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# Influence mechanism of climate change over crop growth and water demands for wheat-rice system of Punjab, Pakistan

Mirza Junaid Ahmad, Gun-Ho Cho, Sang-Hyun Kim, Seulgi Lee, Bashir Adelodun and Kyung-Sook Choi

## ABSTRACT

Conceptualizing the climate change perspective of crop growth and evapotranspiration ($ET_c$) rates and subsequent irrigation water requirements (IWR) is necessary for sustaining the agriculture sector and tackling food security issues in Pakistan. This article projects the future growth periods and water demands for the wheat-rice system of Punjab. Intense and hotter transitions in the future thermal regimes and erratic monsoon rainfall increments were envisaged. The crop growth rates were accelerated by the probable temperature rise resulting in shortened growth periods. The temperature rise increased the reference evapotranspiration rates; however, the future $ET_c$ declined due to reduced growth period and net radiation. Highly unpredictable, but mostly increasing, cumulative seasonal and annual rainfalls were indicative of more effective rainfalls during the future crop seasons. Reduced $ET_c$ and increments in seasonal effective rainfalls gave rise to the declining IWR for both crops. The study findings seemingly undermined the harmful climate change influences on the water requirements of the wheat-rice system of Punjab but alarmingly shortening of growth periods indicates a higher crop failure tendency under the projected future thermal regime.

**Key words** | climate change, Pakistan, water demands, wheat-rice system

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## HIGHLIGHTS

- The crop water demands were projected after considering the probable changes in the future growing season lengths.
- A projected decline in future net radiation counteracted the warming-driven increments in crop evapotranspiration rates and irrigation water requirements.
- The early maturing future crops yielded an overall decline/incline in seasonal/daily water demands making the crops more irrigation-dependent and temperature-sensitive.
- Compared to the rice, the wheat was more vulnerable to future climate change threats.
- A new outlook was provided for developing the optimized irrigation schedules to mitigate the climate stresses on the future crop water demands.

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## INTRODUCTION

Climate plays a critical role in determining the crop growth rates and final yield, thus directly impacting the agriculture sector and food security (Martins *et al.* 2019). However, the recent climate change phenomenon, which is supported by undeniable scientific evidence, is responsible for the rapid diminishing of snow/ice caps, sea-level rise and frequent natural calamities such as floods and droughts (IPCC 2014; Kang *et al.* 2017). The climate change trends are severely threatening the agriculture-dependent economies like Pakistan, which is one of the worst climate-struck and food-insecure nations because of its over-reliance on irrigated agriculture, constantly diminishing river flows, swift population growth and low adaptive capacity (Abid *et al.* 2016; Khan *et al.* 2016).

Wheat and rice are the staples, accounting for up to 50% of daily calorific intake (Arshad *et al.* 2017) and their availability/accessibility dictates the food security of Pakistan. According to the World Food Program, despite having a good wheat harvest in 2014, up to 47% of the country's population was food insecure led by widespread malnutrition, uneven food distribution and water shortages (Kirby *et al.* 2017). Considering the future climate warming in Pakistan, yields of both the crops will drastically decline, accompanied by substantial water shortages (Sultana *et al.* 2009; Kirby *et al.* 2017; Ahmad *et al.* 2019; Ahmad *et al.* 2020).

Previously, the climate change threats against the agriculture sector of Pakistan regarding crop yield and water consumption were discerned as a function of temperature and rainfall perturbations (Pakistan National Communication 2000; Sultana *et al.* 2009; Rasul *et al.* 2012; Ahmad & Choi 2018a). The climatic interactions with crop evapotranspiration ($ET_c$) and the subsequent irrigation water requirement (IWR) are not solely temperature-dependent since other components such as solar radiation, wind speed and vapour pressure deficit also control the $ET_c$ rates (Irmak *et al.* 2012). Recently detected declines in sunshine hours and solar radiations can counteract the warming-driven $ET_c$ increments (Liu *et al.* 2014). An increased ambient temperature often corresponds to a shortened crop growth period (Asseng *et al.* 2015); thus reducing the cumulative seasonal $ET_c$ and IWR (Karimi *et al.* 2018; Ahmad *et al.* 2019, 2020). A combination of the contracted growth period and less solar radiation could reduce the seasonal cumulative $ET_c$ and IWR, but the daily $ET_c$ and irrigation/rainwater consumption rates would increase simultaneously (Saadi *et al.* 2015; Ye *et al.* 2015; Ahmad *et al.* 2019, 2020). Hence, the future $ET_c$ and the associated IWR should be predicted by considering the anticipated reductions in the crop growth period and solar radiation.

This study primarily aims at investigating the primary mechanism of climate change on the crop growth periods and the corresponding water demands of the wheat-rice cropping system in Punjab, the largest agricultural province of Pakistan. Statistically bias-corrected climate change projections from eight general circulation models (GCMs) produced the future climate under the medium and extreme representative concentration pathway scenarios. The future climate was projected during two time periods, 2030s (2021–2050) and 2060s (2051–2080), against the baseline duration of 1980–2010. The future crop growth periods were projected by utilising the growing degree day (GDD) concept and the associated crop water demands were estimated by considering all the climate variables which could influence the $ET_c$ and IWR. The study outcomes would facilitate the policy-makers and stakeholders to optimize the irrigation schedules and regulate canal water supplies according to the future crop water demands for mitigating climate stresses on the wheat-rice system of Punjab, Pakistan.

## MATERIALS AND METHODS

### Study area

Punjab, the bread basket of Pakistan, has two distinct cropping seasons: winter and summer lasting from November–April and May–October, respectively (Ahmad & Choi 2018b). The wheat-rice system of Punjab covers approximately 1.1 million hectares (Mha) primarily irrigated by

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the Upper Chenab Canal (UCC) that has a gross command area of 0.64 Mha and cultivable command area of 0.59 Mha of which up to 60% is mostly allocated for the wheat and rice cultivation during the winter and summer season, respectively (Shakir *et al.* 2010).

This study focuses on the UCC command area (Figure 1) where the canal water is available only during the summers and the rice production is partly, and the wheat production is entirely, dependent on marginal quality groundwater. Seasonal temperature and rainfall fluctuations are intensely characterized by short and dry winters followed by long and hot summers, which also receive the major proportion of annual rainfall as monsoon rainfalls. The average winter and summer temperatures vary in ranges of 8–19 and 20–42 °C, and approximately 60% of annual cumulative rainfall (994 mm) occurs as monsoon rainfalls in July–August. Moderately fine to medium textured soils prevail in most parts of the UCC command area (Jehangir *et al.* 2002, 2007).

## Climate data

Sialkot is the only weather station in the vicinity of the study area with reliable long-term weather data records. A climate dataset for the baseline period of 1980–2010, including daily maximum temperature ($T_{max}$), minimum temperature ($T_{min}$), number of sunshine hours ($n$), net radiation ($R_n$), rainfall ($P$) and monthly average values of relative humidity (RH) and wind speed ($u_2$), was collected from the Pakistan Meteorological Department. The daily RH and $u_2$ values were also retrieved from the National Centers for Environment Prediction (NCEP) Climate Forecast System Reanalysis (CFSR) global climate data set (https://globalweather.tamu.edu/#pubs). The CFSR data had a horizontal resolution of 38 km and daily $T_{max}$, $T_{min}$, RH, $u_2$, and $R_n$ data were available from 1979 to 2014 (Saha *et al.* 2010; Fuka *et al.* 2013; Dile & Srinivasan 2014) which were downloaded for the grid containing the Sialkot station.

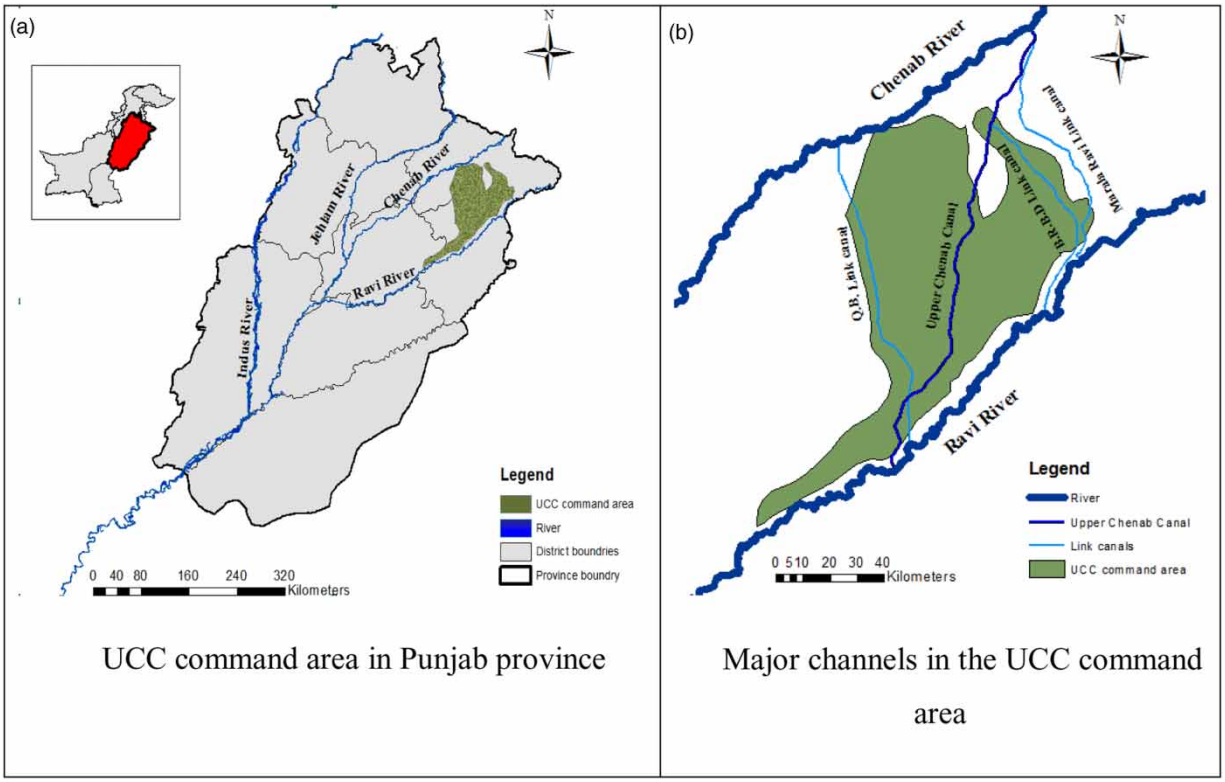


**Figure 1** | Location of the study area.

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A simple linear-scale change-factor bias-correction procedure was applied on the CFSR daily dataset by adding (multiplying) the difference (ratio) between the long-term mean monthly values of a specific climate variable in observed and CFSR datasets. Additive corrections were made for the $T_{max}$ and $T_{min}$ and multiplicative corrections were made for the RH, $u_2$ and $R_n$. Underlying principles, merits and demerits of the bias correction approach can be cited from the literature (Ines & Hansen 2006; Chen *et al.* 2011; Teutschbein & Seibert 2012; Kum *et al.* 2014; Miao *et al.* 2016). After removing the possible biases (Figure 2), it was assumed that the CFSR daily RH and $u_2$ time series could efficiently represent the climate of the study area. The study area's daily baseline climatology was devised by combining the observed $T_{max}$, $T_{min}$, $P$ and $R_n$ time series with the basic-corrected CFSR reanalysis time series of RH and $u_2$.

## GCM data

GCMs are the numerical models which are widely used to simulate the Earth's climate dynamics hundreds of years in the future (Ehret *et al.* 2012; Anandhi *et al.* 2016). A scenario defines the plausible future state of the world after incorporating the anthropogenic and natural variabilities in the climate and socioeconomic conditions (Anandhi *et al.* 2016). In the fifth phase of the coupled model intercomparison project (CMIP5) four new climate scenarios called the representative concentration pathways (RCP) were included. The RCPs were categorized based on a rough estimate of the radiative forcing in 2100 relative to the preindustrial era. For example, in the extreme and medium emission scenarios of RCP 8.5 and 4.5, the radiative forcing increases throughout the 21st century, finally reaching a level of 8.5 and 4.5 $W/m^2$, respectively, at the end of the century (Taylor *et al.* 2011).

In this study, eight GCMs (Table 1) from CMIP5 archives were chosen based on their ability to represent the South Asian monsoon climate after carefully reviewing the latest studies aiming at selecting the suitable GCMs to project future climate-change trends for Pakistan and/or neighbouring countries such as India and China (Biemans *et al.* 2013; McSweeney *et al.* 2015; Sharmila *et al.* 2015; Sooraj *et al.* 2015; Hasson *et al.* 2016; Lutz *et al.* 2016; Su *et al.* 2016; Chaudhuri & Srivastava 2017; Ruane & McDermid 2017). Daily GCM outputs of $T_{max}$, $T_{min}$, RH, $u_2$, $P$ and $R_n$ forced under the RCP 4.5 and 8.5 during two future time periods: 2030s (2021–2050) and 2060s (2051–2080) were included in the study. RCP 8.5 was selected to discern the extreme climate-induced risks because it covered higher radiative forcing and temperature change. RCP 4.5 was preferred over RCP 6.0 because of its relatively better prediction capability of annual average $CO_2$ emission growth rates during 2005–2012 (Peters *et al.* 2013; Sanford *et al.* 2014). We exclude RCP 2.6 as the $CO_2$ mitigation rate proposed by the RCP is unlikely to prevail in the near future in Pakistan (Khan & Koch 2018).

Coarse-resolution of the GCMs outputs lacked indispensable fine-scale, sub-grid information for agricultural impact assessment. Inherent unavoidable biases originating from various sources also distort the intensity and frequency of extreme events like heatwaves and dry/wet spells in the GCMs outputs. The literature suggests a variety of techniques and tools to tackle these biases ranging from complex and computationally extensive dynamical-downscaling techniques to simpler, readily adoptable statistical bias-correction techniques. Among the latter group, quantile mapping (QM) is a commonly followed procedure where the biases in the GCM historic simulations are removed by mapping the cumulative distribution function (CDF) of a certain variable in GCM time series over the CDF of the same variable in the observed time series. The same empirical CDFs are then applied over the GCM-projected future time series. Details about the underlying principles, limitations and extensions of QM and its comparison with other approaches has been extensively discussed in the literature (Ehret *et al.* 2012; Ahmed *et al.* 2013; Kum *et al.* 2014; Rockel 2015; Miao *et al.* 2016; Sippel *et al.* 2016; Eum & Cannon 2017). In this study, the daily GCM outputs of $T_{max}$, $T_{min}$, RH, $u_2$, $P$ and $R_n$ during the historic and future runs were subjected to QM based on daily observed baseline data.

## Estimation of crop growth period

The temperature impacts on the growth periods of both crops during the baseline and future time slices were incorporated using the GDD concept (Hanif Qazi *et al.* 1997;

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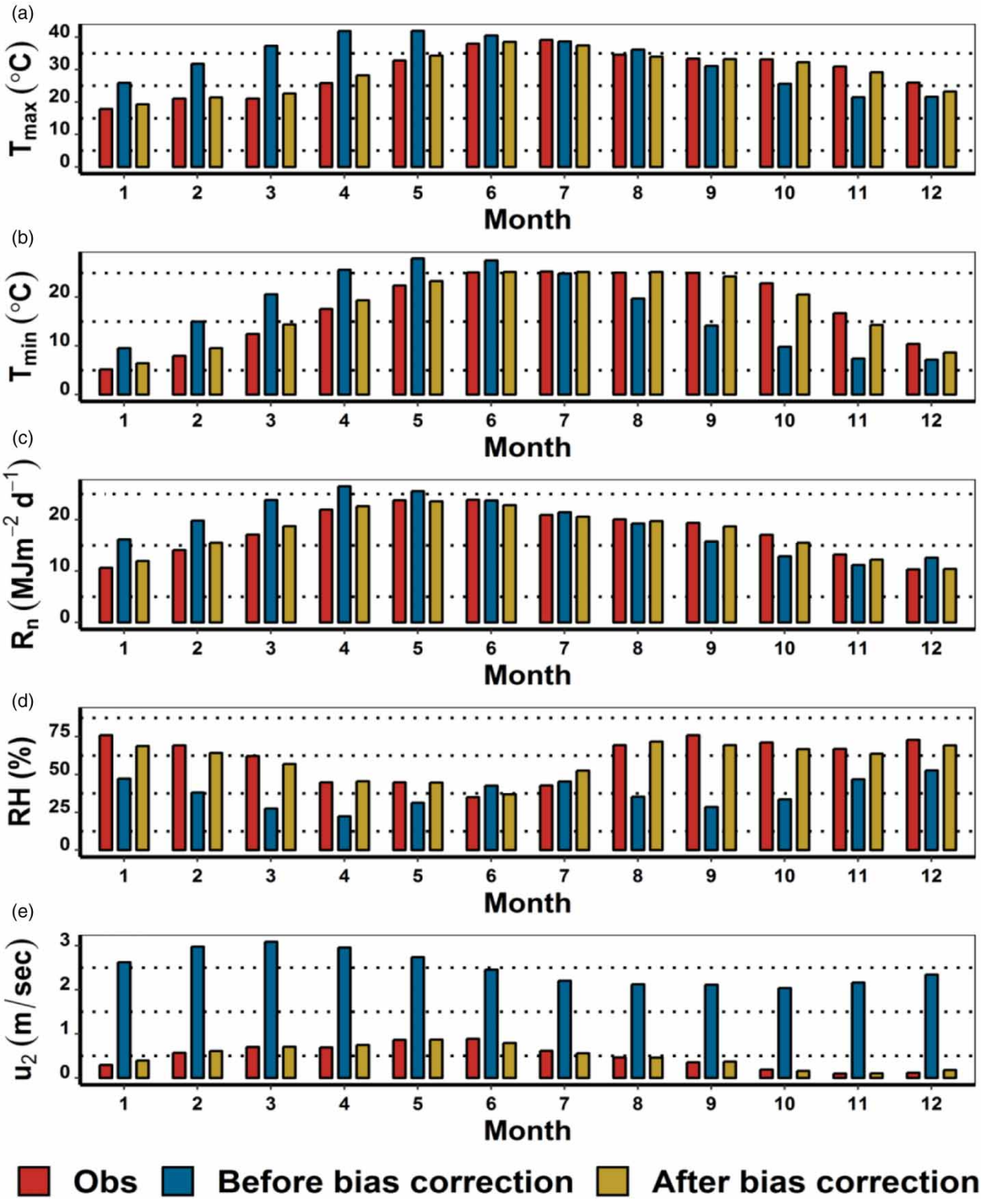


**Figure 2** | Difference between mean-monthly observed and CFSR reanalysis climate datasets before and after the bias correction from 1980 to 2010.

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**Table 1** | Summary of GCMs used in this study

| GCM | Institution | Horizontal resolution |
|---|---|---|
| BCC-CSM-1.1 | Beijing Climate Center, China Meteorological Administration | ~1.25 × 1.875° |
| GFDL-ESM2M | NOAA/Geophysical Fluid Dynamic Laboratory (GFDL) | ~2.0 × 2.5° |
| CCSM4 | US National Center for Atmospheric Research | ~0.9 × 1.25° |
| HadGEM2-ES | UK – Meteorological Office – Hadley Center | ~1.25 × 1.875° |
| inmcm4 | Russian Institute of Numerical Mathematics (INM) | ~1.5 × 2.0° |
| MIROC5 | University of Tokyo, Japanese National Institute for Environmental Studies (NIES), and Japan Agency for Marine-Earth Science and Technology (JAMSTEC) | ~1.4 × 1.4° |
| MPI-ESM-LR | Max Plank Institute of Technology (low resolution) | ~1.9 × 1.875° |
| MPI-ESM-MR | Max Plank Institute of Technology (mixed resolution) | ~1.9 × 1.875° |

Pakistan National Communication 2000) as follows:

$$\mathrm{GDD} = [(T_{\max} + T_{\min})/2] - T_{\mathrm{base}} \quad (1)$$

where $T_{\max}$, $T_{\min}$ and $T_{\mathrm{base}}$ are the maximum, minimum and base temperatures, respectively. The GDDs are routinely used to relate the plant growth rate and ambient temperature as heat accumulated above a certain base temperature ($T_{\mathrm{base}}$), and if the average temperature $< T_{\mathrm{base}}$, the plant growth is assumed to be zero.

For medium duration wheat and rice cultivars, the $T_{\mathrm{base}}$ values were assumed to be 5 and 10 °C, respectively. In Punjab, the seasonal cumulative GDDs for the wheat and rice crops lie in the ranges of 1,200–2,250 and 1,650–2,750 °C, usually accumulated over 120–270 days and 108–125 days, respectively (Hanif Qazi *et al.* 1997; Pakistan National Communication 2000). We assume average optimum GDD of 1,800 and 2,200 °C for the medium duration cultivars of wheat and rice, respectively (Hanif Qazi *et al.* 1997; Pakistan National Communication 2000). The crop growth periods were computed as the number of days required to accumulate the respective crop GDDs during baseline and future time periods to gauge the climate-driven impacts on crop growth rates.

## Estimation of water requirements

The single crop-coefficient methodology proposed by the FAO was adopted to estimate the crop water requirements. The daily reference crop evapotranspiration ($ET_o$) was estimated by the FAO Penman–Monteith equation and the crop evapotranspiration ($ET_c$) was approximated from the product of $ET_o$ and crop coefficients ($K_c$) (Allen *et al.* 1998). The 10-daily $K_c$ values for the UCC wheat-rice system were referenced from Ullah *et al.* (2001). The difference between the effective rainfall (ER) and $ET_c$ was the IWR that have to be applied through irrigation. The ER was calculated using the United States Department of Agriculture method (Luo *et al.* 2015; Ye *et al.* 2015; Tukimat *et al.* 2017; Zhou *et al.* 2017).

The wheat IWR was simply estimated as the difference between $ET_c$ and ER. The rice IWR must also include irrigation demands for land-preparation, percolation losses and ponding depth that have to be maintained during the season. A simple water-balance approach specifically addressing the rice IWR estimation was employed as (Acharjee *et al.* 2017b; Tukimat *et al.* 2017):

$$\mathrm{IWR} = ET_c + W_p + W_{lp} + W_s - \mathrm{ER} \quad (2)$$

where $\mathrm{ET}_c$ = rice crop evapotranspiration, $W_p$ = amount of percolation water loss, $W_{tp}$ = water required for land preparation, $W_s$ = standing water layer depth and ER = effective rainfall.

In Punjab, rice is grown under constant flooded conditions with ponding depths ($W_p$) of 50–75 mm maintained during most of the season, whereas the water usage ($W_{lp}$) for land preparation through puddling varies in the range of 250–900 mm (Soomro *et al.* 2015). We used $W_p$ of 75 mm and $W_{lp}$ of 450 mm as the representative values in

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Equation (2) by following the previously conducted field studies (Aslam *et al.* 2002; Bhatti *et al.* 2009; Soomro *et al.* 2015). Percolation loss ($W_p$) through rice fields is mainly a function of soil texture and it varies from 2 mm/day for heavy clay soils to 6 mm/day for sandy soils (Chapagain & Hoekstra 2011). More than 60% of farms located in the UCC command area had heavy clay loam as dominant soil texture (Hussain *et al.* 2012). Ullah *et al.* (2001) used a percolation rate of 1.5 mm/day for rice consumptive water demand estimation in various canal commands of the Indus Basin. We considered an average percolation rate of 2.5 mm/day as suggested by Chapagain & Hoekstra (2011) for heavy clayey soils.

Growing season lengths of 150–180 and 120–150 days were considered for the wheat/winter season and rice/summer season, respectively. The wheat sowing and harvesting dates were set as November 1 and April 31 whereas for rice these were set as June 1 and October 30 with July 1 being the transplantation date. All the calculations were performed for a 10-day time step during both growing seasons under the baseline and future time slices.

## RESULTS

### Projected climate change

During the baseline (1980–2010) period, annual average $T_{max}$, $T_{min}$ and annual cumulative $P$ outputs from the selected GCMs before and after bias correction and the respective biases are shown in Figure 3. All GCMs underestimated the observed temperature (both $T_{max}$ and $T_{min}$) and $P$ except HadGEM2-ES which showed a temperature overestimation tendency. After bias correction, means, medians and distribution of extreme heat events were significantly reduced. Individually, inmcm4 and MIROC5 showed the highest tendency of duplicating the observed $T_{max}$ and $T_{min}$ time series during the baseline (Figure 3(a) and 3(b)).

The GCMs capacities to reproduce baseline observed $P$ data remained limited even after the QM application. The mean and median mismatches between observed and GCM $P$ time series were adjusted but the misrepresented extreme $P$ events were not fully eliminated (Figure 3(f)). This issue was resolved by taking an ensemble of bias-corrected $P$ data, and the biases in the mean, median and frequency or distribution of intense $P$-events were successfully removed (Figure 3(c)). Thus, we assume that bias-corrected GCM-ensemble $P$ outputs can fairly project the study area's future rainfall patterns.

The projected changes in GCM-ensemble $T_{max}$, $T_{min}$, $R_n$ and $P$, after bias correction, under RCP 4.5 and 8.5 during the 2030 and 2060s compared to the baseline (1980–2010) are shown in Figure 4. An intense and hotter shift in the thermal regime was projected with tangible evidence of climate warming (both $T_{max}$ and $T_{min}$) at seasonal and annual scales irrespective of the GCM, RCP (4.5 and 8.5) or time period (the 2030 and 2060s). The projected climate warming featured various noteworthy trends: $T_{min} > T_{max}$, winter season > summer season, RCP 8.5 > 4.5 and 2060s >2030s.

The area was also projected to receive higher annual $P$, particularly due to intense monsoon $P$ during summer/rice season regardless of the GCM, RCP or time slice. For both RCPs, the winter/wheat seasonal $P$ showed an unnoticeable rising trend during the 2030s and a declining trend during the 2060s. Only the positive monsoon-$P$ shifts during the summer/rice season were actively contributing towards the annual $P$ increments. Climate projections suggested that the area may experience cycles of hot/dry winters followed by hot/wet summers, which can also result in frequent episodes of drought and floods, particularly during the 2060s. The winter season was more susceptible to enduring worst climate change impacts than the summer season.

### Projected changes in reference crop evapotranspiration

$ET_o$, being only a function of climate variables, is a reliable reflector of the climate change impacts on $ET_c$ rates (Ahmad & Choi 2018b). Figure 5 presents the projected change in cumulative seasonal $ET_o$ during the future time slices relative to the baseline. Future climate warming increased the cumulative seasonal and annual $ET_o$. The winter/wheat season $ET_o$-change remained consistently higher than that of the summer/rice season. The $ET_o$ increment under RCP 8.5 was more pronounced than that of under RCP 4.5 regardless of the time slices; whereas the positive $ET_o$

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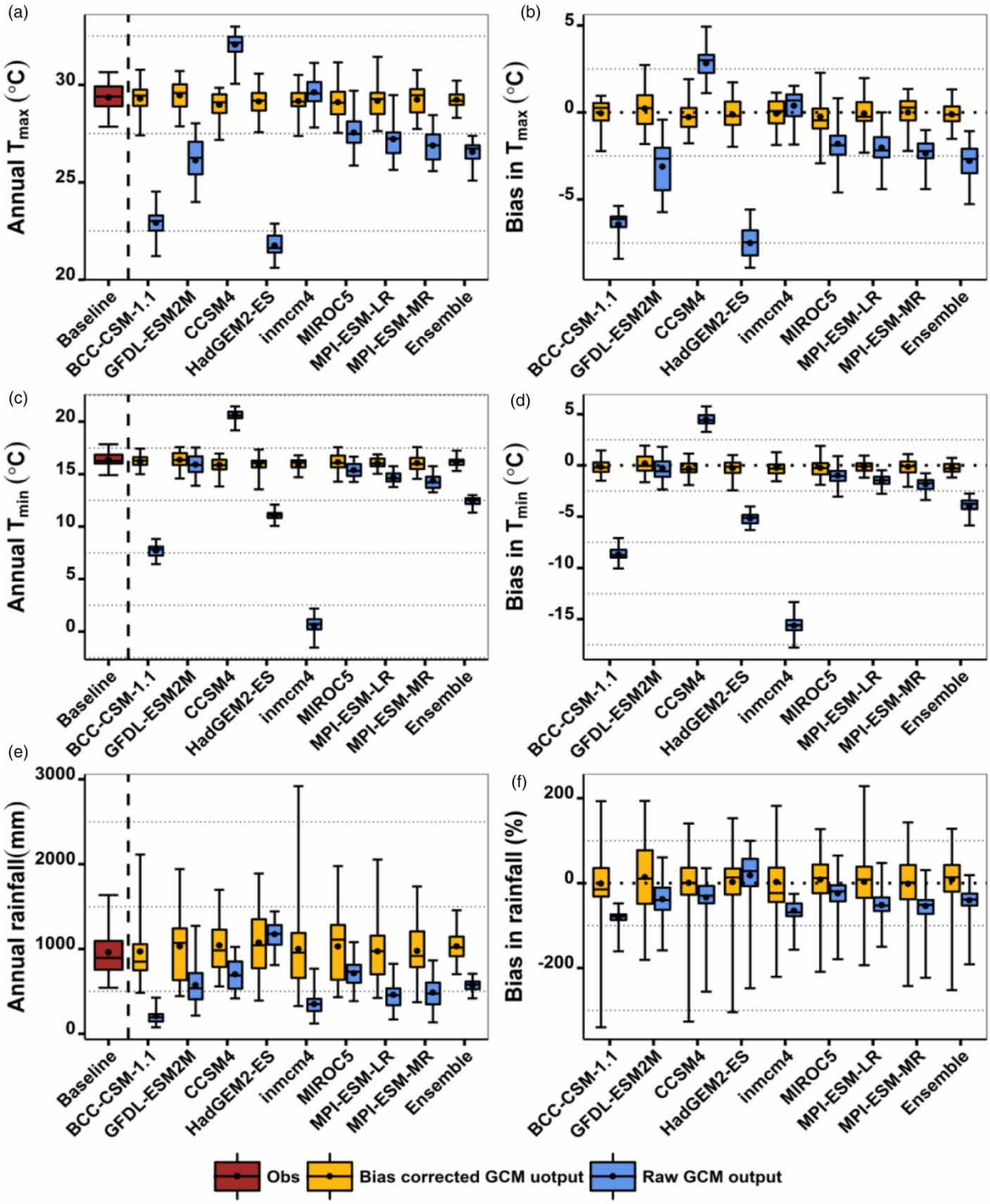


**Figure 3** | Bias correction of the average annual $T_{max}$, $T_{min}$ and annual cumulative rainfall ($P$) in the UCC command area during the baseline period (1980–2010). The box (here in Figure 3 and afterwards) represents the first and third quartiles, dots and horizontal lines inside the box represent mean and median, and whiskers show the maximum and minimum, respectively.

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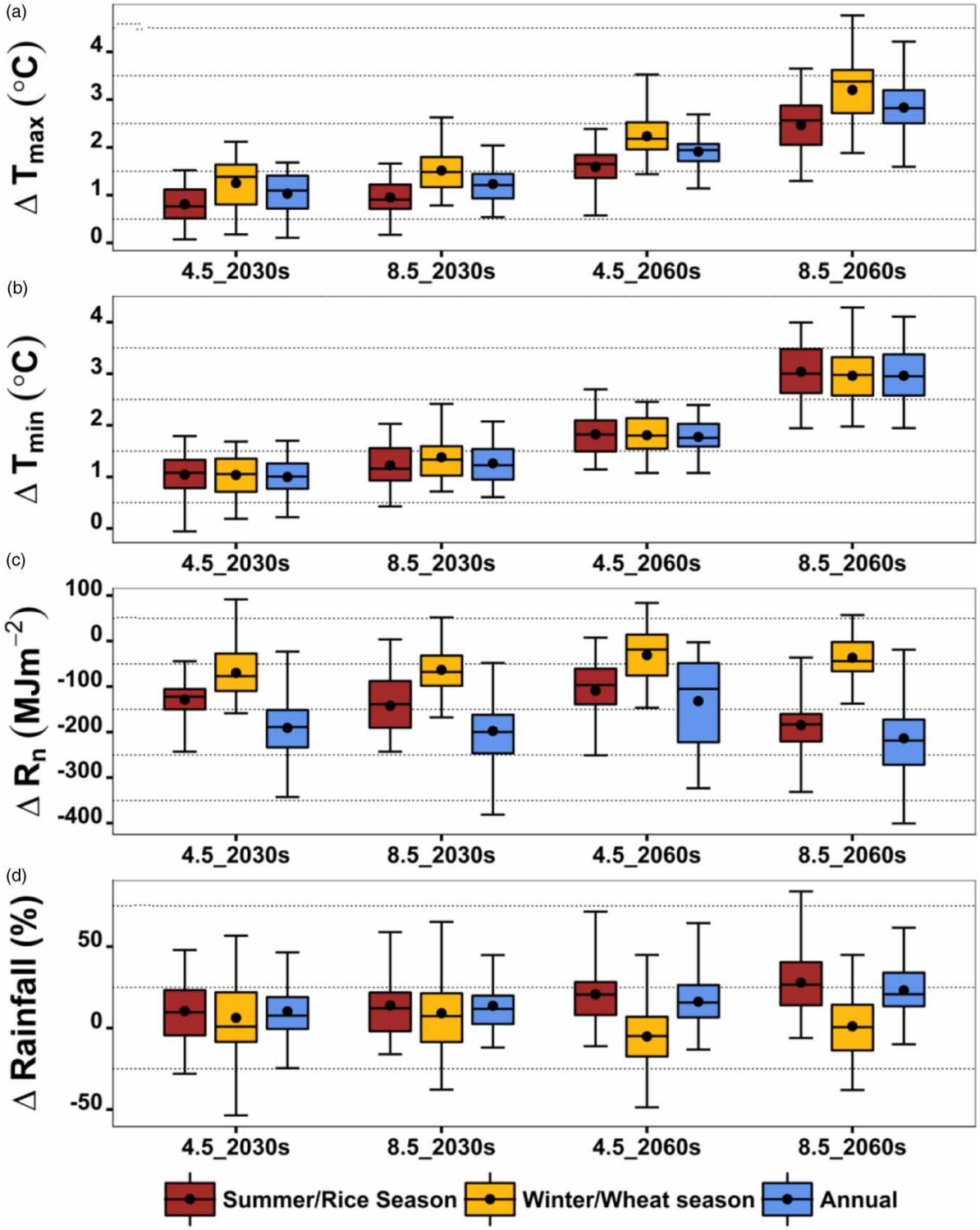


**Figure 4** | Projected change in seasonal and annual $T_{max}$, $T_{min}$, net radiation ($R_n$) and rainfall ($P$) during the 2030 and 2060s.

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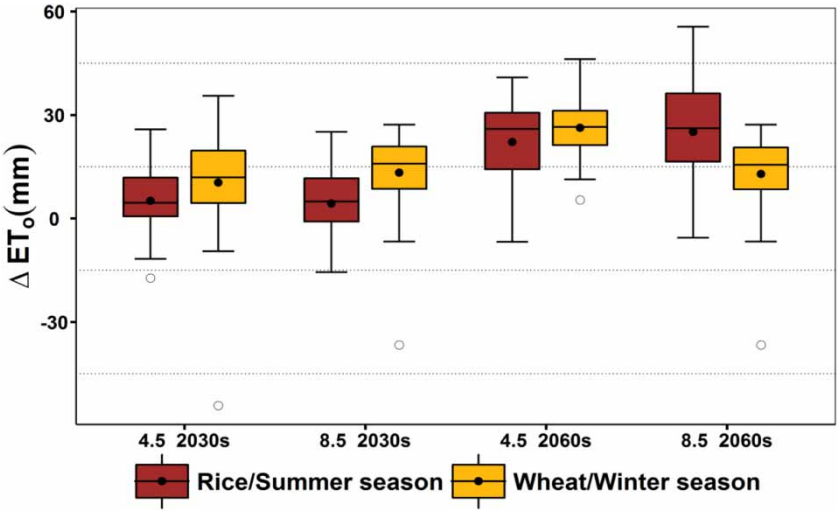


**Figure 5** | Projected change in cumulative seasonal $ET_o$ during the 2030 and 2060s.

shifts during the 2060s were higher as compared to the baseline or 2030s at both seasonal and annual time scales.

Considering the future climate warming, the magnitude of $ET_o$ increment was unusually small. The study area was projected to face a 132 $MJm^{-2}$ (–2.1%) and 213 $MJm^{-2}$ (–3.4%) reduction in annual average $R_n$ by the end of the 2030 and 2060s, respectively. Hence, the warming-driven $ET_o$ increments would be counteracted by the declining $R_n$ in future. This perception was further elaborated when analyzing the monthly $ET_o$ data. Figure 6 shows the GCM-ensemble monthly $ET_o$ variations relative to the baseline during the 2030 and 2060s. Monthly $ET_o$ remained unchanged or even declined in the few cases, despite the temperature rise predictions. Only the November and December monthly $ET_o$ values displayed a rising tendency in the future which were eventually translated as the seasonal and annual $ET_o$ rises. The IQR and whiskers of boxplots in Figure 6 also signify the expectancy of persistence and a lesser range of variability of future monthly $ET_o$ as compared to baseline.

## Projected changes in crop growth period

Ambient temperature is a key driver of crop growth rate, consequently determining the growing season length. The changes in wheat and rice growing season lengths under climate warming of the 2030 and 2060s were gauged using Equation (1) and the results are presented in Figure 7. During the baseline, wheat and rice had an average growth period of 154 and 124 days against average optimum GDDs of 1,800 and 2,200 °C, respectively.

The anticipated climate warming shortened the median growth periods of both crops with wheat being the primary target. During the 2030s, a moderate decline in growth periods of both the crops was shown under the two RCPs whereas during the 2060s, the growth period shortening was alarmingly high under RCP 8.5. The wheat and rice showed a potential decline of 11–13 and 8–11 days during the 2030s, and 21–30 and 15–21 days during the 2060s, respectively. These results suggested higher probabilities of future crop failures due to early maturity; specifically, sustaining wheat production in this area could be a challenging task. However, careful re-adjustments of sowing dates in the context of climate warming for optimum crop yields could be a viable option to negate these climate change impacts.

## Projected changes in crop water requirements

Figure 8 shows the projected changes in wheat and rice seasonal cumulative $ET_c$, ER and IWR during the 2030 and 2060s. Figure 9 compares the GCM-ensemble monthly time-averaged $ET_c$, ER and IWR during the baseline and future time periods.

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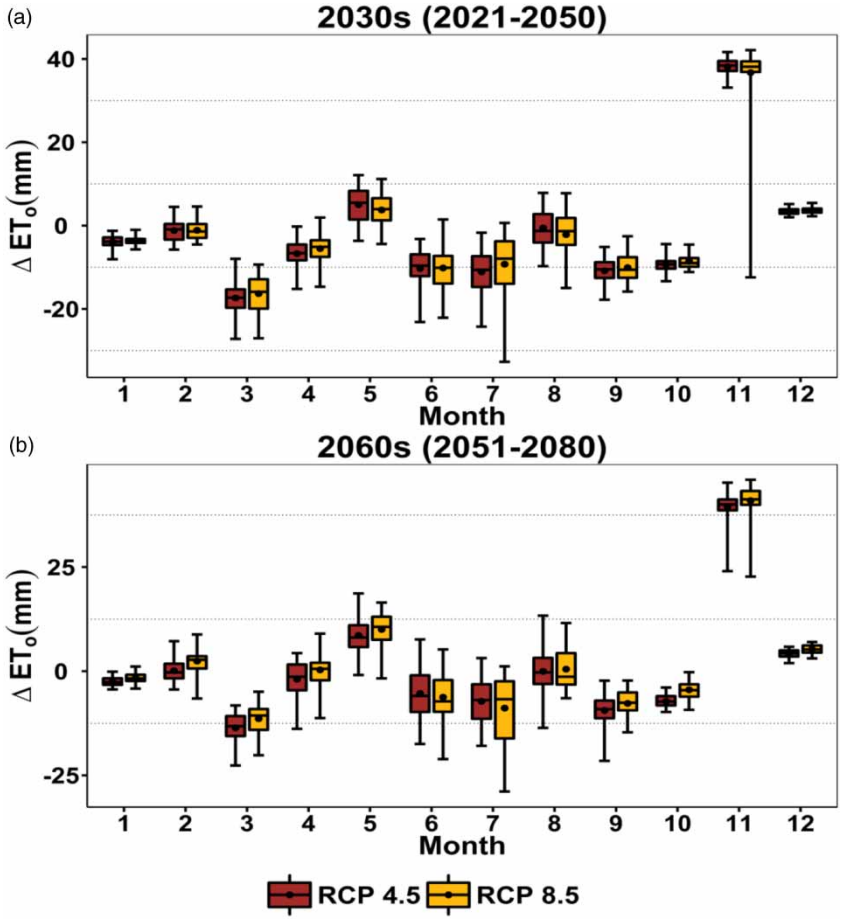


**Figure 6** | Projected change in cumulative monthly $ET_o$ during the 2030 and 2060s.

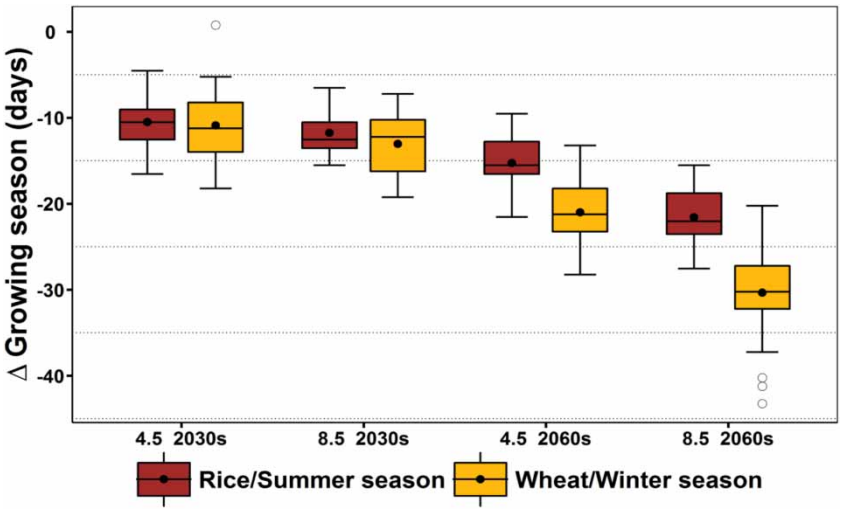


**Figure 7** | Projected change in wheat and rice growing season lengths during the 2030 and 2060s.

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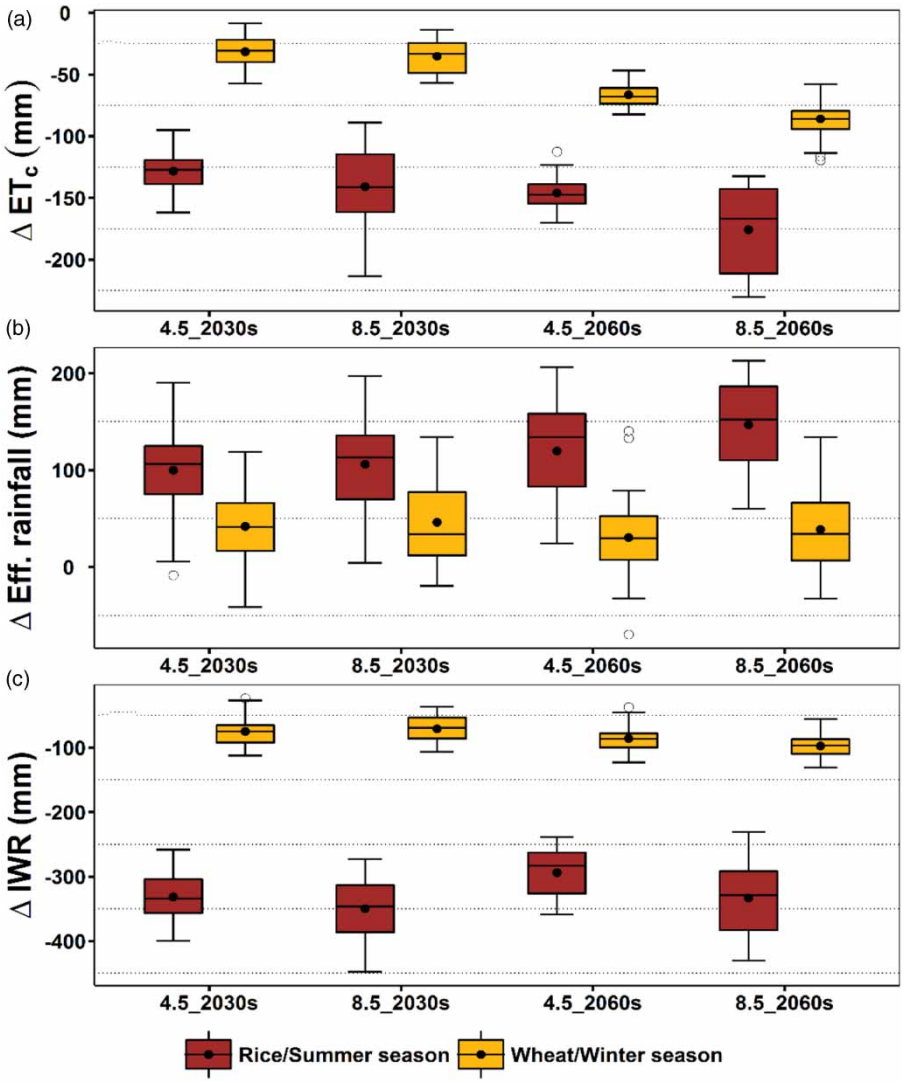


**Figure 8** | Projected variability in wheat and rice crop evapotranspiration ($ET_c$), effective rainfall (ER) and irrigation water requirements (IWR) during the 2030 and 2060s.

A potential decline in future $ET_c$ and IWR of both the crops was detected and the depressions were higher during the 2030s than during the 2060s. RCP 8.5 differentiated from RCP 4.5 by presenting comparatively steeper decline in $ET_c$ and IWR of both crops irrespective of the time period. Rice seasonal cumulative $ET_c$, compared to wheat, showed a higher (lower) tendency to decline during the 2030s (2060s), relative to their counterparts during the baseline.

The future seasonal cumulative ER featured a slight and substantial increase during the winter/wheat season and summer/rice season, respectively. The ER increments were prominently higher during the 2060s than the 2030s and particularly noticeable under RCP 8.5. As the rice IWR assimilated water requirements for both $ET_c$ and percolation losses, it was expected that a shorter growth period would cause a greater decline in rice IWR than that of wheat. However, the wheat IWR had a steeper decline rate than that of rice despite the minor ER increments due to early maturity. These trends emphasized the higher climatic vulnerability of wheat.

Projected changes in the monthly distribution of future $ET_c$, ER and IWR according to GCM-ensemble climate

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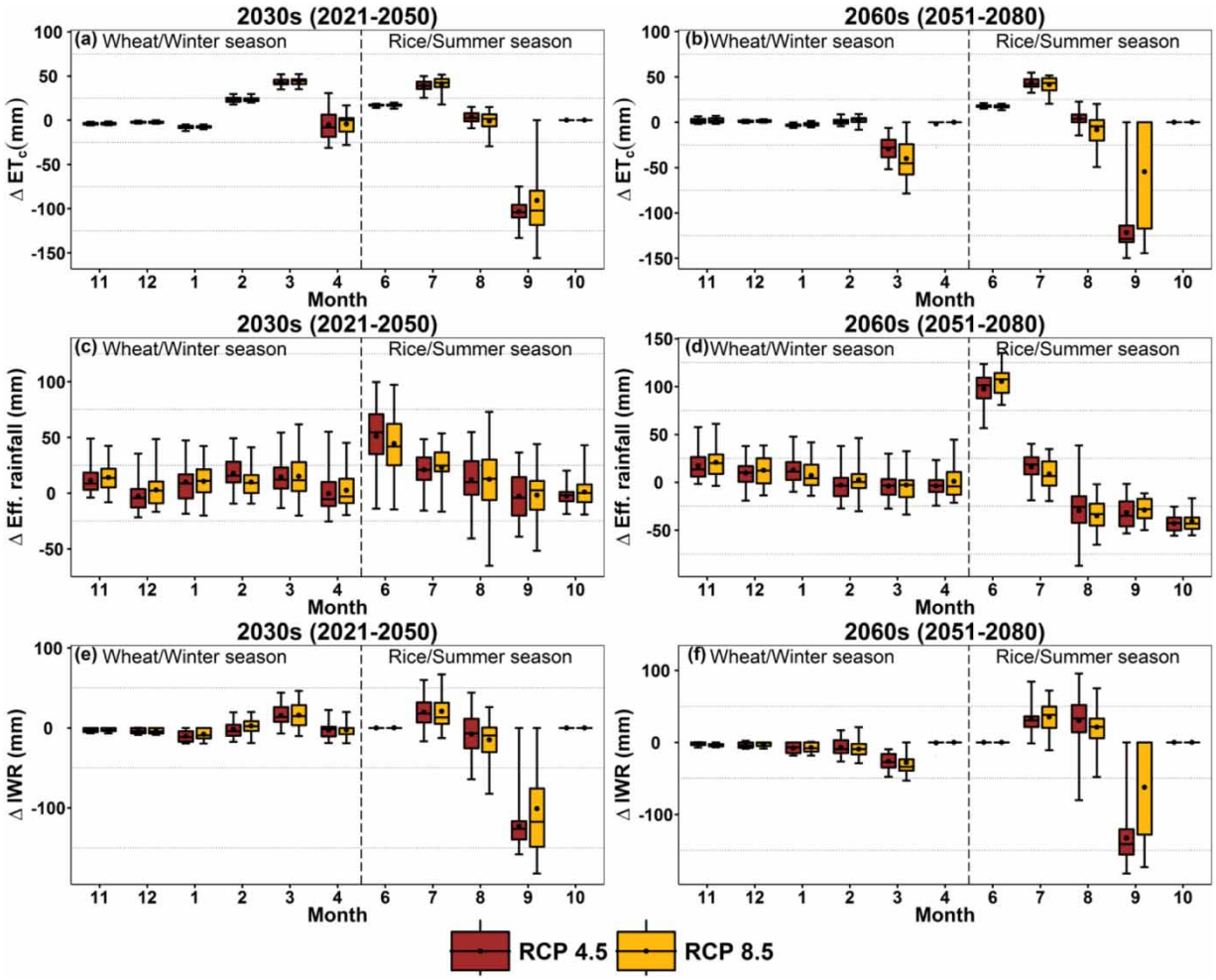


**Figure 9** | Projected variability in GCM-ensemble monthly crop evapotranspiration ($ET_c$), effective rainfall (ER) and irrigation water requirements (IWR) for the wheat-, rice-season during the 2030 and 2060s.

conditions were also examined (Figure 9). An ample ER-reduction was noted during the future wheat seasons while the monthly $ET_c$ and IWR remained unchanged or decline a little, except at the end of the growing season where a small increase was shown. For rice, the monthly ER distribution was characterized by an increase during the early months followed by a decrease approaching the end of the growing season (Figure 9(c) and 9(d)). Rice monthly $ET_c$ and IWR exhibited an increasing tendency right from the beginning of the growing season and then took a dramatic downturn at the end of the season due to early maturity.

The mentioned trends were produced without altering the sowing dates. This means that the same and/or higher irrigation amounts would be required during a shortened growth period; suggesting that the temperature rise would certainly accelerate the daily $ET_c$ rates in the future. The future crops would mature earlier yielding an overall decline in seasonal cumulative $ET_c$ but daily $ET_c$ rates would also increase simultaneously, thus making the crops more irrigation-dependent and temperature-sensitive. Due to uneven distributions, the projected rise in monsoon $P$ may not be able to compensate for the intensive monthly $ET_c$ rates; thus, calling for intensive irrigation applications.

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## DISCUSSION

### Future climate change

Distinctively strong future climate warming in terms of both $T_{max}$ and $T_{min}$ accompanied by minor $P$ increments was projected for the study area. The temperature rise was particularly evident for the winter/wheat season and the plausibility of experiencing warmer future winters was supported by the historic temperature rise trends across Pakistan (Rasul *et al.* 2011; Ahmad *et al.* 2014; Iqbal *et al.* 2016). Ahmad & Choi (2018b) also confirmed that climate of the same area had been gradually warming up since the 1980s due to a temperature rise phenomenon particularly associated with the winter months.

The $T_{max}$ ($T_{min}$) had higher variability during the future winter (summer) season. This implied that winter/wheat season $T_{max}$ and summer/rice season $T_{min}$ could be the key determinants controlling the future warming of the study area and hotter days/nights could be expected during the winter/summer seasons. Rasul *et al.* (2012) also reported that the nighttime temperature is rising at a higher rate than that of daytime across Pakistan. $T_{min}$ is usually associated with nighttime and it tends to rise during cloudy nights marked by greater near-surface longwave radiations; whereas, the $T_{max}$ is typically associated with daytime and it declines or remains unchanged as the cloudy sky blocks the incoming solar radiations (Irmak *et al.* 2012). This phenomenon gave rise to asymmetrical climate warming which seemed to occur in our study area under future climate change projections.

Annually, the future $P$ increments were mainly caused by a sharp rise in magnitude and/or intensity of monsoon $P$ in summer/rice season, especially during the 2060s. The GCM ensemble envisaged an increment of 10–13 and 13–23% in summer/rice season $P$ during the 2030 and 2060s, respectively. The seasonal and annual temperature and $P$ trends predicted in our study were in good agreement with previous studies focused on projecting future climate-change trends in Pakistan (Kazmi *et al.* 2015; Sharmila *et al.* 2015; Sooraj *et al.* 2015; Amin *et al.* 2016; Su *et al.* 2016).

Under the projected climate, the wheat-rice system in the command area of UCC could face multifaceted consequences. Due to higher monsoon $P$, flood conditions and drainage problems may arise in the summer/rice season. Because of its non-perennial irrigation system, wheat production in this area is completely groundwater dependent. Higher temperature would drive daily $ET_c$ at higher rates, which if not compensated by enough ER, would result in intensive groundwater exploitation for irrigation purposes, exerting extra pressure on dwindling groundwater resources.

### Future climate change influences on reference crop evapotranspiration

The baseline (1980–2010) average seasonal cumulative $ET_o$ values for wheat and rice were 395 and 875 mm, respectively. The wheat season $ET_o$ increased by 10–13 and 26–37 mm; and rice season $ET_o$ increased by 5–22 and 5–25 mm during the 2030 and 2060s, respectively. The magnitude of $ET_o$ increment was markedly small, particularly for the summer/rice season, in the context of climate warming threats. Ahmad & Choi (2018b) examined the historic trends of climate variables in this area and identified downward (upward) $ET_o$ trends for the summer/rice season (winter/wheat season) since 1980. Their study attributed these $ET_o$ trends to a steep statistically significant downturn historic trend of $R_n$ and $n$. We also projected a potential decline in seasonal and annual scaled $R_n$ totals during future time periods. As the study area's $ET_o$ is highly sensitive to $R_n$ variations (Adnan *et al.* 2017; Ahmad & Choi 2018b), its decline ceased the rapid $ET_o$-increase and counteracted much of the inverse temperature rise influences on $ET_o$.

Historically, dropping rates of pan evaporation and $ET_o$, despite a clear climate warming, have been reported from all around the globe; most probably triggered by decreased $R_n$ and/or wind speeds. Cloud cover, air pollutants, and manmade aerosols greatly affect the $n$ and $R_n$. An increased concentration of manmade aerosols and other air pollutants in the atmosphere could describe the recent depressions observed in $n$ and $R_n$ (Irmak *et al.* 2012; Liu *et al.* 2014; Vicente-Serrano *et al.* 2014; Jhajharia *et al.* 2015).

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## Future climate change influences on crop water requirements

During the baseline, wheat seasonal cumulative $ET_c$ and IWR were in the ranges of 207–260 and 90–212 mm; and for rice these were in ranges of 519–600 and 950–1,278 mm, respectively. Shakir *et al.* (2010) estimated average wheat and rice $ET_c$ values in the UCC canal command to be 250 and 523 mm, respectively. According to the local agriculture office in this area, the consumptive water demands for wheat and rice were 225 and 1,600 mm, respectively (unpublished data). Bhatti *et al.* (2009) estimated a basin wise average $ET_c$ of 400 mm for wheat and 950 mm for rice in the Indus basin of Pakistan. After conducting field experiments during 2001–2003 at some selected farms located near to our study area, Jehangir *et al.* (2007) reported that wheat $ET_c$ could vary in the range of 251–368 mm and rice $ET_c$ could vary in the range of 537–627 mm. Similarly, IWR values of both crops were also supported by findings of the survey and/or experimental studies previously conducted in this area (Aslam *et al.* 2002; Hussain *et al.* 2012; Soomro *et al.* 2015).

The future $ET_c$ and IWR were projected to decline mainly because of a shortened growth period. A potential decline of 11–13 and 15–21 days for wheat; and of 8–11 and 21–30 days for rice was predicted during the 2030 and 2060s, respectively. These results partly coincide with the findings of the Pakistan National Communication report on climate-change impact assessment over the agriculture sector. The projected shrinkage in crop growth periods was confirmed, whereas the predicted declines in $ET_c$ and IWR were contradicted. The report used the Hargreaves method for $ET_o$ estimation excluding the $R_n$-influence and yielding exaggerated $ET_c$ estimations (Hanif Qazi *et al.* 1997; Pakistan National Communication 2000). Bhatti *et al.* (2016) also identified higher probabilities of reduction in crop water demands due to probable shortening of the growth period for the wheat-cotton system of Punjab. Other studies, which include temperature rise effect over growth rate, also support our findings. An anticipated decline in $ET_c$ and IWR originating from the potential shrinkage of the growing season has been repeatedly reported in the literature (Seung-Hwan *et al.* 2013; Ye *et al.* 2015; Acharjee *et al.* 2017a, 2017b; Tukimat *et al.* 2017).

## Limitations and prospects for future research

Our study had few limitations and assumptions which should be addressed before finalizing various future water management strategies such as identification of suitable planting dates, re-adjustment of crop calendars and irrigation schedules, etc. Due to a lack of detailed soil hydrological characteristics and groundwater-depth data, these two important factors were not included in our analyses, which can significantly shape soil water balances and finally IWR of the crops. In the case of rice, the percolation rates and water usages for nursery and land preparation could be extremely heterogeneous at farm levels due to contrasting soils and farming practices. A generalized version of field conditions could be portrayed by using some representative values but actual farm-level situations may vary dramatically according to crop variety, irrigation method, water quality and soil management practices. Incorporation of such information when devising climate-change mitigation strategies would play a pivotal role in offsetting the adverse climate change impacts.

Although climate change could reduce the $ET_c$ and IWR of both crops, it may also negatively affect the yields. Sultana *et al.* (2009) reported a 6–10% wheat yield decline for ten representative sites spread across Pakistan, due to a shortened growth period caused by a 1 °C temperature rise over the whole season. In this study, the yield reduction influences of climate change were not included but should be an integral part of future proposed studies. A trivial short-term strategy to cope with climate change would be to alter sowing dates to achieve optimum yield and water consumption levels according to the future temperature and rainfall trends. The development of suitable crop varieties to resist climate change may be the long-term and reliable solution to the problem.

We were only able to predict an overall decline in the crop growth periods under the projected thermal regimes. The magnitude of warming at various growth stages could have varying impacts over the final yields. Thermal fluctuations during growth periods have the ability to prolong or shorten certain growth stages, ultimately affecting the yields. Therefore, temperature rise influences on crop development process should be examined at different crop growth stages. Apart from climate variables, crop

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physiological response to increased future $CO_2$ concentrations could also play a decisive role in $ET_c$ estimation and final yield levels. High uncertainties associated with projected rainfall amounts and intensities require careful monitoring to pinpoint the direction of change in the future.

Despite the shortcomings, the study still provides valuable information regarding the response of the wheat-rice system of Punjab to climate change. Stakeholders can employ our results to improve management of the UCC irrigation system under current climate conditions and to meet any challenges that may arise because of climate change in the future. This study also provides key information to irrigation managers for better allocation of limited water resources according to crop water requirements.

## CONCLUSION

In this study, the future climate change threats were discerned concerning the growth periods and water demands for the wheat-rice system of Punjab, Pakistan. Distinctively strong warming rates distinguished the future wheat- from the rice-season, whereas the $T_{\min}$ remained markedly higher than the $T_{\max}$. The possibilities of receiving more annual rainfall were projected primarily because of a sharp rise in erratic monsoon rainfalls during the future rice season; while the wheat season rainfalls were unchanged. Hence, the area may experience cycles of hot/dry winters followed by hot/wet summers, which could also result in frequent episodes of drought and floods.

The temperature rise induced positive changes in reference crop evapotranspiration ($ET_o$) featuring consistently higher increase rates of the wheat season. The $ET_o$ change magnitude in the context of climate warming was unnoticed as the projected solar radiation decline counteracted much of the inverse temperature rise influences.

The future $ET_c$ and IWR declined because of the shortened growth periods instigated by the temperature rise. Steeper recessions in growth spans and the associated $ET_c$ and IWR for the wheat were attributed to higher climate-warming rates inherent to the future wheat season. A prominent negative shift in wheat IWR was projected despite the marginal ER increments, whereas, for rice, it was less noticeable beside substantial ER increments.

The early maturing wheat crop may manifest significant yield losses, thus rendering it more vulnerable to climate change than rice, which may have some more resilience against future climate warming. Moderate negative shifts in rice IWR pointed out that the beneficial contribution of projected rice seasonal ER would be limited due to the intense/erratic nature of the future rainfall events.

## DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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