# ASSESSING THE IMPACTS OF FUTURE CLIMATE ON COTTON PRODUCTION IN THE ARIZONA LOW DESERT

I. T. Ayankojo, K. R. Thorp, K. Morgan, K. Kothari, S. Ale

## HIGHLIGHTS

- Cotton yield was reduced significantly under projected future climate conditions for the Arizona low desert (ALD). Of all the weather variables, yield reduction was primarily due to projected increases in daily maximum and minimum air temperatures.
- Cotton reproductive stages were more susceptible to heat stress than vegetative stages. Projected increases in air temperature may result in a slight increase in cotton growth or biomass production; however, heat stress significantly reduced fruit retention, leading to lower boll number and yield.
- Although future increases in $CO_2$ may improve plant growth and productivity, the potential benefit of $CO_2$ fertilization on cotton growth and yield in the ALD was offset by the projected increase in air temperature.
- The projected average seasonal irrigation requirement increased by at least 10%. This suggests that greater demand for freshwater withdrawal for agriculture can be expected in the future. Therefore, given the projected change in future climate, cotton cultivars tolerant of longer periods of high air temperature, changes in planting dates, and improved management practices for higher water productivity are critical needs for sustainable cotton production in the ALD.

**ABSTRACT.** *Cotton is an important crop in Arizona, with a total cash value of approximately $200 million for fiber and cottonseed in 2018. In recent years, heat stress from increasing air temperature has reduced cotton productivity in the Arizona low desert (ALD); however, the effects of future climate on ALD cotton production have not been studied. In this study, the DSSAT CSM-CROPGRO-Cotton model was used to simulate the effects of future climate on cotton growth, yield, and water use in the ALD area. Projected climate forcings for the ALD were obtained from nine global climate models under two representative concentration pathways (RCP 4.5 and 8.5). Cotton growth, yield, and water use were simulated for mid-century (2036 to 2065) and late century (2066 to 2095) and compared to the baseline (1980 to 2005). Results indicated that seed cotton yield was reduced by at least 40% and 51% by mid-century and late century, respectively, compared to the baseline. Of all the weather variables, the seasonal average maximum ($R^2 = 0.72$) and minimum ($R^2 = 0.80$) air temperatures were most correlated with yield reductions. Under the future climate conditions of the ALD, cotton growth or biomass accumulation slightly increased compared to the baseline. Irrigation requirements in the ALD increased by at least 10% and 14% by mid-century and late century, respectively. Increases in irrigation requirements were due to an increase in crop water use; hence, greater demand for freshwater withdrawal for agricultural purposes is anticipated in the future. Therefore, cotton cultivars that are tolerant of long periods of high air temperature and improved management practices that promote efficient crop water use are critical for future sustainability of cotton production in the ALD.*

**Keywords.** *Arid region, CSM-CROPGRO-Cotton, Future climate,* Gossypium hirsutum *L., Heat stress, Irrigation demand.*

In term of production value (about $200 million), cotton (*Gossypium hirsutum* L.) is an important crop in Arizona, next to lettuce (*Lactuca sativa*) and alfalfa (*Medicago sativa*), with a total planted area of about 71,000 ha in the 2018 production season (USDA, 2019). Thus, Arizona ranked among the top ten states in the U.S. for upland cotton production and second for pima cotton in 2017 (USDA, 2018). In recent years, heat stress has been recognized as a major abiotic factor of concern for upland cotton production in the Arizona low desert (ALD) area (Brown, 2008). This problem becomes even more challenging during the summer monsoon months with elevated air temperatures and relative humidity. The primary impact of heat stress on cotton is reduced fruit retention, which leads to reduced fiber yield and quality (Brown, 2008).

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Cotton yield is a function of growth and flower production rates, flower and boll retention rates, as well as the size of individual bolls during the reproductive phase (Reddy et al., 1992a). Each of these processes is influenced by several abiotic factors, of which the ambient air temperature has been recognized as the primary factor (Reddy et al., 1992b). The effects of heat stress on cotton growth and development are well studied. The most recognized work on heat stress in cotton is the series of studies conducted by Reddy et al. (1992a, 1992b) under natural light conditions in a controlled environment. In those studies, cotton yield and fruit retention were optimum at daily mean air temperatures between 25°C and 28°C. Although the fruiting sites per plant increased by approximately 50% as the air temperature increased from 30°C/22°C to 40°C/32°C (day/night air temperatures for each regime), the retention of bolls and squares for the 40°C/32°C regime decreased by about 93% compared to plants under the 30°C/22°C regime. In addition, pima cotton was more sensitive to heat stress than upland cotton. Hence, pima cotton did not produce fruit, fruiting branches, or squares in the 40°C/32°C regime (Reddy et al., 1991). Similar results were reported by Zeiher et al. (1995) for a similar air temperature regime in Arizona. However, in Arizona, it has been reported that heat stress has less impact on square retention and greater impact on abscission of bolls that are about 3 to 5 days old (Brown, 2008). Therefore, during the reproductive stage, cotton is highly sensitive to air temperature conditions above the optimum range, which can significantly limit productivity.

In Arizona, the potential for heat stress conditions during the cotton growing season typically begins in June and can last through the end of the growing season (September or October). In fact, the total period (days) of heat stress during a typical cotton growing season in most cotton-producing areas in Arizona can range from 15% to 36% of the total season length (table 1) (AZMET, 2019). As a result, cotton production under present weather conditions in most regions of Arizona is conducted with major heat stress. The observed steady increase in the pattern of mean monthly nighttime air temperatures in Maricopa from June to September (from 1987 to 2017, fig. 1) suggests more challenging growing conditions in the near future, especially in the wake of climate change. This is because over the last three decades (1987 to 2017) the mean monthly minimum air temperature (from June to September) increased by approximately 4°C.

Climate change may have a positive impact on agricultural production, as the increase in the atmospheric carbon dioxide ($CO_2$) concentration may enhance crop growth and yield, especially for C3 plants, due to potential increases in crop photosynthetic rate and carbon efficiency (Kimball, 1983; Cure and Acock, 1986; Allen et al., 1987; Adams et al., 1990; Morison, 1993). However, the potential increases in future air temperature and the variability in precipitation patterns could potentially undermine the positive impact of elevated $CO_2$ on crop productivity (Adams et al., 1990, 1998; Sage, 1995; Hatfield et al., 2011). For example, according to Reddy et al. (2002), the fertilization effect of $CO_2$ on cotton yield under the projected future climate in the Mississippi Delta only resulted in increased cotton yield when all other climate variables remained unchanged. In fact, doubling the $CO_2$ concentration did not reduce the negative effects of elevated air temperatures on cotton productivity (Reddy et al., 2005).

Efficient use of irrigation water in agricultural production systems is of global interest, particularly in arid and semi-arid regions with low precipitation and high dependence on irrigation (Ali and Talukder, 2008; Brauman et al., 2013). This is because the potential changes in future growing conditions will have impacts not only on crop yield but also on crop water requirements and availability (Kimball et al., 2002; Hatfield et al., 2011). The potential increase in air temperature and evapotranspiration (ET) will increase crop water demand, hence increasing freshwater withdrawals for agricultural purposes. Future conditions may accelerate water scarcity, especially in desert regions like Arizona with low precipitation and depleted waterbodies. These conditions may become even more challenging for the ALD due to the

**Table 1. Periods of heat stress during the cotton growing season in major cotton-producing areas in Arizona.**

| Year and Area | | L1[a] (days) | L2[b] (days) | Total (days) | Season[c] (%) |
|---|---|---|---|---|---|
| 2018 | Maricopa | 33 | 21 | 54 | 29 |
| | Buckeye | 31 | 22 | 53 | 29 |
| | Paloma | 37 | 19 | 56 | 30 |
| | Harquahala | 43 | 22 | 54 | 29 |
| | Coolidge | 28 | 4 | 32 | 17 |
| 2017 | Maricopa | 51 | 16 | 67 | 36 |
| | Buckeye | 29 | 37 | 66 | 36 |
| | Paloma | 52 | 7 | 59 | 32 |
| | Harquahala | 40 | 10 | 50 | 27 |
| | Coolidge | 27 | 1 | 28 | 15 |
| 2016 | Maricopa | 43 | 21 | 64 | 35 |
| | Buckeye | 35 | 32 | 67 | 36 |
| | Paloma | 37 | 25 | 62 | 33 |
| | Harquahala | 41 | 9 | 50 | 27 |
| | Coolidge | 27 | 1 | 28 | 15 |

[a] Stress level 1 (L1): stress level at crop temperature of 28°C to 30°C.

[b] Stress level 2 (L2): stress level at crop temperature >30°C.

[c] Percentage of days under heat stress with respect to total length of growing season.

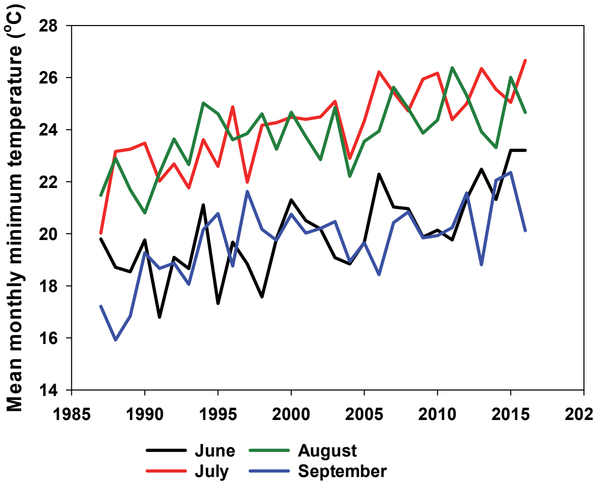

**Figure 1. Average mean monthly air temperature during the cotton growing season in a typical Arizona low desert (ALD) cotton production area (Maricopa). Temperature data are from 1987 to 2017, as recorded by the Arizona Meteorological Network (AZMET).**

ongoing drought in the Colorado River basin, which is a major water source for irrigation in Arizona (Prein et al., 2016), the all-time low level of Lake Mead, which supplies Colorado River water for local irrigation (Holdren and Turner, 2010), competition from domestic and industrial demands, and climate uncertainty (Cayan et al., 2010). Therefore, studies on the potential future impacts of climate change on cotton production in Arizona are important for assessing not only the impacts on crop yield and water use but also as a guide to appropriate decision-making for future production practices and water sustainability.

The Cropping System Model (CSM), as distributed with the Decision Support System for Agrotechnology Transfer (DSSAT; www.dssat.net), is a process-based CSM (Jones et al., 2003) and is considered useful for the evaluation of future climate on ALD cotton production. The DSSAT CSM has been used in several studies to evaluate the effects of management practices on cotton production in the ALD and in west Texas (Thorp et al., 2014a, 2014b, 2017; Modala et al., 2015) and the effects of future climate on cotton production in the Texas High Plains (Adhikari et al., 2016). However, no studies on the effects of future climate on ALD cotton production have been conducted. Therefore, the objectives of this study were to (1) determine the impact of future climate on the growth and yield of cotton in the ALD via simulation analysis and (2) assess the impacts of future climate on cotton water requirements in the ALD cotton production area.

## MATERIALS AND METHODS

### STUDY AREA

In this study, DSSAT CSM simulations were conducted for conditions at the University of Arizona's Maricopa Agricultural Center (33.079° N, 111.977° W, 360 m above sea level) near Maricopa, Arizona. The soil texture at the study location is predominantly sandy loam and sandy clay loam. The environment in central Arizona is arid and hot, with daily maximum air temperatures (from 1987 to 2011) regularly exceeding 38°C during July and August. Over the same period, precipitation during a typical cotton growing season (April to September) averages 67 mm and ranges from 21 to 134 mm (Thorp et al., 2014b), and short crop reference evapotranspiration ($ET_o$) is typically above 1200 mm (Thorp et al., 2017). A typical cotton growing season (planting to maturity) in the ALD starts in mid-April or early May, with irrigation applied through mid-September (Thorp et al., 2017). The long-term (1987 to 2017) weather record for Maricopa (a typical cotton production area in the ALD) suggests that cotton is subjected to heat stress during a large portion of the typical growing season (fig. 2). This is because the average daily air temperatures (from 1987 to 2017) during the growing season (shaded portion in fig. 2) are well above the optimum requirements for cotton production (Reddy et al., 1992a, 1992b).

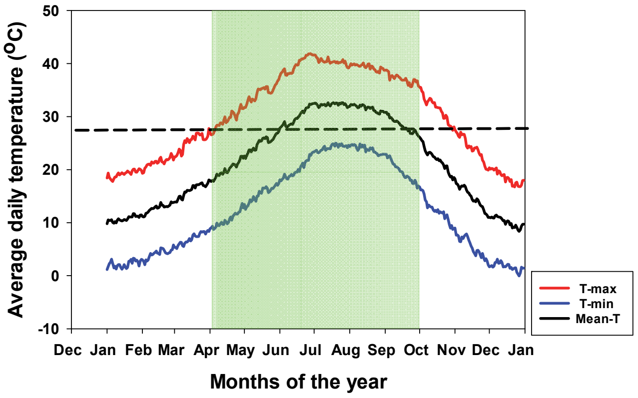

**Figure 2. Average daily minimum, maximum, and mean air temperatures from 1987 to 2017 in a typical Arizona low desert (ALD) cotton production area (Maricopa). The shaded portion of the graph indicates a typical cotton growing season from planting to maturity. The horizontal dashed line indicates the upper threshold for daily mean air temperature for optimum cotton growth. Data were obtained from the Arizona Meteorological Network (AZMET).**

### CSM-CROPGRO-COTTON MODEL

The CSM-CROPGRO-Cotton model distributed with DSSAT 4.7.5 (Jones et al., 2003; Hoogenboom et al., 2019) was used to simulate the effects of climate change on cotton production in the ALD. The CSM-CROPGRO-Cotton model can simulate both plant and soil variables for multiple environmental conditions and management practices. This CSM has been used in numerous studies on the impacts of management practices and environmental variables on cotton production for a wide range of geographical and environmental conditions (Modala et al., 2015; Adhikari et al., 2016; Nagender et al., 2017; Thorp et al., 2017; Amouzou et al., 2018; Rahman et al., 2019). The CSM-CROPGRO-Cotton model uses a mass balance approach to simulate carbon, nitrogen, and hydrological processes and transformations in a cropping system (Thorp et al., 2017). It calculates processes within a cropping system on a daily or hourly time step. Estimations of crop development are based on photothermal unit accumulation from planting to harvesting (Thorp et al., 2014b). Crop stress levels are estimated from deficit soil water conditions, soil nitrogen levels, and air temperatures above the optimum range. Under stress conditions, the model reduces carbohydrate availability for plant growth. Assimilated carbon is partitioned among plant components (leaves, stems, roots, bolls, and seed cotton). The current CSM-CROPGRO-Cotton model simulates seed cotton yield (seed + fiber yield); therefore, based on measured fiber and seed weights after ginning, fiber and seed yields were estimated by multiplying the simulated seed cotton yield by 0.4 and 0.6, respectively (Thorp et al., 2017). More detailed information about operation of the CSM-CROPGRO-Cotton model is provided by Thorp et al. (2014b, 2017).

### MODEL INPUTS

The model inputs required for this study included daily weather (maximum and minimum air temperatures, precipitation, solar radiation, wind speed, and relative humidity), soil properties (texture, rooting depth, water holding capacity, and initial nutrient content), management practices (pre- and post-planting activities), and cotton cultivar data (cultivar-specific genetic coefficients). In this simulation study, cotton seed was planted on 19 April (DOY 109) in rows (102 cm between rows) at 4 cm soil depth and 10.0 plants m$^{-2}$. To ensure that water was not limiting for the simulation exercise, irrigation was automatically simulated using the DSSAT crop management file to specify conditions for irrigation management. As soil water was depleted, irrigation was designed to trigger at 50% depletion of plant-available water within 120 cm of soil depth, a reasonable rooting depth and soil profile management depth for irrigation of cotton in the ALD. The soil water characteristics at the study location are shown in table 2; the soil properties are described in detail by Thorp et al. (2017). Fertilizer was split-applied four times throughout the growing season (DOY 137, 159, 172, and 186) using urea ammonium nitrate (UAN) at 42 kg N ha$^{-1}$ for each application. Fertilizer was incorporated to a depth of 10 cm. No tillage was simulated. Seed cotton yield was determined at simulated plant maturity. In this study, simulations were conducted using seasonal analysis (suitable for long-term simulations) to compare baseline and future climate scenarios.

### MODEL CALIBRATION AND EVALUATION

The calibrated cultivar-specific coefficients used in this study were obtained from previous studies by Thorp et al. (2014b, 2017) in which the model was evaluated using data from several field experiments conducted on irrigation management at Maricopa from 1990 to 2015. The well-watered and well-fertilized cotton treatments from those studies were selected for the calibration exercise. The calibrated coefficients were then evaluated for simulations of emergence, first flower, and maturity as well as cotton yield and ET. The model was able to consistently simulate the emergence and first flower dates within ±0 to ±1 days of the observed dates, while the simulation accuracy for maturity dates was within ±1 to ±3 days of the observed dates across all seasons. The model simulation values for crop growth, development, yield, and responses to environmental variables were within the observed ranges for the region; therefore, the model was considered reliable for accessing the impact of future climate on cotton production at the study location.

**Table 2. Soil water characteristics at the study location.**

| Soil Depth (cm) | SLLL[a] (cm$^3$ cm$^{-3}$) | SDUL[b] (cm$^3$ cm$^{-3}$) | SSAT[c] (cm$^3$ cm$^{-3}$) | Available Water Holding Capacity (cm$^3$ cm$^{-3}$) |
|---|---|---|---|---|
| 5 | 0.109 | 0.241 | 0.410 | 0.132 |
| 15 | 0.109 | 0.241 | 0.410 | 0.132 |
| 30 | 0.109 | 0.241 | 0.410 | 0.132 |
| 55 | 0.106 | 0.228 | 0.389 | 0.122 |
| 60 | 0.099 | 0.202 | 0.346 | 0.103 |
| 90 | 0.096 | 0.197 | 0.343 | 0.101 |
| 120 | 0.091 | 0.188 | 0.337 | 0.097 |
| 150 | 0.089 | 0.175 | 0.314 | 0.086 |
| 180 | 0.080 | 0.161 | 0.319 | 0.081 |
| 210 | 0.076 | 0.154 | 0.321 | 0.078 |

[a] Soil water content at wilting point.

[b] Soil water content at field capacity.

[c] Soil water content at saturation.

### CLIMATE SCENARIOS

Nine global climate models (GCMs) were used to estimate historic and future climate conditions at Maricopa (table 3). Daily weather data for the study location were obtained from each GCM using web-based tools available at https://climate.northwestknowledge.net/MACA/index.php. These GCM data have been corrected for bias and were statistically downscaled using the Multivariate Adaptive Constructive Analogs (MACA) technique (Abatzoglou and Brown, 2012). Data from these GCMs have been used in many other studies on climate change impacts on agricultural crops within the U.S. (Araya et al., 2017; Zhang et al., 2017; Karimi et al., 2018) and internationally (Amouzou et al., 2018; Srivastava et al., 2018). Weather information (maximum and minimum air temperatures, precipitation, wind speed, solar radiation, and relative humidity) for the study location were obtained daily from each GCM. Dew point temperature (°C) was calculated from the minimum and maximum air temperatures and relative humidity. In this study, the future climatic projection for each GCM was based on two possible representative concentration pathways (RCPs) for greenhouse gas emissions: RCP 4.8 and RCP 8.5 (Van Vuuren et al., 2011). The annual $CO_2$ concentration, as predicted by IPCC (2014), was applied daily under each RCP scenario, while the historic $CO_2$ concentration was obtained from NOAA/ESRL (Keeling et al., 1976; Thoning et al., 1989). The impact of future climate on cotton production from each GCM and RCP was simulated for mid-century (2036 to 2065) and late century (2066 to 2095). Simulation results with historic climate data (1980 to 2005), as estimated by each GCM, were used as the baseline.

## RESULTS AND DISCUSSION

### CHANGES IN WEATHER PATTERN

The projected changes in weather variables (maximum and minimum air temperatures and cumulative rainfall) were

**Table 3. Description of the nine global climate models (GCMs) from the Climate Research Program's Coupled Model Intercomparison Project Phase 5 (CMIP5) used in this study.**

| GCM | Modeling Group | Reference |
|---|---|---|
| BCC-CSM1-1 | Beijing Climate Center, China | Wu (2012) |
| CCSM4 | National Center for Atmospheric Research, U.S. | Gent et al. (2011) |
| CNRM-CM5.1 | National Centre of Meteorological Research, France | Voldoire et al. (2013) |
| CSIRO-Mk3-6-0 | Commonwealth Scientific and Industrial Research Organization, Australia | Rotstayn et al. (2012) |
| GFDL-ESM2M | Geophysical Fluid Dynamic Laboratory, U.S. | Dunne et al. (2012) |
| IPSL-CM5A-LR | Institute Pierre Simon Laplace, France | Dufresne et al. (2013) |
| MIROC5 | Atmosphere and Ocean Research Institute, University of Tokyo, Japan | Watanabe et al. (2010) |
| MRI-CGCM3 | Meteorological Research Institute, Japan | Yukimoto et al. (2012) |
| NorESM1-M | Norwegian Meteorological Institute, Norway | Kirkevag et al. (2008) |

**Table 4. Changes in daily maximum and minimum air temperatures and cumulative rainfall during cotton growing season (1 April to 30 Sept.) as projected by nine global climate models (GCMs) under two representative concentration pathways (RCPs) with respect to the baseline.**[a]

| | RCP 4.5 | | | | | | RCP 8.5 | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Mid-Century | | | Late Century | | | Mid-Century | | | Late Century | | |
| GCM | $T_{max}$ (°C) | $T_{min}$ (°C) | Rain (mm) | $T_{max}$ (°C) | $T_{min}$ (°C) | Rain (mm) | $T_{max}$ (°C) | $T_{min}$ (°C) | Rain (mm) | $T_{max}$ (°C) | $T_{min}$ (°C) | Rain (mm) |
| BCC-CSM1-1 | +2.22 | +1.76 | +1.76 | +2.43 | +1.82 | +3.42 | +3.01 | +2.39 | +9.55 | +4.86 | +4.04 | -1.50 |
| CCSM4 | +2.11 | +2.15 | +14.49 | +2.41 | +2.29 | -2.21 | +2.69 | +2.71 | +7.93 | +4.33 | +4.07 | -6.35 |
| CNRM-CM5.1 | +2.46 | +2.82 | +40.06 | +2.96 | +3.40 | +23.79 | +2.61 | +3.24 | +38.39 | +4.69 | +5.61 | +9.66 |
| CSIRO-Mk3-6-0 | +1.93 | +0.63 | +9.46 | +2.40 | +0.97 | +11.15 | +2.48 | +1.67 | +8.36 | +4.45 | +3.28 | -5.29 |
| GFDL-ESM2M | +2.57 | +2.63 | -8.30 | +3.22 | +3.06 | -2.93 | +3.42 | +3.38 | -13.72 | +6.20 | +5.66 | -22.60 |
| IPSL-CM5A-LR | +2.04 | +2.23 | +12.89 | +3.34 | +3.35 | +4.38 | +2.78 | +2.81 | +2.25 | +4.36 | +4.51 | -11.84 |
| MIROC5 | +1.26 | +1.21 | -0.25 | +1.21 | +1.62 | +9.85 | +1.78 | +1.73 | -9.64 | +3.29 | +3.59 | +25.27 |
| MRI-CGCM3 | +2.16 | +1.92 | +6.11 | +2.54 | +2.38 | +14.90 | +2.71 | +2.55 | +15.36 | +3.87 | +3.74 | +23.17 |
| NorESM1-M | +1.50 | +2.03 | +21.16 | +2.24 | +2.66 | +10.55 | +2.15 | +2.60 | +3.49 | +3.49 | +4.44 | +29.15 |

[a] Mid-century = 2036 to 2065, and late century = 2066 to 2095.

studied for each GCM and RCP in both mid-century and late century and are summarized in table 4. All GCMs agreed that both daily maximum and minimum air temperatures will increase in both mid and late century regardless of the RCP. However, changes in cumulative rainfall during the cotton growing season varied widely among the GCMs.

Compared with the baseline, daily average maximum air temperature for RCP 4.5 increased by 2.03°C (ranging from 1.50°C to 2.57°C) and by 2.53°C (ranging from 1.21°C to 3.34°C) for mid and late century, respectively. For the same RCP, daily average minimum air temperature increased by 1.93°C (ranging from 0.63°C to 2.82°C) and by 2.40°C (ranging from 0.97°C to 3.40°C) for mid and late century, respectively. Similar patterns were observed for RCP 8.5, as both daily average minimum and maximum air temperatures in the future were higher than the baseline values. The increases in air temperature for RCP 8.5 were greater than those for RCP 4.5, with projected values above 4°C for both minimum and maximum air temperatures during late century. This increase in air temperature may result in a shorter growing season under the future scenarios. This is because the time from planting to anthesis and maturity was reduced by up to 4 and 7 days, respectively, under the projected future climate conditions, as compared to the baseline (data not shown).

While table 4 shows the changes in air temperatures for the entire growing season, the average changes were similar to those for the reproductive stage only (July and August). Changes in the average daily maximum and minimum air temperatures (with respect to the baseline) during the reproductive stage were 1.6°C and 1.7°C, respectively, for RCP 4.5 in mid-century and 2.7°C and 2.7°C, respectively, in late century. For RCP 8.5, the average changes in minimum and maximum air temperatures during the reproductive stage were 2.0°C and 2.1°C, respectively, in mid-century and 4.7°C and 4.9°C, respectively, in late century. Although the current air temperatures during a large proportion of the cotton-growing season in the ALD are already about 2°C to 5°C above the optimum air temperature for cotton (Brown, 2008; AZMET, 2019), the potential future increases in the air temperature, as reported in this study, could be very detrimental to the Arizona cotton industry. This is because the average daily air temperature in the ALD could be up to 7°C (in mid-century) or 8°C (in late century) above the optimum air temperature for cotton.

Contrary to the projected changes in air temperature, the pattern of change in future precipitation as compared to the baseline may not be reliable. This is because the changes in cumulative rainfall during the cotton growing season varied widely among the GCMs, with values ranging from -22 to +40 mm across RCPs and periods of the century. However, these potential changes in future precipitation patterns may not greatly influence cotton performance, considering that typical current seasonal $ET_o$ values are above 1200 mm for the cotton growing season in the ALD, and the need for irrigation to meet evaporative demand (Thorp et al., 2017). Under the projected climate changes, precipitation will continue to have a minor role for cotton production in the ALD, and irrigation will still be required.

### FUTURE CLIMATE IMPACTS ON SEED COTTON YIELD AND BIOMASS ACCUMULATION

Seed cotton yield in the ALD was greatly affected by the projected climate conditions in both mid and late century. This is because the projected seed cotton yield under the future climate conditions was much lower compared to the baseline regardless of GCM and RCP (fig. 3). The average reduction (for all GCMs) in seed cotton yield under RCP 4.5 was 40% and 50% for mid and late century, respectively, while the projected yield reduction was 51% and 78%, respectively, for RCP 8.5. These large reductions in yield were likely because the air temperatures during the cotton growing season in the ALD are already above the optimum for cotton growth (Brown, 2008; AZMET, 2019); hence, any further increase in air temperature will likely result in a greater yield loss. The interannual variability in yield across the GCMs was slightly higher for the future scenarios compared to the baseline. The maximum yield variation across all years was 61%, 84%, and 84% for the baseline, mid-century, and late century, respectively, while the maximum year-to-year yield variation was 36%, 50%, and 49% for the baseline, mid-century, and late century, respectively.

To further scrutinize this result, cotton growth simulations in CSM-CROPGRO-Cotton were conducted using air temperature measurements from a meteorological station. However, air temperature within a well-watered crop canopy may be several degrees less than the air temperature at a nearby meteorological station. This is because evaporative cooling often causes the microclimate around the canopy of a well-watered crop to have a lower temperature than the temperature of the surrounding air (Thorp et al., 2014b). This

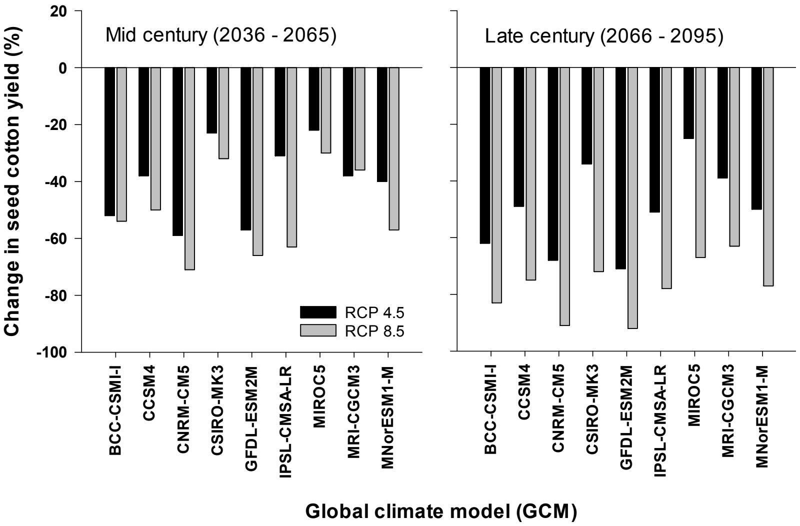

**Figure 3. Changes in seed cotton yield for mid-century and late century with respect to the baseline (1980-2005) as projected by nine global climate models (GCMs) under two representative concentration pathways (RCPs).**

means that model simulations that are based on air temperature rather than canopy temperature could overestimate the effects of heat stress on future cotton yields. Nonetheless, simulated cotton yields responded appropriately under such environmental conditions in previous efforts to evaluate the model (Thorp et al., 2014b, 2017). In addition, the impact of this modeling limitation on the analysis is likely less than the impacts of uncertainty in the climate forcing data from the nine GCMs and two RCPs (table 5 and fig. 3).

In general, seed cotton yield decreased by a greater extent for RCP 8.5 as compared to RCP 4.5 and for late century as compared to mid-century. Of the nine GCMs, the data from CSIRO-Mk3 and MIROC5 provided yield estimates that were most optimistic, especially for RCP 4.5, while the worst-case scenarios (maximum yield reduction) were predicted using data from CNRM-CM5.1 and GFDL-ESM2M. Of all the weather variables, the seasonal average maximum (fig. 4a, $R^2$ = 0.72) and minimum (fig. 4b, $R^2$ = 0.80) air temperatures were most responsible for seed cotton yield reductions in this study, compared to the average seasonal wind speed (fig. 4c, $R^2$ = 0.36) and cumulative rainfall (fig. 4d, $R^2$ = 0.02).

The projected yield reductions under future climate conditions in the ALD are primarily due to lower boll number (figs. 5a and 5b). The reduction in the average boll number is higher in late century (41% to 69%) as compared to mid-century (31% to 41%). This suggests that the projected increase in future air temperature will have negative impacts on fruit set and/or boll retention and hence lower cotton yield. Cotton is sensitive to elevated air temperatures during the reproductive stage; hence, lower boll numbers under heat stress are due to fruit abortion or poor boll retention (Reddy et al. 1992a, 1992b). Reddy et al. (1992a) reported that the cotton boll retention rate during the reproductive stage was reduced by 36% and 100% when the crop was exposed to three weeks of 40°C for 2 and 12 h $d^{-1}$, respectively. Although lower in magnitude compared to the boll number, the boll size may also contribute to lower cotton yield under heat stress conditions in the future (figs. 5b and 5c). Compared to the baseline, the average boll size (g $boll^{-1}$) under the projected future climate conditions was smaller regardless of GCM. Zeiher et al. (1995) also reported a reduction in cotton boll size under Arizona conditions as the mean daily air temperature increased above 28°C.

**Table 5. Changes in cotton biomass production (%) with respect to the baseline as projected by nine global climate models (GCMs) under two representative concentration pathways (RCPs).**[a]

| | Mid-Century | | Late Century | |
|---|---|---|---|---|
| GCM | RCP 4.5 | RCP 8.5 | RCP 4.5 | RCP 8.5 |
| BCC-CSM1-1 | +2 | +2 | +2 | +2 |
| CCSM4 | +4 | +4 | +4 | +4 |
| CNRM-CM5.1 | +1 | +1 | +2 | +2 |
| CSIRO-Mk3-6-0 | +5 | +5 | +5 | +5 |
| GFDL-ESM2M | +1 | +1 | +0 | +0 |
| IPSL-CM5A-LR | +4 | +4 | +3 | +3 |
| MIROC5 | +5 | +5 | +5 | +5 |
| MRI-CGCM3 | +3 | +3 | +5 | +5 |
| NorESM1-M | +4 | +4 | +4 | +4 |

[a] Mid-century = 2036 to 2065, and late century = 2066 to 2095.

The projected increase in air temperature may result in slight increases in cotton growth or biomass production with respect to the baseline (table 4). Average cotton biomass production (from all GCMs) increased by 3% for each RCP in both mid and late century. Contrary to cotton yield, this slight increase in biomass production suggests that vegetative growth of cotton is less susceptible to heat stress than reproductive growth. Studies across several agronomic crops have predicted that increases in atmospheric $CO_2$ concentration will result in increased plant vegetative growth (Erda et al., 2005; Donohue et al., 2013). However, the beneficial impacts of increased $CO_2$ (i.e., fertilizing effects) are often limited or negated when accompanied by other weather variables, such as increased air temperature (Reddy et al., 2002). Our results suggest that the impacts of increasing $CO_2$ concentration on cotton growth or biomass production in the ALD are minimal. This is because the increasing atmospheric $CO_2$ concentration had little or no correlation (average $R^2$ of 0.03 and 0.04 for mid-century and late century, respectively) with cotton biomass production (table 6).

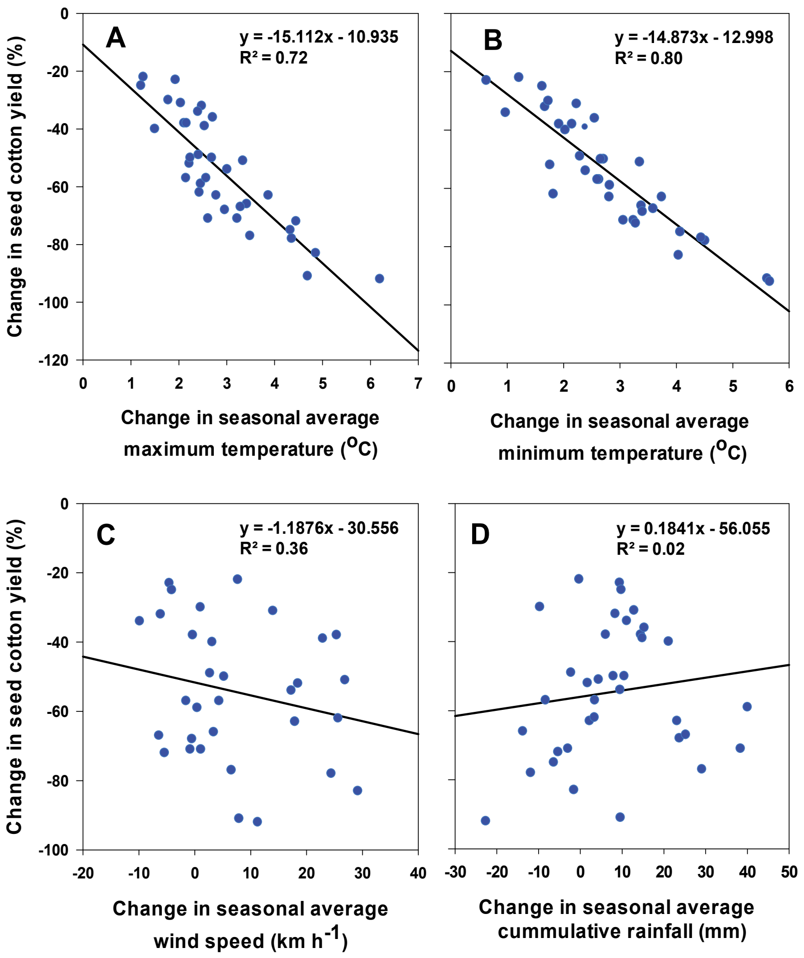

**Figure 4. Relationships between average change in seed cotton yield in response to changes in seasonal average (a) maximum air temperature, (b) minimum air temperature, (c) wind speed, and (d) cumulative rainfall.**

Our results also suggest that the potential benefit of $CO_2$ fertilization on cotton vegetative growth may have been limited by high air temperature during the growing season. This is because plant temperatures above 40°C are often associated with stomatal closure, and hence reduction in plant growth (Reddy et al., 2002). In a similar report by Acock and Acock (1993), cotton biomass production was reduced when the crop was exposed to ambient air temperature of 40°C for more than 6 h. Therefore, increased $CO_2$ concentration in the future may not enhance cotton growth, especially under arid conditions with high air temperatures during the growing season. Overall, our results suggest that cotton grown in the ALD may produce similar or even slightly greater amounts of biomass in the future; however, because yields are projected to decline (fig. 3), with fewer and smaller bolls (fig. 5), carbon partitioning will favor vegetative growth rather than reproductive growth.

These results agree with those reported in the literature (Reddy et al., 2002; Haim et al., 2008; Rahman et al., 2018). Haim et al. (2008) reported that cotton yields under the projected future climate conditions in a semi-arid region of Israel could be reduced by 38% to 52% compared to the baseline. Rahman et al. (2018) projected up to 30% reduction in seed cotton yield by 2069 in Pakistan. Although in lesser proportions, Reddy et al. (2002) also reported reductions in cotton yield under future climate conditions in the Mississippi Delta. The results of the present study confirm the potential drastic reductions in cotton yield in arid regions under future climate scenarios. However, the results obtained in our study contradict those reported by Yang et al. (2014) on the impact of future climate (up to 2090) on cotton production in northwest China. Those authors reported a significant increase in cotton yield (up to 356 kg ha$^{-1}$) compared to the baseline. The predicted annual average maximum and minimum air temperatures in 2090 at their study site were 21.6°C (baseline 18.9°C) and 6.7°C (baseline 3.6°C), respectively. The environmental conditions in the ALD are much warmer than those reported by Yang et al. (2014). In our study, the projected annual average maximum and minimum air temperatures in 2090 were 44°C and 27°C, respectively, compared to the mean optimum air temperature of 25°C to 28°C for cotton (Reddy et al., 1992a, 1992b). Therefore, increases in future air temperature would benefit cotton production in northeast China as the air temperature approaches the optimum. However, the opposite is the case for the ALD, where the future air temperature is projected to increase further above the optimum condition; hence, the potential future yield reduction is a concern.

Although the predicted climate conditions are anticipated to reduce the future productivity of cotton in the ALD, future

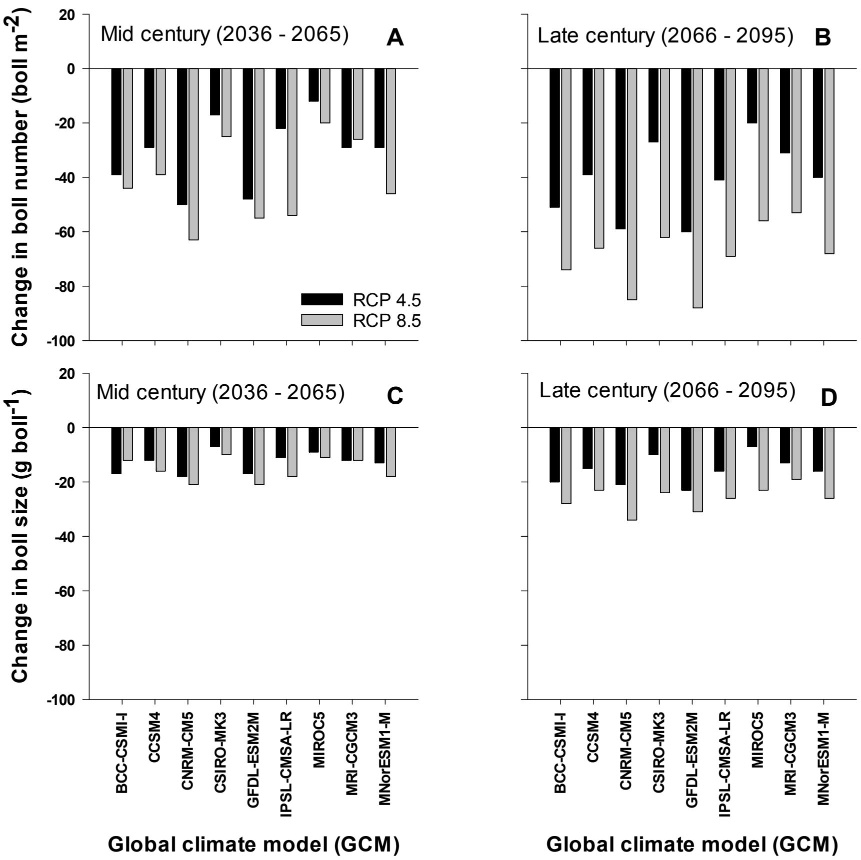

**Figure 5. Changes in boll number and boll size for mid-century and late century with respect to the baseline (1980-2005) as projected by nine global climate models (GCMs) under two representative concentration pathways (RCPs).**

**Table 6. Coefficients of determination ($R^2$) between cotton biomass production and atmospheric $CO_2$ concentration under future climate conditions in the Arizona low desert (ALD). Future $CO_2$ concentration data were obtained from IPCC (2014).[a]**

| | Mid-Century | | Late Century | |
|---|---|---|---|---|
| GCM | RCP 4.5 | RCP 8.5 | RCP 4.5 | RCP 8.5 |
| BCC-CSM1-1 | 0.09 | 0.00 | 0.01 | 0.04 |
| CCSM4 | 0.01 | 0.08 | 0.00 | 0.08 |
| CNRM-CM5.1 | 0.04 | 0.10 | 0.02 | 0.06 |
| CSIRO-Mk3-6-0 | 0.03 | 0.04 | 0.01 | 0.00 |
| GFDL-ESM2M | 0.02 | 0.03 | 0.00 | 0.32 |
| IPSL-CM5A-LR | 0.01 | 0.04 | 0.01 | 0.12 |
| MIROC5 | 0.10 | 0.05 | 0.04 | 0.13 |
| MRI-CGCM3 | 0.02 | 0.00 | 0.05 | 0.09 |
| NorESM1-M | 0.01 | 0.00 | 0.12 | 0.00 |

[a] Mid-century = 2036 to 2065, and late century = 2066 to 2095.

cessation of cotton production in this region is not likely due to the economic importance of cotton production in Arizona, the availability of breeding technologies to mitigate heat and drought stress, and the possibility of modifying planting dates to avoid heat stress during critical growth periods. However, based on drought tolerance, water productivity, and important local markets, potential alternative crops that may be of interest to growers include guayule, which is a drought-tolerant rubber plant (Hunsaker and Elshikha, 2014), and alfalfa, which is the most important crop in Arizona in total harvested area and economic value (USDA, 2019). Other crops such as vegetables, oil seed plants, and hemp may also serve as alternatives to cotton.

### EVAPOTRANSPIRATION AND IRRIGATION REQUIREMENTS

Given the expected future increases in air temperature, the projected ET during the cotton growing season for both mid and late century also increased, as expected. The ET increased compared to the baseline regardless of the GCM, RCP, and period of the century (fig. 6). The average increase in cotton ET was 11% for RCP 4.5 and 14% for RCP 8.5 in mid-century, while ET increased by 14% for RCP 4.5 and 24% for RCP 8.5 in late century. The increase in ET was higher for RCP 8.5 than RCP 4.5 in late century compared to mid-century. This increase in ET was principally influenced by the projected increase in both day and night air temperatures during the cotton growing season, as previously described. Irrigation requirements during the cotton growing season followed a similar pattern as ET (fig. 7). The average seasonal irrigation requirement (over all GCMs) was projected to increase by 10% to 13% in mid-century and by 14% to 24% in late century. Hence, freshwater consumption for cotton irrigation in the ALD may increase by similar amounts in the near future. Of all the weather variables, the increase in irrigation requirement was primarily driven by the increase in both seasonal average maximum (fig. 8a, $R^2 = 0.50$) and minimum (fig. 8b, $R^2 = 0.41$) air temperatures. The projected increases in irrigation requirements in this study were similar to those reported by Diaz et al. (2007) in Spain. Those authors reported a 15% to 20% increase in total seasonal irrigation for cotton production in the Guadalquivir River basin by 2050.

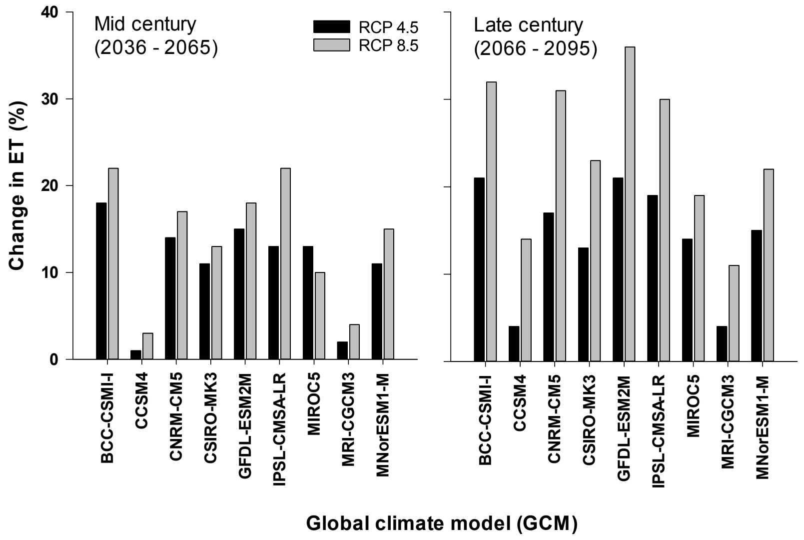

Figure 6. Changes in evapotranspiration (ET) during cotton growing season (planting to maturity) for mid-century and late century with respect to the baseline (1980 to 2005) as projected by nine global climate models (GCMs) under two representative concentration pathways (RCPs).

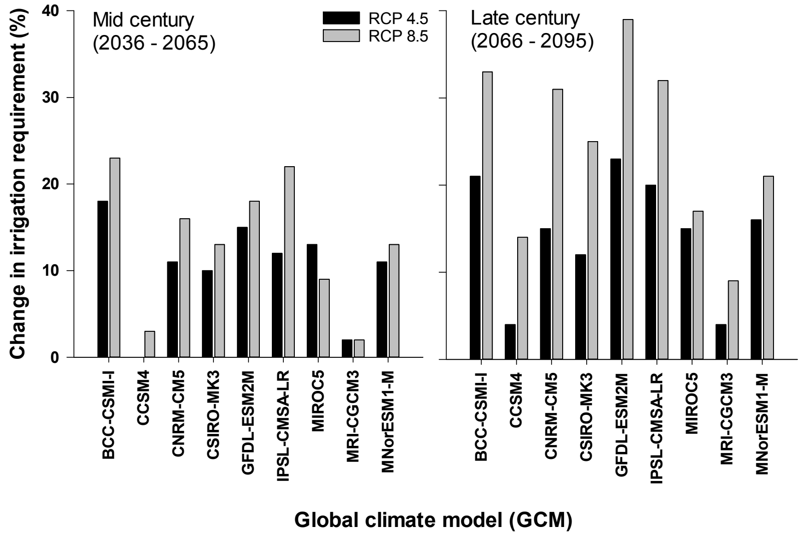

Figure 7. Changes in irrigation requirements during cotton growing season (planting to maturity) for mid-century and late century with respect to the baseline (1980 to 2005) as projected by nine global climate models (GCMs) under two representative concentration pathways (RCPs).

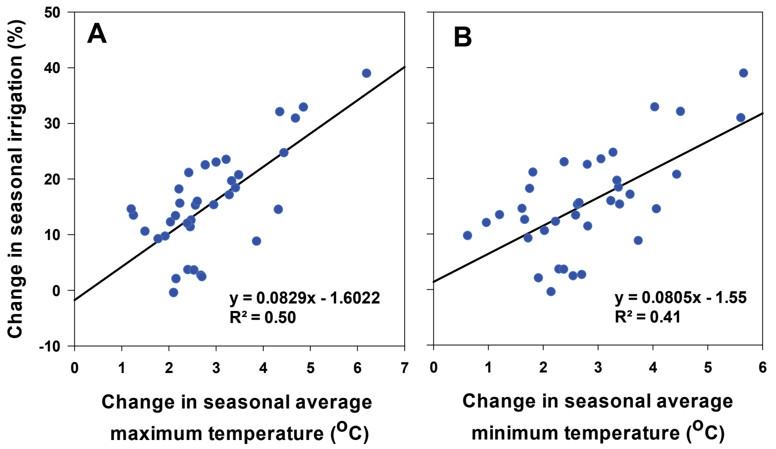

Figure 8. Relationship between average change in seasonal irrigation application in response to changes in seasonal average (a) maximum and (b) minimum air temperatures.

# CONCLUSIONS

The DSSAT CROPGRO-Cotton model, previously evaluated for the ALD area in prior studies, was used to evaluate the effects of future climate conditions on cotton growth, yield, and irrigation requirements in the ALD. Results indicated that daily maximum and minimum air temperatures during the cotton growing season in the ALD increased by at least 2.03°C and 1.92°C, respectively, compared to current conditions. The projected higher air temperatures in the future resulted in seed cotton yield reductions of at least 40%. Although future increases in $CO_2$ may improve plant growth and productivity, the potential benefit of $CO_2$ fertilization was offset by the projected higher air temperature. Yield reduction under heat stress was primarily due to lower fruit set and boll retention rate. However, cotton growth or biomass production slightly increased under the future climate conditions, which resulted from yield reductions and related changes in carbon partitioning from reproductive to vegetative growth. The projected average seasonal irrigation requirements in the ALD increased by 10% to 24%. The increases in irrigation requirements were mainly due to increases in ET, which means that greater demand for freshwater withdrawal for agricultural purposes is expected in the area. Because the cotton growth simulations in CROPGRO-Cotton were conducted using air temperature and not in-canopy temperature, the actual impacts of future climate may be lower than reported. Given the projected changes in future climate conditions, cotton cultivars tolerant of longer periods of high air temperature, modification of planting dates, and improved management practices for more efficient crop water use are critical needs for the sustainability of cotton production in the ALD.

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