The Past and Future Changes in Climate of the Rice-Wheat Cropping Zone in Punjab, Pakistan

Bokhari, S. A. A.[1, 2], G. Rasul[2], A. C. Ruane[3], G. Hoogenboom[4], A. Ahmad[5]

Abstract

Agriculture is ranked top among Pakistan economic sectors vulnerable to the potential impacts of climate change. The agricultural production system is directly affected by weather inputs (temperature, solar radiation, and rainfall) that are projected to change in future (following increases in carbon dioxide and other greenhouse gasses). Although Climatic extremes such as drought, floods and heat waves, are expected to increase with detrimental consequences for agriculture and livestock production, yet changes in mean climates also pose challenges to sustainable development. This study presents climate change results for five districts within the major rice-wheat productivity zone of Punjab province in Pakistan. The results are focused on RCP8.5 mid-century (2040-2069) scenarios derived from five global climate models (GCMs) output and the Kharif (June-October) and Rabi (November-April) seasons. Analysis of recent historical weather data of Sialkot and Sheikhupura districts shows an increase in minimum temperatures and maximum temperatures and a large variation in rainfall. This temperature change and variability in rainfall are expected to enhance further as we approach 2050s. The mean maximum temperature is projected to increase by 2-2.5 ºC during the rice growing (Kharif) season and 2.4-2.7ºC during the wheat growing (Rabi) season. Rainfall during the rice growing season is more uncertain, with projections indicating an increase of 25%-35 % in the study region, while a minimal change is expected during the Rabi season. Climax of the rice growing season corresponds with the projected increase in monsoon intensity, leaving no doubt about the crop water demand satisfaction. However, a simultaneous increase in the day and night temperature may affect the growth and development of some critical phenological stages and thus could impact final yield.

Key Words: Climate Change, Rice-Wheat Cropping System, Delta Scenarios, GCMs, Model Bias

Introduction

Climate plays a key role in the food productivity providing requisite water supplies, reclaiming soil fertility and regulating the optimum environmental conditions for growth and development. Any change in climatic parameters beyond the optimum limits at different phenological phases may cause serious impacts on the economic yield. There is evidence of climate change on global and regional scales in the form of warming, sea level rise and extreme weather events. Such changes have impacted many regions of the world and several economic sectors. South Asia’s climate is already changing and impacts of climate change on water resources, food, health, biodiversity, forestry and socio-economic sectors can already be observed at many places and additional challenges are likely in the future (Field et al., 2014). The global mean temperature has already risen by 0.85°C from 1880 to 2012 (Hartmann et al., 2013). The amount of heat stored in the global oceans has amplified, and the global mean sea level has risen by 225 mm from 1880 to 2012 (Church et al., 2013). Annual average global atmospheric carbon dioxide concentrations reached 400 parts per million (ppm) in 2013 and concentrations of the other major greenhouse gasses responsible for global warming are at their highest levels for at least 800,000 years (Ciais et al., 2013). The occurrence of extreme meteorological events like high temperatures and heavy precipitation is expected to increase as a result of global warming, raising concern over how future climate change will impact natural and human systems. The Global Climate Risk Index 2014 placed Pakistan on 12th rank due to impacts of weather-related loss

---

[1] ahsan@pmd.gov.pk
[2] Pakistan Meteorological Department, Pitras Bukhari Road, Sector H-8/2, Islamabad, Pakistan.
[3] NASA Goddard Institute for Space Studies, New York, NY, USA.
[4] Institute for Sustainable Food Systems, University of Florida, Gainesville, Florida, USA.
[5] University of Agriculture, Faisalabad, Pakistan

events (Sönke et al., 2013). Time series of area weighted mean daily temperatures in Pakistan averaged over each year shows a sharp rise in temperature during the first decade of 21st century except the year 2005 (PMD, 2012). There is 0.6–1.0°C rise in mean temperature along the coastal areas of Pakistan since the early 1900s while 10–15% decline in rainfall in coastal areas and arid plains in the southern half of Pakistan below 30°N latitude (Farooq et al., 2004). The summer and winter precipitation, over the last 40 years, has increased in northern half Pakistan mainly along the foot-hills of the Himalayas.

Any change in local weather conditions due to climate change poses threats to the agricultural productivity. Major sources of climate change in Pakistan include sea level rise, glacial retreats, frequent and devastating floods, higher temperatures, increased frequency of heat waves and an increase in the occurrence of droughts. These climate change risks generate sequential challenges for present and future management as well as policy making and have a direct impact on agriculture, water resources, urban-rural management, and the overall economy. Both irrigated and rain-fed agriculture is vulnerable to extreme weather events. Heavy monsoon rainfall has caused severe recurring floods in major rivers of Pakistan since 2010. The rough monsoon season in 2012 produced flooding conditions killing over 650 people. Floods in 2010 were the worst for Pakistan causing nearly 3000 deaths and affected 20 million people (WMO-No.1119). The 2012 floods affected around 3 million people in Pakistan, damaged thousands of hectares of agricultural crops and claimed approximately 450 lives (Blunden and Arndt, 2012).

Agriculture is extremely vulnerable to climate change, especially in Pakistan, because of its geographical location with arid and semi-arid conditions (Janjua et al., 2010). An increase in temperature could affect arid and semi-arid areas more compared to humid regions. Productivity is being affected in Pakistan by a number of climatic variables including rainfall patterns, rising temperature, and elevated CO2. In 1949-50, the agricultural sector contributed 53 % to Pakistan's GDP, which dropped to 31 % during 1980-81, and to 21.4 % during 2012-13. The floods of 2010 affected 20 % of the land area and the overall production loss of sugar cane, paddy and cotton were estimated at 13.3 million tons. Two million ha of standing crops were either lost or damaged. Between 60 and 88 % of the farming, households reported losses of more than 50 % of their major crops, including rice, vegetables, cotton, sugar, and fodder (GOP, 2011). Agricultural growth suffered a serious setback during 2000-2001 as a result of prolonged drought. The major crops registered decreased growth of almost 10%, while an overall decrease in growth was 2.6 %. Professionals estimate that Pakistan incurs financial losses of $5.2 billion annually as a result of environmental deprivation (Ahmad et al., 2004).

Rice is transplanted in May-June and harvested in October-November, hence its success is mainly dependent upon monsoonal (July-September) behavior. Flood-producing monsoon downpour in September has been damaging for rice as it is at grain formation stage. The heads get heavy, lodge due to associated winds and submerge into water for several days. First fall freeze (frosty night) in October at the milky stage is also damaging for late rice plantation. Wheat in irrigated conditions only suffers from temperature fluctuations such as a sudden rise in day temperatures in February-March (reproduction stage) after a long cold and wet spell cause shrinking of grain. The biological cycle is immediately completed not allowing the grain to gain proper size, weight, and the starch contents; hence reducing the grain yield despite good crop condition in the field. However, crop production is not affected due to precipitation as water supply is sustainable because of canal irrigation until prolonged drought grips the area.

Water supply for agriculture in Pakistan depends not only on rainfall but also on the snow and glacier meltwater that flows through the rivers and replenishes groundwater. During winter, heavy snow deposits over the Himalaya, Karakoram and Hindukush (HKH) mountains accumulate as snowpack and glaciers that melt in the summer to sustain the river flows. The summer monsoon brings about 60% share of the total annual precipitation concentrated over the southern slopes of HKH. There are two cropping seasons in Pakistan, Rabi, and Kharif, which match with the winter and summer precipitation phases, respectively. Rabi crops (wheat, barley, pulses) are normally grown from November to April and Kharif crops (rice, cotton, sugarcane) from June to October. The sowing and harvesting practices have an overlap of 1-2 months for both the growing seasons. Wheat and rice are the two major food crops which are largely consumed as staple food and food security mainly revolve around both of them. Rice is the second source of food after wheat and accounts 2.7 percent in value added to agriculture (Government of Pakistan, 2013).

Previous studies have shown that both crops are sensitive to variations in climate (Kaur and Hundal, 2006; Mahmood et al., 2012; Attri and Rathore, 2003; WWF, 2010; Mathauwda et al., 2000). High temperatures may have a positive impact on agriculture in the mountain areas of Pakistan, like the lessening of growing period for the winter crops. As warming is taking place, the summer season is extending and water is shrinking; providing room to multiple cropping cultures in mountainous regions. It also has a significant impact on reduction in frequency of frosty nights and their sequential occurrence. Due to low temperature, wheat in the high mountain areas cannot even reach to maturity and is harvested early to be used as fodder. Mahmood et al. (2012) showed that an increase in rainfall by 5% and 15% during September-October could have a negative impact on rice productivity. However, a decrease in rainfall during the period is positively associated with rice yield.

The present study is conducted as part of Agricultural Model Inter-comparison and Improvement Project (AgMIP; Rosenzweig et al., 2013) and AgMIP-Pakistan (Ashfaq et al., 2014), which seek to connect climate scientists, crop modelers, agricultural economics modelers, and information technology specialists. AgMIP's emphasis is on assessing climatic vulnerability and projecting crop productivity using integrated crop and economic modeling techniques. In this paper, we focus on the crop-climate relationship by drawing connections with past climatic determinants and examining likely impacts of projected future climate in the rice-wheat cropping system in the province of Punjab in Pakistan. The goal of this study is the analysis of historic/current climate and trends of climate change in the region which are then used to drive crop and economic models investigating the likely impacts on crop productivity and the economy in changing climatic conditions.

Study Area

The rice-wheat cropping system is centered in the districts of Sialkot, Gujranwala, Sheikhupura, Nankana sahib and Hafizabad and covers 1.1 million ha of agricultural land, cultivated under canal irrigation. A major part of sowing is done in an annual rice-wheat cropping fashion with wheat sown after rice chiefly.

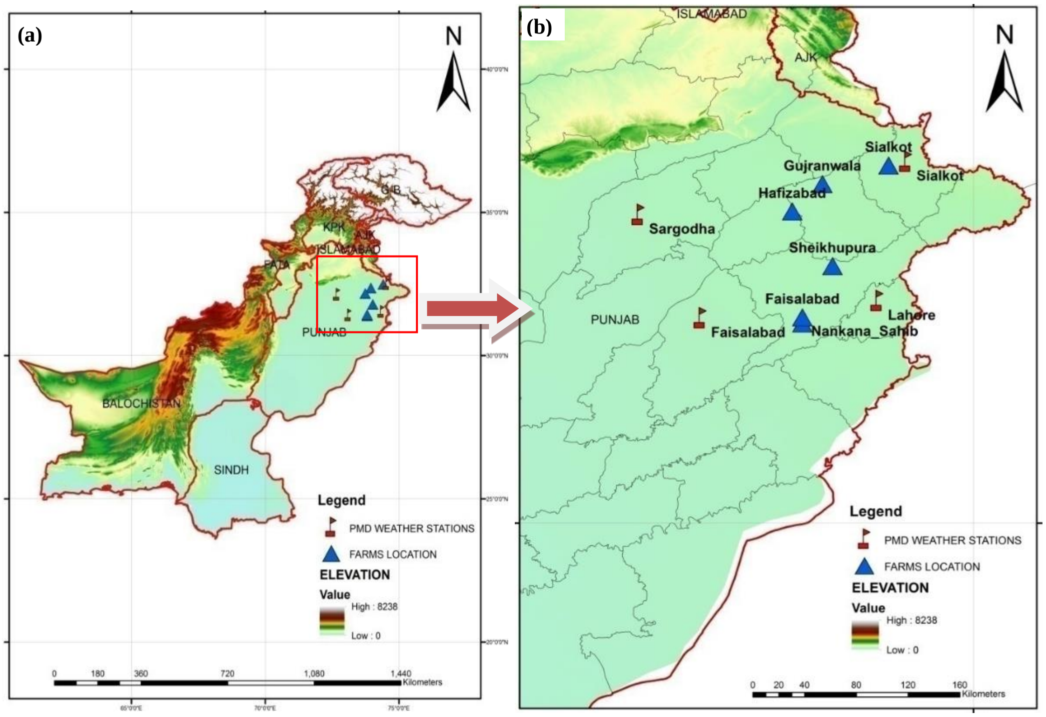

Figure 1: Map of Pakistan (a) and map of study area showing geographical location of the rice-wheat districts (b**).**

Rice in the rice-wheat system is normally sown in late May or June and harvested in October which continues through November. Wheat is best planted in mid-November and late varieties continue to be sown late in December or even mid-January. Harvesting starts in April and continues up to the end of May. The rice-wheat system has some challenging issues related to the crop management. Rice demands puddled firmed soils to hold standing water during the growing season. The process of puddling noticeably reduces and alters the pore distribution thus enhancing water withholding capacity of soil. On the other hand, wheat essentially needs well-drained soils to allow deep percolation into the root zone. However, this hard layer should be made as to avoid problems of water logging. Another concern in rice-wheat management is caused by the domination of late maturing rice varieties that delays the wheat cultivation due to lesser time available for land preparation. Other major issues faced by the farmers are water stress, are also increasing, nutrient imbalance, and a decline in soil organic matter; labor shortages during sowing, harvesting, and threshing.

Observed Climate and Climate Trends

All five districts lie in the Semi-Arid agro-climatic zone classification based on the moisture index (Figure 2a, 2b). Agro-climatic classification for Rabi and Kharif seasons is presented in Figure 2a and 2b respectively. The rice and wheat crops are grown in similar agro-climatic zones in Pakistan in a regular rotation pattern. This region is predominantly irrigated although it is partially reliant on rainfall (Chaudhry and Rasul, 2004). There is intense heat in summer, heavy rainfall in monsoon and cold weather in winter with the meager arrangement of rainfall. Good summer precipitation with the late withdrawal of monsoon helps to maintain water reservoirs at full capacity to serve the sowing needs of Rabi crops from October to December when negligible precipitation occurs in Pakistan (Rasul and Kazmi, 2012). In winter mid-latitude westerly waves generally bring rainfall in the northern parts of the country. Although much smaller in magnitude, winter rains are also very important for the wheat crop in rain-fed areas but the study districts are typically irrigated during Rabi season (Ghazala et al., 2009). Summer precipitation occurs during the monsoon season from July to September and this is usually linked with the monsoon low-pressure systems developed over the Bay of Bengal which cross India and reaches Pakistan due to their westward movement. Rice crop largely depends upon the quantity as well as the spatial and temporal spread of rainfall during monsoon season. During the sowing season of rice crop (May-June), which coincides with the typically hot and dry climatic conditions, canal irrigation is supplemented with groundwater pumping.

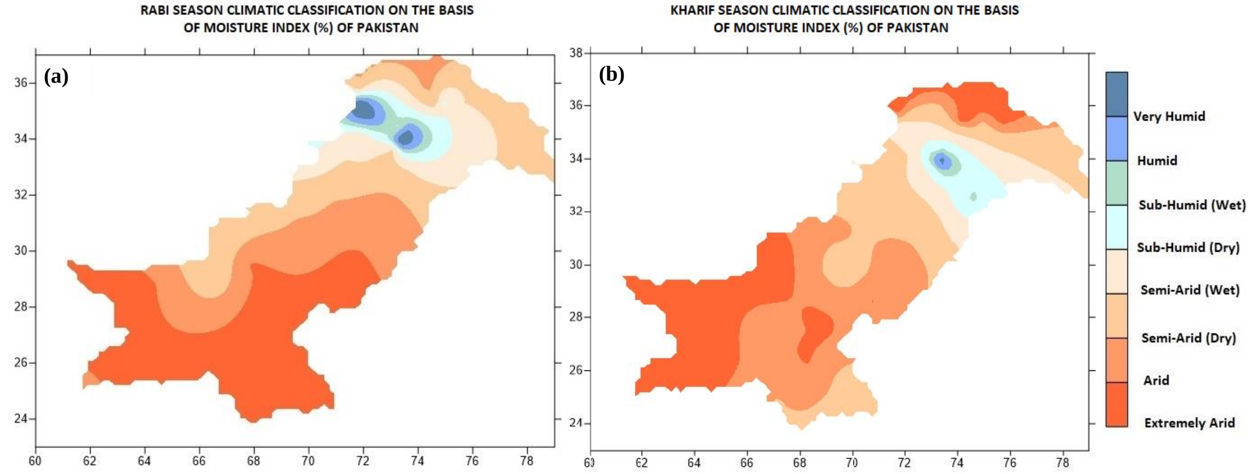

Figure 2: Rice Growing Season (Kharif, a) and Wheat Growing Season (Rabi, b) Agro-Climatic Classification of Pakistan (Adapted from Chaudhry and Rasul. 2004).

During the rice growing season the mean maximum temperature ranges from 34 ◦C to 38 ◦C while mean minimum temperature varies between 22 ◦C and 26.5 ◦C. The monsoon rainfall during the season ranges from 200mm to 800mm following a north-south gradient in the study area. (Climate normal PMD, 1980-

2010). During the wheat growing season the mean maximum temperature ranges from 24 ◦C to 26 ◦C while the mean minimum temperature lies within 10 ◦C to 13 ◦ C. Winter rainfall during the season ranges from 50 mm to 250 mm following the north-south gradient like summer season (Climate normal PMD, 1980-2010).

The daily weather data for the region, obtained from the Pakistan Meteorological Department (PMD) is analyzed (Climate normal PMD, 1980-2010). During 1981-2010, the mean maximum temperature of the region during rice growing season (June to September) ranged from 32 ºC to 36ºC (Figure 3a) and the mean minimum temperature ranged from 21 ºC to 24ºC (Figure 3b). The southwest part of the area was warmer compared to the northeastern region. The monsoon rainfall varied significantly following the reverse trend to the thermal regime ranging from 800 mm in the northeast to 350 mm southwest during the Kharif season. The northeastern districts received frequent spells of rainfall compared to the west and southwest districts (Figure 3c).

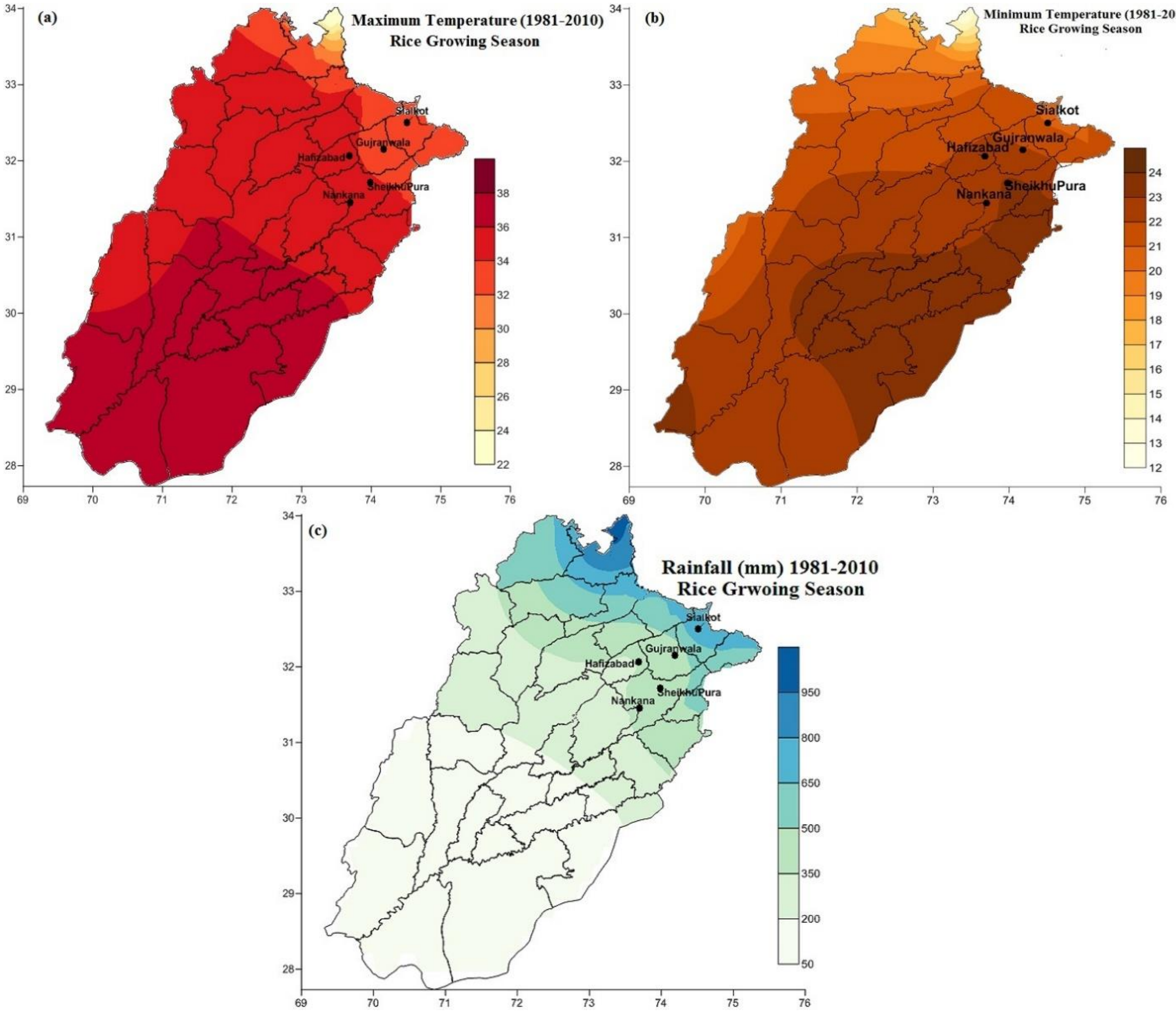

Figure 3: Rice-growing season mean maximum temperature (a), mean minimum temperature (b) and normal rainfall (c) in the Punjab Province of Pakistan.

Temperature during the wheat growing season (November to March) is comparatively lower than rice growing season with the mean maximum temperature ranging from 25 ºC to 29ºC and the minimum temperature ranging from 11ºC to 14ºC. Temperature follows an increasing pattern from the northeast toward west and southwest over the selected study zone. Winter rainfall in the study area is much lower than the summer rainfall with values ranging from 300 mm to 100 mm (Figure 4a, 4b, and 4c).

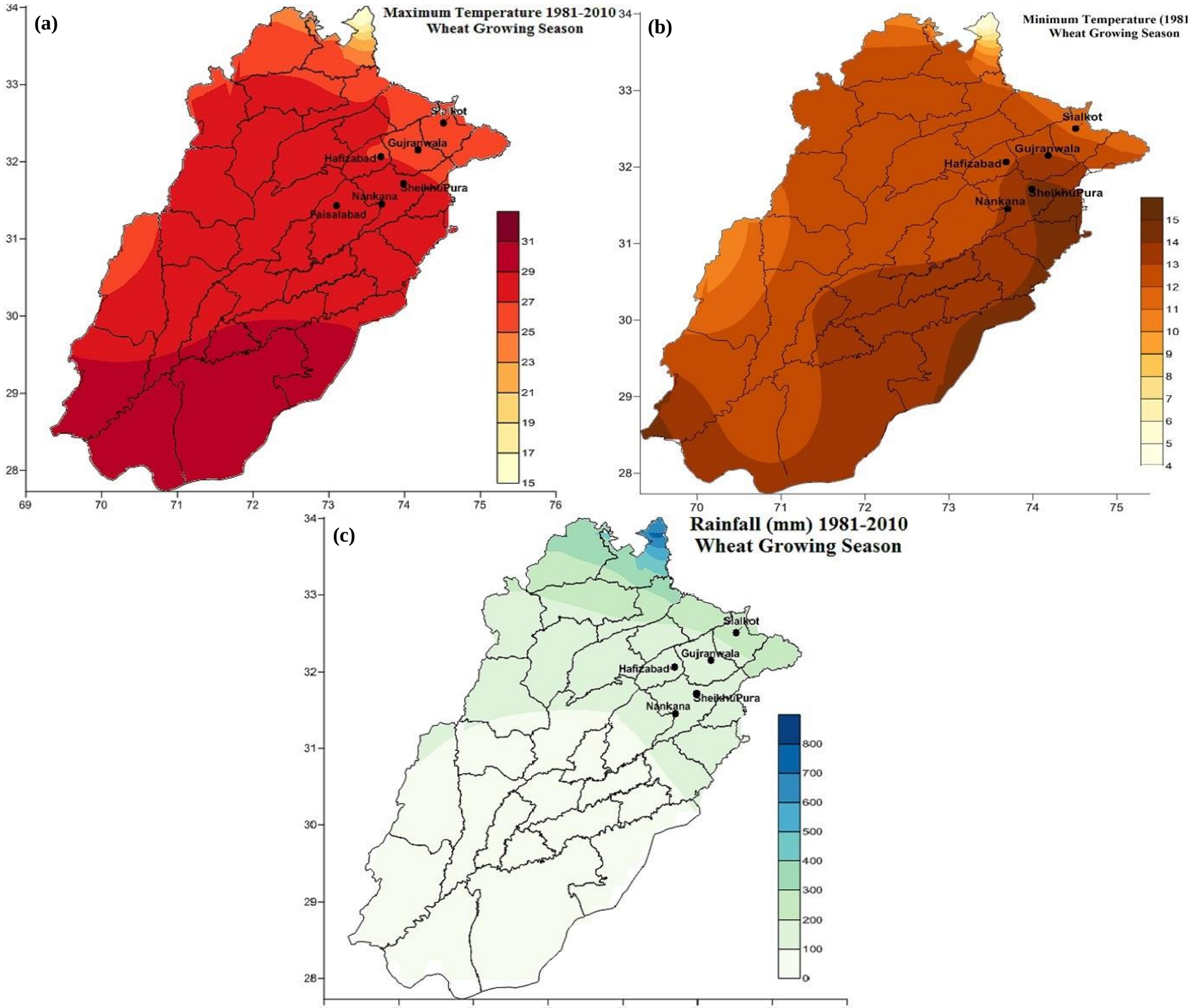

Figure 4: Wheat-growing season mean maximum temperature (a), mean minimum temperature (b) and normal rainfall (c) in the Punjab Province of Pakistan.

Air temperature and precipitation are two key properties of climate and are the most extensively measured variables. To see the historical variation in a climate of the study region, anomalies are calculated for two meteorological observatories, Sialkot and Lahore (representing Sheikhupura). 30-year baseline period of 1981 to 2010 was used to calculate annual anomalies. To generate the temperature and precipitation time series, measurements were converted into monthly anomalies and then were averaged to get an annual temperature anomaly for each year (Figure 5). For both Sialkot and Sheikhupura stations both above and below average maximum temperature can be seen from 1931-2013. For both stations, starting from 1998 last 13 years are warmer than average. (Figure 5a, 5b). Analysis for minimum temperature shows a similar trend for both stations. After the year 2000 warming trend is quite obvious for both stations (Figure 5c, 5d). Rainfall has been highly variable for both the stations. Both above and below normal years were observed with large deviations from baseline 1981-2010 (Figure 5e, 5f).

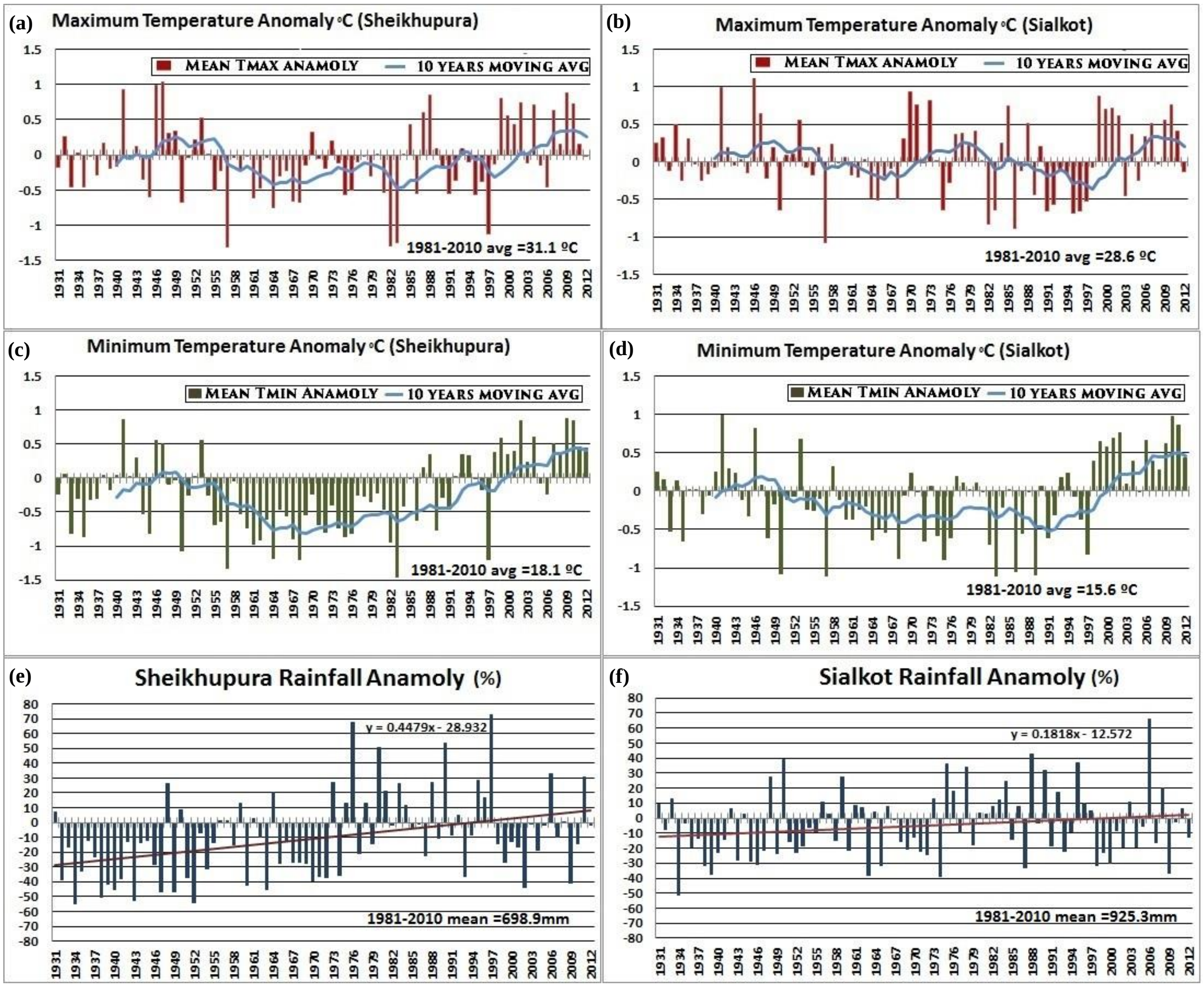

Figure 5: Time series of anomalies in Maximum temperature (a, b) Minimum temperature (c, d) and Rainfall (e, f) over two weather observatories in the Rice-Wheat Cropping region of Pubjab, Pakistan. Anomalies are the departures from the 1981–2010 average climatological period.

Climate Scenarios

General circulation models (GCMs) simulate the many interacting components of climate system and their response to changing atmospheric drivers; most notably the greenhouse gasses responsible for anthropogenic climate change. GCMs have been developed at a number of modeling centers around the world, and produce a range of different outcomes owing to differences in resolution, resolved processes, parameterizations, and model structure. GCMs used in this study are drawn from the Fifth Coupled Model Inter-comparison Project (CMIP5; Taylor et al., 2010), which provided the bulk of GCM inputs for the Intergovernmental Panel on Climate Change’s 5th Assessment Report (IPCC AR5; Stocker et al., 2013). Table 1 shows details about the five CMIP5 GCMs selected as a subset (see Ruane et al., 2015) to generate climate projections for this study in order to allow further assessment of core climate impact questions (Rosenzweig et al., 2013). These questions address the sensitivity of current agricultural production systems to climate change. Simulation for future mid-century (2040-2069) is carried out to assess the impact of climate change on future agricultural production systems. The benefits of climate change adaptations for the agriculture sector and also studied to devise a policy for stakeholders.

CMIP5 employed Representative Concentration Pathways (RCPs; Moss et al., 2010) to denote future atmospheric levels of greenhouse gasses under a range of plausible societal pathways for emissions and international policy. Thus, projected climate for a given period in the future is based on the model and the RCP used, with RCP8.5 representing the most extreme climate change scenario. The RCP8.5 Mid-Century (2040-2069) time slice is the priority period for this study (Ruane et al., 2014). This period is far enough into the future that the climate change signal largely emerges from the noise of climate variability, however, it is also on a timescale that is highly relevant to policy planners and those considering long-term irrigation investments. GCMs have a coarse resolution ranging from ~50 km to ~300 km, often introducing biases in areas like Pakistan where orographic and climatic conditions vary considerably across quite small distances. Downscaling is therefore used to cast GCMs to a finer scale required to assess implications of climate change on food production. Several techniques for downscaling are in wide use, although the use of both dynamical and statistical methods requires a clear understanding of their relative strengths and weaknesses (Mearns et al., 2003; Wilby et al., 2003).

Table 1: Five selected GCM outputs used in the current study.

Model	**Resolution**	**Institution**	**References**
CCSM4	1.25 x ~0.9	National Center for Atmospheric Research	Gent et al., 2011
GFDL-ESM2M	2.5 x ~2.0	National Oceanic and Atmospheric Administration/Geophysical Fluid Dynamics Laboratory	Dunne et al., 2012
HadGEM2-ES	1.875x1.25	Met Office Hadley Centre	Collins et al., 2011
MIROC5	~1.4 x ~1.4	Atmosphere and Ocean Research Institute (The University of Tokyo), National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology	Watanabe et al., 2011
MPI-ESM-MR	1.875 x ~1.9	Max Planck Institute for Meteorology	Raddatz et al., 2007; Jungclaus et al., 2010

Data and Methodology

Here, future climate scenarios for five districts of Punjab province were produced using the relatively simple “Delta Method” (Gleick, 1986; Arnell, 1996; Wilby et al., 2004). The Delta Method is the most common scenario methodology employed in agricultural impacts studies (White et al., 2011) and is relatively efficient for generating future climate data even when high-end computational resources are not available (Ruane and Hudson, 2013; Ruane et al., 2015).

The Delta Method is based upon daily historical observations of rainfall, minimum temperature and maximum temperature from the nearest possible meteorological observatories. Both Sialkot and Sheikhupura districts contained nearby daily observations for the complete baseline period (1980-2010), as shown in Figure 1b. Each file contained daily data for solar radiation, maximum and minimum temperature, precipitation, surface wind, dewpoint temperature, relative humidity, and vapor pressure over the 31-year period. This period satisfies WMO recommendations for a climate period in which the climate indicator is noticeable from inter-annual variability (WMO, 1989), and allows at least 30 growing seasons. Some missing and erroneous values in daily observed data were filled by applying procedures explained in the AgMIP Guide for Regional Integrated Assessments Handbook of Methods and Procedures Version 5.0 (Rosenzweig et al., 2013). If three or fewer days were missing, values were filled in by interpolating from good values on either side (although care was taken not to over-represent a strong outlier on either side of the gap). Longer gaps were filled in using the AgMERRA dataset (Ruane et al., 2014b) and bias-corrected using overlapping good data from the same calendar month. The mean was, therefore, adjusted to ensure a smooth connection with starting and ending points.

Because there was a lack of long-term weather observations at Hafizabad, NankanaSahib, and Gujranwala, we estimated those time series using AgMERRA and WorldClim (Hijsmans et al., 2003). At Hafizabad and NankanaSahib (which are >50km from the nearest station) the AgMERRA historical data were bias-corrected using differences in monthly climatology from surrounding stations (to estimate AgMERRA's regional bias). For Gujranwala (which is <50km from Sialkot) we adjusted the monthly temperature and precipitation according to the corresponding spatial differences in ~5km WorldClim dataset. For temperature monthly bias was subtracted from corresponding month's daily AgMERRA data while for rainfall monthly bias was multiplied to the corresponding month of AgMERRA data. This set of activity produced a continuous, complete, physically-consistent daily climate series for all five districts from 1980-2010 referred as baseline climatology.

$$Basline = X_{1980,} X_{1981,\dots\dots\dots,} X_{2010,}$$

Downscaled future scenarios are generated by first calculating the climate change factors for temperature and precipitation. These change factors are computed by finding the absolute difference of the RCP8.5 Mid-Century (2040–2069) simulation from the 5 GCMs in focus (CCSM4, GFDL-ESM2M, HadGEM2-ES, MIROC5, and MPI-ESM-MR) in comparison to the same GCM's baseline years (1980–2009) for the grid box corresponding to the individual five districts. This method is based upon long-term changes, so the results are best interpreted as shifts in the 30-year climatology suggested by the WMO (WMO, 1989).

$$\Delta X_T\ (Temperature) = \overline{\mathrm{X}}_{GCM:future} - \overline{\mathrm{X}}_{GCM:reference}$$

$$\Delta X_R\ (Rainfall) = \frac{\overline{\mathrm{X}}_{GCM:future}}{\overline{\mathrm{X}}_{GCM:reference}}$$

These change factors are then applied to daily historical observations to match mean monthly climate changes as determined by GCM simulations, with CO2 concentration set at the value related to the mean of the 30-year time slice in the RCP8.5 emissions scenario (571 ppm). For temperature, absolute differences are added to the baseline data, but for rainfall, multiplication is performed on the baseline by a precipitation change factor.

$$Future\ Scenario\ (Temperature) = (X_{1980,} + \Delta X_T).\dots.(X_{2010,} + \Delta X_T)$$

$$Future\ Scenario\ (Precipitation) = (X_{1980} \times \Delta X_R).\dots.(X_{2010,} \times \Delta X_R)$$

The result is 25 future scenarios (5 Locations × 5 GCMs×1 emissions scenario×1 future period), each containing daily weather data for 30 years, which were used to drive crop models for rice-wheat simulations (Ashfaq et al., 2014). Downscaled future scenarios match the baseline period in terms of spatial patterns as well as interannual and day-to-day variability, as all values within a certain month over the 30-year slice are scaled using the same change factor. These future scenarios thus diverge in their mean, maxima and minima from the baseline scenarios, but the underlying sequence of weather events that are familiar to farmers and stakeholders in Punjab are maintained to provide realistic weather statistics.

Results and Discussion

Past climatology of the region has shown an increase in rainfall during summer while temperatures have gone through a minor deviation from the long-term averages. Ensemble climate change projections for the RCP8.5 (2040-2069) scenarios indicate that the mean maximum temperature is likely to increase by 2 -

2.5ºC during rice growing (Kharif) season and 2.4-2.7ºC during the wheat growing (Rabi) season as compared to the baseline thermal regime. Mean minimum temperature is projected to increase by 2.5ºC during Rabi as compared to 2.6 to 3ºC during Kharif season. The increase in temperature is almost consistent among all districts. It is noticeable that there is a significant variation among projections of all the five GCMs. During Kharif season, the range of maximum temperature rise varies from 1ºC to 3.3 ºC and for minimum temperature from 2ºC to 3ºC, while during Rabi season the range of maximum temperature rise is 2.1ºC 3.5ºC and minimum temperature change lies between 2ºC and 3ºC (Figure 6 and 7).

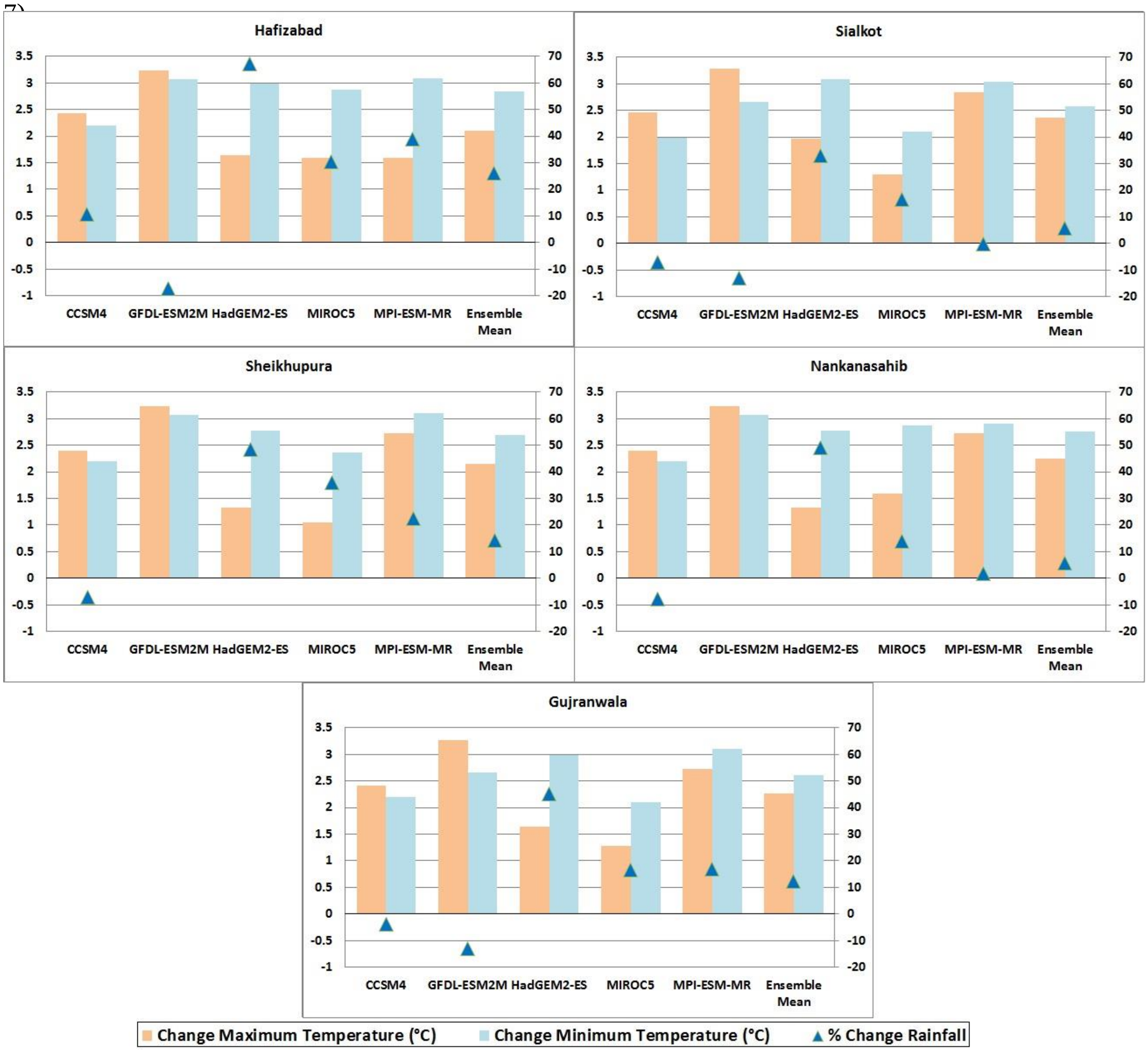

Figure 6: Rice growing (Kharif) season climate projections of Temperature and Precipitation for all the five districts. Projections are departure for future 30-year period (2040-2069) from the baseline (1981-2010).

During the rice-growing season, the GFDL-ESM-2M projects the largest increases in maximum and minimum temperatures as compared to the other four GCMs, while for the wheat-growing season MIROC5 projects the largest temperature increase. This indicates that GCM responses may include seasonal differences that may be important to regional agriculture even when mean temperature increases are consistent. However, there was a common consensus among the GCMs that the day and night temperatures would increase in future.

The ensemble of all the five GCMs depict that rainfall during rice growing season is projected to increase by 25% -35% in the study region while during winter wheat growing season a marginal increase (<10%) is expected. It means that the summer monsoon is likely to intensify during the middle of the 21st century which should be a good news for the rice growers. The rainfall projections are highly variable among all the GCMs. Some of them are wetter while others are drier than the baseline. The range of deviation is much larger in summer i.e. from -9 % to 81% during Kharif and from -14% to 29% during Rabi season. For Kharif season GFDL-ESM-2M is the driest of all while for Rabi season HadGEM2-ES is the driest.

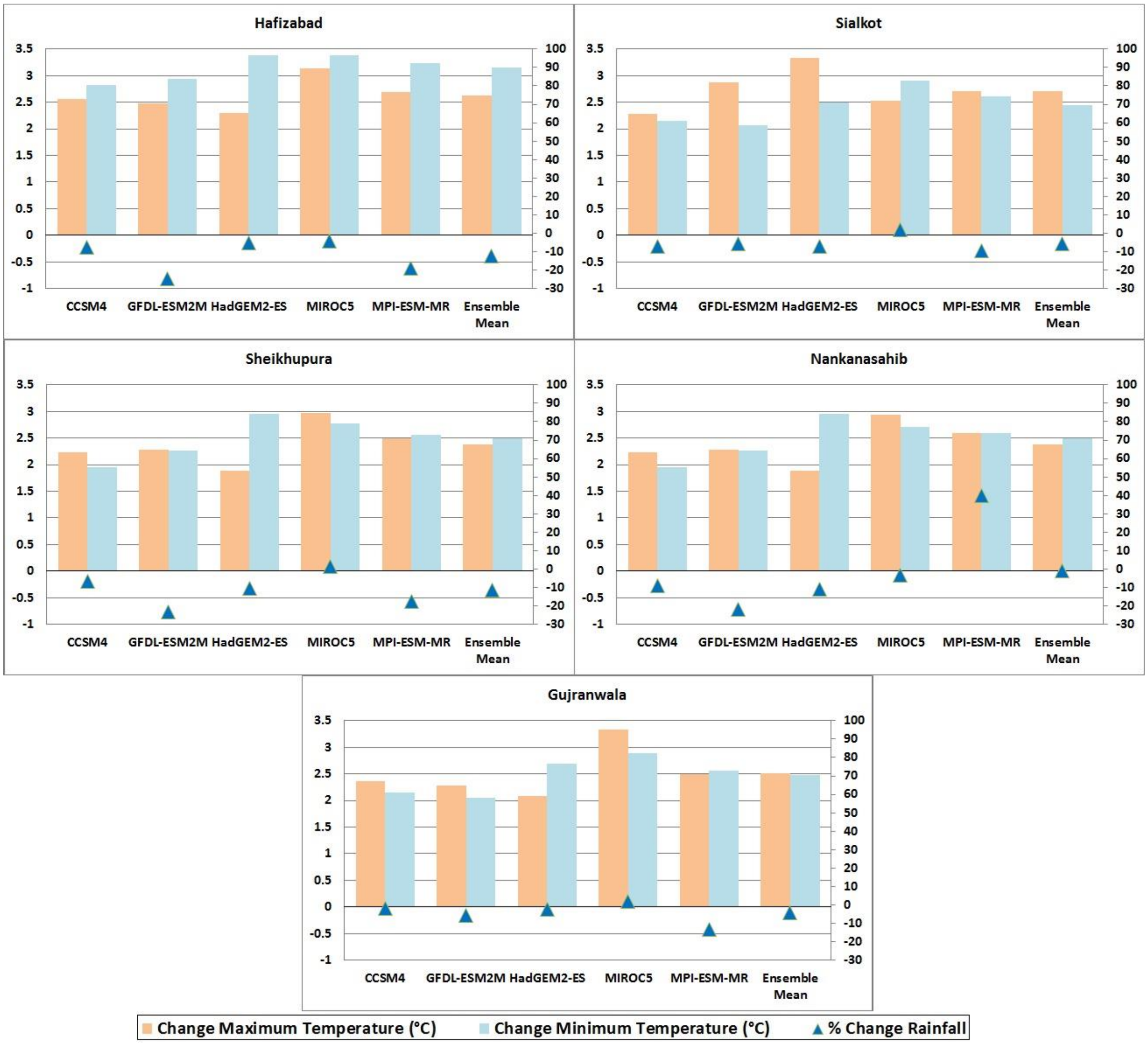

Figure 7: Wheat growing (Rabi) season climate projections of Temperature and Precipitation for all the five districts. Projections are departure for future 30-year period (2040-2069) from the baseline (1981-2010).

Figure 8 (a to c) shows the projected monthly, annual and seasonal temperature changes for the area examined in this study along with the baseline. Both rice and wheat growing seasons are analyzed. When compared to the baseline, a constant temperature rises, and a broader uncertainty among projected precipitation changes is captured. Both day and night temperature changes are clearly following a positive trend for all the months and seasons during the target period (2040-2069). Warming is almost equally spread over the crop growing seasons for both maximum and minimum temperatures, although the model simulations are distributed on a wider scale in summer months. Monsoon rains prevail in the study region from July through September and bring a lot of water leaving hardly any need of irrigation. The monsoon precipitation season matches with the Kharif growing season, therefore, any increase in the water requirement of rice crop resulting from a rise in temperature would be compensated by the rich monsoon. Monthly, annual and seasonal precipitation change projections for the 2050s are shown in Figure 8c. Change in rainfall is not uniform among GCMs, there is a mixed trend seen for all months. Rainfall deviations during the wettest months of the year have very large variations among all the five GCMs as compared to dry months.

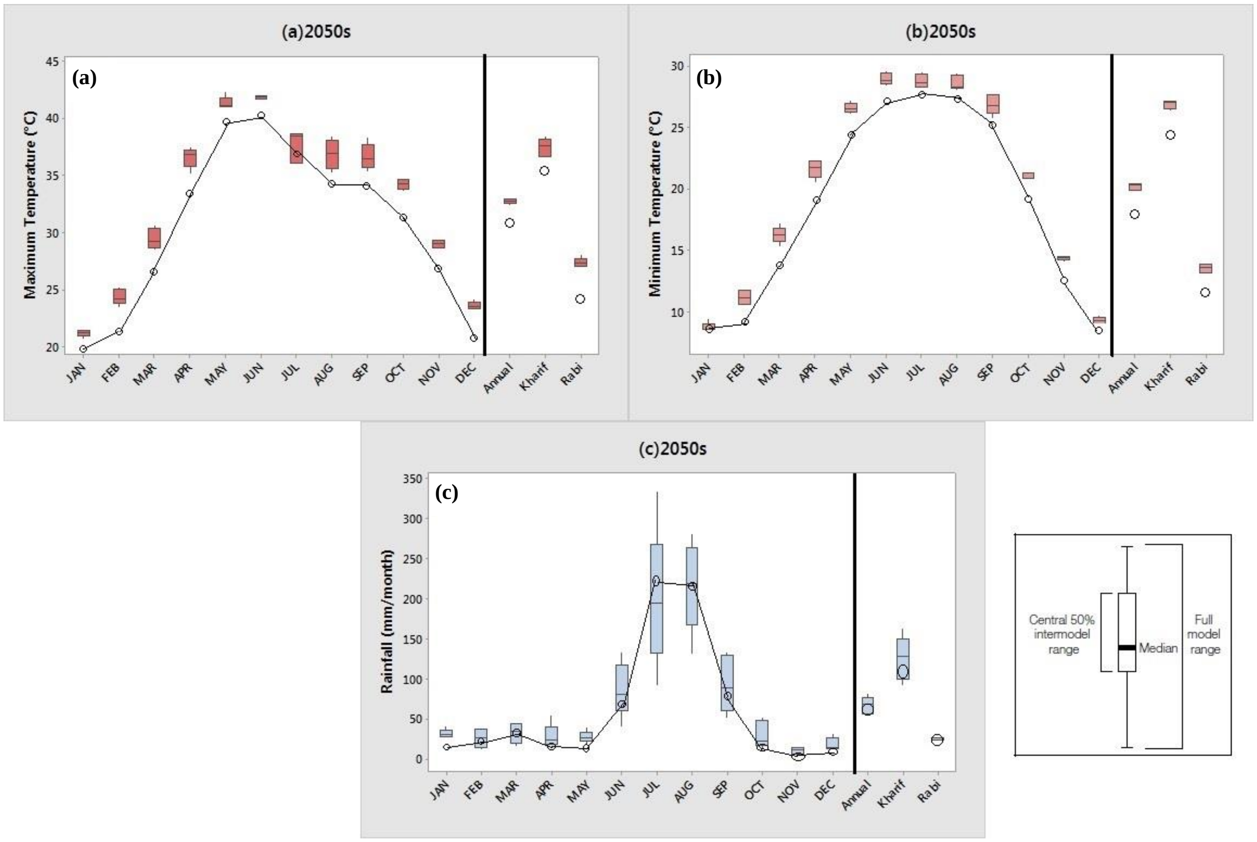

Figure 8: Mean monthly, annual, and seasonal (a) Maximum temperature (b) Minimum Temperature and (c) precipitation (mm/month) for current climate and projected scenarios in the 2050s averaged across all 5 districts. The black line represents the mean of the baseline conditions, while the box and whiskers diagrams represent the 5 GCM for RCP8.5 scenario combinations for each 30-year period. Note: 'Kharif' season = Jun–October (Rice); 'Rabi' = November–April (Wheat).

Summary and Conclusion

The present study was designed to determine the change in the climatic parameters in the past and to depict projected variations as well as changes in the temperature and the rainfall for the rice-wheat cropping zone of Pakistan. The study revealed that there is a clear tendency towards a warmer and wetter future climate and it will obviously impact the agriculture sector in Punjab, Pakistan, mainly if the climatic conditions deviate from the variations found in the historical observations. Warming is projected to enhance towards the end of 21st century, although the model-based projections are distributed widely. The projected future temperature considerably deviates from the background variations. By the 2050s, the median temperatures in most of the months of the future model variability go beyond the 90th percentile of the historical temperature distribution.

Precipitation is indicative of large variations in the past observations and future projections. Despite the consistently noted enhancement of the monsoonal rainfall and a comparative drying trend during the Rabi season in the 2050s, precipitation does not significantly detach itself from the historical variability. These findings are consistent with the global finding that precipitation changes are more uncertain than temperature change and that existing rainfall variability is substantial. This had been explained by applying z-test to selected GCMs (Ruane et al., 2015). The analysis of the output of the five climate models for five districts which represent the main rice-wheat production zone in Pakistan showed that between 1980 and 2070 the most reliable implications will be due to the increase in temperature instead of the variability in precipitation pattern.

The effects of warming concern the increase in the length of the thermal growing season demand. Crop yield is a complex process affected by different biotic and abiotic factors other than temperature and precipitation and all the factors need to be considered to better estimate the potential impacts on rice-wheat crop yields. However, an effort has been put to cope with the biases and uncertainties of individual GCMs still there is room for improvement in terms of removal of uncertainties of the driving GCMs. To address the issues of climate change and its impacts on rice-wheat cropping system, a comprehensive multidisciplinary approach with multiple high-resolution RCM projections would help identify the most likely vulnerabilities for agro-climatic regions. For such studies, the mean climatology would not serve the purpose, rather hydrothermal and hydro-meteorological extremes have to be taken into account along with other indicators.

Acknowledgments

This study has been conducted under the framework of AgMIP, supported by the UK Department for International Development and UKAID, the USDA-Agricultural Research Service, and the NASA Earth Sciences Program. We would like to thank the leaders of AgMIP for putting together the valuable guidelines and protocols for the generation of climate scenarios and agriculturally important climate metrics using the R statistical programming language and Matlab codes. We are also thankful to the Pakistan Meteorological Department for providing historical climate observations for the region. We acknowledge the World Climate Research Programme's Working Group on Coupled Modelling, which is responsible for CMIP5 dataset, and we thank the climate modeling groups of CCSM4, GFDL-ESM2M, HadGEM2-ES, MIROC5 and MPI-ESM-MR for producing and making available their model outputs.

References

Aggarwal, P. K., S. N. Kumar, and H. Pathak, 2010: Impacts of climate change on growth and yield of rice and wheat in the Upper Ganga Basin.WWF, 2010. www.wwfindia.org.

Ahmad, A., M. Ashfaq, G. Rasul, S. A. Wajid, T. Khaliq, F. Rasul, U. Saeed, M. H. Rahman, J. Hussain, I. A. Baig, S. A. A. Naqvi, S. A. A. Bokhari, S. Ahmad, W. Naseem, G. Hoogenboom, and R. O. Valdivia 2015: Impact of Climate Change on the Rice–Wheat Cropping System of Pakistan. Handbook of Climate Change and Agroecosystems: pp. 219-258.doi: 10.1142/9781783265640_0019

Arnell, N. W., 1996: Global Warming, River Flows and Water Resources, Wiley, Chichester, p. 224 Rienecker et al (2011) MERRA: NASA's Modern-Era Retrospective Analysis for Research and Applications. J. Climate, 24, 3624–3648. doi: http://dx.doi.org/10.1175/JCLI-D-11-00015.1

Attri, S. D., and L. S. Rathore, 2003: Simulation of Impact of projected climate change on wheat in India. Int. J. Climatol. 23: 693–705.

Blunden, J., and D. S. Arndt, Eds., 2012: State of the Climate in 2011. Bull. Amer. Meteor. Soc., 93 (7), S1–S264.17 IPCC, 2012: Summary for Policymakers. In: Managing the Risks of Extreme Events and Disasters to Advance.

Chaudhry, Q. Z., and G. Rasul, 2003: Agro-climatic classification of Pakistan. Quarterly cience Vision Vol.9 No.1-2(July-Dec, 2003) & 3-4(Jan-Jun, 2004).

Church, J. A., P. U. Clark, A. Cazenave, J. M. Gregory, S. Jevrejeva, A. Levermann, M. A. Merrifield, G. A. Milne, R. S. Nerem, P. D. Nunn, A. J. Payne, W. T. Pfeffer, D. Stammer, and A. S. Unnikrishnan, 2013: Sea Level Change. In: Climate Change 2013: The Physical Science Basis.

Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1137–1216, doi: 10.1017/ CBO9781107415324.026.

Ciais, P., C. Sabine, G. Bala, L. Bopp, V. Brovkin, J. Canadell, A. Chhabra, R. DeFries, J. Galloway, M. Heimann, C. Jones, C. Le Quéré, R. B. Myneni, S. Piao, and P. Thornton 2013: Carbon and Other Biogeochemical Cycles. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 465–570, doi:10.1017/CBO9781107415324.015.

Cruz, R. V., H. Harasawa, M. Lal, S. Wu, Y. Anokhin, B. Punsalmaa, Y. Honda, M. Jafari, C. Li, N. Huu, 2007: Asia. Climate change, 2007, impacts, adaptation and vulnerability. In: Parry ML, Canziani OF, Palutikof JP et al (eds) Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, pp 469–506.

Farooq, A. B., and A. H. Khan, 2004: Climate change perspective in Pakistan. Proceedings. Capacity Building APN Workshop on Global Change Research, Islamabad, 39-46.

Field et al., 2014: Technical Summary. In: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 35-94.

Giorgi, F., 1990: Simulation of regional climate using a limited area model nested in a general circulation model, J. Clim., 3, 941-963.

Gleick, P. H., 1986: Methods for Evaluating the Regional Hydrologic Impacts of Global Climatic Changes. Journal of Hydrology 88 (1-2): 97-116.

Hartmann, D. L., A. M. G. Klein Tank, M. Rusticucci, L. V. Alexander, S. Brönnimann, Y. Charabi, F. J. Dentener, E. J. Dlugokencky, D. R. Easterling, A. Kaplan, B. J. Soden, P. W. Thorne, M. Wild, and P. M. Zhai, 2013: Observations: Atmosphere and Surface. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 159–254, doi:10.1017/CBO9781107415324.008.

Hijmans, R. J., S. E. Cameron, J. L. Parra, P. G. Jones, and A. Jarvis 2005: Very high resolution interpolated climate surfaces for global land areas. International Journal of Climatology 25: 1965-1978.

Khan, S. A., S. Kumar, M. Z. Hussain, and N. Kalra, 2009: Climate Change, Climate Variability and Indian Agriculture: Impacts Vulnerability and Adaptation Strategies. Climate Change and Crops, Environmental Science and Engineering, DOI 10.1007/978-3-540-88246-6 2.

Kreft, S., and D. Eckstein, 2013: Global Climate Risk Index 2014. Germanwatch e.V. (2013). ISBN 978-3-943704-14-3.

Mahmood, N., B. Ahmad, S. Hassan and K. Bakhsh, 2012: Impact of temperature and precipitation on rice productivity in rice-wheat cropping system of Punjab Province. The Journal of Animal & Plant Sciences, 22(4): 2012, Page 993-997.

Mathauda, S. S., H. S Mavi, B. S. Bhangoo, and B. K. Dhaliwal, 2000: Impact of projected climate change on rice production in Punjab (India).Tropical Ecology 41(1): 95-98, 2000.

Mearns, L.O., F. Giorgi, P. Whetton, D. Pabon, M. Hulme, and M. Lal, 2003: Guidelines for use of climate scenarios developed from regional climate model experiments. Data Distribution Centre of the Intergovernmental Panel on Climate Change. Geneva, Switzerland. 38pp.

Moss, R. H., J. A. Edmonds, K. A. Hibbard, M. R. Manning, S. K. Rose, D. P. V. Vuuren, T. R. Carter, S. Emori, M. Kainuma, T. Kram, G. A. Meehl, J. F. B. Mitchell, N. Nakicenovic, K. Riahi, S. J. Smith, R. J. Stouffer, A. M. Thomson, J. P. Weyant, T. Wilbanks, 2010: The next generation of scenarios for climate change research and assessment. Nature 463, 747–756.

Naheed, G., and G. Rasul, 2010: Recent Water Requirement of Cotton Crop in Pakistan. Pakistan Journal of Meteorology Vol. 6, Issue 12.

Prabhjyot-kaur, and S. S. Hundal, 2006: Effect of Possible Futuristic Climate Change Scenarios on Productivity of Some kharif and rabi Crops in the Central Agroclimatic Zone of Punjab. Jour. Agric. Physics, Vol. 6, No. 1, pp. 21-27.

Rosenzweig, C., J. Jones, J. Hatfield, J. Antle, A. Ruane, K. Boote, P. Thorburn, R. Valdivia, C. Porter, S. Janssen, C. Mutter, 2013: AgMIP Guide for Regional Integrated Assessments: Handbook of Methods and Procedures Version 5.0.

Rosenzweig, C., J. Jones, J. Hatfield, J. Antle, A. Ruane, K. Boote, P. Thorburn, R. Valdivia, C. Porter, S. Janssen, C. Mutter, 2011: Protocols for AgMIP Regional Integrated Assessments R (available for download at www.agmip.org).

Ruane, A., and N. Hudson, 2013: Guide for Running AgMIP Climate Scenario Generation Tools with R (available for download at www.agmip.org).

Ruane, A.C., J. M. Winter, S. P. McDermid, and N. I. Hudson, 2015: AgMIP Climate Datasets and Scenarios for Integrated Assessment. Chapter 3 in the Handbook of Climate Change and Agroecosystems: pp. 45-78.

Ruane, A.C., R. Goldberg, and J. Chryssanthacopoulos, 2014: AgMIP climate forcing datasets for agricultural modeling: Merged products for gap-filling and historical climate series estimation. Agr. Forest Meteorol., in review.

Sathaye, J., P. R. Shukla, and N. H. Ravindranath, 2006: Climate change, sustainable development and India, Global and national concerns. Current Science, 90(3), 314-325.

Tabor, K., and J. W. Williams, 2010: Globally downscaled climate projections for assessing the conservation impacts of climate change. Ecological Applications, 20(2), 2010, pp. 554–565.

Taylor, K. E., R. J. Stouffer, and G. A. Meehl, 2012: An overview of CMIP5 and the experiment design. Bulletin of the American Meteorological Society 93(4):485-498, doi: http://dx.doi.org/10.1175/BAMS-D-11-00094.1.

Wilby, R. L., S. Charles, E. Zorita, B. Timbal, P. Whetton, L. Mearns, 2004: Guidelines for use of climate scenarios developed from statistical downscaling methods. In: IPCC Supporting Material, available from the DDC of IPPC TGCIA.