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Key Points:
- During the last century, significant changes were observed in the surface climate over the irrigated area in Eastern China during summer
- Over the North China Plain, numerical experiments simulate surface cooling and enhanced precipitation due to irrigation during summer
- Inclusion of the irrigation module in regional climate models is necessary for more accurate simulations and attribution

Impact of Irrigation on Regional Climate Over Eastern China

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Abstract Irrigated area has rapidly expanded over the North China Plain (NCP), over the second half of the twentieth century. Simultaneously, there has been an observed increase in specific humidity and precipitation and a decrease in surface temperature during summer. The impacts of irrigation on regional climate in Eastern China are investigated using the Massachusetts Institute of Technology-Regional Climate Model with irrigation module. The results of our experiments clearly support that surface cooling as well as enhanced precipitation are attributable to irrigation over the NCP. The irrigation-induced soil moisture change simulated over the NCP during summer resulted in cooler surface temperatures by 1~4°C over this region, which led to a reduction of the planetary boundary layer, higher surface pressure, and significant changes in low-level circulation. Our results indicate that moisture convergence is enhanced over Hebei and Henan province along the Taihang-Mountain, which generated a significant increase in precipitation by 20~40% over this region.

Plain Language Summary The North China Plain is the largest irrigated area in Eastern China. During the second half of the twentieth century, there was an observed increase in irrigation extent, humidity, and precipitation, with a concurrent decrease in surface temperature. The Massachusetts Institute of Technology-Regional Climate Model, including the irrigation module, was used to investigate the impact of irrigation on regional climate over Eastern China. Massachusetts Institute of Technology-Regional Climate Model experiments clearly support that the irrigation extension altered local climate through surface cooling and enhanced precipitation over the North China Plain during the boreal summer time.

1. Introduction

China has succeeded in producing 25% of the world's grain and feeding 22% of the world's population with less than 10% of the world's available arable land (Food and Agricultural Organization, 2012; Piao et al., 2010). The North China Plain (NCP, 34°N to 41°N; 113°E to 121°E; Figure 1a) is the largest irrigated area in China, and the irrigated area has been dramatically increased from 1.9 to 14 million ha over the second half of the twentieth century (Figure 1b). Partly because irrigation has added the necessary supplemental water for crop maintenance and improved yield, the crop (i.e., wheat) yield of the NCP has increased rapidly and is now almost twice that of the global average (Chen & Jeong, 2018). Although irrigation contributed to improvement in crop-yield, it has also led to perceptible environmental problems such as the significant reduction of groundwater storage and potential accumulation of salt in the topsoil layer in the NCP (Chen, 2010; Taylor et al., 2013). Moreover, recent observational studies show significant changes in surface temperature and precipitation over irrigated regions in China (Han & Yang, 2013; Wen & Jin, 2012; Zhang et al., 2015; Zhu et al., 2012).

The rapid development of large-scale irrigation can cause changes in regional climate due to land-atmosphere interactions. Many studies demonstrate that incremental change in soil moisture through irrigation can lead to increasing local evapotranspiration and latent heat flux and to decreasing temperature and sensible heat flux, which is a first-order effect on the local surface energy and water budget (Adegoke et al., 2003; Alter et al., 2015; Cook et al., 2015; Douglas et al., 2009; Huber et al., 2014; Im & Eltahir, 2014; Im, Marcella, et al., 2014; Kang & Eltahir, 2018; Kueppers et al., 2007; Mueller et al., 2016; Qian et al., 2013; Sacks et al., 2009). However, the effect of irrigation on precipitation is more complex because of the multiscale processes, including the role of atmospheric circulations. In some cases, irrigation enhances precipitation as a result of a positive feedback between soil moisture and precipitation at the local scale (Adegoke et al., 2003; Moore & Rojstaczer, 2001; Pal & Eltahir, 2001; Segal et al., 1998). In other cases, evaporative cooling locally drives a precipitation decrease over irrigated areas due to lower height of the
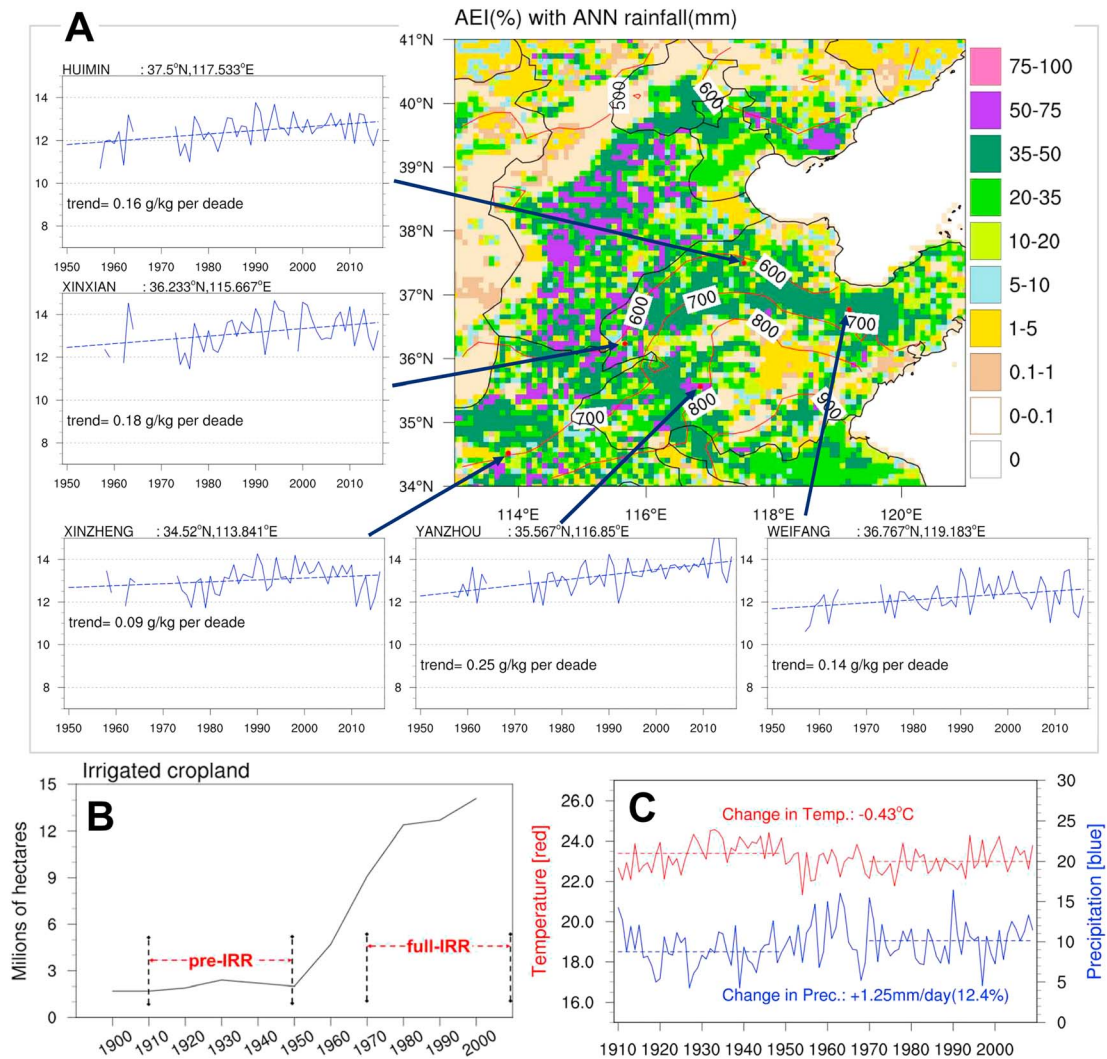
Figure 1. Background information regarding irrigated cropland over the North China Plain (NCP). (a) Map of the area equipped for irrigation around the year 2005 expressed as a percentage of the total area from Historical Irrigation Data (shading, unit: %) with annual total precipitation from Tropical Rainfall Measuring Mission (TRMM; contour, unit: mm) in modern record (1998–2015). Time series in (a) are summer (May-June-July) specific humidity (unit: g/kg) for the period 1950-2016 from five meteorological stations. (b) Temporal evolution of irrigated cropland over the NCP (millions of hectares) from Historical Irrigation Data. Two horizontal arrows in (b) indicate pre-IRR (1910–1949) and full-IRR (1970–2009) time periods. (c) Time series of summer (May-June-July) precipitation (blue, unit: mm/day) and surface temperature (red, unit: °C) over the NCP. The Kolmogorov-Smirnov test *p*-values are 0.05 (*N*=40) in precipitation and 0.03 (*N*=40) in surface temperature comparing pre-IRR (1910–1949) and full-IRR (1970–2009) time periods. The data in (c) are derived from the University of Delaware (UDel) gridded observational data (Willmott & Matsuura, 2015).

planetary boundary layer, and the anomalously high pressure (Alter et al., 2015; Im & Eltahir, 2014; Im, Marcella, et al., 2014). This higher pressure also causes the low-level circulation to change and modulates the precipitation change at remote location surrounding the irrigated area (Alter et al., 2015; Douglas et al., 2009; Im & Eltahir, 2014; Im, Marcella, et al., 2014; Huber et al., 2014).

This study aims to investigate the impact of irrigation on regional climate based on observational data and model simulations over Eastern China. We test the hypothesis advanced in Im & Eltahir (2014) and Im, Marcella, et al. (2014) (Figure S1 in the supporting information) that irrigation with a scale of millions of hectares, such as in NCP, would reduce temperature, increase surface humidity and surface pressure, and induce an anticyclonic circulation that forces changes in precipitation over surrounding regions. The specific objectives of this study are (1) to estimate the local climate change due to irrigation over Eastern China based on observations and (2) to investigate the nature of the physical mechanisms shaping the observed changes in precipitation that are caused by irrigation using numerical modeling experiment.

2. Methods and Materials

Based on Regional Climate Model Version 3 (RegCM3; Pal et al., 2007), the Massachusetts Institute of Technology-Regional Climate Model (MRCM; Im, Gianotti, et al., 2014) maintains much of the structure of that RCM but with several improvements (Gianotti et al., 2012; Gianotti & Eltahir, 2014a; Im, Gianotti, et al 2014; Im, Marcella, et al., 2014; Winter et al., 2009), including coupling to the IBIS land surface scheme and a new irrigation module implemented within the IBIS land surface scheme. Previous studies (Alter et al., 2015; Im & Eltahir, 2014; Im, Marcella, et al., 2014; Im, Gianotti, et al., 2014; Marcella & Eltahir, 2014) extensively tested the performance of the irrigation module used within MRCM across several regions (e.g., West Africa and East Africa). Hence, MRCM, including the irrigation module, was used here to investigate the impact of irrigation on precipitation over Eastern China, a region which has one of the largest irrigated areas across the globe (Siebert et al., 2015). In this study, irrigation is simulated in the model (see Text S1 in the supporting information for irrigation module), by replenishing the root-zone soil moisture to field capacity at the beginning of each month, whenever needed between the months of May to September, and wherever the grid point is equipped for irrigation according to the Historical Irrigation Data Set (Siebert et al., 2015). The model domain covers Eastern China, which is centered at 115°E and 31.5°N with a 25-km grid spacing on a Lambert conformal projection (Figure S3).

Two historical climate simulations were performed with and without irrigation (IRR and CONT) for the years 1982–2011 (simulations start from December 1981, but the first month is not included in the analysis to allow for model spin-up) using the same initial and lateral boundary conditions from the ERA-Interim reanalysis data (1.5°×1.5°, 6-hourly time scale; Dee et al., 2011) and National Oceanic and Atmospheric Administration optimum interpolation sea surface temperatures for the ocean surfaces (1°×1°, weekly time scale; Reynolds et al., 2002). To evaluate the two historical climate simulations, we compare the simulated surface conditions to the Climate Research Unit (Harris et al., 2014) data, focusing on precipitation, specific humidity, and surface temperature (see Text S1 for model evaluation).

The following station data and observational grid data are used: (1) historical irrigation data (Siebert et al., 2015), (2) Tropical Rainfall Measuring Mission (1998-2015; Huffman et al., 2007), (3) Integrated Surface Database (National Centers for Environmental Information (NCEI), 2016), and (4) University of Delaware gridded observational data (Willmott & Matsuura, 2015).

3. Results

The annual total precipitation is relatively low compared to similar locations in South China, making irrigation water necessary to sustain NCP agriculture (Figure S2). For that reason, irrigation is concentrated in the major regions of agricultural production over Eastern China, particularly over the NCP (Figures 1a and S2), which includes Hebei, Henan, Shandong, Anhui, and Jiangsu provinces (Figure S3a). Over the NCP, the extent of historical irrigation can clearly be divided into two eras, with the year 1950 being the breakpoint (Figure 1b). These historical increases in an area equipped for irrigation may cause significant climatic changes at the regional scale. Hence, we first investigate the relationship between climate variables by comparing observational time series of specific humidity, precipitation, and temperature over the NCP during summer (May-June-July) when irrigation mainly occurs for crop growing. The evolution of summer specific humidity and area-averaged surface temperature and precipitation over the NCP is shown in Figure 1. The specific humidity in all stations has increasing trends of about 0.09~0.25 g/kg per decade (Figure 1a). These trends are particularly strong around high area equipped for irrigation regions. It implies that irrigation enhances soil moisture, linking to increasing specific humidity. The surface temperature (precipitation) decreased (increased) significantly by 0.43°C (1.25 mm/day) between the pre-IRR (pre-irrigation development, 1910-1949) and full-IRR (full-irrigation development, 1970-2009) time periods (Figure 1c), according to the Kolmogorov-Smirnov test (see Text S1 for statistical analysis). The time series indicate simultaneous increases in specific humidity and precipitation, with a concurrent decrease in surface air temperature over irrigation region, which are consistent with previous studies (Adegoke et al., 2003; Alter et al., 2015; Qian et al., 2013; Huber et al., 2014).

Based on the extent of historical irrigation, climatological summer (May-June-July) surface temperature and precipitation changes are calculated between pre-IRR and full-IRR over Eastern China (Figure 2). Statistically significant decreases in surface temperature (up to 1°C) are found over Shandong, Henan, and Eastern Sichuan provinces, according to the Kolmogorov-Smirnov test, while significant increases in
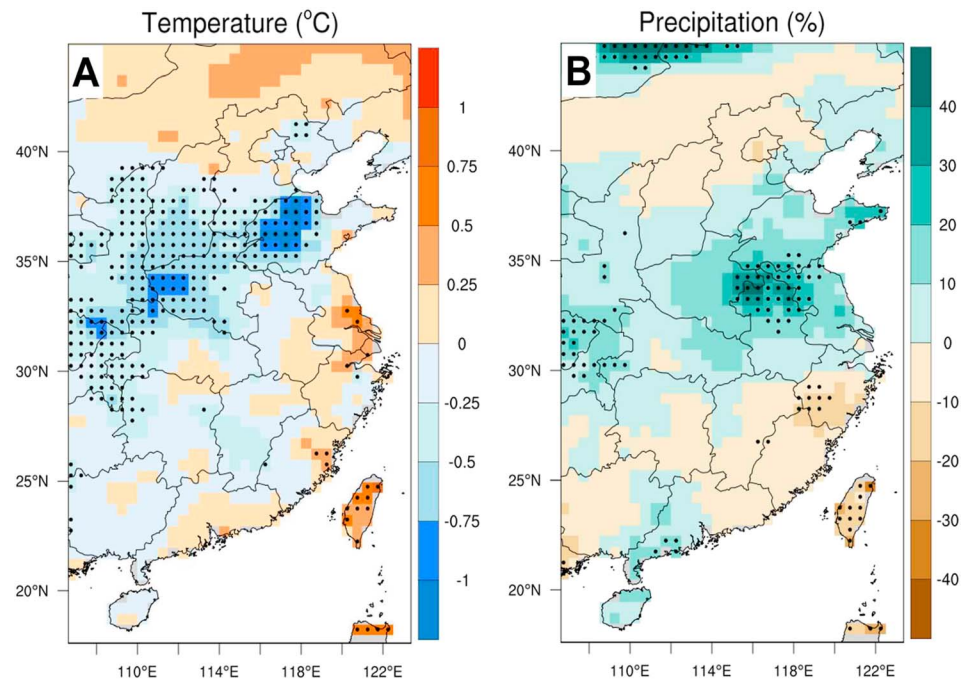
Figure 2. Observed spatial changes in regional climate over Eastern China. Historical difference in observed (a) surface temperature (absolute difference, unit: °C) and (b) precipitation (relative difference, unit: %) from pre-IRR (1910-1949) to full-IRR (1970-2009) during summer (May-June-July). The black dots indicate differences are statistically significant at the 5% level as the Kolmogorov-Smirno test ($N = 40$, $p \leq 0.05$). The data used in this figure are May-June-July mean monthly values of surface temperature and precipitation derived from the University of Delaware gridded observational data (Willmott & Matsuura, 2015).

precipitation (up to 30%) are found over Shandong, Henan, Anhui, and Eastern Sichuan provinces. Most of the region with increased precipitation (decreased surface temperature) overlaps with the irrigated area (land use type 13 in Figure S3b) but with one exception in the Eastern Sichuan province. The absolute magnitude of the observed increase in summer (May-June-July) precipitation over this region is the largest in the world (along the same latitudes), and the magnitude of the concurrent decrease in surface temperature is only matched in the Central and Eastern United States (Figure S4).

To study the impact of irrigation on precipitation over Eastern China, the spatial distributions of irrigation-induced changes (i.e., IRR minus CONT) in surface temperature, surface pressure, low-level (925hPa) wind flow, and precipitation during summer (May-June-July) are shown in Figure 3. In general, the irrigation effect on surface temperature is mainly localized within the irrigated areas, with nonirrigated areas less affected. Surface temperature is significantly decreased by 1~4°C over irrigated areas. These results are consistent with those of our previous studies, which showed the direct effects of irrigation are to enhance evapotranspiration and cool the surface temperature (Alter et al., 2015; Im & Eltahir, 2014; Im, Marcella, et al., 2014; Kang & Eltahir, 2018).

The small increase of precipitation (not significant) over irrigated areas is probably due to increased soil moisture by irrigation at the local scale (positive feedback, Adegoke et al., 2003; Moore & Rojstaczer, 2001; Pal & Eltahir, 2001; Segal et al., 1998). However, the mechanism described by Im & Eltahir (2014) and Im, Marcella, et al. (2014) may describe how irrigation induces the statistically significant increases in precipitation by 20~40% over Hebei and Henan province along the Taihang Mountains. Over irrigated areas, the height of the planetary boundary layer is lowered, and subsidence occurs associated surface cooling. This subsidence leads to the development of high pressure (Figure 3b) and significant development and enhancement of anticyclonic circulation (Figure 3c). This circulation interacts with the background regional wind pattern associated with the evolving monsoon circulation. As a result, the moisture convergence caused by anomalous anticyclonic circulation induces significant increases in precipitation over Hebei and Henan province along the Taihang Mountains.
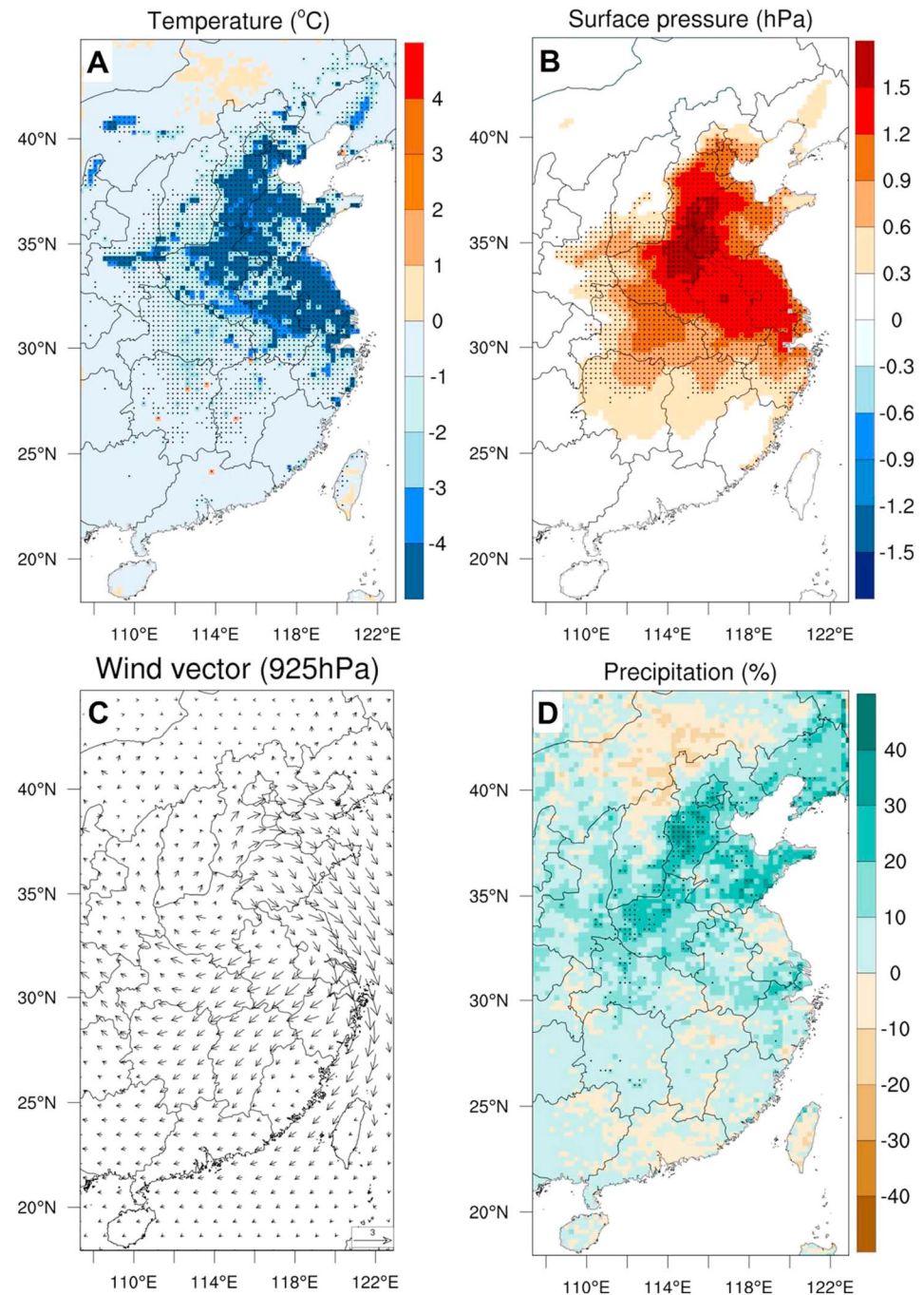
Figure 3. Simulations of the impact of irrigation on surface variables and low-level winds. 30-year May-June-July mean difference (IRR-CONT) in (a) surface temperature (unit: °C), (b) surface pressure (unit: hPa), and (c) wind vector at 925hPa. (d) The relative difference ([IRR-CONT]/CONT) in 30-year May-June-July mean precipitation (unit: %). The stippling area in (a), (b), and (d) indicates that differences are statistically significant at the 5% level as determined by a two-sided Student's *t* test.

4. Summary and Discussion

In this study, the climatic impacts of irrigation over the NCP in East China are investigated based on observations and using the MRCM with an irrigation module to conduct numerical experiments. First, during the twentieth century there was an observed increase in irrigation extent, specific humidity, and precipitation over the NCP during summer (May-June-July), with a concurrent decrease in surface temperature. That

is, the observed precipitation and surface temperature changes are associated with the increased specific humidity due to the expansion of irrigation. Second, regional climate model experiments clearly support that the irrigation extension altered local climate through surface cooling and enhanced precipitation over the NCP during the boreal summer time. The model results demonstrate that the irrigation-induced soil moisture has a cooling effect on surface temperatures by about 1~4°C, which in turn leads to a reduction of the planetary boundary layer with higher surface pressure (subsidence) generating favorable conditions for anticyclonic circulation. Consequentially, the altered land cover causes low-level moisture convergence over Hebei and Henan province along the Taihang Mountains where precipitation is significantly increased by about 20~40%.

Irrigation experiments could not simulate statistically significant changes in precipitation and surface temperature over the Eastern Sichuan province (Figure 2). It is worthy to note that due to the limited domain of our simulations, it is difficult to reproduce the full extent of the circulation induced by irrigation. In addition, major increases in anthropogenic greenhouse gas (GHG) emissions over the same time period may have also been an important forcing of these observed changes. To advance our understanding of local climate change, we are planning to perform numerical studies reflecting anthropogenic effects (land cover and GHG changes) within an extended model domain including the major river basins over China. The results can help to explain the roles of the irrigation and GHG emissions in local climate change and its influence on water availability in China.

The volume of irrigated water is rather large over the irrigated area in our domain. The irrigated water intensity (unit: $km^3 \cdot [million\ ha^{-1}]$ per year) is about 1.9 times higher than those estimated by Siebert et al. (2010) over five provinces (Anhui, Henan, Hebei, Jiangsu, and Shandong). Therefore, future work will consider more realistic designs for irrigation experiments by applying new irrigation scheduling (Im, Marcella, et al., 2014) and using data assimilation to calibrate soil moisture over irrigated areas (Felfelani et al., 2018).

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