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# Memory of irrigation effects on hydroclimate and its modeling challenge

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## Abstract

Irrigation modifies land-surface water and energy budgets, and also influences weather and climate. However, current earth-system models, used for weather prediction and climate projection, are still in their infancy stage to consider irrigation effects. This study used long-term data collected from two contrasting (irrigated and rainfed) nearby maize-soybean rotation fields, to study the effects of irrigation memory on local hydroclimate. For a 12 year average, irrigation decreases summer surface-air temperature by less than 1°C and increases surface humidity by 0.52gkg$^{-1}$. The irrigation cooling effect is more pronounced and longer lasting for maize than for soybean. Irrigation reduces maximum, minimum, and averaged temperature over maize by more than 0.5°C for the first six days after irrigation, but its temperature effect over soybean is mixed and negligible two or three days after irrigation. Irrigation increases near-surface humidity over maize by about 1 gkg$^{-1}$ up to ten days and increases surface humidity over soybean (~ 0.8gkg$^{-1}$) with a similar memory. These differing effects of irrigation memory on temperature and humidity are associated with respective changes in the surface sensible and latent heat fluxes for maize and soybean. These findings highlight great need and challenges for earth-system models to realistically simulate how irrigation effects vary with crop species and with crop growth stages, and to capture complex interactions between agricultural management and water-system components (crop transpiration, precipitation, river, reservoirs, lakes, groundwater, etc.) at various spatial and temporal scales.


**Figure 1.** Fraction of irrigated lands in the contiguous US (left) and the landscape of the AmeriFlux USNe2 (irrigated) and USNe3 (rainfed) agricultural sites (right).

## 1. Introduction

Advancing the understanding of the nexus among food, energy, and water systems has recently emerged as a new science frontier, and the research community has started to model the agricultural management (especially irrigation) on earth-system models in order to develop an integrated modeling tool for investigating relevant science and sustainability issues. However, the development of crop irrigation models is still in its infancy stage and substantial discrepancies exist in the simulated irrigation effects by earth-system models. This study explores how irrigation memory influences hydroclimatic variables by using long-term data from two AmeriFlux sites located in irrigated and rainfed agriculture systems near Mead, Nebraska (NE), USA. Figure 1 shows that a significant majority of farmland in the US is irrigated, especially in semi-arid and arid regions. About 55.8 million acres in the US were irrigated for 2012 according to the most recent Census of Agriculture, and the total irrigation withdrawals were 115 billion gallons per day (about 38 percent of total freshwater withdrawals (Maupin *et al* 2014). Moreover, irrigation modifies land-surface characteristics such as albedo and emissivity, available water for evaporation, the evolution of plant phenology (e.g. leaf-area index, LAI), and the land-atmospheric exchange of heat, moisture, and carbon, which in turn, affect local and regional weather and climate.



Fowler and Helvey (1974) performed one of the earliest studies on the influence of irrigation on air temperature and precipitation for the Columbia Basin, Washington, using data for prior-irrigation (1924–1950) and post-irrigation (1951–1971) periods, but concluded that the changes in those climatic variables were statistically insignificant. However, uncertainty when using two different time periods for comparison, influences of surrounding mountains, and changes in the location and exposure of weather stations prevented a rigorous analysis of irrigation effects. Schickedanz (1976), and Barnston and Schickedanz (1984) reported increased precipitation as a result of irrigation over various regions. Nevertheless, the specific aspects and impacts of irrigation memory have not yet been thoroughly investigated.

Extensive literature exists demonstrating substantial uncertainties in the modeled effects of irrigation on regional climate by earth-system models (ESMs). For instance, August mean temperature was reduced by 3.7 °C in California (Kueppers *et al* 2007); irrigation cooled annual temperature by ~0.5 °C in the central and southeast US, and southeast China (Sacks *et al* 2009); Lobell *et al* (2009) showed a temperature reduction by up to 10°C in average monthly temperatures. However, there are tremendous uncertainties inherent to numerical modeling and their results, which are likely influenced by differing climate-model responses to physics parameterization, by model sensitivity to the treatment of irrigation processes (e.g. the timing and amount of irrigation in models), and by the methodology of conducting sensitivity or idealized numerical experiments. Thus, an observation-focused study is imperative to quantify the impact of irrigation memory on near-surface hydroclimatic variables such as air temperature, humidity, and surface-heat fluxes.

Data collected from two long-term AmeriFlux agricultural sites, USNe2 site with irrigation and USNe3 site without irrigation, provide an ideal opportunity to systematically examine the effects of irrigation. These two sites are near Mead, NE (figure 1) and are planted with a maize-soybean rotation, representing a typical cropping system in the US Corn Belt that has expanded over the last 20 years. This trend may continue to increase due to emerging biofuel demand. In 2010, across the eight states of the Corn Belt (Illinois, Indiana, Iowa, Michigan, Minnesota, Missouri, Nebraska, and Ohio), 83% of agricultural lands were planted in maize and soybean (http://usda.mannlib.cornell.edu/usda/current/Acre/Acre-06-30-2011.pdf). Improved management practices (e.g. irrigation, fertilization, conservation tillage, etc.) have increased grain yield over the last few decades (Cassman *et al* 2003).

The sites selected for this study were uniformly tilled by disking prior to 2001, and have been under no-till since then. They are located within 1.6 km from each other over aflat and relatively homogeneous environment, are characterized by the same silty-clay-loam soils, and undergo the same rotation of maize and soybean. Except for the lower planting density at the rainfed site USNe3, the only meaningful difference between these two sites for a given year is irrigation (Verma *et al* 2005). Data obtained from these two sites have been used to study $CO_2$ exchanges, crop phenology, and gross primary production and respiration (e.g. Verma *et al* 2005, Suyker *et al* 2005, Wagle *et al* 2016). However, no systematic evaluation ofirrigationimpactsonhydro-meteorological variables has been conducted. Therefore, the present study, taking advantage of long-term data from those two contrasting sites, aims to address the following science questions. (1) How long does the memory of irrigation affect summer near-surface hydroclimatic variables such as temperature, humidity, and surface-energy budgets? (2) Are the irrigation impacts over maize different than over soybean?

## 2. Study area and observations

ThestudysitesarelocatedattheUniversityofNebraska Agricultural Research and Development Center near

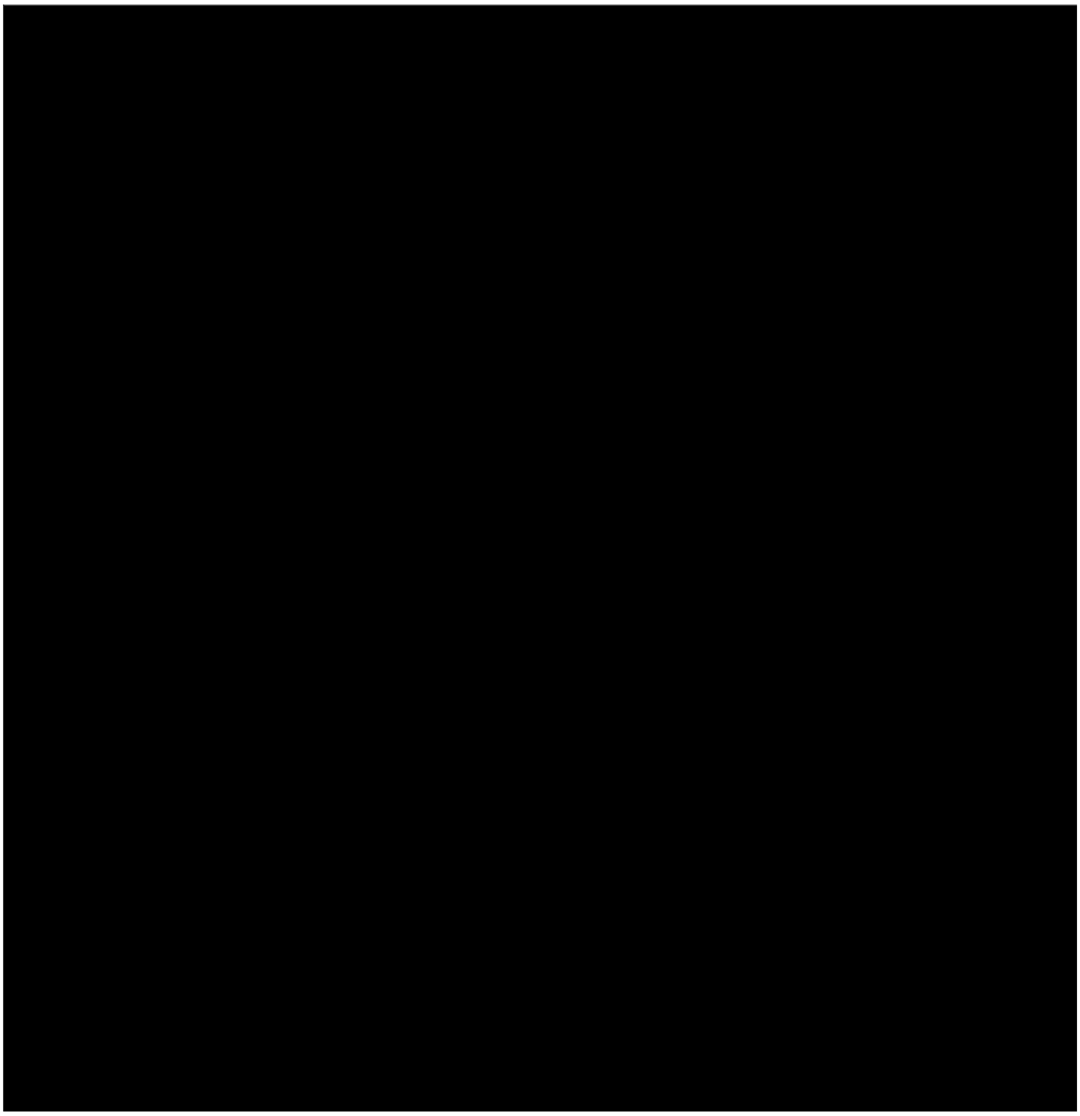

**Figure 2.** Daily spring-fall (May 1—September 30) precipitation and irrigation amount (mm) for 2001 ¯2012 at the USNe2.

Mead, NE. They arelarge production fields planted in a maize-soybean (*Zea mays,* L.; *Glycine max* [L.] *Merr.*) rotation. Each field is 49–65 ha, providing sufficient upwind fetch of uniform cover required for adequately measuring mass and energy fluxes using tower eddy covariance systems (Verma *et al* 2005). These types of maize and soybean represent a major share of the annual total irrigated planted area in the central Great Plains. Site 1 (USNe2, 41°09′53.5″ N, 96°28′12.3″ W, 362 m) is irrigated withcenter-pivot irrigation systems, andtheSite2(USNe3,(41°10′46.8″N,96°26′22.7″ W, 363 m, figure 1) is arainfed agricultural system; thetwo sites are within 1.6 km of each other. To satisfy management practices, crop-planting densities were lower in the rainfed field (USNe3) than in the irrigated field (USNe2). Detailed site information can be found in Verma *et al* (2005) and Suyker and Verma (2012).

This study used hourly gap-filled surface heat flux and near-surface meteorological data collected from USNe2 (52.4 ha) and USNe3 (65.4 ha) for the period of 2001–2012 obtained from the AmeriFlux website (http://ameriflux.lbl.gov/). Above-crop-canopy fluxes of water vapor and energy were measured with the eddy-covariance flux tower systems, with companion air temperature and humidity measurements, at those study sites. The measurement heights for the eddy-covariance systems for both sites were 3 m (6.2 m during growing season). While they may vary from year-to-year due to canopy growth and crop rotation, they were normally above the crop canopy.

## 3. Results and analysis

Figure 2 shows 101 irrigation applications from 15 June 2001 to 30 September 2012. The number of irrigation applications exhibits significant interannual variability, e.g. 13 irrigation applications totaling 361 mm in 2003 (maize rotation) and four applications totaling 127 mm in 2006 (soybean). This variability is highly anti-correlated with its counterpart in precipitation as shown in table 1. The years (i.e. 2001, 2003, 2012)

**Table 1.** Accumulated June–August precipitation and irrigation amount (mm), averaged 2m air temperature Ta (°C) for USNe2 and USNe3, and the differences in Ta (°C) and 2m mixing ratio qa ($gkg^{-1}$) between USNe2 (irrigated) and USNe3 (rainfed) for 2001–2012. Note that the data in 2001 started on 15 June.

| Year | Crop type | Precipitation (mm) | Irrigation (mm) | Ta | | ΔTa (°C) | qa ($gkg^{-1}$) | | Δqa |
|---|---|---|---|---|---|---|---|---|---|
| | | | | USNe2 | USNe3 | (°C) | USNe2 | USNe3 | ($gkg^{-1}$) |
| **2001** | maize | 104.26 | 305.22 | 24.03 | 24.49 | −0.46 | 14.23 | 14.30 | −0.07 |
| **2002** | soybean | 239.30 | 256.88 | 24.36 | 24.70 | −0.34 | 13.90 | 14.48 | −0.58 |
| **2003** | maize | 150.60 | 366.74 | 23.08 | 23.47 | −0.39 | 13.51 | 12.57 | 0.94 |
| **2004** | soybean | 202.80 | 155.17 | 20.99 | 20.97 | 0.02 | 13.02 | 12.15 | 0.87 |
| **2005** | maize | 217.20 | 310.66 | 23.75 | 24.09 | −0.34 | 14.46 | 13.21 | 1.25 |
| **2006** | soybean | 294.80 | 161.62 | 23.67 | 23.71 | −0.04 | 14.15 | 12.88 | 1.27 |
| **2007** | maize | 362.12 | 275.33 | 23.84 | 24.13 | −0.29 | 15.52 | 14.05 | 1.47 |
| **2008** | soybean | 412.50 | 211.40 | 22.49 | 22.61 | −0.12 | 13.69 | 12.63 | 1.06 |
| **2009** | maize | 359.20 | 129.39 | 20.61 | 21.50 | −0.89 | 12.16 | 12.37 | −0.21 |
| **2010** | soybean | 456.00 | 176.98 | 23.46 | 23.48 | −0.02 | 15.13 | 14.31 | 0.82 |
| **2011** | maize | 308.30 | 159.60 | 23.65 | 23.84 | −0.19 | 14.63 | 14.43 | 0.20 |
| **2012** | soybean | 134.50 | 368.85 | 24.34 | 24.35 | −0.01 | 12.52 | 12.01 | 0.51 |

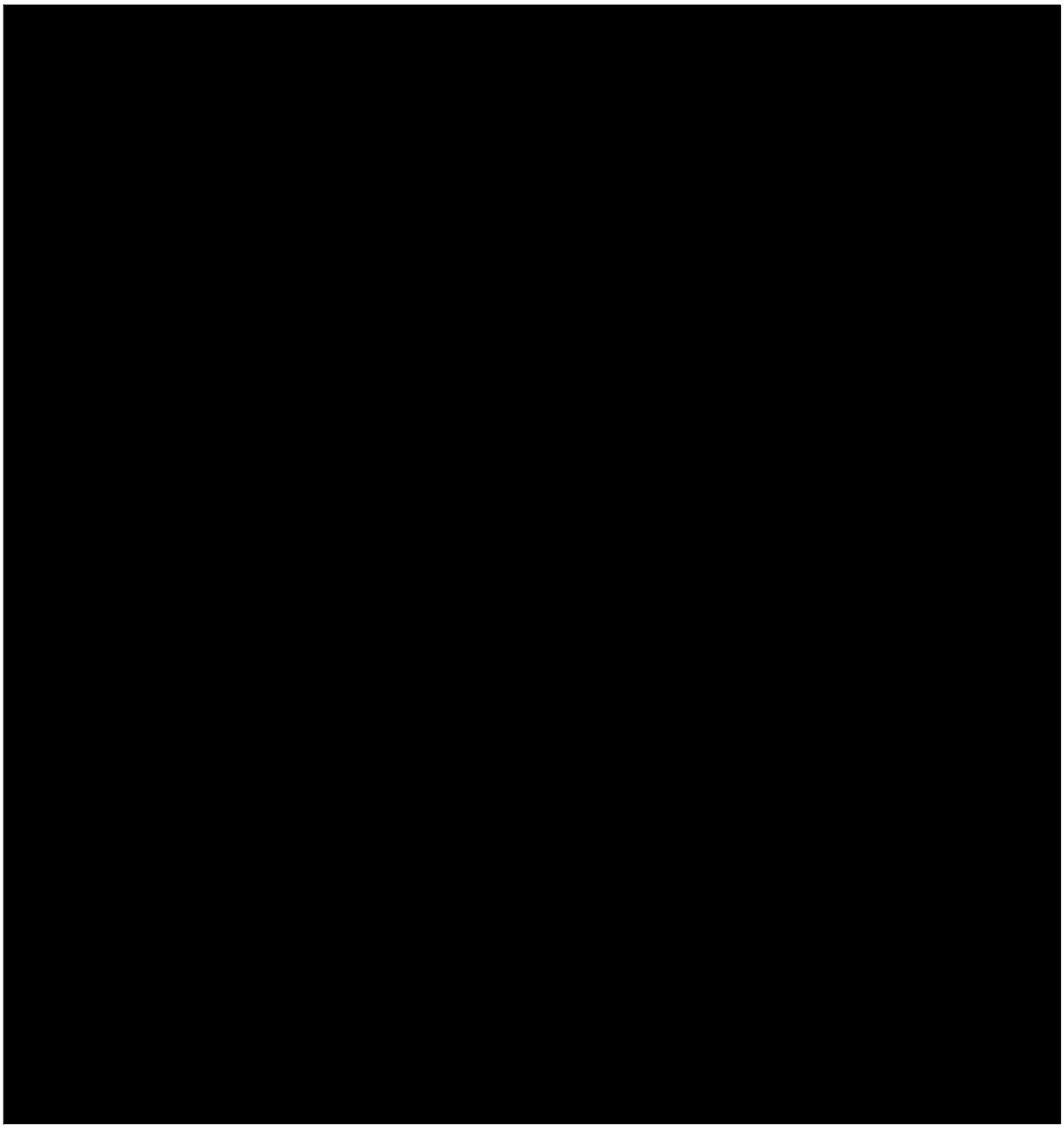

**Figure 3.** Observed differences in daily volumetric soil moisture (or soil water content SWC, $m^3 m^{-3}$) (USNe2 minus USNe3) at 0.1 m depth (in red) and at the 0.25 m depth (in green) for 2001–2012.

with more than ten irrigation applications represent August for soybean. This type of irrigation schedule, at dry years with summer precipitation less than 150 mm. least for the soybean, concurs with the report of Kranz

Most irrigation was conducted in June and July for andBenham(2001)inthatirrigationisusuallyrequired maize and soybean, withsome meaningful irrigation in only during the mid- to late-reproductive stages.

**Figure 4.** The *x*-axis represents days from an irrigation application with amount > 7.5 mm $day^{-1}$. The *y*-axis represents the differences in daily Tmin (°C, top), Tmax (°C, middle) and Tave (°C, bottom) between USNe2 and USNe3. Samples were taken from all irrigation events from 2001–2012 and the red stars represent their averaged values for a given day after irrigation.

Irrigation was regularly applied, mostly with 4–11 day intervals, during significant dry spells (e.g. July 2001, 2002, 2003, 2004, and 2010, August 2008, etc.). During the driest year (2012), irrigation was applied throughout the summer growing season. The maximum daily irrigation amount was, with a few exceptions, about 30 mm per day.

As expected, irrigation increased the soil moisture during the growing season at the USNe2 site (figure 3). The soil moisture differences at the shallow 0.1 m depth were generally greater than that at the 0.25 m depth, and the increased volumetric soil moisture reached 16 $m^3\ m^{-3}$, which is roughly half of the available water content for evaporation.

Table 1 also shows that the summer mean air temperature at the irrigated USNe2 site is lower than that at the rainfed USNe3 site, except for 2004. The differences in air temperature between the two sites are usually less than 1 °C. Temperature declined more significantly over maize (ranging from −0.19 °C to −0.89 °C) than over soybean where the temperature reduction is less than 0.2 °C, except for 2002. In addition, the surface air over the irrigated USNe2 site was generally wetter than the air over the rainfed USNe3 site. On average, irrigation increases the 12 year summer surface humidity by 0.52 g $kg^{-1}$ (roughly 4%) when compared to the USNe3 site.

Furthermore, to understand the effects of irrigation memory on near-surface temperature, the differences in daily maximum (Tmax), minimum (Tmin), and daily mean temperature (Tave) are plotted as a function of days after irrigation application (figure 4). The trends for those three temperature indices generally agree with each other. Nevertheless, irrigation reduces maximum temperature slightly more than minimum and mean temperature. Figure 4 also confirms what was revealed in table 1: the irrigation cooling effect is more pronounced for the maize than for soybean. For maize, irrigation reduces Tmin, Tmax, and Tave by more than 0.5 °C for the first six days. Tmax and Tave remain lower for maize 11 days after irrigation, but with reduced amplitude of changes (~0.2 °C). By contrast, for soybean, the cooling signal of irrigation is mixed and brief, and its effect is negligible after two or three days. The irrigation-induced temperature decrease revealed at those sites is largely on par with the Sacks *et al* (2009) modeling study (i.e. 0.5 °C irrigation cooling), but lower than most climate model results (e.g. Kueppers *et al* 2007, Lobell *et al* 2009).

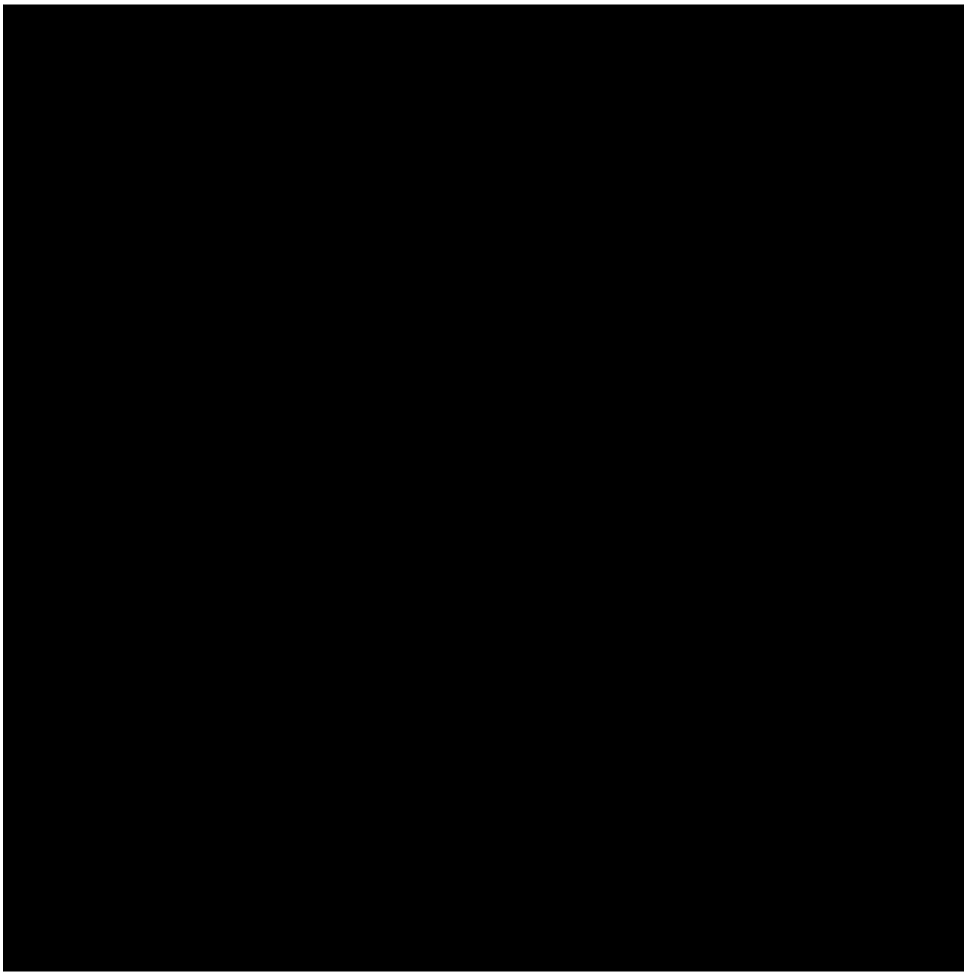

**Figure 5.** Same as figure 4, but for differences, between USNe2 and USNe3, in daily mean 2m mixing ratio qa (gkg$^{-1}$, top), sensible heat flux SH (W m$^{-2}$, middle), and latent heat flux LH (W m$^{-2}$, bottom).

Since the mean temperature reveals similar variations as the daily minimum and maximum temperature, in the following analysis, for the sake of brevity, only daily mean values of surface humidity, surface-sensible heat flux (SH), and surface latent heatflux(LH,i.e.evaporation/transpiration)areexamined here. Note that the average summer net radiation around the peak noontime at the irrigated USNe2 site was slightly higher than that at USNe3 for dry years, presumably due to lower surface albedo from the wetter canopy surface at USNe2. But their differences are usually less than 20Wm$^{-2}$, so the radiative forcing difference between these two sites is not a significantly factor contributing to the differences in surface heat fluxes and to the irrigation cooling effect.

Similar to irrigation-induced temperature differences, the irrigation impact on humidity are clear for maize: irrigation increases near-surface humidity by approximately 1 gkg$^{-1}$ with measurable impacts remaining for up to ten days (figure 5(*a*)). Unlike its negligible effect on temperature over soybean, irrigation clearly increases surface humidity (~0.8 gkg$^{-1}$, figure 5(*b*)) with similar memory to the humidity measured over maize. Note that figures 5(*a*)–(*b*) show higher humidity over both maize and soybean even up to two weeks after irrigation, but the sample size is small.

This demonstrated decrease in temperature and increase in humidity caused by irrigation is consistent with changes in the land-atmosphere exchange of heat and watervapor shown in figures 5(*c*)–(*f*). That is: the more significant temperature reduction for the irrigated maize is correlated with a notable reduction in the transport of heat (i.e. lower sensible heat flux by ~25 Wm$^{-2}$, figure 5(*c*)), while the lack of temperature change for irrigated soybean can be mostly attributedtoitsnegligiblechangeinsensibleheatfluxes (figure 5(*d*)). Moreover, wetter air over both irrigated maize and soybean is associated with the similar magnitude in augmented latent heat fluxes (~20 Wm$^{-2}$, figures 5(*e*) and (*f*)).

The analysis presented thus far naturally raises a question. Why does the irrigation affect temperature over a maize field more than that over a soybean field? To answer this question in exhaustive fashion is beyond the scope of this study. Nonetheless, our analysisof thedaily ratioof totalturbulent flux (i.e. SH+LH) to the net radiation (not shown) for 2001–2012 reveals a slightly higher ratio for maize than for soybean. Considering the similar changes in LH (figures 5(*e*) and (*f*)) due to irrigation, it seems the transport of heat from maize fields is more efficient than for soybean, which is perhaps related to crop phenology such as higher plant height and leaf-area index for maize. Similarly, Verma *et al* (2005) pointed out that the value of integrated gross primary productivity (GPP) for maize was substantially higher than for soybean, indirectlyindicatingamoreefficientuseoflightandgreat er turbulence energy for maize.

Lastly, we examine the effects of irrigation on crop evapotranspiration asshown in figure 6. Clearly, irrigationincreasesevaporationfordryyears(e.g.2002, 2003,

**Figure 6.** Accumulated irrigation amount at USNe2 and cumulative differences in evaporation (USNe2 minus USNe3) (mm) for 2001–2012.

2005,2012)buthasminimumeffectonevaporationfor wet years (e.g. 2008 and 2010). In general, the amount of increased cumulative evaporation (usually less than 50 mm during the growing season) is low compared to the irrigation amount ranging from 150 to 370mm applied during the same period. Therefore, a significant amount of irrigation goes to increased soil water storage and runoff. Moreover, it is notable that, based on the available 2001–2006 biomass data at these two sites, irrigation increases the maize yield (in terms of bushels per acre) by 59%, but only by 13%for soybean. Nevertheless, such a relatively low increase in yields for the irrigated soybean field is mostly consistent with previous reports (Verma *et al* 2005, Irwin *et al* 2017) in that the GPP is significantly higher for maize than for soybean. Kranz and Benham (2001) also pointed out thatirrigationwater-useefficienciesforsoybeanarenot as high as for corn and resulted in less than 1.0 bushel per acre per inch of irrigated water.

## 4. Concluding remarks

This study used long-term data collected from two contrasting (irrigated and rainfed) nearby maizesoybean rotation fields to study the effects of irrigation memory on local hydroclimate. For a 12 year average, irrigation decreases summer surface-air temperature by less than 1 °C (2%) and increases surface humidity by 0.52 $\mathrm{g\,kg^{-1}}$ (4%). The irrigation cooling effect is more pronounced and longer lasting for maize than for soybean. Irrigation reduces maximum, minimum, and averaged temperature over maize by more than 0.5 °C for the first six days after irrigation, but its temperature effect over soybean is mixed and negligible two or three days after irrigation. Irrigation increases near-surface humidity over maize by about 1 $\mathrm{g\,kg^{-1}}$ up totendaysandincreasessurfacehumidityoversoybean (~0.8 $\mathrm{g\,kg^{-1}}$) with a similar memory. These differing temperature effects of irrigation are associated with a significant reduction in the surface-sensible heat flux for maize, though the effect over soybean is negligible. Both maize and soybean have increased latent heat fluxesafterirrigationevents.Thereasonswhyirrigation exhibits a more pronounced cooling effect for maize are still unknown. Moreover, the irrigation effects on the local hydroclimate are expected to be dependent on the local climate regime. A future investigation that scales up the current local study to large scales would be important for enhancing the understanding of these processes.

It is particularly noteworthy that not only does the irrigation cooling effect have a clear dependence on crop species, so does the increase in crop yields. For nearlythesameamountofirrigationwater,theincrease in maize yield is remarkably higher (~59%) than that for soybean (~13%). This occurs despite most soybean irrigation being applied during its flowering reproductive stage when the irrigation is assumed to be more effective for increasing yield. This significant variation is important to consider in agricultural management, given the ever-increasing groundwater depletion and cost of water and energy associated with irrigation.

The above findings pose great challenges for ESMs. While many modeling studies suggested that the irrigation cooling effect may be comparable tothe impacts of greenhouse warming and contribute to mitigating high temperature biases in models (e.g. Kueppers *et al* 2007, Lobell *et al* 2009, Sacks *et al* 2009, Puma and Cook 2010), these models might have exaggerated its cooling effects. This study suggests that the irrigation cooling varies with crop species, and the memory of irrigationeffectsisdifferentamongsurfacemeteorological components. Inaddition, theirrigation application rate in the best agricultural practices is not only determined by soil-moisture deficit (a common modeling approach in current ESMs), but also by crop-growth stages. Therefore, the current modeling approach for simulating a 'generic' crop and using simple irrigation triggers and schedules in ESMs will need to be refined to enhance their fidelity. Recent incorporation of crop-specific growth models (e.g. Levis *et al* 2012, Liu*etal*2016),ofhumanwater-managementmodeling (e.g.Voisin*etal*2017),andofirrigationmethods(Leng *et al* 2017) in ESMs will accelerate the inclusion of more realistic irrigation-crop-water resource models and improve the representation of their interactions with weather and climate.

Furthermore, it is even more challenging to connect agricultural management (e.g. irrigation timing and amount) with other components of the water cycle at regional and continental scales. For instance, ESMs need to take into account the important role of irrigation water use in depleting groundwater storage (Famiglietti *et al* 2011), and the complex relationships between irrigation, latent heat flux and subsurface water budgets that depend on whether the irrigation water is withdrawn from surface or from groundwater (Leng *et al* 2014). Thus, modeling the connection of irrigation to other human-managed water systems such as rivers, reservoirs, lakes, and groundwater will be the next logical and critical challenge for ESMs to capture the effects of irrigation on the water cycle more robustly.

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