Exploring the Impact of Climate Change and Atmospheric Oxidant on Crop Productivity in Pakistan

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It is certified that the contents and form of the thesis entitled

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DEDICATION

This thesis is dedicated to my loving family, especially my father & mother.

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List of Abbreviations

AR5	Assessment Report Five
CCSM4	Community Climate System Model Version 4
CH_4	Methane
CO	Carbon Monoxide
CO_2	Carbon Dioxide
DU	Dobson Unit
FAO	UN Food & Agriculture Organization
GDP	Gross Domestic Product
GHGs	Greenhouse Gases
GoP	Government of Pakistan
IPCC	Inter-governmental Panel on Climate Change
MLS	Microwave Limb Sounder
NMVOCs	Non-Methane Volatile Organic Compounds
NOx	Nitrogen Oxides
O_3	Ozone
OMI	Ozone Monitoring Instrument
PBS	Pakistan Bureau of Statistics
PMD	Pakistan Meteorological Department
PSRSP	Pakistan Rural Support Program
RCP	Representative Concentration Pathways
SRES	Special Report on Emissions Scenarios
TCO	Tropospheric Ozone Column
TOR	Tropospheric Ozone Residual

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Abstract

Pakistan is highly vulnerable to climate change and extreme weather events, both spatially and inherently. Considering the country's high dependence on agricultural products, to support the economy and a growing population, it is vital to gauge factors impacting the crop productivity. This study quantifies the change in temperature, precipitation and tropospheric ozone, overt the study region. Coupled with their respective effects, on productivity of three major crops; wheat, rice and cotton, within two of Pakistan's largest provinces: Punjab and Sindh. Based on the primary and secondary data, multivariate regression analysis is conducted. Moreover, highly vulnerable areas to climate change have been identified under RCP scenarios 4.5 and 8.5, till the end of this century. Results reveal a substantial increasing trend in temperature, whereas precipitation has high inter–annual variability. Tropospheric ozone concentrations; especially, in rice and cotton growing seasons observe rigorous upsurge. Regression results, based on fixed/random effects models, indicate that temperature above threshold values: 24.3°C, 33.0°C, 32.0°C for wheat, rice and cotton, respectively, negatively impacts productivity (statistically significant). Precipitation is statistically insignificant in explaining its impact on crop productivity. Tropospheric ozone adversely effects rice and cotton productivity, whereas its effect on wheat crop productivity is statistically insignificant. Overall, the region is heading towards temperature & pollution threshold exceedances at an alarming rate, which will impact the overall availability of suitable crop growing areas.

Chapter 1: Introduction

1.1. Background

Pakistan is an agrarian backed economy, which has a place amongst the top ten agro-based producers in the world (Rehman *et al.,* 2015). The country is among the world's top ten producers of wheat, cotton, sugarcane, and holds the thirteenth position in rice production. Wheat, rice, cotton and sugarcane contributes 6.5 %, while other minor crops amount to 2.3 % of the country's GDP. Furthermore, 43% of the country's workforce is currently employed in the agriculture sector (FAO, 2015). Despite Pakistan's efforts to increase agricultural production, the country is struggling with significant levels of food insecurity. According to World Food Programme (2009), more than 48 % of the population is food insecure, with approximately 41.4 million under-nourished people. Therefore, agriculture will plays a critical role with regards to both the food security and socioeconomic welfare of the country.

Concurrently, Pakistan ranked on the seventh position of the 'most vulnerable countries to climate change' (German Watch, 2017). This position entails numerous salient features, such as frequent extreme weather events, rise in sea levels, potential melting of glaciers, erratic patterns of temperature and precipitation. All these are forecasted to impact crop productivity coupled with economic instability, climate induced health hazards and increased pressure on resources. The most prominent impact of climate change is expected to be on the agriculture and fisheries sectors (IPCC, 2012).

This current research essentially focuses on evidence from past studies, data on agricultural production, temperature, precipitation and tropospheric ozone in particular will be analysed; thus, verifying the relationship between change in climatic variables, and/or pollutant (tropospheric ozone) concentration, degree and measure of change in yield. Long term historical crop yield data from the PBS, data of temperature and precipitation retrieved from Pakistan Metrological Department, whereas tropospheric ozone concentration inventory (satellite based) over Pakistan will be collated from past researches undertaken in IESE – NUST. This will allow the exploration of the relationship between both the individual and synergistic climate and pollutant variables against historical crop yield. Thus, allowing the calculation of thresholds, and change in crop productivity in the presence of observed climate change and tropospheric ozone concentrations.

1.2. Study Area

The regions under study are the wheat, rice and cotton growing districts of Punjab & Sindh as depicted in Fig 1.1. These crops are mainly divided into two seasons of cultivation. *Kharif,* (summer crops), and *Rabi* (winter crops). 16.68 million hectares of the province of Punjab is under cultivation; contributing to 83% cotton, 76 % rice (97% of fine aromatic Basmati), and 80% wheat in the agriculture economy (GoP, 2018). Whereas, the total cropped area of Sindh amounts to 3.10 million

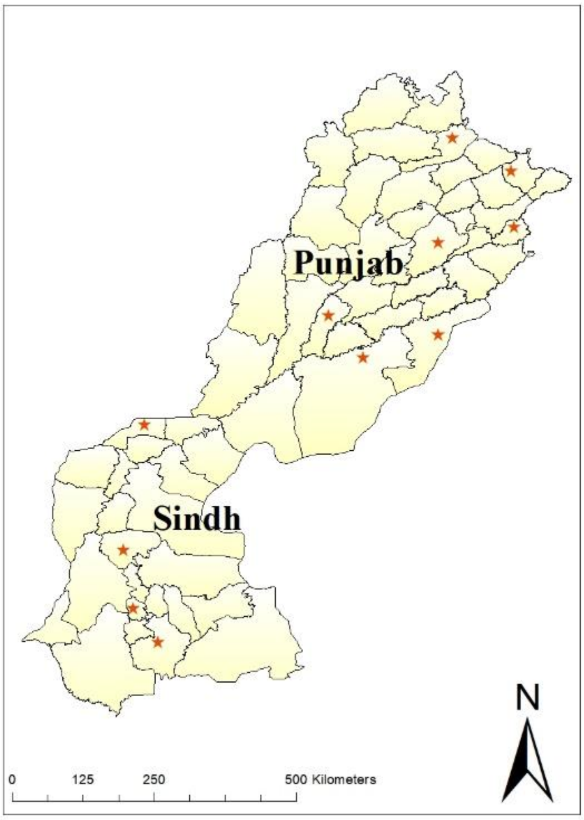


Figure 1.1: Study area map, districts under study are denoted with a star.

hectares. Of the total output in Pakistan, Sindh produces 35% of the rice, 12% of wheat, and 20% of the cotton (USDA, 2015). The two provinces are primarily divided into three climatic zones namely Mild Cold, Dry & Hot, and Arid to Hyper-arid (Qasim *et al.*, 2014, Haider *et al.*, 2016). The diversity in the climate allows a number of crops to be cultivated, across different districts and months. This diversity also entails varied conditions, and response to stressors.

1.3. Justification for Selection of Study

As stated in the previous section, Pakistan is highly vulnerable to the effects of climate change. The evidence is clear from the greater frequency of extreme events such as 2010 flooding, 2015 heat waves, unpredictable rainfall patterns, glacial melting, etc. The inconsistency and deviation of climate variables from the norm, presents a problem, especially for a country that although termed an agrarian economy, predominantly falls in the arid and semi-arid category. Thus, temperature and rainfall play a critical role in the behaviour of agricultural production.

Along with climate variables the study also assesses the effect of air pollution on agriculture, specifically tropospheric ozone. Tropospheric ozone is a pervasive secondary air pollutant, it occurs when carbon monoxide, oxides of nitrogen, methane, along with non-methane volatile organic compounds, react in the atmosphere in the presence of sunlight. It contributes to the greenhouse gas effect, with a forcing of approximately 24% that of carbon dioxide (Ramaswamy *et al.*, 2001). Rapid growth in anthropogenic emissions as a result of development (industry, vehicular emissions) has been largely responsible for the surge in tropospheric ozone. Coupled to its ability to contribute to change in climate, it is notorious in its impact to crop health and productivity (W.L. Chameide *et al.*, 1999).

It is therefore, of paramount importance that the impact of both climate change and air pollutants such as tropospheric ozone is examined with respect to crop yield in Pakistan. Additionally, explore the synergetic effect of the two, allowing a contribution to the base of knowledge, on which future policies and adaptive strategies can be designed.

1.4.Relevance of proposed study to national needs

When conducting research, it is important to identify the relevance and gaps it will fill, in the face of national needs. Enlisted below are identified requirements:

1. “Pakistan is a major rice exporter and annually exports about 2 million tons, or about 10 percent of world trade” (Abdul Rehman *et al.*, 2015). Impacts on crop yield due to pollution or climate change may impact the country’s ability to do so; proper knowledge is crucial.
2. Pakistan is generally classified as arid to semi-arid, due to the insufficiency in rainfall for growth of agricultural crops (FAO). Therefore, in order for profitable agricultural production supplemental water is required, through irrigation or water harvesting. Erratic weather patterns, may impact the supply of both ample rain and irrigation supplies.
3. Pakistan’s population is growing at a high rate (Pakistan Bureau of Statistics), and food insecurity is a major concern (FAO, 2015). In order to ensure that the food production and population gap remains narrow.
4. Rural economy is heavily dependent upon agriculture, both directly & indirectly (PSRP, 2013).

5. In spite of high prices for agri-products, the profitability has not improved in this sector as costs of production continue to rise. Leading to a lack of facilities for small farmers (PSRP II, 2016). Further stress, especially on small farmers may prove detrimental.
6. "Low yields, low productivity of water, non-reliability of water services, under-performance of rural factor markets and under-investment in research and technology development" (PRSP, 2003) are all major issues facing Pakistan's agriculture sector. This research can aid in the opening of the proposed uncertainties, to ensure timely forecasts.

1.5.Significance of Study

The results of the study will impact the following aspects:

1. Agriculture 47% of the national employed labour force, and contributes 24 % of the gross domestic product (FAO, 2015). Thus, understanding the future prospects of future crop productivity is essential.
2. This study will highlight the crucial effects of tropospheric ozone and climate change on crop productivity in various major agriculture districts of Pakistan.
3. It will forecast crop behaviour in order to monitor changes and suggest interventions.
4. Considering the growing population and development of Pakistan and the continued high levels of air pollution, this study will substantiate the urgency of air pollution abatement strategies.
5. The results will enable policy-makers and decision-makers to design relevant adaptation and mitigation strategies, especially to create awareness/ train farmers.
6. Further it will aid in setting a precedent for other studies.

1.6 Objectives:

1. To identify & assess the change in climate variables (temperature and precipitation) in Pakistan.
2. To investigate plausible impacts of climate change variables on agriculture crop productivity in Pakistan.
3. To explore the linkage between climate change, tropospheric ozone and crop productivity.

Chapter 2: Literature Review

2.1. Climate change

Climate change is generally defined as ‘change in the statistical distribution of weather patterns, when that change lasts for an extended period of time.’ Climate has been changing continuously throughout Earth’s history (NASA, 2018). The system operates in presence of numerous natural and anthropogenic interactions (see, figure 2.1). The current warming trend is peculiar in its nature as it is extremely likely (95 percentile) the result of human activity with the advent of mid-twentieth century, moreover the warming is proceeding at a relentless rate (NASA, 2018).

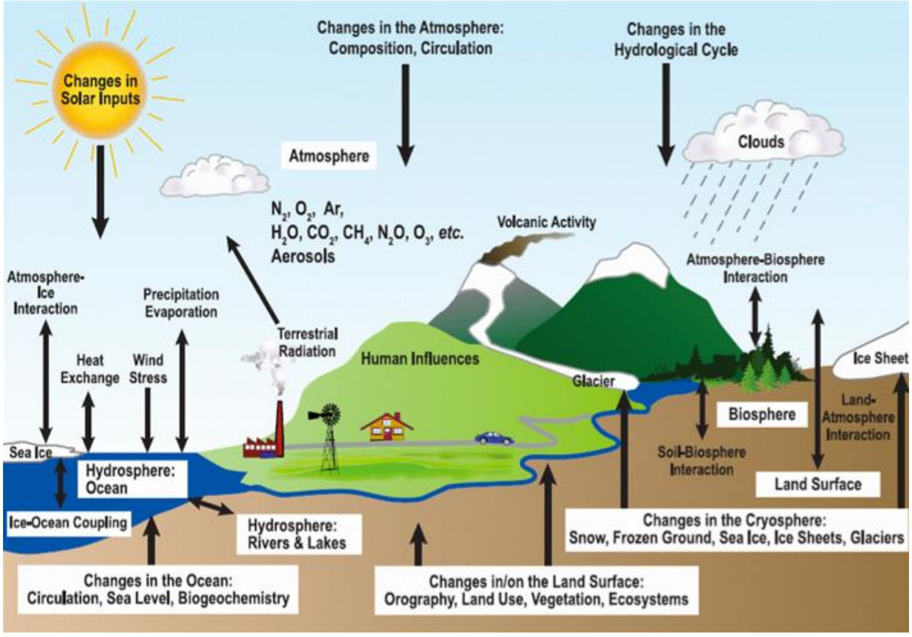


Figure 2.1: Components & interactions of a climatic system (Source: IPCC, 2007)

The Fifth Assessment report of IPCC (AR5), reports that despite the global efforts of reduction in greenhouse gas emissions, the level of GHGs in the atmosphere continue to increase exponentially. Within the 21st century, global climate models suggest a rise of 0.3 °C to 1.7°C (low emission scenario), and 2.6°C to 4.8°C (emission intensive scenario).

The AR5 introduced scenarios known as Representation Concentration Pathways (RCPs), which proceed the SRES. As the name suggests the RCPs represent a varied range of probable future-settings in terms of anthropogenic greenhouse gas emissions globally (Table 2.1).

Table 2.1: Detailed description of IPCC's Representative Concentration Pathways

Name	Radiative Forcing in 2100	Pathway	Behaviour of GHG emissions Globally (measured in CO_2 equivalents/year)
2.6	2.6 Wm^2	Peak and decline	Emission peaks between 2010–2020, with a decline substantially thereafter
4.5	4.5 Wm^2	Stabilization without overshoot	Emission peak around 2040, then decline
6.0	6 Wm^2	Stabilization without overshoot	Emissions peak by 2080, then decline.
8.5	8.5 Wm^2	Rising	Emissions carry on rising all through the 21st century

Source: Meinshausen, M.; *et al.* (2011), IPCC (2015)

This particular study works with RCP 4.5 (stabilization scenario), and 8.5 (extreme scenario), the details are as below:

(i) RCP 4.5 as mentioned in Table 2.1 is the stabilization scenario. Within this scenario the accumulative radiative forcing levels off soon after 2100; as it peaks mid-century 2040 – 2050 (50% higher than 2000 levels), after which it begins to descend. It remains within the limits of the "long-run radiative forcing target level" **(**Smith& Wigley 2006, Wise *et al.,* 2009)**.**

Carbon dioxide concentration stays on trend to approximately 520 ppm (by 2070), continuing to increase, rather sluggishly. The scenario works on the basis of a model capturing a state of moderate population, economic growth, and energy consumption (fairly constant petroleum consumption) throughout the century. Coupled with a significantly declining crop land area, and increasing reforested natural vegetation.

(ii) RCP 8.5 is categorized as a ‘worst-case’ scenario, with growing greenhouse gas emissions throughout the century, especially in early and mid - 21st century (Riahi *et al.* 2007). CO_2 concentration in the atmosphere will rapidly reach 950 ppm by the 2100 mark tipping into the next century, with a similar pattern. The RCP 8.5 scenario embodies a high population growth, unbalanced economic growth with considerably lower incomes, and GDP in less developed countries. It describes a high consumption of energy (3 times current levels); with intensive use of oil (until 2070) and coal (bulk contribution). Land use carry on existing trends with increasing crop areas, and depleting forested areas.

Less developed nations such as Pakistan are relatively more susceptible to the damaging impacts of climate change compared to developed countries (IPCC, 2013). According to Asian Development Bank’s 2017 report on climate change in Pakistan, the yearly rainfall has shown unpredictability historically, however the last five decades show a relative increase. The number of heatwave days per year has increased 5-folds in the past 30 years. Annually, the mean temperature is estimated to grow by 3 to 5 degrees for stabilizing scenarios (RCP 4.5). Whereas, for scenarios with high powered global emissions (RCP 8.5), the rise could be up to 4 to 5°C. Annual rainfall on average is expected to continue to exhibit inter-annual variability, however a long-term trend cannot be captured. By the conclusion of this century the sea-level is predicted to rise a further 60 centimetres, likely affecting low-lying coastal areas and the Indus delta.

Pakistan is expected to experience increased variability of river flows resulting from increased unpredictability of precipitation and glacial melting. Furthermore, irrigation water demand may increase, from higher evaporation rates. Future temperature projections show a warming trend of 1.5 to 5 °C rise in temperature by the end of the 21st century (Haider *et al.,* 2016).

2.2. Impact of climate change on agricultural crop productivity

Climate plays a pivotal role in the growth and total productivity of crops. Each crop has certain threshold or requirement of climatic conditions, in which they optimally grow. Thus, change in the temperature, precipitation, humidity, solar radiation can affect the crop sowing and harvesting dates, the duration of growing season, and overall yield and health of the crops (Iqbal *et al.,* 2009).

Demand for food crops is expected to approximately double globally, towards the mid – 21st century. This is mainly due to the growth in population, and a gradual shift to westernized diets even in the developing countries. Regardless of the upkeep of the agricultural productivity with advancement in technology, better varieties of seeds, and policy measures, future productivity may still face decline due to sensitivity to both air pollution and climate change.

Various major crops can be damaged due to extremes in average temperature. Agricultural regions are projected to respond differently to change in climate, with some areas experiencing an increase in crop yields, whilst others a decrease. This may be attributed to the latitude, agro climatic conditions and irrigation application system (Kang *et al.,* 2009, Hussain & Bangash 2017). Likewise, different stages of crop growth may also react differently to change in climatic conditions (Siddiqui *et al.,* 2016).

This change in conditions not only threatens the ample food supply but also impacts the agricultural farm revenues Rise in temperature and rainfall have converse impacts on agricultural revenues; positively with respect to rainfall and negatively with temperature (Shakoor *et al.*, 2011). Thus, largely past studies conclude and emphasize, the need for adaption and mitigation measures to enhance the pros and avoid the cons of change in climate.

2.3. Tropospheric Ozone & its impact on productivity of crops

Tropospheric Ozone is a secondary pollutant that forms as a result of precursory emissions, mainly NOx, NMVOCs, CO and CH_4. According to US Environmental Protection Agency, tropospheric ozone is one of the criteria pollutants; leading to harmful impacts on human & plant health (Chameides *et al.,* 1999). Surface ozone, arising from precursor emissions from anthropogenic activities, is phytotoxic and thus detrimental to crop productivity (Tai *et al.*, 2014). It continues to become a major cause of concern globally due to increase in precursor emission, and proceeding photochemical oxidation (Klumpp *et al.*, 2006). In terms of plants/ crops tropospheric ozone (Delfino *et al.*, 1998, Wahid, 2006, Rai & Agarwal 2012):

i. Reduces photosynthesis, along with decreased stomatal conductance and response.
ii. Slow the plant's growth: By decreased biomass accumulation, altered reproduction, carbon allocation and overall quality
iii. Alteration of leaf senescence, and chemical composition.
iv. Increase sensitive plants' risk to disease, pest attacks, impact of other plants & changing climatic conditions.

v. Below-ground (soil): altered litter production & decomposition. Impacting the nutrient cycling.

Simplified Formation of Tropospheric Ozone (Lagzi *et al.*, 2013)

1. Nitrous Oxide synthesises in an internal combustion engine (Pressure & Temperature):

$$\mathrm{N_2 + O_2 \rightarrow 2NO}$$

2. Oxidation of nitrous oxide to nitrogen oxide:

$$\mathrm{2NO + O_2 \rightarrow 2NO_2}$$

3. Decomposition of nitrogen oxide by UV:

$$\mathrm{NO_2 + UV\ light\ (240\ nm) \rightarrow NO + O}$$

4. The activated oxygen atom forms ozone molecule by attaching to a diatomic oxygen molecule:

$$\mathrm{O + O_2 \rightarrow O_3}$$

Agricultural production is globally affected by high concentrations of tropospheric ozone. Rural areas experience elevated ozone levels for longer periods, potentially causing a wide variety of damage to various ecosystems. This results in a notable decrease in crop yields, especially in crops harvested in the winter (Wang et al., 2005; Mills et al., 2007). Estimates suggest that the range of relative loss in yield currently amount from 7–12 % to 36 – 50% in other areas for wheat, and 3–4 % for rice; 90 per cent of these losses have been reported to be the direct effect of air pollutants (specifically ozone precursors) (Wilkinson *et al.,* 2012, Tai *et al.,* 2014, Burney & Ramathan 2014).

2.4. Conclusion

Various different techniques have been applied over the years to represent the impact of air pollutants and climate variables both qualitatively and quantitatively. It is quite evident from the literature that tropospheric ozone has detrimental impact on plant health and productivity, whereas change in climate variables may positively or negatively impact different climatic zones and plants. Some crops are primarily sensitive to either ozone (e.g. cotton) or heat (e.g. maize). Therefore, future food production is at risk to both drastic changes in climate and air pollution with direct repercussions for global food security. In Pakistan, there is a dearth of studies exploring climate variables, and tropospheric ozone on crop productivity, especially using statistical models, which utilize actual observed production, climate and tropospheric ozone panel data.

The current study attempts to quantify the change in climate variables specifically in districts of Sindh and Punjab within wheat, rice and cotton crop growing season, furthering into the climate scenarios of representative concentration pathways 4.5 and 8.5. It explores the exact impact of average temperature and average precipitation on the crop productivity using an econometric regression model, with the help of historical observed data. Followed by identification of vulnerable crop growing regions. Providing the basis of impact quantification and thresholds for management of these major crops.

Chapter 3: Materials and Methodology

3.1.General Methodology

Climate data over the study area, specifically, variables temperature and precipitation, have been structured to the averaged growing season of the crops wheat, rice and cotton. Mainly focusing on the decade 2006 – 2016, in comparison to the baseline created over the years 1978 – 2005.

Furthermore, projections under the IPCC Fifth Assessment Report's representative concentration pathways 4.5 and 8.5 were also assessed and compared to observed data. Decadal change was measured till the end of the century, with respect to baseline.

Under the second objective, crop productivity data over districts of Sindh and Punjab was analysed. Including time-series and percentage relative change over the years. To explore the impact of temperature and precipitation on the historical production data a multivariate regression model was run. Similarly, tropospheric ozone data from 2005 – 2016 time-series data was analysed and run against crop productivity data, along with the temperature and precipitation variables.

3.2.Climate data

There were two different types of climate data (temperature (°C) and precipitation (mm)) that was utilized in the study:

i) Pakistan Meteorological Department Observatory Data:

Monthly Station-wise data from PMD weather stations across the study area, over the period of 1978 – 2016.

ii) Pakistan Meteorological Department Projected Model Data

The projected data acquired included a baseline period (1975 – 2005), along with forecasted data under the RCP 4.5 and 8.5 scenarios stretching from the year 2010 to 2100. The temperature and precipitation data used in this specific study has been statistically downscaled to a resolution of 25 km. The projections were made by the Numerical Modelling group of Research and Development Division, PMD, Islamabad, Pakistan using the 'Community Climate System Model', version 4 (CCSM4), under the IPCC Fifth Assessment Report (AR5).

The obtained raw data were arranged according to districts specific to the crops under study (Wheat, Rice and Cotton) using the 'Agriculture Cropping Pattern – Pakistan' mapped by FAO – ERCU Pakistan, 2012. The average crop growing season (months) were extracted from the total temperature and precipitation data using the crop calendar (FAO, 2012).

Table 3.1: District-wise Crop Calendar for Cotton Crop

District	Cultivation Dates	Growing Season	Harvest Dates
Faisalabad	May – Mid June	May – November	August to November
Bahawalnagar	May – Mid June	May – November	August to November
Multan	May – Mid June	May – November	August to November
Bahawalpur	May – Mid June	May – November	August to November
Hyderabad	April to May	April – November	August to November
Badin	April to May	April – November	August to November
S. Benazir Abad	May – Mid June	May – November	August to November

Table 3.2: District-wise Crop Calendar for Rice Crop

District	Cultivation Dates	Growing Season	Harvest Dates
Sialkot	June	June – November	October – November
Faisalabad	June	June – November	October – November
Bahawalnagar	June	June – November	October – November
Lahore	June	June – November	October – November
Bahawalpur	June	June – November	October – November
Multan	June	June – November	October – November
Jacobabad	Mid May - June	May – March	March

S. Benazir Abad	Mid May - June	May – March	March
Badin	May – Mid June	May – September	August - September
Hyderabad	May – Mid June	May – September	August - September

Table 3.3: District-wise Crop Calendar for Wheat Crop

District	Cultivation Dates	Growing Season	Harvest Dates
Jhelum	November-December	November – April	April
Lahore	November-December	November – April	April
Faisalabad	November-December	November – April	April
Bahawalnagar	November-December	November – April	April
Sialkot	November-December	November – April	April
Multan	November-December	November – April	April
Bahawalpur	November-December	November – April	April
Hyderabad	November-December	November – March	March
Jacobabad	November-December	November – April	March–April
S. Benazir Abad	November-December	November – April	March–April
Badin	November-December	November – March	March

3.3. Mann Kendall Trend Test

MK test allows a statistical perspective whether a trend is present in a time-series. The null hypothesis states; there is no trend, and alternative states there is a visible trend. This test is applied to all the variables assessed.

3.4. Error Analysis for Climate Model (CCSM4)

Error Analysis was conducted on the output of the CCSM4 model projections and observed real-time data for the time period of 1978 – 2005.

The average analysis included calculation of Root Mean Square Error and Mean Average Error. Below are the equations for the analysis respectively:

$$RMSE = \sqrt{\frac{1}{n}\sum_{i}^{n}\left(T_{(model)i} - T_{(observation)t}\right)^{2}}$$

$$\mathrm{MAE} = \frac{1}{n}\sum_{i=1}^{n}\left|T_{(model)i} - T_{(observation)t}\right|$$

'n' represents the number of observations.

Additionally, Mean Bias was calculated to gauge whether there is over/under estimation in the model output.

$$\text{MB} = \frac{1}{n}\sum_{i}^{n}(T_{(model)i} - T_{(observation)t})$$

If Mean Bias is negative, then the model is underestimating the values, in the case of a positive MB the model overestimates the values. Climatological mean for both temperature and precipitation over the time period 1978 – 2005 was mapped using Arc Map 10.3.1, under crop specific seasons.

3.5. Crop Productivity

Datasets for crop yield (kg) and cultivated area (hectares) over the study area was acquired from Pakistan Bureau of Statistics, and Directorate of Agriculture, Crop reporting Service, Punjab. For the following years:

i) Wheat, Rice & Cotton Crop Growing Districts of Punjab: 1981 – 2016

ii) Wheat, Rice & Cotton Crop Growing District of Sindh: 1981 – 2013

The regression model was run on pooled Punjab & Sindh districts, as well as separately according to agro-climatic zones:

Table 3.4: Climatic Zones of Punjab and Sindh (Salma et al. (2012))

Zone	Climate	Major Cities/Districts
B	Mild Cold	Lahore, Sialkot, Jhelum
D	Dry And Hot	Bahawalpur, Bahawalnagar, Multan, Faisalabad, Jacobabad
E	Arid to Hyper Arid	Hyderabad, Shaheed Benazir Abad, Badin

Prior to the computation of the impact of climate variables on crop productivity, data was fine-tuned by estimating missing data, using nearest neighbour method, and following tests were run to identify the reliability of data and specificity of the model to be used to undertake the analysis.

3.5.1. Harris-Tzavalis Unit Root Test

Test used for balanced datasets, showing whether there is a systematic pattern that is unpredictable in the series; a possible presence of a unit root.

H_0: Panels contains unit root

H_a: Panels are stationary

3.5.2. Pearson's Chi-Squared Test

Pearson's chi-squared test tests the freedom of variables, whether the relationship between two variables is significant. The null hypothesis of this test states that variables are independent of each other and any correlation is due to chance.

3.5.3. Ramsey Test

To test the specification of the model. The null hypothesis states that there is no misspecification in the model.

3.5.4. Haussmann Test:

Haussmann test checks the endogeneity of the data, that is whether the error term are correlated with the observed variables. The H_0 assumes that the favoured model is Random Effect (Green, 2008). Thus, it aids in selecting the correct model for the regression of the panel data in question, i.e. Fixed or Random Effect Model. Values less than 0.05 indicate that fixed is the correct choice, rejecting the null hypothesis (Torres-Reyna, 2007).

3.5.5. Fixed & Random Effects Model

Fixed effects essentially explores the relationship between predictor (independent) variable, and outcome (dependent) variables within an entity, in this case districts/zone. It eliminates the influence of time invariant features so we can assess the overall effect of the ‘observed variables’ on the dependent variable (Torres-Reyna, 2007). In contrast to the fixed-effects model, random effects assumes that disparity across entities is randomized and uncorrelated with the observed variables included.

Regression Model Overview

To carry out the impact exploration of climate and pollution variables on crop productivity, a multivariate econometric model was used; fixed/random effects.

$Y_{it} = \alpha_i + \beta_1(T) + \beta_2(P) + \epsilon_{it}$ Model I

$Y_{it} = \alpha_i + \beta_1(T) + \beta_2(P) + \beta_3(T^2) + \epsilon_{it}$ Model II

$Y_{it} = \alpha_i + \beta_1(T) + \beta_2(P) + \beta_3(P^2)\ \epsilon_{it}$ Model III

$Y_{it} = \alpha_i + \beta_1(T) + \beta_2(P) + \beta_3(O) + \epsilon_{it}$ Model IV

where,

α_i Constant term.

Y_{it} = Productivity in the i^{th} district for time period *t* (kg/hectare).

β: Measures the dependence of productivity on the climate variables.

T: Averaged temperature for crop growing season.

P: Average precipitation for crop growing season.

O: Average tropospheric ozone for crop growing season.

ϵ_{it}: Error terms.

3.6. Tropospheric Ozone

Global monthly mean tropospheric ozone columns captured during the time period 2005 – 2016, are assessed. Tropospheric ozone columns are derived by using tropospheric ozone residual (TOR) method; on the combined product of OMI and MLS datasets (Noreen *et al.*, 2018).

Tropospheric ozone column is extracted by subtracting the stratospheric ozone column (SCO) from MLS from total ozone column retrieved by OMI.

$$\text{TOC} = \text{TCO} - \text{SCO}$$

The data obtained were in Dobson Unit where:

$$1 \text{ DU of } TO_3 = 1.53 \text{ ppb of } TO_3 \text{ (IPCC, 2013)}$$

For use in this study the columns were converted to concentrations using the formula above, over the selected study areas in wheat, rice and cotton crop growing months.

Table 3.5: Software used in the research study

Sr no.	Software	Purpose
1	MS Excel	Refining raw data, creating time-series and graphical representations of data.
2	XLSTAT	Assessment of trends in time-series.
3	Arc Map 10.3.1 (ESRI, 2015)	Generation of climate maps.
4	Stata SE 14 (STATACorp., 2015)	Statistical modelling and diagnostic testing of data

3.7 Methodology Flow Chart

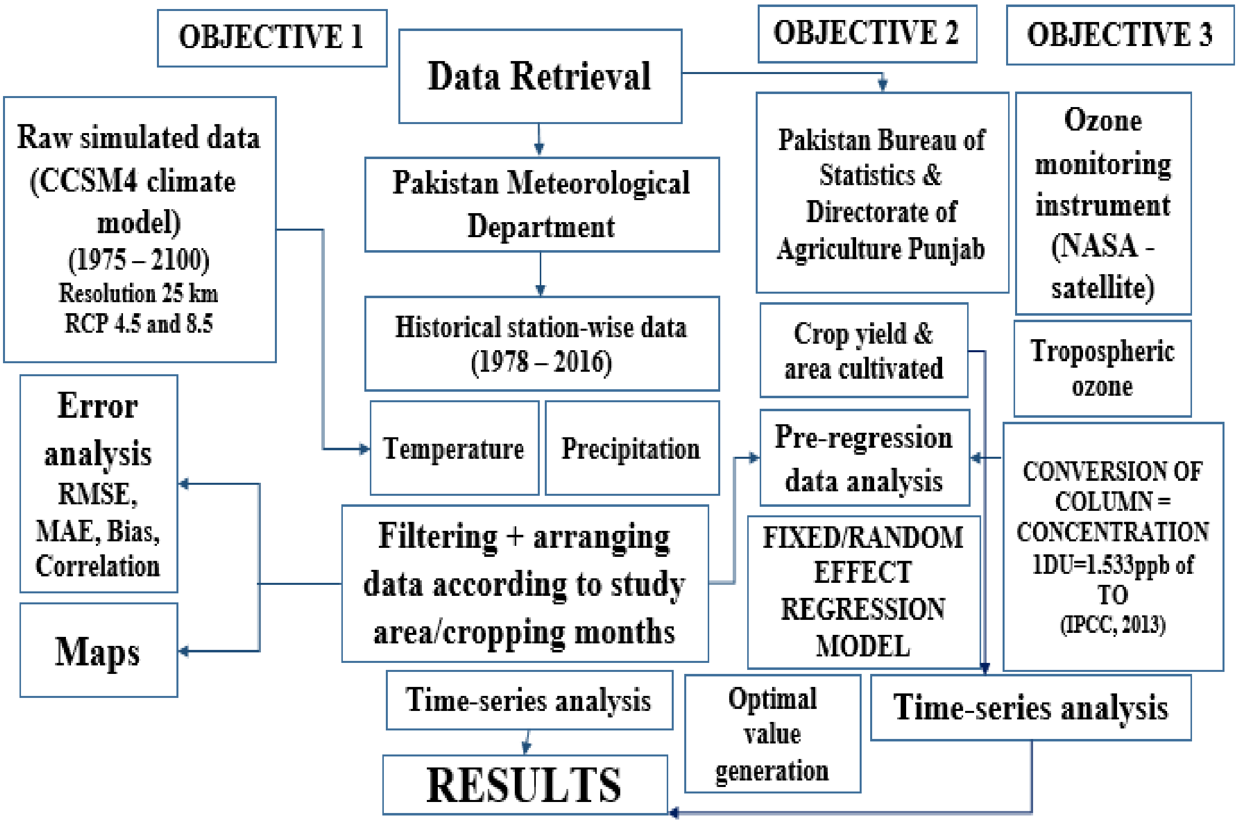


Figure 3.1: Detailed diagram of work plan

Chapter 4: Results & Discussion

4.1. Temporal analysis of average temperature and precipitation within wheat, rice and cotton growing season in selected climatic zones of Punjab & Sindh

Assessing the climate through the decade of 2006 – 2016, with respect to baseline period (1978 – 2005); the observed data from weather stations across the study area, was collated and divided into climatic zones (see methodology). Figures 4.1-4.3, are the climate graphs depicting the average temperature and precipitation over the specific crop growing season.

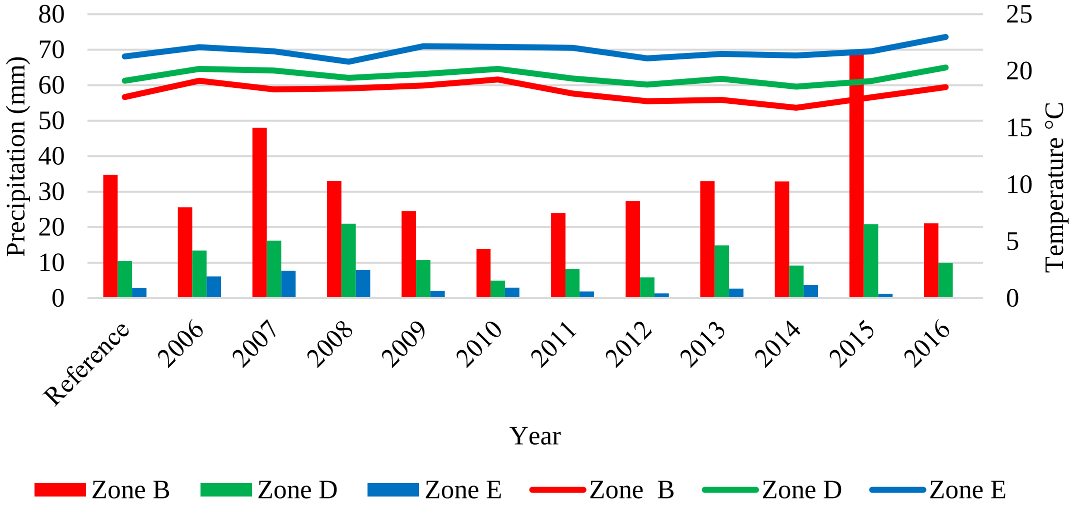


Figure 4.1: Zonal Average Climate in Wheat Crop Growing Season

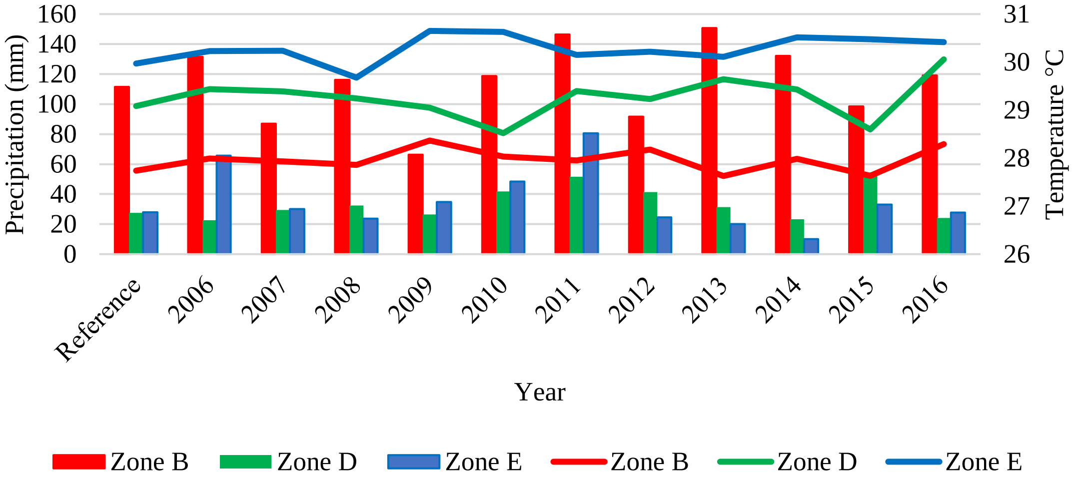


Figure 4.2: Zonal Average Climate in Rice Crop Growing Season

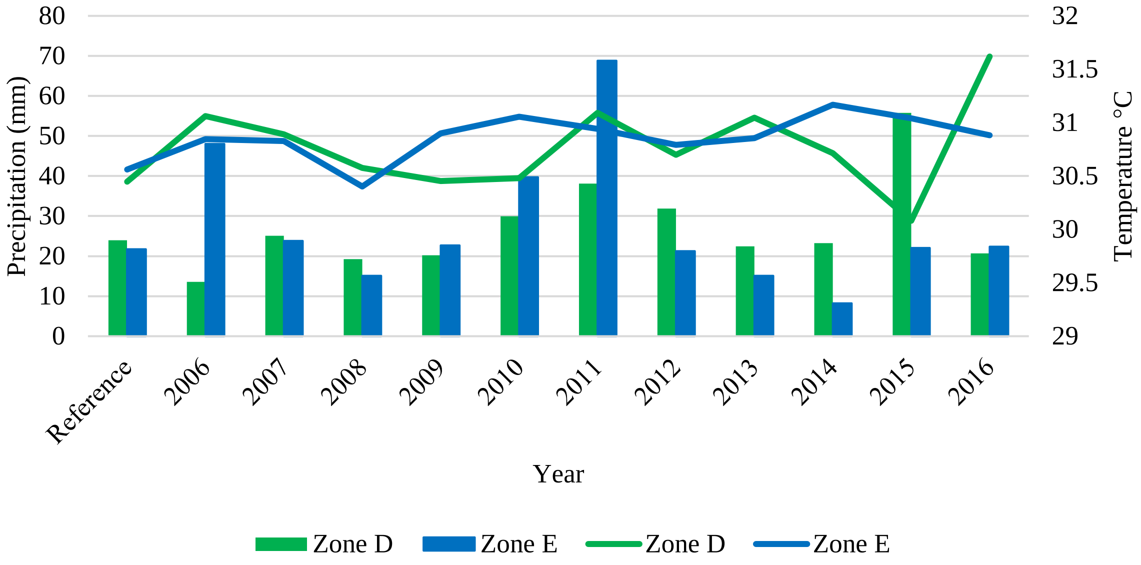


Figure 4.3: Zonal Average Climate in Cotton Crop Growing Season

The results show high inter-annual variability within precipitation trends in all zones, whereas temperature remains steady (with slight fluctuation). Mann Kendall Trend test validates this analysis; >0.05 p-value for precipitation, whereas for temperature p-value is <0.05 (see, Annexure for details).

The bars show the average precipitation, and line graphs show average temperature. Zone B (Upper Punjab) shows the greatest amount of precipitation received in wheat crop growing seasons, followed by Zone D (southern Punjab and Upper Sindh) and finally the lowest recorded precipitation falls in the Zone E category (Lower Sindh). In comparison temperature showed an inverse trend with Zone E having the highest followed by Zone D (19.26°C), and Zone B at (17.84°C). The average temperature in all 3 zones over the study period was 19.56°C; with a minimum of 17.7 and maximum of 23.0degrees centigrade. The precipitation was on average 14.88mm, with a minimum of 0.08mm and maximum of 69.5 mm. Similar trends were obtained in rice crop season. The average temperature in rice growing season overall in the three climatic zones was 29.13°C, with a minimum of 27.7, and maximum of 30.6°C. Whereas, average precipitation was 46.7mm, the highest average precipitation was recorded at 150.6mm, and a minimum of 10.1 mm. Cotton growing districts selected for our region mainly fall in zones D & E (south), similar trends of precipitation and trends were recorded, as for the other crop seasons. Mean temperature over the study period was 30.57°C, with a maximum of 31.6°C. The mean precipitation over cotton growing season amounted to 23.29mm, with a minimum of 8.28, and a maximum of 68.82.

Overall, temperature has an increasing trend whereas, precipitation has inter-annual variability i.e. no distinct trend in all climatic zones, as illustrated by the Mann Kendall Trend Test Results.

4.2. Absolute Change in Precipitation and Temperature in Crop Growing Season

This section outlines the change observed in temperature and precipitation in years 2006 – 2016 in detail, in comparison to the baseline period defined as 1978 – 2005 (Tables 4.1 – 4.6). The change over the years has been tumultuous, especially so in terms of rainfall events. Assessing the overall temperature trend there is a predominant increase relative to the baseline years (Haider *et al.*, 2017). Conversely, the precipitation showed a relative decrease in all crop seasons (Chaudhary, 2017), compared to base period; approximately 8 out of 10 cropping seasons showed a negative record. The highlighted cells in proceeding tables illustrate this.

Table 4.1: Change in Precipitation (mm) in Wheat Growing Districts of Punjab & Sindh; Baseline (1978-2005)

District Name	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
Zone B											
Jhelum	-4.7	15.0	8.2	-6.6	-24.5	-51.2	-35.2	13.1	17.5	17.6	8.6
Lahore	-3.2	12.9	-9.5	9.4	-34.5	-29.7	-32.6	-2.5	15.6	29.8	-12.3
Sialkot	-19.6	12.3	0.6	-9.6	-28.2	-55.9	-18.3	21.2	5.9	58.9	-7.3
Zone D											
Bahawalnagar	-2.0	3.3	-5.9	3.9	-2.9	-4.9	-3.2	15.9	10.32	10.2	-3.1
Bahawalpur	3.5	-0.9	-6.1	0.8	-2.5	-11.1	-6.6	6.8	0.1	16.1	1.2
Faisalabad	1.8	-0.1	-17.5	0.7	-12.9	-23.1	-5.6	5.8	6.0	24.8	-1.6
Jacobabad	6.6	10.9	15.1	4.6	-5.8	-3.9	-2.4	8.6	0.3	15.5	-3.0
Multan	5.2	13.8	8.9	4.2	-1.8	-11.7	-2.4	8.3	1.1	9.6	6.7
Zone E											
Badin	-1.2	-3.1	4.5	-3.0	2.2	-1.2	2.1	0.00	0.00	1.5	0.2
Hyderabad	5.9	13.0	-1.2	-1.8	-7.1	-3.9	-0.5	-5.6	0.00	-0.5	-2.8
S.Benazirabad	5.0	1.8	4.9	1.7	-7.8	-0.2	-3.9	6.5	0.4	1.0	0.2

Table 4.2: Change in Precipitation (mm) Rice Growing Districts of Punjab & Sindh; Baseline (1978-2005)

District Name	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
Zone B											
Jhelum	56.5	-28.3	-2. 9	-47.7	13.0	7.5	-16.1	13.3	-10.0	-11.6	3.0
Lahore	15.5	-12.0	-6.2	-48.6	-6.3	110.2	-10.4	40.9	15.7	9.8	29.2
Sialkot	-11.7	-33.1	23.4	-39.0	15.0	-13.0	-32.9	63.2	56.7	-36.9	-9.2
Zone D											
Bahawalnagar	-10.4	11.0	-4.2	10.6	0.2	44.2	15.5	7.4	-2.6	45.0	0.6
Bahawalpur	-3.9	3.6	-0.3	-4.5	4.4	13.1	5.0	-3.0	-13.3	44.7	-9.2
Faisalabad	7.4	-6.1	30.9	9.7	37.9	47.3	-0.4	-1.3	7.0	17.8	2.1
Jacobabad	-0.7	5.9	10.6	-8.1	8.6	19.9	40.9	21.1	-10.3	-0.2	-8.4
Multan	-16.3	-4.2	-11.9	-12.3	20.2	-3.7	8.4	-4.2	-1.9	23.4	-1.6
Zone E											
Badin	33.9	-9.2	-5.1	11.7	22.7	120.9	-5.9	-17.7	-21.4	12.6	-5.7
Hyderabad	63.7	7.1	-4.9	12.7	14.6	-13.1	-7.1	-2.0	-23.1	5.4	5.8
S.Benazirabad	15.6	8.5	-2.8	-3.9	24.6	50.3	3.0	-3.9	-8.8	-2.2	-0.5

Table 4.3: Change in Precipitation (mm) in Cotton Growing Districts of Punjab & Sindh; Baseline (1978 – 2005)

District Name	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
Zone D											
Bahawalnagar	-10.0	7.8	-0.3	6.7	-1.2	38.3	12.2	5.1	0.2	35.5	3.1
Bahawalpur	-4.7	1.7	-1.5	-4.6	4.1	8.1	6.6	-4.2	-8.9	40.7	-9.0
Multan	-16.4	-6.0	-12.4	-13.3	15.2	-3.9	5.1	-5.5	6.5	19.2	-3.8
Zone E											
Badin	20.4	-6.6	-6.0	3.6	16.0	66.0	-3.8	-9.9	-12.6	4.1	-4.4
Hyderabad	40.3	2.2	-3.4	5.8	7.4	-10.4	-5.2	-1.9	-15.9	-0.6	4.4
S.Benazirabad	18.2	10.5	-10.4	-6.5	30.5	85.6	7.5	-8.2	-12.1	-2.7	1.9

Table 4.4: Change in Precipitation (mm) in Cotton Growing Districts of Punjab & Sindh; Baseline (1978-2005)

District Name	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
Zone B											
Lahore	1.5	0.8	0.9	1.0	1.5	0.3	-0.8	-0.8	-1.5	-0.3	0.7
Sialkot	1.4	0.8	1.0	1.3	1.8	0.5	-0.1	0.1	-0.6	0.2	1.3
Zone D											
Bahawalnagar	1.1	1.2	0.6	0.9	1.6	0.4	-0.2	0.2	-0.3	0.2	1.5
Bahawalpur	1.1	1.1	0.0	0.5	0.4	0.1	-0.5	0.3	-0.5	0.2	1.0
Faisalabad	1.1	0.7	0.5	0.5	1.1	0.3	-0.3	0.3	-0.5	0.3	1.4
Jacobabad	0.9	0.9	0.3	0.5	0.9	-0.1	-0.5	0.0	-0.9	-0.6	0.7
Multan	0.9	0.5	-0.2	0.5	1.2	0.2	-0.3	0.1	-0.5	-0.2	1.1
Zone E											
Badin	1.4	1.1	0.2	1.2	1.2	1.6	0.7	0.8	0.3	1.1	2.5
Hyderabad	0.2	0.0	-0.5	0.5	0.4	-0.2	-1.3	-0.6	-0.2	-0.6	0.9
S.Benazirabad	0.9	0.2	-1.0	1.0	1.0	0.9	0.1	0.5	0.2	0.8	1.8

Table 4.5: Change in Temperature (°C) Rice Growing Districts of Punjab & Sindh; Baseline (1978-2005)

District Name	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
Zone B											
Jhelum	1.3	0.4	0.3	0.7	1.3	0.1	-0.2	-0.1	-0.8	-0.1	0.6
Lahore	1.5	0.8	0.9	1.0	1.5	0.3	-0.8	-0.8	-1.5	-0.3	0.7
Sialkot	1.4	0.8	1.0	1.3	1.8	0.5	-0.1	0.1	-0.6	0.2	1.3
Zone D											
Bahawalnagar	1.1	1.2	0.6	0.9	1.6	0.4	-0.2	0.2	-0.3	0.2	1.5
Bahawalpur	1.1	1.1	0.0	0.5	0.4	0.1	-0.5	0.3	-0.5	0.2	1.0
Faisalabad	1.1	0.7	0.5	0.5	1.1	0.3	-0.3	0.3	-0.5	0.3	1.4
Jacobabad	0.9	0.9	0.3	0.5	0.9	-0.1	-0.5	0.0	-0.9	-0.6	0.7
Multan	0.9	0.5	-0.2	0.5	1.2	0.2	-0.3	0.1	-0.5	-0.2	1.1
Zone E											
Badin	1.4	1.1	0.2	1.2	1.2	1.6	0.7	0.8	0.3	1.1	2.5
Hyderabad	0.2	0.0	-0.5	0.5	0.4	-0.2	-1.3	-0.6	-0.2	-0.6	0.9
S.Benazirabad	0.9	0.2	-1.0	1.0	1.0	0.9	0.1	0.5	0.2	0.8	1.8

Table 4.6: Change in Temperature (°C) in Cotton Growing Districts of Punjab & Sindh Baseline (1978-2005)

District Name	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
Zone D											
Bahawalnagar	0.2	0.8	0.3	-0.1	0.2	0.4	0.4	0.6	0.4	-0.1	1.4
Bahawalpur	0.9	0.2	-0.1	-0.1	-0.4	0.7	0.0	0.5	0.2	-0.7	0.9
Multan	0.8	0.3	0.2	0.2	0.2	0.8	0.4	0.7	0.2	-0.2	1.2
Zone E											
Badin	0.5	0.8	0.3	0.5	1.0	0.5	0.6	0.3	1.0	1.0	0.5
Hyderabad	-0.4	0.4	0.0	0.1	0.2	-0.4	-0.4	-0.3	-0.1	-0.2	-0.6
S.Benazirabad	0.8	-0.3	-0.8	0.4	0.3	1.0	0.4	0.9	0.9	0.7	1.0

The years 2010, 2011, and 2012 show the steepest dip in precipitation in wheat crop season (winter rain), in parallel the year 2010, 2011 showed highest rise in precipitation in rice & cotton cropping season (summer rain). This is mainly due to the presence of varying degrees of La Niña (strongest in 2010). La Niña brings a combination of rain patterns in the Indian sub-continent, with strong monsoon, and suppressed winter rainfall (Khan, 2004, Bhutto & Ming, 2013, Adnan *et al.* 2016). Similarly, 2009 shows a dominant decrease in precipitation in rice & cotton growing regions. This fall can be attributed to the presence of strong El Niño forces, which tend to supress the summer rainfall (Kumar *et al.* 2006, Adnan *et al.*, 2016).

Regardless, of the impact of ENSO pattern affecting the precipitation in Pakistan, the uncertainty remains as some years behave erroneously, despite the pattern in place (Park *et al.*, 2010, Bhutto & Ming, 2013). Inter-annual variability in weather in Pakistan is attributed to a number of factors including topography, winds – systems in the Bay of Bengal & Arabian Sea along with western disturbances in Mediterranean Sea, topped with indigenous climate (aridity) (Rodman E. Snead, 1968). Therefore, large climate anomalies occur as a result of local conditions, exasperated by the global teleconnections.

4.3. Error Analysis CCSM4 Climate Model with respect to Pakistan Meteorology Department Weather Station Observations (Period 1978 – 2005)

Error analysis is conducted in order to gauge the effectiveness of the model; how well can it predict. In this case reanalysis modelled data were compared to observed PMD weather station data.

Table 4.7: Error Analysis of CCSM4 for Wheat Growing Season

District Name	Precipitation (mm)			Temperature °C		
Error Analysis	**RMSE**	**MAE**	**Bias**	**RMSE**	**MAE**	**Bias**
Bahawalnagar	19.53	11.88	-8.29	0.33	0.23	0.05
Bahawalpur	7.63	5.31	-3.62	0.70	0.55	0.38
Faisalabad	16.41	12.27	-12.42	0.40	0.30	0.24
Multan	13.64	9.55	-8.92	0.35	0.21	0.16
Badin	2.54	1.49	-0.04	0.79	0.69	0.66
Hyderabad	5.54	2.15	-1.19	0.46	0.32	0.11
Jacobabad	3.20	2.18	-0.68	0.45	0.39	0.40
S. Benazir Abad	1.71	1.40	0.61	0.45	0.35	0.23

Table 4.8: Error Analysis of CCSM4 for Rice Growing Season

District Name	Precipitation (mm)			Temperature °C		
Error Analysis	**RMSE**	**MAE**	**Bias**	**RMSE**	**MAE**	**Bias**
Bahawalnagar	16.97	10.76	-7.02	0.35	0.27	-0.03
Bahawalpur	8.58	5.79	-4.01	0.51	0.43	0.35
Faisalabad	18.80	13.82	-13.92	0.38	0.28	0.15
Lahore	51.38	39.56	-37.62	0.86	0.81	-0.84
Multan	14.83	10.35	-8.82	0.35	0.23	0.10
Sialkot	56.53	43.58	-45.19	0.81	0.75	0.78
Badin	14.83	9.16	-8.12	0.70	0.61	0.64
Hyderabad	8.85	6.70	-6.00	0.40	0.31	-0.10
S. Benazir Abad	8.20	5.96	-3.60	0.54	0.40	-0.13

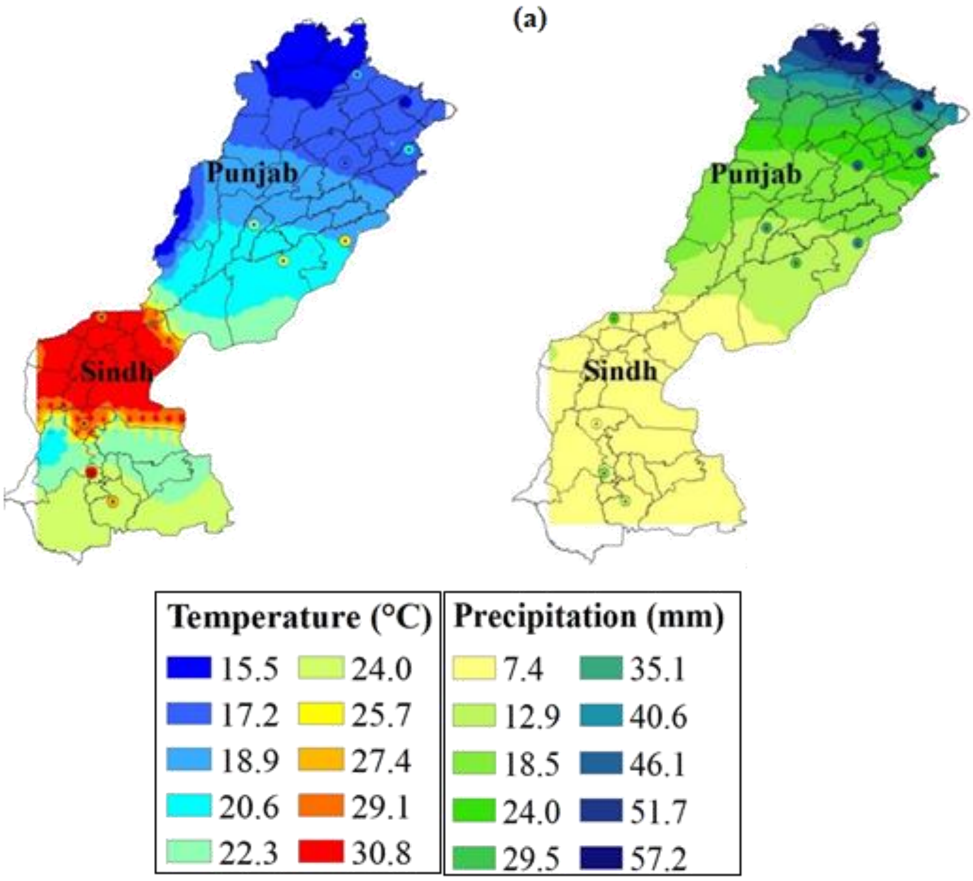
Table 4.9: Error Analysis of CCSM4 for Cotton Growing Season

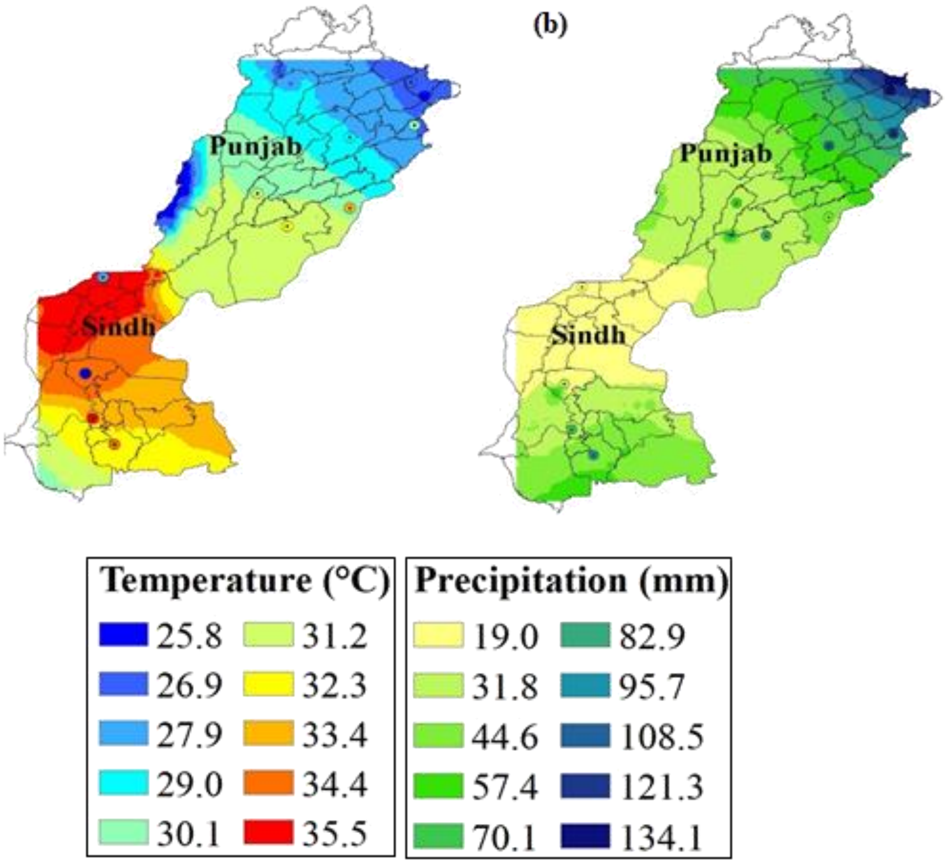
District Name	Precipitation (mm)			Temperature °C		
Error Analysis	**RMSE**	**MAE**	**Bias**	**RMSE**	**MAE**	**Bias**
Bahawalnagar	6.74	5.02	-3.28	0.22	0.17	0.005
Bahawalpur	3.59	2.46	-2.11	0.95	0.91	0.95
Faisalabad	5.76	4.38	-3.23	0.53	0.49	0.50
Jhelum	10.36	7.38	-1.15	0.62	0.49	-0.48
Lahore	10.38	8.40	-8.34	1.10	1.06	-1.10
Multan	3.76	3.11	-1.62	0.58	0.46	0.48
Sialkot	8.55	6.88	-4.58	0.51	0.45	0.46
Badin	24.35	14.98	-12.74	0.67	0.60	0.62
Hyderabad	12.33	8.86	-7.73	0.64	0.42	-0.03
Jacobabad	9.91	6.53	-5.48	0.41	0.36	0.37
S. Benazir Abad	6.30	4.08	-2.80	0.55	0.36	0.08

Table 4.10: Correlation (R^2) Model Simulation of Reanalysis Data Vs PMD Station Observed Data

District Name	Precipitation			Temperature		
	Wheat	Rice	Cotton	Wheat	Rice	Cotton
Badin	0.46	0.82	0.82	0.66	0.59	0.63
S. Benazir Abad	0.89	0.49	0.89	0.76	0.51	0.33
Jacobabad	0.32	0.53	-	0.87	0.77	-
Hyderabad	0.44	0.96	0.91	0.56	0.14	0.52
Bahawalpur	0.76	0.78	0.78	0.89	0.47	0.42
Bahawalnagar	0.38	0.68	0.72	0.92	0.57	0.73
Faisalabad	0.80	0.71	0.73	0.92	0.49	0.71
Lahore	0.80	0.61	-	0.89	0.62	-
Sialkot	0.75	0.53	-	0.88	0.56	-
Jhelum	0.67	-	-	0.76	-	-
Multan	0.66	0.52	0.55	0.78	0.52	0.66

The error analysis as shown in Tables 4.7 – 4.9 show the accuracy of the model varies within districts and crop seasons. Districts with high errors are mainly due to anomalous projections in isolated years, impacting the overall error diagnosis. The bias calculation shows that the CCSM4 model tends to overestimate temperature and underestimate precipitation, with a few exceptions. The overall correlation (Table 4.10) between observed and projected data (1978–2005) shows an R^2 above 0.5–0.96, thus the capability of the model to perform is statistically satisfactory. Especially, in projection of temperature trends. Figure 4.4 cartographically represents the mean temperature and precipitation through 1978 – 2005, representing the reanalysis modelled and PMD observed values, as assessed through the error analysis.


(a)
Punjab
Sindh
Punjab
Sindh
Temperature (°C)
15.5
17.2
18.9
20.6
22.3
24.0
25.7
27.4
29.1
30.8
Precipitation (mm)
7.4
12.9
18.5
24.0
29.5
35.1
40.6
46.1
51.7
57.2


(b)
Punjab
Sindh
Punjab
Sindh
Temperature (°C)
25.8
26.9
27.9
29.0
30.1
31.2
32.3
33.4
34.4
35.5
Precipitation (mm)
19.0
31.8
44.6
57.4
70.1
82.9
95.7
108.5
121.3
134.1

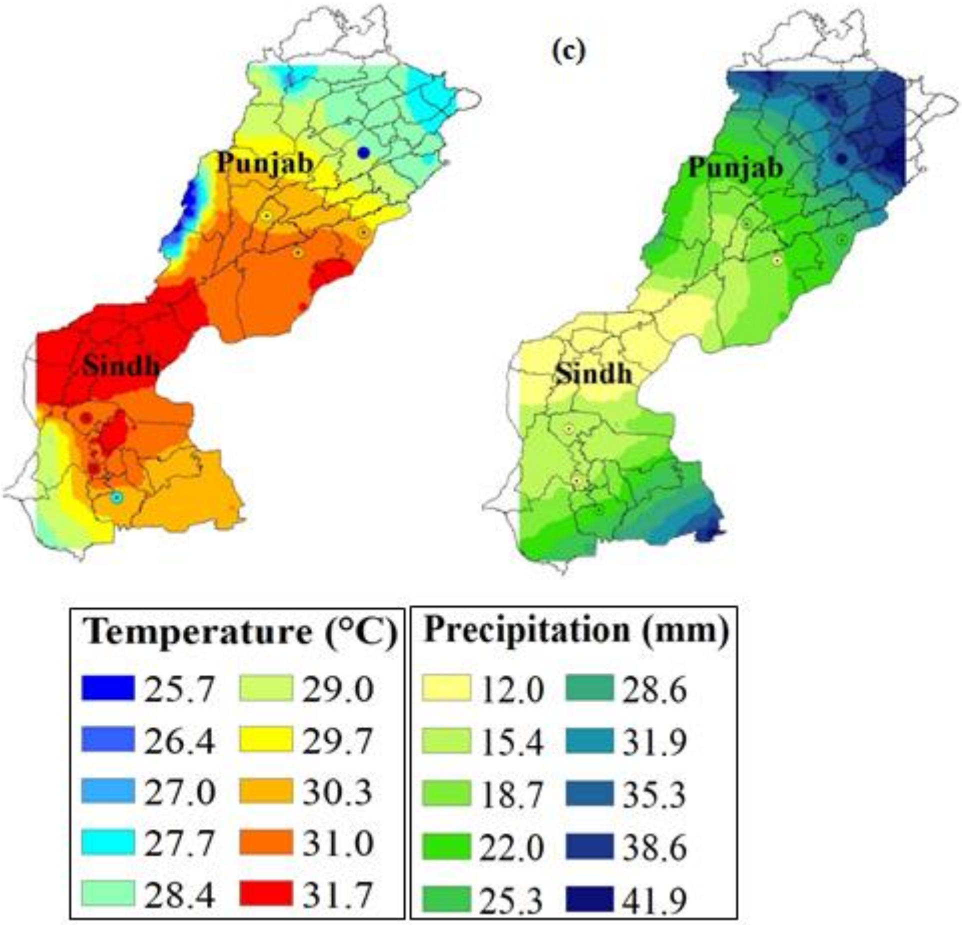
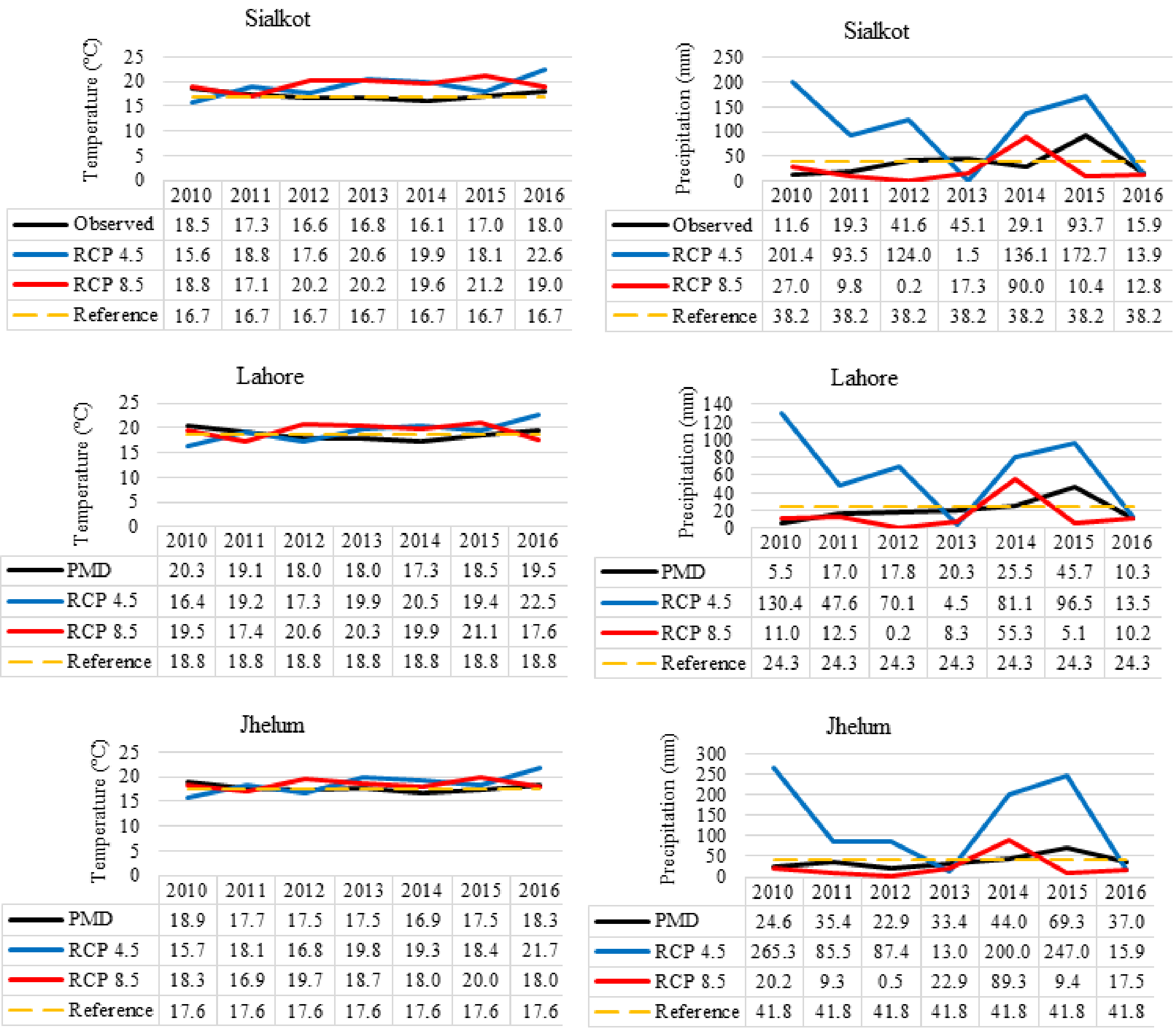


Figure 4.4: Climatological Mean (1978 – 2005) (a) Wheat Crop Season; (b) Rice Crop Season; and (c) Cotton Crop Season. Model simulations represented by the background colours, while surface observations from PMD-Network for respective seasons are represented by the circles.

4.4. PMD Observed Temperature & Precipitation Data in comparison to CCSM4 Modelled under RCP scenarios 4.5 and 8.5 (Reference Period: 1978 – 2005)



Sialkot

	2010	2011	2012	2013	2014	2015	2016
Observed	18.5	17.3	16.6	16.8	16.1	17.0	18.0
RCP 4.5	15.6	18.8	17.6	20.6	19.9	18.1	22.6
RCP 8.5	18.8	17.1	20.2	20.2	19.6	21.2	19.0
Reference	16.7	16.7	16.7	16.7	16.7	16.7	16.7

Sialkot

	2010	2011	2012	2013	2014	2015	2016
Observed	11.6	19.3	41.6	45.1	29.1	93.7	15.9
RCP 4.5	201.4	93.5	124.0	1.5	136.1	172.7	13.9
RCP 8.5	27.0	9.8	0.2	17.3	90.0	10.4	12.8
Reference	38.2	38.2	38.2	38.2	38.2	38.2	38.2

Lahore

	2010	2011	2012	2013	2014	2015	2016
PMD	20.3	19.1	18.0	18.0	17.3	18.5	19.5
RCP 4.5	16.4	19.2	17.3	19.9	20.5	19.4	22.5
RCP 8.5	19.5	17.4	20.6	20.3	19.9	21.1	17.6
Reference	18.8	18.8	18.8	18.8	18.8	18.8	18.8

Lahore

	2010	2011	2012	2013	2014	2015	2016
PMD	5.5	17.0	17.8	20.3	25.5	45.7	10.3
RCP 4.5	130.4	47.6	70.1	4.5	81.1	96.5	13.5
RCP 8.5	11.0	12.5	0.2	8.3	55.3	5.1	10.2
Reference	24.3	24.3	24.3	24.3	24.3	24.3	24.3

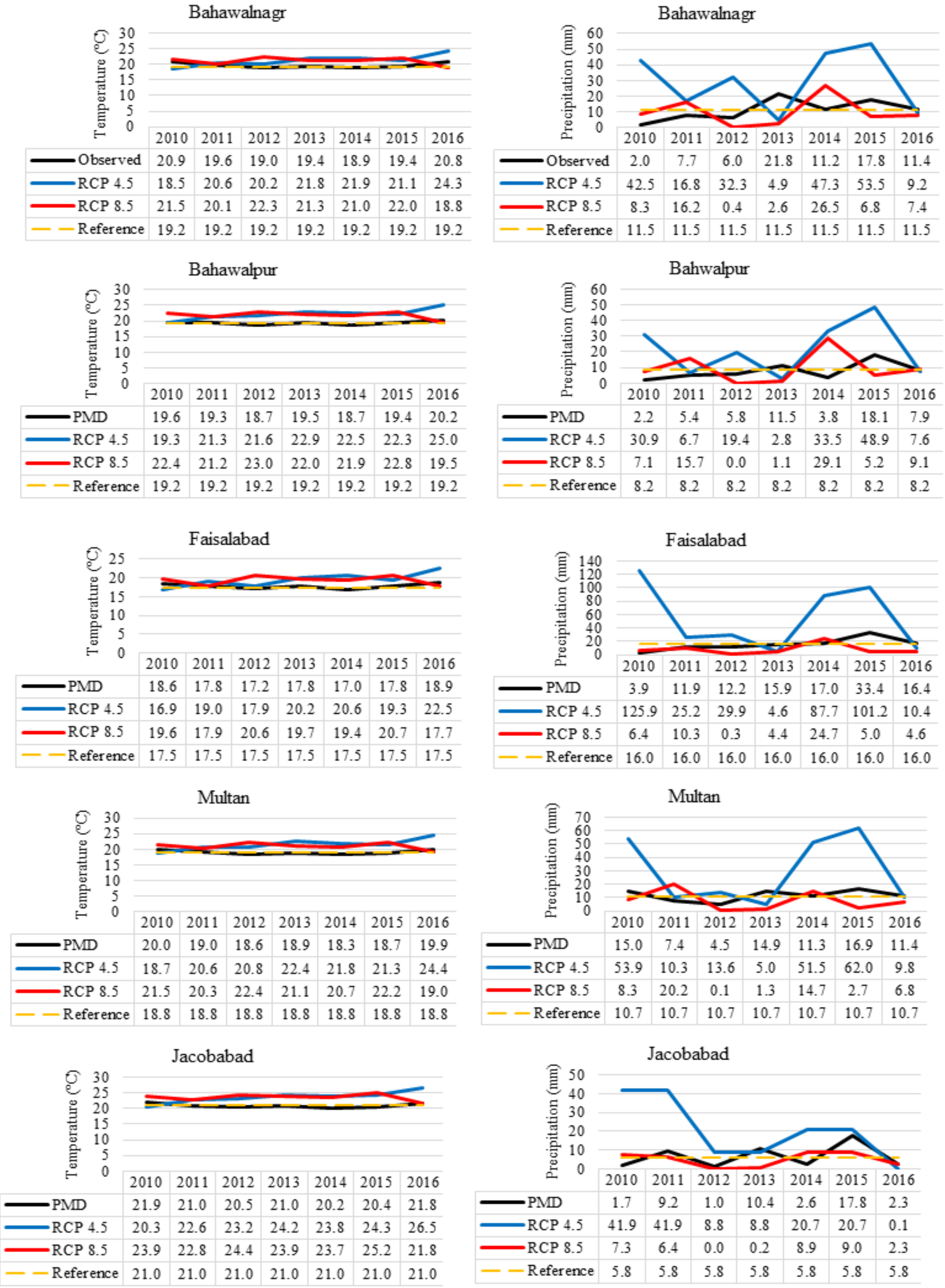
Jhelum

	2010	2011	2012	2013	2014	2015	2016
PMD	18.9	17.7	17.5	17.5	16.9	17.5	18.3
RCP 4.5	15.7	18.1	16.8	19.8	19.3	18.4	21.7
RCP 8.5	18.3	16.9	19.7	18.7	18.0	20.0	18.0
Reference	17.6	17.6	17.6	17.6	17.6	17.6	17.6

Jhelum

	2010	2011	2012	2013	2014	2015	2016
PMD	24.6	35.4	22.9	33.4	44.0	69.3	37.0
RCP 4.5	265.3	85.5	87.4	13.0	200.0	247.0	15.9
RCP 8.5	20.2	9.3	0.5	22.9	89.3	9.4	17.5
Reference	41.8	41.8	41.8	41.8	41.8	41.8	41.8

Figure 4.5: PMD Observed Temperature & Precipitation Data in Comparison to CCSM4 Modelled Data (Wheat – Zone B)



Bahawalnagr

	2010	2011	2012	2013	2014	2015	2016
Observed	20.9	19.6	19.0	19.4	18.9	19.4	20.8
RCP 4.5	18.5	20.6	20.2	21.8	21.9	21.1	24.3
RCP 8.5	21.5	20.1	22.3	21.3	21.0	22.0	18.8
Reference	19.2	19.2	19.2	19.2	19.2	19.2	19.2

Bahawalnagr

	2010	2011	2012	2013	2014	2015	2016
Observed	2.0	7.7	6.0	21.8	11.2	17.8	11.4
RCP 4.5	42.5	16.8	32.3	4.9	47.3	53.5	9.2
RCP 8.5	8.3	16.2	0.4	2.6	26.5	6.8	7.4
Reference	11.5	11.5	11.5	11.5	11.5	11.5	11.5

Bahawalpur

	2010	2011	2012	2013	2014	2015	2016
PMD	19.6	19.3	18.7	19.5	18.7	19.4	20.2
RCP 4.5	19.3	21.3	21.6	22.9	22.5	22.3	25.0
RCP 8.5	22.4	21.2	23.0	22.0	21.9	22.8	19.5
Reference	19.2	19.2	19.2	19.2	19.2	19.2	19.2

Bahwalpur

	2010	2011	2012	2013	2014	2015	2016
PMD	2.2	5.4	5.8	11.5	3.8	18.1	7.9
RCP 4.5	30.9	6.7	19.4	2.8	33.5	48.9	7.6
RCP 8.5	7.1	15.7	0.0	1.1	29.1	5.2	9.1
Reference	8.2	8.2	8.2	8.2	8.2	8.2	8.2

Faisalabad

	2010	2011	2012	2013	2014	2015	2016
PMD	18.6	17.8	17.2	17.8	17.0	17.8	18.9
RCP 4.5	16.9	19.0	17.9	20.2	20.6	19.3	22.5
RCP 8.5	19.6	17.9	20.6	19.7	19.4	20.7	17.7
Reference	17.5	17.5	17.5	17.5	17.5	17.5	17.5

Faisalabad

	2010	2011	2012	2013	2014	2015	2016
PMD	3.9	11.9	12.2	15.9	17.0	33.4	16.4
RCP 4.5	125.9	25.2	29.9	4.6	87.7	101.2	10.4
RCP 8.5	6.4	10.3	0.3	4.4	24.7	5.0	4.6
Reference	16.0	16.0	16.0	16.0	16.0	16.0	16.0

Multan

	2010	2011	2012	2013	2014	2015	2016
PMD	20.0	19.0	18.6	18.9	18.3	18.7	19.9
RCP 4.5	18.7	20.6	20.8	22.4	21.8	21.3	24.4
RCP 8.5	21.5	20.3	22.4	21.1	20.7	22.2	19.0
Reference	18.8	18.8	18.8	18.8	18.8	18.8	18.8

Multan

	2010	2011	2012	2013	2014	2015	2016
PMD	15.0	7.4	4.5	14.9	11.3	16.9	11.4
RCP 4.5	53.9	10.3	13.6	5.0	51.5	62.0	9.8
RCP 8.5	8.3	20.2	0.1	1.3	14.7	2.7	6.8
Reference	10.7	10.7	10.7	10.7	10.7	10.7	10.7

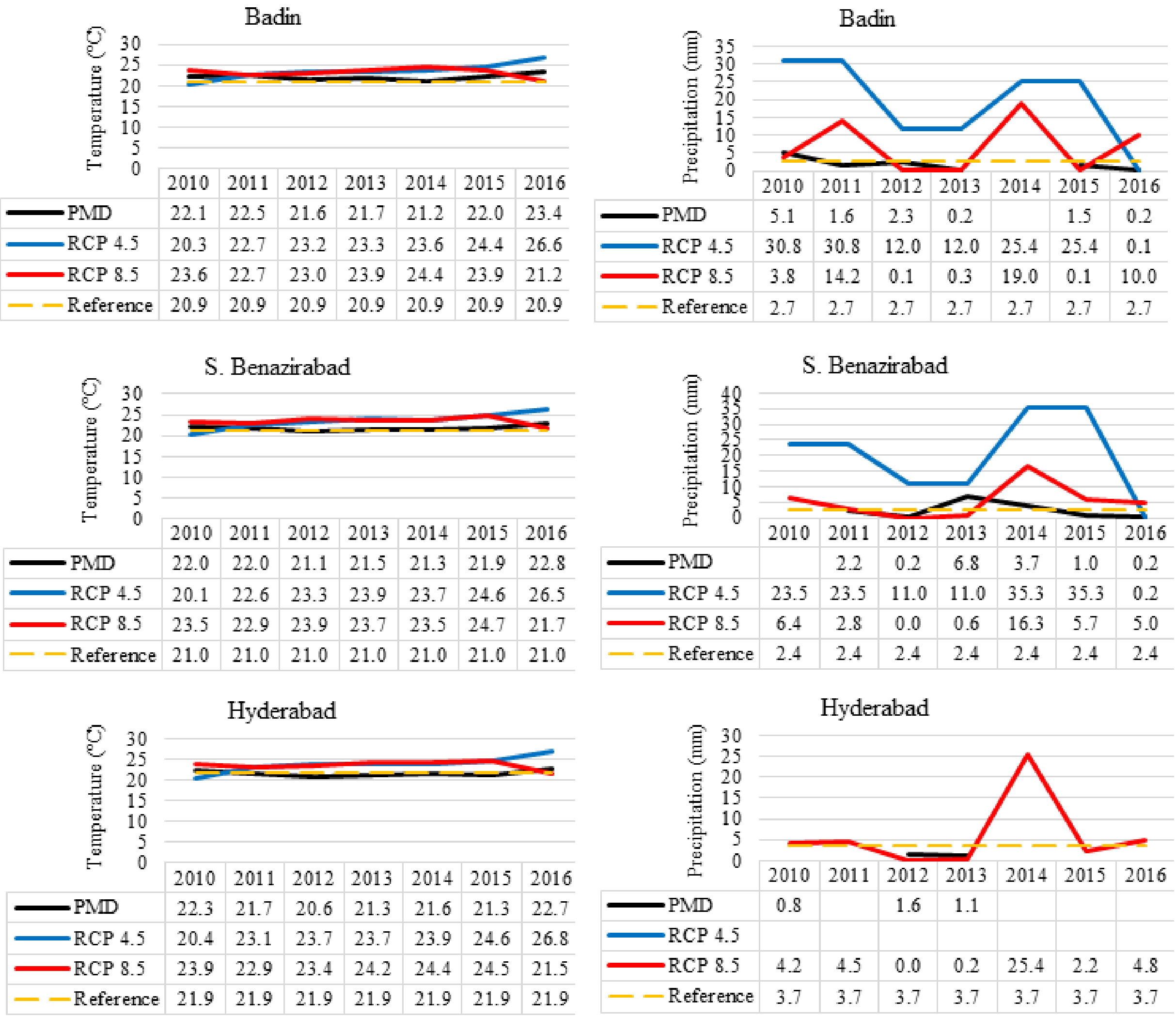
Jacobabad

	2010	2011	2012	2013	2014	2015	2016
PMD	21.9	21.0	20.5	21.0	20.2	20.4	21.8
RCP 4.5	20.3	22.6	23.2	24.2	23.8	24.3	26.5
RCP 8.5	23.9	22.8	24.4	23.9	23.7	25.2	21.8
Reference	21.0	21.0	21.0	21.0	21.0	21.0	21.0

Jacobabad

	2010	2011	2012	2013	2014	2015	2016
PMD	1.7	9.2	1.0	10.4	2.6	17.8	2.3
RCP 4.5	41.9	41.9	8.8	8.8	20.7	20.7	0.1
RCP 8.5	7.3	6.4	0.0	0.2	8.9	9.0	2.3
Reference	5.8	5.8	5.8	5.8	5.8	5.8	5.8

Figure 4.6: PMD Observed Temperature & Precipitation Data in Comparison to CCSM4 Modelled Data (Wheat – Zone D)



Badin – Temperature (°C)

	2010	2011	2012	2013	2014	2015	2016
PMD	22.1	22.5	21.6	21.7	21.2	22.0	23.4
RCP 4.5	20.3	22.7	23.2	23.3	23.6	24.4	26.6
RCP 8.5	23.6	22.7	23.0	23.9	24.4	23.9	21.2
Reference	20.9	20.9	20.9	20.9	20.9	20.9	20.9

Badin – Precipitation (mm)

	2010	2011	2012	2013	2014	2015	2016
PMD	5.1	1.6	2.3	0.2		1.5	0.2
RCP 4.5	30.8	30.8	12.0	12.0	25.4	25.4	0.1
RCP 8.5	3.8	14.2	0.1	0.3	19.0	0.1	10.0
Reference	2.7	2.7	2.7	2.7	2.7	2.7	2.7

S. Benazirabad – Temperature (°C)

	2010	2011	2012	2013	2014	2015	2016
PMD	22.0	22.0	21.1	21.5	21.3	21.9	22.8
RCP 4.5	20.1	22.6	23.3	23.9	23.7	24.6	26.5
RCP 8.5	23.5	22.9	23.9	23.7	23.5	24.7	21.7
Reference	21.0	21.0	21.0	21.0	21.0	21.0	21.0

S. Benazirabad – Precipitation (mm)

	2010	2011	2012	2013	2014	2015	2016
PMD		2.2	0.2	6.8	3.7	1.0	0.2
RCP 4.5	23.5	23.5	11.0	11.0	35.3	35.3	0.2
RCP 8.5	6.4	2.8	0.0	0.6	16.3	5.7	5.0
Reference	2.4	2.4	2.4	2.4	2.4	2.4	2.4

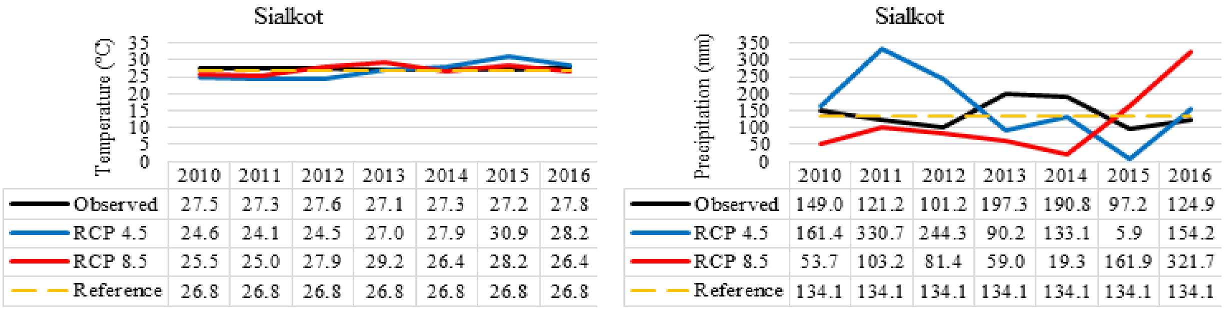
Hyderabad – Temperature (°C)

	2010	2011	2012	2013	2014	2015	2016
PMD	22.3	21.7	20.6	21.3	21.6	21.3	22.7
RCP 4.5	20.4	23.1	23.7	23.7	23.9	24.6	26.8
RCP 8.5	23.9	22.9	23.4	24.2	24.4	24.5	21.5
Reference	21.9	21.9	21.9	21.9	21.9	21.9	21.9

Hyderabad – Precipitation (mm)

	2010	2011	2012	2013	2014	2015	2016
PMD	0.8		1.6	1.1			
RCP 4.5							
RCP 8.5	4.2	4.5	0.0	0.2	25.4	2.2	4.8
Reference	3.7	3.7	3.7	3.7	3.7	3.7	3.7

Figure 4.7: PMD Observed Temperature & Precipitation Data in Comparison to CCSM4 Modelled Data (Wheat – Zone E)

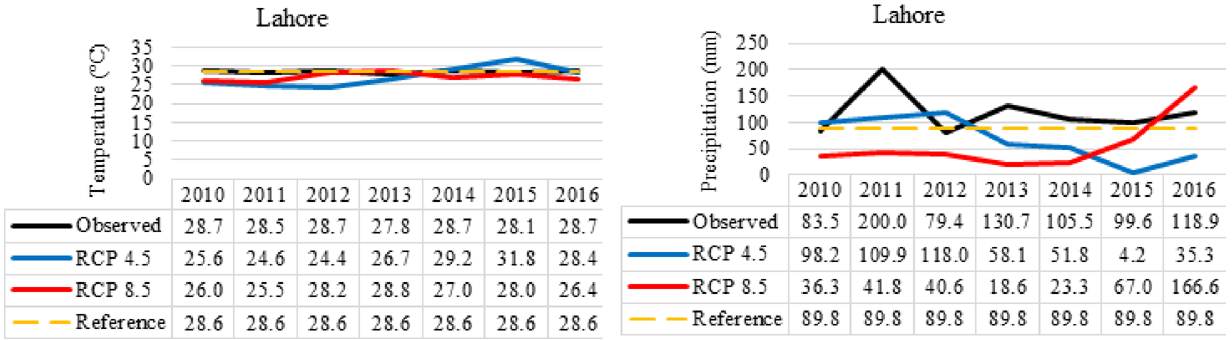


Sialkot – Temperature (°C)

	2010	2011	2012	2013	2014	2015	2016
Observed	27.5	27.3	27.6	27.1	27.3	27.2	27.8
RCP 4.5	24.6	24.1	24.5	27.0	27.9	30.9	28.2
RCP 8.5	25.5	25.0	27.9	29.2	26.4	28.2	26.4
Reference	26.8	26.8	26.8	26.8	26.8	26.8	26.8

Sialkot – Precipitation (mm)

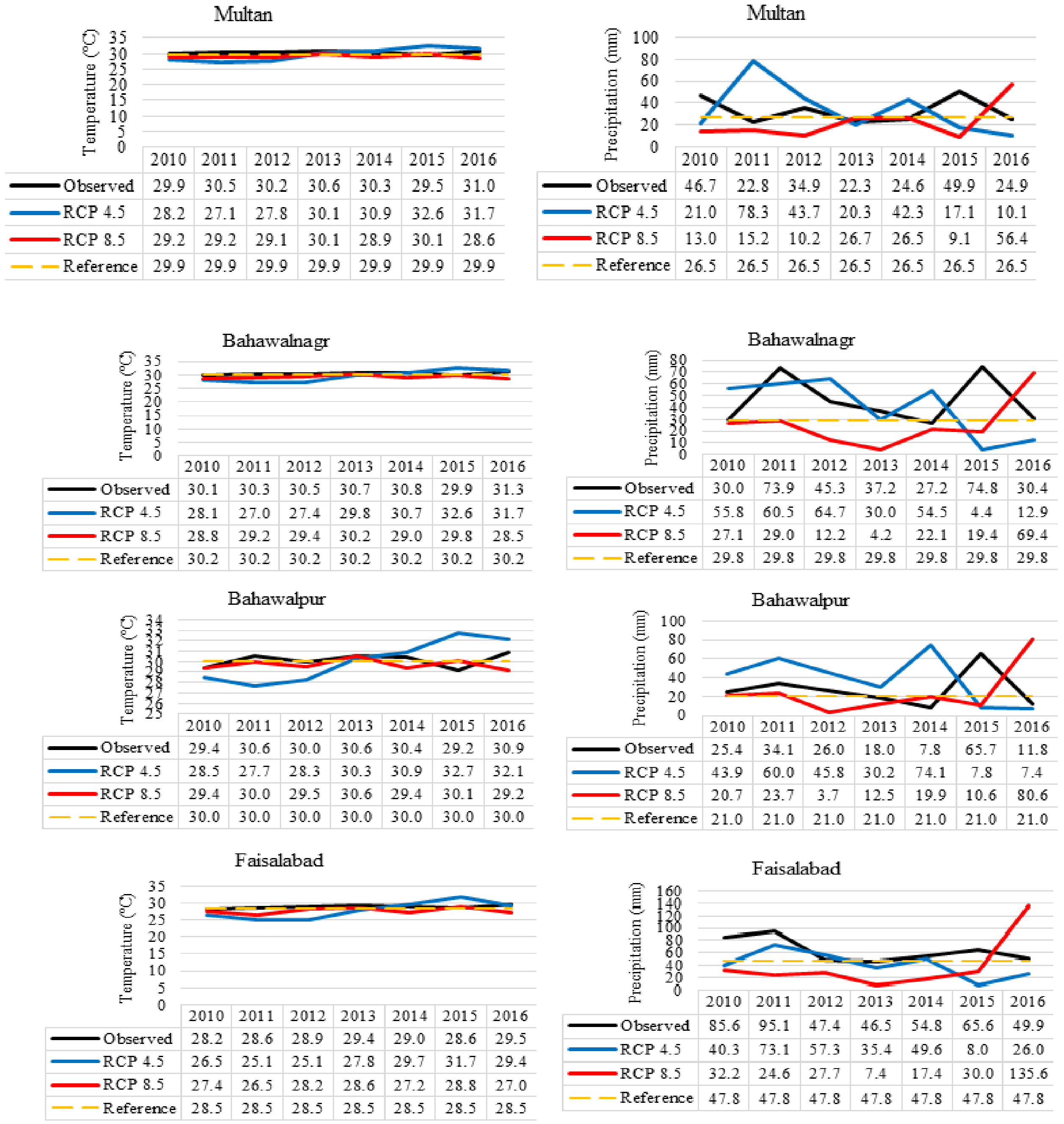
	2010	2011	2012	2013	2014	2015	2016
Observed	149.0	121.2	101.2	197.3	190.8	97.2	124.9
RCP 4.5	161.4	330.7	244.3	90.2	133.1	5.9	154.2
RCP 8.5	53.7	103.2	81.4	59.0	19.3	161.9	321.7
Reference	134.1	134.1	134.1	134.1	134.1	134.1	134.1



	2010	2011	2012	2013	2014	2015	2016
Observed	28.7	28.5	28.7	27.8	28.7	28.1	28.7
RCP 4.5	25.6	24.6	24.4	26.7	29.2	31.8	28.4
RCP 8.5	26.0	25.5	28.2	28.8	27.0	28.0	26.4
Reference	28.6	28.6	28.6	28.6	28.6	28.6	28.6

	2010	2011	2012	2013	2014	2015	2016
Observed	83.5	200.0	79.4	130.7	105.5	99.6	118.9
RCP 4.5	98.2	109.9	118.0	58.1	51.8	4.2	35.3
RCP 8.5	36.3	41.8	40.6	18.6	23.3	67.0	166.6
Reference	89.8	89.8	89.8	89.8	89.8	89.8	89.8

Figure 4.8: PMD Observed Temperature & Precipitation Data in Comparison to CCSM4 Modelled Data (Rice – Zone B)



	2010	2011	2012	2013	2014	2015	2016
Observed	29.9	30.5	30.2	30.6	30.3	29.5	31.0
RCP 4.5	28.2	27.1	27.8	30.1	30.9	32.6	31.7
RCP 8.5	29.2	29.2	29.1	30.1	28.9	30.1	28.6
Reference	29.9	29.9	29.9	29.9	29.9	29.9	29.9

	2010	2011	2012	2013	2014	2015	2016
Observed	46.7	22.8	34.9	22.3	24.6	49.9	24.9
RCP 4.5	21.0	78.3	43.7	20.3	42.3	17.1	10.1
RCP 8.5	13.0	15.2	10.2	26.7	26.5	9.1	56.4
Reference	26.5	26.5	26.5	26.5	26.5	26.5	26.5

	2010	2011	2012	2013	2014	2015	2016
Observed	30.1	30.3	30.5	30.7	30.8	29.9	31.3
RCP 4.5	28.1	27.0	27.4	29.8	30.7	32.6	31.7
RCP 8.5	28.8	29.2	29.4	30.2	29.0	29.8	28.5
Reference	30.2	30.2	30.2	30.2	30.2	30.2	30.2

	2010	2011	2012	2013	2014	2015	2016
Observed	30.0	73.9	45.3	37.2	27.2	74.8	30.4
RCP 4.5	55.8	60.5	64.7	30.0	54.5	4.4	12.9
RCP 8.5	27.1	29.0	12.2	4.2	22.1	19.4	69.4
Reference	29.8	29.8	29.8	29.8	29.8	29.8	29.8

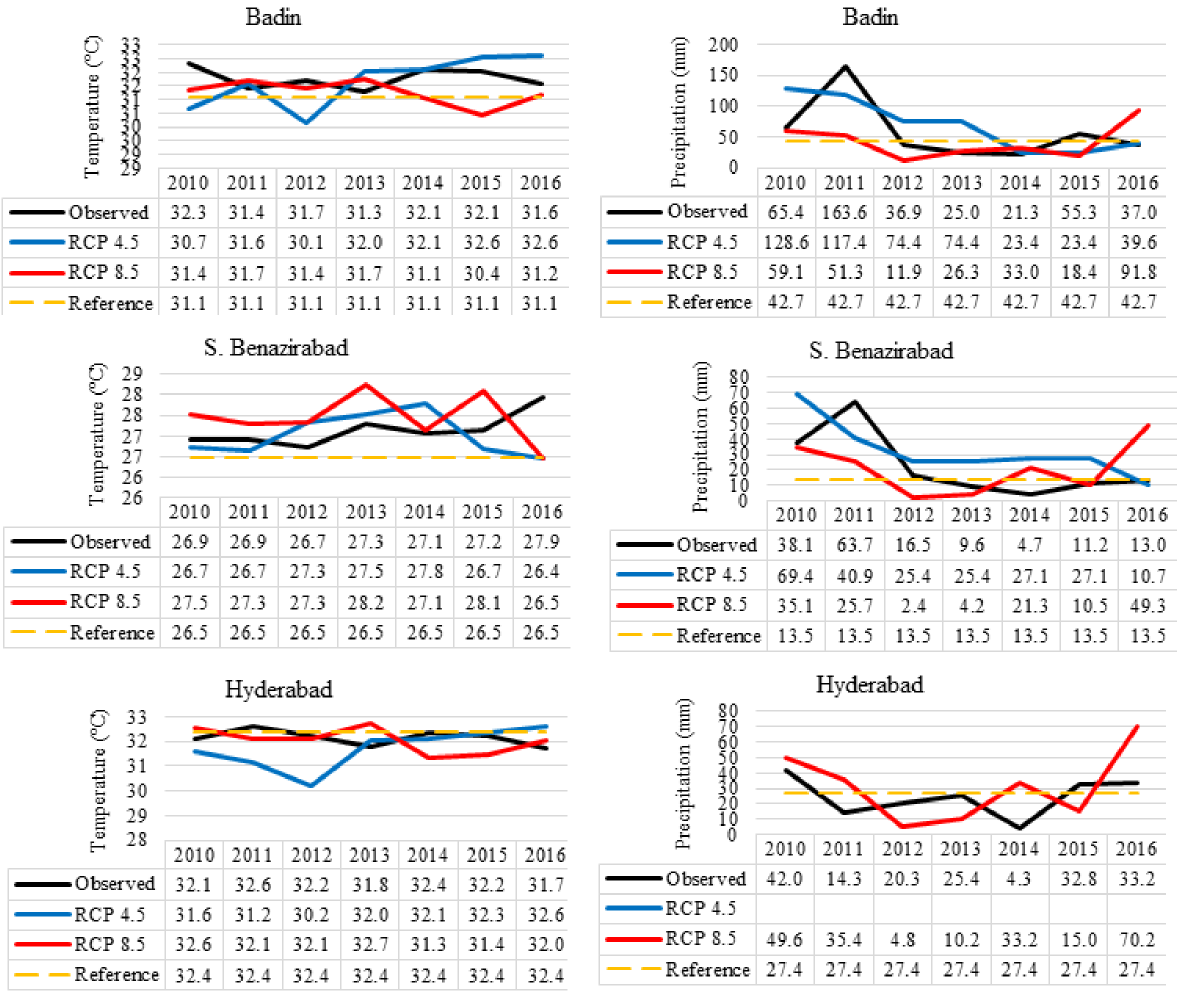
	2010	2011	2012	2013	2014	2015	2016
Observed	29.4	30.6	30.0	30.6	30.4	29.2	30.9
RCP 4.5	28.5	27.7	28.3	30.3	30.9	32.7	32.1
RCP 8.5	29.4	30.0	29.5	30.6	29.4	30.1	29.2
Reference	30.0	30.0	30.0	30.0	30.0	30.0	30.0

	2010	2011	2012	2013	2014	2015	2016
Observed	25.4	34.1	26.0	18.0	7.8	65.7	11.8
RCP 4.5	43.9	60.0	45.8	30.2	74.1	7.8	7.4
RCP 8.5	20.7	23.7	3.7	12.5	19.9	10.6	80.6
Reference	21.0	21.0	21.0	21.0	21.0	21.0	21.0

	2010	2011	2012	2013	2014	2015	2016
Observed	28.2	28.6	28.9	29.4	29.0	28.6	29.5
RCP 4.5	26.5	25.1	25.1	27.8	29.7	31.7	29.4
RCP 8.5	27.4	26.5	28.2	28.6	27.2	28.8	27.0
Reference	28.5	28.5	28.5	28.5	28.5	28.5	28.5

	2010	2011	2012	2013	2014	2015	2016
Observed	85.6	95.1	47.4	46.5	54.8	65.6	49.9
RCP 4.5	40.3	73.1	57.3	35.4	49.6	8.0	26.0
RCP 8.5	32.2	24.6	27.7	7.4	17.4	30.0	135.6
Reference	47.8	47.8	47.8	47.8	47.8	47.8	47.8

Figure 4.9: PMD Observed Temperature & Precipitation Data in Comparison to CCSM4 Modelled Data (Rice – Zone D)



Badin

	2010	2011	2012	2013	2014	2015	2016
Observed	32.3	31.4	31.7	31.3	32.1	32.1	31.6
RCP 4.5	30.7	31.6	30.1	32.0	32.1	32.6	32.6
RCP 8.5	31.4	31.7	31.4	31.7	31.1	30.4	31.2
Reference	31.1	31.1	31.1	31.1	31.1	31.1	31.1

Badin

	2010	2011	2012	2013	2014	2015	2016
Observed	65.4	163.6	36.9	25.0	21.3	55.3	37.0
RCP 4.5	128.6	117.4	74.4	74.4	23.4	23.4	39.6
RCP 8.5	59.1	51.3	11.9	26.3	33.0	18.4	91.8
Reference	42.7	42.7	42.7	42.7	42.7	42.7	42.7

S. Benazirabad

	2010	2011	2012	2013	2014	2015	2016
Observed	26.9	26.9	26.7	27.3	27.1	27.2	27.9
RCP 4.5	26.7	26.7	27.3	27.5	27.8	26.7	26.4
RCP 8.5	27.5	27.3	27.3	28.2	27.1	28.1	26.5
Reference	26.5	26.5	26.5	26.5	26.5	26.5	26.5

S. Benazirabad

	2010	2011	2012	2013	2014	2015	2016
Observed	38.1	63.7	16.5	9.6	4.7	11.2	13.0
RCP 4.5	69.4	40.9	25.4	25.4	27.1	27.1	10.7
RCP 8.5	35.1	25.7	2.4	4.2	21.3	10.5	49.3
Reference	13.5	13.5	13.5	13.5	13.5	13.5	13.5

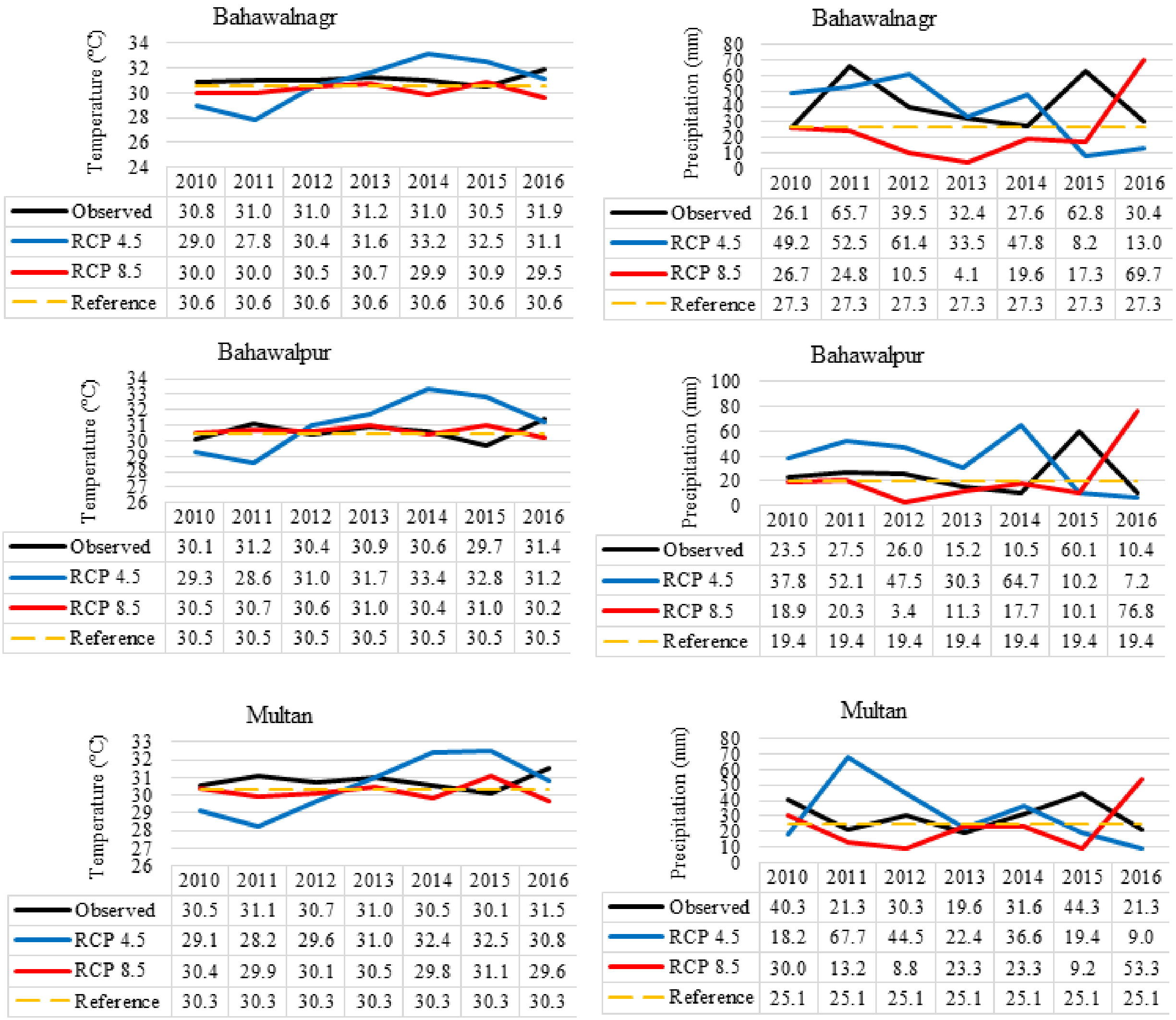
Hyderabad

	2010	2011	2012	2013	2014	2015	2016
Observed	32.1	32.6	32.2	31.8	32.4	32.2	31.7
RCP 4.5	31.6	31.2	30.2	32.0	32.1	32.3	32.6
RCP 8.5	32.6	32.1	32.1	32.7	31.3	31.4	32.0
Reference	32.4	32.4	32.4	32.4	32.4	32.4	32.4

Hyderabad

	2010	2011	2012	2013	2014	2015	2016
Observed	42.0	14.3	20.3	25.4	4.3	32.8	33.2
RCP 4.5							
RCP 8.5	49.6	35.4	4.8	10.2	33.2	15.0	70.2
Reference	27.4	27.4	27.4	27.4	27.4	27.4	27.4

Figure 4.10: PMD Observed Temperature & Precipitation Data in Comparison to CCSM4 Modelled Data (Rice – Zone E)



Bahawalnagr

	2010	2011	2012	2013	2014	2015	2016
Observed	30.8	31.0	31.0	31.2	31.0	30.5	31.9
RCP 4.5	29.0	27.8	30.4	31.6	33.2	32.5	31.1
RCP 8.5	30.0	30.0	30.5	30.7	29.9	30.9	29.5
Reference	30.6	30.6	30.6	30.6	30.6	30.6	30.6

Bahawalnagr

	2010	2011	2012	2013	2014	2015	2016
Observed	26.1	65.7	39.5	32.4	27.6	62.8	30.4
RCP 4.5	49.2	52.5	61.4	33.5	47.8	8.2	13.0
RCP 8.5	26.7	24.8	10.5	4.1	19.6	17.3	69.7
Reference	27.3	27.3	27.3	27.3	27.3	27.3	27.3

Bahawalpur

	2010	2011	2012	2013	2014	2015	2016
Observed	30.1	31.2	30.4	30.9	30.6	29.7	31.4
RCP 4.5	29.3	28.6	31.0	31.7	33.4	32.8	31.2
RCP 8.5	30.5	30.7	30.6	31.0	30.4	31.0	30.2
Reference	30.5	30.5	30.5	30.5	30.5	30.5	30.5

Bahawalpur

	2010	2011	2012	2013	2014	2015	2016
Observed	23.5	27.5	26.0	15.2	10.5	60.1	10.4
RCP 4.5	37.8	52.1	47.5	30.3	64.7	10.2	7.2
RCP 8.5	18.9	20.3	3.4	11.3	17.7	10.1	76.8
Reference	19.4	19.4	19.4	19.4	19.4	19.4	19.4

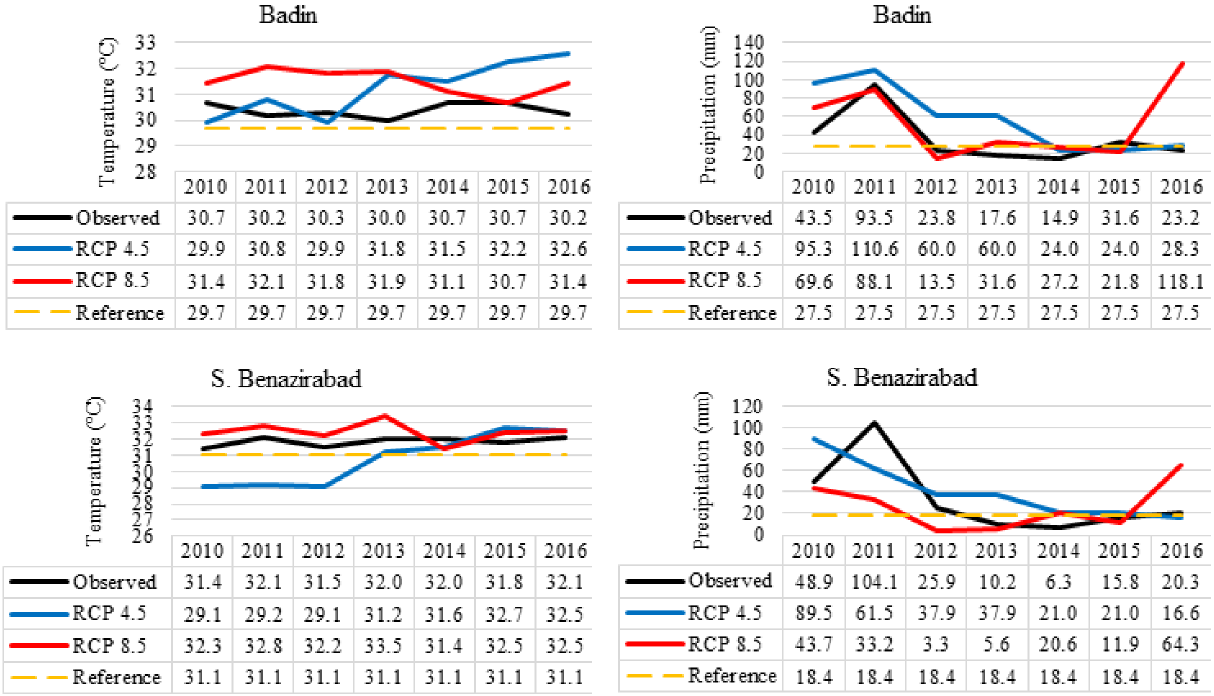
Multan

	2010	2011	2012	2013	2014	2015	2016
Observed	30.5	31.1	30.7	31.0	30.5	30.1	31.5
RCP 4.5	29.1	28.2	29.6	31.0	32.4	32.5	30.8
RCP 8.5	30.4	29.9	30.1	30.5	29.8	31.1	29.6
Reference	30.3	30.3	30.3	30.3	30.3	30.3	30.3

Multan

	2010	2011	2012	2013	2014	2015	2016
Observed	40.3	21.3	30.3	19.6	31.6	44.3	21.3
RCP 4.5	18.2	67.7	44.5	22.4	36.6	19.4	9.0
RCP 8.5	30.0	13.2	8.8	23.3	23.3	9.2	53.3
Reference	25.1	25.1	25.1	25.1	25.1	25.1	25.1

Figure 4.11: PMD Observed Temperature & Precipitation Data in Comparison to CCSM4 Modelled Data (Cotton – Zone D)



Badin

	2010	2011	2012	2013	2014	2015	2016
Observed	30.7	30.2	30.3	30.0	30.7	30.7	30.2
RCP 4.5	29.9	30.8	29.9	31.8	31.5	32.2	32.6
RCP 8.5	31.4	32.1	31.8	31.9	31.1	30.7	31.4
Reference	29.7	29.7	29.7	29.7	29.7	29.7	29.7

Badin

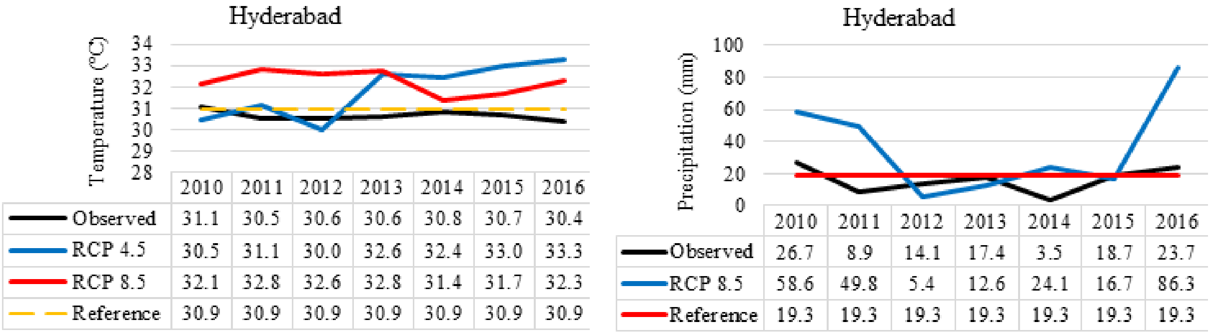
	2010	2011	2012	2013	2014	2015	2016
Observed	43.5	93.5	23.8	17.6	14.9	31.6	23.2
RCP 4.5	95.3	110.6	60.0	60.0	24.0	24.0	28.3
RCP 8.5	69.6	88.1	13.5	31.6	27.2	21.8	118.1
Reference	27.5	27.5	27.5	27.5	27.5	27.5	27.5

S. Benazirabad

	2010	2011	2012	2013	2014	2015	2016
Observed	31.4	32.1	31.5	32.0	32.0	31.8	32.1
RCP 4.5	29.1	29.2	29.1	31.2	31.6	32.7	32.5
RCP 8.5	32.3	32.8	32.2	33.5	31.4	32.5	32.5
Reference	31.1	31.1	31.1	31.1	31.1	31.1	31.1

S. Benazirabad

	2010	2011	2012	2013	2014	2015	2016
Observed	48.9	104.1	25.9	10.2	6.3	15.8	20.3
RCP 4.5	89.5	61.5	37.9	37.9	21.0	21.0	16.6
RCP 8.5	43.7	33.2	3.3	5.6	20.6	11.9	64.3
Reference	18.4	18.4	18.4	18.4	18.4	18.4	18.4



	2010	2011	2012	2013	2014	2015	2016
Observed	31.1	30.5	30.6	30.6	30.8	30.7	30.4
RCP 4.5	30.5	31.1	30.0	32.6	32.4	33.0	33.3
RCP 8.5	32.1	32.8	32.6	32.8	31.4	31.7	32.3
Reference	30.9	30.9	30.9	30.9	30.9	30.9	30.9

	2010	2011	2012	2013	2014	2015	2016
Observed	26.7	8.9	14.1	17.4	3.5	18.7	23.7
RCP 8.5	58.6	49.8	5.4	12.6	24.1	16.7	86.3
Reference	19.3	19.3	19.3	19.3	19.3	19.3	19.3

Figure 4.12: PMD Observed Temperature & Precipitation Data in Comparison to CCSM4 Modelled Data (Cotton – Zone D)

Figures 4.5 – 4.12 depict the temperature and profile of selected districts as observed, and projected values under RCP scenarios 4.5 & 8.5. In all cases, the temperature has remained constant or slightly above the reference period. In terms of precipitation in some cases the observed is higher than reference, whereas in others it is below this average (as discussed in the previous section). Rajbhandari *et al.*, 2014 suggested an overall non-homogenous change in precipitation. However, the higher precipitation, cannot be generalized as an increase in precipitation, as it is important to take into account the intense rainfall events and consequent dry days (period), which could have possibly been averaged out. Ashfaq *et al.*, 2009 found that enhanced forcing of GHG induced an increase in dry spells, conversely Nicholls *et al.*, 2012 showed an increased frequency of extreme precipitation events. (This is also noteworthy in interpretation of section 4.5 results). Largely, the real-time data within the 2006 – 2016 time frame suggest that within the wheat crop growing season, both scenarios over-estimate temperature slightly, whereas the opposite is true for rice and cotton seasons that shows observed temperature to be higher than that under RCP 4.5 & 8.5. Precipitation patterns are less clear, generally RCP 4.5 overestimates the precipitation, whereas RCP 8.5 under-reports, with a few exceptions (details in Tables 4.11 – 4.13).

Table 4.11: Mean Bias in Wheat Crop Growing Season in RCP scenarios 4.5 and 8.5 w.r.t PMD observed values

District Name	Temperature (°C)		Precipitation (mm)	
	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5
Zone B				
Jhelum	0.8	0.8	92.5	-13.9
Lahore	0.7	0.8	43.1	-5.6
Sialkot	1.8	2.2	69.6	-12.7
Zone D				
Bahawalnagar	1.5	1.3	18.4	-1.4
Bahawalpur	2.8	2.5	13.6	1.8
Faisalabad	1.6	1.5	39.2	-7.8
Jacobabad	2.6	2.7	14.0	-1.6
Multan	2.4	2.0	17.8	-3.9
Zone E				
Badin	1.4	1.2	17.9	5.2
Hyderabad	2.1	1.9	-0.5	5.4
S. Benazir Abad	1.8	1.6	18.0	3.3

Table 4.12: Mean Bias in Rice Crop Growing Season in RCP scenarios 4.5 and 8.5 w.r.t PMD observed values

District Name	Temperature (°C)		Precipitation (mm)	
	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5
Zone B				
Sialkot	-0.6	-0.5	19.8	-25.9
Lahore	-1.2	-1.3	-48.8	-1.3
Zone D				
Jacobabad	0.7	-1.3	3.9	1.0
Bahawalnagar	-0.9	-1.2	-5.1	-19.3
Bahawalpur	-0.1	-0.4	11.5	-2.4
Faisalabad	-1.0	-1.2	-22.1	-24.3
Multan	-0.5	-1.0	1.0	-9.8
Zone E				
Badin	-0.1	-0.5	10.9	-16.1
Hyderabad	-0.4	0.3	-24.6	-3.8
S. Benazir Abad	-0.1	0.3	9.9	-1.2

Table 4.13: Mean Bias in Cotton Crop Growing Season in RCP scenarios 4.5 and 8.5 w.r.t PMD observed values

District Name	Temperature (°C)		Precipitation (mm)	
	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5
Zone D				
Bahawalnagar	-0.3	-0.9	-2.7	-16.0
Bahawalpur	0.5	0.0	11.0	-2.1
Multan	-0.3	-0.6	1.3	-6.8
Zone E				
Badin	0.9	1.1	22.0	17.4
Hyderabad	1.2	1.6	-	20.1
S. Benazir Abad	-1.1	0.6	7.7	-7.0

4.5 Decadal projected average climate in wheat, rice & cotton under RCP scenarios 4.5 and 8.5 (2010-2100)

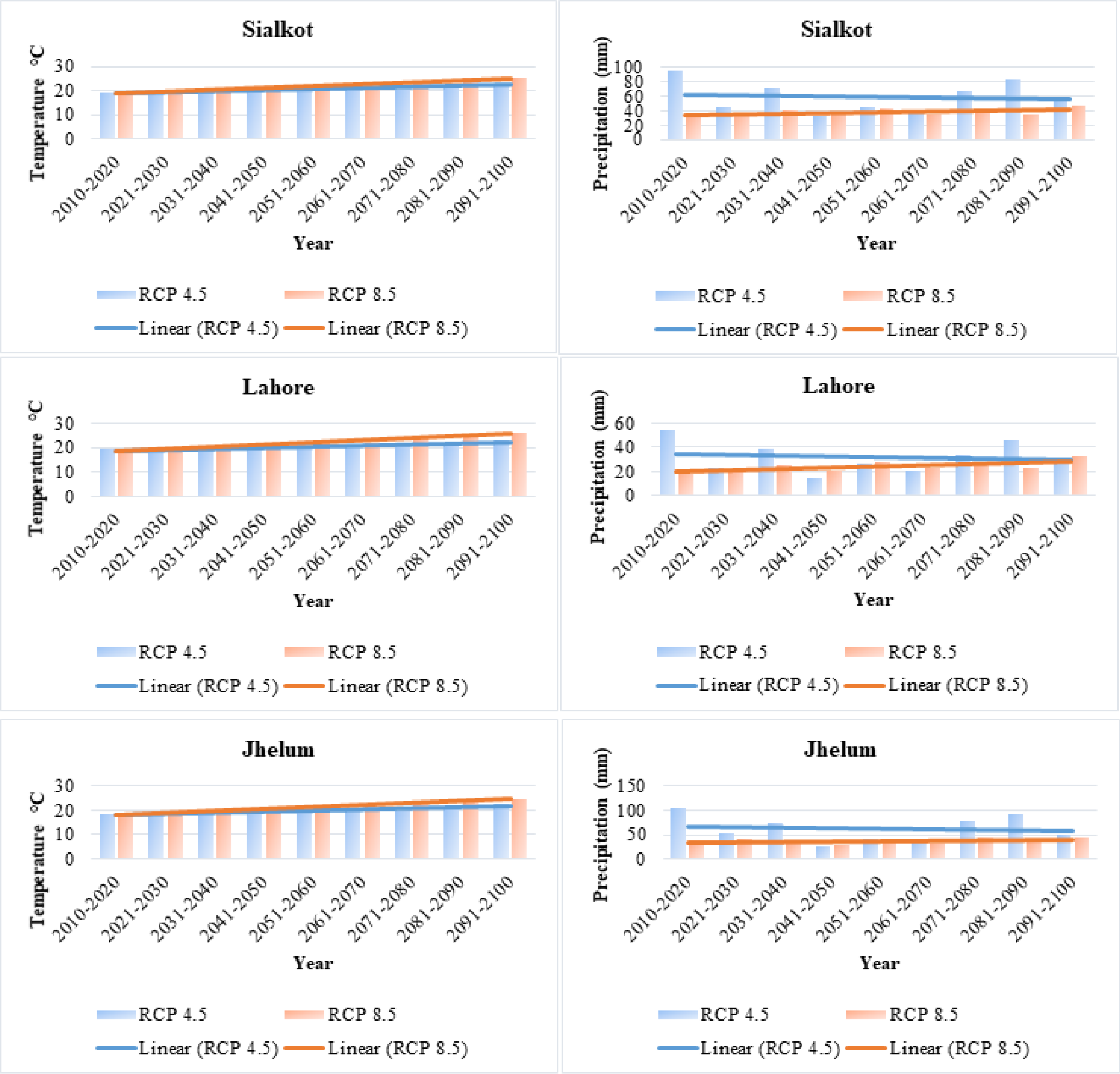


Figure 4.13: Decadal Projected Average Temperature & Precipitation till End of 21st Century under RCP 4.5 & 8.5 (Wheat – Zone B)

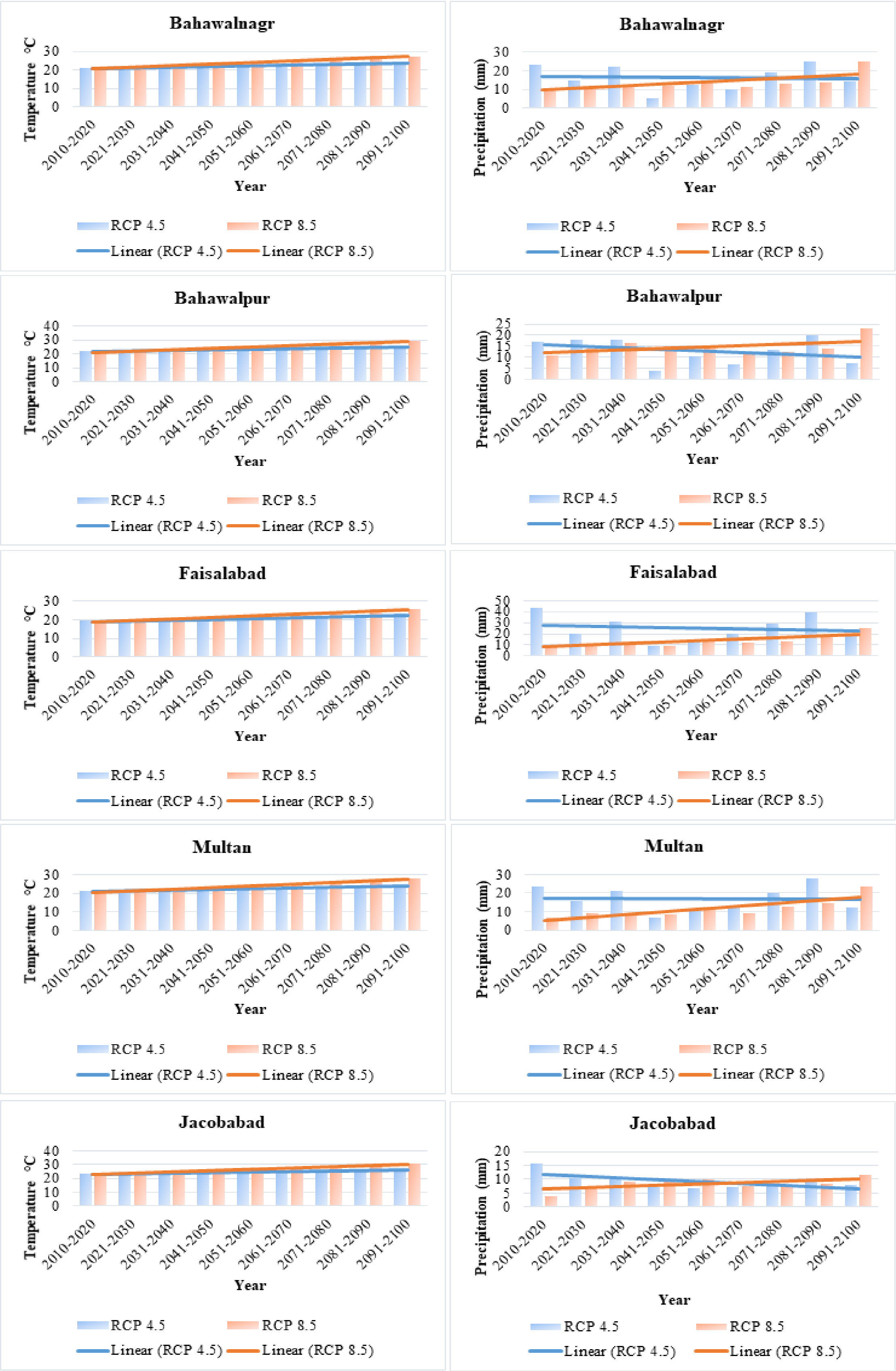


Figure 4.14: Decadal Projected Average Temperature & Precipitation till End of 21st Century under RCP 4.5 & 8.5 (Wheat – Zone D)

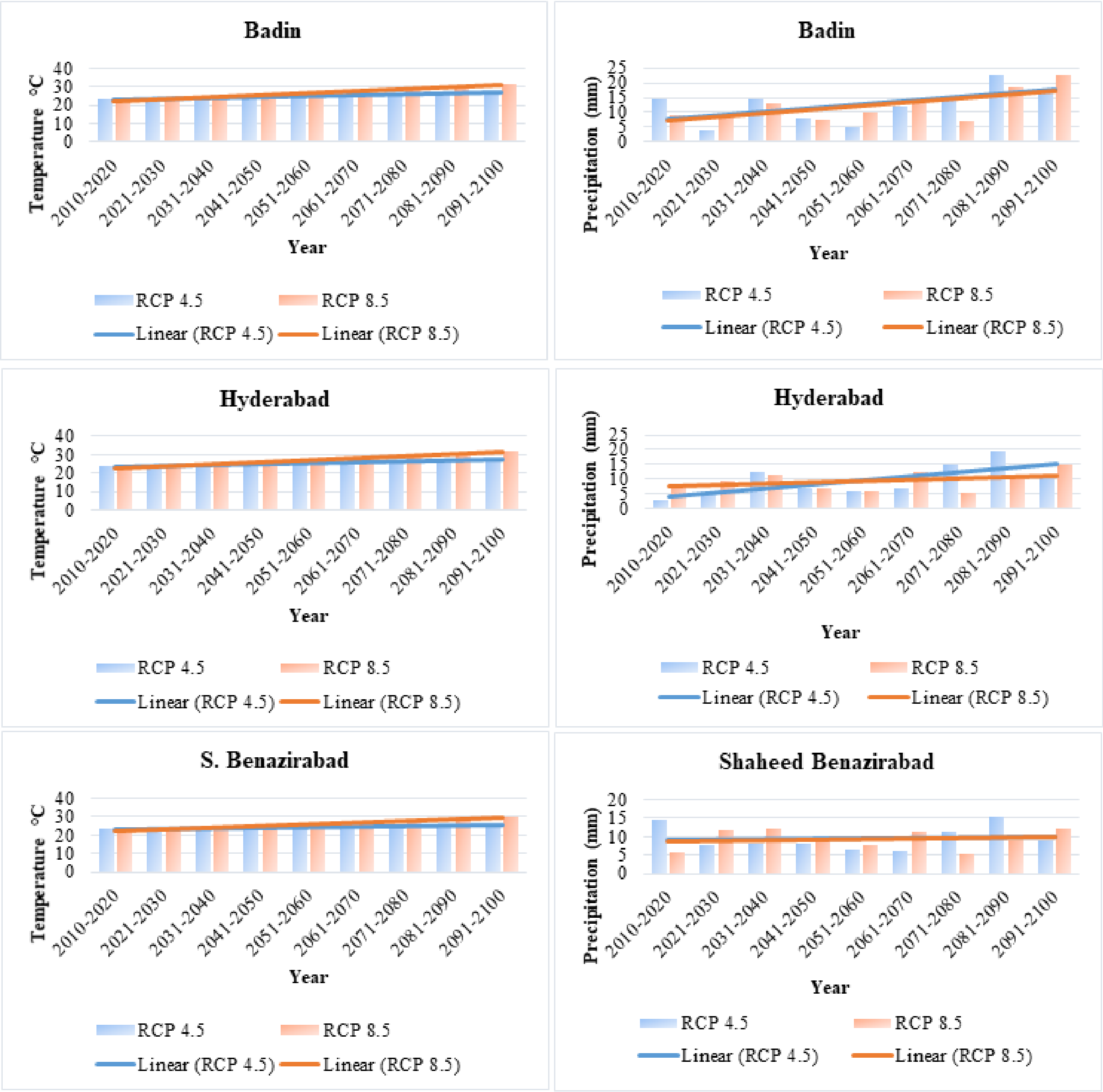


Figure 4.15: Decadal Projected Average Temperature & Precipitation till End of 21st Century under RCP 4.5 & 8.5 (Wheat – Zone E)

Figures 4.13 – 4.15, above show a definitive increase in temperature throughout, precipitation has a fluctuating trend (see also, Chaudhary, 2017). In RCP 4.5 there was a pronounced increase in rainfall within the decade 2010 – 2020 (especially in zone B districts (Jhelum, Lahore and Sialkot). Proceeding decades remain positively inclined, (until 2041 – 2050) in which zones B and D show a negative change. After this decline, it picks up slightly, ending with above baseline average rainfall by the end of the century. Within the RCP 8.5 scenario the change in precipitation is negative, especially in zone B and parts of zone D

(Multan, Faisalabad) till 2070. Subsequently, it emerges to an increasing trend. In comparison zone E districts show a positive trend throughout the century. Overall, RCP 8.5 provides a more ‘wetter’ outlook compared to RCP 4.5, towards 2100. Ikram *et al.* (2016) in their study on Pakistan’s monsoon season, support this notion; observing longer breaks (dry periods) and frequent intense precipitation events in the future.

The temperature is increasing from the onset, with as much as a 2°C rise by 2020 in some regions, especially the arid districts of zones D & E. In RCP 4.5 the increase remains around 2 – 3°C till mid-century, leading to a 5 – 6°C rise in 2091 – 2100. RCP 8.5 indicates, similar trend as RCP 4.5 scenario till mid-century, after which it shoots up to a staggering 9 – 10.8°C (greatest increase being in zone D & E).

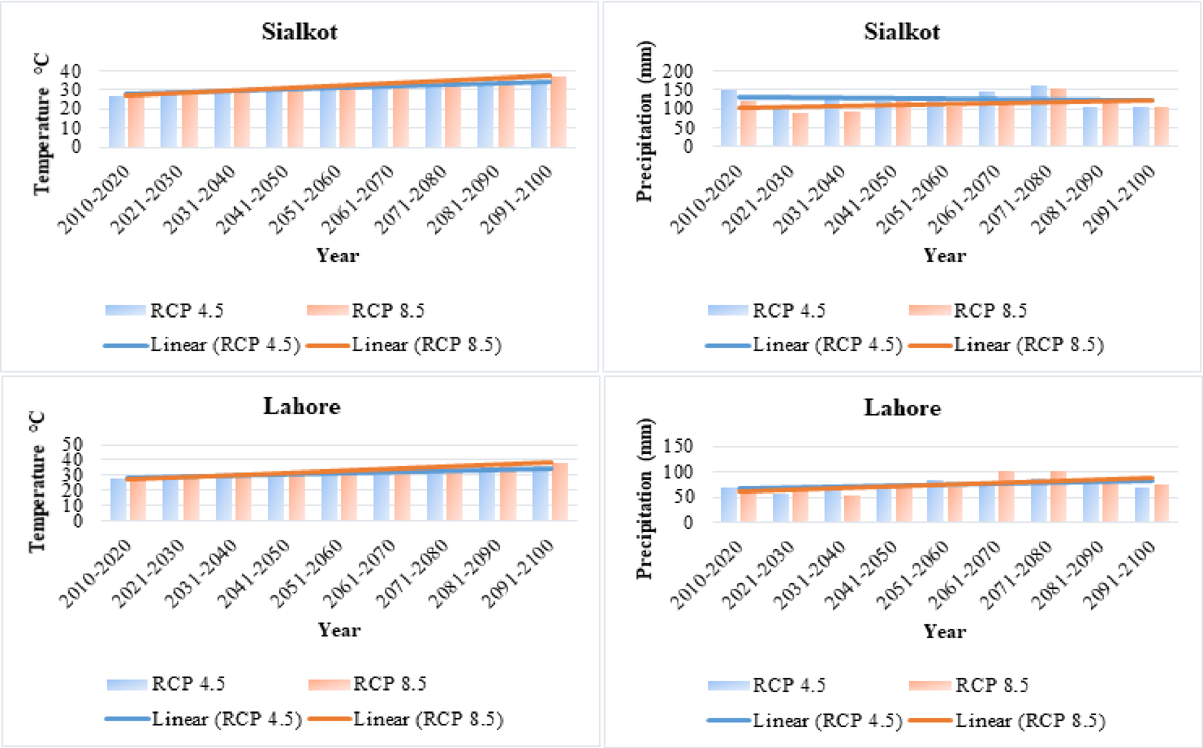


Figure 4.16: Decadal Projected Average Temperature & Precipitation till End of 21st Century under RCP 4.5 & 8.5 (Rice – Zone B)

Figure 4.17: Decadal Projected Average Temperature & Precipitation till End of 21st Century under RCP 4.5 & 8.5 (Rice – Zone D)

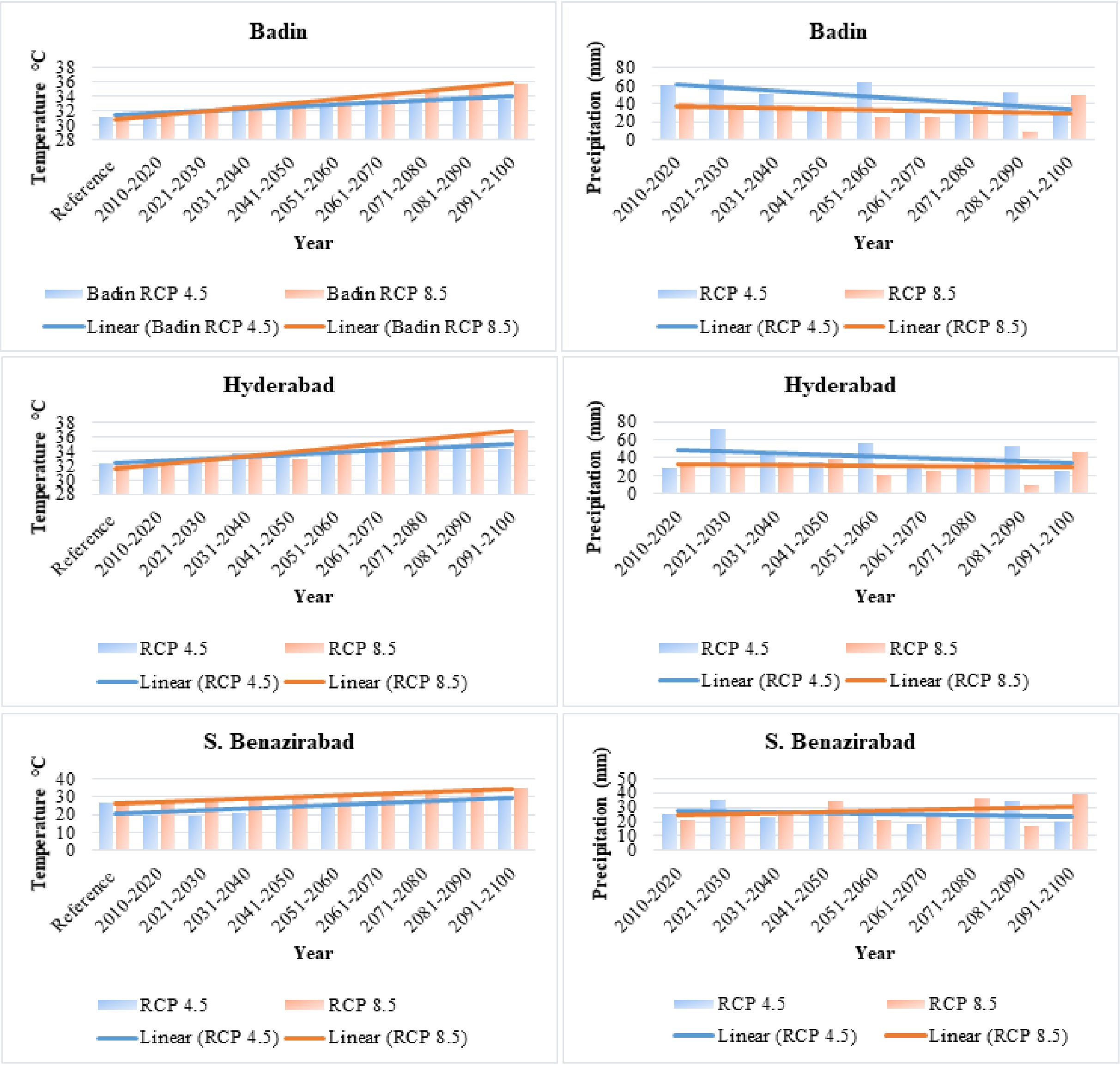


Figure 4.18: Decadal Projected Average Temperature & Precipitation till End of 21st Century under RCP 4.5 & 8.5 (Rice – Zone E)

As with the wheat growing season, in rice growing season, the overall temperature is increasing with time, whereas precipitation tends to increase/decrease in some cases (Figures 4.16 – 4.18).

In RCP 4.5 zone B (Lahore & Sialkot) and in some cases shows a negative change in precipitation till and beyond mid-century. Moreover, in the last decade of the 21st century (i.e. 2099 – 2100), Faisalabad, Multan, Sialkot, Lahore, Badin, Hyderabad all show a decrease in precipitation compared to the base period. Similar trends are visible in the RCP 8.5 scenario, especially in Lahore, Sialkot and Badin.

On the temperature front the latter half of the century is warming, ending with an increase of 6 – 7°C. In RCP 8.5, there is a similar pattern observed till 2020 especially, zones B and D. The rest of the century there is an increase, up to 8 – 10°C across the study area.

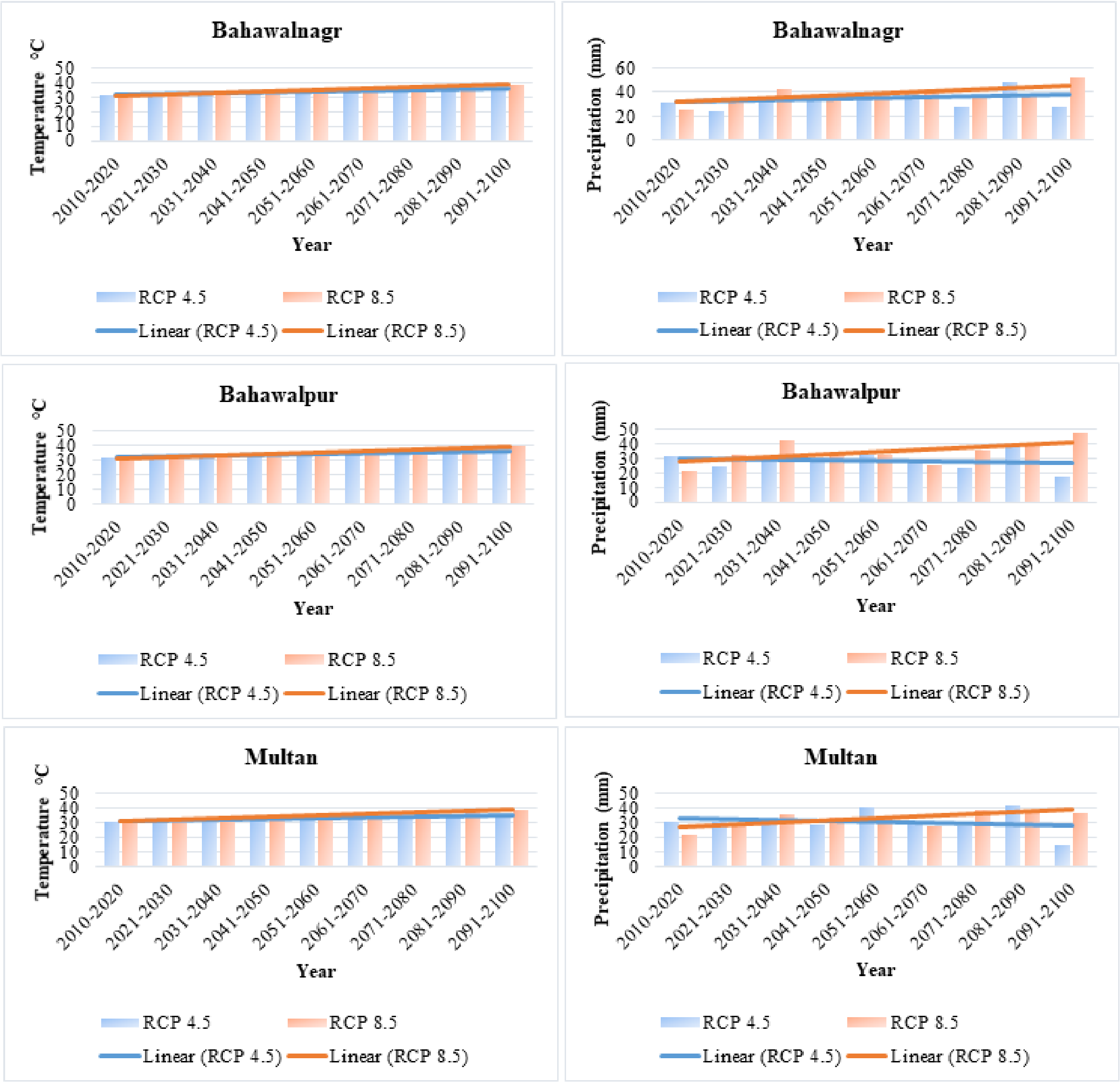


Figure 4.19: Decadal Projected Average Temperature & Precipitation till End of 21st Century under RCP 4.5 & 8.5 (Cotton – Zone D)

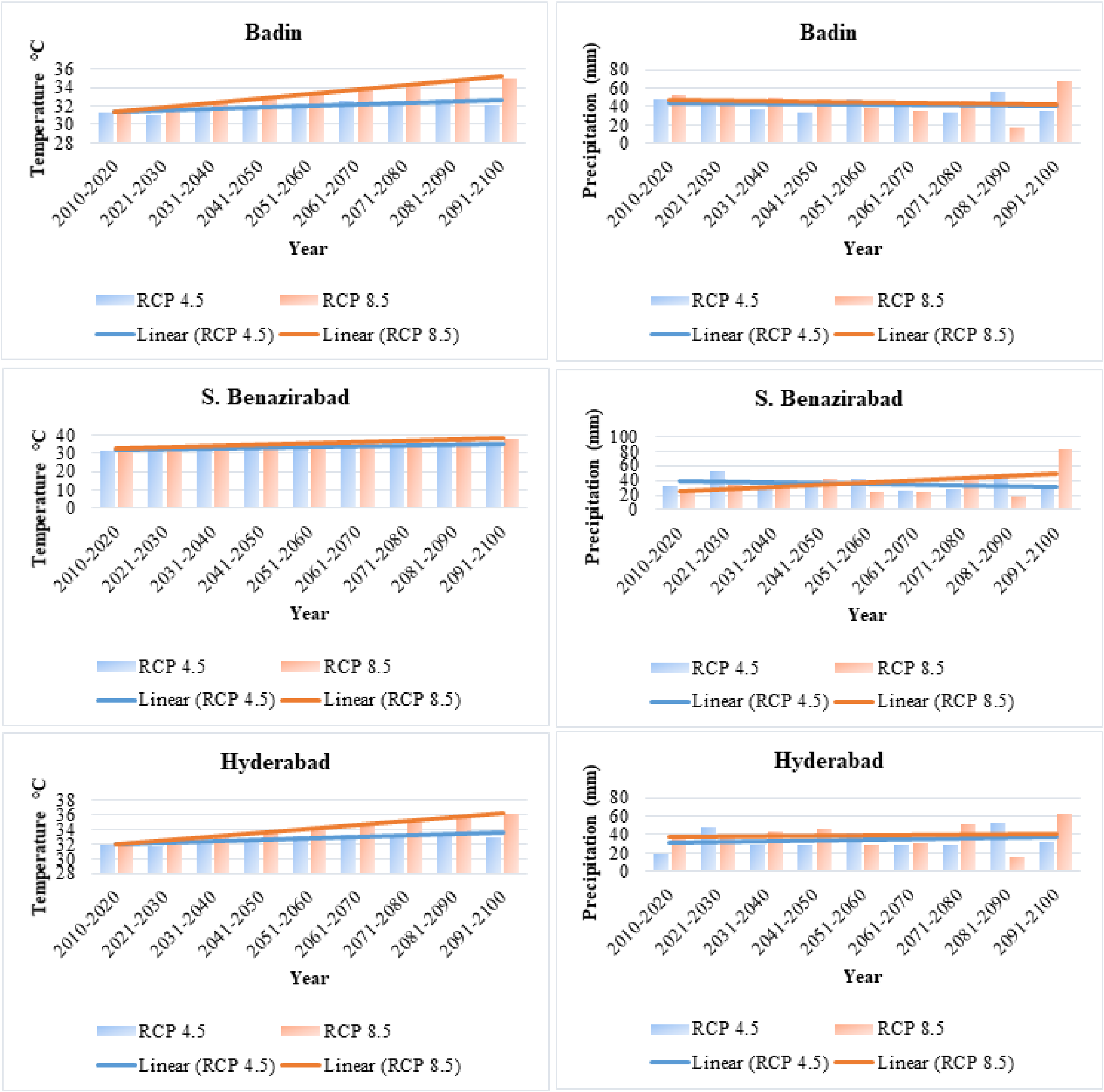


Figure 4.20: Decadal Projected Average Temperature & Precipitation till End of 21st Century under RCP 4.5 & 8.5 (Cotton – Zone E)

In RCP 4.5 within the cotton crop growing season there is a positive change in precipitation, with the exception of a decrease in the decade 2099 – 2100 in districts Multan and Bahawalpur. In RCP 8.5, there is an increase in precipitation throughout the projected period. In terms of temperature change, there is a continual rise, the final increase is 2 – 4.8°C, and 5 – 8.6°C in RCP 4.5, and 8.5 respectively. The warming accelerates in the second half of the century.

4.6. Percentage relative change in crop productivity of wheat, rice & cotton crop in Y2006 – 2016

The overall inclination of crop productivity is towards a positive growth throughout the study period. With some years showing greater increase than others (Tables 4.14 – 4.16). It is important to understand that there are a number of inputs that constitute the final yield of crops. Ranging from climatic conditions, technological/mechanical development, fertilizer intake, pesticide use, seed variety, soil type, water irrigation (availability & quality), cultivated area utilized, and policy/market incentives (Burney & Ramnathan 2014, Bruinsma *et al.,* 1983). Although, crop productivity seems to increase positively domestically, on the global level Pakistan has one of the lowest growing productivity (Pakistan Business Council, 2018).

Factors responsible for slow growth in productivity, include lack of annual per capita availability of water in Pakistan, change in climate, pollution, lack of upgradation of technology & infrastructure, seed variety, and land management (Murgai *et al.,* 2001; Aslam, 2016; FAO, 2018). This current study uses a multivariate regression model to analyse the impact of change in temperature, precipitation and tropospheric ozone on the productivity of wheat, cotton, and rice crop.

Table 4.14: Percentage Relative Change in Wheat Crop Productivity (kg/hectares) w.r.t baseline period 1981 – 2005

District	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**
Bahawalnagar	54.5	30.8	46.0	-	59.4	50.2	52.4	55.0	60.6	55.8	66.9
Bahawalpur	39.1	23.2	43.2	-	50.3	52.5	43.4	44.5	45.6	54.2	62.6
Faisalabad	32.4	12.0	24.8	-	35.0	29.9	33.2	34.5	36.6	34.2	39.9
Jhelum	60.1	23.2	54.7	-	43.4	5.3	36.4	23.8	50.6	70.6	35.6
Lahore	9.2	1.8	3.9	-	19.2	24.8	28.4	21.6	13.9	23.9	31.0
Multan	30.7	6.5	35.4	-	28.9	19.2	33.3	35.4	38.6	38.8	48.7
Sialkot	36.6	34.5	38.1	-	41.8	55.9	60.7	62.0	60.7	31.4	37.5
Badin	80.9	76.2	86.2	-	97.9	82.6	104.3	102.7	-	-	-

Hyderabad	33.0	98.2	62.5	-	61.7	59.9	55.4	53.2	-	-	-
Jacobabad	118.7	84.5	85.7	-	108.0	87.4	60.8	92.4	-	-	-
S. Benazir Abad	30.0	29.0	28.5	-	57.7	42.5	37.1	43.9	-	-	-

Table 4.15: Percentage Relative Change in Rice Crop Productivity (kg/hectares) w.r.t baseline period 1981 – 2005

District	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
Bahawalnagar	54.2	44.6	49.2	-	67.5	68.2	77.1	73.6	73.4	63.6	67.2
Bahawalpur	23.2	1.0	21.9	-	20.6	13.2	17.0	12.4	36.4	44.7	32.4
Faisalabad	17.2	30.8	29.6	-	47.7	38.8	49.5	41.4	47.2	46.1	52.8
Jhelum				-							
Lahore	21.7	41.8	46.2	-	37.4	37.5	48.3	54.1	49.3	44.5	36.4
Multan	7.6	28.5	15.5	-	46.3	24.1	41.0	21.4	37.5	44.5	48.4
Sialkot	258.1	269.7	48.8	-	41.8	55.2	60.8	52.3	47.5	50.7	52.7
Badin	-16.2	63.2	117.7	-	159.4	-0.3	174.3	168.7	-	-	-
Hyderabad	-4.7	8.0	60.2	-	81.6	16.4	84.4	77.8	-	-	-
Jacobabad	30.2	28.4	55.5	-	-13.2	48.2	39.0	57.1	-	-	-
S. Benazir Abad	63.2	46.9	104.5	-	101.7	64.5	109.0	94.8	-	-	-

Table 4.16: Percentage Relative Change in Cotton Crop Productivity (kg/hectares) w.r.t baseline period 1981 – 2005

District	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
Bahawalnagar	47.3	26.1	44.4	-	35.8	63.3	56.6	57.8	55.4	22.5	35.5
Bahawalpur	31.5	9.7	20.6	-	11.5	32.6	18.8	18.6	26.9	-8.6	21.1
Multan	26.6	16.7	16.5	-	5.8	40.6	33.1	26.7	32.1	-37.2	1.8
Badin	164.1	136.8	259.9	-	429.3		325.0	245.4	-	-	-
Hyderabad	35.0	23.4	141.6	-	176.4	278.5	119.2	104.3	-	-	-
S. Benazir Abad	35.8	32.0	58.6	-	121.6	214.6	102.8	81.9	-	-	-

4.7. Regression model results

Table 4.17: Harris-Tzavalis unit root test results

Wheat			
Variable	**Statistic**	**z**	***p value***
Rho (Crop Productivity)	0.852	-1.994	0.02
Rho (Temperature)	0.176	-26.43	0.00
Rho (Precipitation)	0.270	-23.05	0.00
Rho (Ozone)	-0.419	-12.30	0.00
Rice			
Rho (Crop Productivity)	0.697	-7.46	0.00
Rho (Temperature)	0.100	-27.79	0.00
Rho (Precipitation)	0.007	-30.98	0.00
Rho (Ozone)	0.158	-4.40	0.00
Cotton			
Rho (Crop Productivity)	0.848	-1.94	0.04
Rho (Temperature)	0.202	-18.83	0.00
Rho (Precipitation)	0.009	-23.93	0.00
Rho (Ozone)	0.097	-6.32	0.00

The Harris – Tzavalis test (Table 4.17) shows whether there is a systematic pattern that is unpredictable in the time –series (**unit root**). A p-value below 0.05 and z test above 1.92 allows the null hypothesis to be rejected, suggesting that there is no unit root in the data. The Pearson's Chi-Squared Test tests the null hypothesis that the variables are independent. The overall value calculated averages to 0.234 (agreeing with previous study by Bhutto & Ming 2013), thus, there is no significant dependence between the two independent variables. The null hypothesis is accepted and hence there is no issue of multicollinearity.

Table 4.18: Haussmann Test Results for Climate Variables

Crop	Prob > Chi²	Model Selected
Wheat	0.01	Fixed Effect
Rice	0.01	Fixed Effect
Cotton	0.13	Random Effect

The Haussmann tests (Table 4.18) for testing endogeneity that is whether the ‘over-time error’ has any correlation with the observed explanatory variables. The null hypothesis states that error term is uncorrelated with observed valuables, hence random effect model is the preferred model. In the case that Prob > Chi² is less than 0.05 (i.e. significant) the null hypothesis is rejected & Fixed Effect Model is used to undertake the regression (Torres-Reyna, 2007, Green 2008).

Table 4.19: Pooled Data for Punjab and Sindh (Wheat, Rice and Cotton)[1]

Variable	**Model I**	***p value***	**Model II**	***p value***	**Model III**	***p value***
Wheat						
Temperature (T)	**231.73 (6.76)**	**0.000**	1191 (2.55)	0.011	**231.67 (6.77)**	**0.000**
Precipitation (P)	2.79 (0.94)	0.349	4.51 (1.47)	0.144	10.52 (1.62)	0.106
T^2			**-24.58 (-2.06)**	**0.042**		
P^2					-0.11 (-1.34)	0.182
Rice						
Temperature (T)	**193.0 (3.30)**	**0.001**	**1704.93 (2.26)**	**0.03**	**195.36 (3.33)**	**0.001**
Precipitation (P)	0.083 (0.07)	0.946	0.205 (0.17)	0.87	2.360 (0.92)	0.358
T^2			**-25.83 (-2.01)**	**0.044**		
P^2					-0.012 (-1.01)	0.312
Cotton						
Temperature (T)	**121.73 (4.48)**	**0.000**	**3005.83 (2.09)**	**0.036**	**120.06 (4.37)**	**0.000**
Precipitation (P)	1.58 (1.42)	0.157	1.68 (1.52)	0.129	0.550 (0.20)	0.838
T^2			**-46.97 (-2.01)**	**0.044**		
P^2					- 0.013 (0.42)	0.674

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[1] N.B The value within parenthesis denotes the t-statistic in Wheat & Rice Tables, & z-statistic in cotton table

Table 4.20: Statistics for Pooled Panel Data for Districts of Punjab & Sindh

	Wheat			*Rice*			*Cotton*		
Statistic	Crop Productivity (kg/hectares)	Temperature (°C)	Precipitation (mm)	Crop Productivity (kg/hectares)	Temperature (°C)	Precipitation (mm)	Crop Productivity (kg/hectares)	Temperature (°C)	Precipitation (mm)
Mean	2224.7	19.6	14.8	1722.7	29.1	46.70	609.06	30.6	23.4
Minimum	598.9	15.4	0.1	763.5	24.4	0.10	113.39	28.9	0.1
Maximum	4725.2	23.2	86.7	4446.1	33.4	262.6	1971.8	33.4	114.2
Standard Deviation	696.6	16.1	1.7	741.1	2.0	46.7	282.0	0.7	18.0

Table 4.21: Diagnostics tests for pooled panel data for districts of Punjab & Sindh

Test	Wheat	Rice	Cotton
R Squared	0.47	0.41	0.13
Adjusted R Squared	0.46	0.39	0.10
F statistic	23.34	5.79	10.24
Probability (F –stat)	0.000	0.003	0.001

Table 4.22: The optimum average temperature & precipitation values for crop growing season retrieved from coefficients of (T, T^2, P and P^2) generated by regression model

Variable	Optimum Average Temperature (°C)	Optimum Average Precipitation (mm)
Wheat	24.23	47.8
Rice	33.00	98.33
Cotton	32.00	21.15

The diagnostic test results (Table 4.21) indicate that the models are satisfactory to produce statistically sound results, as the F test for all three models have values less than 0.05. The R squared and Adjusted R squared values indicate there is an average correlation between crop productivity, and the climate variables (temperature and precipitation) which can be attributed to non – availability of other input data at district level e.g. technological advancement (discussed in section 4.7), as well as the fact that we use a panel data set that, unlike time-series, normally give lower Adjusted R^2 values (i.e. less than 0.5).

Table 4.19 details the regression results generated from the regression models, for each crop and respective variables under study. The proceeding sub-sections elaborate the results further.

4.7.1 Wheat Crop

The Model I generated shows that crop productivity indicates a positive response to temperature 231.73 kg/ha increase in wheat crop with 1°C increase. Similarly, it shows a positive response to increasing rainfall; 1mm increase leads to an increase of 2.79 kg/ha wheat production. Model II gives a coefficient for T^2 at -24.58 kg/ha. The negative sign of coefficient, in the squared variable (extremes), specifies the presence of an inverted parabola; where values below the maxima of temperature/ precipitation show that productivity increases till maximum value is reached, after which further rise reduces productivity. This applies to precipitation as well. Therefore, using this coefficient the optimum average temperature can be obtained for wheat in the study area. After which any further increase in temperature will lead to a decline in production. The P^2 coefficient derived from Model III is -0.11 kg/ha. The thresholds calculated (Table 4.22) for wheat are the following; temperature is 24.3°C and precipitation is 47.8 mm.

4.7.2 Rice Crop

Model I calculates the temperature coefficient with productivity increase of 193.0 kg/ha per rise in 1°C. The precipitation leads to rising productivity of 0.083 kg/ha per mm increase. Model II gives an output for T^2 as -25.83 kg/ha, Model III generates P^2 coefficient as -0.012 kg/ha. That is in case of 'extremes' the productivity starts to fall. The thresholds calculated (Table 4.22) for rice are the following; temperature is 33.0°C and precipitation is 98.33 mm.

4.7.3 Cotton Crop

With Model I the temperature coefficient is + 115.3 kg/ha with one degree increase. The precipitation is + 1.90 kg/ha per mm increase. Model II gives an output for T^2 as -44.28 kg/ha, Model III resultant P^2 coefficient is -0.019 kg/ha. The thresholds calculated (Table 4.22) for cotton are the following; temperature is 32.1°C and precipitation is 11.21 mm.

It is important to note that in all crop models, the temperature variable is statistically significant. These findings are consistent with earlier studies including; Ali *et al.* (2017) and Siddiqui *et al.* (2011). Conversely, precipitation is observed as statistically insignificant in all cases. Interestingly, these findings are also consistent with earlier studies such as; Burney & Ramnathan (2014), Exenberger *et al.* (2014), Javed *et al.* (2014), Hussain & Bangash (2017). This may imply that, the remaining water 'requirement' is met through the irrigation systems for attaining maximum output per hectare (Hussain & Bangash, 2017). Furthermore, weak statistical relationship between precipitation and crop productivity in a multiple regression, may occur due to the reduced sensitivity of the former variable in the presence of multiple soil types in different climatic zones, alternative irrigation sources and potential magnitude of measurement error in rainfall due to spatial heterogeneity (Lobell and Burke 2010, Lobell, 2008). Changes in precipitation are seldom the governing factor for productivity impact prediction, in the presence of more dominating factors, like temperature, and tropospheric ozone (Lobell & Asseng, 2017).

4.8 Identification of Vulnerable Crop Growing Areas under RCP 4.5 & 8.5

Vulnerable areas within the study area were demarcated, by classifying the temperature and precipitation data, in accordance to the thresholds calculated from regression model (Table 4.22). These are defined as areas identified that will have below optimum productivity for the respective crops (lower than current averages).

Figure 4.21 – 4.26[2] maps out the vulnerable areas to temperature (red areas) and precipitation (dark blue) in the wheat, rice and cotton production areas. It is evident that in all cases temperature exceeds the threshold, especially post mid-century. RCP 8.5, as is, paints a wary picture with complete depletion of suitable areas for crop growth towards the end of the century. Figure 4.21 illustrates that southern region of the study area (south Punjab & Sindh) is impacted more than the central/northern Punjab in wheat growing season, whereas, the pattern is reversed in rice growing season. Precipitation is largely, insignificant in terms of impact, in both rice (figure 4.24) and wheat (figure 4.25) season. Figure 4.23 & 4.26 indicates that cotton crop is greatly affected by change in both temperature and precipitation, with complete depletion of suitable areas from 2040 onwards. This is mainly due to the proximity of the minimum/average temperature to the threshold value, leaving behind a small window of avoidance of exceedance. Even though cotton can grow in hot climates, heat stress is a major constraint in production of cotton in various countries including Pakistan, thus any further rise in temperature, and water starvation, can deplete production (Houth, 2017, Raza and Ahmed, 2015).

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[2] See Annexure (p.78): study area map, with selected districts labelled.

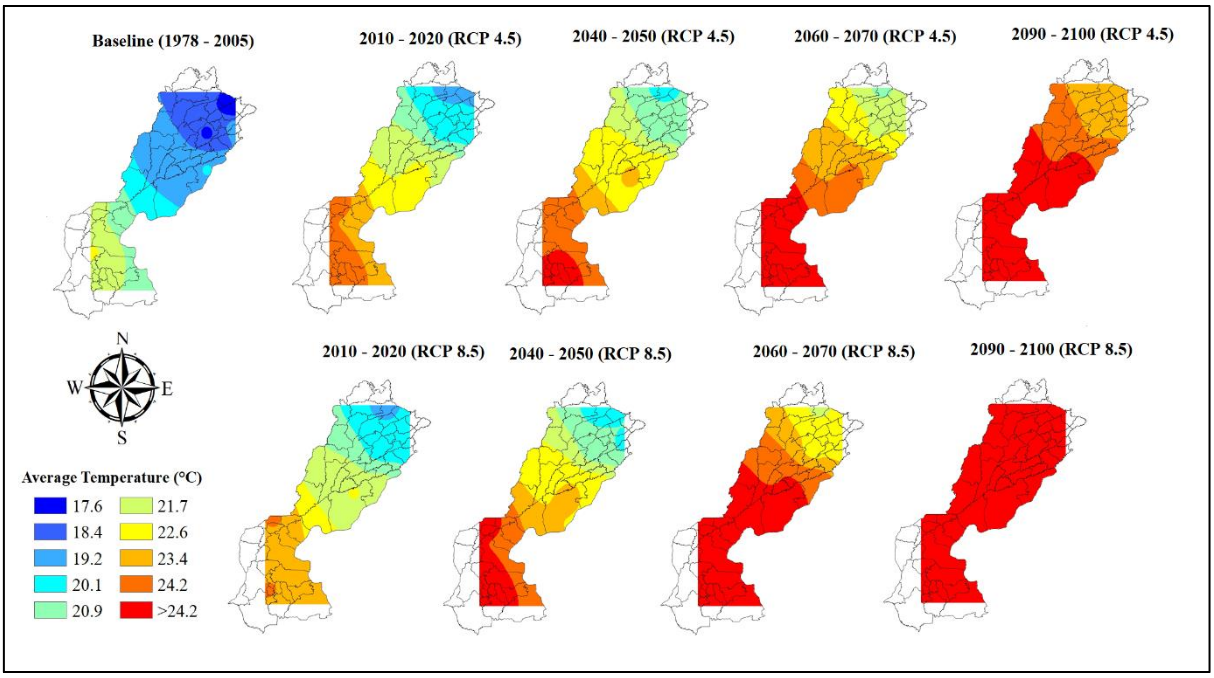

Figure 4.21: Average temperature in Wheat growing season under IPCC RCP 4.5 and 8.5. Decadal change of 2010 – 2020, 2040 – 2050, 2060 – 2070, 2090 - 2100

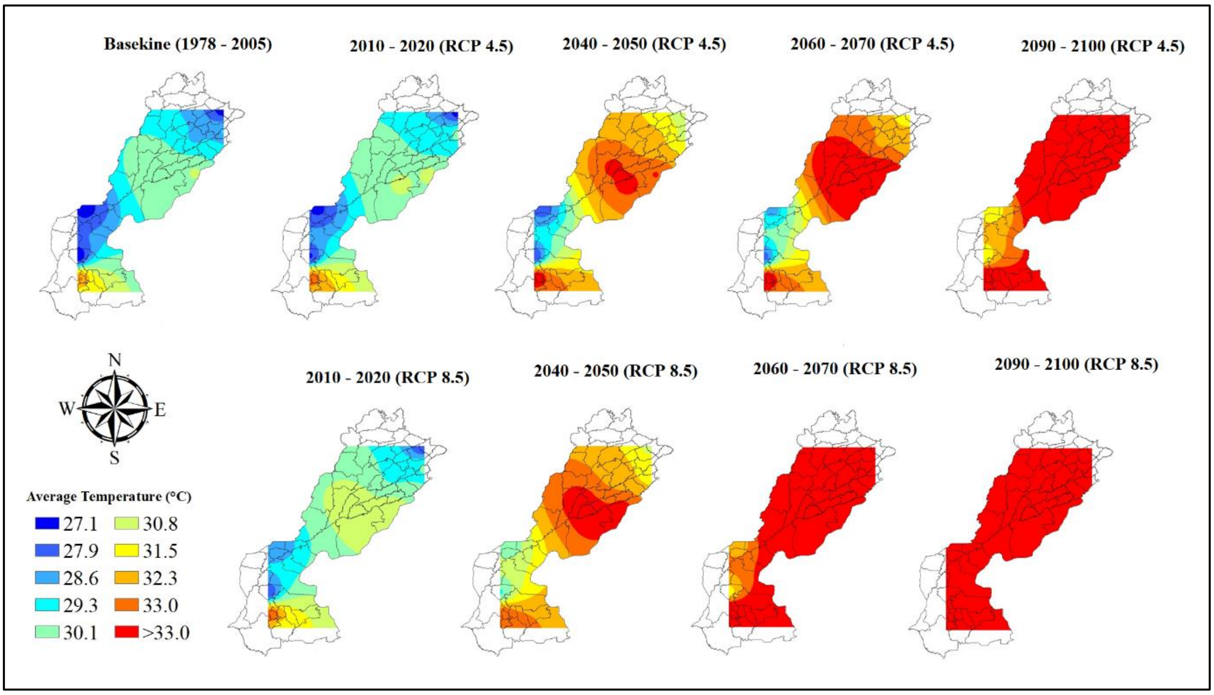

Figure 4.22: Average temperature in Rice growing season under IPCC RCP 4.5 and 8.5. Decadal change of 2010 – 2020, 2040 – 2050, 2060 – 2070, 2090 - 2100

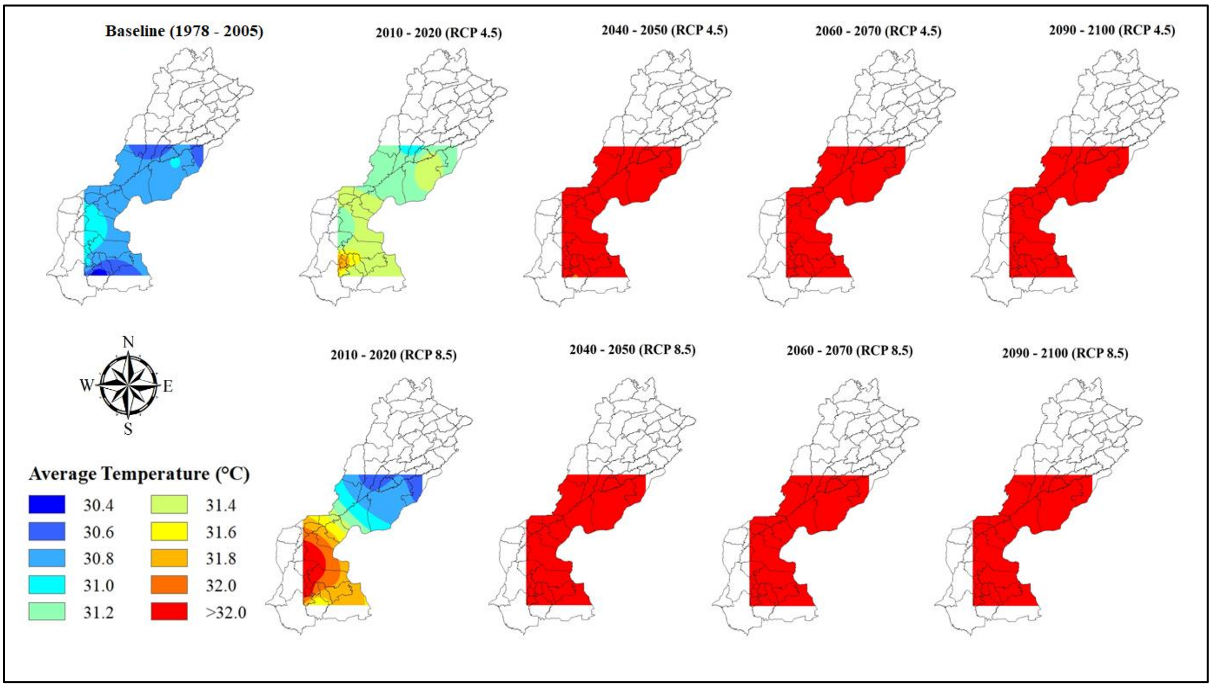

Figure 4.23: Average temperature in Cotton growing season under IPCC RCP 4.5 and 8.5. Decadal change of 2010 – 2020, 2040 – 2050, 2060 – 2070, 2090 - 2100

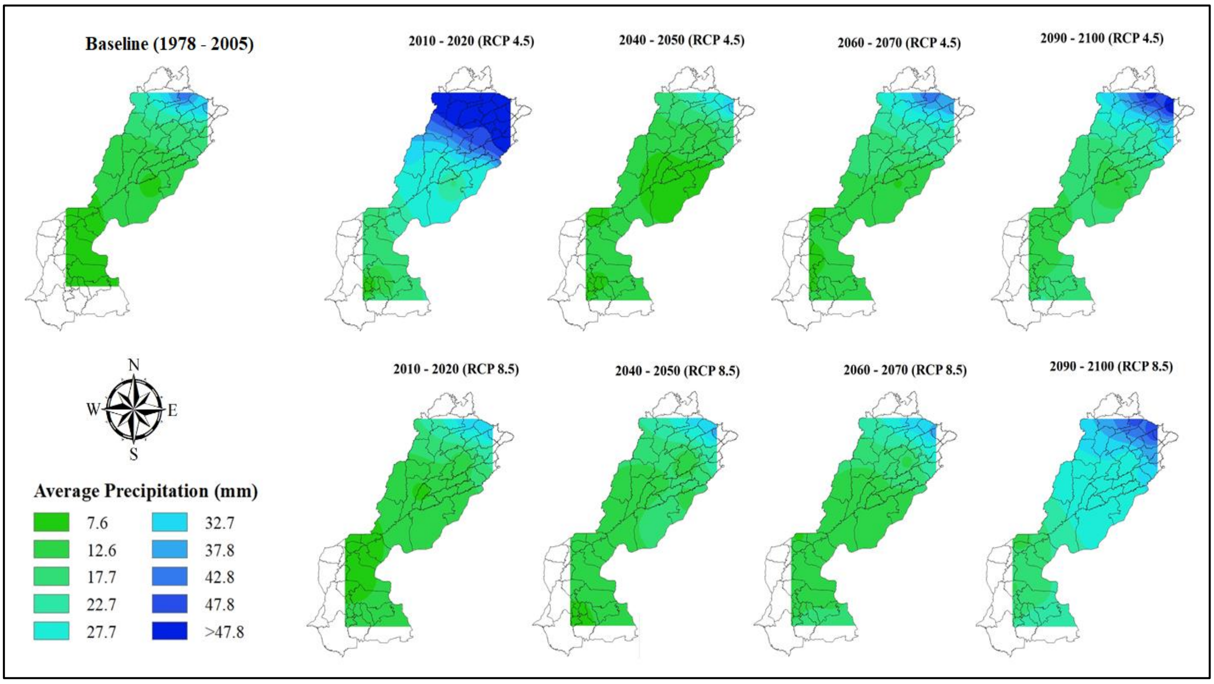

Figure 4.24: Average precipitation in Wheat growing season under IPCC RCP 4.5 and 8.5. Decadal change of 2010 – 2020, 2040 – 2050, 2060 – 2070, 2090 - 2100

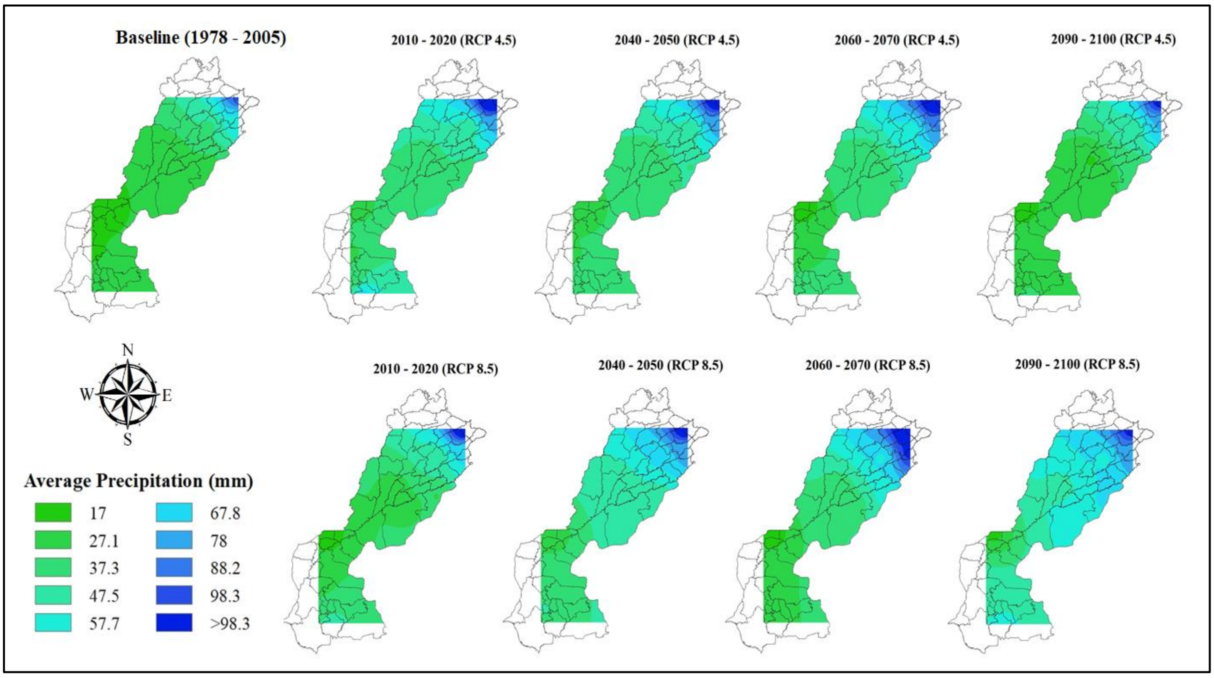

Figure 4.25: Average precipitation in Rice growing season under IPCC RCP 4.5 and 8.5. Decadal change of 2010 – 2020, 2040 – 2050, 2060 – 2070, 2090 - 2100

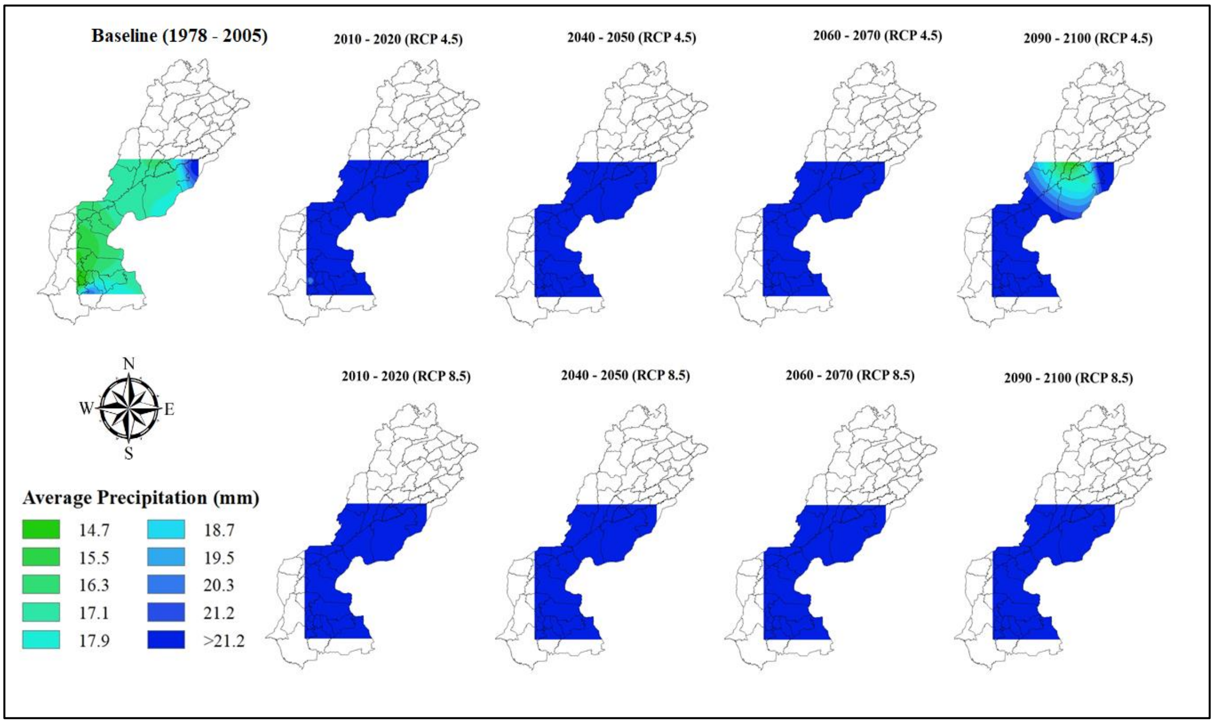

Figure 4.26: Average precipitation in Cotton growing season under IPCC RCP 4.5 and 8.5. Decadal change of 2010 – 2020, 2040 – 2050, 2060 – 2070, 2090 - 2100

4.9 Temporal Analysis of Tropospheric Ozone Concentrations over Punjab & Sindh

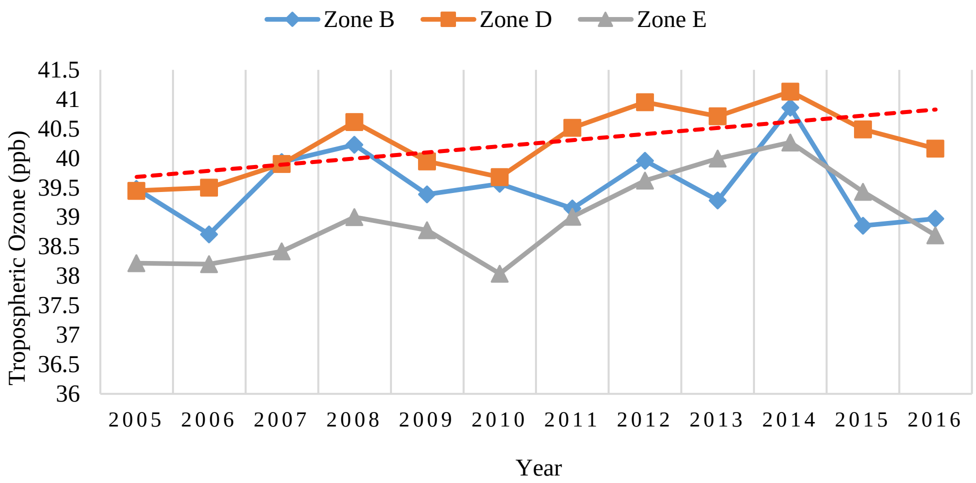

Figure 4.27 Tropospheric ozone concentration over study area 2005 – 2016

Chiefly the trend over the last decade in terms of tropospheric ozone within wheat growing season is increasing, with the exception of the districts in Zone B (see, Table 4.23). However, the Mann Kendall test shows that the trend is not statistically significant (p-value: 0.502). Rice crop season shows an increasing and statistically significant trend (p-value <0.0001), unanimously across all zones/districts under study. Average tropospheric ozone concentration within the cotton growing season is increasing (p-value: <0.0001) across the study area. The greatest rise is 9.37% in Zone E, over wheat growing season.

Table 4.23: Percentage Relative Change in Concentration of Tropospheric Ozone within Crop Growing Season (2005 – 2016)

Zone	Wheat	Rice	Cotton
B	-4.4	0.97	-
D	2.16	2.18	1.82
E	9.37	1.95	1.82

Table 4.24: Correlation between temperature, precipitation and tropospheric ozone.

Zone	Precipitation	Temperature
Wheat		
B	0.00	0.05
D	0.36	0.24
E	0.17	0.16
Rice		
B	0.08	0.002
D	0.06	0.02
E	0.05	0.07
Cotton		
D	0.03	0.01
E	0.03	0.08

There is no apparent significant relationship between temperature and precipitation, with tropospheric ozone, over the study period (2005 – 2016) in Punjab & Sindh. As is evident from the low R^2 values in Table 4.24. However, there is a seasonal pattern in place, as displayed in Figure 4.28; with peaks in the month of June and dips in December/January. This, pattern, however, can have a higher relation to number of sunny (UV-B flux) or clear days, than solely temperature spikes, as ozone fundamentally forms as a result of 'photo' chemical reactions (Noreen *et al.* 2018, Somvanshi, 2016). Climate warming and ozone are said to impact each other only in terms of increased biogenic emissions and rate of chemical processes (Fu *et al.*, 2015), there remains a lack of consensus in the atmospheric chemistry community, as to whether increasing temperature will enhance ground-level ozone levels (ASM, 2015). Determining variables, such as presence of precursor emissions, solar radiation (ultra-violet), atmospheric stagnation and circulation, all play an important part in providing an ideal environment for formation and total concentration of ozone produced in the troposphere (This is further discussed in proceeding paragraphs).

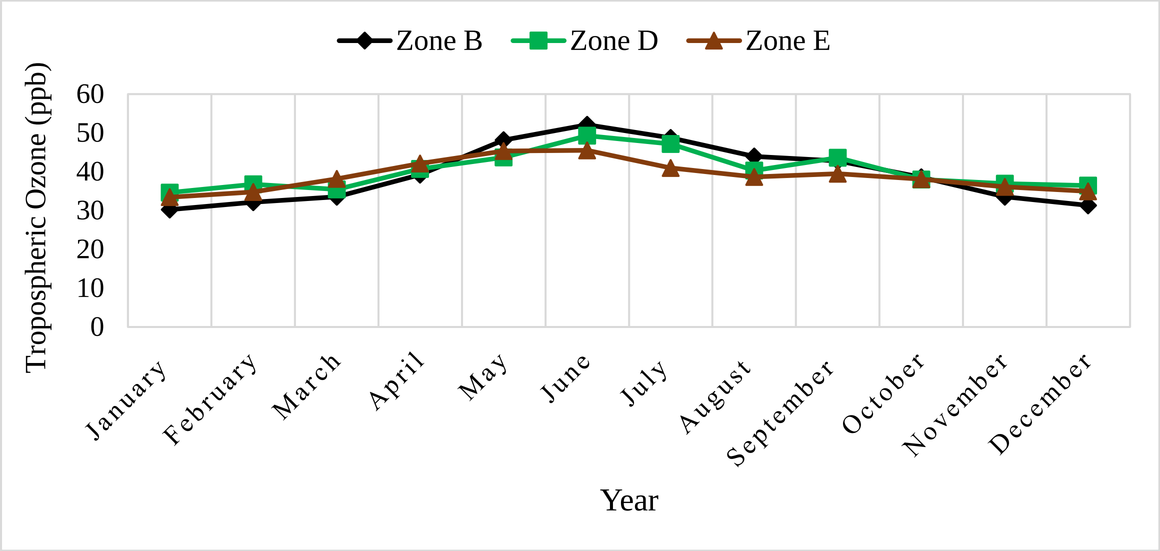

Figure 4.28: Seasonal variation in tropospheric ozone concentration over the study area (2005 - -2016)

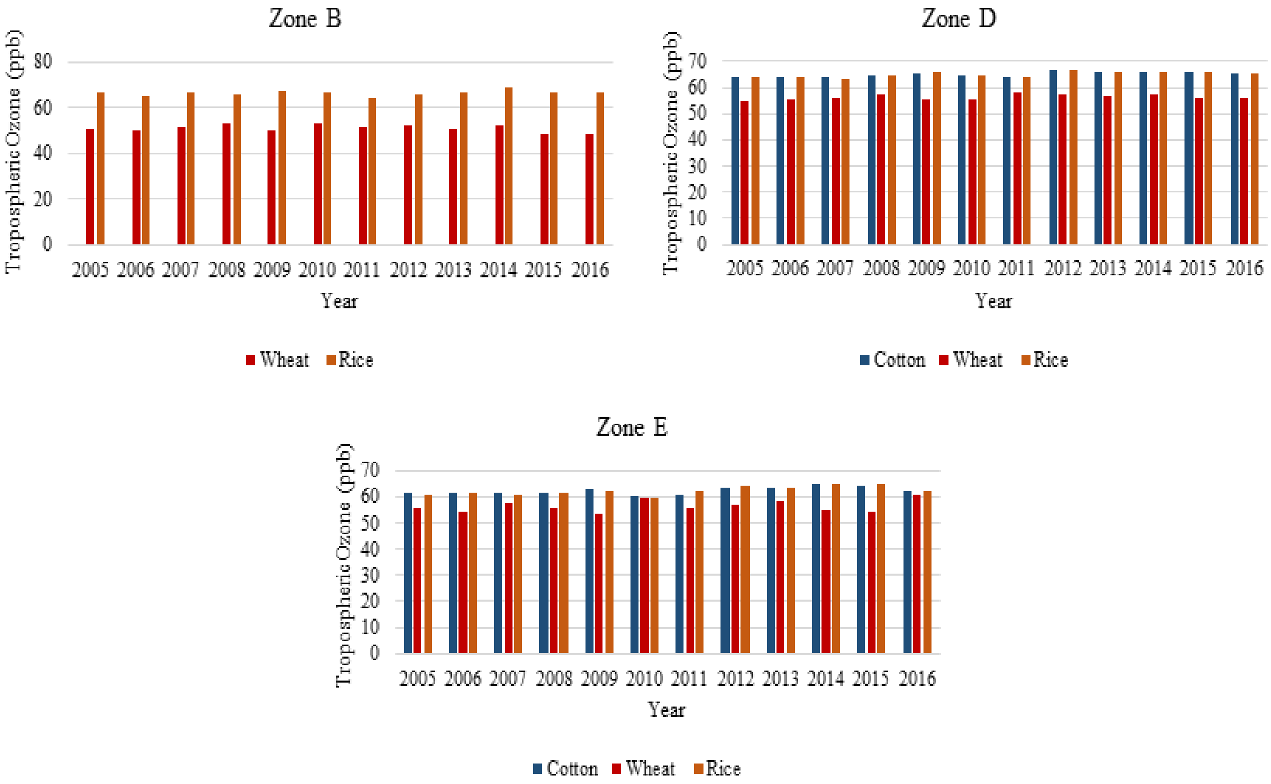

Figure 4.29: Variation in concentration of tropospheric ozone between crop seasons

Generally, tropospheric ozone exhibits relatively low levels in wheat growing season (winter), average of 54.78 ppb (Table 4.28). For rice and cotton growing season (summer) average concentration was 63 ppb, with maximum values of 68 ppb. This trend is in line with previous studies conducted by Tiwari *et al.*, (2008), Worden *et al. (*2009) and Noreen *et al. (*2018) that state maxima of tropospheric ozone occur in summer months (June), which also coincides with the Asian monsoon, whereas the minima is observed during the winter months (Figure 4.29).. This variation can be attributed to high temperatures, biomass fires, biogenic emissions of VOCs and actinic fluxes, coupled with trans-boundary movement of pollutant-ridden air masses (Khokhar *et al.*, 2015). Past studies observe that post-wheat harvesting contributes to around 51.7% of the total ozone abundance, whereas post-rice is 10%, resulting from crop residue burning in the province of Punjab (Noreen *et al.*, 2018)

4.10 Regression Model Results (Climate change & Tropospheric Ozone)

Table 4.25: Haussmann Test Results for Tropospheric Ozone Variable

Crop	Prob > Chi^2	Model Selected
Wheat	0.11	Random Effect
Rice	0.19	Random Effect
Cotton	0.21	Random Effect

Table 4.26: Pooled Data for Punjab and Sindh (Wheat, Rice and Cotton)[3]

Variable	Coefficient	P > z
Wheat		
Temperature (T)	66.59 (1.66)	0.096
Precipitation (P)	-1.61 (-0.47)	0.64
Tropospheric Ozone (O)	19.79 (1.31)	0.189
Rice		
Temperature (T)	-43.11 (-0.65)	0.519
Precipitation (P)	-2.61 (-1.10)	0.271
Tropospheric Ozone (O)	**-81.91** **(-2.09)**	**0.037**
Cotton		
Temperature (T)	27.06 (0.34)	0.73
Precipitation (P)	4.26 (1.89)	0.06
Tropospheric Ozone (O)	**-56.27** **(-3.25)**	**0.00**

Table 4.27: Diagnostic Tests over Study Period

Test	Wheat	Rice	Cotton
R Squared	0.341	0.250	0.267
Adjusted R Squared	0.321	0.222	0.223
F statistic	16.45	9.13	6.08
Probability (F –stat)	0.000	0.000	0.001

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[3] N.B The value within parenthesis denotes the z-statistic

Table 4.28: Statistics for Pooled Panel Data for Districts of Punjab & Sindh

Statistic	Crop Productivity (kg/hectares)	Temperature (°C)	Precipitation (mm)	Ozone (ppb)
Wheat				
Mean	2224.7	19.6	14.8	54.78
Minimum	598.9	15.4	0.1	46.79
Maximum	4725.2	23.2	86.7	62.94
Standard Deviation	696.6	16.1	1.7	3.37
Rice				
Mean	1722.7	29.1	46.70	63.67
Minimum	763.5	24.4	0.10	59.59
Maximum	4446.1	33.4	262.6	68.20
Standard Deviation	741.1	2.0	46.7	2.24
Cotton				
Mean	609.06	30.6	23.4	63.67
Minimum	113.39	28.9	0.1	59.59
Maximum	1971.8	33.4	114.2	68.20
Standard Deviation	282.0	0.7	18.0	2.24

Haussmann Test results (Table 4.25) indicate that Random Effects Model is the correct model to utilize for regressing ozone against crop productivity. The diagnostic results favour the appropriateness of the produced results (Table 4.27). The model demonstrates the association between tropospheric ozone and crop productivity (Table 4.26). The estimated relationship between ozone and wheat productivity is positive, however statistically insignificant: *p* value, >0.05 (see also, Burney & Ramanathan, 2014; Yi *et al.,* 2015). In the study region; the wheat growing season has the lowest level of tropospheric ozone concentrations observed. Moreover, wheat grown in winter is not impacted by ozone as much as wheat grown in spring, due to the time of the year, ozone concentrations and temperature within growing period (see also, Burney & Ramanathan, 2014; Aunan *et al.,* 2000; Mulholland 1997; Lesser *et al.,* 1990). When only the districts of Punjab are included in the panel, the estimate, however, depicts a negative coefficient of -9.85 kg/ha (*p* value: >0.05). This indicates adverse impact of tropospheric ozone on wheat productivity. However, for the panel including Sindh only, the coefficient remains positive and statistically insignificant. This variation in impact within two provinces may be attributed to the difference in growing months (in lower Sindh (Zone E), wheat is harvested in March), when concentrations are comparatively lower than Punjab.

Rice and cotton crops both show statistically significant decrease in crop productivity in the presence of tropospheric ozone (81.26 and 56.27 kg/ha decrease per increase in 1ppb, respectively). This can be due to their growing seasons coinciding with the highest concentration levels of tropospheric ozone (60–68 ppb). Ozone sensitivity is another factor that can contribute to yield loss. Studies by National Crop Loss Assessment Network USA, depict that dicot (e.g., cotton) are more sensitive to loss in yield than monocot species of crops (e.g., wheat) in the presence of tropospheric ozone (Heagle, 1989).

Interestingly, the estimates of temperature change to statistically insignificant with the inclusion of the tropospheric ozone variable. This could be due to the masking effect of the ozone on the temperature. This is despite that no multicollinearity was detected statistically (variance inflation factor values <5), but an inherent relationship does exist between the two, as illustrated by the seasonal variation. Studies in the past, have shown that impacts of climate variables are undermined in the presence of the dominant air pollution inputs (Burney & Ramanathan, 2014; Wang, 2005). Nevertheless, impacts of all contributing factors need to be simultaneously assessed for their full impact on crop productivity.

Chapter 5: Conclusions & Recommendations

5.1 Conclusions

Results discussed in chapter 4 and aforementioned findings lead to the following conclusions:

1. Temperature in all climatic zones is increasing within the 2006–2016 decade over regions under study. Downscaled regional forecasts suggest that under RCP 4.5 and RCP 8.5 temperature may increase 3° to 10°C in all crop growing seasons by the end of 21st century;
2. Precipitation has high inter–annual variability with no distinct pattern, and observed changes are statistically insignificantly.
3. Tropospheric ozone has predominantly intensified over time within rice and cotton growing districts of Punjab and Sindh.
4. Regression results indicate that wheat, rice and cotton productivity is significantly and positively impacted by rise in temperature until it reaches the threshold level, precipitation has a similar impact but is statistically insignificant
5. Future temperature and precipitation projections under RCP 4.5 & 8.5 show, that the study area is highly vulnerable to changes in temperature, and in future suitable areas will be limited for ample productivity (especially for cotton) in Pakistan.
6. Tropospheric ozone emerges as a highly dominant damaging factor, especially for the productivity of rice and cotton crops.

Conclusively, findings of this study suggest that the mitigation of tropospheric ozone pollution, and climatic variables are important in terms of increasing crop productivity, and thus abating future food crises.

5.2 Recommendations

Having identified and quantified the potential impact of the three variables under study, it is evident that policies need to be carved to retard, if not diminish the causative factors. It necessitates management of cropland and rigorous study of indigenous agricultural applications. Practices like improvement and diversification of crop varieties (increasing tolerance), updating crop calendars and rotations, climate-smart agricultural practices (aiding decision-making), and recognition of the importance of incorporation of holistic farming and technology. In terms of abating tropospheric ozone and related short-lived pollutants, stringent pollution control techniques and standards need to be introduced. Prior to which identification of point and non-point sources of said pollutants is required. Integrative studies comprising crop models such as DSSAT in collaboration with statistical models, as used in this current research, can further enable a more accurate picture of crop productivity from small scale to large scales.

Above all, greater research is required, aided by creation of baseline emission, and data inventories, which are currently lacking. This study would provide a more comprehensive impact assessment if long-term data, at district level, are available on agricultural technology used, infrastructure, fertiliser intake, pesticide usage, daily monitored tropospheric ozone (both satellite and on–site), etc. Nevertheless, this research provides apt indication and direction for planning and strategizing sustainable crop productivity in future.

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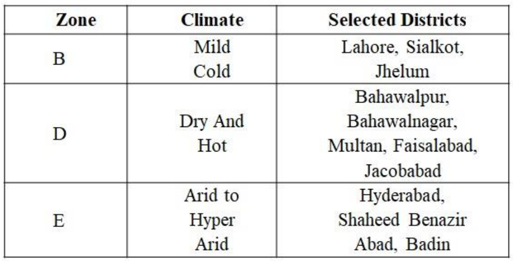
Annexure

Selected Districts Under Study (Punjab & Sindh)



Zone	Climate	Selected Districts
B	Mild Cold	Lahore, Sialkot, Jhelum
D	Dry And Hot	Bahawalpur, Bahawalnagar, Multan, Faisalabad, Jacobabad
E	Arid to Hyper Arid	Hyderabad, Shaheed Benazir Abad, Badin

Mann Kendall Test p-value results

District Name	Precipitation	Temperature
Bahawalpur	0.610	0.001
Bahawalnagar	0.536	<0.0001
Multan	0.351	0.010
Faisalabad	0.973	0.001
Sialkot	0.368	0.001
Lahore	0.277	0.004
Jhelum	0.601	0.004
Jacobabad	0.269	0.001
Badin	0.156	0.000
Hyderabad	0.586	0.405
S. Benazir Abad	0.506	0.012

Crop	Crop Productivity	Tropospheric Ozone
Wheat	0.002	0.502
Rice	<0.0001	<0.0001
Cotton	0.002	<0.0001

Variance Inflation Factor

Wheat	
Variable	**VIF**
Precipitation	2.06
Temperature	1.51
Ozone	1.46
Mean VIF	1.67

Rice	
Variable	**VIF**
Precipitation	1.58
Temperature	1.48
Ozone	1.38
Mean VIF	1.48

Cotton	
Variable	**VIF**
Precipitation	1.10
Temperature	1.10
Ozone	1.00
Mean VIF	1.07

Climate Variables (Temperature & Precipitation) Regressed Against Crop Productivity

A. Pooled Panel Data for Districts (Zone B) Mild Cold

Wheat Fixed Effect Model; Haussmann Test = 0.000						
Variable	Model – 1	P > t	Model – 2	P > t	Model – 3	P > t
Temperature (T)	**235.20 (4.08)**	**0.000**	1572.6 (1.69)	0.093	**236.40 (3.94)**	**0.000**
Precipitation (P)	2.23 (0.73)	0.465	2.54 (0.84)	0.404	2.94 (0.30)	0.762
T^2			-36.5 (1.44)	0.152		
P^2					-0.008 (-0.08)	0.938

Rice Fixed Effect Model; Haussmann Test = 0.040						
Variable	Model – 1	P > t	Model – 2	P > t	Model – 3	P > t
Temperature (T)	**463.3 (2.64)**	**0.010**	**9315 (2.15)**	**0.035**	**508.88 (2.87)**	**0.006**
Precipitation (P)	2.39 (1.23)	0.224	2.27 (1.20)	0.236	12.35 (1.65)	0.104
T^2			**-160.42 (-2.04)**	**0.045**		
P^2					-0.035 (-1.38)	0.174

B. Pooled Panel Data for Districts (Zone D) Dry & Hot

Wheat Fixed Effect Model; Haussmann Test = 0.000						
Variable	Model – 1	P > t	Model – 2	P > t	Model – 3	P > t
Temperature (T)	**301.3 (6.14)**	**0.000**	**1655.7 (2.07)**	**0.040**	**300.82 (6.11)**	**0.000**
Precipitation (P)	**12.28 (2.28)**	**0.024**	**13.67 (2.53)**	**0.012**	18.33 (1.15)	0.251
T^2			-35.1 (-1.7)	0.092		
P^2					-0.18 (-0.40)	0.686

	Rice Fixed Effect Model; Haussmann Test = 0.000					
Variable	Model – 1	P > t	Model – 2	P > t	Model – 3	P > t
Temperature (T)	**189.8 (4.11)**	**0.000**	**3325 (4.60)**	**0.000**	**185.41 (4.04)**	**0.000**
Precipitation (P)	**5.67 (3.60)**	**0.000**	**6.05 (4.05)**	**0.000**	**11.84 (3.02)**	**0.003**
T^2			**- 52.70 (4.35)**	**0.000**		
P^2					-0.069 (-1.72)	0.088

	Cotton Fixed Effect Model; Haussmann Test = 0.007					
Variable	Model – 1	P > t	Model – 2	P > t	Model – 3	P > t
Temperature (T)	**81.57 (3.41)**	**0.001**	1216 (1.20)	0.233	**82.03 (3.40)**	**0.001**
Precipitation (P)	0.72 (0.70)	0.483	0.80 (0.78)	0.435	0.058 (0.02)	0.986
T^2			-18.46 (-1.12)	0.265		
P^2					0.0095 (0.21)	0.831

C. Pooled Panel Data for Districts (Zone E) Arid to Hyper Arid

Wheat Random Effect Model; Haussmann Test = 0.560						
Variable	Model – 1	P > z	Model – 2	P > z	Model – 3	P > z
Temperature (T)	140.37 (1.64)	0.100	1317 (0.71)	0.480	143.97 (1.68)	0.092
Precipitation (P)	25.99 (1.47)	0.141	24.98 (1.41)	0.160	56.93 (1.63)	0.103
T^2			-28.4 (-0.63)	0.527		
P^2					-1.284 (1.02)	0.305

	Rice Random Effect Model; Haussmann Test = 0.56					
Variable	Model – 1	P > z	Model – 2	P > z	Model – 3	P > z
Temperature (T)	19.12 (0.59)	0.557	332.45 (0.29)	0.772	15.98 (0.49)	0.627
Precipitation (P)	-5.31 (-1.9)	0.056	-5.50 (-1.91)	0.056	-1.08 (-0.17)	0.865
T^2			-5.38 (-0.27)	0.784		
P^2					-0.032 (-0.74)	0.472

	Cotton Random Effect Model; Haussmann Test = 0.72					
Variable	Model – 1	P > z	Model – 2	P > z	Model – 3	P > z
Temperature (T)	**156.3 (3.37)**	**0.001**	**8060 (2.49)**	**0.013**	**156.98 (3.32)**	**0.001**
Precipitation (P)	2.398 (1.34)	0.180	2.64 (1.51)	0.131	2.75 (0.64)	0.525
T^2			**-128 (-2.44)**	**0.015**		
P^2					-0.004 (-0.09)	0.929

Pooled Panel Data for Districts of Climatic Zone B Summary						
	Wheat			***Rice***		
Statistic	**Crop Productivity (kg/hectares)**	**Temperature (°C)**	**Precipitation (mm)**	**Crop Productivity (kg/hectares)**	**Temperature (°C)**	**Precipitation (mm)**
Mean	2032.73	18.24	34.45	1492.67	27.7	115.73
Minimum	598.90	15.35	4.00	852.84	25.73	42.92
Maximum	3209.79	20.68	93.7	4446.13	29.85	262.58
Standard Deviation	646.31	1.26	18.16	594.18	0.96	47.38

Pooled Panel Data for Districts of Climatic Zone E (Diagnostics Tests)			
Test	***Wheat***	***Rice***	***Cotton***
R Squared	0.050	0.034	0.111
Adjusted R Squared	0.029	0.017	0.092
F statistic	2.59	1.84	6.00
Probability (F –stat)	0.08	0.164	0.003

Pooled Panel Data for Districts of Climatic Zone D Summary

Statistic	*Wheat*			*Rice*			*Cotton*		
	Crop Productivity (kg/hectares)	**Temperature (°C)**	**Precipitation (mm)**	**Crop Productivity (kg/hectares)**	**Temperature (°C)**	**Precipitation (mm)**	**Crop Productivity (kg/hectares)**	**Temperature (°C)**	**Precipitation (mm)**
Mean	2213.64	19.27	10.91	1711.13	29.13	29.23	621.42	30.53	25.44
Minimum	1101.10	16.08	0.85	857.14	24.95	0.23	174.76	28.89	2.39
Maximum	3257.59	22.80	38.95	4223.28	33.3	109.68	925.30	33.42	77.58
Standard Deviation	583.84	1.36	7.56	708.81	1.41	21.24	161.93	0.654	15.75

Pooled Panel Data for Districts of Climatic Zone D (Diagnostics Tests)

Test	*Wheat*	*Rice*	*Cotton*
R Squared	0.046	0.450	0.10
Adjusted R Squared	0.034	0.440	0.10
F statistic	3.940	64.95	4.27
Probability (F –stat)	0.021	0.000	0.020

Pooled Panel Data for Districts of Climatic Zone E Summary

Statistic	*Wheat*			*Rice*			*Cotton*		
	Crop Productivity (kg/hectares)	**Temperature (°C)**	**Precipitation (mm)**	**Crop Productivity (kg/hectares)**	**Temperature (°C)**	**Precipitation (mm)**	**Crop Productivity (kg/hectares)**	**Temperature (°C)**	**Precipitation (mm)**
Mean	2534.38	21.35	3.20	1976.42	29.94	29.17	624.91	30.61	22.56
Minimum	934.98	17.3	0.08	763.456	24.36	0.10	113.39	29.08	0.10
Maximum	4725.19	23.16	35.33	4237.26	33.42	182.66	1971.78	32.34	114.24
Standard Deviation	816.21	0.95	4.60	839.55	2.66	31.11	379.21	0.80	20.63

Pooled Panel Data for Districts of Climatic Zone B (Diagnostics Tests)

Test	*Wheat*	*Rice*
R Squared	0.121	0.013
Adjusted R Squared	0.104	0.016
F statistic	7.22	0.44
Probability (F –stat)	0.001	**0.65**

Tropospheric Ozone (ppb) & Climate Change Regressed Against Crop Productivity (Punjab & Sindh) – Wheat Crop

Punjab only		
Variable	Coefficient	P > t
Temperature	-24.43	0.574
Precipitation	-4.05 (-1.35)	0.182
Ozone	-9.85 (-0.61)	0.546

Sindh only		
Variable	Coefficient	P > t
Temperature	175.3 (1.96)	0.06
Precipitation	14.98 (0.16)	0.163
Ozone	59.16 (1.82)	0.080

Test	*Punjab*	*Sindh*
R Squared	0.48	0.341
Adjusted R Squared	0.44	0.321
F statistic	17.90	16.45
Probability (F –stat)	0.000	0.000