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Human-induced modifications to land surface fluxes and their implications on water management under past and future climate change conditions

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ABSTRACT

We used a coupled land-atmospheric simulation framework to quantify the feedback impacts of water resources in a changing climate. The simulations dynamically downscaled data from the North American Regional Reanalysis (NARR) data, Climate Forecast System (CFS) Version 2 and the North American Regional Climate Change Assessment Program (NARCCAP), to investigate irrigation effects on temperatures and surface fluxes under current and future scenarios in Southern Idaho. This study implements irrigation schemes within the Noah Land Surface Model (LSM) coupled with the Weather Research and Forecast (WRF) 3.4 at a 4-km resolution to diagnose irrigation-induced changes to surface energy fluxes and boundary layer properties. Our results suggest that induced cooling via evaporation causes a decrease of 0.8 °C to the air temperature over April – October, a decrease of up to 90 m of the planetary boundary layer depth and an increase of 2.0 °C in the dew point over the irrigated areas. On average, the growing season start date trends 0.46 days/year earlier and the growing season termination date trends 0.60 days/year later. A decrease in precipitation with time is also seen at all elevation ranges from the year 2040–2070, with the lowest elevation levels seeing a bigger decrease than the higher levels. Thus, irrigation-induced increases in growing degree days and modifications to surface fluxes are shown in the basin and it is critical to consider when planning both crop and water management.

1. Introduction

The Snake River, which is the largest tributary of the Columbia River and the ninth largest river in the United States, drains a semi-arid region that covers approximately 281,000 km^2. Agriculture in this basin, without irrigation, is not sustainable due to the dry hot summers. Irrigation diversion canals are the lifeblood of agriculture in Idaho. Water from the Snake River is used to irrigate over 14,100 km^2 of cropland. Milner Dam diverts the entire river in the summer to 1600 km of canals near Twin Falls, Idaho (Slaughter, 2004). Climate change impacts on hydrology and water resources in many basins in the Northwest region are causing some concern in terms of future water availability, agricultural practices, and water management (Jin and Sridhar, 2012; Sridhar et al., 2013). However, coupled feedback analysis under climate change conditions in this managed water system has not been studied previously (Sridhar, 2013). The motivation for this study stems from the need for understanding the impact of land surface feedbacks on evapotranspiration and consumptive water use estimates in order to effectively allocate limited water resources available for irrigation. The hypothesis of this study is that irrigation mitigates warming on a local scale by evaporative cooling under future climate scenarios. There is no study that integrates irrigation effects on boundary layer fluxes for this basin. However, many investigations suggested that the regional climate and land surface fluxes needed to be assessed for current as well as future climate conditions.

Numerous irrigation-related land-atmosphere studies conducted in the Great Plains of the United States have identified importance of irrigation in modifying the boundary layer properties (Adegoke et al., 2003; Barnston and Schickedanz, 1984; DeAngelis et al., 2010; Harding and Snyder, 2012a,b; Lobell et al., 2008; Mahmood and Hubbard 2004; Mahmood et al., 2006; Mahmood et al., 2008; Moore and Rojstaczer 2001, 2002; Ozdogan et al., 2010). Adegoke et al. (2003) used the Regional Atmospheric Mod-

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eling System (RAMS) to perform four 15-day simulations using different vegetation datasets in the U.S. High Plains. Simulations of irrigation schemes watered the top soil daily at 0000 UTC to saturation down on average to a depth of 0.2 m. A 36% increase in surface latent heat flux, a 2.6 °C increase in dew point temperature, a 15% decrease of surface sensible heat flux, and a 1.2 °C decrease in air temperature was observed between the irrigated and a dry (non-irrigated) simulation. Furthermore, Adegoke et al. reported a decrease in observed long-term (1921–2000) monthly mean and monthly mean maximum temperature at the irrigated site (York, NE), while the non-irrigated site (Halsey, NE) reported an increase in mean monthly and mean maximum temperature during the same time period. DeAngelis et al. (2010) concluded that irrigation could have increased the precipitation up to 15–30% downwind of the Ogallala Aquifer from eastern Kansas to Indiana. DeAngelis et al. (2010) and Harding and Snyder (2012a,b) employed a dynamic recycling model (DRM) developed by Dominguez et al. (2008), and Dominguez and Kumar (2008). The DRM uses a Lagrangian method to track the atmospheric vapor transport and calculates the amount of ET-based precipitation in the Ogallala Aquifer region based on North American Regional Reanalysis (NARR) data. In their DRM study, DeAngelis et al. (2010) found that ET contributes to a 0.3–0.5 mm/day or 2–6% increase in downwind July precipitation. Harding and Snyder (2012a,b) reported precipitation attributed to irrigation was found to be responsible for precipitation increases on average of 1% over the Great Plains and 1.6% over north central Nebraska. Furthermore, they reported a significant amount of moisture was advected out of their study region before falling as precipitation which resulted in a net loss in water balance. They raised the concern that this phenomenon would create a positive feedback mechanism in the Great Plains that would further reduce the total soil moisture and ground water aquifer supply, which have agricultural implications due to future water shortages within the Ogallala Aquifer. Ozdogan et al. (2010) combined a MODIS irrigated area map, a 1-km land cover use global map, and incorporated 19 crop types at 1-km resolution within the Land Information System (LIS) which used the Noah-LSM across the continental United States to investigate irrigation. They assigned maximum root depth values and represented seasonal variability in greenness fraction and reported a 4% increase in ET across the continental United States during 2003, which is substantial on a nationwide scale.

Coleman et al. (2010) reported that irrigation improved the simulation of daytime surface temperature by decreasing the warm bias via evaporative cooling but enhanced the nighttime temperature cold bias over heavily irrigated areas of Bakersfield in California. Sorooshian et al. (2011) implemented irrigation schemes using a maximum allowable water depletion method in the Penn State University-National Center for Atmospheric Research (NCAR) Mesoscale model (MM5). They reported the temperature surrounding otherwise non-irrigated grids is only slightly impacted by irrigation, showing decreases of less than 0.5 °C. Furthermore, increasing model resolution from 36-km to 4-km improved the simulated temperature and humidity biases by 1 °C and 5%, respectively. Sorooshian et al. (2012) set up three experiments using the MM5 model coupled with the Noah-LSM: one with soil moisture conditions at field capacity, a no-irrigation run, and a realistic run. The realistic run applies water to the soil column when the soil moisture is less than the maximum allowable water depletion; a method practiced closely by irrigators in California. They reported the water depletion scheme used in their study produces accurate amounts of ET in the Central Valley of California when compared to the MODIS ET observations (Sorooshian et al., 2012).

Jaksa and Sridhar (2015) quantified surface energy fluxes in regions with and without irrigation in arid regions of Southern Idaho using coupled (WRF and Noah-LSM) and uncoupled Noah-LSM runs at 4-km grid-scale resolution and identified the need for a similar study under climate change conditions. The WRF-ARW 3.4 was used to dynamically downscale reanalysis data from three datasets: The Climate Forecast System Reanalysis (CFSR; Saha et al., 2010), The Climate Forecast System Reanalysis Version 2 (Saha et al., 2011), and the North American Regional Reanalysis (NARR; Mesinger et al., 2006). It important to note that reanalysis datasets such as the CFSR and NARR implicitly include irrigation as a result of the assimilation of meteorological observations (Wei et al., 2013). Irrigation code based on (Sridhar, 2013) was added to the NOAH-LSM code and was adapted for use within the NOAH-MP model. Thus, the objective of this study is to examine the surface energy balance components impacted by irrigation, validate with observational flux data, and to investigate the differences within the PBL depth, clouds, precipitation, and water balance using the data from North American Regional Climate Change Assessment Program (NARCCAP), NARR and CFSR products, with and without irrigation, for past, present, and projected future climates.

The paper is organized as follows. Section 2 briefly describes the study area, meteorological forcing data for the model, observational datasets, experimental model design, irrigation representation and constraints. Section 3 describes the results of the simulations. Section 4 describes the conclusions and limitations of the study.

2. Methods

2.1. Study area

The focus of our study area encompasses the concave-shaped Snake River Plain located in southern Idaho, where a majority of irrigation takes place. The domain of the WRF model (Skamarock et al., 2008) used in this study encompasses the Snake River Basin in Southern Idaho. This area extends from 112.5°W to 118.0°W longitude and from 41.8°N to 44.5°N latitude and more than 90% of cropland area of this region is irrigated (Sridhar, 2013). This study used the 20-category MODIS land use dataset, at 30-arcsecond resolution to define vegetation and soil texture. Precipitation in the basin can vary widely and most of it is received in the winter as snow. Topography dictates the pattern and magnitude of rainfall with high mountains receiving over 1600 mm a year and the Snake River plains receiving 200 mm (Fig. 1a). There is a strong correlation between spring soil moisture and summer temperatures in southern Idaho; warmer than usual summer temperatures correlate with below normal spring soil moisture values (Alfaro et al., 2005). The basin is expected to be impacted by climate change through changing snow to rain ratios, temperature-induced early snowmelt and increased water demand (Hoekema and Sridhar, 2011; Hoekema and Sridhar, 2013).

2.2. Meteorological forcing data

2.2.1. Climate forecast system version 2 forecast data

The operational NCEP Climate Forecast System Version 2 (CFSv2; Saha et al., 2010) was implemented in March 2011 to replace the Climate Forecast System Version 1 (CFSv1). CFSv2 plays a substantial role in operational forecasts for 6–10 days up to 2 weeks. CFSv2 provides forecasts of 3–6 weeks of forecasts for use in operations at the Climate Prediction Center (CPC; Saha et al., 2011). Saha et al. (2011) report that CFSv2 is superior to the CFSv1 on the intraseasonal time scales from the improved resolution, data assimilation, and physics in the model. CFSv2 data are used to initialize the past climate runs. For the 3D model boundary conditions, specific humidity, zonal wind component, meridional wind component, vertical wind component, geopotential height, and temperature were downloaded at 25 pressure levels ranging between 1000 and 100 hPa. For the 2D model boundary conditions, surface data were