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Climate change effects on wheat yield and water use in oasis cropland

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Abstract

Agriculture of the inland arid region in Xinjiang depends on irrigation, which forms oasis of Northwest China. The production and water use of wheat, a dominant crop there, is significantly affected by undergoing climate variability and change. The objective of this study is to quantify inter-annual variability of wheat yield and water use from 1955 to 2006. The farming systems model APSIM (Agricultural Production Systems Simulator) was used to evaluate crop yield, evapotranspiration (ET), and water use efficiency of winter and spring wheat (*Triticum aestivum* L.) in Xinjiang from 1955 to 2006. The APSIM model was first calibrated and validated using 6 years of experimental data. The validated model was then applied to simulated wheat yield and ET using climatic and soil data for present crop cultivar. Simulated wheat yield under full irrigation have no significant decreasing trend from 1955 to 2006. Simulated growth duration of winter wheat was significantly decreased. Simulated ET of winter wheat was significantly correlated with measured pan evaporation. Simulated ET of winter wheat decreased significantly during the 52 years, with a decrease rate of 0.813 mm year⁻¹. Cluster analysis showed that the variations of ET were mainly determined by solar radiation, nothing to do with the changes in temperature. The results identified the change trend of field ET under historical climate change, and determined the main meteorological factors which affect ET in this oasis. These results provide a measure for water demand, crop production and irrigation management under climate change in the oasis.

Keywords: Yield; Water use; Climate change; Climate variability; Xinjiang.

Introduction

There is growing body of evidence of climate change. The surface air temperatures are rising, precipitation altered, and frequency of severe weather events increased (IPCC,

2007). Climate is the major driving force of crop production and water use (Harmsen et al., 2009; Fang et al., 2010). The increased air temperature and changed precipitation pattern will significantly affect crop yield and water use efficiency (Kattge and Knorr, 2007). However, there are interactions between climatic factors and their combined impact on crop production is complicated (Dhungana et al., 2006; Walker and Schulze, 2008).

Process-based models are broadly applied to investigate the potential impacts of climate variability/change on crop production (Keating et al., 2003; Wang et al., 2008a; Wang et al., 2008b) and how crop yield responds to climate change (Lu et al., 2008; Liu et al., 2010). Simulation results under various climate patterns and regions had significant difference. By using Water Erosion Prediction Project (WEPP) model Zhang and Liu (2005) predicted that the productivities and evapotranspiration of wheat and maize would noticeably increase over the Loess Plateau during 2070-2099, mainly because of the increase of precipitation. Wang et al. (2009) showed that temperature increase had little impact on long-term average water balance while increase in atmospheric CO₂ concentration reduced evapotranspiration and increased deep drainage in Southeast Australia by utilizing APSIM. Chen et al. (2009) reported that simulated crop water demand and potential yield was significantly decreased from 1961 to 2003 because of the declining trend in solar radiation in the North China Plain. Similar studies have not been conducted in Xinjiang.

Xinjiang is a typical mountain-basin system that lies in the semiarid and arid areas of Northwest China. The climate of Xinjiang province is controlled by inland dry continental masses, with wide daily temperature range and low precipitation and humidity. Great changes in climate and hydrology were found over the past 30 years, and the strong signals of climatic shift to warm humid pattern have been emerged in the northern Xinjiang since the mid- and late 1980s (Shi et al., 2002; Shi et al., 2003). Crop growth in oasis depends on irrigation water from glaciers in the mountains. Defining the effect of climate variability/change on evapotranspiration would help planning and improve efficient management of irrigation in Xinjiang and other areas.

The objectives of this study are: (1) to evaluate the performance of the APSIM model to simulate the growth and water use of winter wheat and spring wheat in oasis of Xinjiang, (2) to use the validated APSIM model to investigate the effect of climate variability/change on wheat yield and water use to support efficient management of irrigation, and (3) to investigate the variations of evapotranspiration under different climatic patterns to define the relationship between evapotranspiration and climate factors.

Materials and Methods

Study sites and climate data

Two study sites, Wulanwushu Agrometeorology Experimental Station (WLWS) (44.3°N, 85.8°E, a.s.l. 468.5 m) and Dongkan Agrometeorology Experimental Station (DK) (42.8°N, 89.3°E, a.s.l. -48.7 m), were selected to reflect the effects of climate change in the past 52 years on evapotranspiration and water use efficiency of winter wheat and spring wheat in oasis of Xinjiang. WLWS is located in reclaimed land of Shihezi city, where winter wheat is usually grown; while DK is located in Turfan Basin, where spring wheat is

planted. The growing period for winter wheat is from the mid of September to the next June, and from the middle February to the mid June for spring wheat. The study sites are two of the observational stations of the National Meteorological Networks of China Meteorological Administration (CMA).

Both sites have a loam soil, with sandy and silty loam textures in the surface soil (0-50 cm) at WLWS and DK, respectively. Due to the lack of detailed soil physical data below 50 cm, the soil texture at 40-50 cm depth was assigned to the rest of root zone (50-200 cm). The soil profile properties at two sites are given in Table 1.

Table 1. Soil properties of experimental sites at Wulanwushu and Dongkan Agrometeorology experimental station.

Soil depth		0-10	10-20	20-30	30-40	40-200
Wulanwushu	Texture	Sandy loam	Sandy loam	Sandy loam	Sandy loam	Sandy loam
	BD (g/cm ³)	1.26	1.28	1.28	1.33	1.34
	SAT (mm/mm)	0.44	0.46	0.43	0.45	0.41
	DUL (mm/mm)	0.33	0.33	0.30	0.30	0.26
	LL (mm/mm)	0.05	0.06	0.06	0.07	0.10
Dongkan	Texture	Silty loam	Silty loam	Silty loam	Silty loam	Silty loam
	BD (g/cm ³)	1.41	1.49	1.48	1.40	1.32
	SAT (mm/mm)	0.40	0.41	0.43	0.41	0.42
	DUL (mm/mm)	0.25	0.23	0.23	0.22	0.21
	LL (mm/mm)	0.10	0.11	0.14	0.14	0.14

BD: bulky density; SAT: saturation; DUL: field capacity; LL: lower limit.

For the modeling study, daily weather data from 1955-2006 were obtained from two weather stations close to the experimental sites. Climate data include sunshine duration, maximum and minimum temperature, precipitation, and evaporation measured by pan with diameter of 20 cm. Sunshine duration was converted into solar radiation using the Ångström formula (Black et al., 1954; Jones, 1992).

Experimental data for model evaluation

Field experiments were conducted for winter wheat at WLWS during the period of 2000-2003, and for spring wheat at DK from 2003 to 2005. The cultivars of winter wheat and spring wheat were Kuidong4 and Xinchun2, respectively, which were used for each year of experimental studies. Winter wheat was sown at a rate of 150 kg ha⁻¹ on 28 September each year, while spring wheat was sown at a rate of 180 kg ha⁻¹ on 22 February each year. It was applied for 300 kg ha⁻¹ of urea for winter wheat in mid April and 150 kg ha⁻¹ for spring wheat in early April each year. In order to avoid excess salt accumulation, large amounts of irrigation water were applied. Irrigated 7 and 5 times for winter and spring wheat during their growth seasons, total irrigation amounts were about 680 mm and 600 mm, respectively. Soil water content was measured by using drying method. Solar radiation, maximum and minimum temperature and precipitation at each of the two experimental sites were recorded associated with an automatic meteorological station. Observed and measured data on crop phenological stages, leaf area index (LAI), biomass, yield, ET and soil water were used to validate the APSIM model.

APSIM model and calibration

The Agricultural Production Systems Simulator (APSIM) (Keating et al., 2003; Wang et al., 2003) was used in this study to explore the effects of climate change on wheat growth and water balance. APSIM is a component-based simulation framework with various modules such as crop growth and development, soil water, soil nitrogen and crop management. The model runs at a daily time-step using soil data, weather data, crop parameters and management data as input. APSIM has been widely used to simulate cropping systems around the world (Lyon et al., 2003; Ludwig and Asseng, 2006; Heng et al., 2007; Chen et al., 2009). This model has not been calibrated and applied in Xinjiang until now.

Based on the field experiments conducted at WSWL during 2000-2002 and at DK during 2003-2004, the APSIM model was calibrated with a trial-and-error method. The calibrated genetic coefficients for winter and spring wheat were listed in Table 2. The phenological parameters of wheat were derived from observed flowering and maturity dates. The parameters affecting wheat yield formation were obtained based on measured LAI, biomass production and grain yield. The calibrated model was then validated using the experimental data during 2002-2003 and 2005.

Table 2. Derived cultivar parameters for winter wheat at Wulanwushu (Kuidong4) and spring wheat at Dongkan (Xinchun2).

Parameters	Cultivars	
	Kuidong4	Xinchun2
Vern-sens (sensitivity to vernalisation)	3.0	3.0
Photop-sens (sensitivity to photoperiod)	3.5	2.0
Startgf-to-mat (thermal time from beginning of grain-filling to maturity (°C d)	650	250
Grains-per-gram-stem (coefficient of kernel number per stem weight at the beginning of grain-filling (g per stem)	27.0	27.0
Potential-grain-filling-rate (potential grain-filling rate (g per kernel per day)	0.0024	0.0025
phyllochron (phyllochron interval (°C d/leaf appearance)	80.0	55.0

The performance of the model was tested by using simulated results of all cropping seasons. The coefficient of determination of regression line was forced through the origin to represent the true deviation of the modeled results from observations. The slope (β) presents a possible over or underestimation. The root mean square deviation (RMSD) was calculated to provide a measure of the absolute magnitude of the simulation error.

Modelling the impacts of past climate during 1955-2006 on evapotranspiration and wheat yield

The calibrated APSIM model was used to evaluate the effects of climate trend during 1955-2006 on evapotranspiration, wheat yield and water use efficiency at two study sites. The same winter wheat variety (Kuidong4) and spring wheat variety (Xinchun2) were used for all simulation years at WLWS and DK, respectively. Winter wheat and spring wheat were harvested at physiological maturity. Wheat yield and water use were simulated under the full irrigation condition by using the automatic irrigation facility in the APSIM model. Soil water content was maintained at field capacity during the whole wheat growing season.

Cluster analysis was applied to identify significant climatic factors determining ET within winter wheat growth seasons. K-means method of clustering was adopted using SPSS (SPSS 16.0) after ET, solar radiation, maximum and minimum temperature, and precipitation during winter wheat growing seasons were standardized respectively.

Results

Observed climate trend during winter and spring wheat growing seasons from 1955 to 2006

Figure 1 shows the trends in climate variables during the winter wheat growing season at WLWS and during spring wheat growing season at DK. For winter wheat, there was a significant increasing trend in maximum and minimum temperatures from 1955-2006. The increases during winter wheat growing seasons were $0.027\text{ }^{\circ}\text{C year}^{-1}$ and $0.064\text{ }^{\circ}\text{C year}^{-1}$, respectively. Minimum temperature increased significantly during spring wheat growth seasons at the rate of $0.062\text{ }^{\circ}\text{C year}^{-1}$. Solar radiation over the last 52 years declined in general, especially during winter wheat growing season at WLWS at the rate of $0.021\text{ MJ m}^{-2}\text{ year}^{-1}$. Precipitation had a significant increasing trend at WLWS during wheat growing season and there was no significant variation trend at DK during spring wheat growing season. However, precipitation had limited impact on wheat yield and water use because irrigation water was applied to reduce deleterious effects on soil salinity.

Model calibration and validation

The model performance was evaluated by comparing simulated LAI, aboveground biomass and grain yield with measured values during wheat growing seasons (Figure 2). The model tended to overestimate winter wheat LAI and biomass at early growing seasons, and to underestimate them at late growing seasons nearly after jointing stage. Temperature in December and January is very low which changes between $-12.5\text{ }^{\circ}\text{C}$ and $-16.6\text{ }^{\circ}\text{C}$, LAI of the early growth stage (before period of turning green) of winter wheat is lower. The temperature increased rapidly from February to April, with the rate of $10\text{ }^{\circ}\text{C month}^{-1}$. There was plenty of sunlight during March and April. As a result LAI and biomass increased to a higher value quickly at this stage. The reason may be that the APSIM model couldn't sensitively reflect the impact of this temperature changes on the biomass accumulation process of winter wheat in Xinjiang. Consequently the simulated LAI and biomass were higher than measured values at early growth season and lower than measured values after jointing stage. Simulations of grain yield agreed well with the measurements. In general, the model was able to capture the interannual variability of wheat grain yield.

Figure 3 shows the statistical comparison of all simulated and observed values. The performance of the model to simulate crop growth and yield was satisfactory, because the coefficients of determination r^2 (1:1) were 0.82, 0.93 and 0.86 for LAI, biomass and grain yield respectively. The high β value (0.97) indicated close matches of simulated grain yield to measured values. The above results indicated that the calibrated APSIM model can be used confidently to simulate wheat growth and grain yield in these two study area.

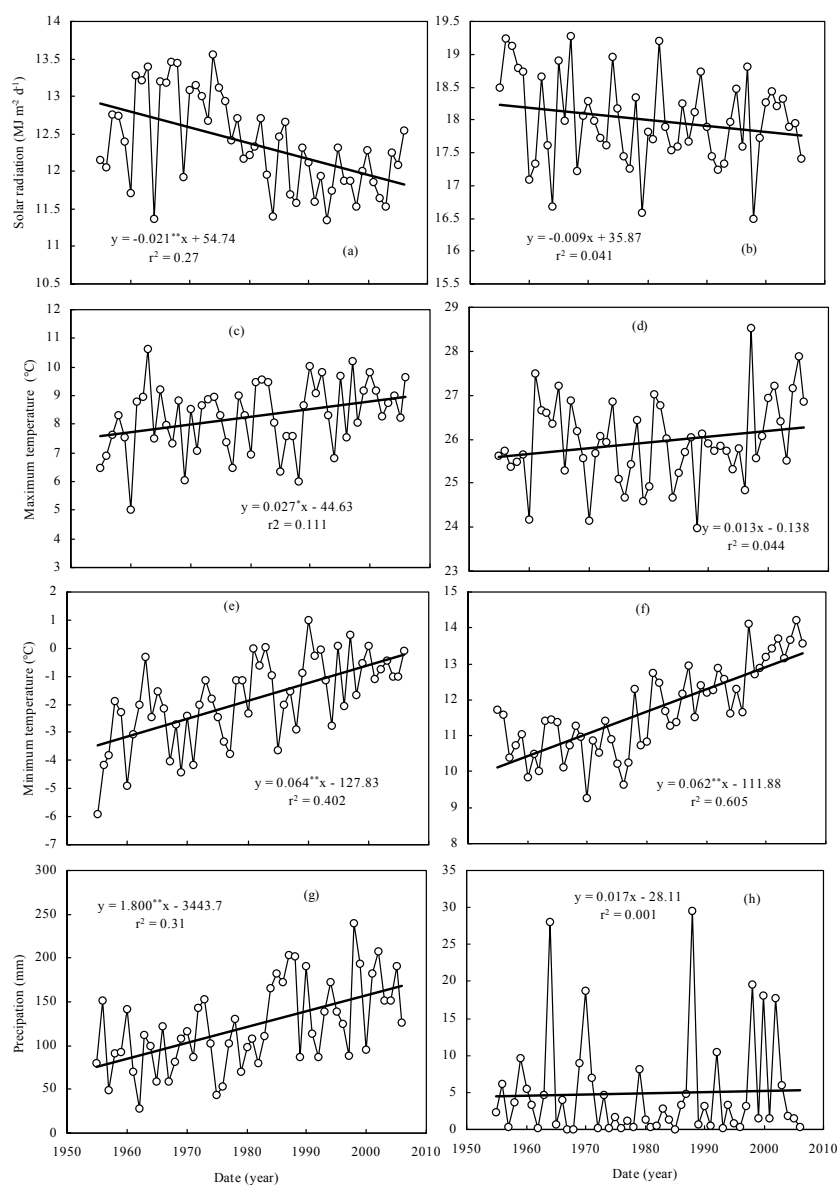


Figure 1. Solar radiation, temperature and precipitation of wheat growing seasons at Wulanwushu (a, c and e) and Dongkan (b, d and f) from 1955 to 2006. Straight lines show the linear trends. **Significant at $P < 0.01$.

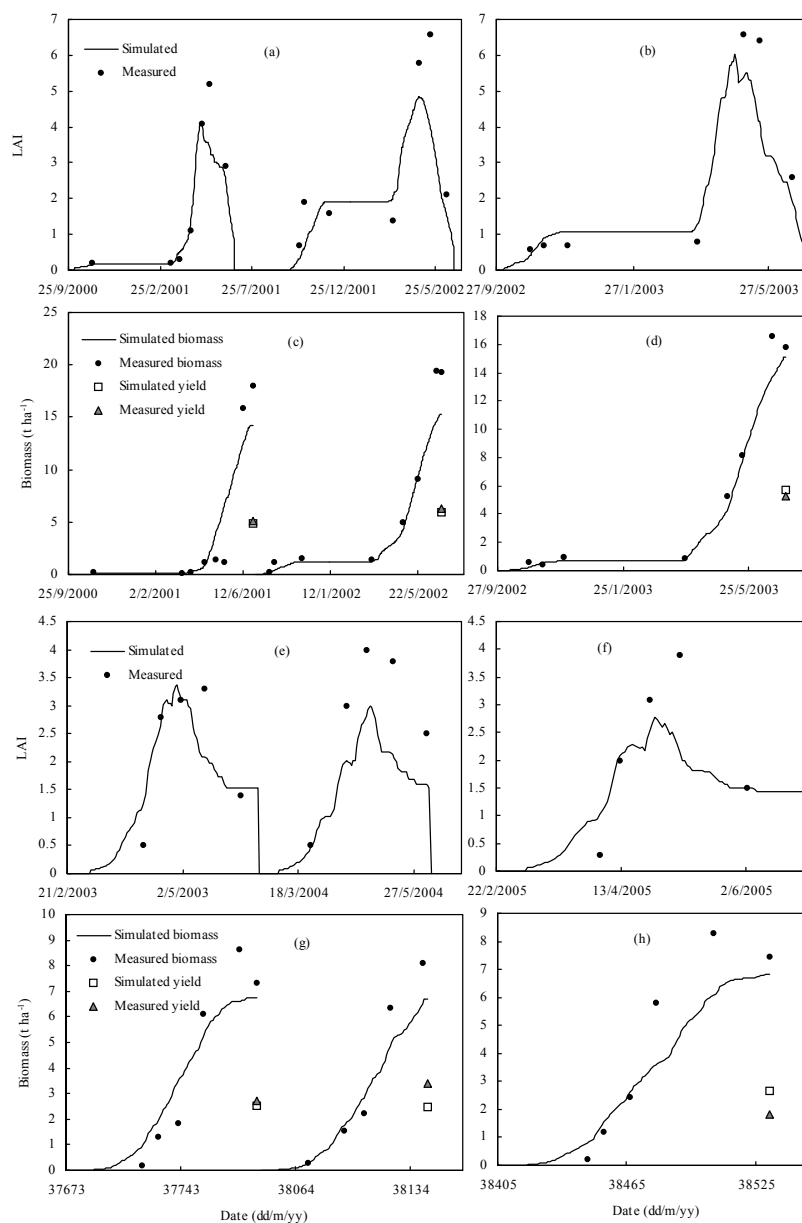


Figure 2. Comparison of observed and APSIM simulated LAI (a, b, e and f) and above-ground biomass and yield (c, d, g and h) at Wulanwushu station (a, b, c and d) and Dongkan station (e, f, g and h). Experimental data from 2000-2002 (winter wheat: a and c) and 2003-2004 (spring wheat: e and g) were used to calibrate the APSIM. Experimental data from 2002 to 2003 (winter wheat: b and d) and 2005 (spring wheat: f and h) were used to validate the APSIM.

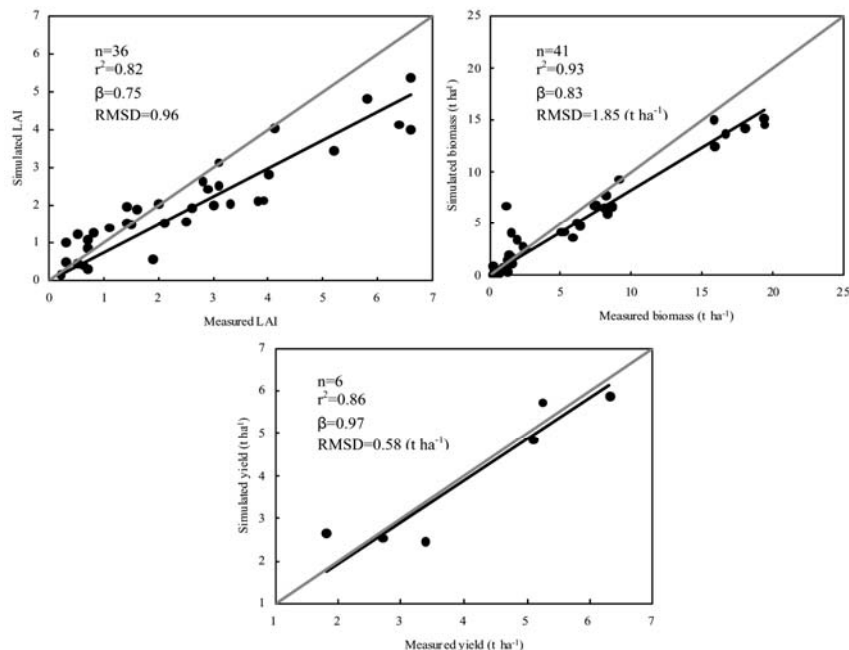


Figure 3. Comparison of observed and simulated values of above-ground biomass, LAI and grain yield of wheat with data from both Wulanwushu (2000-2003) and Dongkan (2003-2005) considered.

Relationship between measured pan evaporation and simulated ET

Linear correlation relationship between measured pan evaporation and simulated evapotranspiration (ET) were significant ($P < 0.01$) (Figure 4). It was showed that the APSIM model was able to simulate the effect of climate change on ET. Figure 4 obviously showed the relationship between measured pan evaporation and simulated ET for two periods July to next February and March to June. The slope of Figure 4a and b were 0.108 and 0.655. There were no winter wheat growth from July to October and LAI of winter wheat was small. Therefore simulated ET mainly was soil evaporation in this period. Simulated ET was nearly one-tenth of measured pan evaporation from July to October. The stage from March to June was the flourishing growth stage of winter wheat and the simulated ET was more than half of measured pan evaporation.

The impact of climate change on wheat growth and water use

The simulated wheat growth duration and ET of winter wheat were all decreased during 1955-2006 if no variety change is considered (Figure 5). Simulated grain yield and water use efficiency have no significant variation trends. The decreases in winter wheat growth duration and ET were significant ($P < 0.01$), which were $0.147 \text{ days year}^{-1}$ and $0.813 \text{ mm year}^{-1}$ respectively. The simulated grain yield, wheat growth duration, ET and water use efficiency of spring wheat had no significant variation trend during 1955-2006.

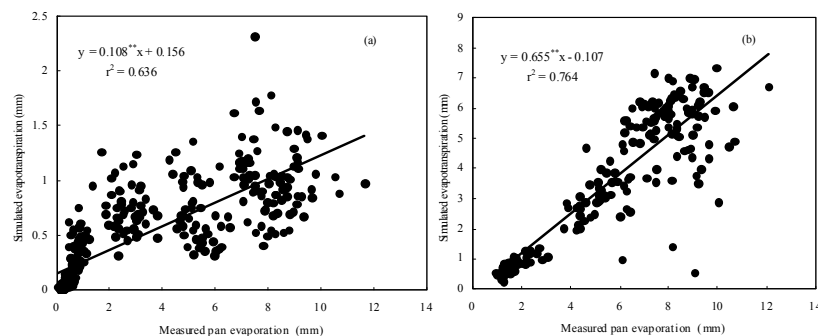


Figure 4. Relationship between measured pan evaporation in Shihezi and simulated evapotranspiration in Wulanwushu, monthly data from July to next February during the period of 1954-2001 (a), monthly data from March to June for 1955-2001 (b). **Significant at $P < 0.01$.

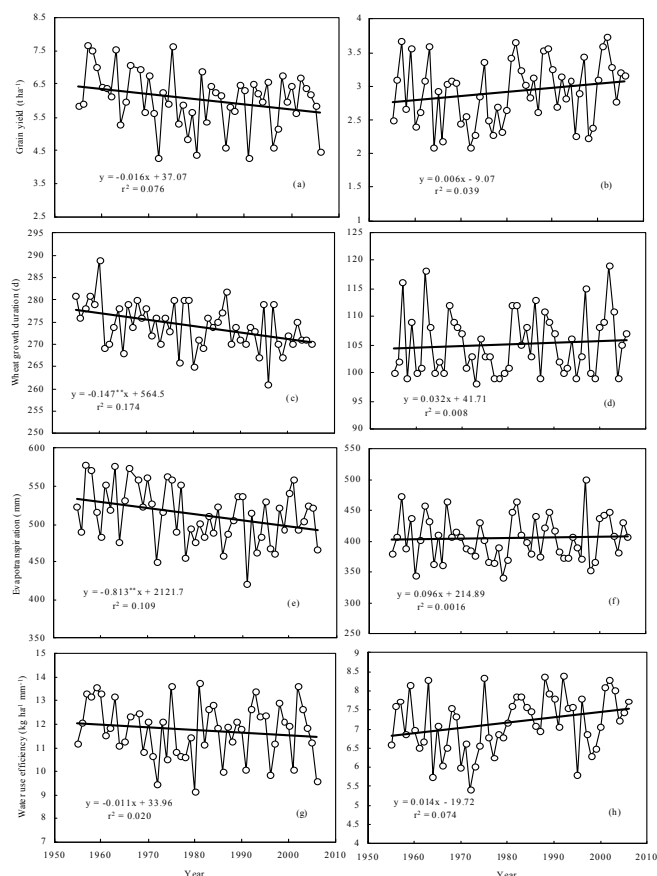


Figure 5. Simulated grain yield, wheat growth duration, evapotranspiration and water use efficiency during winter wheat growing seasons (a, c, e and g) and spring wheat growing seasons (b, d, f and h) from 1955 to 2006. Straight lines show the linear trends. **Significant at $P < 0.01$.

According to simulated ET, solar radiation, maximum and minimum temperatures, and precipitation of winter wheat growing seasons from 1955 to 2006, 52 years were clustered into four categories (Table 3). Clusters A and B compared with C and D, the years with higher solar radiation and lower precipitation had higher ET, the years with lower solar radiation and higher precipitation had lower ET. The relationship between ET and temperature was not significant among the four clusters. So ET during winter wheat growth stages was determined by solar radiation and precipitation.

Table 3. Mean values of evapotranspiration (ET), solar radiation (Ra), maximum (Tmax) and minimum (Tmin) temperatures, mean temperature (T), and precipitation during winter wheat growth stages. A, B, C, and D represent four different clusters. n is the number of data for each cluster.

Clusters	n	ET (mm)	Ra (MJ m ⁻² d ⁻¹)	Tmax (°C)	Tmin (°C)	T (°C)	Precipitation (mm)
A	14	544.08	13.01	8.98	-1.61	3.69	95.79
B	10	518.71	12.65	7.12	-3.65	1.73	76.98
C	14	492.47	11.80	7.30	-2.28	2.51	170.61
D	14	486.97	12.09	9.33	-0.30	4.52	131.56

Discussion

This study investigated the impacts of climate variability/change on wheat growth, yield and water use in oasis of Xinjiang. With the decrease of solar radiation (0.021 MJ m⁻² year⁻¹), and increase of maximum (0.027 °C year⁻¹) and minimum (0.064 °C year⁻¹) temperature during winter wheat growth seasons from 1955 to 2006, potential yield with full irrigation had no significant variation trend and simulated ET was significantly decreased at a rate of 0.813 mm year⁻¹ if changes in crop variety were not considered. The negative trends in solar radiation and an increase in minimum temperature resulted in declining trends of potential yields of wheat in India (Pathak et al., 2003; Aggarwal, 2003).

Chen et al. (2009) found that winter wheat yield declined and water demand decreased by 2.3 mm year⁻¹ from 1961 to 2003 on average at four sites in North China Plain (NCP). This value is higher than that of our study. This can be attributed to greater reduction in radiation (6.2~13.2 MJ m⁻² year⁻¹) in their study compared to ours. Mo et al. (2009) used the Vegetation Interface Processes (VIP) model with a fixed photosynthetic capacity rates and found that wheat yield was significantly increased and there is no evident intensification in ET in the NCP from 1951 to 2006. Our simulated results were that ET of winter wheat was significantly decreased in oasis. Differences between these results maybe because the effect of CO₂ enrichment was not considered in our research. Model projections suggest that although increased temperature and decreased soil moisture will reduce global crop yields, the direct fertilization effect of rising CO₂ will offset these losses (Long et al., 2006).

The variations of ET under the condition of climate factors change and CO₂ enrichment were complicated. Previous studies showed controversial results. Actual evaporation simulated by NCAR Community Land Model (CLM) increased over the half past century in Xinjiang, accompanied by the decreasing trend of annual pan evaporation (Liu et al., 2009). Goyal (2004) used Penman-Monteith equation to estimate reference evapotranspiration (RET) during 1971-2002 in India. RET was more sensitive to temperature increase and less sensitive to increase in net solar radiation and wind speed. Some studies showed that RET was

decreased during past 50 years due to reduced wind speed and sunshine hours (Tong et al., 2007; Li et al., 2008; Zhang et al., 2009). Simulated results without considering CO₂ enrichment in our study showed that ET was related with solar radiation and precipitation, and there was no significant relationship with temperature in oasis of Xinjiang. ET, the major component of hydrological cycle, will affect crop water requirement and future planning and management of water resources.

Conclusions

The APSIM model was used to investigate the response of wheat yield, evapotranspiration (ET) and water use efficiency to historical climate variations/changes in oasis inland arid areas of Xinjiang. The calibration and validation of the APSIM model showed that it could reasonably reproduce the dynamics of winter and spring wheat growth, yield and water use in the study area. Simulated LAI and biomass at the early stage of winter wheat were higher than measured values; they were lower than measured values at the late growth stages. The sensitivity of model was not enough to reflect the effect of temperature changes on winter wheat growth in Xinjiang.

The relationship between simulated ET of winter wheat and measured pan evaporation was significant. Simulated results using the validated model combined with historical climate records showed that ET of winter wheat was significantly decreased in the past 52 years. Cluster analysis showed that the year with high solar radiation and low precipitation had high ET. Variation of ET had no significant relationship with temperature.

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