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Climate Change

Estimating the impact of climate extremes and their future projections over drought prone regions of Punjab, Pakistan

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ABSTRACT

Climate change is unequivocally altering natural systems and impacts on drought prone regions of Pakistan. Extreme climate often has a substantial impact on agricultural production. The Punjab province is the primary food production region of Pakistan. Over the time it has become increasingly sensitive to alternating extremes like droughts and floods. Current study provides an outlook of Coupled Model Intercomparison Project Phase 5 (CMIP5) in simulating climate extremes indices defined by the Expert Team on Climate Change Detection and Indices (ETCCDI) for historical (1850-2005) and future periods (2020-2100) under two representative concentration pathways (RCPs) 4.5 and 8.5 across Punjab districts. Changes generally present relatively larger magnitudes under RCP8.5 than RCP4.5. Projected ensemble results show a significant increase in summer days over Rajanpur and DG Khan Districts. Additionally, significant increases in warmest days and nights are seen widespread over central Punjab districts. The precipitation related indices are reported to significantly increase over the district of Narowal. Meanwhile, the districts of the Western belt are likely to experience more drought events with increasingly warming temperatures. The study findings indicate that the projections of precipitation-based indices are closer to historical patterns with smaller variability and changes in the future period, while temperature-related extreme indices show significant shifts and increases along the projections. It would result in drought frequencies to recur with similar patterns of the historical period, but with augmented warmer climate in the RCPs forced future climate over the Punjab province. This study provides complementary information of climate extremes over Punjab province for local decision-makers to incorporate into policymaking, disaster management, and infrastructure planning.

Keywords: Extreme Climate; Drought; Global Warming

1. INTRODUCTION

Climate change and global warming are one of the most extensively discussed topics in the late 20th and early 21st century on our planet. Climate change refers to significant, long term changes in the global climate due to an increase in average atmospheric temperature. An increase in the average temperature of the troposphere is called global warming (Wang & Huang, 2020). According to the Global Climate Risk Index, Pakistan was ranked 10th in 2013 among climate change vulnerable countries (Kreft, Eckstein, & Melchior, 2013). The frequency and intensity of extremes like droughts, floods, and heat waves are expected to change as the earth's climate changes and these changes could occur even with a relatively smaller change in mean climate.

Drought is known to be the worst hydro-meteorological hazard of nature. It is a temporary event that lasts for months to years, which generally begins with a precipitation deficit and can result in enormous socioeconomic losses. It can appear in any region in the world and in any kind of environmental conditions (arid, semi-arid, or humid). The inter-annual variability in precipitation puts arid regions always at drought risk due to below-average precipitation (M. Adnan, Din, Khan, & Jehan, 2017). Moreover, the frequency, severity, and duration of drought vary across different climatic zones (Khan et al., 2020).

In the recent decades, numerous droughts have occurred in various parts of the world i.e. 2012 drought in Texas and the United States Central Great Plains, East African drought in 2010–2011, and 2012–2015 Californian drought, (1997–2010) Millennium drought in Australia (Hao, Singh, & Xia, 2018), the Balochistan drought in Pakistan (1997–2003) (Ahmed, Shahid, bin Harun, & Wang, 2016; Jehan & Waqas, 2020).

These major droughts have resulted in immense losses to agriculture, impacting the water supply and production of crops, posing substantial risks of societal, economic, and environmental impacts (Liu et al., 2020; Sinha, Gupta, & Senthil-Kumar, 2017). These effects are more significant in Pakistan which is one of the vulnerable countries to droughts because of its large reliance on agriculture. About 43% of the labor force is employed in the agriculture sector, and agriculture contributes to about 21% of the gross domestic product (GDP) of the country (Ullah, Khan, & Zheng, 2018). However, nearly 70% of the country's land area receives less than 250mm of precipitation, 22% of it gets 250–500mm, whereas those parts which get more than 500mm of rainfall constitute less than 10% of the terrestrial area. Large regions of Sindh and Baluchistan have less than 125 mm of rainfall (I. Ahmad, Tang, Wang, Wang, & Wagan, 2015). The study on extreme temperature suggests that temperature may fall to -26°C in the northern area and reach 52°C in the central and southern parts of Pakistan (Hassan & Du, 2018). The air temperature has increased to 0.64°C with a rising trend of 0.06°C per decade in Pakistan (Afzaal, Haroon, & Zaman, 2009). The latest study on statistical downscaling of temperature reveals that air temperature will increase in the southern parts of Pakistan (S. Adnan & Ullah, 2020; Kazmi et al., 2015).

The increase in temperature and changing patterns of climate will probably keep causing more intense and prolonged droughts in the future(S. Adnan, Ullah, Khan, & Gao, 2017; S. Adnan et al., 2018; I. Ahmad et al., 2015). Therefore, extreme climate prediction is important for early warning and preparing the most vulnerable communities for the impacts of these hazards.

There are many strategies for determining extreme weather or drought through different indices as just a single drought index does not provide the comprehensive drought information since climatic conditions vary from region to region. For example, Palmer drought Severity index (PDSI), standardized precipitation index (SPI), standardized precipitation evapotranspiration index (SPEI), and comprehensive meteorological drought index (CI), are used to study extreme drought events in different regions of the world(S. Adnan & Ullah, 2020; S. Adnan et al., 2018; Kamruzzaman, Cho, Jang, & Hwang, 2019). However, the lack of long-series global climate data and a non-unified definition of extreme event indicators and thresholds in various countries hinders the usage of a generic indicator to some extent. In order to address this situation, the World Meteorological Organization (WMO) and the World Climate Research Program (WCRP) jointly established the Expert Team on Climate Change Detection and Indices (ETCCDI) in the early 21st century and defined 27 representative climate indices to assess extreme climate change globally and regionally (Hong & Ying, 2018).

The purpose of this study is to analyze the characteristics of extreme temperature and precipitation averaged over Pakistan using the extreme temperature and precipitation indices recommended by the ETCCDI. These indices can be divided into intensity indices, absolute threshold indices, relative threshold indices, duration indices, and so on. Extreme climate indices unified by the ETCCDI effectively promote detection research of extreme weather and climate change, allowing for a comparison between extreme weather and climate change in different regions.

2. DATA AND METHODOLOGY

Study area

This study focuses on the second largest of four provinces in Pakistan, Punjab, with an area of 205,344 km^2 (Figure 1), which represents approximately one-quarter of the country. It is located at the northwestern border of the geologic Indian plate in South Asia. Furthermore, it has the strongest economy and hosts more than half of the country's population, driving rapid urbanization and agriculture. Punjab is the land of five rivers, namely Jhelum, Chenab, Ravi, Sutlej that are the tributaries of the Indus River. Punjab topography is plain and predominantly consists of fertile land along river valleys bound by bare land of Cholistan desert in southeast, hilly landscapes in south and northwest, and Potohar Plateau in the north (Saeed et al., 2019). The Punjab province is the leading province of Pakistan with respect to agriculture. The Punjab province is comprised of both level plains and mountainous areas along its stretch (M. I. Ahmad & Ma, 2020).

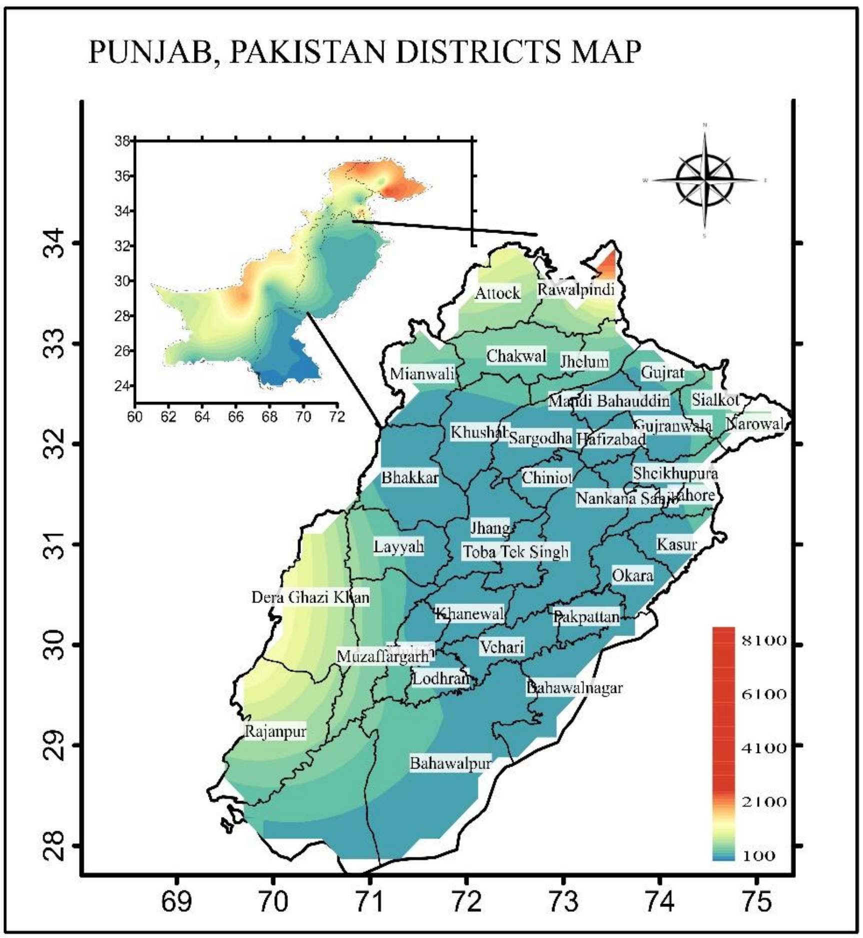

Figure 1: Location of the study area

Punjab province is an area of semiarid climate with high temperatures and moderate rainfall. Temperature differences between the upper and lower Indus basin plains are quite noticeable. Mean winter temperature (December to February) in the lower plain is 14–20 °C and 2–23 °C in the upper plain, while during summer (March to June), the temperature varies between 42–44 °C in the lower plain and 23–49 °C in the upper plain. The winters start in November and last till the end of March, while January is the coldest month. The temperature decreases from north to south over the Punjab province. Northern Punjab is wetter than the southern Punjab. The summer season starts in April and ends in September. The temperature during this season increases steadily and reaches high in June. Rabi and Kharif are two major cropping seasons in the Punjab. Rice is the major crop of the Kharif season(M. I. Ahmad & Ma, 2020).

Data

Studies using several models are necessary to verify the possible uncertainties in future scenarios since individual models tend to display heterogeneity in their outputs over similar regions. The selected models (Table 1) have the ability to emulate climatology and statistics of the historical climate are deemed more certain for assessment of future scenarios over Punjab, Pakistan (Ahmad & Mahmood, 2017).

Table 1. List of CMIP5 models used in this study

No.	Models	Institutions	Country	Resolution
1	bcc-csm1-1	The Beijing Climate Center Climate System, Beijing Climate Center (BCC), China Meteorological Administration	China	128 × 64
2	CanESM2	Canadian Centre for Climate Modelling and Analysis, Canada	Canada	128×64
3	CCSM4	National Center for Atmospheric Research (NCAR), USA	USA	288×192
4	MIROC5	AORI, NIES, JAMSTEC, Japan	Japan	256×128

Methodology

Characteristics of extreme climate events were used to describe their frequency, intensity, and duration along with historical and projected time scales over the districts of Punjab province (Table 2). In this research, 8 indices defined by ETCCDI were retrieved from Canadian Centre for Climate Modelling and Analysis's ETCCDI extremes indices archive (http://climate-modelling.canada.ca/climatemodeldata/climdex/index.shtml) and analyzed, including 5 temperature indices (SU, TN90p, TNx, TX90p, TXx) and 3 precipitation indices (Rx5days, CDD, CWD), as shown in Table 3. The indices focus on changes in temperature and precipitation related extreme events during the 21st century for representative concentration pathways RCP4.5 (medium-low radiative forcing) and RCP8.5 (high radiative forcing) scenarios which correspond to radiative forcing maximizing at approximately 4.5 and 8.5 W/m2 by years 2100 and 2300 respectively.

Table 2: Districts of Punjab province based on geographical regions

Region	Districts
Southern Punjab	R.Y. Khan, Bahawalpur, Bahawalnagar, Rajanpur, D.G. Khan, Muzaffargarh, Multan, Vehari, Lodhran, Layyah, Bhakkar, Jhang.
Central Punjab	T.T. Singh, Sahiwal, Pakpattan, Okara, Kasur, Faisalabad, Lahore, Chiniot, Nankana Sahib, Sheikhupura, Gujranwala, Sialkot, Narowal, Gujrat, M.B. Din, Sargodha.
Northern Punjab	Rawalpindi, Attock, Jhelum, Chakwal.

Table 3: Information on climate extreme indices analyzed in this study

INDEX	INDEXLONG NAME	INDEX DETAILS	IMPACTS	UNIT
Temperature related to extreme indices				
SU	Number of summer days	The annual count of days when TX (daily maximum temperature) >25℃	Drier summer, increased death rate, soil microbes affect crop yield, deterioration of health, exhaustion, and heat stroke	Days
TXx	Monthly maximum value of daily maximum temperature	The maximum of daily maximum temperature for each month	Increased evapotranspiration, more energy consumption, affects crop yield, deterioration of health	℃

TNx	Monthly maximum value of daily minimum temperature	The maximum of daily minimum temperature for each month	Crop yields decline, more energy consumption, deterioration of health, heat stroke	℃
TN90P	Warm nights	The parentage of days when TN < 90th percentile	The fraction of days with warm nighttime temperature are triggers of crop damage and heatwave risks	%
TX90P	Warm days	The parentage of days when TX < 10th percentile	Increased evapotranspiration, risk of droughts, affects crop yield, deterioration of health	%
Precipitation-related extreme indices				
Rx5 day	Max 5-day precipitation amount	Monthly maximum consecutive 5-day precipitation	Flooding risk to human life, damage to buildings and infrastructure, loss of crops and livestock, land sliding	mm
CDD	Consecutive dry days	Maximum number of consecutive days with RR<1mm	Triggers droughts, crop damage, water shortage	Days
CWD	Consecutive wet days	Maximum number of consecutive days with RR>1mm	Floods, loss of crops and livestock, land sliding	Days

3. RESULTS

The individual projections show relatively high uncertainty between the models, so the ensemble approach is recommended for the robustness of these climate indices. Ensemble modeling is a process where multiple diverse models are created to predict an outcome. The comprised of several weak models that are not so great themselves, known as weak learners. When combined, they fill in each other's weaknesses and render better performance than they would when deployed alone. Therefore in the current study, all model's results are in the ensemble for both historical and future climate extreme data.

Historical climate extreme indices

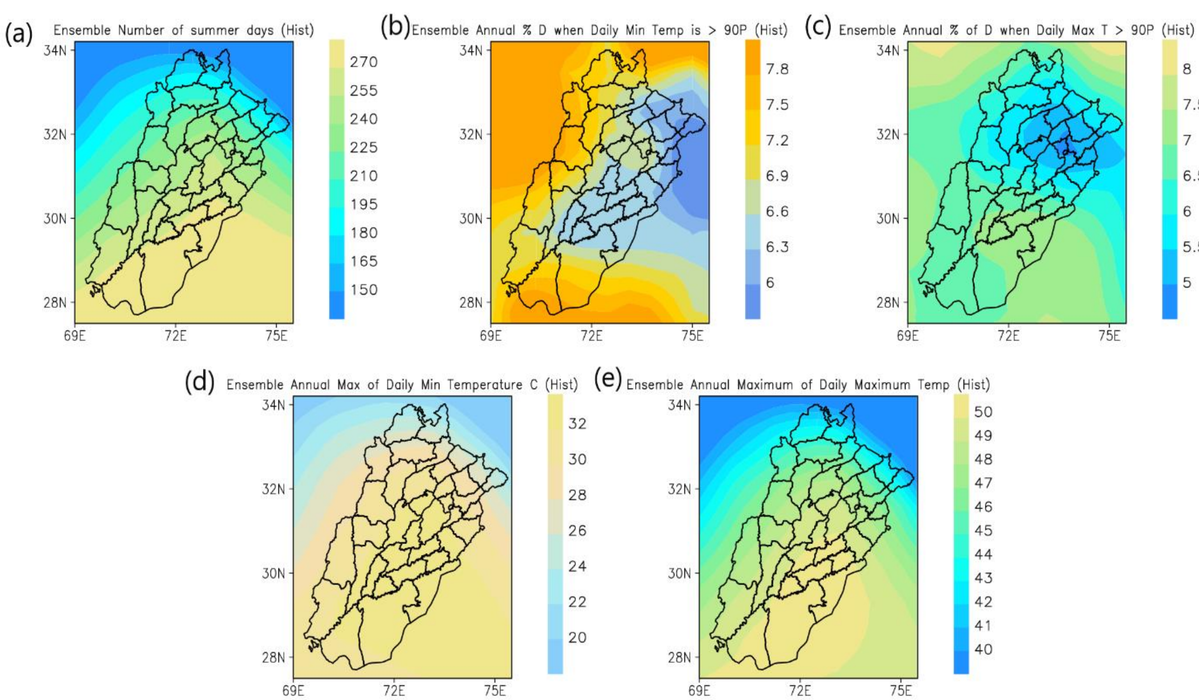

Figure 2: Historical temperature-related extreme indices for the period of 1850–2005: (a) SU (unit: days); (b) TN90p (unit:%); (c) TX90p (unit:%); (d) TNx (unit: ℃); (e) TXx (unit: ℃)

Figure 2 shows the temperature-related extreme indices during the period 1850–2005. Figure 2a shows the number of summer days (SU), which depicted 270 summer days observed over the past years. Figure 2(d,e) represents temporal variations of the annual maximum of daily maximum temperature (TXx) and annual maximum of daily minimum temperature (TNx), respectively. The TXx warmest days reach 50 ℃ whereas the TNx warmest nights reach 32℃ temperature records annually. Similarly, percentile-based threshold indices TN90p and TX90p shown in Figure 2(b,c) change by 7.8% and 8%, respectively over the historical period.

The precipitation related extreme indices during the period 1850–2005 is shown in Figure 3. Figure 3a represents the Consecutive 5 days of precipitation (RX5 days) over Punjab Pakistan. The upper threshold magnitude of RX5days is about 100 mm along the historical period. Yet, the number of consecutive wet days (CDD) and consecutive dry days (CDD) presented in Figure 3 (b,c) has upper threshold trends of 18 wet days and 120 dry days respectively.

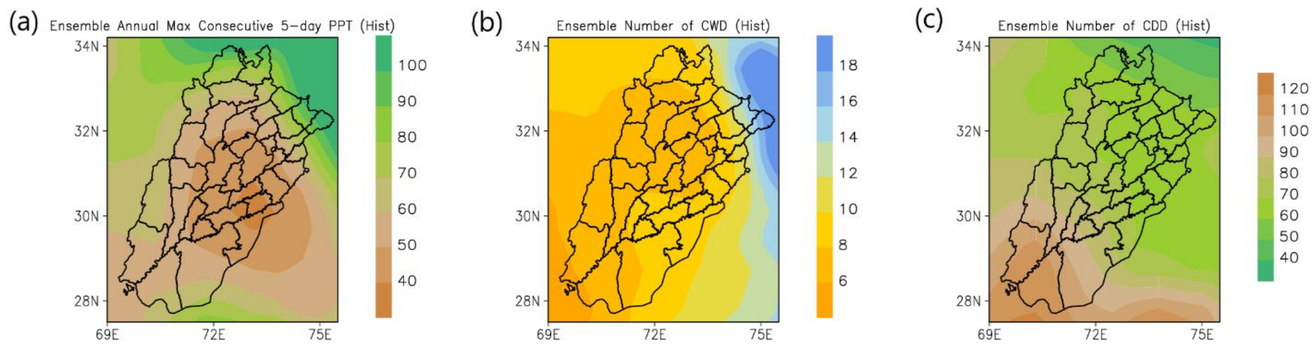

Figure 3: Historical precipitation-related extreme indices for the period of 1850–2005: (a) RX5days (unit: mm); (b) CWD (unit: days); (c) CDD (until: days)

Future climate extreme changes

Changes in temperature-related extreme indices

Figure 4 depicts the temporal evolutions of projected changes in annual temperature extreme indices, including the number of summer days (SU), the monthly maximum value of daily maximum temperature (TNx), the monthly maximum value of daily minimum temperature (TXx), warm nights (TN90p), warm days (TX90p) under RCP4.5 and RCP8.5.

Warmest Night (TNx)

Temporal variations in annual TNxtime series are shown in Figure 6(d1, d2, d3), under the historical timescale and under both the RCPs (4.5 and 8.5), respectively. In historical time series of the TNx, prominent changes in increasing patterns only occur in the recent years (after the 1960s). The thresholds of intra-regional variability reside between 24 °C to 33 °C before the 1960s. However, with increased natural variability, the threshold parameter slides up to a window that stays between 25 °C to 33 °C. This means that over the historical TNx time series, a significant increment in the lower threshold of the recent historical period has squeezed the intra-regional variability which indicates that more consistent and increased TNx has occurred over the recent periods as compared to the former historical period.

By analyzing projections of the TNx based on the RCP4.5, it is seen that the lower thresholds of the initial period reside between 26 °C to 34 °C (which is already 1 °C higher than the recent period of the historical time series). However, as the time series progresses, the threshold window escalates to an intra-regional range of 27 °C to 35 °C (which is again 1 °C higher than that in the initial projection period under the RCP4.5). Due to induced climate adaptations designed under the RCP4.5 emission scenario, the carbon forcing moderates at around the mid-21st century and hence nearly stable TNx thresholds are seen beyond the 7th decade till end of the century.

The RCP8.5 is a high end scenario owing to which ingested carbon is seen to force the TNx time series to a continuous rise till the end of the century. The initial intra-regional window of the TNx resides between 26 °C to 34 °C. However, by the end of the 21st century, the TNx threshold window rises to a range of 30 °C to 38 °C which is exceptionally high in terms of negative impacts such as crop yields decline, more energy consumption, deterioration of health, and heat stroke.

Warmest Day (TXx)

Figure 4 (e1, e2, e3) describes the time series patterns of the TXx for the historical and the carbon forced projected time periods. In the historical time series of the TXx, notable increasing patterns also occur in only recent years (after the 1960s). The thresholds of intra-regional variability tend between 41 °C to 50 °C before the 1960s. However, at the end of the 20th century, the threshold parameter slides up to a window between 42 °C to 52 °C. This means that the historical time series of the TXx has increased by 2 °C in both of its lower and upper thresholds.

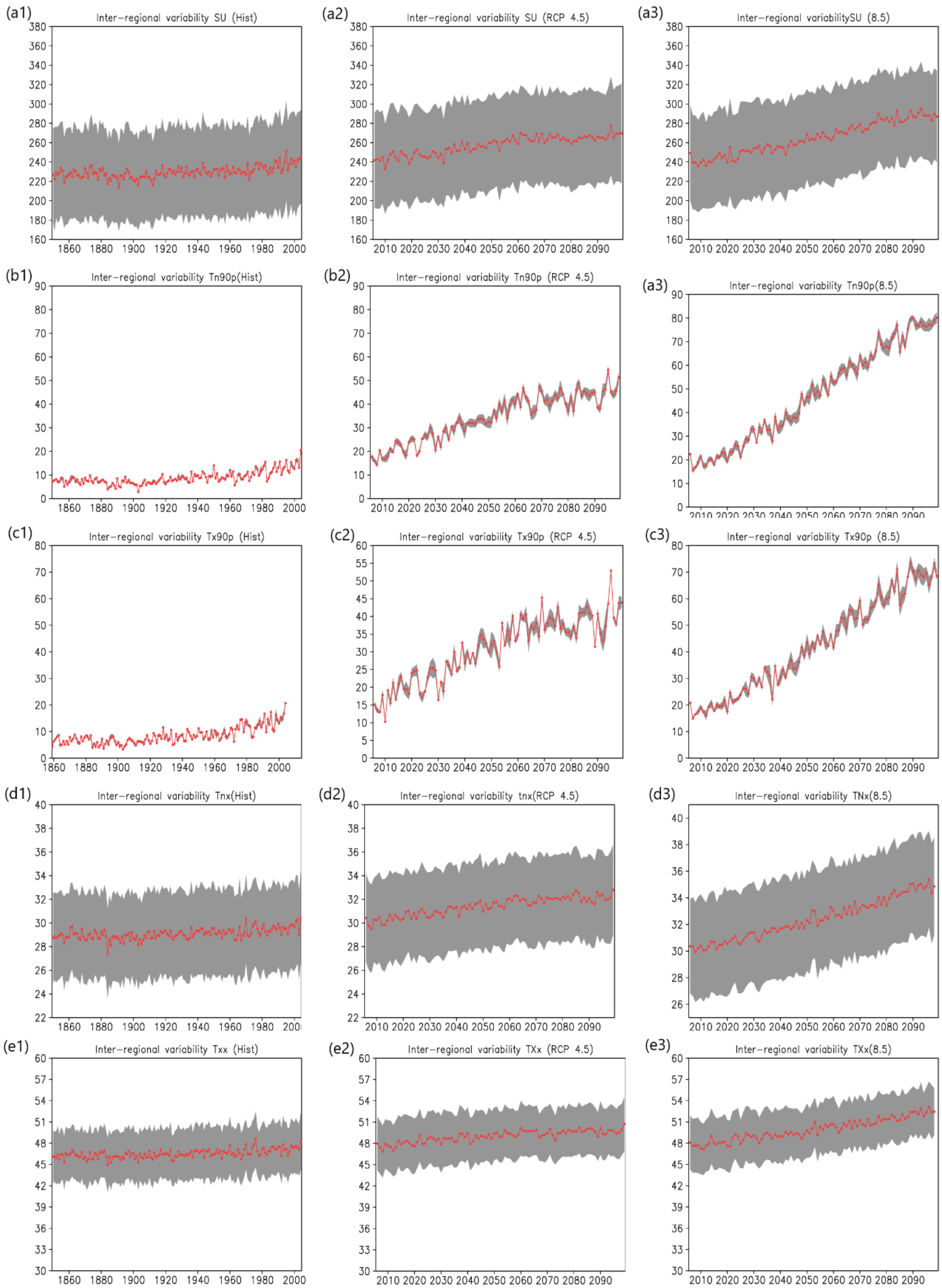

Figure 4: Plots of the temporal variations of temperature-related extremes in the future (2010-2100) under both RCP4.5 and RCP8.5 against the current climate state (19850–2005) over Punjab: (a1) SU hist, (a2) SU RCP4.5, (a3) SU RCP8.5; (b1) TN90p hist, (b2) TN90p RCP4.5, (b3) TN90p RCP8.5; (c1) TX90p hist, (c2) TX90p RCP4.5. (c3) TX90p RCP8.5; (d1) TNx hist, (d2) TNx RCP4.5, (d3) TNx RCP8.5; (e1) TXx hist, (e2) TXx RCP4.5, (e3) TXx RCP8.5.

From projections based on the RCP4.5, it is seen that the lower thresholds of the initial period tend to remain between 43 °C to 52 °C (which is already 1 °C higher in the lower threshold than that of the recent period along with the historical time series). However, as the time series progresses, the threshold window rises to a window between 44 °C to 53 °C (which is again 1 °C higher than that in the initial projection period under the RCP4.5). Due to induced moderate carbon forcing under the RCP4.5 emission scenario, steadily increasing patterns moderate at around the mid-21st century, and hence the upper thresholds of the TXx are seen to remain below a threshold of 54°C by the end of the 21st century. It is also seen that as opposed to historical patterns in the TXx, the interannual variability is smaller, and therefore more years with relatively similar TXx could be detected under the RCP4.5 emissions scenario.

The high-end emission scenario RCP8.5 tends the TXx to rise continuously until the end of the century. The initial window of the TXx remains between 43 °C to 52 °C, however by the end of the 21st century, the TXx threshold window increases and oscillates between 45 °C to 55 °C which is 3 °C higher than the recent period of the historical time period.

Even with a 3°C increase in the high carbon forced TXx, a significant increase in evapotranspiration could be expected. Higher amount of energy could be consumed to generate cooling degree days in order to reduce impacts. Moreover, crops that are sensitive to extreme heat could suffer from enhanced wilting processes. Furthermore, in an increased TXx climate, heat strokes are more likely in the districts of southern Punjab when no mitigation and adaptation plans are adopted and the climate is left over on a business as usual model. In a scenario where the TXx thresholds crosses 57 °C (as a result of the ingested RCP8.5 emission scenario), life would become impossible to sustain, and hence migratory tendencies would emerge in the Punjab region. Owing to the severely increased TXx, people would be forced to move from southern Punjab region to the central Punjab region to sustain life and living under the high end emission forced climate.

Summer Days (Su)

Figure 4 (a1, a2, a3) describes the time series patterns of the SU for the historical and the carbon forced projected time periods. Over the course of historical period, the SU has a high inter-annual variability. In temporal variation of the SU under the historical period, no significant changes can be detected over the course of the 19th century, and the index tends to reside between thresholds of 170 to 280 days. However, at the end of the 20thcentury, the threshold parameter slides up to a window between 180 to 290 days. Hence, historical patterns of the SU has forced its trend to increase by 10 days in about 150 years (0.66 day per decade).

Along the projections based on the RCP4.5, initial period tend to remain between 180 to 310 summer days. However, as the time series progresses, in the mid of 21st century, the threshold increases to a window between190 to 310 days. By the end of the 21st century, the SU further increase, but with an unequal rate of change of the upper and the lower thresholds and resides between a window of 200 to 320 days (Lower threshold increases faster than the upper one). Under this scenario, inter-annual variability is seen to lower down as compared to historical series, which means that more consistent years (consecutive) of similar SU magnitudes could be detected in the projection period. It is also seen that intra-regional variability lessens by 10 days in the lower threshold of the SU representing the upper Punjab districts. This means that districts experiencing smaller impacts in historical period are prone to higher vulnerability under the RCP4.5 projections in terms of a higher number of days added to the index (10 more days added to the SU index).

The high-end emission scenario RCP8.5 is seen to rise the SU index at a continuous pace until the end of the 21st century. The initial SU window tends to remain between 180 to 300 days, however by the end of the 21st century, the SU threshold window reaches its maximum value between 220 to 340 summer days. This means that under the high end emission scenario, more than 40 days are added to the current number of the SU days. This further means that out of the total 365 days of a year only 25 days will be termed as non-summer days. It also establishes that spring and autumn days are prone to diminish significantly under this high-end emission scenario and seasonal transition from summer to winter would take place directly without going through intermediate relieving months. Significant impacts under this scenario are remarkably high in terms of adverse impacts on crop yield, mortality rate, reproduction of soil microbes, deterioration of health, exhaustion, and heatstroke (Hatfield & Prueger, 2015; Marchetti, Capone, & Freda, 2016).

Warm Nights (TN90p)

Figure 4(b1) describes historical features of the time series patterns for the TN90p extreme index over the Punjab region. There is a meager change of trend in the initial years of the TN90p till the end of the 19th century. As the period progresses to 20th century, significant changes in the viability patterns are seen which altogether direct towards an increasing trend instigating from a modest 0 to 10 % increase and finalizing on 5 to 20% increase by the end of the control period. Altogether the upper threshold of the TN90p has risen at a higher pace as compared to the lower threshold of the same. This means that in the recent historical time period, TN90p extremes with higher magnitude have recurred over the end of the 20th century. Also, intra-regional variability is negligible in the control period of TN90p which means that whole of the Punjab region experienced a similar increase in warm night extremes over the course of 150 years in the control period.

Figure 4(b2) explains patterns of the percentage variability of the TN90p along the course of the 21st century under the RCP4.5 emission scenario. A close inspection of the time series suggests that intra-regional variability is small in the initial years, and as the period progresses towards end of the 21st century, higher intra-regional variability can be seen with higher magnitudes of extremes. This indicates all three bifurcations of the Punjab province will have dissimilar changes in the TN90p by the end of the 21st century. Initial window of TN90p thresholds resides between 10 to 35%, however, after the mid-21st century, the threshold window rises exponentially and rests at a window between 35 to 55% increase by the end of 21st century. Although there are increasing extremes of the TN90p in the initial years of the TN90p projections under the RCP4.5 emission scenario, yet owing to a higher increase (25%) of the lower threshold as compared to the upper one (20%) makes the variability window to squeeze after the mid-21st century. Hence more consistent and higher magnitude extremes of the TN90p can be expected under the RCP4.5 emission scenario by the end of the century.

Figure 4(b3) describes potential increase of the TN90p index over the course of 21st century in the Punjab region. There is a continuous increase in the trend percentage of the TN90p with progressively higher increase in the lower threshold (ranging from null to 70%) than that in the upper threshold (ranging from 40 to 90%) over the course of 21st century under the RCP8.5 emission scenario. Rise in the TN90p index is substantial and consistent around the whole Punjab region which is predominantly visible through its smaller intra-regional variability. A significant increase in such an indicator is liable to bring negative impacts on wheat yields that are not heat tolerant and require adequate cooling in the night time(Hatfield & Prueger, 2015). Also, energy demands would go significantly high for air conditioning purposes in the region (Isaac & Van Vuuren, 2009), since even the northern districts of Punjab might face similar anomalies as those for the southern and central Punjab districts. This will further make bifurcation of the Punjab districts into different climatic zones less significant as whole of the Punjab might face similar increase in the TN90p index.

Warm Days (TX90p)

Figure 4 (c1) portrays historical time series of the warm days index TX90p over the Punjab region. It is interesting to note that the index agrees well with the patterns of the TN90p over the same time period of 150 years of the past. The increase window is similar to that of the TN90p with starting window residing between null to 10% increase and gradually attaining boost at terminal window residing between 5 to 20 % by the end of 20th century. It is also seen that the upper threshold of the variability has shown higher increase (by 5%) as compared to that in the lower threshold.

Figure 4 (c2) identifies the TX90p index forced with the RCP4.5 emission scenario over Punjab region. There is a significant increase in the index which starts from a threshold window of 10 to 30 % increase in the initial years. However, it halts at around mid-21st century where the index reaches between threshold window of 20 to 40 % increase and stabilizes its further exponential boost. By the end of the 21st century, the index regresses due to low carbon forcing and manages to reside between 30 to 50 % increase over the Punjab districts.

Figure 4 (c3) describes potential change in the TX90p index over the terminus of the projected period. Rise in the index is sharp with almost similar recurrences of extremes over the entire course. The initial threshold of the index varies between a threshold window of 0 to 20 % increase, while at the terminal side it ascends by an enormous magnitude of a threshold window between 60 to 80 % in the Punjab districts. This means that neither of the thresholds have risen at different paces over the entire period and thus whole of the Punjab districts are liable to face consequences of extreme warm days in the projection periods forced with RCP8.5 emission scenario. Increase in warm days can result in lengthier summers, shorter winters, increased evapotranspiration, lower soil moisture, higher heat index, higher vulnerability to heat strokes, wilted cotton crops and higher health hazards for the Punjab region.

Changes in precipitation-related extreme indices:

Figure 5 depicts the temporal evolutions of projected changes in annual precipitation extreme indices, including the consecutive 5-day precipitation (RX5day), consecutive wet days (CDD), consecutive dry days (CDD) under RCP4.5 and Rcp8.5.

Consecutive 5-Day Precipitation (RX5day):

Figure 5(a1) demonstrates the temporal variation of historical consecutive 5 days precipitation (Rx5days). The inter-annual variation is very high with higher intra-regional variability. That means that more regions face different conditions every year, revealing a haphazard trend across the historic Rx5days time sequence. Although no noticeable trend could be observed due to the high fluctuating frequency shift, waves like structure could be seen with 2 to 3-year periodicity. Over the historical time sequence, the Rx5days threshold window is between 30 to 150 mm. However, with increased natural variability, the threshold parameter became declined to a 20 to 100 mm window.

Figure 5(a2) illustrates the projection-based temporal variance of consecutive 5 days precipitation (Rx5days) under RCP4.5. Through evaluating the projections, the estimate for the initial duration is 20 to 140 mm precipitation. However, as the time series goes, the lower thresholds of Rx5days rise marginally to a window of 30 to 130 mm (which is an improvement of 10 mm rain in the lower regions (southern Punjab) and a drop of 10 mm in the higher regions (Northern Punjab)). In addition, the inter-annual range is shrinking over time, which means that identical weather conditions can be observed with 4 or 5 years of repetition.

Figure 5(a3) indicates the projection-based temporal variance in consecutive 5-day precipitation (Rx5days) under RCP8.5. The high-end Rx5day precipitation scenario could be seen as a consistent growth until the end of the century. The initial intra-regional window of the Rx5days varies between 20 to 100 mm. By the end of the 21st century, though, the Rx5days median window had grown to between 30 and 150 mm. In addition, the intra-annual variability is very high, indicating a haphazard trend, which means that each year the volume of consecutive 5-day precipitation fluctuates over the historical time series.

Consecutive Wet Days (CDD):

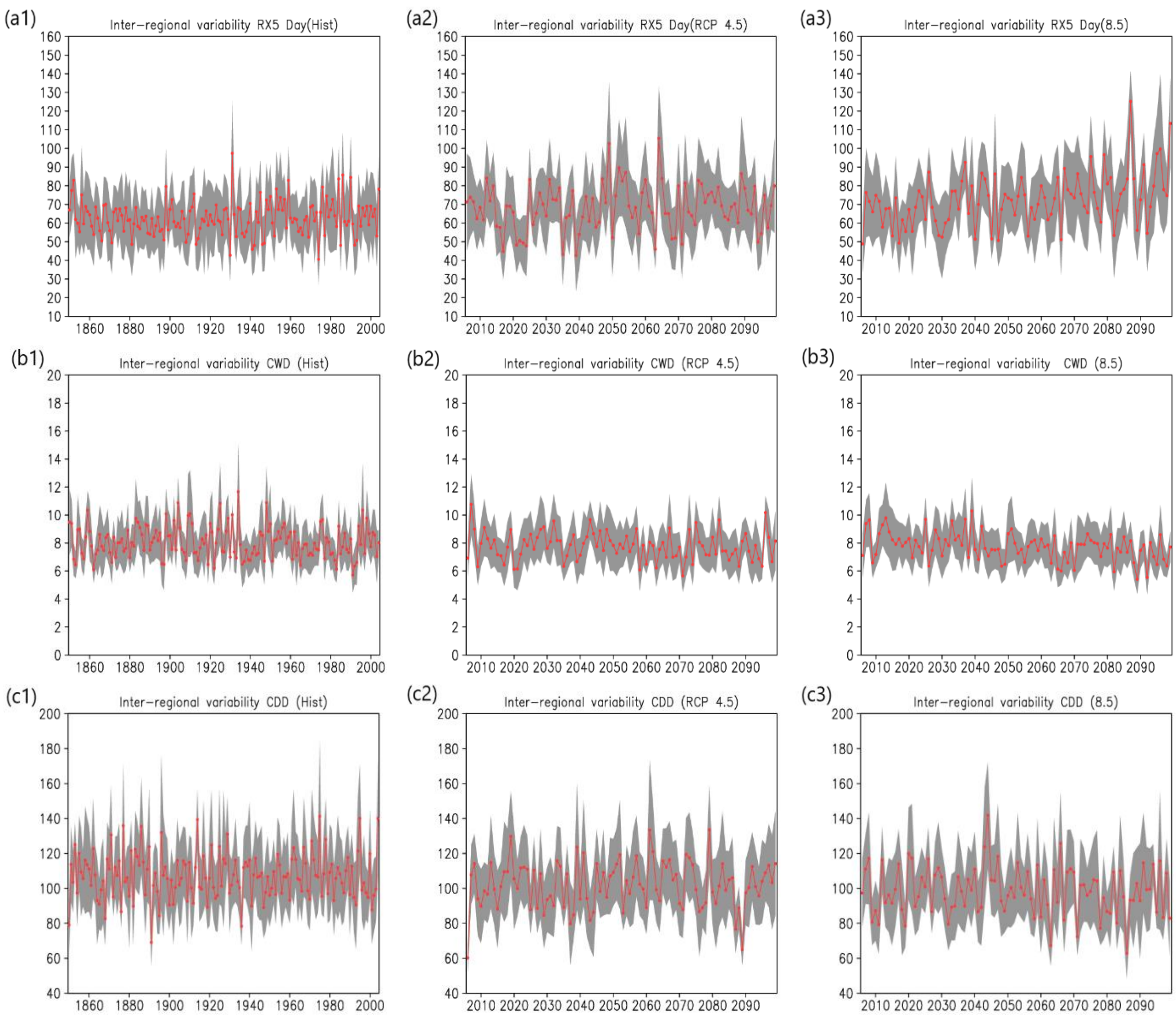

Figure 5: Plots of the temporal variations of precipitation-related extremes in the future (2010-2100) under both RCP4.5 and RCP8.5 against the current climate state (19850–2005) over Punjab: (a1) RX5days hist, (a2) RX5days RCP4.5, (a3) RX5days RCP8.5; (b1) CWD hist, (b2) CWD RCP4.5, (b3) CWD RCP8.5; (c1) CDD hist, (c2) CDD RCP4.5. (c3) CDD RCP8.5

Figure 5(b1) displays the temporal variation in historical consecutive dry days (CDDs). The inter-annual variability of CDDs is very high and is more likely to have a slapdash trend with a high fluctuating frequency change. The initial threshold for CDD windows is between 50 and 170 days, however with the increasing frequency of dry days it also rises and the threshold window exceeds 70 to 190 days (> 20 days), which means that between 150 years 20 dry days rose over the historical period (0.13 per year).

Figure 5(b2) demonstrates the projection-based temporal variation of consecutive dry days (CDD) under RCP4.5. Analyzing the estimated RCP4.5, the inter-annual variability of the CDD is smaller relative to the historical time frame, with more years showing a stable trend. The initial threshold of the CDD window is between 60 and 150 days, but the lower threshold began to decline with an increase in time, whereas the upper threshold rose to mid-century and reached 55 to 190 days.

Figure 5(b3) presents the projection-based temporal variation in consecutive dry days (CDD) under RCP8.5, which shows that the number of CDDs is steadily diminishing over time. The original threshold of CDD is between 55 and 190 days, with the period it begins to fall to 55 to 150 days by the end of the 21st century. In comparison, the inter-annual variation is significantly larger than the other RCP scenario. That means that the number of dry days will be seen fluctuating per year. Similarly, the intra-regional variability is still very high, with the trend changing from time to time.

Consecutive Dry Days (CDD):

Figure 5(c1) depicts the temporal variation of the historical consecutive wet days (CWD). The series reveals that there is a strong inter-annual variation with higher intra-regional variability. That means more of the districts in the Punjab facing a different condition every several years. Though there is no constant trend present between the historical time frame, however, overall, the small decline pattern seen and the end of the 20th century. The initial CWD threshold is around 5 and 17 days, with the time it reduces and hits 4 to 13 days (a higher drop of 5 days in the upper threshold window (Northern distracts)).

Figure 5(c2) reveals the projection-based temporal variation of consecutive wet days (CWD) under RCP4.5. Evaluating the time series reveals that inter-annual variability declines under RCP4.5, more years after a steady rising or declining trend. In comparison, the intra-regional variability is therefore relatively smaller than the historical time series, and there is more consensus between the region over the RCP4.5 scenario. CWD's initial window somewhere between 5 and 13 days and eventually falls to 4 to 11 days at the end of the 21st century (ensuring 2 to 1 day’s decline in upper and lower thresholds, respectively)

Figure 5(c3) demonstrates the projection-based temporal variance of Consecutive Wet Days (CWD) under RCP8.5. The number of CWDs steadily reduces with time. The initial CWD threshold is between 13 and 5 days, with the duration it begins to drop to 4 to 11 days by the end of the 21st century. In addition, the inter-annual variation is relatively greater than the other RCP scenario. Moreover, the intra-regional variability is still very high, with the pattern changing from time to time.

Drought prone regions of Punjab

Temperature-related:

Warm Nights (TNx)

Figure 6(d) indicate variations in the annual maximum daily minimum temperature (TNx) under RCP4.5, while TNx under the RCP 8.5 emission scenario is seen in Figure 7(d). Both RCPs were estimated to rise by 2.8 and 3.5 °C, respectively, compared to the historical period of 1850–2005. Significant rises in TNx are widespread in the central districts of Punjab, i.e. Bhakkar, Jhang, Layyah, D.G. Khan, Toba Tek Singh, Sahiwal, Vehari, Muzaffargarh, Bahawalnagar, Pakpattan, Okara. TNx is much more sensitive to future warming than TXx in both RCP projections.

Warm Days (TXx)

Figure 6(e) shows variations in the annual maximum daily maximum temperature (TXx) under RCP4.5, whereas TXx under the RCP 8.5 emission scenario is seen in Figure 7(e). Both RCPs were estimated to rise by 1.7 and 3.5 °C, respectively, compared to the historical period. The highest rise in TXx occurs in western-south Punjab, i.e. Rajanpur and DG Khan.

Summer Days (SU)

Figure 6(a), 7(a) demonstrates the annual summer days (SU) under RCP4.5 and RCP 8.5. Both RCPs illustrates an increasing trend in the southern districts with the highest increase of 40 days in Rajanpur and D G khan, which indicate the vulnerability of these both districts.

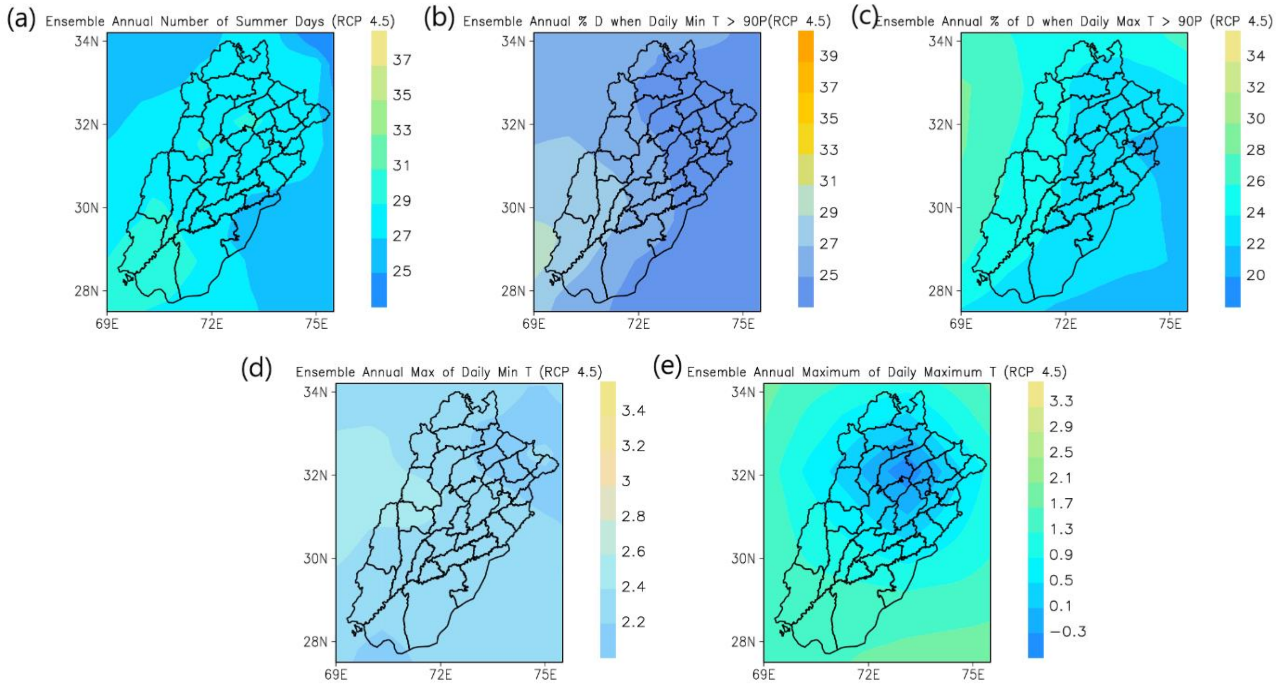

Figure 6: Projected RCP 4.5 temperature-related extreme indices for the period of 2005–2100: (a) SU (unit: days); (b) TN90p (unit:%); (c) TX90p (units:%); (d) TNx (unit: ℃); (e) TXx (units: ℃).

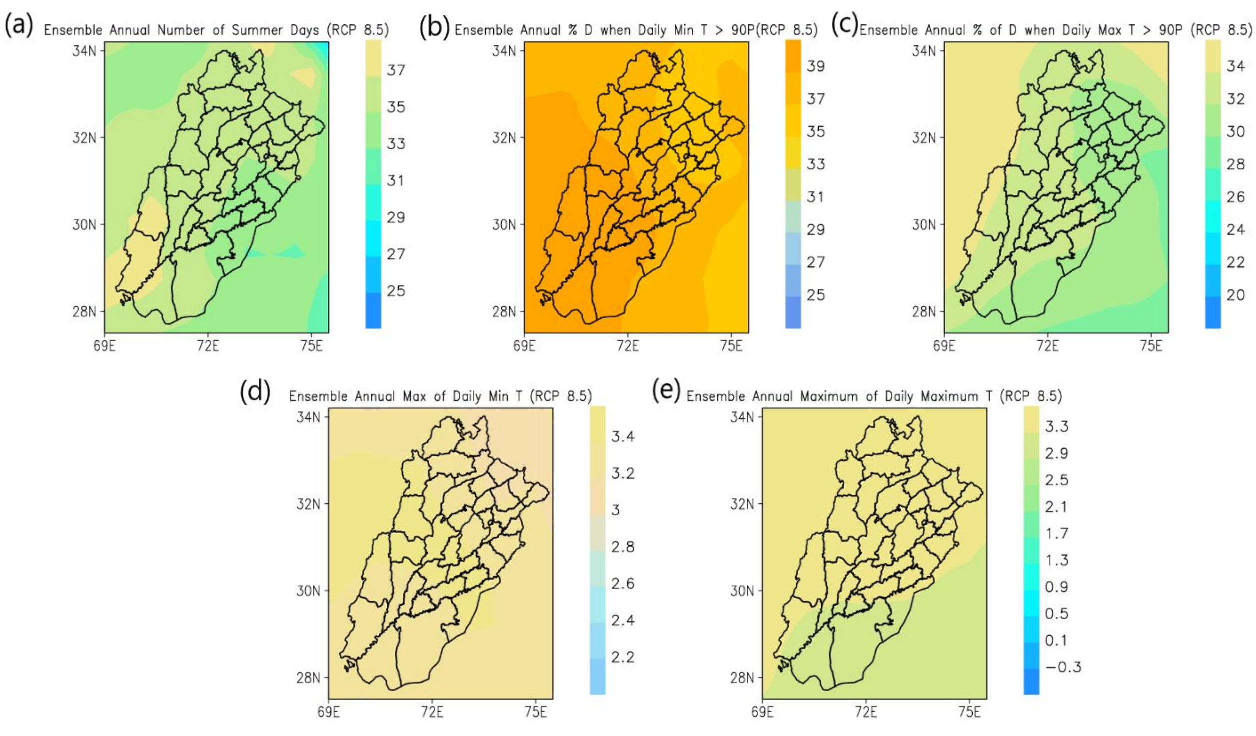

Figure 7: Projected RCP 8.5 temperature-related extreme indices for the period of 2005–2100: (a) SU (unit: days); (b) TN90p (unit:%); (c) TX90p (units:%); (d) TNx (unit: ℃); (e) TXx (units: ℃)

Warmest Night (TN90p)

In the case of percentile-based indices Warmest TN90p,Whatever the emission scenario RCP8.5 or RCP4.5 is, the warming gradually increases and reaches its maximum value in 2100 with values of 30% increase in warm nights and a 40% increase in the warm night (Figure 6b,7b).

Considerable changes in the warm night are evident over Rajanpur and DG Khan. which can help accurate prediction of an increase in warm nights, as temperatures will be unusually high, and extremely dry weather conditions will continue, the impacts of the warm night and dry extremes on health, ecosystems, agriculture, and economy would grow significantly the longer these conditions persist. In many places of Punjab, the harvest will begin remarkably early.

Warmest Days (TX90p):

Figure 6(c), 7(c) reveals the warmest days (TX90p) under RCP4.5 and RCP 8.5. It is seen that warming rises steadily and hits its highest value at the end of 21 century with 26 percent and 35 percent rise in the warmest days under RCP4.5 and RCP8.5, respectively. Increased warm days will have a major effect on the climate and will also cause harm to agriculture and society, including water shortages, harvest failures, and rising food prices, which threaten to exacerbate drought and severity.

Precipitation-related:

Consecutive 5-Days Precipitation (Rx5Days):

Figure 8a and 9a depicted the Consecutive 5 days precipitation under RCP4.5 and RCP8.5. both the RCPs show the increasing pattern against the historical period and the increase is also significant at most points of the area, showing a homogeneous pattern, particularly over the central east side showing in the shaded area. The change average increase of this index goes up to 9.5 mm by the end of this century under RCP 8.5 which indicates the chances of the increased flood in the central-eastern region of Punjab, Narowal and Sialkot.

Consecutive Wet Days (CWD)

Consecutive Wet Days (CWD) are defined as the total number of days when precipitation is greater than 1 mm. However, Figures 8b, 9b demonstrates that both RCPs are showing decreasing trends up to 0.5 days under RCP4.5 and 0.7 days under RCp8.5, particularly over the Bahawalpur and Bahawalnagar districts.

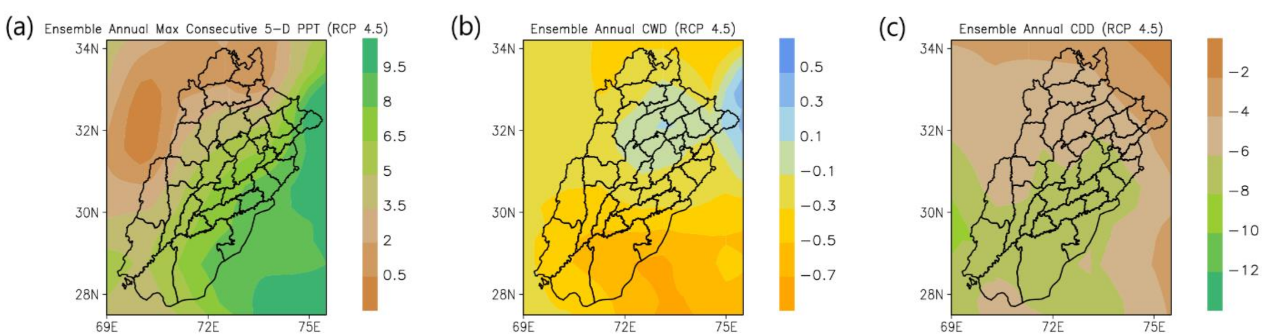

Figure 8: Projected RCP 4.5 precipitation-related extreme indices for the period of 2005–2100: (a) RX5days (unit: mm); (b) CWD (unit: days); (c) CDD (until: days).

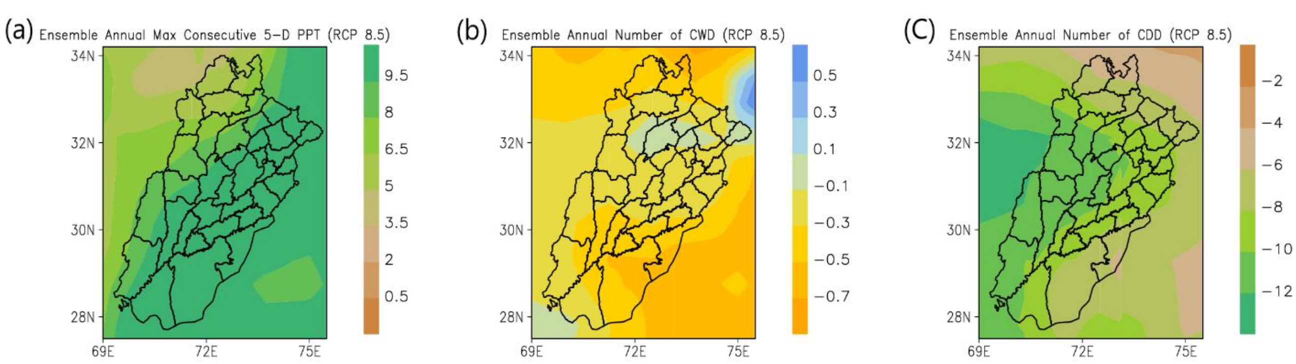

Figure 9: Projected RCP 8.5 precipitation-related extreme indices for the period of 2005–2100: (a) RX5days (unit: mm); (b) CWD (unit: days); (c) CDD (until: days).

Consecutive Dry Days (CDD)

Figure 8c, 9c shows the Consecutive Dry Days (CDD) which also depicted declining days up to12 dry days under both RCP4.5 and RCP8.5, particularly over central and southern Punjab. Figures represent the low consensus, with more than half of the country agreeing on the sign of deterioration, suggesting that there are likely to be a few rainy days in the region. If future developments follow the paths of the RCPs.

4. DISCUSSION AND CONCLUSIONS

In the past decades, the whole Punjab has experienced more extreme events in the context of the frequency, magnitude, and duration, which caused drought conditions, water shortage, severity, widespread causalities, and economic losses. Therefore, it is imperative to acquire the information of future projections of these extremes to minimize their likely adverse impacts. This study provides an observed (1850-2005) and future (2020-2100) extreme events over Pakistan.

Overall, the results indicate increased extreme warming events and intensified precipitation-related extremes in a future warmer world. The main findings are summarized as follows

1. CMIP5 models show the consistency in the increase in temperature-based extremes (i.e. TN90p, TX90p, TXx, TNx, and SU) across Punjab in terms of frequency and magnitude in overall Punjab districts. The changes of these climate extremes generally increasing, relatively weak changes in the RCP4.5 scenario than that in RCP8.5. Whereas across the whole Punjab the temperature is increasing at a higher rate in daily minimum temperature, warm and warmest night (TNx, TN90p) are more prominent than that for daily maximum temperature, warm and warmest day (TXx, TX90p) with respect to duration and frequency. However, night temperature warming has a greater contribution to the overall warming process as compared to the warming of day temperatures. The results over Punjab agree with global studies which indicate that anthropogenic activities would cause fewer cold extremes and more warm extremes in the 21st century. Moreover, the highest increase in temperature is observed over southern Punjab as compared to northern Punjab. Summer days (SU) are also increasing in southern districts with the highest increase of 40 days in Rajanpur and D G khan, which indicate the vulnerability of these both districts. This increased warming will result in more rainfall events and can also intensify the hydrological cycles in most of the parts of Punjab that may lead to flooding and drought at the regional scale.
2. However, the lower agreement is observed in the case of precipitation extremes among CMIP5 models than temperature extremes. The consecutive 5 days of precipitation (RX5 days) is increasing and indicating climate change response. Additionally, the decrease in consecutive dry days (CDD) and decrease in consecutive wet days (CWD) present uniform responses to warming. In southern Punjab (Rajanpur, DG Khan, and central Punjab districts), there is a significant increase in consecutive 5 days precipitation (RX5days) and a decrease in consecutive dry days (CDD). The results of future projections of precipitation extremes also suggest a consistent increase in extreme precipitation contribution to total annual precipitation. Although there is an increase in the extreme precipitation but a decrease of consecutive wet days CWD in these districts.
3. The study findings indicate that the precipitation-based indices have a more consistent pattern in their RCPs and historical period with small variability, while temperature-related extreme indices show a significant increase, for example, if there is a decrease of 108 days of annual dry days instead of 120 days, the maximum of maximum temperature retain will be reached at least will be 53.3°C instead of 50°C and also the maximum of the minimum will reach 35.5°C instead of 32°C and the warm days will be 43% more and warm night will be 48% more in their percentage (Table 4), similarly, there will be more summer days 310 days instead of 270 days that will cross the threshold of 25°C (Table 4), so the frequency pattern of precipitation related to drought indices will remain constant like they were before in the historical period but temperature-related indices for those drought days will be more severe in the future projection.

Table 4: Color-coded assessment of ETCCDI indices of hazard and vulnerability risk assessment

Temperature-related extreme indices:

Indices	SU	TN90p	TX90p	TNx	TXx
Historical	300 days	20%	20%	34℃	52℃
RCP 4.5	320 days	55%	50%	36℃	54℃
RCP 8.5	350 days	90%	80%	39℃	56℃

Precipitation-related extreme indices:

Indices	Rx5Days	CWD	CDD
Historical	100mm	13 days	180 days
RCP 4.5	120mm	11 days	190 days
RCP 8.5	140mm	10 days	160 days

Considering advanced innovations and approaches, numerous scientists have taken numerous efforts to improve the model capacity for the future prediction and projection of climate change in recent years. However, large uncertainty still exists. This uncertainty in projection is due to the inter-model variability and external forcing. These may emerge from the boundary and initial conditions, scenarios, carbon cycle feedbacks, structural uncertainty, parameter uncertainty, and other forces. Recent studies have indicated that the internal variability and the inter-model difference are the dominant contributors to the large uncertainty of the climate change projection at both decadal timescales and regional scales. Such acknowledgment welcomes more consideration towards these two angles for progress in atmosphere science, towards improving climate model resolution. Moreover, it is important to utilize the high-resolution regional models (RCMs) to assess the future dry spell conditions and changes of extreme events over Pakistan.

Conflict of Interest

The authors declare that there is no conflict of interest.

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Peer-review

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Data and materials availability

All data associated with this study are present in the paper.

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