicative of dry conditions that may facilitate the occurrence of heatwave conditions in dry years. Monsoon quantitative precipitation is expected to increase, especially in the late monsoon season, which increase the risk of flooding as soil is already saturated in late monsoon season and it may cause runoff instead of percolation. Such conditions reduce the amount of effective rainfall available to soil for agriculture.

The AZC of Balochistan is comprised of a dry arid region with speedily growing population. Daytime temperatures are likely to increase with increase in probability of heatwaves in spring and autumn season in future warmer period. Moreover, probability of warm, uneasy, stressful nights is expected to increase with a decrease in probability of cold nights. Frequency of wet days is expected to decrease. Winter and spring rainfall over high elevated mountainous areas is expected to decrease and summer monsoon in low-lying areas in east of Balochistan is expected to increase with an increase in high intensity events in warm future period, that can increase the frequency of hill torrents. Whereas, decrease in winter precipitation may affect the food security of the region that would affect other areas of Pakistan as well.

In ACZ of mixed Punjab, spring is the warmest season of the year and probability of heatwaves is very high in late spring and summer period, especially in case of dryness. Annual frequency of warm and hot days, along with warm uneasy nights, is expected to increase with decrease in that of wet days. However, the intensity of individual rainfall events is expected to increase in future warmer period, especially in summer and autumn season. Late winter and spring season cumulative precipitation is likely to decrease in magnitude, and monsoon is likely to be weaken in early season, while being strong and intense in late season that may increase the risk of flooding. On the other hand, increase in autumn season rainfall may have a positive effect on fall (Rabi) crops as soil would be moister (in case there is no flood).

ACZ of Gilgit-Baltistan is comprised of mountains, valleys and plateaus, it is host to some of world tallest mountains and largest glaciers, as well. The winters over here are extremely cold, whereas, summers are mildly warm. Low-lying valleys are vulnerable to heatwave in $2°C$ warm future period since both day and nighttime temperatures are expected to increase. Though, very high temperature events are not fully presented in areal averages of temperature on regional scale, nevertheless, frequency of cold nights is decreasing and region is expected to be warmer in future warmer period. Although, winter and early spring will remain below freezing even if the temperature increases. Change in precipitation in future warmer period is positive throughout the year. Though, distribution of precipitation events indicates an increase in changes of convective and short-lived micro and meso-scale precipitation. An increase in precipitation across the year may turn the mass balance of the glaciers in the region, positive, especially when summer monsoon will approach to high elevation[36] and high elevated location are perennially below $0°C$ and precipitation accumulates in the form of snow.

The ACZ of Azad Jammu Kashmir is comprised of mountainous topography. An analysis of future $2°C$ warm period indicates that averagely temperature is expected to increase in future warm years, with higher increase in summers. Annual frequency of warm days are expected to increase in warm future period. Although, very hot days and very warm nights are not traced in future warm scenarios. Another indicator of future warming in AJK is decrease in cold nights. In future warmer period, a decrease in winter and spring precipitation, along with an increase in summer and autumn precipitation is expected, although, the intensity of individual events is expected to increase in all seasons. Decrease in winter and spring cumulative precipitation has got a negative effect on annual frequency of wet days as it is expected to decrease in future warmer period. Moderate to heavy rainfall events are expected to increase. Precipitation in late monsoon season is expected to increase till autumn. Such conditions are more likely to generate flooding in late monsoon and early autumn season. That is the time when snow and glaciated ice is also melting and torrential rainfall on top of ice melting may cause flood in downstream areas and it may also damage the hydropower generation plants and affect the water reservoirs such as Mangla Dam on River Jhelum.

CHAPTER 6: FUTURE CLIMATE EXTREMES UNDER $2°C$ SCENARIO IN MAJOR URBAN CITIES Of PAKISTAN

Introduction

The term ‘heat island’ describes a built-up area that is hotter than nearby rural areas. The annual mean temperature of a city with 1 million people or more can be $1-3°C$ warmer then its surrounding.

Extreme heat events due to the stagnation of warm air masses, coupled with warm nights and lack of precipitation for a prolonged period of time, can significantly affect public health, especially in the urban location where paved areas decrease the albedo and increase the amount of sensible heat as lack of vegetation reduces evapotranspiration. The urban infrastructure is also very vulnerable to the flooding as streams in the urban areas of Pakistan are usually encroached that leaves only a narrow channel for the flow of the water (urban swage in most of the cases), moreover, lack of open fields halts percolation, that compounds the problem and increases the vulnerability of the urban community toward flooding. Recently, another factor is the rapid expansion of the elite housing societies in the suburbs, and many of them are in the flood plains that also increases the vulnerability of the residents.

Despite the high mortality associated with extreme meteorological events, there is a lack of public recognition of the hazard of extreme events. We are covering public recognition of extreme climatic events in Chapter 8. Metropolitans in Pakistan generally lack preparedness measures such as heatwave response plans. Heat waves are silent killers type disasters that do not leave a trail of destruction in their wake. Unlike other disasters such as earthquake, flood, and storms that leave lasting reminders of the devastation, memories of the high temperature disappear once cooler weather arrives[37]. Similarly, unlike heat waves, other disasters have a potential to affect all the fractions of the society, whereas, heatwaves affect the elderly, sick and the poor fraction of the society, more than others.

In $2°C$ warmer Pakistan, the impact of greenhouses gases induced warming will be worse for the urban centers then the other locations. Since the urban centers are equipped with better education, health, employment and business opportunities, therefore, their population is increasing due to migration. Moreover, the annual birth rate is high in Pakistan, however in the urban setting it is even higher as a lot of mortalities can be avoided due to the availability of health facilities.

Urban centers can affect its population by an increase in carbon dioxide emission from automobile and industry, an increase in peak electricity demand, air conditioning cost, air pollution, and greenhouse gas emissions. The urban micro-climate has long been recognized as the most vulnerable location to climate change and future extreme events [38]. Prolonged exposure to high temperatures can cause heat-related illness, such as heat cramps, heat syncope, heat exhaustion, heat stroke, and death[39]. Heat exhaustion is the most common heat-related illness. Signs and symptoms include intense thirst, heavy sweating, weakness, paleness, discomfort, anxiety, dizziness, fatigue, fainting, nausea or vomiting, and headache. Core body temperature can be normal, below normal, or slightly elevated, and the skin can be cool and moist. If unrecognized and untreated, these mild to moderate signs and symptoms may progress to heat stroke[40]. Heat stroke is a severe illness. Clinically it is defined as core body temperature $\geq\ 40.6°C$, accompanied by hot, dry skin and central nervous system abnormalities, such as delirium, convulsions, or coma. Those at particularly high risk of adverse health effects from extreme heat exposure include the elderly, those living alone, and people without access to air conditioning. Additionally, people with chronic mental disorders or with ongoing medical conditions such as, cardiovascular disease, obesity, neurologic or psychiatric disease and those receiving medications that interfere with salt and water balance (e.g., diuretics, anticholergic agents, and tranquilizers that impair sweating), are at greater risk for heat-related illness and death. In addition, these strenuous outdoor physical activates (manual labor that is one of the most common employment in Pakistan) in hot weather also are risk behavior associated with heat-related illness[37].

Provincial and state capital of Pakistan holds more potential in terms of livelihood, educational, health, and recreational facilities. The megalopolis of Karachi, Lahore, twin cities of Islamabad and Rawalpindi, and Peshawar are expanding exponentially. Previously sub-urban areas are rapidly integrated into urban areas. Pavement is replacing natural landscaping. Such urban environments are highly vulnerable to climatic extremes such as heatwaves and torrential precipitation. Therefore, these urban centers demand evaluation of occurrence of extreme events in changing climate, especially under $2°C$ warming scenarios.

Data and Methodology

The data utilized and the methodology employed is already discussed in Chapter 3 and Chapter 4.

Results

The provincial capitals of Pakistan namely Karachi (capital of Sindh), Lahore (Punjab), Quetta (Balochistan) and Peshawar (Khyber-Pakhtunkhwa) along with federal capital i.e., Islamabad are the megalopolis cities. These cities hold more potential and opportunities in terms of livelihood, education, health, and recreational facilities. Therefore, public migration influx is higher in these cities. Consequently, the urban build area is continuously expanding enormously.

The changes in the meteorological extreme of these mega-cities are discussed over here:

Karachi

Karachi is the capital of the province of Sindh, that is located on the coastline along with the Arabian Sea (see Figure 16, '***a***'). It is the most populous city of Pakistan. According to the 1998 census report, the population living in West, South, East and central district along with Malir and Korangi was 9.8 million, that is now increased to 16.0 million in year 2017[27], with a mean annual growth rate of 3.32% that is the higher than the average growth rate of Pakistan (~2.8%). It is 6a th most populous city in the world. With diversified population, it is the most cosmopolitan city of Pakistan.

The winters in Karachi are mildly cold, while summers are hot and humid. Sea breeze circulation cools down the temperature of the city all around the year and especially in summer's season that is dominated with monsoon rainfall, as well. Autumns are moderately hot if wet, otherwise, heatwaves are expected in the dry autumn season, as well. The winter season is mainly dry. Land-sea breeze circulation keeps the temperature of the Karachi moderate all around the year. Due to high-pressure circulation on the city that halts sea breeze, or a low-pressure circulation situated over Indian province of Gujrat, that advects inland continental warm air to Karachi, the temperature soars above $40°C$ for several days and can create a severe heatwave type conditions. A severe heatwave with temperature as high as $49°C$ struck Karachi in June 2015 and over 2000 people died because of dehydration and heat stroke. In addition to human life losses, domesticated and zoo animals and livestock also died (https://en.wikipedia.org/wiki/2015_Pakistan_heat_wave). Again in 2017 and 2018 heat wave with exceptional high temperature in spring and autumn season cause elderly and ailing fraction of society to suffer for several days.

Maximum temperature (T_x), minimum temperature (T_n) and Precipitation (P_r) from GCM ensemble in baseline period (1971-2000) along with *in-situ* observations (Meteorological Observatory, PMD) are compared with RCP 4.5 $(2027 - 2069)$ and RCP 8.5 $(2027 - 2045)$ from future $2°C$ warm period. A 365-day annual cycle of change in maximum (T_x) and minimum (T_n) temperatures are presented (see Figure 16, '***b***'). GCM ensemble in the baseline period is underestimating T_x in late autumn, winter and spring as compared to in-situ observations of the same period, whereas, it is overestimating it in summer and early autumn. On the other hand, the GCM ensemble is underestimating T_n in the baseline period throughout the year except for the autumn season. Interestingly, in-situ observations are comparable to the future warmer period CGM ensemble in magnitude, as well. It indicates the limitation of the GCM on small spatial scales. Nevertheless, the GCM ensemble is fully imitating the 365-day temperature and precipitation cycle, effectively (see Figure 16, '***b***' & '***d***'). Around $1.8°C$ and $1.5°C$ increase in the annual maximum and minimum temperatures of Karachi in the future warmer period, respectively. That is less than the mean increase of $2°C$, mainly due to the coastline location of the city. Because of the same reason the temperature of the city is moderate throughout the year, however, due to disruption of Sea-breeze, it get warmer and heat-waves are likely to prevail. Such heatwaves are a disaster for the population living in a congested urban environment. March to July, and September-October are the warmer periods of the year when the likelihood of the heatwaves increases especially when the season is dry (see Figure 16, '$\boldsymbol{e}$'). April –October is the period of warm nights, where the likelihood of extreme warm nights increases with an increase in humidity (see Figure 16, '$\boldsymbol{f}$').

A 365-day annual cycle of precipitation is also effectively imitated by GCM ensemble in both baseline period and future warmer period (see Figure 16, '$\boldsymbol{c}$'). Little rain is received in Karachi, except for summer monsoon. Few episodes of deep penetration of western disturbances troughs in winters and early springs delivers a little rain. The future warmer period GCM ensemble indicates a little decrease in winter and spring season's cumulative monthly precipitation, along with an increase in the likelihood of extreme precipitation events in summer and autumn seasons, though monthly cumulative precipitation amount is not much changed (see Figure 16, '$\boldsymbol{d}$'). Single mass curve analyses for the mean inter-annual cumulative precipitation from the baseline and the future warmer period indicates little decrease in precipitation in the winter, spring, and autumn seasons. Early monsoon precipitation is relatively unchanged, however, the late monsoon season precipitation is likely to increase in the future warmer period (see Figure 16, '$\boldsymbol{d1}$'). Moreover, the annual cumulative precipitation is likely to increase from $\sim 100mm/year$ to $\sim 110mm/year$ in the future warmer periods. The annual frequency of the wet days is expected to increase in the future warmer period and the frequency of intense events are also expected to increase (see Figure 16, '$\boldsymbol{w}$', '$\boldsymbol{x}$' and '$\boldsymbol{y}$') and complementing the annual frequency of the dry days is expected to decrease (see Figure 16, '$\boldsymbol{z1}$').

Threshold-based analysis of T_x indicates that in the future warmer environment, days below $25°C$ will cease to exist (see Figure 16, '**g**'). In addition to this, the frequency of days with $T_x > 30°C$ will increased by 30, whereas, that of $35°C$ is expected increase by more than 50 days (see Figure 16, '***h***', '***i***').

Another group of indices that reflects a change in climate is an increase in magnitude of maximum and minimum temperature and their distributions (see Table 4). Maximum of maximum temperature (T_{x_x}) magnitude is expected to increase from an average of $36.9°C$ in the baseline period to $38.5°C$ in the future warming period (see Figure 16, '***k***'). Even higher increase is expected in the minimum of maximum temperature (T_{x_n}) i.e., $23.9°C$ to $25.8°C$ (see Figure 16, '**l**'). Similarly, the maximum of minimum temperature (T_{n_x}) is expected to increase from $27.5°C$ to $28.9°C$ (see Figure 16, '***m***'), and the minimum of minimum temperature (T_{n_n}) is expecteddd to increase by almost $\sim 2°C$ i.e., $9.5°C$ to $11.5°C$ (see Figure 16, '***n***').

Percentage of days above or below a specific percentile of the baseline period is also very instrumental to identify the change in the distribution of a meteorological variable in the wake of climate change (see Table 4). Percentage of days for $T_x > 90^{th}P$ (see Figure 16, '***o***'), $T_x < 10^{th}P$ (see Figure 16, '***p***'), $T_n > 90^{th}P$ (see Figure 16, '***q***'), and $T_n < 90^{th}P$ (see Figure 16, '***r***') in the baseline and the future warmer period are computed while using the baseline period percentiles. This analysis indicate that in the future warmer climate 100% days are warmer then the corresponding Julian days in the baseline period. Similarly, percentage of colder days than the 10th percentile of the corresponding Julian day are expected to be zero.

Another index is warm spell duration indicator (WSDI, see Figure 16, '***s***') indicates the longevity of warms days ($\boldsymbol{TX > 90th}$) for 5 consecutive days. Since percentile are based on baseline period data, therefore, the future warmer period is entirely above the 90th percentile of the baseline period. Frequency of very warm nights are expected to increase from 110 to more than 150 ($T_n > 25°C$, see Figure 16, '***t***') also increases from 110 to more then 150,) that may increase the number of air conditioning units required to maintain in-door temperature for relief from very hot nights and demand of electricity to keep air conditioning functional for a city with multimillion inhabitants. On the other hand, the annual frequency of cold nights ($T_n < 10°C$, see Figure 16, '$\boldsymbol{u}$') is decreasing and very cold nights cease to exist in the future warmer period, in the megalopolis of Karachi, as suggested by Figure 16, '$\boldsymbol{v}$'.

Summarizing the changes, in the extreme events distribution of megalopolis of the coastal city of Karachi, it is a densely populated city with moderate temperature as long as sea breeze from the Arabian Sea keeps on circulating. If it ceases the city of Karachi turn very much vulnerable to very high temperatures for numerous days that may badly affect elderly, infants and people engaged in outdoor activities. Atmospheric pressure patterns over Karachi regulates the longevity and the intensity of the heatwaves. Comparison of in-situ meteorological observations with the historical GCM ensemble of the same period indicates a discrepancy that is a well-known limitation of the GCM for small spatial scales, mainly because of the land use and topographic effects. Nevertheless, the GCM ensemble is imitating a 365-day annual cycle, effectively. The mean annual increase in the temperature of Karachi in the future warmer period is less than$2°C$. Probability of the heatwaves are high in the dry period of spring and autumn season that is likely to increase in the future warmer years. Since, moderately warm days are substituted by hot days and the span of very hot days is expected to increase by almost a month. The magnitude of extreme events in both maximum and minimum temperature, along with exposure to high temperature, is increasing, that may pose a serious risk to the urban population living in a congested concrete structures. Apart from an increase in prevailing temperature, rainfall is likely to decrease in future warmer period in winter and spring seasons, in addition to that, though quantity of the summer monsoon precipitation is not much changed in the future warmer period but there an increase in the intensity that is indicative of irregular and intense showers that may decrease the effectiveness of the rainfall for agriculture. In addition to that, late monsoon season precipitation and intensity is likely to increase indicating a seasonal shift in monsoon toward the end of the season. Though, rainfall in the future warmer period, especially, in monsoon is expected to be intense, however, it is coupled with an increase in the annual frequency of wet days.

Lahore

Lahore is provincial capital of Pakistan's Punjab (see Figure **17**, '***a***'). The city of Lahore is full of opportunities for every person and it is rapidly growing in terms of size and population. According to Statistical Bureau of Pakistan[27], its population was recorded as 6.3 million in the year 1998 that is increased to 11.1 million in the year 2017, with an annual growth rate of almost 3.7 % ,that is higher than mean population growth rate of Pakistan.

There are not many discrepancies among in-situ observed temperature and historical GCM ensemble of the same period (see Figure **17**, '***b***'), that made GCM ensemble more credulous in the both historical and future period. Winters are mildly cold in Lahore with little rainfall from western disturbances, whereas, spring season is dry and is marked with soaring temperatures with frequent occurrence of heatwaves, especially in dry years. Summer season is marked with monsoon precipitation that is sometimes more than 450 mm in a season alongwith a decrease in daytime temperature. Autumn receives a little monsoon rainfall in the early season and late autumn is mainly dry, although, temperature keep on decreasing till winter (see Figure **17**, '***b***' & '***c***'). Annualy city of Lahore receives $> 500mm$ precipitation that is expected to increase a bit in the future warmer climate.

Maximum temperature (T_x) in expected to increase by $2.1°C$ in future $2°C$ warmer period, whereas, minimum temperature (T_n) is expected to increase by$2°C$. More increase in T_x than T_n is indicative of absorption of solar radiation by concrete and paved structures that is a peculiarity of the urban environments. Averagely, future $2°C$ warm period is almost 1.5 to $2\ °C$ warmer than baseline period for Lahore.

The temperature distribution of Lahore city is market with higher and lower temperature extremes in different months. High-temperature extremes indicate future warm and dry climate and low-temperature extremes are indicative of future cool and wet climate. They are coexisting in some months (June, see Figure **17**, '***e***') that indicates the inter-annual cyclic variability between wet and dry years

May, June, and July are exceptionally hot months in Lahore (see Figure **17**, '***e***'), in addition to that, nights in months of June, July and August are very warm (see Figure **17**, '***f***'), therefore, the months of June and July are very uncomfortable for the people living in urban settings, especially if there is no rainfall for long periods. In future warmer periods, the winter season is marked with the occurrence of extremely high temperature as compared to the distribution of the baseline period, however, such extreme events in winters are not threatening for life. On the other hand, in the future warmer period, months of March to July are highly susceptible to extreme events and heatwaves. This will increase the demand of electricity for air conditioning. Districts governments need to take precautionary measures in this regard. Such precautionary actions may include cold shelters for the public where people without air-conditioning may take refuge. Moreover, it is time to reconsider the provision of electricity to big megalopolis like Lahore in the light of information on its demand growth.

Analysis of exceedance of temperature over different threshold indicates that annual frequency of warm days is expected to increase from ~268 in the baseline period to ~292 days in the future warmer period (see Figure **17**, '***g***'). Moreover, the annual frequency of hot days is expected to increase from ~218 to ~238 averagely (see Figure **17**, '***h***). That of very hot days is expected to increase from ~118 days averagely to ~183 days in the future warmer period (see Figure **17**, '***i***), these two indices indicates the longievity of hot days that were confined to the 4 months in the baseline scenarios may expand to almost 6 months in the future warmer period. In addition to that, the annual frequency of days with occurrence of extreme hot temperature were not more than a month that are expected to stretch to more than two long months (see Figure **17**, '***j***). This is the most intimidating aspect of the climate change in the urban areas that are expanding exponentially. Such future climate change projections warrants reconsideration on distribution of resources to other locations so that rapid migration can be countered with equally good opportunities at door steps of the people, everywhere.

Change in the magnitude of extreme temperature is also very daunting as T_{x_x} is expected to increase from an inter-annual average of $41.2°C$ to $43.6°C$ with frequent occurrence of events above $45°C$ temperature (see Figure **17**, ‘$\boldsymbol{k}$’). Similarly, z lower limit of maximum temperature T_{x_n} is also expected to increase from $\sim 18.9°C$ to $\sim 20.8°C$ that indicates an increase in daytime temperature of winter in the future warmer period with respect to baseline period (see Figure **17**, ‘$\boldsymbol{l}$’). In the same manner the maximum of minimum temperature (T_{n_x}, see Figure **17**, ‘$\boldsymbol{m}$’) is expected to increase from inter annual average of $28.0°C$ in baseline period to $30.2°C$ in a future warmer period, and that of (T_{n_n}, see Figure **17**, ‘$\boldsymbol{n}$’) is expected to increase from $4.7°C$ to $6.5°C$.

Analysis of percentage of days above 90th percentile and below 10th percentile of temperature on a particular Julian day across the baseline period indicates that future temperature of each Julian day is expected to be warmer than corresponding Julian day in the baseline period (see Figure **17**, ‘$\boldsymbol{o}$’, ‘$\boldsymbol{p}$’, ‘$\boldsymbol{q}$’ & ‘$\boldsymbol{s}$’). Moreover, the warm season duration index (WSDI) is expected to cover almost whole year (see Figure **17**, ‘$\boldsymbol{s}$’). As already mentioned earlier, that duration of warm nights is expected to expand in the future warmer period as compared to the baseline period, same is corroborated by analysis of annual frequency of minimum temperature ($T_n > 25°C$, see Figure **17**, ‘$\boldsymbol{t}$’) where an average duration of warm nights is increased from 105 in the baseline period to almost 138 in the future warm projections. On the other hand, the annual frequency of the minimum temperature below a specific threshold is decreasing ($T_n > 10°C$ & $T_n > 5°C$, see Figure **17**, ‘$\boldsymbol{u}$’, ‘$\boldsymbol{v}$’), as well.

Annual cumulative precipitation (~500 mm/year) is expected to increase a bit in the future warmer period (see Figure **17**, ‘$\boldsymbol{d1}$’). Comparison of monthly cumulative precipitation on a seasonal basis from baseline and future warm scenario reveals a little decrease in winter and spring precipitation, almost unchanged in summer with an increase in the intensity of individual events, and little increase in monthly cumulative precipitation with an increase in its intensity (see Figure **17**, '***d***'). Such a situation is indicative of an increase in the risk of urban flooding, when monsoon season rainfall are concentrating on the end of the rainy season with intense events.

Lahore being a big urban center is highly vulnerable to climate change. Per head water availability is decreasing with an increase in population. The warm season is stretching with an increase in the number of warms days by 24 days, hot days are increased by 30 days and very hot days are increased by almost to two months in the future warmer period from less than a month in the baseline period. Months of June and July are expected to be very warm and uncomfortable in future warm days. Extreme events such as highest and lowest maximum and minimum temperatures will be readjusted at a higher magnitude. The annual cumulative precipitation is expected to increase in the future warm climate with a decrease in winter and spring season and an increase in late monsoon season with a higher intensity that may cause urban flooding, as well. On the average, number of rainy days are expected to decrease in Lahore city in future warmer periods.

Islamabad

Islamabad is the capital of Pakistan (see Figure **18**, '***a***'). It is a planned city that was built in 1the 960s to replace Karachi as Pakistan's capital. It is surrounded by Margallah hills that has got a positive impact on the climate of the city. Its neighboring city, Rawalpindi is a congested urban location. Population increase rate of Islamabad is amongst the highest of Pakistani cities. Its population was recorded as ~0.8 million in 1998 that has been increased to 2.0 million[27] in 2017 with a mean annual growth rate of ~7.4%.

Islamabad has mildly cold winter with the hot spring season. Summer is dominated by monsoon rainfall and moderate temperatures. Summer temperature is higher in dry years. Early autumn is like summer as it receives rainfall, as well, late autumn is dry and mildly cold (see Figure **18**, '***b***'). The annual mean temperature of the future warmer period is expected to be averagely 2.1°C warmer than that of the baseline in-situ observations in terms of maximum temperature (T_x) and 2.6°C in terms of minimum temperature (T_n).

Monthly distribution of T_x in the baseline period and the future warmer period indicates that spring and summer seasons are highly susceptible to an increase in temperature (see Figure **18**, '***e***'). April is the month with highest increase in temperature with the largest variability that indicates that wet years are expected to be cool, whereas dry years are expected to be very hot. Months of May, June and July are expected to be hotter in the future warmer period and likelihood of extreme high temperature also increases in these months. Same analysis of T_n indicates that very warm nights are expected to stretch from May to September (5-months) whereas in baseline period it was confined to June, July and August (3-months), along with extremely hot nights in the month of July and August (see Figure **18**, '***f***'). Duration of warm season ($T_x > 25°C$, see Figure **18**, '***g***') is expected to increase from 238 days annually to 266 days (an increase of almost a month) though its variability is high that indicates dry years will be exceptionally warm and wet years will be moderately warm. Similarly, annual frequency of very hot days is expected to increase from 185 to 209 days (~24 days, $T_x > 30°C$, see Figure **18**, '***h***') and that of very hot and extremely hot days is expected to increase from 70 to 145 (more than two months) and virtually 0 to 23, respectively (see Figure **18**, '***i***' & '***j***'). This analysis indicates that the city of Islamabad is extremely vulnerable to climate change with the likelihood of an increase in temperature, the longevity of warm, hot and very hot days, along with the possibility of prevalence more than 20 extremely hot days (though the last metric has a higher variability).

Magnitude of maximum and minimum of maximum and minimum temperature (T_{x_x}, T_{x_n}, T_{n_x}, T_{n_n}) is also expected to increase (see Figure **18**, '***k***', '***l***', '***m***', & '***n***'). T_{x_x} is expected to increase from 39.8°C to 41.8°C . T_{x_n} is expected to increase from 16.7°C to 18.7°C. T_{n_x} is likely to increase from 25.9°C to 27.9°C, and expected increase in T_{n_n} is almost

$2.1°C$, i.e., from $2.6°C$ to $4.7°C$. Therefore, all measures of estimation of temperature extremes are expected to increase in future warmer period from baseline period.

Other indices, such as $\%days\ T_x > 90p$ see Figure **18**, '***o***', $\%days\ T_x < 10p$ Figure **18**, '***p***', $\%days\ T_n > 90P$ Figure **18**, '**q**', and $\%days\ T_N < 10p$, Figure **18**, '***r***') indicates that the future temperature distribution is expected to be warmer then 90th percentile of the baseline period throughput the year on average and cold extremes will shifted to the higher temperatures. Similarly warm spell duration index (WSDI) is also likely to expand throughout the year (see Figure **18**, '***s***') coupled with an increase in the annual frequency of warm nights from averagely 18 nights to around three months (see Figure **18**, '***t***').

An increase in overall temperature of urban city of Islamabad in future warmer period is also supported from the analysis of the annual frequency of cold events (see Figure **18**, '***u***' & '***v***'), that indicates a decrease in future cold events below a certain threshold.

Among all urban cities of Pakistan, the city of Islamabad receives the highest annual cumulative precipitation (i.e., $> 1000mm/year$, see Figure **18**, '***c***', '***d***' & '***d*1**'). Islamabad receives precipitation in winter from the interception of western disturbances by lesser Himalayan mountain ranges. In summer, monsoon moisture from both Arabian Sea and Bay of Bengal converges over here. Though it receives tail of monsoon moisture originating from the Bay of Bengal but it sometimes synergizes with the moisture from the Arabian Sea or compensates it. Monthly cumulative precipitation in winter season is expected to be unchanged with a little decease in the intensity of extreme events. In spring it is expected to decrease, that indicates the likelihood of extreme high temperature and prevalence of heatwaves in Islamabad. Summer monsoon is expected to be stronger in the future warmer climate in terms of quantity and intensity that indicates more chances of flooding in the urban areas, and flooding episodes like one in Rawalpindi (2001) may be repeated. Autumn season precipitation is also expected to increase in quantity and intensity as well. Single mass curve analysis of mean annual accumulative precipitation indicates that March to June months of the years are expected to be dryer in future and late season monsoon in autumn is expected to be stronger. Such events are more likely to be micro-scale and short lived but intense that can cause inundation in the urban paved environment.

Frequency of the annual wet days is likely to decrease in the future warmer period as compared to the baseline period (see Figure **18**, '***w***', and '***z1***'). Increase in the intensity of the individual events is supported by the analysis of the change in the annual frequency of the individual precipitation events above a certain threshold (see Figure **18**, '***x***' & '***y***'). In the future warmer period, intense precipitation events are likely to be increased and their distribution is positively skewed, that indicates an increase in the likelihood of such events.

Being capital of Pakistan the city of Islamabad is highly vulnerable to climate change as this issue is compounded by an increase in population. The annual population growth rate in Islamabad is higher than the country's average. Increase in population decreases per head availability of water resources and within the next few years, this is likely to happen in all big cities of Pakistan. Existing water storage capacity of Islamabad will not be enough to serve a larger population in near future. Groundwater abstraction is already exhausting this precious resource in Islamabad and its neighboring areas, and a further stress on groundwater will definitely affect the quality and quantity of the groundwater in the city of Islamabad.

Islamabad receives the highest precipitation among all the megalopolis of Pakistan. Duration of warm season is expected to stretch with the expansion of extremely hot duration from few days to almost a month in the future warmer period. Extremes of temperature will adjust to high temperatures, therefore, temperature extremes will set new records in the warm future period. Since Islamabad receives monsoon from both Bay of Bengal and the Arabian Sea, therefore, monsoon precipitation is expected to increase but in late monsoon season only. Moreover, a decrease in frequency of wet days and an increase in the intensity of late monsoon events is indicative of microscale, short-lived, intense convective precipitation events that may cause urban flooding.

The city administration of Islamabad requires to build water storages for Islamabad. This can be attainted trough uprising of the existing dam, the building of new reservoirs and replenishment of groundwater. Groundwater can be replenished by adopting building codes that facilities infiltration on every possible location.

Peshawar

Peshawar is the capital city of Khyber Pakhtunkhwa and located in the northwest of Pakistan (see Figure 19, '$\boldsymbol{a}$'). Similar to the other megalopolis of Pakistan its population is also increasing rapidly. According to the 1998 census report, the population of the Peshawar city was 2.0 million that has been increased to ~4.2 million [27] with a mean annual growth rate of 5.5%.

The mean annual maximum temperature (T_x) of the Peshawar urban areas is expected increase by 2.3$°C$ in the future warmer period as compared to the baseline period. With the highest increase in spring season and lowest in summer. On the other hand, the mean annual increase in minimum temperature (T_n) is expected to be 2.16$°C$ that is less then (T_x). Increase in (T_n) is highest in winters and autumn and lowest in spring and summer (see Figure 19, '$\boldsymbol{b}$').

Early spring season is marked with the occurrence of extremely high temperature and it continues till summer. T_x above 40$°C$ frequently occurs in the months of May, June and July and in future warmer period an increase in likelihood of the occurrence of such extremes events is suggested by GCMs (see Figure 19, '$\boldsymbol{e}$'). In the baseline period, T_x seldom shoots above 40$°C$ in the months of August and September, however, GCM ensemble suggests the frequent occurrence of $T_x > 40°C$ in the future warmer period, in the same period.

As already mentioned that highest increase in T_n is expected in late winter, early spring and autumn seasons, nevertheless, such increase do not fall in the ambit of warm uncomfortable nights. However, T_n distribution in the summer season in future warmer period indicates frequent occurrences of uncomfortable nights (see Figure 19, '$\boldsymbol{f}$'). The annual frequency of warm days ($T_x > 25°C$, see Figure 19, ‘***g***’) is expected to increase by a month in the future warmer period as compared to the baseline scenario. Similarly, the annual frequency of very warm days ($T_x > 30°C$, see Figure 19, ‘***h***’), is also expected to increase by a month i.e., 188 to 213. Hot and very hot seasons are expected to be stretched more in future warmer periods i.e., the frequency of hot days ($T_x > 35°C$, see Figure 19, ‘***i***’), is expected to increase from 128 to 158 and that of versy hot days ($T_x > 40°C$, see Figure 19, ‘***j***’) is expected to increase from 15 to 50.

Change in the magnitude of extreme temperatures is also expected to be in a positive direction in the future warmer period as compared to the baseline period. T_{x_x} is expected to increase from $41.2°C$ to $43.7°C$ averagely with a higher variability, T_{x_n} is expected to increase from $17.2°C$ to $19.5°C$, similarly average occurance of T_{n_x} is expected to increase from an average of $27.6°C$ to $29.8°C$ with higher variability and T_{n_n} is expected to increase from $3°C$ to $5.3°C$, see Figure 19, ‘$\boldsymbol{k}'$,$'\boldsymbol{l}'$,$'\boldsymbol{m}'$ & $'\boldsymbol{n}'$.

The distribution of temperature in future warmer period indicates that it is expected to be warmer than the 90th percentile in baseline temperature distribution, whereas, there are virtually no events below the 10th percentile of the baseline period in the future warmer period (see Figure 19, ‘***o***’, ‘***p***’, ‘***q***’ and ‘***r***’**)**. Additionally, it is already stated that warm season is expected to stretch and ***WDSI*** (see Figure 19, ‘***s***’) is also stretched to the almost whole year, along with an increase in the frequency of warm nights ($T_n > 25°C$, see Figure 19, ‘***t***’) from ~75 (baseline period) to ~ 112 (future warmer period). On the other hand, the frequency of cold nights period ($T_n < 10°C$) is expected to decrease from 112 in the baseline period to ~88 in the future warmer period (see Figure 19, ‘***u***’), similarly frequency of very cold nights ($T_n < 5°C$) are also expected to decrease from ~38 to virtually none (see Figure 19, ‘***v***’).

Future 365-days precipitation pattern of Peshawar is very much similar to that of observations and historical GCM in the baseline period (see Figure 19, ‘***c***’). City of Peshawar receives a handful amount of rainfall in both winter and summer monsoon season. The early summer and autumn are the driest period, nevertheless, Peshawar receives rain in these seasons from western disturbances, as well. Future winter season monthly cumulative precipitation is not much changed from the baseline period (see Figure 19, '$\boldsymbol{d}$'). Spring season is expected to be drier with an increase in the intensity of individual events. On the other hand, cumulative monthly precipitation of summer and autumn season is expected to be greater and more intense. It suggests an increase in the frequency of short-lived micro scale precipitation events and an increase in the likelihood of such events may cause flooding in the urban built environment. Single mass curve analysis of mean inter-annual 365-days cumulative precipitation both from baseline and future warmer period indicates a decrease in precipitation in spring and early monsoon, whereas in late monsoon precipitation is expected to increase (see Figure 19, '$\boldsymbol{d1}$'). It shows a little decrease in early monsoon is compensated by an increase in late season though their effect will not be the same on the urban built environments. Torrential rain in late monsoon season increases the likelihood of flooding as soils are already saturated from early season rainfall and hence more runoff is likely to happen. Increase in probability of future intense rainfall events is also corroborated by a decrease in annual frequency of wet days (see Figure 19, '$\boldsymbol{w}$'), complemented by an increase in the annual frequency of dry days (see Figure 19, '$\boldsymbol{z1}$'). With a decrease in the annual frequency of wet days and an increase in annual rainfall the likelihood of occurrences of extreme events increases ($P_r > 5mm$ and $P_r > 10mm$, see Figure 19, '$\boldsymbol{x}$' and '$\boldsymbol{y}$').

Concluding the discussion on climate change in the urban city of Peshawar under $2°C$ warming scenario, it is identified that warm period is stretched and duration of the very hot period is also expected to increase in future under a warming scenario. Likelihood of extreme events in early spring to summer season is expected to increase, togather with an increase in magnitude of extreme temperature and precipitation events. Spring season is expected to be drier and hot. Monsoon is expected to deliver more rainfall toward the end of the season and may cause flooding in the urban setting, since soil is already wet and urban paved environment favors flood and inundation. Future warmer period are dominated by two combinations, i) hot and dry, and ii) wet and cool. Spring season is expected to be more dry and exceptionally hot that will increase the demand for electricity. Since it is a dry season as well, therefore, it will cause disaster for the residents of the Peshawar City. Where, the heatwaves are exacerbated by water deficit.

Quetta

Quetta is the provincial capital and largest city of Balochistan. Quetta is located in the central western part of Pakistan in the Sulaiman Mountains (see Figure 20, '***a***'). Its average elevation is 1680 m.a.sl, that makes it the highest elevated urban location in Pakistan. The city is famous for the fruits orchids in and around it. It is one the fastest growing urban center among Pakistani cities. Its population was recorded at 0.7 million in 1998 that rose up to 2.2 million in 2017[27] with an annual mean growth rate of 9.7% that is the highest in Pakistan.

Quetta is also affected by climate change, though it is high elevation urban environment, nevertheless, averagely it is expecting warming in future warmer periods. Annual mean maximum temperature is expected to increase by $1.8°C$, whereas annual mean minimum temperature is expected to increase by $2.1°C$ in the future warmer period, when the mean annual temperature of Pakistan is expected to increase by $2°C$ averagely (see Figure 20, '***b***'). The 365-days cycle of maximum (T_x) and minimum (T_n) temperature is effectively imitated by GCM in the historical baseline period. Diurnal Temperature Range (DTR) is relatively narrow in the moist period and it is wide in dry period.

Comparison of the monthly distribution of temperature indicates more probability of cold extremes than hot extremes, nevertheless, the magnitude of cold extreme is warmer than that of the baseline period (see Figure 20, '***e***' and '***f***'). Future warmer period (T_x) are expected to be more warmer in the dry season and (T_n) are expected to be higher in autumn, probably because of the increase in atmospheric water vapor. Being an elevated location, the metropolitan of Quetta is not as vulnerable to change in temperature as its lower elevated counterparts does. Nevertheless, the annual frequency of warm days ($T_x > 25°C$, Figure 20, '$\boldsymbol{g}$') is expected to increase by a month. Similarly, annyal frequency of very warm days ($T_x > 30°C$) and hot days ($T_x > 35°C$) is expected to increase by 25 and more than two months, respectively (see Figure 20, '$\boldsymbol{h}$' and '$\boldsymbol{i}$'). Similar to other cities, the magnitude of extreme temperature is increasing. T_{x_x} is expected to increase from $36°C$ to $38.6°C$, $T_{x_n}$is expected to increase from $9.8°C$ to $12°C$, $T_{n_x}$is expected to increase from $20.1°C$ to $22.6°C$ and T_{n_n} is expected to increase averagely from $-4°C$ to $-2.2°C$ (see Figure 20, '$\boldsymbol{k}$', '$\boldsymbol{l}$', '$\boldsymbol{m}$' and '$\boldsymbol{n}$'). Moreover, percentage of occurrences of extreme events above the 90^{th} percentile of he baseline scenario is expected to be 100% in future warmer period, along with that of below 10th percentile is virtually zero (see Figure 20, '$\boldsymbol{o}$', '$\boldsymbol{p}$', '$\boldsymbol{q}$' and '$\boldsymbol{r}$').

Interestingly, there are no events of extremely warm nights, nevertheless, the annual frequency of nights below $10°C$ and $5°C$ are decreasing (see Figure 20, '$\boldsymbol{u}$', and '$\boldsymbol{v}$').

Winter and spring season in Quetta is dominated by precipitation (see Figure 20, '$\boldsymbol{c}$'). Mid-latitude storms penetrating southward are intercepted by lofty mountains and delivers substantial rainfall in Quetta. It also receives a little rainfall in monsoon season, as well. The amount of rainfall received in both winter and spring are expected to decrease in the future warmer period (see Figure 20, '$\boldsymbol{d}$'). Frequency of wet days is also expected to decrease in the future warmer period and that of dry days in increasing (see Figure 20, '$\boldsymbol{w}$' and '$\boldsymbol{z1}$').

The decrease in future warmer period precipitation is also suggested by single mass curve analysis that indicates a decrease in precipitation in the spring season, nevertheless, summer monsoon season precipitation is sustained (see Figure 20, '$\boldsymbol{d1}$'). Decrease in winter and spring precipitation in Quetta has a severe implication for the area. As this area receives rainfall only in winter and spring, therefore, the groundwater and agriculture is dependent on it. Decrease in water availability to orchids and agriculture can cause a severe food security threat to the growing population of Quetta. That will make it heavily dependent oon import of food from other parts of the country and people from neighboring areas may move to the city in the search of employment that will increase the urban population and may result in a tremendous stress on civic amenities.

Conclusions

The urban city environments are now called "heat islands" since their concrete pavements and lack of vegetation cause them to be warmer than neighboring natural environment. Urban cities especially megalopolis like Karachi, Lahore, and Islamabad are vulnerable to prolonged heatwaves and to the flooding and inundation, as well. Since concrete built structures absorb in-coming solar radiations that result in a decrease in surface albedo, and prevalence of higher temperatures, moreover these structures occupy open spaces, that were once facilitating percolation of incoming precipitation into the soil, therefore, moderate precipitation may results in flooding and inundation as infiltration is reduced.

Urban centers such as Karachi, Lahore, Islamabad, Peshawar and Quetta and many other cities of the same size are better equipped with educational, health, business, employment, and recreational activities, therefore people are pulled toward these areas. Such pull migrations result in a higher growth rate of these cities and exponential growth of concrete structures for business centers, housing and connecting roads on the behalf of formerly open spaces and vegetation.

As already mentioned that urban centers are warmer than their surrounding and in-case of occurrence of extreme prolonged temperatures (heatwaves) the elderly, infants and poor fractions of society fell victim to these environmental disasters.

In global warming scenarios, a high increase in minimum temperature is expected as compared to the increase in day time temperature. In large urban built environments, that covers a large area where pavements is higher in ratio than open spaces and vegetation, the case is the opposite as we are expecting more increase in maximum (daytime) temperature in comparison to minimum (nighttime) temperatures.

Karachi, being the most densely populated and biggest city of Pakistan is highly vulnerable to climate change and global warming. Since its temperature is maintained by land-sea breeze circulation, therefore, a halt in this circulation can cause severe heatwaves in warming seasons. Though the increase in mean annual temperature of Karachi is less than $2°C$, nevertheless, it is highly vulnerable to the occurrence of frequency heatwaves in dry periods of spring and autumn season and probability of such occurrence is expected to increase in future. The magnitudes of extreme temperature events are likely to increase along with prolonged exposure in a future warmer period that may risk the health condition of the civic population. Annual cumulative precipitation of future warmer period is expected to increase a little but intensities of the individual rainfall events is expected to increase especially in late monsoon season. Such irregularities may cause a decrease in the amount of effective rainfall.

Similar to Karachi, Lahore is also expected to experience urban center climate change syndrome. The increase in T_x $(2.1°C)$ is higher than that for T_n $(20.°C)$, which is associated with climate change characteristics in urban settings. Presence of higher and lower extremes in temperature distribution of Lahore indicates the cyclic variability between warmer dry and cooler wet years. March to July months are highly susceptible to extreme events and heatwaves.

This will increase the demand for electricity for air conditioning. Districts governments need to take precautionary actions in this regard. Such precautionary actions may include cold shelters for the public where people without air-conditioning may take refuge. Moreover, it is time to reconsider the provision of electricity to big megalopolis like Lahore in the light of information on its demand growth.

The increase in minimum temperature (T_n) is higher than maximum temperature (T_x) in case of Peshawar, Lahore, and Karachi since the proportion of paved and concrete build structure area is higher than that of the natural landscape. Whereas, in Islamabad and

Quetta the case is the opposite, as the proportion of the natural landscape is these cities is higher than that of concrete built areas. Nevertheless, these cities are equally vulnerable to climate change under $2°C$ warming scenario, as well.

CHAPTER 7: RAINFALL VARIABILITY IN MONSOON DOMINATED REGIONS OF PAKISTAN UNDER 2°C WARMING SCENARIO

Introduction

The monsoon season has a profound influence on the lives of people and the economy of Pakistan. Social life and agricultural practices are very influenced by monsoon precipitation. since, many regions such as south and southeast of Pakistan, the monsoon is the only rainy season throughout the year. It is the only source of groundwater recharge in such locations. The variability of monsoon rainfall in Pakistan has severe consequences on the socio-economic life. Extremely high temperatures in summer season came to end on the onset of monsoon rains. Increase in monsoon downpour cause flooding in the different catchment of Pakistan and its decrease may cause prolonged drought and severe water shortage apart from putting regional food security on risk. In short, agrarian-based society of Pakistan is because of the combination of abundant solar radiation and precipitation, two essential ingredients for successful agriculture[41].

Monsoon rainfall is the product of mechanically driven winds converging overland mainly due to differential heating of land and neighboring large water bodies. These winds bring the copious amount of moisture from Indus Ocean (the Bay of Bengal and the Arabian Sea), to the subcontinent. As already mentioned, that agricultural practices in Pakistan are shaped by the arrival of monsoon moisture and its precipitation. therefore, a little delay in timing and little decrease in the quantity of rainfall can fail agriculture on a large scale and severely affect the food availability on the regional scales. In addition to that, a weak monsoon is attributed to low crop yield, whereas, abundant monsoon can lead to plentiful yield, although too much rainfall may cause destructive flooding as well. Such flooding, again causes damage to crops, may facilitate an outbreak of epidemics and can cause a large number of people to migrations from flood plains to safe locations.

The timing of the onset of monsoon is also very important for agricultural practices in Pakistan. late arriving monsoon will reduce the availability of the length of growing season to the crop and early or untimely monsoon may affect early growth stages of a plant. Monsoon in Pakistan is regulated by ENSO to some extent. There is the influence of MJO and other climatic teleconnections as well. However, this study is mainly concerned with the variability of monsoon in Pakistan under $2°C$ warming scenarios.

Results and Conclusion

Pakistan receives variables amount of rainfall in monsoon season in its different areas. Lower Sindh receives as much as 100 mm in monsoon season averagely and it increases up to 500 mm in Barani-Potohar region and decreases north and westward (see Figure 21, '$\boldsymbol{a}$'). Since monsoon moisture from the Indian Ocean is transported on relatively low levels (usually below 700 hPa) in the atmosphere, therefore, monsoon moisture usually precipitates at low elevations. For same reason, monsoon do not precipitate a lot on western and northern mountains. Onset of monsoon usually occurs in the month of June. In June, a little monsoon rainfall (~20 mm) occurs in southeastern Sindh, however, around 100 mm rainfall occurs in upper reaches of potohar region (see Figure 21, '$\boldsymbol{a1}$'). Amount of monsoon rainfall gradually increases in July and August (see Figure 21, '$\boldsymbol{a2}$' & '$\boldsymbol{a3}$'). Baluchistan plateau and western Sindh receives less then 20 mm/month rainfall in monsoon season.

In future $2°C$ warmer scenarios the monsoon is expected to strengthen on western and northern mountainous areas. Seasonally accumulated rainfall is expected to increase in some of the areas of Balochistan, although, an increase of $20 - 30\%$ or even $40 - 50\%$ is not a lot since these areas are receiving little precipitation in baseline period averagely (see Figure 21, '$\boldsymbol{b}$' & '$\boldsymbol{c}$').

Highest percentage increase in June accumulated precipitation is expected in western Sindh (>70%, see Figure 21, '$\boldsymbol{b1}$' and '$\boldsymbol{c1}$'), followed by 10% increase in southern KPK and central Punjab. Since these areas are not receiving much precipitation in the baseline period therefore the percentage increase of 10% is not substantial. On the other hand, southeastern Punjab and eastern Sindh is expected to be dryer in the month of June.

The almost similar percentage increase is noticed in the month of July and August (see Figure 21, '$b2$', '$c2$', '$b3$' and '$c3$'), although little increase is witnessed in northern Pakistan (Gilgit-Baltistan), western mountains of KPK and Balochistan. Since, the change is quantified in terms of percentage therefore the actual change is higher in northern Pakistan than southern Pakistan (Balochistan).

Since it is already discussed in the previous chapter that monsoon is strengthening in late season toward autumn, and it is corroborated by the analysis presented in Figure 21. Therefore, it can be concluded that in the future warming period monsoon is expected to strengthen and approaching at a relatively higher altitude. Though the increase in precipitation in Balochistan is not much in magnitude but it is substantial in-case of northern and western mountains. This will increase the likelihood of hill torrents and accumulated run-off from mountains. On the other hand, southeastern (Southern Punjab and southeastern Sindh) are expected to be dryer. This situation will affect the sowing of Rabi crops in southeastern Pakistan. Whereas, an increase in northern and western Pakistan may cause flooding.

In conclusion, the monsoon is strengthening in Pakistan over higher elevations (mainly northern and western Pakistan) and it is weakening in southeastern Pakistan. this situation is explained by Kevin E. Trenberth as wet is getting more wet and dry is getting dryer or "rich is getting richer and poor is getting poorer". A decrease in monsoon rainfall in southeastern Pakistan, where monsoon is only rainy season throughout the year is alarming. Since the population is growing in these regions, therefore, water resources will be further stressed in these areas. Prolonged dryness may cause drought and famine. To avert this situation, there is a need to redistribute water from water surplus regions to water deficit regions through canals with minimal losses.

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TABLES

Table 1. Agro-Climatic Zones of Pakistan and their districts[25].

S.No.	Agro-Climatic Zones	Districts
1	Rice/Wheat Punjab	Sialkot, Gujrat, Gujranwala, Sheikhupura, Lahore, Kasur, Narowal, Mandi Bahauddin, Hafizabad.
2	Mixed Punjab	Sargodha, Khushab, Jhang, Faisalabad, Toba Tek Singh, Okara.
3	Cotton/Wheat Punjab	Sahiwal, Bahawalpur, Bahawalnagar, Rahimyar Khan, Multan, Vehari, Lodhran, Khanewal, Pakpatan.
4	Low Intensity Punjab	Dera Ghazi Khan, Rajanpur, Muzaffargarh, Layyah, Mianwali, Bhakkar, Dera Ismail Khan.
5	Barani/Rain-fed Punjab	Attock, Jhelum, Rawalpindi, Islamabad, Chakwal.
6	Cotton/Wheat Sindh	Sukkur, Khairpur, Shaheed Benazirabad, Hyderabad, Tharparkar, Nowshehro Feroz, Ghotki, Umerkot, Mirpurkhas, Sanghar.
7	Rice/Other Sindh	Jacobabad, Larkana, Dadu, Thatta, Badin, Shikarpur, Karachi.
8	KPK	All KPK except Dera Ismail Khan.
9	Balochistan	All Balochistan.

Table 2. Population and Growth Rate of Agro-Climatic Zones[27].

S.No.	Agro-Climatic Zones	Population (1998)	Population (2017)	Annual Growth Range (%)
1	Rice/Wheat Punjab	23446707	35522065	2.2
2	Mixed Punjab	2379536	3225114	1.8
3	Cotton/Wheat Punjab	7029940	9858586	2.08
4	Low Intensity Punjab	2357865	3935687	3.28
5	Barani/Rain-fed Punjab	2014393	7464763	3.26
6	Cotton/Wheat Sindh	2011034	3202236	2.9
7	Rice/Other Sindh	3646925	5303156	2.2
8	KPK	17743645	30523371	3.6
9	Balochistan	6565885	12344408	4.4

FIGURES

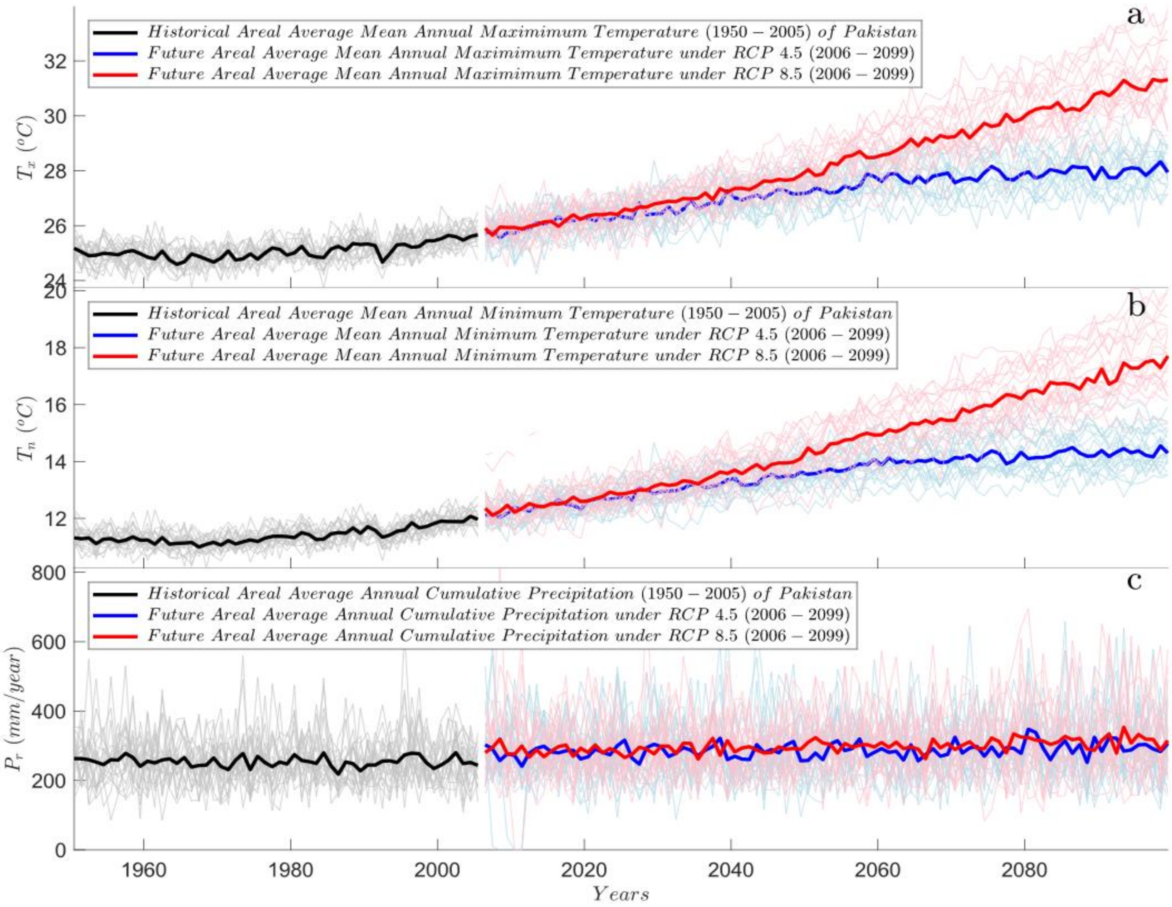

Figure 1. Comparison of the GCM runs for temperature and precipitation in the retrospect and the prospect, along with their ensemble.
(a) The GCM Runs (21- members) for the areal average mean annual maximum temperature (T_x) of Pakistan for the both retropect (1950-2005) and prospect (2006-2099) are presented. Individual runs in retrospect are presented by light grey, whereas individual runs of prospect RCP 4.5 and RCP 8.5 scenarios are presented by light blue and light red colors, respectively. Ensemble medians of the GCM runs are presented by thick lines for each category. (b) same as (a) for minimum temperature (T_n). (c) same as (a) for areal average annualy accumulated precipitation (P_r).

Figure 1

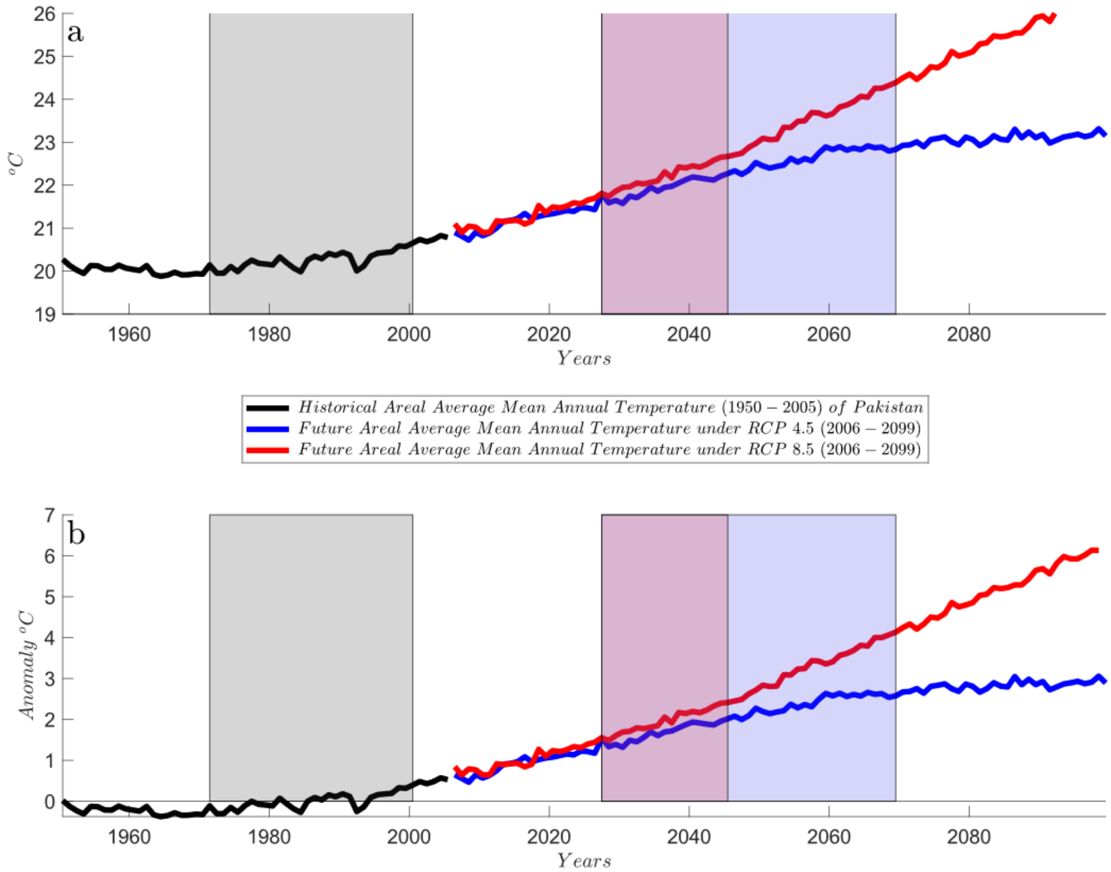

Figure 2: Areal average mean annual temperatures of Pakistan from 1950-2099. (a) Black Line presents the retrospect areal average annual mean temperature (1950-2005) , whereas, blue and red lines present the prospect areal average annual mean temperatures in RCP 4.5 and 8.5 scenarios, respectively (2006-2099). (b) Presents temperature anomalies (black, blue and red lines) with respect to the areal average mean annual temperature of the base period (1971-2000, grey box). Red box (2027-2045, 19 years) for which average mean annual temperature of Pakistan will remain averagely 2 ^{o}C higher than the base period under RCP 8.5 scenario. Red-blue box presents (2027-2069, 43 years) for which the average mean annual temperature of Pakistan will remain averagely 2^{o}C higher than the base period (1971-2000) under RCP 4.5 scenario.

Figure 2

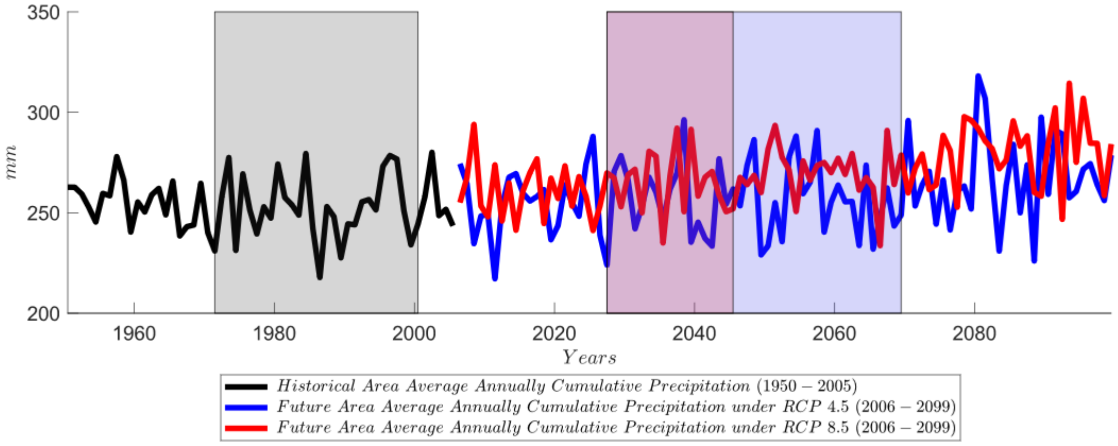

Figure 3. Areal average annually accumulated precipitation of Pakistan.
Black Lines presents historical areal averaged annually accumulated precipitation for retrospect (1950-2005). Red and blue lines present areal average annually accumulated precipitation of Pakistan under RCP 8.5 and 4.5 scenarios (2006-2099). Grey box presents the base period (1971-2000), whereas, red and red-blue boxes presents the period when average annual temperatures of Pakistan would be averagely 2°C higher than the base period under RCP 8.5 and 4.5 scenarios, respectively.

Figure 3

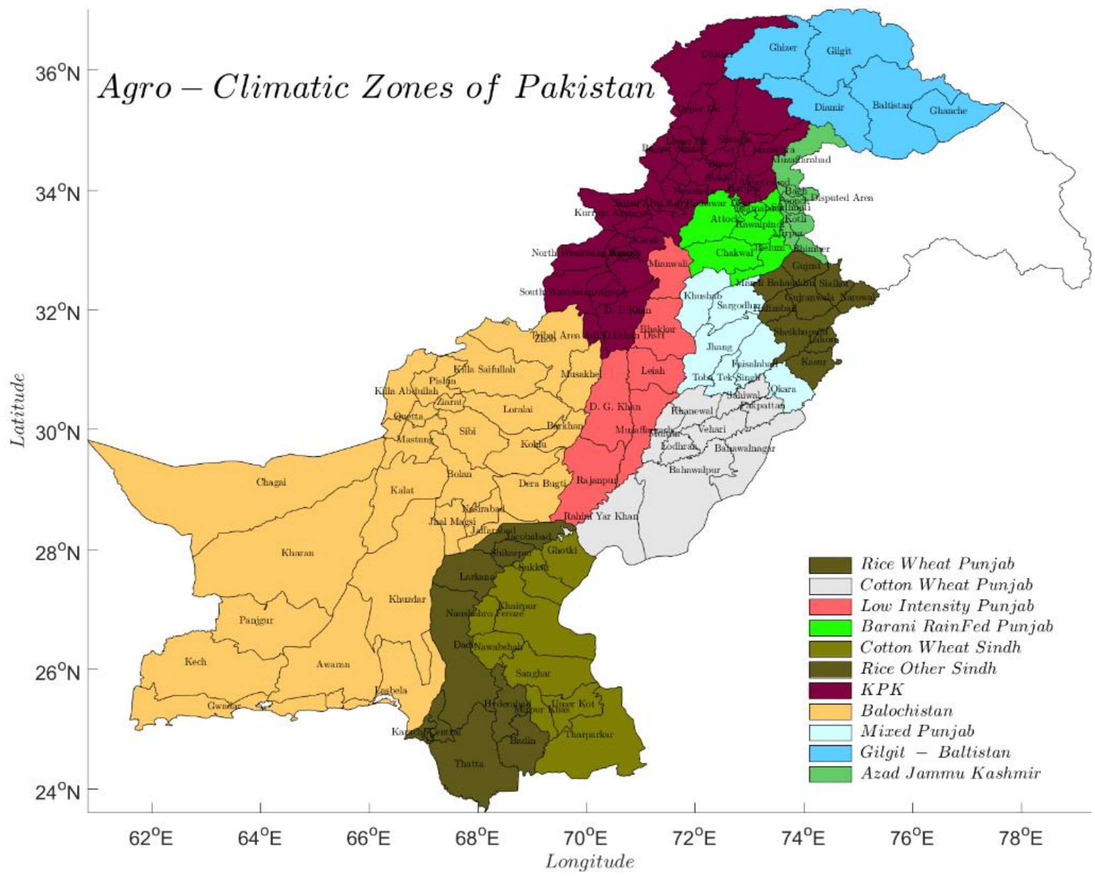

Figure 4. Agro-Climatic Zones of Pakistan[25].

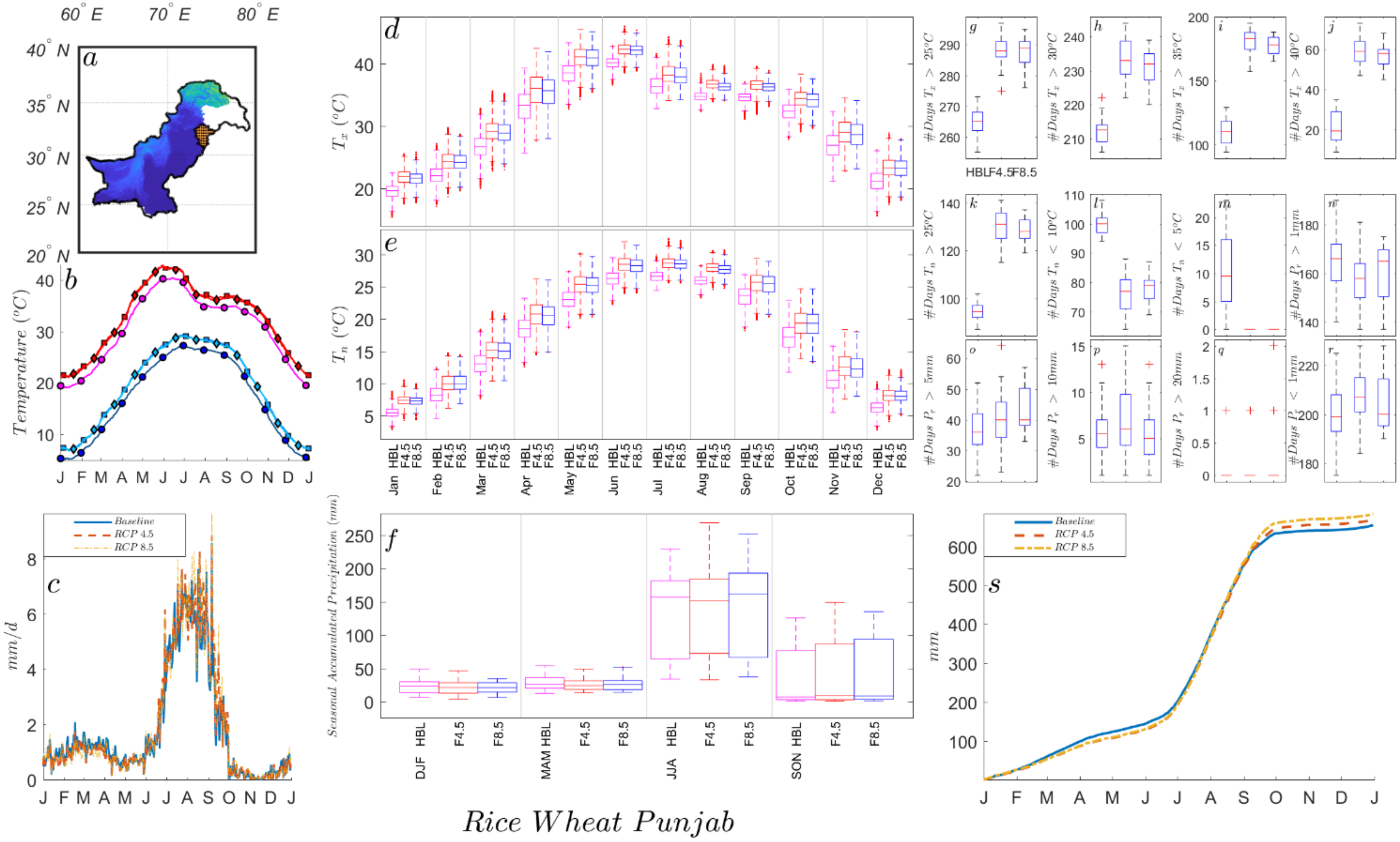

Figure 5. The Agro-Climate Zone of Rice-Wheat Punjab.

(***a***) Map of Pakistan's International boundary with DEM in the background, the boundary of agro-climatic zones of Rice-Wheat Punjab is highlighted with black line, the black dots within the boundary of agro-climatic zone presents the GCM grid points. (***b***) The daily mean (365 day annual cycle) of the areal average maximum temperature ($T_x, °C$) of the Baseline (1971-2000) GCM ensemble median is presented with magenta line and red circles. 365 day annual cycle of the areal average daily maximum temperature ($T_x, °C$) of the Rice Wheat Punjab under future RCP 4.5 (2027-2069) and RCP 8.5 (2027-2045) GCM ensemble median are presented with red lines (red filled squares and squares, respectively). Similarly, the 365 day annual cycle of the areal average daily minimum temperature ($T_n, °C$) of the Baseline is presented with dark blue line (dark blue circles). Whereas, same of the future RCP 4.5 and 8.5 are presented by light blue lines along with filled squares and diamonds, respectively. (***c***) The 365 day annual cycle of the areal average daily precipitation (mm/d) computed from the ensemble mean of GCM for the baseline (blue line) and the future (red dashed line for RCP 4.5 and yellow dotted line for RCP 8.5) are presented. (***d***) The statistical summaries of the daily maximum temperature ($T_x, °C$) under the Historical Baseline (1971-2000) period and the future period under RCP 4.5 (2027-2069) and 8.5 (2027-2045) of the agro-climatic zones are presented through box plots on monthly scales. Similar summaries of the daily minimum temperature ($T_n, °C$) on monthly scales and monthly accumulated precipitation (mm) on the seasonal scales are presented in (***e***) and (***f***), respectively. (***g***) presents the annual frequency of days ($T_x > 25°C$) in the historical baseline period (1971-2000) and the future RCP 4.5 (2027-2069) and RCP 8.5 (2027-2045) period, respectively. (***h***) similar to (***g***) with ($T_x > 30°C$). (***i***) similar to (***g***) with ($T_x > 35°C$). (***j***) similar to (***g***) with ($T_x > 40°C$). (***k***) similar to (***g***) with ($T_n > 25°C$). (***l***) similar to (***k***) with ($T_n < 10°C$). (***m***) similar to (***k***) with ($T_n < 5°C$). (***n***) Annual frequency of wet days ($P_r > 1mm$). (***o***) Annual frequency of wet days ($P_r > 5mm$). (***p***) Annual frequency of wet days ($P_r > 10mm$). (***q***) Annual frequency of wet days ($P_r > 20mm$). (***r***) Annual frequency of wet days ($P_r < 1mm$). (***s***) Mean mass curve of daily rainfall for historical baseline period (1971-2000) and future RCP 4.5 (2027-2069) and 8.5 (2027-2045) scenarios.

Figure 5

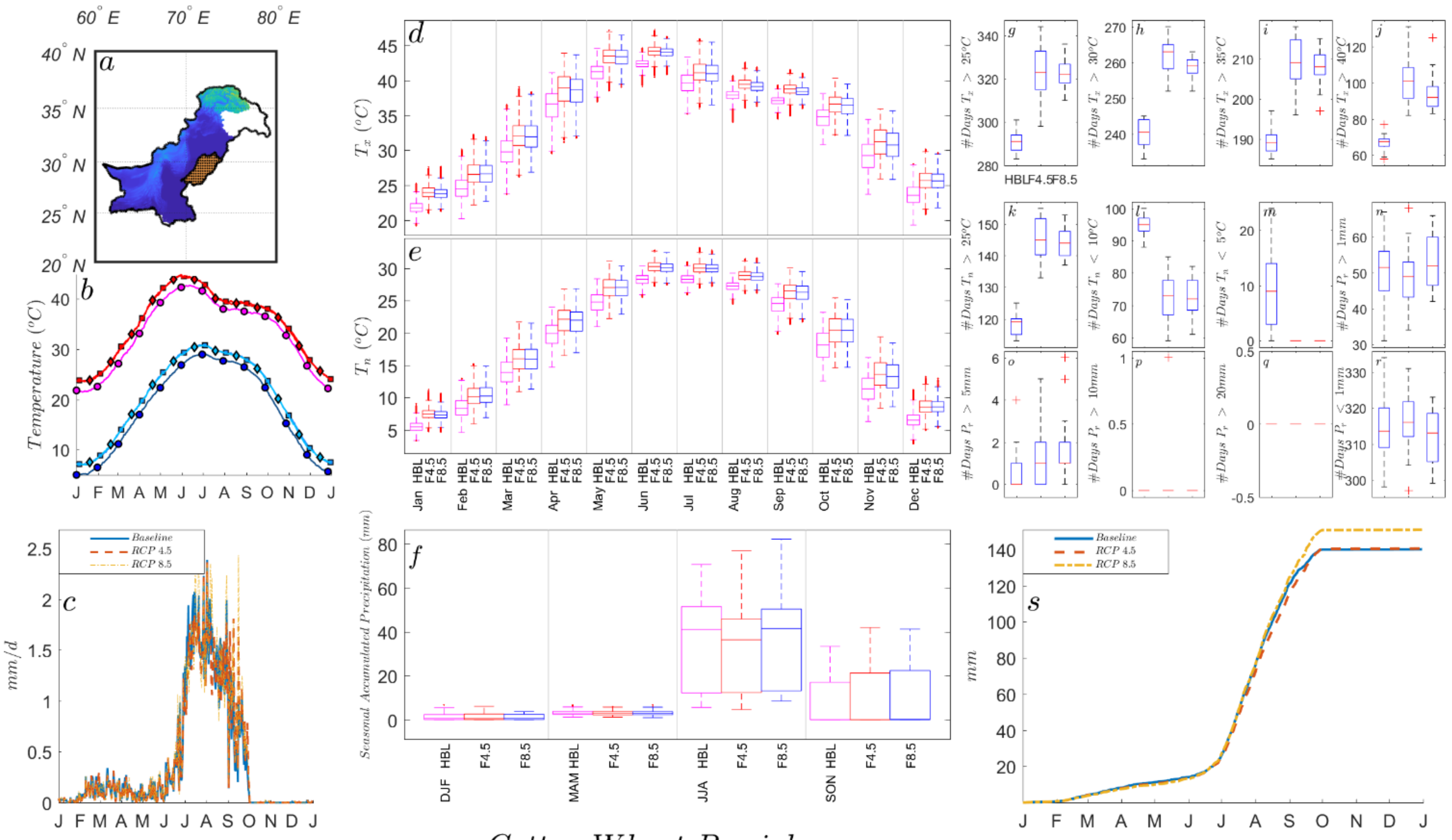

Figure 6. Similar to Figure 5 for the agro-climatic zone of Cotton-Wheat Punjab.

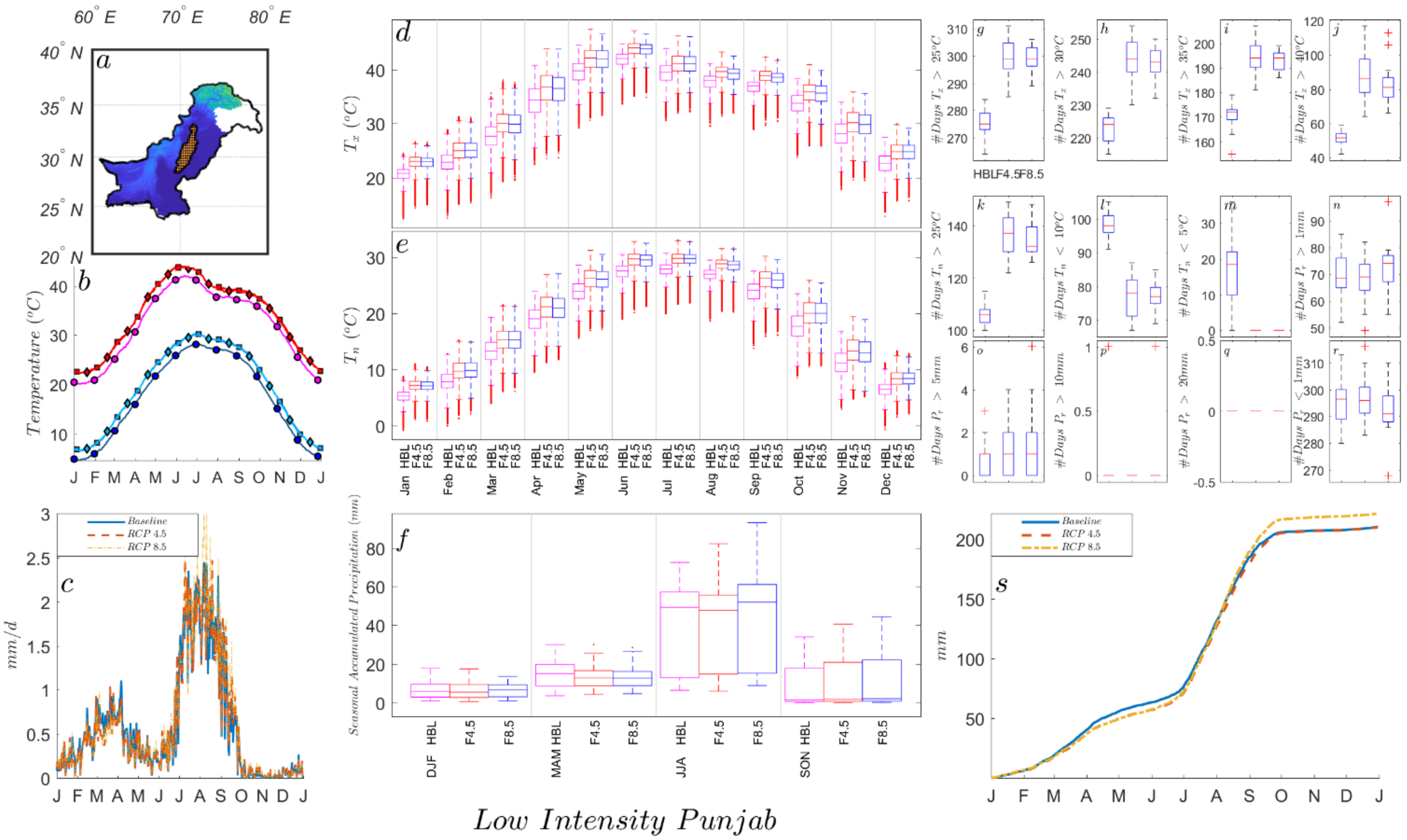

Figure 7. Similar to Figure 5 for the agro-climatic zone of Low-Intensity Punjab.

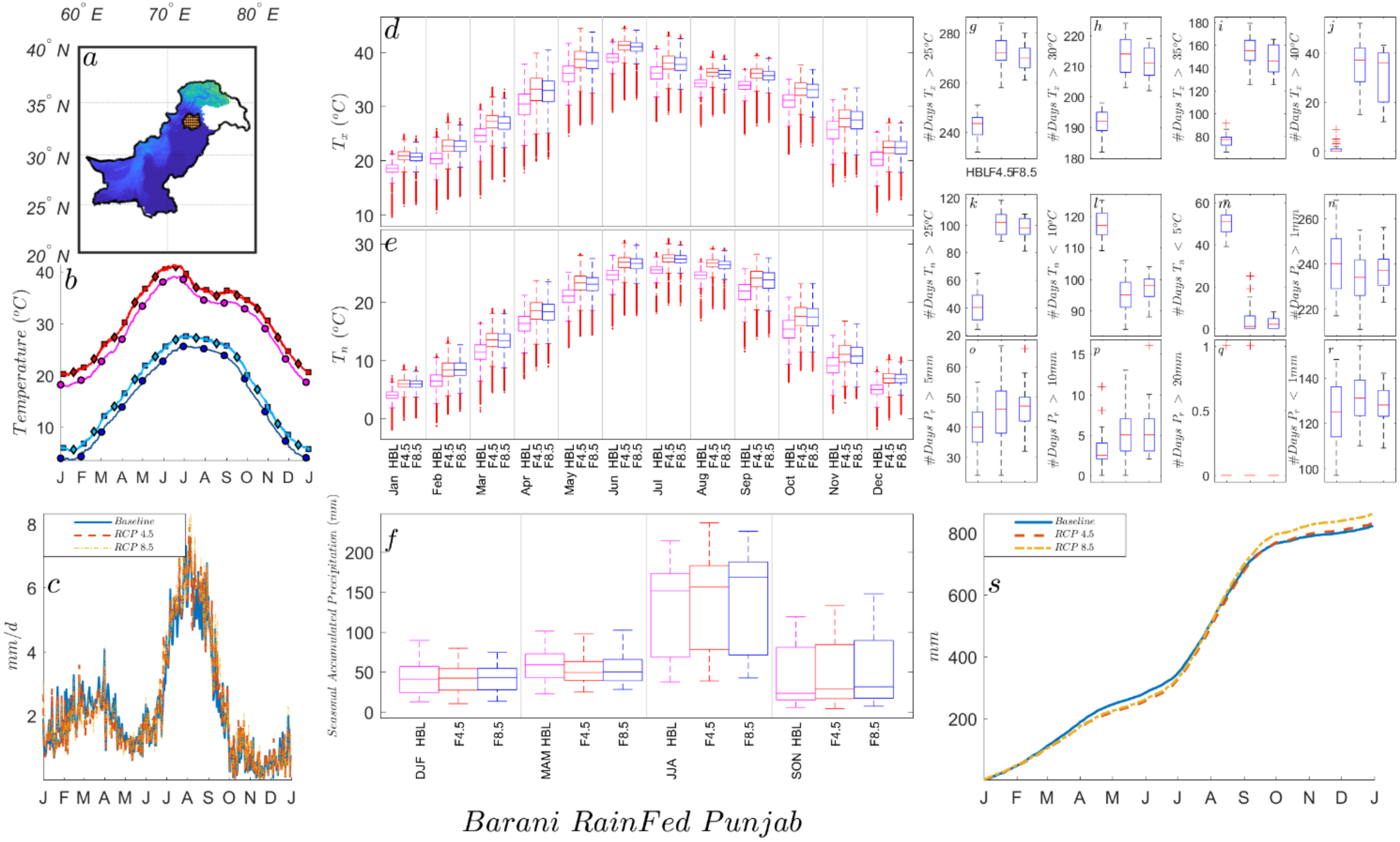

Figure 8. Similar to Figure 5 for the agro-climatic zone of Barani- Rainfed Punjab.

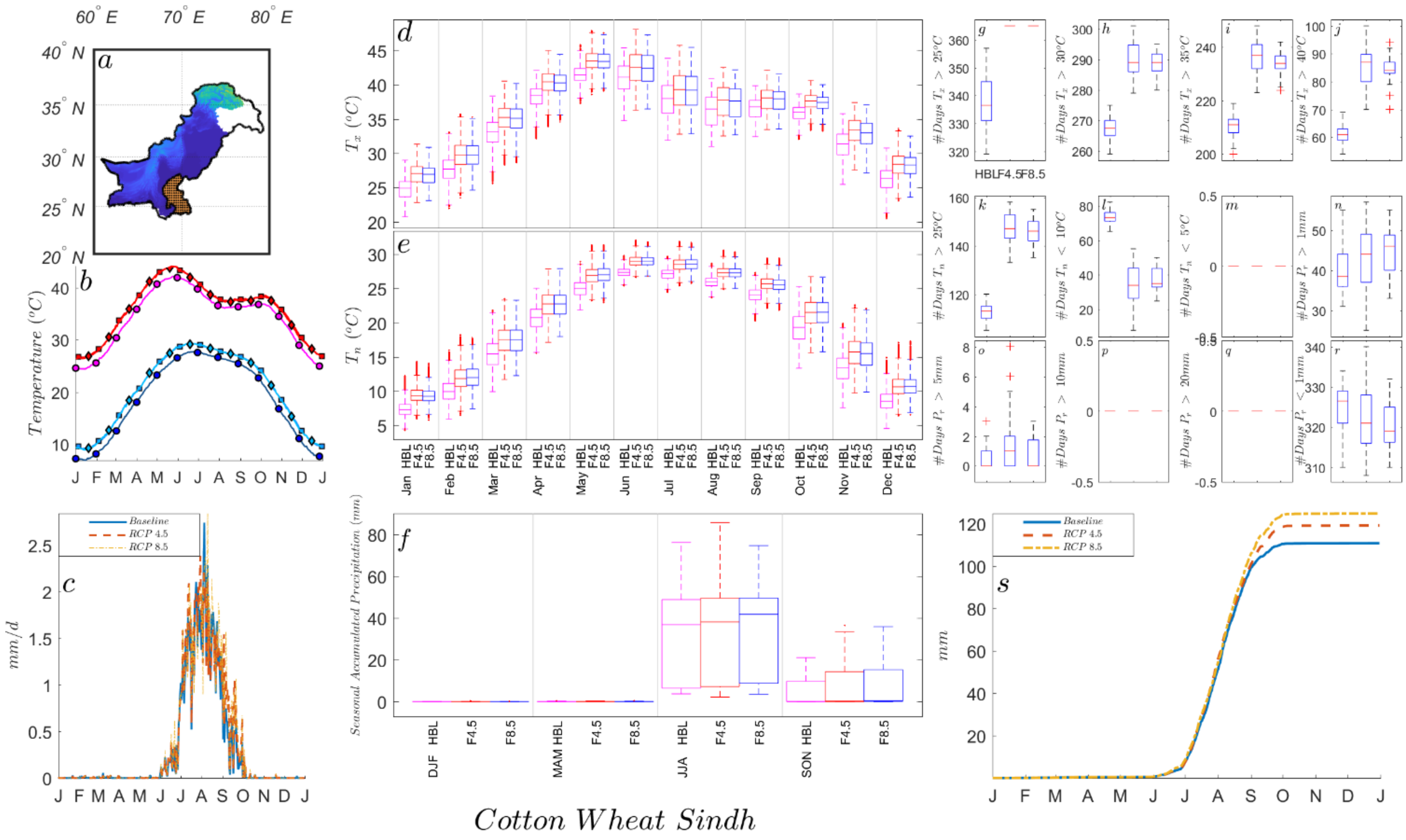

Figure 9. Similar to Figure 5 for the agro-climatic zone of Cotton-Wheat Sindh.

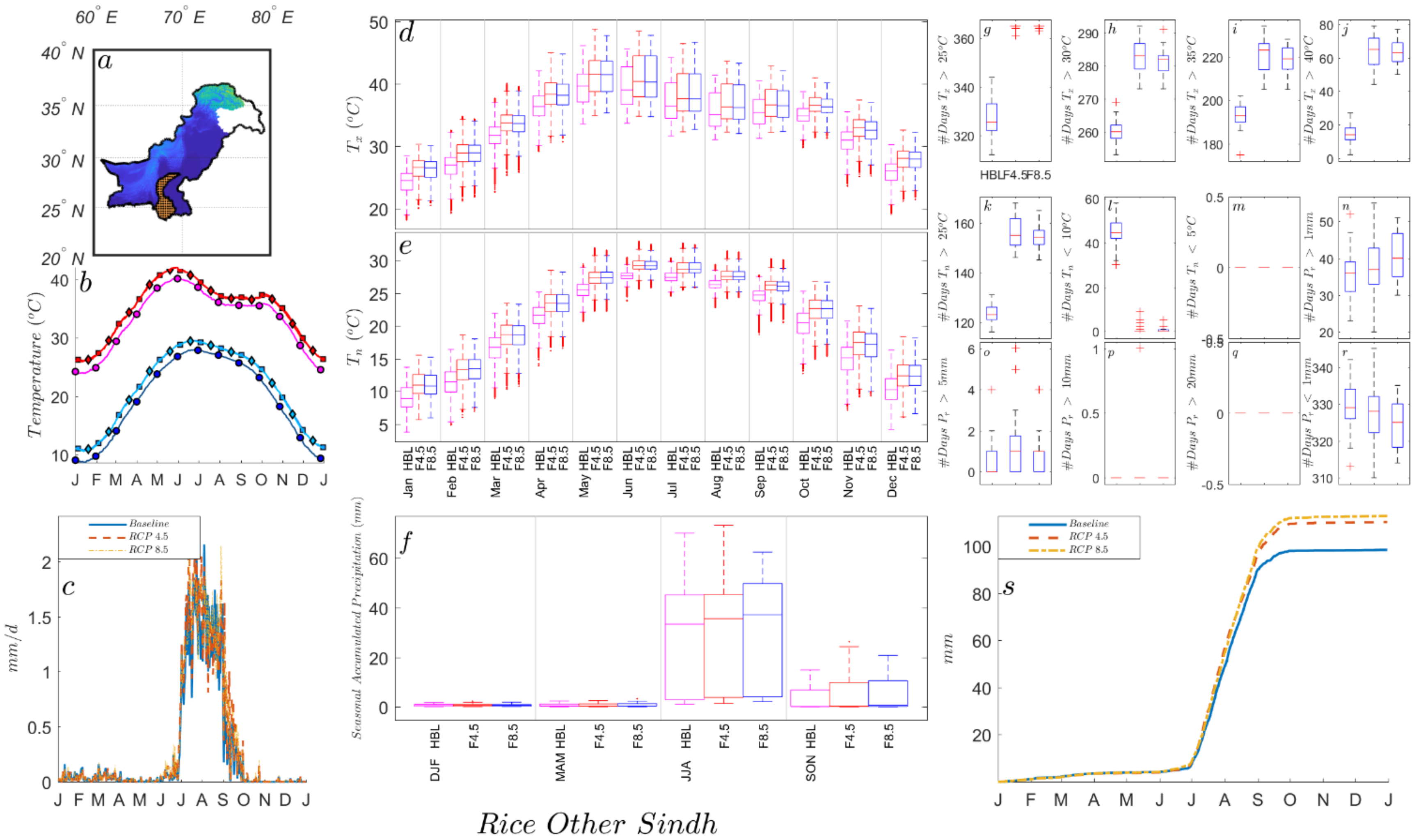

Figure 10. Similar to Figure 5 for the agro-climatic zone of Rice-Other Sindh.

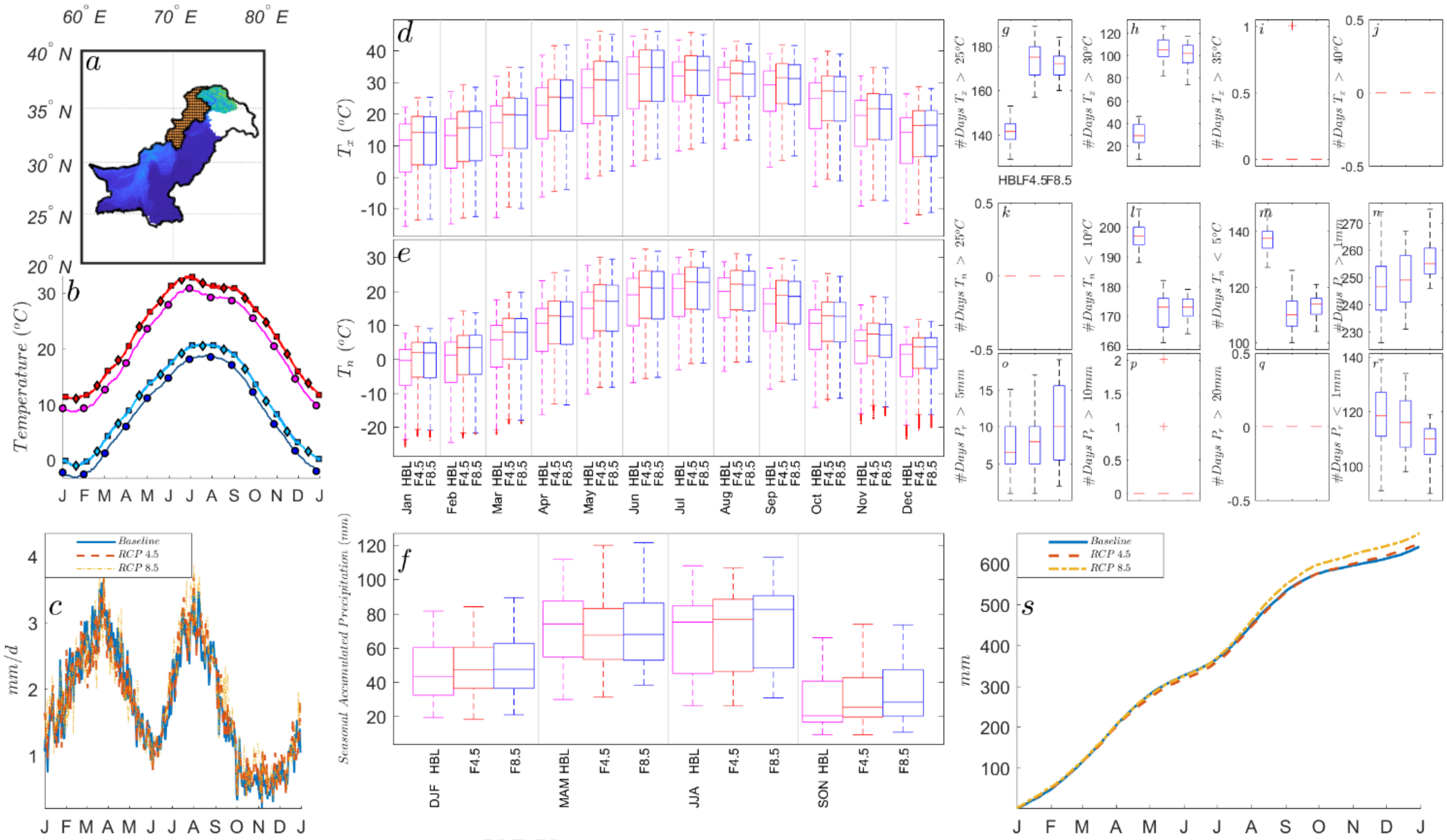

Figure 11. Similar to Figure 5 for the agro-climatic zone of Khyber-Pakhtunkhwa.

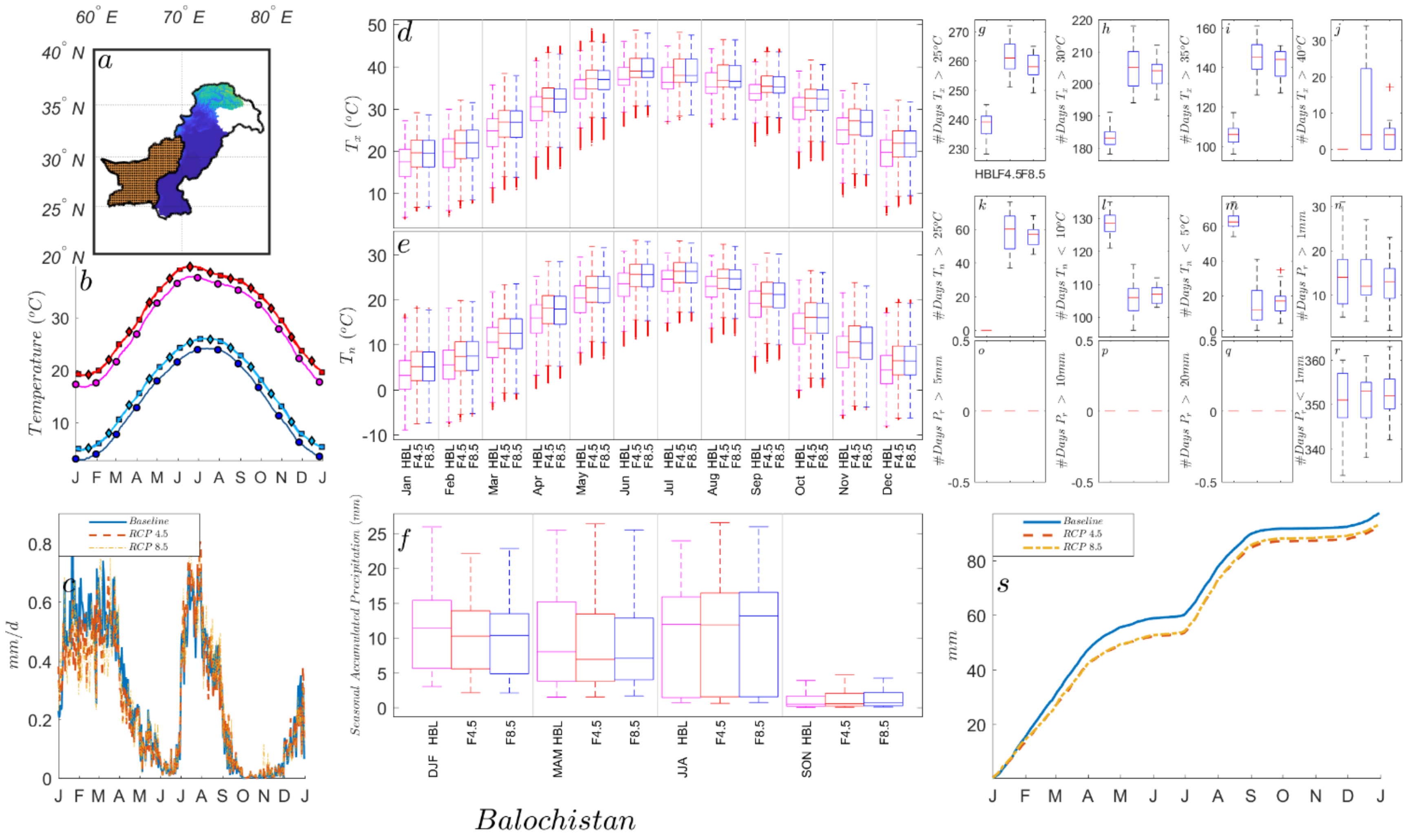

Figure 12. Similar to Figure 5 for the agro-climatic zone of Balochistan.

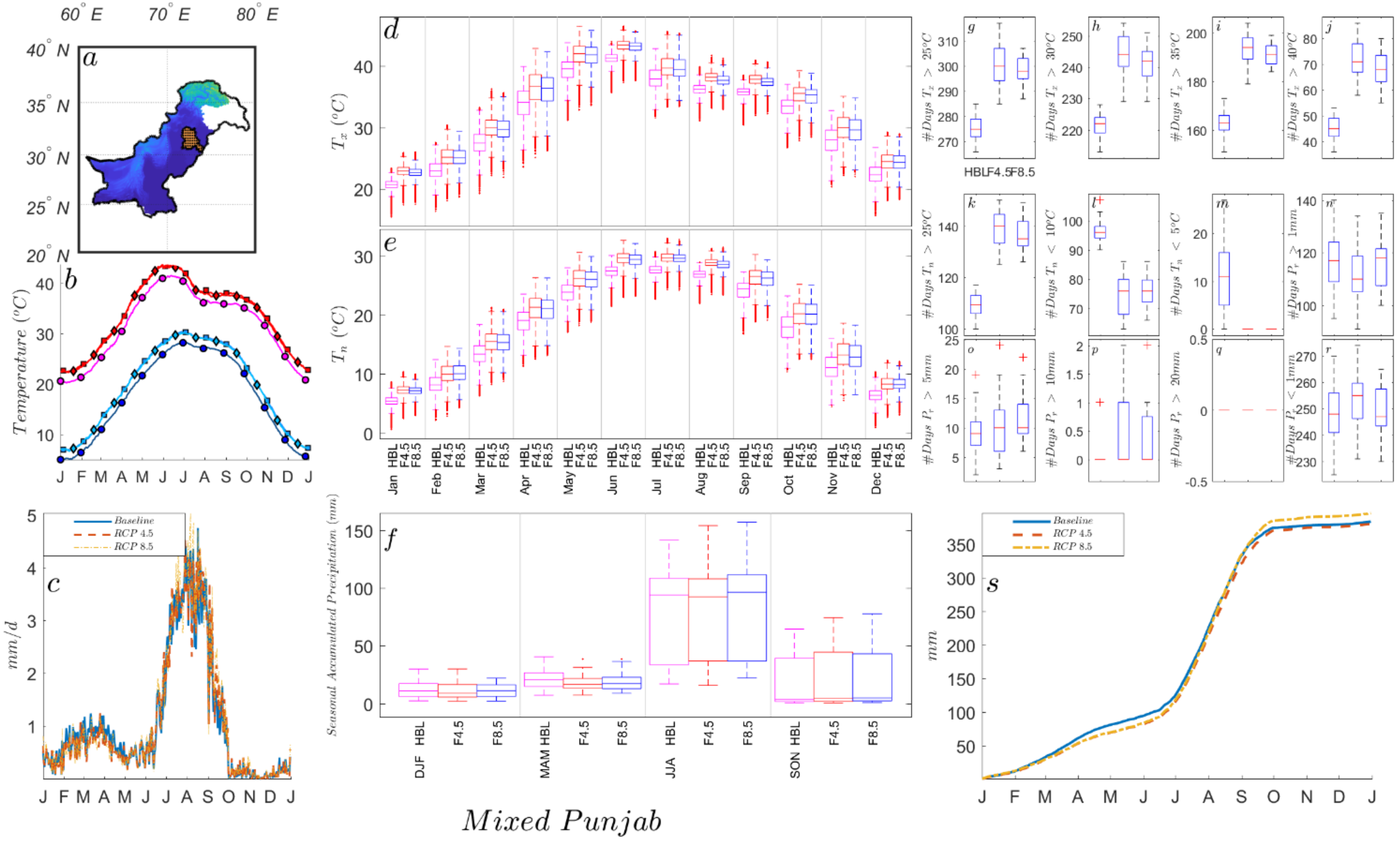

Figure 13. Similar to Figure 5 for the agro-climatic zone of Mixed Punjab.

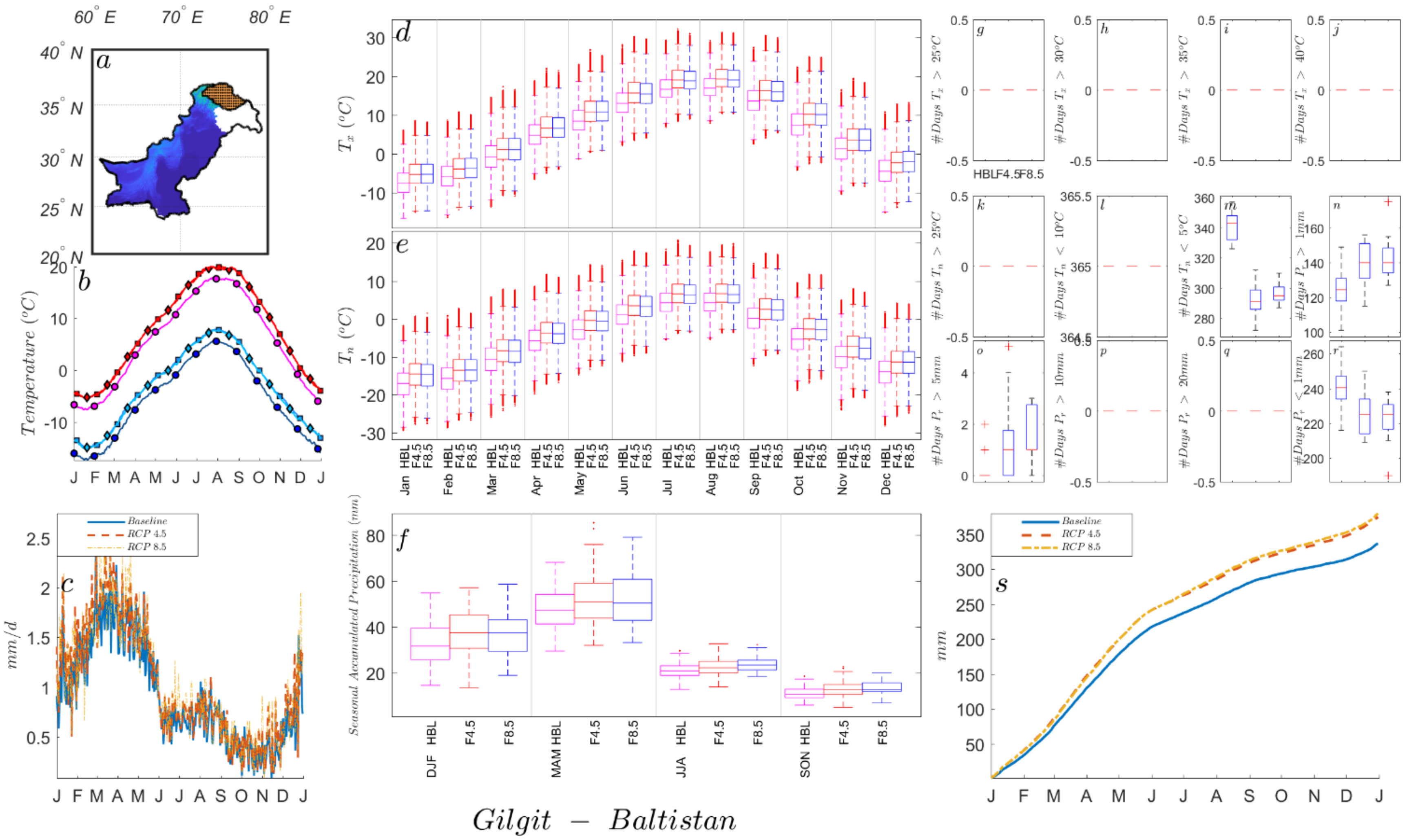

Figure 14. Similar to Figure 5 for agro-climatic zone of Gilgit-Baltistan.

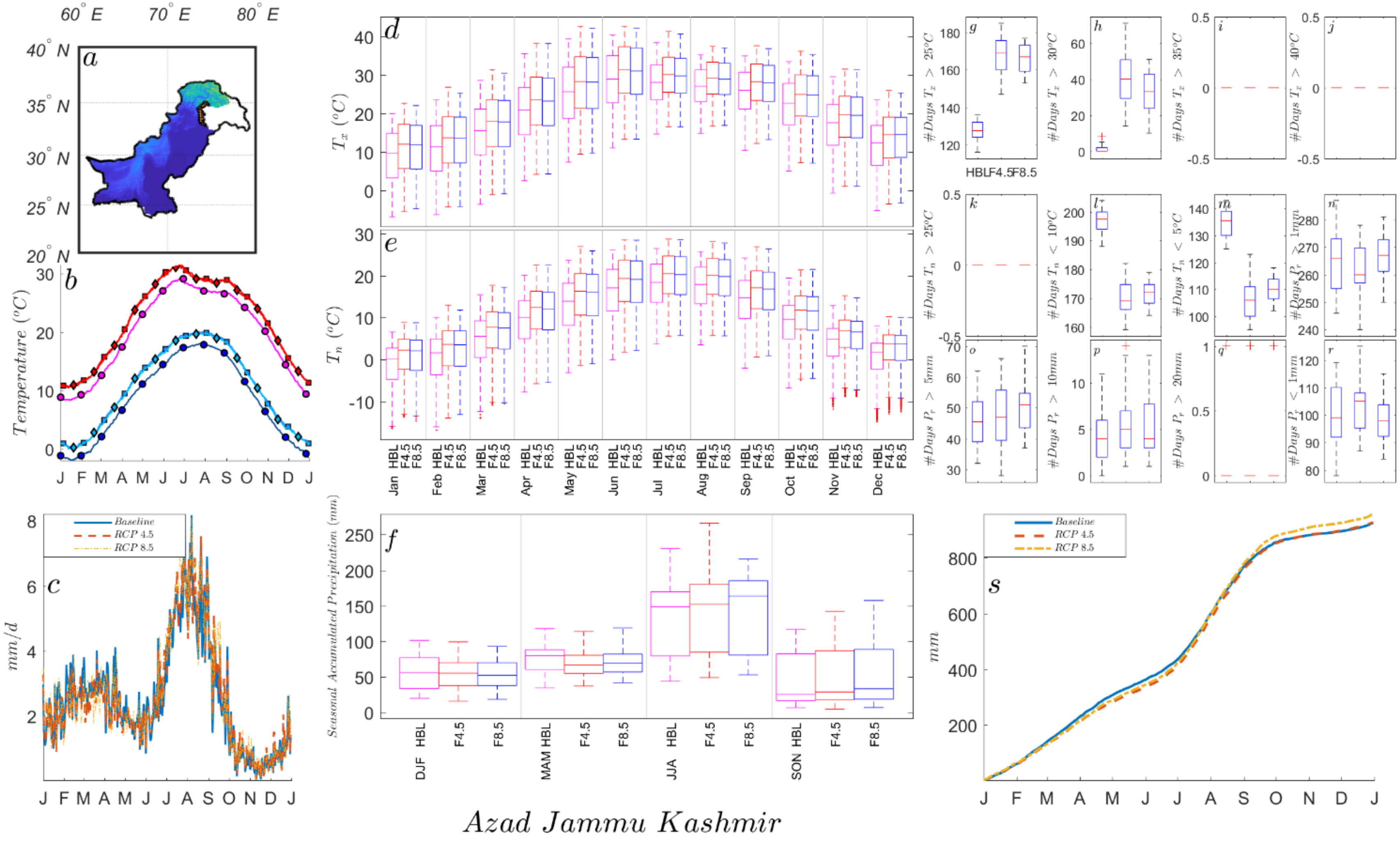

Figure 15. Similar to Figure 5 for agro-climatic zone of Azad Jammu Kashmir.

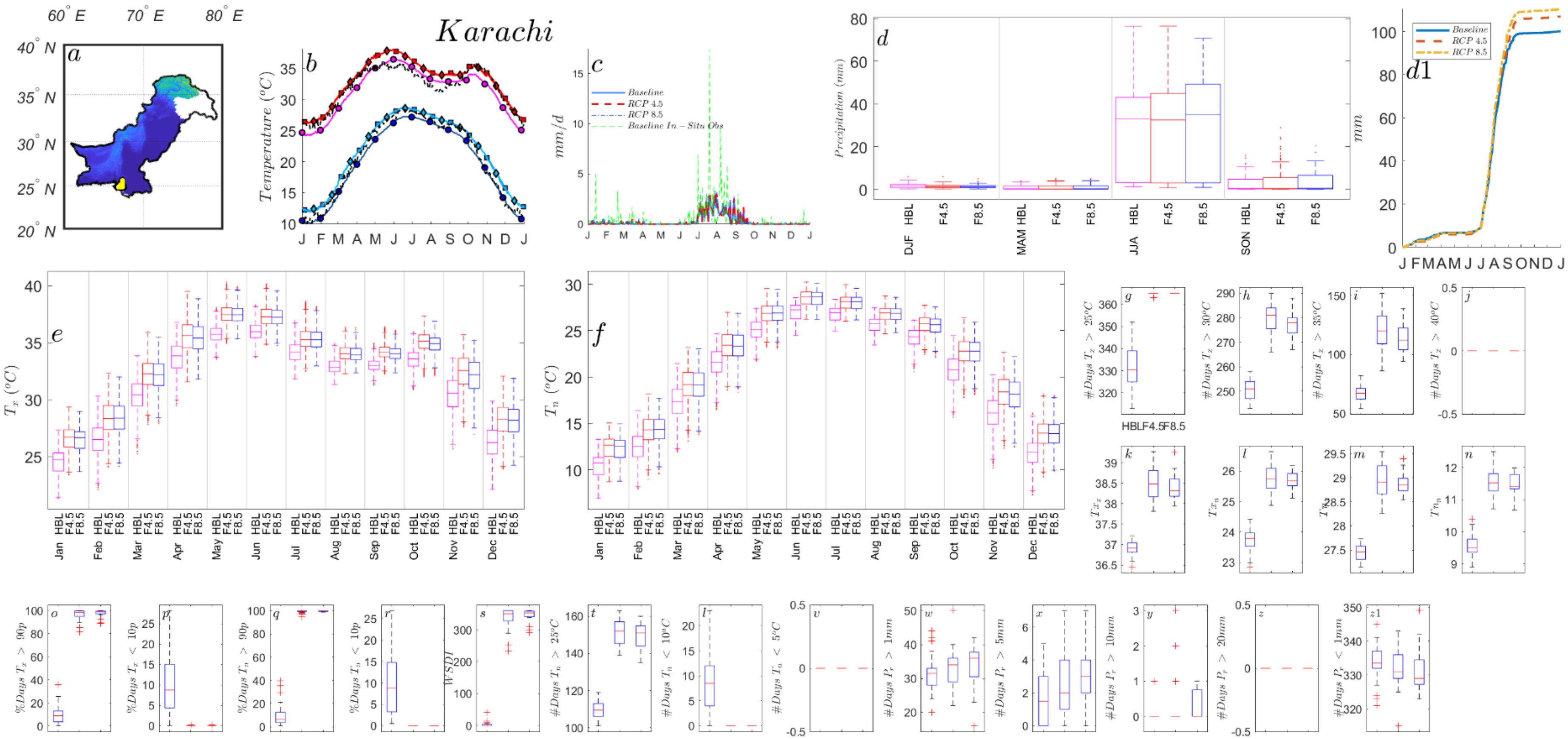

Figure 16. Change in extreme events in urban setting of Karachi under 2°C warming scenario.

($\boldsymbol{a}$) Map of Pakistan's International boundary with DEM in the background, the boundary of urban center of Karachi is highlighted with yellow color polygon. ($\boldsymbol{b}$) The daily mean (365 day annual cycle) of the areal average maximum temperature ($T_x, °C$) of the Baseline (1971-2000) GCM ensemble median is presented is with magenta Line and red circles. The 365 day annual cycle based on in-situ observed ($T_x, °C$) is presented with black line. The 365 day annual cycle of the areal average daily maximum temperature ($T_x, °C$) under future RCP 4.5 (2027-2069) and RCP 8.5 (2027-2045) GCM ensemble median are presented with red Lines (red filled squares and squares, respectively). Similarly, the 365 day annual cycle of the areal average daily minimum temperature ($T_n, °C$) of the Baseline is presented with dark blue line (dark blue circles). Whereas, same of the future RCP 4.5 and 8.5 are presented with light blue lines along with filled squares and diamonds, respectively. Furthermore, the 365 day annual cycle based on in-situ observed ($T_n, °C$) is presented with black line. ($\boldsymbol{c}$) the 365 day annual cycle of areal average daily precipitation (mm/d) computed from the ensemble mean of GCM for the baseline (blue line) and the future (red dashed line for RCP 4.5 and yellow dotted line for RCP 8.5) are presented along with *in-situ* observations (green dashed line). Statistical summaries of the monthly accumulated precipitation (mm) on seasonal scale under the Historical Baseline (1971-2000) period and the future period under RCP 4.5 (2027-2069) and 8.5 (2027-2045) of the Karachi urban center are presented through Box Plots ($\boldsymbol{d}$). Similarly, analysis of the daily maximum temperature ($T_x, °C$), and of daily minimum temperature ($T_n, °C$) on monthly scales are presented in (e) and (f), respectively. ($\boldsymbol{d1}$) The mean single mass curve of daily rainfall for the historical baseline period (1971-2000) and future the RCP 4.5 (2027-2069) and 8.5 (2027-2045) scenarios for Karachi are presented. ($\boldsymbol{g}$) presents the annual frequency of days ($T_x > 25°C$) in the historical baseline period (1971-2000) and the future RCP 4.5 (2027-2069) and RCP 8.5 (2027-2045) period, respectively. ($\boldsymbol{h}$) similar to ($\boldsymbol{g}$) with ($T_x > 30°C$). ($\boldsymbol{i}$) similar to ($\boldsymbol{g}$) with ($T_x > 35°C$). ($\boldsymbol{j}$) similar to ($\boldsymbol{g}$) with ($T_x > 40°C$). ($\boldsymbol{k}$) the monthly maximum value of daily maximum temp (T_{x_x}). (l) the monthly minimum value of daily maximum temp (T_{x_n}). ($\boldsymbol{m}$) the monthly maximum value of daily Minimum temp (T_{n_x}). ($\boldsymbol{n}$) the monthly minimum value of daily minimum temp (T_{n_n}). ($\boldsymbol{o}$) Percentage of days when $T_X > 90^{th}$ percentile of the baseline period. ($\boldsymbol{p}$) Percentage of days when $T_x < 10^{th}$ percentile of the baseline period. ($\boldsymbol{q}$) Percentage of days when $T_n > 90^{th}$ percentile of the baseline period. ($\boldsymbol{r}$) Percentage of days when $T_n < 10^{th}$ percentile of the baseline period. ($\boldsymbol{s}$) the annual count of days with at least 5 consecutive days when $T_X > 90^{th}$ percentile in baseline period. ($\boldsymbol{t}$) similar to ($\boldsymbol{g}$) with ($T_n > 25°C$). ($\boldsymbol{u}$) similar to ($\boldsymbol{t}$) with ($T_n < 10°C$). ($\boldsymbol{v}$) similar to ($\boldsymbol{t}$) with ($T_n < 5°C$). ($\boldsymbol{w}$) the annual frequency of wet days ($P_r > 1mm$). ($\boldsymbol{x}$) the annual frequency of wet days ($P_r > 5mm$). ($\boldsymbol{y}$) the annual frequency of wet days ($P_r > 10mm$). ($\boldsymbol{z}$) the annual frequency of wet days ($P_r > 20mm$). ($\boldsymbol{z1}$) the annual frequency of wet days ($P_r < 1mm$).

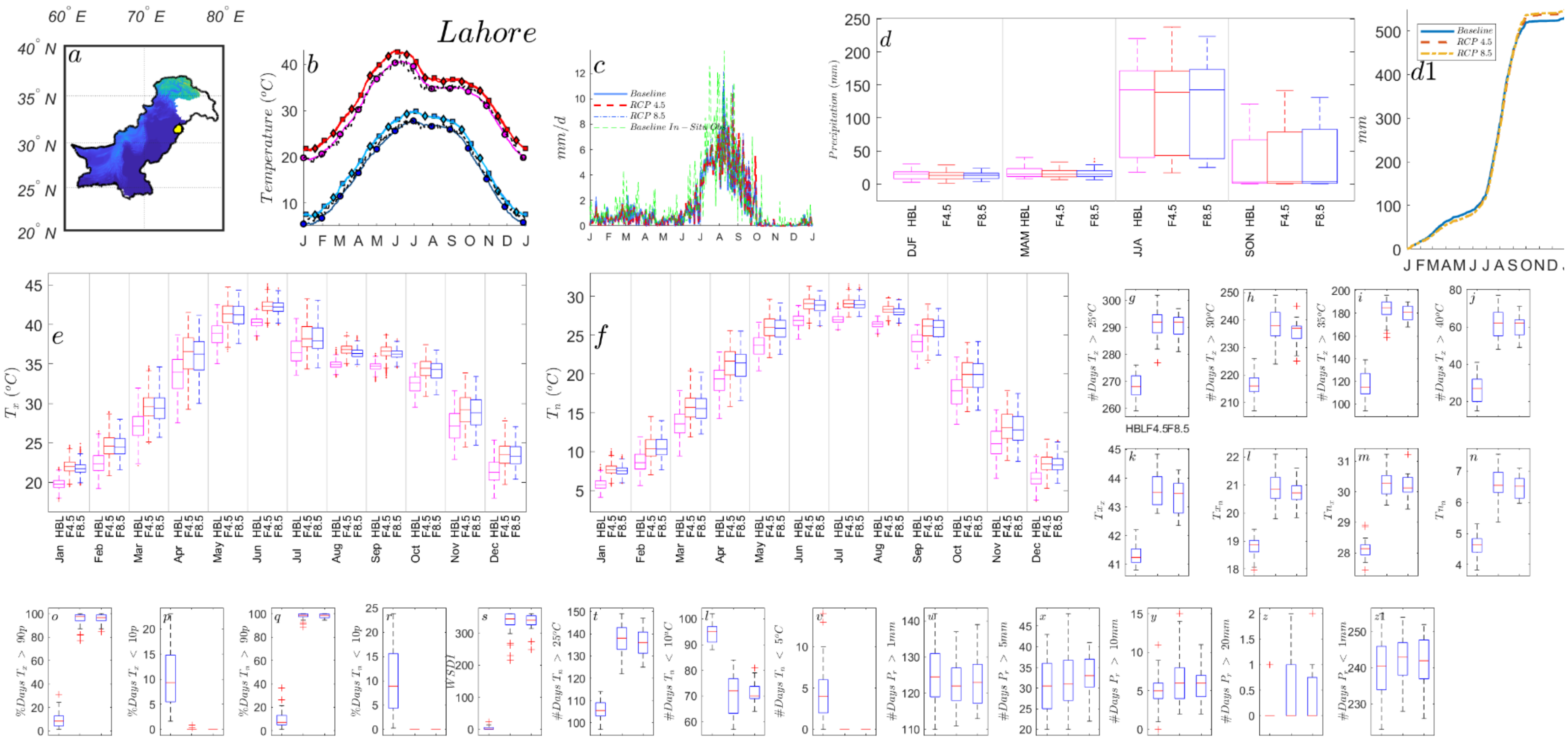

Figure 17. Similar to Figure 16, but for the city of Lahore.

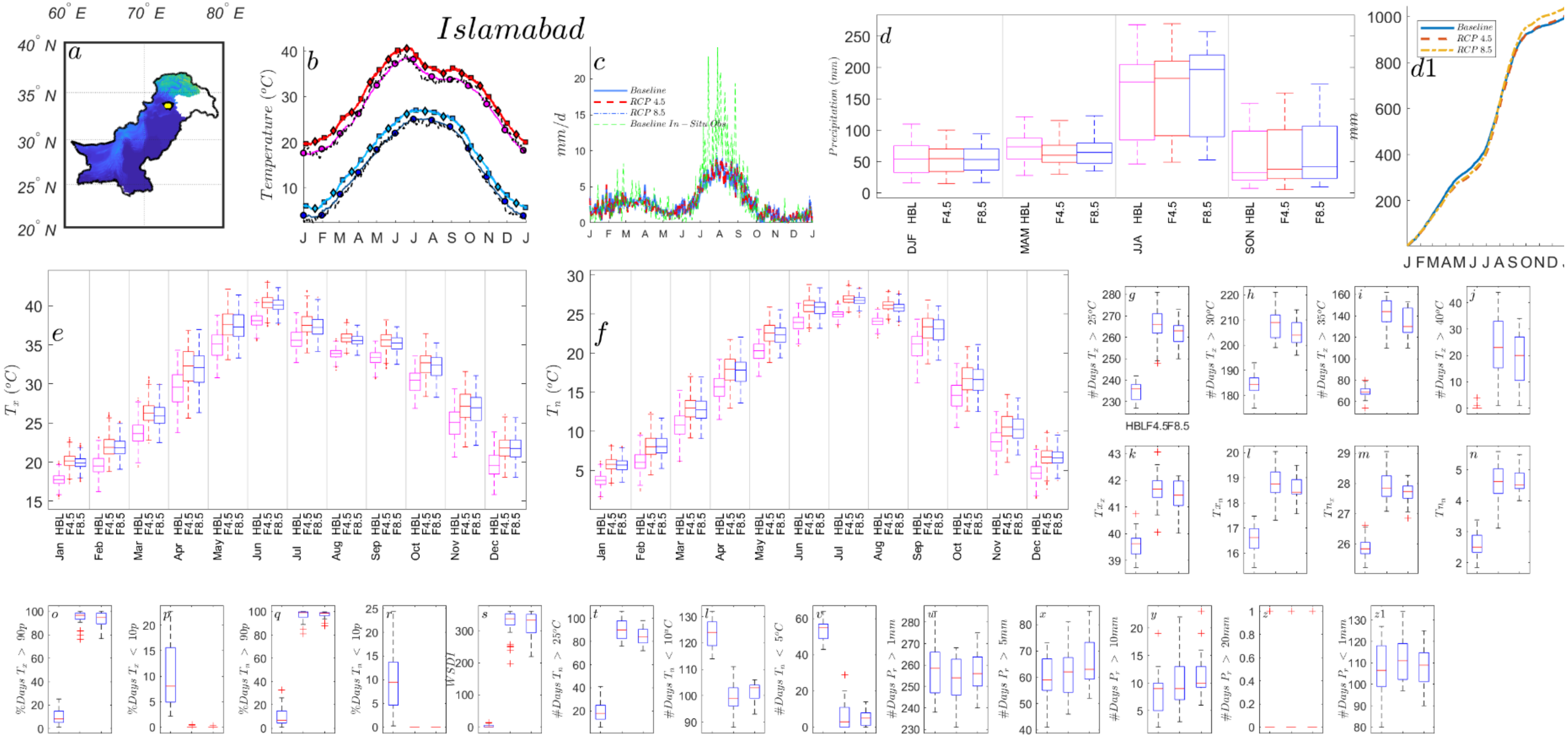

Figure 18. Similar to Figure 16, but for the city of Islamabad.

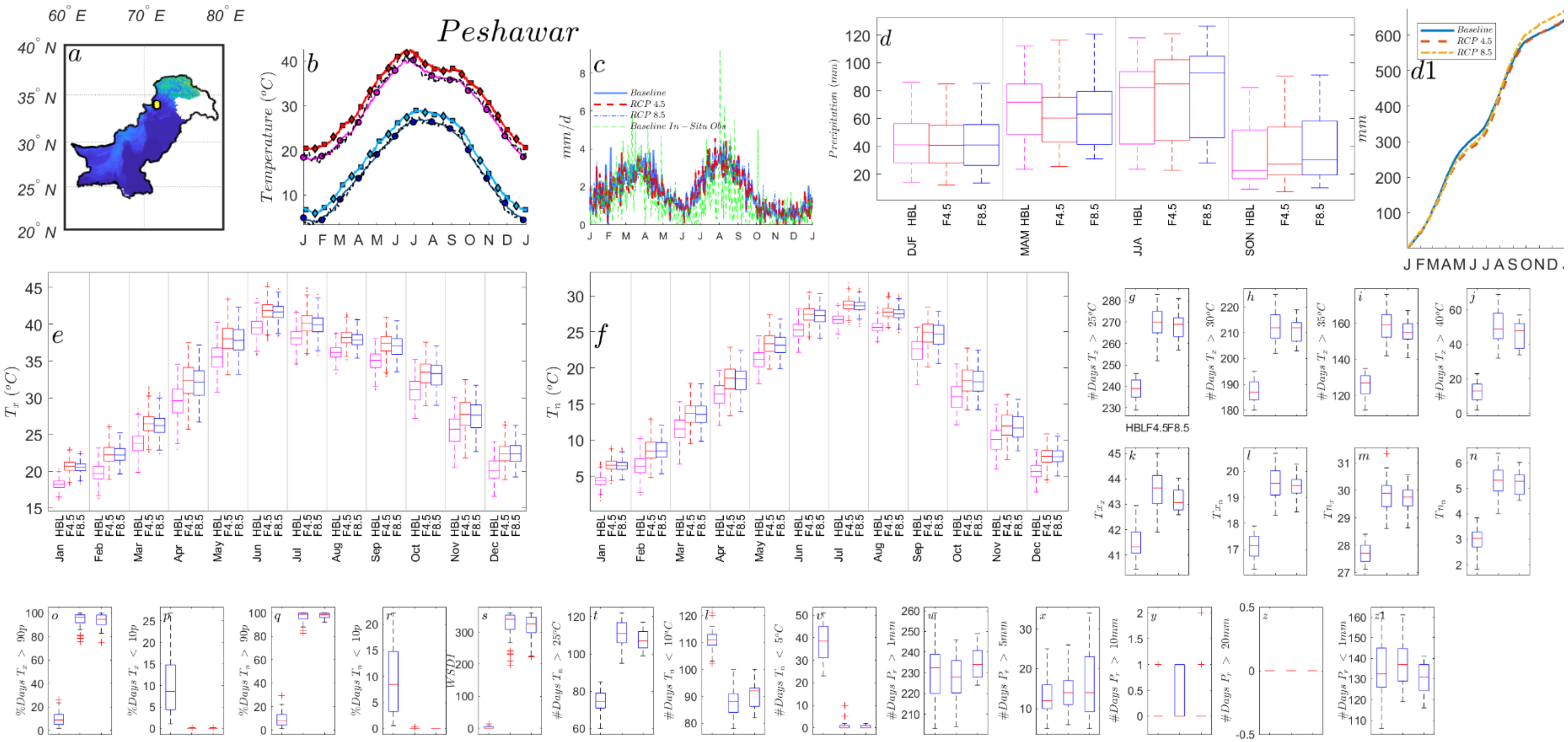

Figure 19. Similar to Figure 16, but for the city of Peshawar.

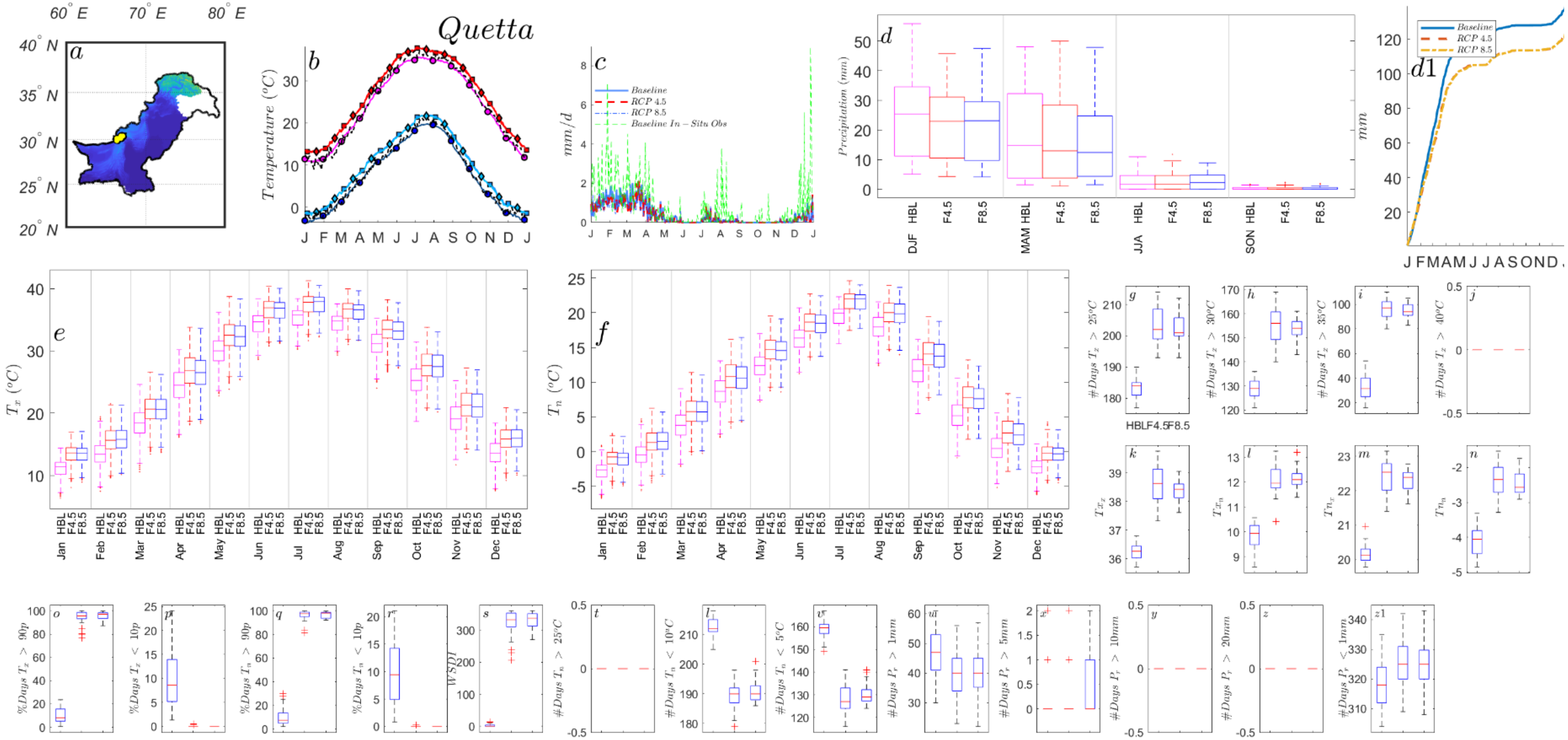

Figure 20. Similar to Figure 16, but for the city of Quetta.

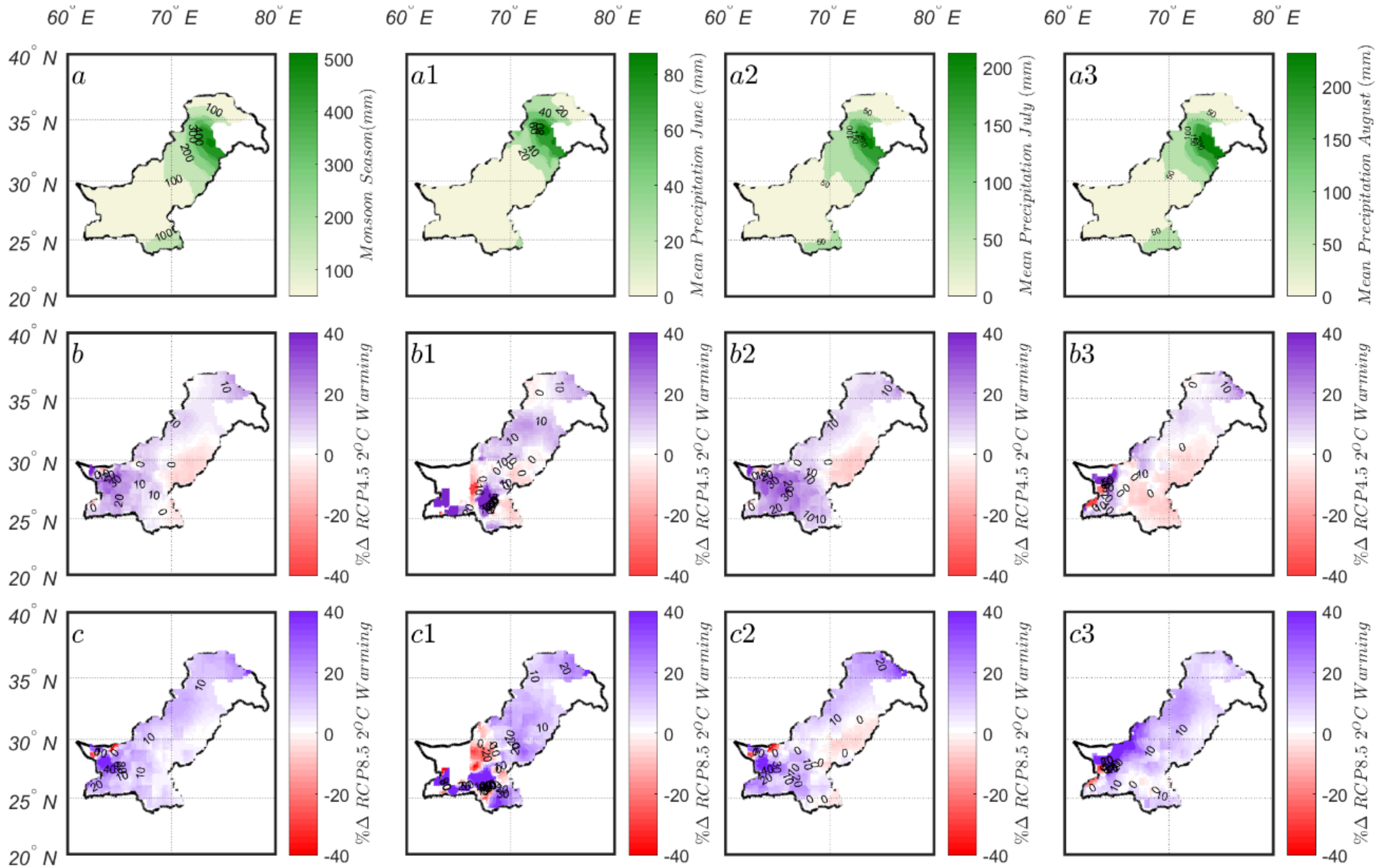

Figure 21. Change in Monsoon season precipitation under 2°C warming scenario in Pakistan.

$(\boldsymbol{a})$ the mean accumulated rainfall in monsoon season (June-August) in Pakistan in the baseline period $(1971-2000)$, $(\boldsymbol{b})$ percentage change $(\%\Delta)$ in the mean accumulated rainfall in monsoon season from the baseline period under $2°C$ warming in RCP 4.5 scenario $(2027-2069)$, $(\boldsymbol{c})$ same as (b) under RCP 8.5 scenario $(2027-2045)$, $(\boldsymbol{a1})$ the accumulated rainfall of June in the baseline period $(1971-2000)$, $(\boldsymbol{b1})$ percentage change $(\%\Delta)$ in June precipitation in future $2°C$ warm period under RCP 4.5 scenario, $(\boldsymbol{c1})$ percentage change $(\%\Delta)$ in June precipitation in the future $2°C$ warm period under RCP 8.5 scenario, $(\boldsymbol{a2})$ the accumulated rainfall of July in the baseline period $(1971-2000)$, $(\boldsymbol{b2})$ percentage change $(\%\Delta)$ in July precipitation in future $2°C$ warm period under RCP 4.5 scenario, $(\boldsymbol{c1})$ the percentage change $(\%\Delta)$ in July precipitation in the future $2°C$ warm period under RCP 8.5 scenario, $(\boldsymbol{a3})$ the accumulated rainfall of August in the baseline period $(1971-2000)$, $(\boldsymbol{b2})$ the percentage change $(\%\Delta)$ in August precipitation in future $2°C$ warm period under RCP 4.5 scenario, $(\boldsymbol{c2})$ percentage change $(\%\Delta)$ in August precipitation in future $2°C$ warm period under RCP 8.5 scenario.

CHAPTER 8: FUTURE CLIMATE EXTREMES UNDER 2°C SCENARIO IN PAKISTAN

1 Prelude

Naturally, occurring greenhouse gases (GHGs) accentuate a pivotal role for the Earth's atmospheric system. These gases, while being transparent to incoming solar radiation, block outgoing radiation from the Earth's surface. This phenomenon is known as the greenhouse effect, which causes a rise in the planet's average temperature. The phenomenon has been taking place since time immemorial. Beginning at the industrial revolution, greenhouse gasses have been increasing beyond their permitted levels owing to anthropogenic activities such as fossil fuel burning for power generation and deforestation. The resulting rise in global temperature has severely impacted the Earth's environment by altering the rainfall patterns, rise in sea level and causing an unpredictable change in extreme weather events such as cyclone, floods, droughts and heat waves (Hanif et al, 2010).

The South Asian region, nest of one fifth of the world population, is vulnerable to frequent and intense heat waves, particularly its urban areas due to urban heat island effect (UHI). It is further projected that in some parts of South Asia, human life cannot sustain without umbrella of protection during high levels of heat waves along with humidity in summer season. Being agrarian economies, mostly South Asian countries depend upon natural vagaries for agricultural production. Their Gross Domestic Product turned to be sensitive with frequent and intense heat waves. Thus, heat waves are closely linked to health and state of food security of a vast majority of the South Asian's population1.

Occurrence of more frequent and intense heat waves has been projected for Indus river valley of Pakistan in the South Asian region. Geographical location of these future heat waves pointed out the vulnerability of the population in its densely populated areas i.e. urban

[1] . http://news.mit.edu/2017/deadly-heat-waves-could-hit-south-asia-century-0802

centres. It is further projected that being and agrarian economy, Pakistan's Gross Domestic Product will be adversely affected due to heat waves in future (Im, S.Pal and Eltahir, 2017).

Heat waves are acknowledge as a major threat to global as well as regional food supply chain as Teixeira et al(2013) explored that agricultural yields generally reduce during short spell of high temperatures, particularly in the course of plant reproductively.

Campbell et al (2018) argued that heat waves expose all sections of the population to the risks of morbidity and mortality, susceptibility in marginal population groups is particularly higher as compared to others.

2. Theoretical Underpinnings of the Study

2.1 Introduction

The objective of this study is to examine the consequences of heat waves and resilience behaviour of people in major cities of Pakistan. This section reviews the literature on heat waves. Section 2.2 of this chapter reviews the background of heat waves in Pakistan. Section 2.3 reviews the relation between climate change and the heat waves. Section 2.4 reviews the impact of heat waves on human health and section

2.2 Background

According to The World Meteorological Organization, heat wave can be defined as noticeably unfamiliar hot weather over a geographical region which persists for a minimum of two consecutive days through the hot time period of the year based on local climatic conditions and with thermal conditions recorded above given threshold[2]. Heat waves happen as a result of a high pressure system persisting over an area for a longer duration.

Pakistan has been experiencing severe heat waves that have resulted in high mortality besides causing considerable inconvenience for the general population. Scientific studies project that with the rise in global temperatures, the intensity and frequency of heat waves

[2] https://www.metoffice.gov.uk/learning/temperature/heat wave retrieved on 22 September 2018.

will also rise in Pakistan (Zahid and Rasul, 2012). This calls for a dire need to address the situation through effective climate change mitigation and adaptation policies.

During the summer of 2010, extremely hot weather persisted in 12 cities of Pakistan from 22nd of May to 31st of May. Temperatures exceeded $45C^{\circ}$ resulting in the loss of 18 lives across Pakistan. Furthermore, 11 cities recorded temperature above $50C^{\circ}$ with 5 cities recording the temperature at $53C^{\circ}$ breaking all previous records. Similarly, during the intense heat wave in 2015 which occurred in southern part of Pakistan, mainly Sindh province, temperatures reached $49C^{\circ}$ in Districts Larkana, Sibi and Turbat (Saleem et al. 2018). During the heat wave of 2015 in Karachi the overall death toll reached 1,200 mostly affecting the old, sick and homeless[3].

2.3 Climate Change and Heat waves

Climate induced catastrophes have never been more imminent than at present, threatening the course of life as across the globe. The death toll attributed to climate change is growing at an alarmingly high pace (UNESCAP, 2015). Heat wave an indicator of climate change includes risk of mortality to not just humans but livestock and even plants. Moreover, heat waves are known to diminish development activities as a result of halt in construction and other physical labour (Russo et al. 2015).

More intense and frequent heat waves are predicted to increase globally. Fischer and Schär (2010) predict that the occurrence of summer heat waves would increase in Europe in the future. Intense heat waves lasting multiple days with high temperatures at night along with high humidity are expected to have the most severe impact. The analysis in the study is based on set of regional climate simulations and argues that there is a geographically steady pattern in the climatic models across Europe. The analysis forecasts that the most noticeable changes are likely to occur in southern Europe in terms of frequency and duration, in northern Europe in terms of heat wave amplitude and in low elevation southern Europe in

3 https://www.theguardian.com/world/2018/may/22/death-toll-climbs-in-karachi-heat wave

terms of health related indicators. The study also forecasted that for the Mediterranean region the frequency of the heat waves would increase to around 13 days for time period 2021-2050 and around 40 days for period 2071-2100

Catastrophes such as hurricanes, floods and heat waves are becoming frequent around the globe. Pakistan is no alien to the threats of climate change. Floods and heat waves are two of the most commonly occurring climatic disasters in Pakistan. Zahid and Rasul (2012) measured the intensity and frequency of the heat waves in Pakistan and also identified the most vulnerable regions within the country. The study has performed both country level as well as provincial level analysis. The results revealed that Punjab, Sindh, and Baluchistan regions are the most vulnerable. A consistent and increasing trend has also been seen for Baluchistan which indicated that the region might suffer from droughts in future. The country level analysis showed a rise in frequency of heat waves that lasted for 5-7 days from 1961 to 2009.

2.4 Impact of Heat waves on Human Health

It is a well-established fact that heat waves have an adverse impact on human health (Haines et al. 2006; D'Ippoliti et al. 2010). Studies have indicated that wet bulb temperature (temperature exceeding $35°C$) is considered as an upper limit for human survival (Im et al. 2017). Heat waves are known to aggravate and cause multiple diseases such as cardiac disease, respiratory illness, renal failures, and effects on mental health (Guirguis et al. 2014).

D'Ippoliti et al. (2010) developed a standard definition of heat wave to estimate the effects on mortality by age, gender and causes of death in Europe for the time period of 1990-2004. The heat wave was defined by considering the apparent maximum and minimum temperatures and classified by timings during summer, duration, and intensity. The estimation was based on percent increase in mortality in the heat waves days in comparison to non-heat wave days in the population aged above 65 years. City wise pooled estimates were estimated. The results showed geographic heterogeneity among the cities. Pooled results indicated a high impact of heat wave on the cities in Mediterranean region as compared to the North Continental region. Respiratory diseases in women aged 75 to 84 years were found to be increased during heat wave days. The study concluded that extreme events are likely to increase in future in the areas where heat waves do not occur commonly at present. In order to reduce mortality due to heat wave, prevention programs should focus on women, elderly and the chronic respiratory patients.

Health impacts of heat waves can be seen around the world. In Europe, Fischer and Schär (2010) have projected that the most severe impacts of heat waves on human health could be seen in river basins in southern Europe and cities in Mediterranean region. Im et al. (2017) projected that the south Asian region is expected to experience wet-bulb temperatures ($35C^{\circ}$) and in some parts temperatures even greater than that in near future as a result of ongoing rise in global temperatures. The study indicates that densely populated regions of Indus and Ganges River Basin will be the areas where hazard from heat waves will be concentrated. The study also pointed out the need for climate change mitigation in South Asia which is home to one fifth of world's population.

Andersen and Bell (2010) analysed the mortality risk related to heat waves in 43 cities of USA and investigated how heat waves' intensity, duration and timing effects mortality. They defined the heat waves as temperatures in 95^{th} percentile of the city for 2 or more days form 1^{st} of May to 30^{th} of September. Mortality risk associated with heat wave was estimated by comparing each heat wave day with non-heat wave day. Bayesian Hierarchal modelling was used to create the complete effect at the regional and national levels by combining the individual heat wave estimates. The estimates showed how heat wave characteristics such as intensity, duration, and timing modify heat wave mortality effects. The results showed that mortality increased by 3.74% because of heat wave at the national level from 1987-2005. Heat waves' impact on mortality was found to be more noticeable in the Northeast and Midwest regions of USA. The study concluded that heat waves with high intensity and longer duration had higher impact on mortality risk thus having implications for health effects from Climate Change.

Guirguis et al. (2014) examined the effects of heat waves on health across California in six regions namely Northern forests, north and south coasts, Central Valley, southern deserts and Mojave deserts for the time period of 1999-2009. The study identified heat waves which had a significant impact on health by using the canonical correlation analysis applied to the data on everyday maximum temperature and the data for morbidity in the form of unscheduled hospitalization records. This method helped identify 19 heat waves with duration of 3 to 15 days. The results revealed that hospitalization increased by 7 % during heat waves. Despite the excess cases of hospital admission, there was found to be no warning from the weather service. The maximum impact was observed in Central valley and the north and south coasts. The study suggests that the heat warning measure should reflect local percentile thresholds for acclimation to local climatic conditions.

Anderson and Bell (2009) used time series analysis to explore the connection between cold, heat, and heat waves and mortality in USA. 14 year data from 107 communities across the country was obtained to test the community specific variables such as cause of death, age, susceptibility, exposure timeframe, and confounding from pollutants. Results revealed that mortality associated with heat was linked to shorter lag whereas mortality related to cold was linked to a longer lag. Mortality risk however amplified with the intensity and duration of heat wave. Spatial heterogeneity indicated that weather- mortality relationship of one community could not be applied to another. The study concluded that acclimatization, characteristics of the community and individual's susceptibility have an impact on heat related mortality.

Tan et al. (2007) has explained the difference in mortality between the two heat wave events that occurred separately in Shanghai, one in 1998 and the other in 2003. The study examined a number of social, environmental and meteorological variables to test the relationship between human health and heat waves and also the difference in mortality during the heat wave events. The results revealed that mortality in both the events was strongly related with the duration of heat wave. However the study concluded that improvement in conditions of living such as air conditioning and increased green spaces in Shanghai along with an early warning system led to a decrease in death toll during the heat wave event of 2003 in comparison to 1998.

Coumou and Rahmstorf (2012) argue that certain weather extremes such as precipitation and heat wave to be specific are linked with the anthropogenic influence on climate. However the evidence for other types of extremes such as storms is not conclusive but an increase is expected on the basis of observed trends.

Bunker et al. (2016) presented a review and meta-analysis on impacts of hot and cold temperatures on mortality and morbidity in elderly population (above 65 years of age). The study pooled the cause-specific cases of mortality and morbidity in the elderly to get a percentage change in risk of temperature exposure on cause specific disease by means of random effect met analysis. The results revealed that an increase in cold was linked with the diseases like respiratory and cardiovascular mortality whereas an increase in temperatures was linked with cardiovascular, respiratory and cerebrovascular mortality. it is also expected that these risks will aggravate in future because of climate change and the globally ageing population.

Lee et al. (2018) argued that it is crucial to determine the heath burden of the diurnal temperature range (DTR) being major climate change index. The study evaluated the attributable risk fraction of DTR on mortality and its temporal variations for 308 cities of 10 countries from across the globe for the time period 1972-2013. Time varied distributed lag model was used to measure time-based change in DTR related mortality. The pooled estimates indicated that the fraction of mortality attributable to DTR was 2.5 percent for the study period which indicated that DTR has considerably contributed to mortality in all the selected countries with an even greater impact in UK, USA, Spain and South Korea

Gasparrini et al. (2017) estimated the link between temperature and mortality using a two stage time series method. Time series data for daily mean temperatures and mortality was collected for 451 locations across 23 countries from around the globe from 1984 to 2015. The study predicted excessive mortality for cold as well as heat and its net variation in 1990-2099 under four different scenarios of climate change. It was assumed no change in population size or adaptation would occur. The results revealed that under high emissions scenario of climate change poorer and warmer parts of the globe would be adversely and disproportionately affected due to climate change in terms of mortality. However the study also emphasized the importance of mitigation measures to limit global warming and the related health risks.

3. Geographical Profile of the Study Area

3.1 Introduction

This section of the study discusses the geographical profile of the study area. This section elaborates upon the geographical features such as population, area, climate, and precipitation of the districts in the study area.

3.2 Karachi

Karachi is the most populous city of Pakistan with an estimated total population of 16,051,521 persons. The total area of Karachi is 3,780km^2. Karachi is situated on the coast line of Sindh province with a natural harbour on the Arabian Sea. The climate of Karachi is arid with scanty rainfall of about 250 mm per annum. Precipitation mainly occurs during the monsoon months of July and August. The city experiences long and hot summer months from March to October while winter months are short and dry from December to February. Humidity levels remain constant throughout the year due to coastal proximity.

3.3 Lahore

Lahore is Pakistan's second largest city after Karachi. The estimated total population of Lahore is 11,126,285 persons as of 2017. The total area of Lahore is 1,772km^2. Lahore is a landlocked city situated in the north east of the Punjab province. Lahore borders with Indian state of Punjab on its East while River Ravi flows on the north side of the city. The climate of the city is semi-arid. The summer months are extremely hot with temperatures averaging above 40c°. Winter months on the other hand are short and cool with temperatures averaging below 10c°. Precipitation mostly occurs from June to September during Monsoon.

3.4 Faisalabad

Faisalabad the second largest city in Punjab and a major industrial hub has a population of 7,874,790 persons. The total area of Faisalabad is 1269Km^2. The city is landlocked and situated in the east of the province at an altitude of 604 feet above sea level. The river Chenab and River Ravi pass through the district. Faisalabad has a hot desert climate with an average rainfall of just 375 millimetres that occurs mainly during the monsoon season starting from July. The city experiences long hot summers and short dry winters.

3.5 Sialkot

Sialkot a major industrial centre in Punjab is thickly populated with the total estimated population of 3,893,672 persons. The total area of Sialkot is 19Km^2. River Chenab flows in the north of the city and multiple seasonal streams flow through the city. Climate of Sialkot is humid subtropical. The summers are hot and humid with Monsoon rains occurring during the summers whereas winters are cool and short.

3.6 Multan

Multan is one of the oldest towns in South Asia and the biggest city in southern Punjab. The total estimated population of Multan as of 2017 is 4,745,109. The total area of the district is 132Km^2. River Chenab and River Sutlej flow in close proximity to the district. The land of the region is alluvial and flat and suitable for cultivation. The climate is arid with extremely hot summer months but mild winters. Low precipitation of 188mm on average occurs in the city. The hottest average temperature is recorded in June at 42c° which makes Multan one of the hottest cities in Pakistan.

3.7 Peshawar

Peshawar the largest city in the KPK province also serves as its capital. The total population of the district is 4,269,079 persons. The district is situated in the Gandhara plains of Peshawar Valley, bordered on three sides with mountain ranges. The district is situated near the border to Afghanistan. The city has a hot semi-arid climate with very hot summer season and cool winter season. The average rainfall in the district is 403.9 millimetres. The city does not fall in the monsoon region like most of the country but it does receive rainfall in summer as well as winter.

3.8 Quetta

Quetta the capital city of Baluchistan is also its largest city. The total population of Quetta according to the population census of 2017 is 2,275,699. The total area of Quetta is 3,501Km^2. The average elevation of the city is 1,680 meters above sea level. The climate of Quetta is semi-arid. Summer months are warm and short that starts from May and last till September. Winter months are cold with occasional snowfall, starting in November and last till March. Quetta receives little precipitation and does not experience the Monsoon season.

3.9 Chaman

Tehsil Chaman in District Killa Abdullah has a total estimated population of 433,768. Chaman has a hot and semi-arid climate. Summer months are dry whereas winter months are wet with an average annual precipitation of 232mm.

3.10 Rahim Yar Khan

Rahim Yar Khan is a district in southern Punjab with a total estimated population of 4,814,006. The total area of Rahim Yar Khan is 45Km^2. The city is situated at close proximity of River Indus which flows to the west whereas the Cholistan Desert is situated on the eastern side of the district. Much of the district is barren and uncultivable however a small part of the district that is irrigated by the canals is suitable for cultivation. The summer season is very hot and dry however nights are cool. On the other hand winter season is short and mild.

3.11 Hyderabad

After Karachi, Hyderabad is the second largest city in Sindh province with an estimated total population of 2,199,463. The total area of the district is 319Km^2. The city is situated on the eastern bank of river Indus. The city has a very hot desert climate consistent throughout the year. The heat is offset by the coastal winds. The city experiences monsoon rains during the summer months starting from June. Winter months are also hot with average temperature of $25C^{\circ}$. The average annual precipitation is recorded at 177.9mm.

4. Methodology

4.1. Introduction

This section narrates the literature pertaining to resilience behaviour of people for heat waves. It also reviews the variables, sampling framework, data description, methodology and method applied for estimation of the model.

4.2. Ingredients of Heat Wave Resilience

In the "Theory of Moral Sentiments" by Adam Smith (1759) mentions that perceived fairness and social norms often influence human's decision behaviour along with their own pay offs. Such personal behaviour is of particular relevance for environmental policies (Carlsson, and Stenman, 2012).

Viktoria and Luiza (2013) used data from Euro barometer database to analyse the determinants of climate change and environmental protection attitude and behaviour for United Kingdom Greece. They applied logistic regression analysis by enveloping the behavioural and attitude determining factors of age, education, political belief, purchasing power, type of community, access to information, household size, and perception about climate change. They found that access to information; education and perceived level of climate change and environmental degradation played a vital role in determining human attitude and behaviour towards fighting climate change and environmental protection in Great Britain and Greece.

Kulatunga (2010) advocated that people's norms and values sharpened by collective culture would give birth to a common belief system. Consequently, this inferred belief system plays a major role in determining people's attitude about environmental protection and natural disaster risk management resulting from climate change.

While, availability and accessibility to internet and mass media have been found to shape up the human behaviour towards environmental protection and combat with climate change practices. (Nelkin 1987; Smith 2000 ; Burgesss 1990).

Socio economic and demographic factors such as income, environmental tax, gender, type and place of community where people live, education, political situation and beliefs are considered to influence the environmental behaviour of people (Corttrel, 2003, McCright, 2010).

Onuma, Shin & Managi (2017) examined the impact of country's experience with disasters in the past on damages caused by disasters in subsequent years. The analysis was based on global data on disasters obtained from 1990-2010 which included the death toll related to disasters. The authors on the basis of their findings argued that the damages of the past have a reduction effect on the damages caused in the future. Moreover the damages occurred in the past have promoted adaptation in certain types of disasters and level of development. The results further revealed that a country's own previous experience with natural disasters reduced future damages but the marginal effect was found to be larger for countries with low income. Contrary to that, in case of technological disasters, robust impact was observed for countries with higher income.

Frankhauser & Mcdermott (2014) analysed the relationship between climate change adaptation and income both empirically and theoretically. The authors claim that the poor countries and regions tend to suffer more from extreme climatic events and climate change as compared to wealthy countries. They present two bases for their argument, one being "demand effect" which is explained as demand for the good "climate security" increases with income. The second is "efficiency effect" which is explained as "the spill over externality on the supply side". It implies that factors such as strong institutions and improved public services increase the "adaptation productivity" in wealthy countries. The study found a strong evidence for the demand effect but the results for efficiency effect are rather inconclusive. The study suggests that international initiatives must include inclusive growth as policy measure to address the adaptation deficit.

Akompab et al. (2012) examined the heat wave perception in Australian city Adelaide in a cross-sectional study in 2012. The study conducted on a sample of 267 individuals showed that TV, radio, and newspaper happen to be the main source of access to information. The study found that people having access to information sources play an important role in developing high perception and understanding of people for heat waves and respond to early warnings of heat waves on time .

Lowe et al. (2011) identified the main characteristics of the heat wave early warning system (HEWS) for European countries to develop a new system. The study collected information on the existing heat wave early warning systems from 33 countries across Europe and pulled out the details on threshold for actions, trigger indicators, strategies for notifications, communication and dissemination strategies and prevention strategies. The study concludes that only 12 European countries have HEWS. Some HEWS have common elements however the differences in main characteristics could lead to an improvement in developing a new heat wave early warning system to prevent possible loss of life.

Kiberia (2016) found that the women of low income countries and developing countries are found to be more vulnerable to the incidents of climate change including heat waves. Climate change events affect women disproportionality as compared to men and thus lead to widen up the existing gender gap in these countries.

4.3 Population and Sampling Framework

The population of the study includes all those city regions of Pakistan which are severely hit by the heat waves. These regions include cities of Lahore, Faisalabad, Karachi, Hyderabad, Peshawar, Quetta, Sialkot, Multan, Peshawar and Rahim Yar Khan and their adjacent areas.

4.4 Model

The model proposed by the study is presented in equations (1) and (2).

$$Behavior_i = f(Precepton_i,\ Economic\ Factors_i,$$
$$Access\ to\ Information_i,\ Demographics_i, Location_i) \ldots\ldots.. (1)$$

The details of the demographics related control variable shown in equation (1) are discussed in Table 4.1. The variable includes age, household size and education level.

4.5 Variables and Construction:

Table 4.1 provides the description of the variables included in the estimation model. The indices are constructed using the Principle Axis Factoring Method (PAF) (Thompson, 2004). This method starts by assuming same number of possible indices which can be formed from provided constructs. Further it uses the Eigen value approach to rank the indices. This study has selected the best possible index which has highest possible Eigen value. The advantage of this method as compared to simple mean is that, it uses non-constant weightage, there is no need to rescale variables into same direction and we can provide constructs with different number of Likert scale options.

Table 4.1. *Description of Variables*

Variable	Symbol	Construction
Age	Age	Continuous Form
Household Size	HS	Discrete Form
Education of Respondent	EDU	0 = Illiterate 1 = Primary 2 = Middle 3 = Matriculation 4 = Intermediate 5 = Baccalaureate 6 = Masters 7 = Doctorate 8 = Any higher
Access to Information Index	ACC	Index constituted using PAF from questions 2.1 to 2.6. Higher value means higher access
Perception about heat wave	PREC	Index constituted using PAF from questions 3.1 to 3.6. Lower value means higher perception
Economic Costs	ECO	Index constituted using PAF from questions 4.1 to 4.9. Lower value means higher economic cost
Resilience Behavior	BEH	Index constituted using PAF from questions 6.1 to 6.5. Higher value means higher resilience behaviour
City	Dummy variables	

4.6 Estimation Model

Since the data is cross sectional, this study will use Ordinary Least Squares (OLS) approach as proposed by (Gujarati, 2009). This approach helps to measure the marginal effect of proposed independent variables on the dependent variable. Further, since the respondents are from different cities, this heterogeneity is controlled using region wise dummy variable (Jaccard et al., 1990; Jaccard & Turrisi, 2003).

$$Beh_i = \alpha + \beta_1 Eco_i + \beta_2 Acc_i + \beta_3 Precp_i + \beta_4 Precp * ACC_i + \beta_5 Age_i + \beta_6 HS_i + \beta_7 Education_i + \beta_8 \sum_2^n City\ Dummy + \varepsilon_i \ \ ......(2)$$

4.7 Descriptive Statistics

Table 4.2 shows the frequency distribution of sample corresponding to each city. Four major cities like Karachi, Lahore, Peshawar and Multan are covered with higher frequency. The data is collected using random sampling method. The questionnaire is added in appendix A.

Table 4.2: *Description of the Sample Distribution*

City	Freq.	Percent
Chaman	7	3.61
Faisalabad	15	7.73
Karachi	24	12.37
Lahore	32	16.49
Multan	25	12.89
Quetta	14	7.22
Rahim Yar Khan	20	10.31
Sialkot	12	6.19
Peshawar	29	14.95
Hyderabad	16	8.25
Total	194	

The age composition of the sample respondents is shown in Figure 4.1. The statistics show that majority of the respondents are young people since their ages lie between 20 to 40 years. This composition corresponds to the age composition of Pakistan; also these are the people who have to face the heat wave for longest while going for college, university or jobs.

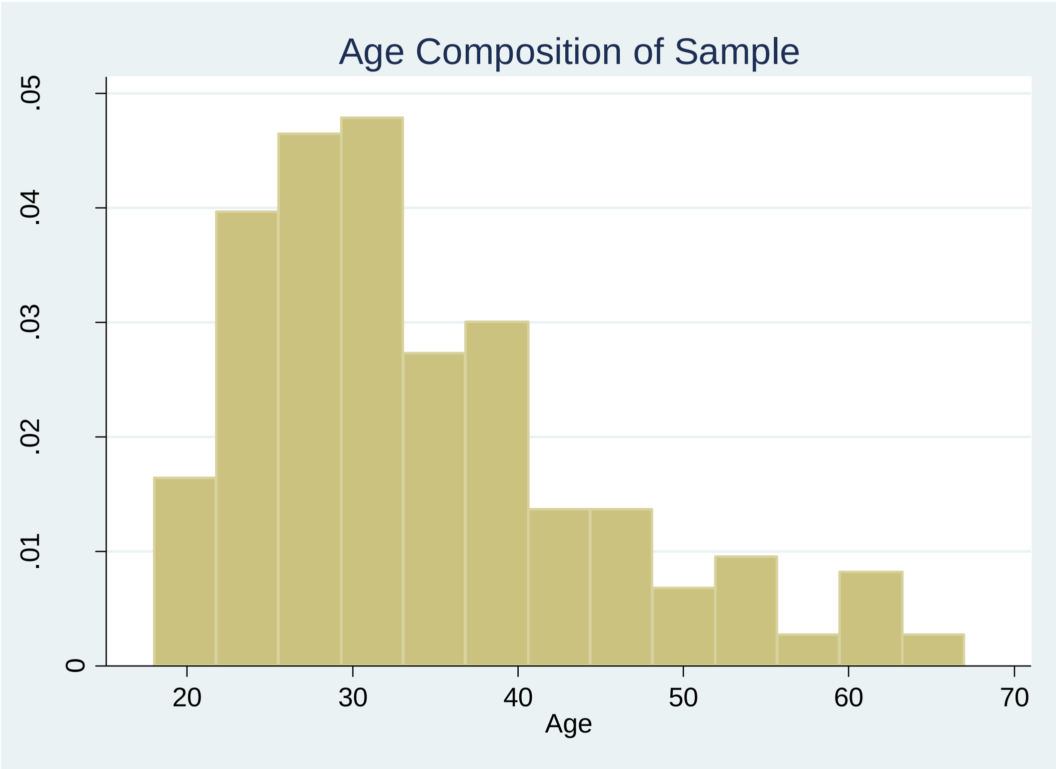

Figure 4.1: Age Composition of the Sample

The statistics regarding the composition of the household in Figure 4.2 reveal that the majority of the households have a size of less than 6 people, indicated by household size of 6 being 75th percentile.

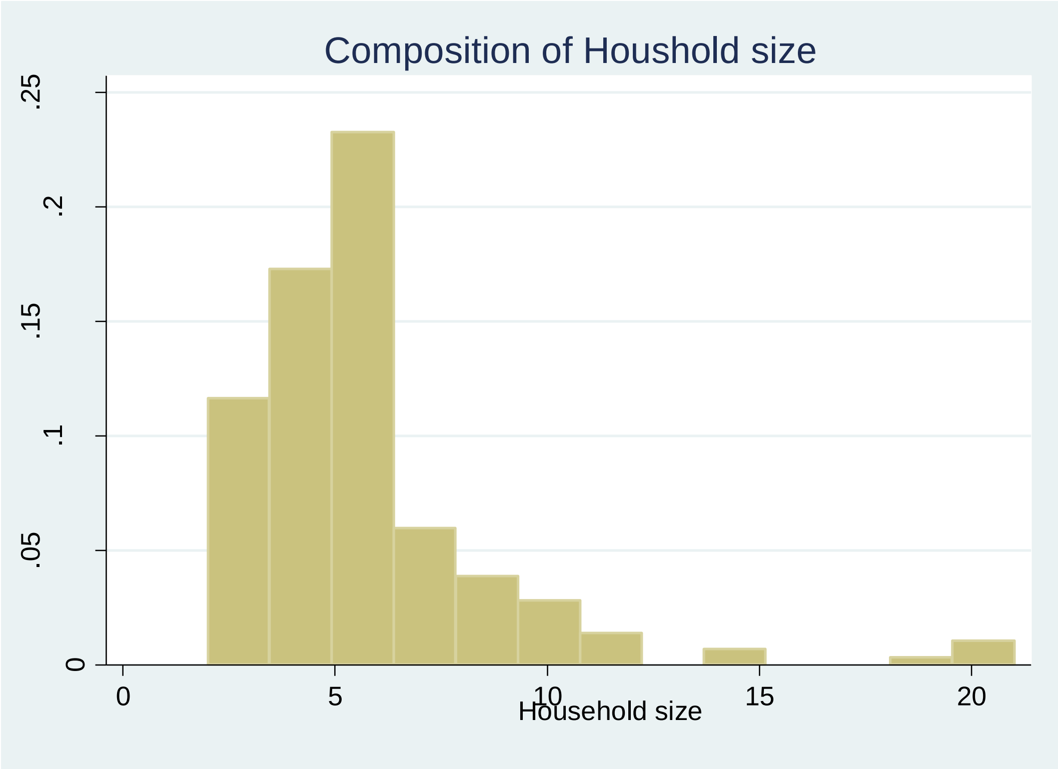

Figure 4.2: Distribution of the Household Size

The distribution of the education level of the respondents can be seen from table 4.3 that the surveyed respondents from the population have education level either Baccalaureate or Masters. This depicts that the sample is focusing on the skilled population.

Table 4.3: *Educational Status of the Sample*

Categories	Frequency	Percent
Illiterate	1	0.52
Primary	2	1.04
Middle	5	2.59
Matriculation	13	6.74
Intermediate	20	10.36
Baccalaureate	61	31.61
Masters	80	41.45
Doctorate	10	5.18
Any other	1	0.52
Total	193	100.00

Table 4.4 shows the dispersion in the education level of the parents of the population. It can be seen that it is well dispersed as compared to the education of the respondents. A few parents are illiterate but most others have studied up to Baccalaureate.

Table 4.4: *Dispersion in Education Level of parents*		
Categories	Frequency	Percent
Illiterate	31	16.06
Primary	14	7.25
Middle	6	3.11
Matriculation	30	15.57
Intermediate	15	7.77
Baccalaureate	48	24.87
Masters	31	16.06
Doctorate	16	8.29
Any Other	2	1.04
Total	192	100.00

From the demographics regarding the occupation status of the sample, shown in table 4.5, it can be see that around 56% of the sample is comprised of employed population (i.e. self-employed, manager, other white collar, and manual worker). All of these including 18% of students are the people who face the major force of heat wave while in going to work, during work and while going to get education.

Table 4.5: *Occupation Status of the Sample*

Categories	Frequency	Percent
Self employed	39	20.10
Manager	35	18.04
Other white collar	21	10.82
Manual worker	14	7.22
House person/house wife	13	6.70
Unemployed	9	4.64
Retired	10	5.15
Student	35	18.04
Any other	18	9.28
Total	194	100.00

In terms of purchasing power, 68% of the respondents have claimed that their purchasing power has improved over past few years as shown in table 4.6. The positive change can be attributed to the fact that the sample mostly comprises of educated and young respondents. While there are 10% respondents who claim that the purchasing power has been deteriorated.

Table 4.6: *Purchasing Power Status*		
Categories	Frequency	Percent
Improved	133	68.56
Stayed the same	40	20.62
Got worse	21	10.82
Total	194	100.00

Regional differences in purchasing power have been shown in table 4.7. Chaman and Quetta in Baluchistan have witnessed a higher proportion of decline in the purchasing power. This is expected as this province has experienced low development over the past few years. On the other hand developed regions like Faisalabad, Karachi, Lahore, Multan have witnessed highest raise in the purchasing power.

Table 4.7: *Regional Difference in Purchasing Power*

	Cities										
	Chaman	Hyderabad	Peshawar	Faisalabad	Karachi	Lahore	Multan	Quetta	Khan Rahim Yar	Sialkot	Total
Improved		9	24	10	16	21	17	9	17	8	133
Stayed the same		4	3	5	7	7	4	2	3	4	40
Got worse		3	2	0	1	4	4	3	0	0	21
Total		16	29	15	24	32	25	14	20	12	194

Gender differences in purchasing power have been shown in table 4.8. There is a high ratio of males 13% as compared to 6% of females who claim that their purchasing power has gotten worse during the past 5 years. This difference might not be significant enough if we account for the fact that the majority of females are housewives in Pakistan.

Table 4.8: *Gender Difference in Purchasing Power*

	Gender		
	Male	Female	total
Improved	89 (67%)	44 (66%)	133
Stayed the same	27 (20%)	13 (21%)	40
Got worse	17(13%)	4 (6%)	21
Total	133	61	194

Figure 4.3 shows the number of responses for access to information. Access to information plays a significant role in providing evidences to the respondent to assist them in making decisions. A high degree of access is available for telephone and television. 184 out of 194 respondents claimed to have access to television and telephone. In case of receiving the early warnings regarding heat wave, there were only 107 people out of 194 who received or noticed the early warning.

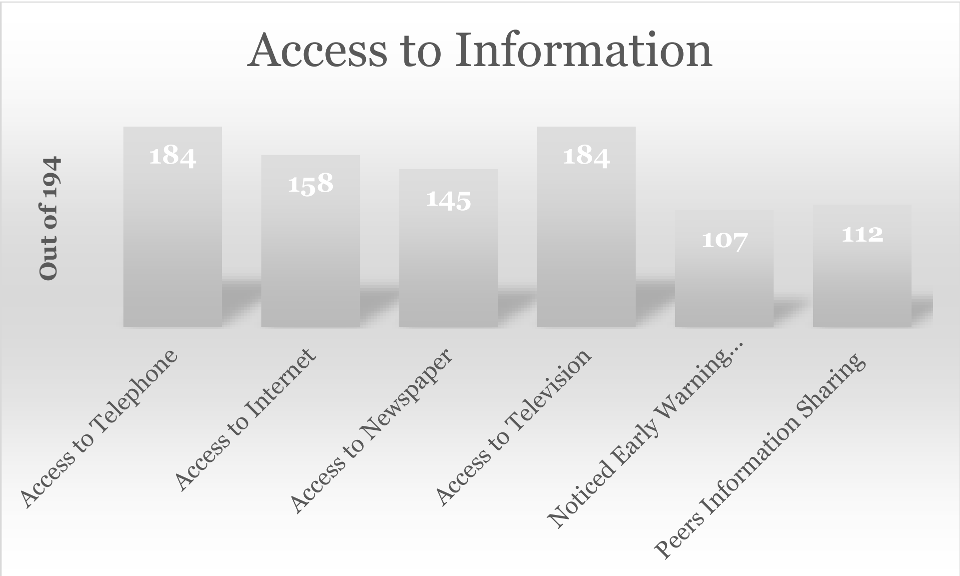

Figure 4.3: Access to Information

Table 4.9 shows the response regarding the perception '*Heat wave is an unstoppable processes*'. The result shows that almost 77.70% of the respondents agree to the fact that this process is inevitable and nothing can be done about it.

Table 4.9:

Perception Regarding Heat Wave As An Unstoppable Process

	Frequency	Percent
Strongly Agree	45	23.3
Agree	105	54.4
Don't Know	19	9.8
Disagree	23	11.9
Strongly Disagree	1	0.5
Total	193	100.00

While assessing the perception of the change in intensity of heat wave in Pakistan, 64.55% of the respondents were convinced that heat wave has intensified in recent years as shown in table 4.10. This calls for action by the government to reform the perceptions and develop appropriate policies that can help in reverting the souring heat wave issue.

Table 4.10

Perception about Heat wave Intensity

	Freq.	Percent
Happened too much	122	64.55
Moderate	59	31.22
Not happened much	8	4.23
Total	189	100.00

Table 4.11 shows the response to 'Is heat wave a serious problem? A huge proportion of almost 88.54% respondents agreed that heat wave is a serious issue and it needs to be addressed, but previously it has been seen that majority people did not know how to tackle the heat wave problem.

Table 4.11

Perception about Importance of Heat Wave Issue

	Frequency	Percent
Strongly Agree	81	42.19
Agree	89	46.35
Don't Know	12	6.25
Disagree	9	4.69
Strongly Disagree	1	0.52
Total	192	100.00

The bar chart in Figure 4.4 shows how individuals' percentage of expenses has increased because of prevalent heat wave. Majority people mentioned that expenses have increased up to 21-30%.

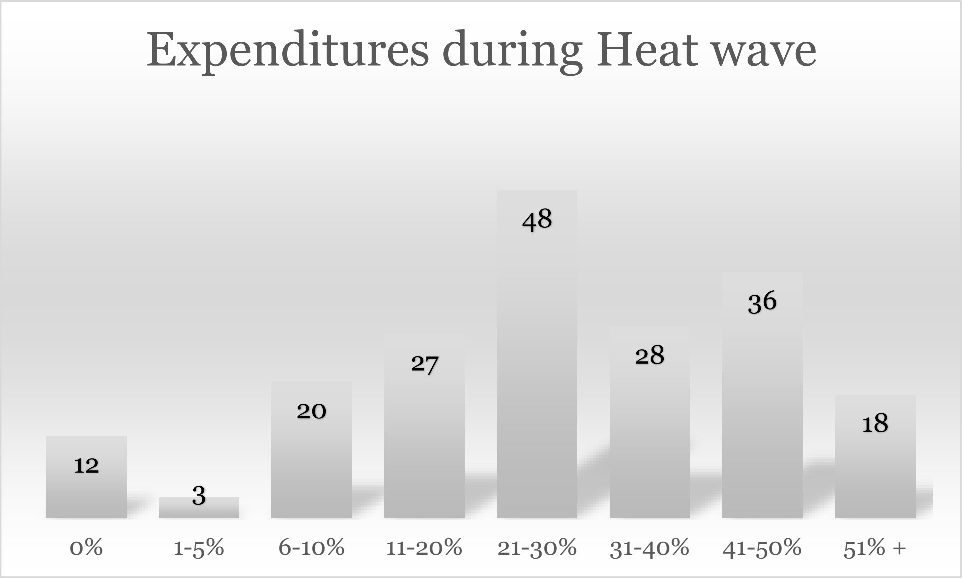

Figure 4.4: Expenditures during Heat wave

Table 4.12 shows the increase in expenditures on health during Heat waves. 70.83 percent respondents claimed that the expenditures on health increased due to heat wave.

Table 4.12

Expenditures on health during Heat wave

	Frequency	Percent
Increased	136	70.83
Stayed the same	52	27.08
Decreased	4	2.08
Total	147	100.00

The statistics regarding the perception whether heat wave and the road congestion are correlated as shown in table 4.13. 85.5% respondents claimed that both intensify each other.

Table 4.13

Heat wave and Road Congestion Correlation

	Frequency	Percent
Strongly Agree	97	34.7
Agree	98	50.8
Don't Know	19	9.8
Disagree	6	3.1
Strongly Disagree	3	1.55
Total	193	100.00

Bar chart in Figure 4.5 shows the number of responses out of 194 who claimed that expenses have increased because of the prevailing heat waves. Here the leading factors for raise in expenses are cooling appliances (166) and expenses on safe water (150).

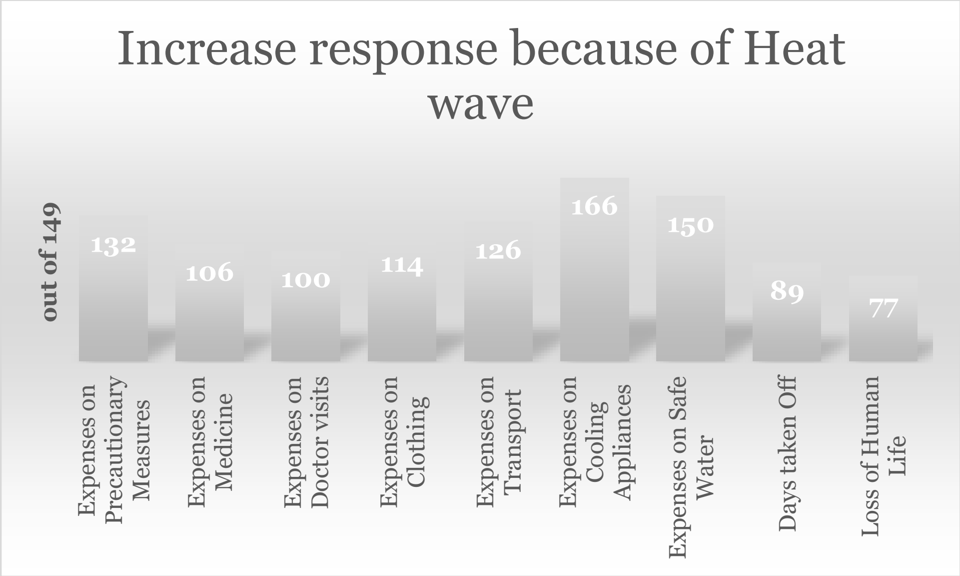

Figure 4.5: Expenses on Heat wave Associated Aspects

In response to early warning systems it can be seen in table 4.13 that a major share of 53.72% respondents claimed that they occasionally responded to early warning system. While a big number 30% people do not respond to the early warning system which points towards another issue that people may not trust the early warning system or the counter measures proposed seem impractical to the people.

Table 4.13

Heat wave Precautionary Measures

	Frequency	Percent
Never	56	29.79
Occasionally	101	53.72
Every time	31	16.49
Total	188	100.00

While assessing the frequency of the precautionary measures in table 5.14, 52.43% people claimed that they occasionally pursued the precautionary measures against the heat waves.

Table 4.14

Frequency of Precautionary Measures

	Frequency	Percent
Never	31	16.76
Occasionally	97	52.43
Every time	57	30.81
Total	185	100.00

When asked about the participation in public tree plantation programs in the locality, 46.28% responded that they do not participate in such programs in anticipation to reduce heat wave. Results are shown in table 4.15.

Table 4.15

Tree Plantation

	Frequency	Percent
Never	87	46.28
Occasionally	65	34.57
Every time	36	19.15
Total	188	100.00

Statistics from table 4.16 reveal that majority of the respondents; about 74% claimed that they do not have any sort of life or health insurance which might help in countering any losses because of the heat wave. This is another concern where people are not precautionary saving.

Table 4.16

Access to Health Insurance

	Frequency	Percent

No	138	73.8
Yes	49	26.2
Total	187	100.00

Statistics in table 4.17 show that people are concerned for their future when they vote for political leaders. 52.13% people claimed that they voted to the party which had a policy planned for countering heat waves.

Table 4.17

Voting the Political party

	Frequency	Percent
No	90	47.87
Yes	98	52.13
Total	188	100.00

4.8 Index construction

This section comprises of the tests applied to check the validity of the indices constructed from the survey data.

4.8.1. Index Statistics

Table 4.18

KMO and Bartlett's Test

		Perception	Economic cost	Resilience Behavior	Access to information
Kaiser-Meyer-Olkin Measure of Sampling Adequacy.		0.643	0.716	0.546	0.647
Bartlett's Test of Sphericity	Approx. Chi-Square	87.609	473.87	64.50	109.9
	Df	15	36	10	15
	Sig.	0.00	0.00	0.00	0.00

The KMO (Kaiser – Meyer – Olkin) test and Bartlett's test is used to assess if the sample is adequate and spherical, so that it can be used in the index construction process. Here index is constituted for Perception, Economic Cost, Resilience behaviour and Access to Information, for these, all of the KMO values are above sufficiently above 0.5 while Bartlett's test is statistically significant. This hints that index can be constituted from the available input questions and the sample size.

4.8.2 Index of Perception

Table 4.19 confirms that all the input questions are able to explain the 20.9% changes in the index of perception. Here the variance explained by first index explains variance 14.3% more than the second index.

Table 4.19: *Total Variance Explained*

Factor	Initial Eigenvalues			Extraction Sums of Squared Loadings		
	Total	% Variance	Cumulative %	Total	% Variance	Cumulative %
1	1.890	31.505	31.505	1.257	20.953	20.953
2	1.027	17.109	48.614			
3	0.932	15.529	64.142			
4	0.862	14.363	78.505			
5	0.783	13.047	91.552			
6	0.507	8.448	100.000			

Table 4.20: *Factor Matrix*

	Factor 1
p1	.285
p2	.311
p3	.798
p4	-.292
p5	.236
p6	.548

Extraction Method: Principal Axis Factoring.
1 factor extracted. 17 iterations required.

Table 4.20 proves that the correlation coefficient of the input questions with the overall index of perception. Here question 3 and question 6 of perception section are highly correlated while others are moderately correlated. The question 3 is 'heat wave is perceived to be a serious problem' and question 6 is 'do you think that impact of heat wave exaggerates in congested areas of the city?'

4.8.2 Index of Economic Cost

Table 4.21 shows that the questions regarding economic cost explain 28.4% changes in the index for economic cost. Here the first index explains more than twice of second index.

Table 4.21: *Total Variance Explained*

Factor	Initial Eigenvalues			Extraction Sums of Squared Loadings		
	Total	% Variance	Cumulative %	Total	% Variance	Cumulative %
1	3.178	35.306	35.306	2.560	28.448	28.448
2	1.432	15.915	51.221			
3	1.208	13.419	64.641			
4	0.852	9.462	74.103			
5	0.631	7.007	81.109			
6	0.585	6.497	87.607			
7	0.525	5.831	93.438			
8	0.395	4.391	97.828			
9	0.195	2.172	100.000			

Extraction Method: Principal Axis Factoring.

The table 4.22 shows the correlations among the survey questions. All questions from 1 to 5 in economic cost section show high correlation while others represent the low correlation. These questions from 1 to 5 asked about change in cost of these aspects due to heat wave during last 5 years. These aspects were, e1 = precautionary measures, e2 = medicine, e3 = visit to doctors, e4 = clothing and e5 = cooling.

Table 4. 22: *Factor Matrix*

	Factor
	1
e1	0.528
e2	0.776
e3	0.746
e4	0.521
e5	0.565
e6	0.477
e7	0.417
e8	0.257
e9	0.254

Extraction Method: Principal Axis Factoring.
1 Factor extracted. 5 iterations required.

4.8.3 Index of Resilience Behaviour

The table 4.23 shows that the questions regarding resilience behavior explain 18.69% changes in the index for resilience behavior.

Table 4.23: *Total Variance Explained*

Factor	Initial Eigenvalues			Extraction Sums of Squared Loadings		
	Total	% Variance	Cumulative %	Total	% Variance	Cumulative %
1	1.520	30.397	30.397	.935	18.696	18.696
2	1.382	27.645	58.042			
3	.824	16.475	74.518			
4	.677	13.549	88.066			
5	.597	11.934	100.000			

Extraction Method: Principal Axis Factoring.

Lastly, only question 1 of this section is highly correlated with the resilience behavior while others are weakly correlated as shown by table 4.24. Question 1 was 'do you respond to the information provided by the early warning system to reduce the impact of heat waves?'

Table 4.24: *Factor Matrix*[a]

	Factor
	1
b1	.811
b2	.435
b3	.253
b4	.121
b5	-.095

Extraction Method: Principal Axis Factoring.

a. Attempted to extract 1 factor. More than 25 iterations required. (Convergence=.005). Extraction was terminated.

4.8.4 Index of Access to Information

The table 4.25 shows that the questions regarding access to information explain 18.69% changes in the index for access to information. The first index is explaining 11% more variation as compared to second index.

Table 4. 25: *Total Variance Explained*

Factor	Initial Eigenvalues			Extraction Sums of Squared Loadings		
	Total	% Variance	Cumulative %	Total	% Variance	Cumulative %
1	1.935	32.244	32.244	1.172	19.536	19.536
2	1.270	21.173	53.417			
3	.848	14.128	67.544			
4	.739	12.317	79.861			
5	.631	10.524	90.385			
6	.577	9.615	100.000			

Extraction Method: Principal Axis Factoring.

Table 4.26 shows that only question 2 is highly correlated with the index while others are weekly correlated with the index of access to information. The question 2 was 'do you have access to internet at home?'

Table 4.26: *Factor Matrix*[a]

	Factor
	1
a1	.395
a2	.648
a3	.437
a4	.321
a5	.372
a6	.404

Extraction Method: Principal Axis Factoring.

a. 1 factor extracted. 10 iterations required.

5. Results of the Study

5.1 Introduction

Using the indexes for perception, economic cost and access to information and Age, regression has been run to check the impact on resilience behaviour of the respondents in 10 cities of Pakistan. Ordinary Least Squares (OLS) technique has been used and heterogeneity among cities has been controlled by the use of region wise dummy variables. This section will discuss the results of the regression.

5.2 Regression Analysis

Table 5.1 shows the results of the OLS regression and the overall statistics of the model used to estimate the cross sectional data.

Table 5.1: *Regression Results*

BEH	Coefficient	Std. Err.	t	P > [t]
ECO	0.0072693	0.0777139	0.09	0.926
ACC	0.1762536	0.1001538	1.76	0.080
PREC	-0.1810716	0.0794141	-2.28	0.024
AGE	0.015024	0.0055205	2.72	0.007
HS	-0.0632871	0.0294305	-2.15	0.033
EDU	0.0150111	0.603939	0.25	0.804
		Region		
Hyderabad	1.039818	0.4348255	2.39	0.018
Peshawar	0.8001016	0.4184043	1.91	0.058
Faisalabad	0.5676411	0.4353939	1.30	0.194
Karachi	0.6379792	0.4456995	1.43	0.154
Lahore	0.3684924	0.44119	0.84	0.405
Multan	0.528346	0.4302642	1.23	0.221
Quetta	0.8772084	0.4155073	2.11	0.036
R. Y. Khan	-0.3018956	0.445721	-0.68	0.499
Sialkot	0.3450115	0.5019488	0.69	0.493
PREC*ACC	-0.1469802	0.867628	-1.69	0.092
Cons	0.7675848	0.5780738	-1.33	0.186
		Model Statistics		
No. of observations			170	
R squared			0.326	
Adjusted R squared			0.2555	
Prob. > F			0.0000	
F (16,153)			4.63	

$$0.01Eco_i + 0.18Acc_i - 0.18Precp_i - 0.15Precp * ACC_i + 0.01Age_i + -0.06HS_i + 0.01Education_i + \beta_8 \sum_2^n City\ Dummy + \varepsilon_i$$

The estimation results of OLS model controlled for the differences of cities are shown in table 5.1. Here 170 observations are used after excluding incomplete survey questionnaires.

R squared shows that overall 32% of the resilience behaviour is explained by the proposed independent variables. And the significant F test confirms the fitness of the model.

Estimation results show that the index of economic cost is statistically insignificant. It implies that in the case of Pakistani cities, cost associated with the heat waves is not significantly creating resilience behaviour.

In case of access to information, a 1% increase in access to information leads to 0.18% increase in the resilience behaviour. This indicates that when people are connected with means of information, they are more likely to pursue resilience behaviour to heat waves.

Similarly 1% increase in perception of harmful effects of heat waves (indicated as decrease in index), shows a 0.18% increase in resilience behaviour. It is evident from the fact that when people realize the harmful effect of any event they tend to respond to avoid it. Here the cross product of perception and access to information shows the moderating role of access to information in setting the appropriate perceptions. Here 1% increases in access to information increase the negative effect of perception by 0.15% on average.

Further, increase in age (shown by D1), lead to higher experience, increase the resilience behaviour. While analysing the household size (D3) leads to difficulty by the household members to sustain the resilience behaviour. Lastly increase in education level (D4) shows awareness and leads to increase in the resilience behaviour. Here we can see that cities like Hyderabad, Peshawar and Quetta has resilience behaviour as compared to benchmark city which is Chaman.

Further diagnostics are tested for the estimation model. First is the BP – CW heteroscedasticity test. The probability value 0.58 shows that the results are homoscedastic. The insignificant value of Ramsey RESET test shows that model has no omitted linear or quadratic variables.

5.3 Gender, Heat wave and Resilience

Table 5.2 shows the results of female sample of respondents.

Table 5.2: *Results of Female Sample*

beh	Coefficient	Standard error	t	P > [t]
eco	-0.0727853	0.1738175	-0.42	0.680
acc	-0.0200371	0.2157883	-0.09	0.927
prec	0.1972067	0.24254	0.81	0.425
D1	-0.0024233	0.0178206	-0.14	0.893
D3	-0.2401122	0.1027939	-2.34	0.029
D4	0.1121892	0.1529907	0.73	0.471
Region				
Faisalabad	-2.083031	1.699341	-1.23	0.234
Karachi	-4.345867	2.07638	-2.09	0.049
Lahore	-2.898597	1.79684	-1.61	0.122
Multan	-2.830686	1.719863	-1.65	0.115
Quetta	-1.861969	1.293446	-1.44	0.165
Rahim Yar Khan	-3.403138	1.672255	-2.04	0.005
Sialkot	-3.026596	1.967728	-1.54	0.139
c prec.c.acc	0.5794233	0.2933864	1.97	0.062
cons	3.416318	2.225472	1.54	0.140
Model Statistics				
Number of obs.				36
F (14,12)				1.62
Prob. > F				0.1550
R squared				0.5189
Adjusted R squared				0.1981

The sample has only 36 values, which has led to insignificant overall F test. A possible explanation for such behaviour is the fact that females in Pakistan are generally dependents of male household head in terms of decision making. While R squared as 51%. In this model only the household size had negative significant effect on the resilience behaviour, and this negative effect is higher as compared to overall sample, indicating that females face higher difficulty in observing resilience behaviour when the family size is bigger.

Table 5.3 shows the results for male sample of respondents.

Table 5.3: *Results of Male Sample*

beh	Coefficient	Standard error	t	P > [t]
eco	0.0013336	0.1101897	0.01	0.990
acc	0.3981188	0.1365282	2.92	0.005
prec	-0.2765422	0.1132682	-2.44	0.017
D1	0.0188832	0.008476	2.22	0.029
D3	-0.058018	0.0422759	-1.37	0.175
D4	-0.0909054	0.0846931	-1.07	0.287
Region				
Faisalabad	0.7271528	0.4556598	1.60	0.115
Karachi	0.8713909	0.4656414	1.87	0.065
Lahore	0.4837211	0.4869633	0.99	0.224
Multan	0.7425282	0.4803382	1.55	0.126
Quetta	1.387231	0.4457052	3.11	0.003
Rahim Yar Khan	-0.0528858	0.4833498	-0.11	0.913
Sialkot	0.4466322	0.546224	0.82	0.416
c.prec.c.acc	-0.2565788	0.1182672	-2.17	0.033
cons	0.6341407	0.6561829	-0.97	0.337
Model Statistics				
No. of obs.			89	
F(14, 74)			3.66	
Prob. > [F]			0.0001	
R squared			0.4088	
Adjusted R square			0.2970	

The sample size is 89 with significant overall F test and independent variables are explaining 41% changes in dependent variable. Access to information has positive effect of 0.398% which is considerably higher than effect noted in overall sample which is 0.18%. It shows that males respond faster as compared to females.

Here increase in perception has an effect of 0.276% as compared to overall sample value of -0.18% this is evident as there are higher number of males who are experiencing heat waves while their commute to work or education.

Here the positive effect of age on resilience is almost same in both male and overall sample.

The cross product of perception and access to information in make sample is bigger in terms of magnitude pointing out that access to information plays as a better catalyst/moderator to males as compared to females.

5.4 Diagnostic Test Results

Diagnostics are tested for the estimation model. Table 5.4 shows the results of Breusch-Pagan/ Cook-Weisberg test for heteroscedasticity. The probability value 0.58 shows that the results are homoscedastic. The insignificant value of Ramsey RESET test shows that model has no omitted linear or quadratic variables.

Table 5.4: *Post Regression Diagnostics.*

	Test (P value)
Ramsey RESET Test for Misspecification	0.65 (0.58)
Breusch-Pagan / Cook-Weisberg Test for Heteroscedasticity	0.30 (0.58)

Table 5.5 of effect size shows the variable wise Eta square values (partial R squares), it will help to identify the variables which have highest contribution in explaining changes in dependent variable[4]. Here we can see that the difference in cities have highest contribution in the difference in resilience behaviour while Age and Perception follows as second and third indicator.

Table 5.5: *Effect sized of linear models*

Source	Eta-square
Model	0.326
ECO	0.00006
ACC	0.0198
PREC	0.0328
AGE	0.046
HS	0.029
EDU	0.0004
Region	0.197
PRECP*ACC	0.0184

[4] They are also denoted has f^2

5.5 Stability of Partial Effects Plots

Here the lines are constructed using partial correlation coefficient, controlling for other variables in the model. Below graph confirms that the scatter plots are following the similar pattern and the slope of the line. Hence all the respondents are closely representing the negative effect of decrease in perception and resilience behaviour.

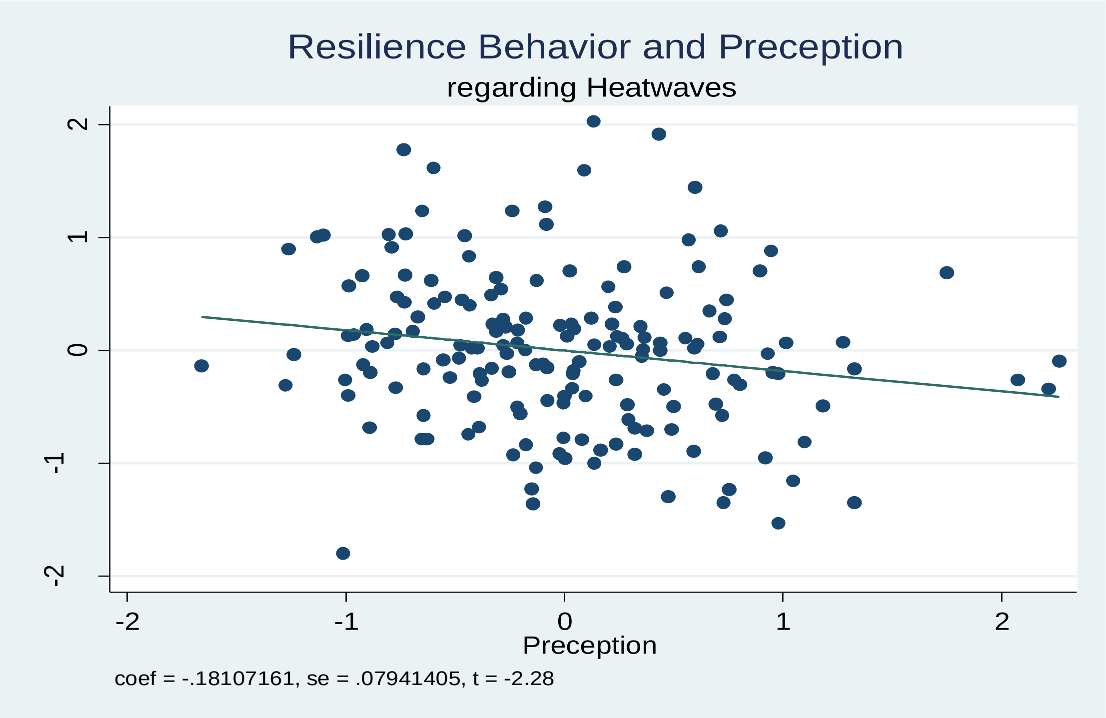

Figure 5.1: Resilience Behaviour and Perception

Here the scatter plots are representing the horizontal line, confirming that economic cost has no effect on resilience behaviour.

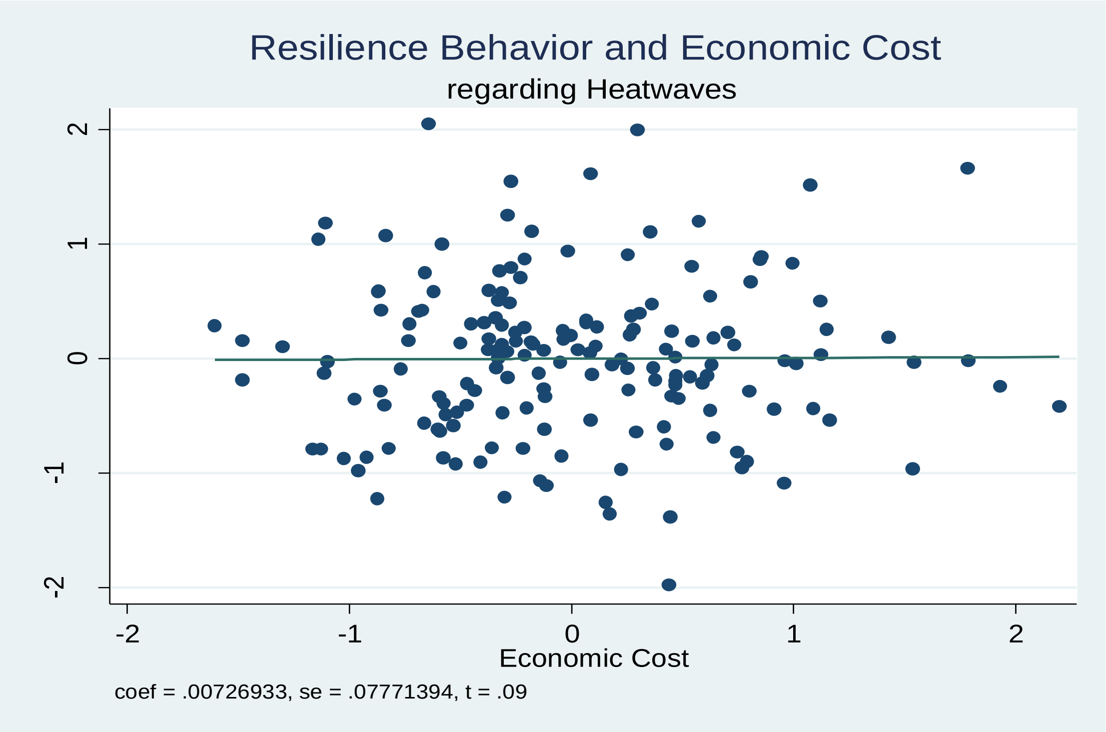

Figure 5.2: Resilience Behaviour and Economic Cost

In Figure 5.3 the scatter plots in access to information are not closely represent the line as compared to perception, but since its t value is significant, there is evidence that access to information has positive effect on resilience behaviour.

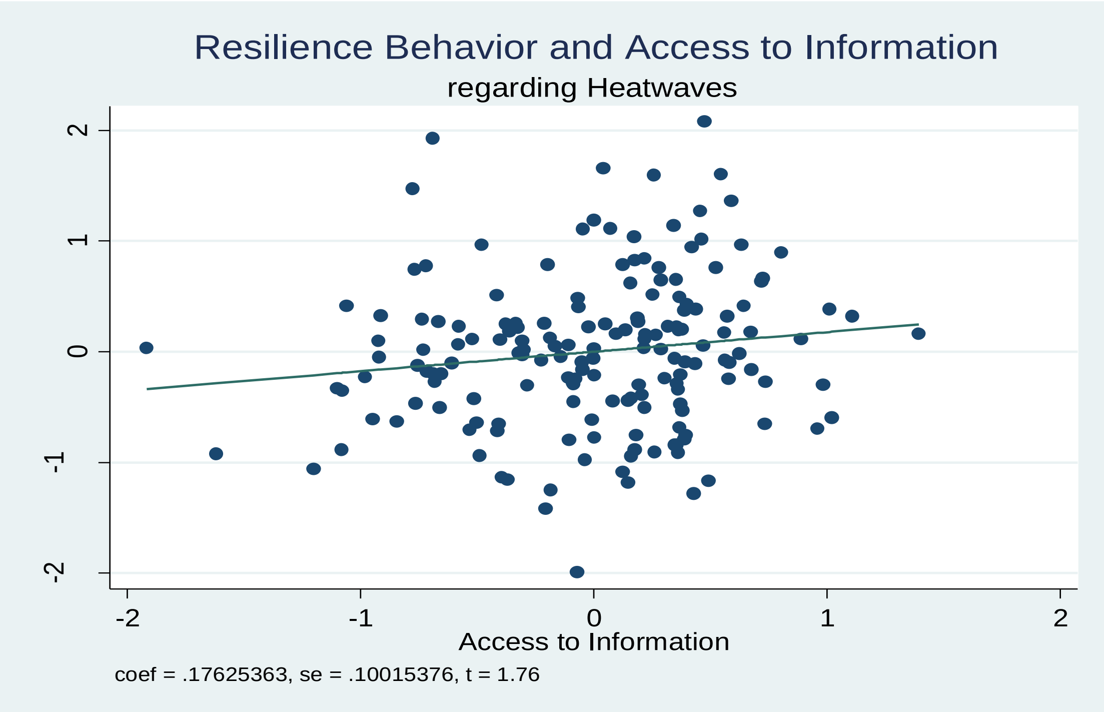

Figure 5.3: Resilience Behaviour and Access to Information

Further the scatter dots are closely following the line, confirming the positive effect of age on resilience behaviour.

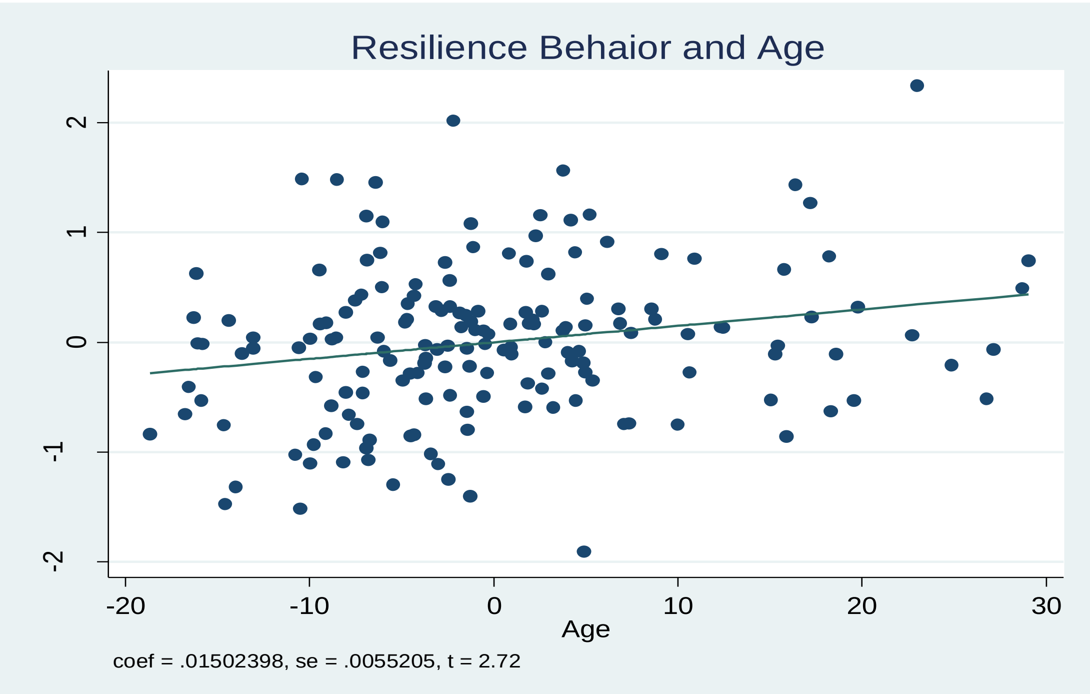

Figure 5.4: Resilience Behaviour and Age

5.6 Discussion

It is a surprising fact that the marginal effects of demographics are found to be smaller than the independent index forms used. The effect size indicates that all demographics variables (AGE, HS, EDU) and the location dummies are explaining 27% changes in the dependent variable while the independent variables (ECO, ACC, PREC and cross-product) are jointly explaining 6.9% changes in the dependent variable. A possible explanation for this is the differences in the variation of the demographic related variables and the independent variables, as standard deviation of AGE, HS and EDU are 10.33, 3.35, and 1.32 while the standard deviation of PERC, ECO, BEH and ACC are 0.85, 0.90, 0.93 and 0.79 respectively.

6. Conclusion

Climate change have assumed a universal problem both for the developed and developing economies via its effects on optimal utilization of physical and natural resources and reduction in human power capabilities. The economic growth rates have been impinges with its consequences on the peoples' health and general welfare. There is no country and region across the world, which have remained unaffected from climate change. Pakistan, developing country, has been affected severely and the situation is forecasted to aggravate in future.

The Inter-government Panel on Climate Change (IPCC), in its Fifth Assessment Report, identified heat waves as the key climatic events, which will pose threats to infrastructure, economic growth, the people, and livelihood. This threat is particularly grave in South Asia region where economies are dependent solely on agriculture, which are sensitive to weather heat waves. The vulnerabilities of climate change are more in quantum to Pakistan's agriculture. The fast pace of urbanization, the recurrent heat waves, in particular over the last three years have caused fatal incidents of precious human lives. This discourse in perspective, the study in hand have examines the factors that determine the resilience behaviour of people to combat with the heat waves in urban habitats in the country.

The higher the age, the higher the resilience power. Resilience behaviour of people increases with age. It reveals that learning and experience of the past plays an important role in determining resilience behaviour. Within demographic index, the variable of age is found to be positive and significant, where, age is used as proxy of heat wave experience and learning.

It is also revealed that level of education is one the important factors which determines the path and level to combat the heat waves. This variable, however, is found to be insignificant. People could be more resilient with higher education but heat waves hit the people across age, gender, and education. Moreover, the education system may not have the capacity required to transfer resilience and abatement skills against climate change

With the increase in household size, the combating behaviour of people to cope with heat waves decreases. It is found to be a significant variable as well. As a big chunk of Pakistan's[5] population is living under poverty line, the educated guess shows that resilience will become costly with increase in household size.

More access to information will lead towards more resilient behaviour of people towards heat waves. The positive effect of access to information on resilience has been obtained from the respondents by using internet services. The access to internet facilitates the people to comprehend the gravity of heat waves. In other words, the people become conscious and aware of the adverse effects of heat waves and may adopt measure to combat in an effective way. It shows the trust of respondents on the source of information i.e. internet facility and they respond effectively to early warning system then. Perception index including prior knowledge of heat waves will enhance the resilience behaviour, which is found to be

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[5] https://profit.pakistantoday.com.pk/2018/04/26/pakistans-percentage-of-people-living-below-poverty-line-falls-to-24-3-percent-economic-survey-2018/

significant as well. Therefore, access to information is referred to as catalyst variable and it plays a complementary role to perception of heat waves as well.

The study has revealed that the marginal effects (dy/dx) of demographics are found to be smaller than the independent index forms used. The effect size indicates that all demographics variables (AGE, HS, EDU) and the location dummies are explaining 27% changes in the dependent variable while the independent variables (ECO, ACC, PREC and cross-product) are jointly explaining 6.9% changes in the dependent variable. A plausible explanation for this is the differences in the variation of the demographic related variables and the independent variables[6], as standard deviation of AGE, HS and EDU are 10.33, 3.35, and 1.32 while the standard deviation of PERC, ECO, BEH and ACC are 0.85, 0.90, 0.93 and 0.79 respectively. Hence, regression analysis has compensated for high variation in demographic variables by notifying smaller slope coefficients, but as partial R squares indicate in table 5.3, control variables contribute a larger portion in changes in resilience behaviour.

A distinguished revelation is that women are prone to heat wave more than males.

While analysing the effect of location dummies (cities) on the resilience behaviour to heat waves, it is evident that cities which have low-income give attention to resilience to the heat wave and their behaviour is found to be resilient as well. The impact of heat waves in cities which have a comparative lower income households are more vulnerable to negative effects resulting from the decrees in purchasing power of money.

7. Policy Implications

The study has brought out that perception index is highly significant in determining heat wave resilience which is moderated by access to information. Within the information index, internet is found to be positively significant as well as complements in determining the

[6] Δ demographic variables > Δ independent variables.

overall perception of heat waves. Internet is recommended for early warning and also dissemination of information regarding heat waves.

Age is used as proxy of learning and experience. Higher age is showing high level of resilience. Learning and experience of the youth can be enhanced through “heat wave” drills in urban centres of the country, in particular for the people with little experience to combat heat waves.

As said the “small is beautiful”, the lesser number of household members can manage during heat waves more effectively. This will require population welfare program implementation in letter and spirit as supporting policy to heat wave resilience.

Location dummies (cities) also capture the income inequality in comparatively rich and poor cities for resilient behaviour of heat waves. The same degree of heat wave will inflict more cost to low-income city residents. Therefore, low-income cities and the people should be given high priority while drawing heat wave resilient policies.

Policy makers and economic planners will need to develop policies to increase resilience of people in urban centres of Pakistan to minimize its impacts through dissemination and an effective early warning system, namely internet. Heat wave drills in urban centres (especially for the lower age groups), size of small households especially in low income cities. These policy measures will augment resilience of heat waves which will accrue benefits of cost effectives to the economy. It is recommended that policy planning be focused more on females as they are more vulnerable and managers who control household chores.

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Appendix A

Survey Questionnaire

The aim of the study is to analyze the human behavior towards heat wave perception in major cities of Pakistan. Any material from this data will not be reproduced or used for any commercial purposes. Please, do not use lead pencils for this survey.

Date: _______ Sr. no.: ____________

City: ________ Locality: ___________

1. Demographics	
1.1 Age	_____________ years
1.2 Gender	0 = Female 1 = Male
1.3 number of people living in household	_____________
1.4 education level	0 = illiterate 1 = primary 2 = middle 3 = matriculation 4 = intermediate 5 = baccalaureate 6 = masters 7 = doctorate 8 = any other state _________
1.5 Education level of parents	0 = illiterate 1 = primary 2 = middle 3 = matriculation 4 = intermediate 5 = baccalaureate 6 = masters 7 = doctorate 8 = any other: state _________
1.6 occupation	0 = self employed 1 = manager 2 = other white-collar 3 = manual worker

2. **Access to information**	
2.1 Do you have access to telephone or mobile phone?	0 = no 1 = yes
2.2 Do you have access to internet at home?	0 = no 1 = yes
2.3 Do you have access to newspaper?	0 = no 1 = yes
2.4 Do you have access to television?	0 = no 1 = yes
2.5 Have you ever received/noticed early warning information via any of the information source about heat wave?	0 = no 1 = yes
2.6 Have your peers (neighbors, colleagues at work place, friends) ever shared information about heat wave and its consequences?	0 = no 1 = yes

	4 = house person / house wife 5 = unemployed 6 = retired 7 = student 8 = any other: state ________
1.7 What is your status of purchasing power during past 5 years	1 = improved 2 = stayed the same 3 = got worse

3. **Perception about heat wave**	
3.1 Occurrence of heat wave is an unstoppable activity due to Climate Change	1 = Strongly agree 2 = Agree 3 = Don't know 4 = Disagree 5 = Strongly Disagree
3.2 perceived level of heat wave activity as compared to last 5 years	1 = happened too much 2 = moderate 3 = not happened much
3.3 heat wave is perceived to be a serious problem of Pakistan	1 = Strongly agree 2 = Agree 3= Don't know 4 = Disagree 5 = Strongly disagree
3.4 On average, how much more (percent of household expenditures) electricity bills you have to pay during the time of heat wave? On cooling: fans, desert coolers, air condition etc.	0= no 1 = 1 – 5% 2 = 6 – 10% 3 = 11 – 20% 4 = 21 – 30% 5 = 31 – 40% 6 = 41 – 50% 7 = 51 % +
3.5 Do you think that monthly expenditures on health have changed during summer months because of heat waves as compared to last 5 years?	1 = increased 2 = stayed the same 3 = decreased
3.6 Do you think that impact of heat wave exaggerates in congested areas of the city?	1 = Strongly agree 2= Agree 3= Don't know 4= Disagree 5= Strongly Disagree

4. **Economic indicators**			
For each category state whether there is any change due to **heat wave** occurrence as compared to last 5 years			
	increased	Stayed the same	Decreased
Expenditure on precautionary measures			
Expenditure on medicine			
Expenditures on visit to doctors			
Expenditures on clothing			
Expenditures on transport			
Expenditures on cooling			
Expenditures on safe drinking water/more liquid intake			
Days off due to heat wave occurrence			
Loss of human life: family, neighborhood, workplace			

5. **Behavior regarding Heat Wave Resilience**	
6.1 do you respond to the information provided by the early warning system to reduce the impact of heat waves?	1= never used 2= occasionally 3= every time
6.2 do you prepare yourself or take any precautionary measures for heat waves?	1= never used 2= occasionally 3= every time
6.3 do you participate in the public tree plantation campaigns?	1= never used 2= occasionally 3= every time
6.4 do you have any type of financial / life insurance?[7]	0 = no 1 = yes
6.5 In elections, do you cast your vote to a political party after getting information about climate change policies prescribed in its manifesto?	0=no 1=yes

Appendix – A

The future climate scenarios used in this study are taken from NASA Earth Exchange (NEX) Global Daily Downscaled Projections (GDDP) datasets.

The NEX-GDDP dataset is comprised of downscaled climate scenarios for the globe that are derived from the General Circulation Model (GCM) runs conducted under the Coupled Model Intercomparison Project Phase 5 (CMIP5) [11] and across two of the four greenhouse gas emissions scenarios known as Representative Concentration Pathways (RCPs)[12]. The CMIP5 GCM runs were developed in support of the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC AR5). This dataset includes downscaled projections from the 21 models and scenarios for which daily scenarios were produced and distributed under CMIP5. The purpose of these datasets is to provide a set of global, high resolution, bias-corrected climate change projections that can be used to evaluate climate change impacts on processes that are sensitive to finer-scale climate gradients and the effects of local topography on climate conditions.

In NEX-GDDP 42 climate projections from 21 CMIP5 GCM simulations and two RCP scenarios (RCP 4.5 and RCP 8.5) are compiled. Each of the climate projections includes daily maximum temperature (K), minimum temperature (K), and precipitation ($Kgm^{-2}s^{-1}$) for the periods from 1950 through 2005 ("Retrospective Run") and from 2006 to 2100 ("Prospective Run") at 0.25-degree (Daily from 1950-01-01 00:00:00 to 2100-12-31 11:59:59). During the downscaling process, the retrospective simulations served as the training data, and was compared against the observational climate records. The relationships derived from the comparison are then applied to downscale the prospective climate projections.

Table 3. CMIP5 models included in GDDP dataset.

ACCESS1-0	CSIRO-MK3-6-0	MIROC-ESM
BCC-CSM1-1	GFDL-CM3	MIROC-ESM-CHEM
BNU-ESM	GFDL-ESM2G	MIROC5
CanESM2	GFDL-ESM2M	MPI-ESM-LR
CCSM4	INMCM4	MPI-ESM-MR
CESM1-BGC	IPSL-CM5A-LR	MRI-CGCM3
CNRM-CM5	IPSL-CM5A-MR	NorESM1-M

Dataset URL: https://nex.nasa.gov/nex/projects/1356/.

Data access URL: https://cds.nccs.nasa.gov/nex-gddp/.

Appendix – B

Table 4. List of ETCCDMI core Climate Indices.

ID	Indicator name	Definitions	UNITS
FD0	Frost days	Annual count when TN(daily minimum)<0ºC	Days
SU25	Summer days	Annual count when TX(daily maximum)>25ºC	Days
ID0	Ice days	Annual count when TX(daily maximum)<0ºC	Days
TR20	Tropical nights	Annual count when TN(daily minimum)>20ºC	Days
GSL	Growing season Length	Annual (1st Jan to 31st Dec in NH, 1st July to 30th June in SH) count between first span of at least 6 days with TG>5ºC and first span after July 1 (January 1 in SH) of 6 days with TG<5ºC	Days
TXx	Max Tmax	Monthly maximum value of daily maximum temp	ºC
TNx	Max Tmin	Monthly maximum value of daily minimum temp	ºC
TXn	Min Tmax	Monthly minimum value of daily maximum temp	ºC
TNn	Min Tmin	Monthly minimum value of daily minimum temp	ºC
TN10p	Cool nights	Percentage of days when TN<10th percentile	Days
TX10p	Cool days	Percentage of days when TX<10th percentile	Days
TN90p	Warm nights	Percentage of days when TN>90th percentile	Days
TX90p	Warm days	Percentage of days when TX>90th percentile	Days
WSDI	Warm spell duration indicator	Annual count of days with at least 5 consecutive days when TX>90th percentile	Days
R10	Number of heavy precipitation days	Annual count of days when PRCP>=10mm	Days
R20	Number of very heavy precipitation days	Annual count of days when PRCP>=20mm	Days
R95p	Very wet days	Annual total PRCP when RR>95th percentile	mm
R99p	Extremely wet days	Annual total PRCP when RR>99th percentile	mm
PRCPTOT	Annual total wet-day precipitation	Annual total PRCP in wet days (RR>=1mm)	mm