Regional Impacts of Irrigation in Mexico and the Southwestern United States on Hydrometeorological Fields in the North American Monsoon Region

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(Manuscript received 10 November 2015, in final form 20 July 2016)

ABSTRACT

In this study, the impacts of Mexican and southwestern U.S. agricultural and urban irrigation on North American monsoon (NAM) rainfall and other hydrometeorological fields are investigated using the Weather Research and Forecasting (WRF) Model by implementing an irrigation scheme into the WRF–land surface model. Taking the 2000–12 monsoon seasons as examples, multiple WRF simulations with irrigation are conducted by designing different crops' maximum allowable water depletions (SW_m). In comparison with gridded rainfall observations in urban and rural area, the WRF simulations with/without irrigation generally capture the observations very well, but with underestimation along the western slope of the Sierra Madre Occidental (SMO) and overestimation over southern Mexico. The simulations of WRF with irrigation are slightly improved over those without irrigation, compared with rainfall and sounding observations. Sensitivity studies reveal that the impact of irrigation on rainfall varies with location and NAM rainfall variability. Irrigation increases rainfall in eastern Arizona–western New Mexico and in northwestern Mexico because of the irrigation-induced increases of convective available potential energy (CAPE) and precipitable water. Overall, irrigation decreases rainfall in western Arizona, along the western slope of the SMO, and in central Mexico because of irrigation-induced increases of convective inhibition (CIN), decreases of CAPE, and/or large-scale water vapor divergence.

1. Introduction

The North American monsoon (NAM) is characterized as the seasonal shift in the regional-scale atmospheric circulation system that leads to a pronounced increase in rainfall during summer over northwestern Mexico and the southwestern United States (SWUS;

Douglas et al. 1993; Adams and Comrie 1997). The monsoon typically starts in early June over southern Mexico, migrates northward along the Sierra Madre Occidental (SMO) to the SWUS (mainly Arizona–New Mexico) by early July, and lasts until mid-September (Adams and Comrie 1997). Monsoon rainfall accounts for a major portion of the region's annual rainfall, contributing as much as 30%–50% to annual precipitation in the SWUS (McKendry and Gutzler 2014) and 50%–80% in Mexico (Mitchell et al. 2002; Adams and Comrie 1997). NAM precipitation exhibits large intraseasonal and interannual variability, considerably larger than the mean values (Higgins et al. 1999). Furthermore, NAM rainfall is extremely variable in time and space and is characterized by short, intense events paired with extreme thunderstorms. Monsoon thunderstorms are routinely responsible for locally severe weather including flooding, hail, wind, lightning, and dust storms (Adams and Comrie 1997). In the last five decades, this

Denotes Open Access content.

Supplemental information related to this paper is available at the Journals Online website: <http://dx.doi.org/10.1175/JHM-D-15-0223.s1>.

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DOI: 10.1175/JHM-D-15-0223.1

region has experienced a marked increase in population coupled with gradually increasing temperatures and decreasing precipitation—trends that are projected to continue into the future (Garfin et al. 2013). A better understanding and more accurate prediction of NAM variability is therefore critical for hazard mitigation and for the more efficient management of water resources, urban, agriculture, and ecosystems.

The research history, synoptic background, and temporal and spatial scope of the NAM have been extensively reviewed (e.g., Adams and Comrie 1997; Douglas et al. 1993; Higgins et al. 1997; Higgins and Gochis 2007; McKendry and Gutzler 2014). In the modeling and observational studies related to the NAM, large-scale dynamics (such as sea surface forcings and their associated atmospheric teleconnections), land processes (such as vegetation, snow cover, soil moisture), and aerosol loading (such as wildfires and dust storms) have been identified as modulators of the timing and intensity of the NAM [see review of McKendry and Gutzler (2014), and references therein].

Modeling studies on the impacts of soil moisture on the NAM were essentially based on sensitivity experiments. For example, Small (2001) investigated the effect of soil moisture on NAM rainfall by fixing soil moisture to field capacity in one of his modeling experiments: he found that increasing soil moisture increases monsoon rainfall. In Small's study, he focused on a single year and fixed sea surface temperatures (SSTs). Xu et al. (2004) investigated the feedback of soil moisture on NAM rainfall by prescribing climatological precipitation to specific levels (i.e., low and high in amounts) and confirmed the positive feedback between soil moisture and monsoon rainfall in the monsoon core region. Vivoni et al. (2009) investigated the effects of initial soil moisture on rainfall and hydrologic response during the NAM using the Weather Research and Forecasting (WRF) Model and suggested the importance of initial conditions in predicting hydrologic variables.

Recently, Feng et al. (2013) asserted that the actual impact of soil moisture on NAM variability may not be well understood. In their sensitivity studies they have examined the impacts of soil moisture on NAM rainfall in summer of 2004 by prescribing soil moisture using the daily data from the Global Land Data Assimilation System (GLDAS; Rodell et al. 2004). Feng et al. (2013) find that the feedback of soil moisture on rainfall could be both positive and negative in the NAM region. Soil moisture in Feng et al.'s experiments is more realistic than in other studies; nevertheless, agricultural irrigation-induced soil moisture has yet to be considered in either GLDAS or in the Community Land Model, version 2 (CLM2; the land surface model used by Feng et al.). The irrigated lands in

the NAM region comprise 15.0 million acres in Mexico (Johnson 1997), 1.0 million acres in Arizona (<http://water.usgs.gov/edu/wuir.html>), and over 0.5 million acres in California's Imperial Valley (<http://www.iid.com/>). Soil moisture in irrigated lands will be highly underestimated unless the effects of the irrigation itself are accounted for.

It is well recognized that large-scale irrigation generates local tropospheric circulations and that it affects local/regional weather and climate, including precipitation. Several studies have been focused on the spatial and temporal variation of precipitation, especially in the United States (e.g., Lo and Famiglietti 2013; Alter et al. 2015a; DeAngelis et al. 2010; Harding and Snyder 2012; Huber et al. 2014; Qian et al. 2013; Harding et al. 2015), and more publications can be found in the review literature (e.g., Mahmood et al. 2014; Pielke et al. 2007). Agricultural irrigation has been found to impact the Asian monsoon (e.g., Douglas et al. 2006; Saeed et al. 2009) and the Africa monsoon (e.g., Im et al. 2014; Im and Eltahir 2014; Alter et al. 2015b). No consensus has emerged on whether irrigation in the Central Valley of California impacts NAM rainfall [e.g., Lo and Famiglietti (2013) vs Sorooshian et al. (2014)]. Lo and Famiglietti (2013), based on NCAR GCM, found that irrigation in the Central Valley of California increases streamflow in the Colorado River by 30% and increases monsoon precipitation over the SWUS by 15%, while part of the water is recycled back to California by canal from the Colorado River. On the other hand, Sorooshian et al. (2014), based on the Fifth-generation Pennsylvania State University–NCAR Mesoscale Model (MM5) for 27-yr simulations forced by reanalysis data, suggest that the effects of irrigation in the Central Valley on the SWUS rainfall can be ignored. In this study we investigate whether irrigation in the NAM region (SWUS and Mexico) affects its rainfall and other hydrological processes in the urban and rural areas, a topic that thus far has received little attention.

2. Methodology

a. WRF setup

Because it has been successfully used in this region (e.g., Vivoni et al. 2009), we chose the WRF Model (version 3.7; Skamarock et al. 2008) for this study's simulations. The WRF setup, used in all domains, consists of the following modules: the WSM6 graupel microphysics scheme (Hong and Lim 2006), the Rapid Radiative Transfer Model for GCMs (RRTMG) radiation scheme (Mlawer et al. 1997; Iacono et al. 2008), the Noah land surface model (Chen and Dudhia 2001), the revised Monin–Obukhov surface layer treatment (Jiménez

FIG. 1. Terrain elevations (km) of model domain 2. Blue masked areas indicate grids with irrigation area fractions greater than 10%. Gray masked areas represent urban areas. Black dots represent NERN. Red stars represent NAME sounding locations: Puerto Penasco (NPP; 31.344°N, 113.509°W), Kino Bay (BKN; 28.814°N, 111.927°W), and Los Mochis (IS4; 25.689°N, 109.082°W). AZNM, NWMX, and CNMX represent eastern Arizona and western New Mexico, northwestern Mexico, and central Mexico, respectively.

et al. 2012), the Yonsei University boundary layer scheme (Hong et al. 2006), and the Grell–Devenyi ensemble cumulus scheme (Grell and Devenyi 2002). The last module allows for subsidence and spreading at high resolution.

Two nested domains are used. The first (domain 1) has 30-km grid spacing and covers the western and central United States, Mexico, the western Gulf of Mexico, the Gulf of California, and the tropical and eastern Pacific. Nested domain 2 uses grid spacings of 10 km (Fig. 1). Domain 2 covers the monsoon area (Arizona and New Mexico, Mexico, the eastern Pacific, the Gulf of California, and west of the Gulf of Mexico) and Texas. This domain (10-km grid spacing) consists of 210×228 grid cells. The vertical configuration of the model comprises 41 full layers: the lowest 15 layers are within 1500 m AGL and the first half-vertical layer above ground surface is at 14.5 m AGL.

b. Data for model initialization and evaluation

Final analysis (FNL; NCEP 2000) data provide the initial and boundary conditions for both atmospheric and land variables (e.g., temperature and soil moisture). FNL data are distributed on a 0.5° grid with a 6-h temporal frequency. Land-cover and land-use data come from the U.S. Geological Survey's 1-km resolution dataset, in which irrigated lands are separated from other crop lands.

The North American Monsoon Experiment (NAME) data (http://data.eol.ucar.edu/master_list/?project=NAME) are used to evaluate model performance. Specifically, precipitation from the NAME Event Rain Gauge Network (NERN) [Gochis 2007; Gochis et al. (2003, 2007) and locations labeled in Fig. 1 as dots] are used to evaluate modeled precipitation performance. Soundings from NCAR's Integrated Sounding System (ISS; UCAR/NCAR 2008) are used to validate the model performance throughout the vertical layers.

Two gridded precipitation datasets are used to assess the WRF Model's performance in its spatial distribution of rainfall. One is extracted from the North American Regional Reanalysis (NARR; Mesinger et al. 2006) 3-hourly data. NARR has been found to provide reasonable estimates of land surface states and fluxes as well as atmospheric conditions (e.g., Nigam and Ruiz-Barradas 2006; Luo et al. 2007). Since the gridded gauge data from the Climate Prediction Center (CPC) are assimilated into NARR (Mesinger et al. 2006), NARR 3-h data should be representative of CPC gauge data (Xia et al. 2012). However, this dataset may have negative biases over mountains where its network is sparse (Nesbitt et al. 2004). The other one is satellite retrieval, named Precipitation Estimation from Remotely Sensed Information Using Artificial Neural Networks [PERSIANN; hereafter called PERSIANN–Climate Data Record (PCDR); Sorooshian et al. 2000].

c. Irrigation scheme

In the NAM region, there are two main irrigated areas: one is the southern lower Colorado River basin (SLCR; including the Imperial Valley from California into Baja California, Mexico; the lower Colorado River Valley; and the lower Gila River Valley in Arizona). The second is the irrigated area on the western slope of the SMO (WSMO), from Nayarit and Sinaloa to southern Sonora, Mexico. In addition, there are irrigated lands in the southern Mexican Plateau and Texas. Defined as grids whose irrigated land fraction exceeds 10%, the main irrigation areas are masked in blue in Fig. 1. Urban land covers are shown as gray.

Three methods to incorporate irrigation have been employed in global/regional climate models:

1) prescribing soil moisture using actual data (Segal et al. 1998; Lo and Famiglietti 2013)—this method reasonably conserves the total water amounts being applied but does not account for the effects of weather and climate on irrigation (Kueppers et al. 2007);

2) fixing soil moisture to field capacity or saturation (e.g., Adegoke et al. 2003; Kueppers et al. 2007)—this method may result in wet and cool biases in some regions (e.g., Kanamaru and Kanamitsu 2008); and

3) mimicking realistic irrigation processes (e.g., Kanamaru and Kanamitsu 2008; Sorooshian et al. 2011,

2012, 2014; Im and Eltahir 2014; Harding et al. 2015; Li et al. 2016). Most recently, Lawston et al. (2015) have parameterized actual irrigation methods—flooding (surface irrigation), sprinklers, and drip irrigation—into WRF and conducted a 2-day forecast to investigate the impact of irrigation on WRF initializations in the U.S. Great Plains.

In this study, we employ the third irrigation scheme, which has been implemented into limited area models including WRF by Sorooshian et al. (2014) and Li et al. (2016). Its basic concept is to use the minimum amount of water that ensures the maximum crop yield. In practice, irrigation starts when the following two conditions are satisfied: 1) the root zone's relative available soil water (SW) content is less than the maximum allowable water depletion (SW_m), where the magnitude of SW_m depends on soil type, crop type, and crop growth period (larger values of SW_m mean more irrigation water applied); and 2) when downward solar radiation is less than 50 W m^{-2} for the purpose of model numerical stability during the simulations and for avoiding water loss due to evapotranspiration (ET) at higher solar radiation levels (Sorooshian et al. 2012, 2014). Irrigation ceases when soil moisture reaches field capacity. The method employs the surface irrigation concept, which is the most widely used in Mexican irrigation. In Mexico, surface irrigation covers $58\,000 \text{ km}^2$, sprinkler irrigation covers 3100 km^2 , and localized irrigation covers 1400 km^2 (Johnson 1997): surface irrigation clearly dominates (about 92.8%) in Mexico.

In Mexico, the main crops are corn, sugarcane, sorghum, wheat, tomatoes, bananas, chili peppers, oranges, lemons, limes, and mangos (Johnson 2009). Since different crops are planted in Mexico than in the SWUS (i.e., NAM region), we conduct two sensitivity studies to investigate the impacts of irrigation on precipitation in the NAM region by changing the magnitudes of SW_m . Specifically, we set SW_m to 30% and 90%, respectively, to examine the effects of irrigation on precipitation under different allowable water depletion conditions. In other words, we have conducted three simulations: a control run (i.e., running WRF as a default setup) and two irrigation runs (test run) with different values of SW_m .

3. Results

The monsoon seasons from 2000 to 2012 are selected as case studies. During the analysis, the two irrigation runs for each year with different SW_m values are averaged into a single irrigation simulation. The model runs start on 1 May and end on 1 October each year. The data from May were discarded, and June–September (JJAS) data are analyzed each year.

a. Model evaluations

A realistic model “climatology” is a crucial prerequisite for examining the hydroclimate response to changes in soil moisture due to agricultural irrigation—hence, the importance of evaluating model performance. Figure 2 shows the mean precipitation comparisons within domain 2 among satellite retrieval (PCDR; Fig. 2a), NARR data (Fig. 2b), the WRF control run (CTRL; Fig. 2c), and WRF irrigation runs (TEST; Fig. 2d) for JJAS in all simulation years (2000–12). The model basically captured the observed patterns from the NARR and satellite data, such as rainfall along the mountains of the SMO in western Mexico, the orographic precipitation patterns in Arizona and New Mexico, and rainfall in southern Mexico and the western coast of the Gulf of Mexico. For the domain average, the 13-yr mean precipitation is $2.531 \text{ mm day}^{-1}$ (with grid-point standard deviation $1.759 \text{ mm day}^{-1}$) for NARR, $3.133 \text{ (}2.345\text{) mm day}^{-1}$ for PCDR, $2.718 \text{ (}4.057\text{) mm day}^{-1}$ for CTRL, and $2.729 \text{ (}3.839\text{) mm day}^{-1}$ for TEST. The correlation coefficients R are 0.359 between PCDR and CTRL, 0.387 between PCDR and TEST, 0.305 between NARR and CTRL, and 0.343 between NARR and TEST. The standard deviation from WRF is relatively high compared with NARR and PCDR while the average precipitation amounts from WRF are between NARR and PCDR, indicating the reliability of model simulations. Compared with NARR and PCDR in standard deviation and R , TEST performed slightly better than CTRL did.

However, the model overestimated rainfall in southern Mexico and northern New Mexico, when compared with either NARR or satellite data, while it underestimated rainfall along the western slope of the SMO and along the southern Texas coast. Along the mountains of the SMO, the magnitude of precipitation differs among the different data sources. Discrepancies among the different observations of precipitation reflect the uncertainty of precipitation measurements, partly due to the scarcity of gauge observations over high elevations (Nesbitt et al. 2004), which is undoubtedly a major obstacle to validate model performance. In comparing CTRL and TEST, the results have similar patterns, including the locations of overestimations and underestimations, and therefore contained no systematic bias, as discussed by Harding and Snyder (2012).

Figure 3 shows the mean daily precipitation comparison at the NERN sites from 2002 to 2004. In comparison with NERN data, WRF reproduced reasonable precipitation over mountains and high elevations (Fig. 3a), but highly underestimated it over the western slope of the SMO (Fig. 3b). In comparison with the CTRL run,

FIG. 2. Precipitation distributions averaged for monsoon seasons (JJAS) during 2000–12 from (a) PCDR, (b) NARR, (c) CTRL, and (d) TEST. The domain averages from all grids are given.

the irrigation test runs produced slightly better precipitation over mountains in 2002 and 2004. Note that there are differences in amounts for NERN gauge, NARR, and PCDR, indicating the complicated precipitation features in this region. In Fig. 3, the standard deviation is represented by the whisker, which indicates the large precipitation variability in this region, consistent with previous data analyses (e.g., Higgins et al. 1999).

In addition, we evaluated model performance using sounding data from mid-July to mid-August during the 2004 NAME. Figure 4 shows the vertical distributions of model mean biases in temperature and relative humidity at three ISS sounding sites (shown in Fig. 1 as red stars). In general, the mean biases are within 2°C for temperature and within 20% for relative humidity, indicating the model's adequate reliability. In comparing the model control runs with the irrigation test runs, the latter generally mitigate the dry biases.

These performance metrics indicate that, in comparison with station observations, the model with irrigation improves the simulations of mean precipitation over the

irrigated regions as well as the region of domain 2. The model can also remove the vertical dry biases shown in the WRF control run.

b. Changes in response to irrigation

In this section, we discuss the irrigation-induced changes of hydrometeorological fields in Mexico and SWUS. The changes in Texas due to irrigation were discussed in previous studies (e.g., Qian et al. 2013) and are not included here.

1) IRRIGATION-INDUCED HYDROMETEOROLOGICAL DIFFERENCES IN ALL SIMULATION YEARS

Eltahir (1998) suggests that high soil moisture tends to lower surface albedo and the Bowen ratio, which together increase net radiation. This increase of total available energy promotes a larger moist static energy (MSE) and increased convective potential. Eltahir's soil moisture–precipitation positive feedback mechanism (i.e., higher soil moisture leads to higher precipitation) is

FIG. 3. Total precipitation comparisons between gauge (NERN) and grid data closest to NERN sites (see Fig. 1) from NARR, PCDR, CTRL, and TEST in western Mexico during NAME periods. (a) Comparison over the sites along the SMO where terrain elevations are greater than 500 m, and (b) where terrain elevations are less than 500 m. Bar represents mean and whiskers represent the std dev.

confirmed in the NAM region by a few studies (e.g., Small 2001; Vivoni et al. 2009; Dominguez et al. 2008; Adams and Souza 2009; Feng et al. 2013). However, Feng et al. (2013) found that there is a negative feedback in the western slope of the SMO, as suggested by Ek and Holstag (2004) and Seneviratne et al. (2010). Figure 5 shows the changes of some selected hydrometeorological variables due to irrigation for all simulation years. The insignificant differences (less than 60% significance for the Student's *t* test) are masked in Fig. 5. The data in Fig. 5 are monthly data, which are averaged from hourly data. In the irrigation areas, irrigation increases soil moisture by $0.2 \text{ m}^3 \text{ m}^{-3}$ or 63.3% (Fig. 5a), ET or latent heat fluxes (LHF) by $30\text{--}80 \text{ W m}^{-2}$ (Fig. 5b), 2-m mixing ratios by $1\text{--}2 \text{ g kg}^{-1}$ (Fig. 5c), and vertical water vapor fluxes by $2\text{--}5 \text{ mm day}^{-1}$ (Fig. 5d). The increase of LHF reduces sensible heat fluxes (SHFs) and Bowen ratios (not shown), decreases surface temperature by $0.5\text{--}2 \text{ K}$ (Fig. 5e), and lowers PBL height by $100\text{--}200 \text{ m}$ (Fig. 5f). The results shown in Fig. 5 are consistent with previous

studies in other regions (e.g., Harding and Snyder 2012; Sorooshian et al. 2011).

Figure 6 displays the changes of other hydrometeorological variables due to irrigation. In the irrigated areas, irrigation increases MSE by $800\text{--}1500 \text{ J kg}^{-1}$ (Fig. 6a), precipitable water by $0.5\text{--}2 \text{ g kg}^{-1}$ in the western slope of the SMO (Fig. 6b), convective available potential energy (CAPE) by $30\text{--}100 \text{ J kg}^{-1}$ (Fig. 6c), and convective inhibition (CIN) by $5\text{--}65 \text{ J kg}^{-1}$ (Fig. 6d). However, as shown in Fig. 6e, irrigation decreases precipitation in the irrigation areas, such as in the Texas Panhandle, the western slope of the SMO, and the SLCR. Precipitation changes in these areas show negative signals with magnitudes from -0.01 to -0.2 mm day^{-1} . One of the reasons is that irrigation decreases surface temperatures (note that one irrigation run has SW_m set to 90%) and restrains convective development (Fig. 6f), in which CIN increases although CAPE increases.

There are nonirrigation areas in which precipitation increases are shown in Figs. 6e and 6f: southeastern

FIG. 4. Mean biases of (top) relative humidity and (bottom) air temperature between model simulations and observations (simulation minus observation) at different sounding sites (labeled in Fig. 1) during the 2004 NAME study (from 7 Jul to 15 Aug 2004): (a),(d) BKN; (b),(e) IS4; and (c),(f) NPP.

Arizona and southwestern New Mexico (AZNM) and the borders of southeastern Arizona, southwestern New Mexico, and northwestern Mexico. In these areas MSE increases by $300\text{--}600\text{ J kg}^{-1}$ (Fig. 6a), precipitable water increases by $0.2\text{--}1.0\text{ mm}$ (Fig. 6b), and CAPE increases by $15\text{--}45\text{ J kg}^{-1}$ (Fig. 6c), while CIN does not change at all (Fig. 6d). The precipitation increases (shown in Fig. 6e) arise from the enhancement of convective potentials and precipitable water. Harding and Snyder (2012) reported that increases of both CAPE and precipitable water favor precipitation generation in the Great Plains. Precipitation changes in Fig. 6e are consistent with their results. This explanation can be further enforced by comparing the total precipitation (Fig. 6e) with convective rainfall (Fig. 6f) in this area, where the precipitation changes are mainly from convective rainfall changes. Because of precipitation increasing, there is more available water to evaporate, as shown in Fig. 5b for increasing LHF, and Fig. 5c for increasing 2-m mixing ratios in this area.

In central Mexico (location shown in Fig. 1), the CAPE also increases in some areas (Fig. 6c) due to irrigation, but precipitation decreases (Figs. 6e,f). To explain the precipitation changes, the water vapor fluxes and large-scale water vapor flux horizontal divergences/convergences are examined. Figure 7a shows the water vapor fluxes in all years. The vectors in Fig. 7a are the horizontal water vapor fluxes (integrated from surface to model top). The model represents the “climatologic” pattern of horizontal water vapor fluxes well: a water vapor flux pattern forms along the northern Gulf of California and intrudes into southern Arizona. The other water flux pattern originates in the Gulf of Mexico, moves into south-central Texas, passes into western Texas, and finally turns northeastward into the Great Plains. In central Mexico, water vapor fluxes, also originating from the Gulf of Mexico, are transported westward toward the SMO, merge with the fluxes already there, and are transported north along the Gulf of California or transported to the Pacific—all patterns consistent with reported studies (e.g., Mo et al. 2005).

FIG. 5. Hydrometeorological changes induced by irrigation in all simulation years: (a) soil moisture ($\text{m}^3 \text{m}^{-3}$), (b) LHF (W m^{-2}), (c) 2-m mixing ratios (g kg^{-1}), (d) water vapor vertical fluxes (mm day^{-1}), (e) surface air temperature (K), and (f) PBL height (m). Data that are insignificant per the Student's t test under the 60% confidence level are masked. Data in the irrigated lands are significant at the 90% confidence level. Data in the approximate areas circled with purple dashes are significant at the 80% confidence level. Data in the approximate areas circled with yellow dashes are significant at the 90% confidence level.

FIG. 6. As in Fig. 5, but for (a) MSE ($\times 100 \text{ J kg}^{-1}$), (b) precipitable water (mm), (c) CAPE (J kg^{-1}), (d) CIN (J kg^{-1}), (e) total precipitation changes (mm day^{-1}), and (f) convective precipitation changes (mm day^{-1}).

Figure 7b shows the differences of horizontal water vapor fluxes (vectors) and water vapor flux horizontal increasing convergence/divergence (color filled), estimated by the method of Saeed et al. (2009). Positive values in Fig. 7b indicate increasing divergence; negative values represent increasing convergence. Figure 7b

indicates that enhanced convergence occurs in eastern Texas and enhanced divergence occurs in western Texas, central Mexico, and the western slope of the SMO. These water vapor convergence/divergence changes can partly explain the precipitation changes that occur in the regions shown in Fig. 6e but absent from

FIG. 7. (a) Mean horizontal water vapor fluxes in all simulation years from control runs. (b) Differences of water vapor fluxes in all simulation years (vector) and horizontal water vapor divergence/convergence (mm day^{-1} ; color filled) between irrigation and control runs.

Fig. 6f. Further discussion on rainfall mechanism will be presented in next subsection.

Table 1 summarizes the changes (percent of changes relative to control runs) of all hydrometeorological variables in the 13 monsoon seasons. Following Feng et al. (2013) and Feng and Houser (2015), AZNM is located at 31° – 36°N , 112° – 106°W and the mainland in northwestern Mexico is located at 24° – 31°N , 112° – 106°W (NWMX). Table 1 indicates that irrigation-induced rainfall increases in AZNM by 0.20 mm day^{-1} (16.6%) for total precipitation and 0.15 mm day^{-1} (14.81%) for convective rainfall. Irrigation increases

total rainfall in NWMX by $0.088 \text{ mm day}^{-1}$ (7.2%) and convective rainfall by $0.107 \text{ mm day}^{-1}$ (10.6%). On the other hand, irrigation decreases precipitation in central Mexico (CNMX; defined as 21° – 26°N , mainland of Mexico, longitude 108° – 98°W) by $0.173 \text{ mm day}^{-1}$ (−8.83%) for total rainfall and $0.075 \text{ mm day}^{-1}$ (−5.38%) for convective rainfall. Irrigation reduces rainfall in irrigated grid cells by $0.153 \text{ mm day}^{-1}$ or −8.25% for total rainfall and $0.084 \text{ mm day}^{-1}$ or −7.7% for convective rainfall. At the domain scale, irrigation increases rainfall over land by $0.046 \text{ mm day}^{-1}$ (or 2.11%) for total rainfall and $0.047 \text{ mm day}^{-1}$ (or 3.25%) for convective rainfall (i.e., large-scale rainfall decreases).

Based on Figs. 5 and 6 and Table 1, irrigation increases soil moisture, which increases surface mixing ratios and LHF. Increase of LHF decreases Bowen ratios and SHFs. Decreases of SHF decrease surface air temperatures and PBL heights. At the same time, increased soil moisture increases MSE and CAPE and finally increases the convection potential. In the irrigated areas, because irrigation highly decreases surface temperatures, the CIN increases and therefore restrains convective precipitation. Over nonirrigated areas such as AZNM and NWMX, the increase of both CAPE and precipitable water favors convective rainfall generation as long as the CIN changes little. Therefore, irrigation mainly results in convective rainfall increases.

Note that the above discussion indicates that the rainfall and other variable changes due to irrigation are significant at the 60% confidence level for the Student's t test. We also examined hydrometeorological field changes, due to irrigation, with 80% and 90% confidence levels, respectively. The model results can pass the tests at 90% significance level in the irrigated lands. The approximate areas that data can pass the tests at 80% or 90% significance level are circled in Figs. 5 and 6.

2) IRRIGATION-INDUCED RAINFALL CHANGES IN DIFFERENT YEARS

Based on NARR long-term (1979–2014) monthly precipitation data, we have generated precipitation time series in the regions of AZNM and NWMX (see Fig. S1 in the supplemental material) to obtain dry, normal, and wet years. The changes of hydroclimate fields in response to irrigation during dry, normal, and wet years are examined separately (details can be found in the supplemental material).

Figure S2 in the supplemental material shows the changes of total precipitation (top), CAPE (middle), and integrated water vapor fluxes and water vapor divergence/convergence (bottom) in dry (left), normal (center), and wet (right) years. In all cases irrigation increases rainfall near the border of Mexico and Arizona,

TABLE 1. The areal changes of meteorological variables due to irrigation for all simulated years. “Irrigated” represents the irrigated grids where the irrigation fraction is greater than 10%, AZNM is the monsoon core region in Arizona and New Mexico (location shown in Fig. 1), NWMX is the monsoon core region in northwestern Mexico, and CNMX is central Mexico (location shown in Fig. 1). “Domain 2/land” represents all the land grid cells in domain 2. Divergence is water vapor horizontal divergence (positive)/convergence (negative).

	Irrigated	AZNM	NWMX	CNMX	Domain 2/land
PBL height (m)	−79.5 (−11.25%)	−23.7 (−2.3%)	−24.67 (−3.39%)	−13.3 (−2.21%)	−22.6 (−2.77%)
Soil moisture content ($\text{m}^3 \text{m}^{-3}$)	0.104 (63.31%)	0.007 (4.01%)	0.023 (15.0%)	0.006 (0.8%)	0.009 (4.55%)
LHF (W m^{-2})	31.99 (76.18%)	2.74 (8.57%)	8.13 (23.49%)	2.34 (5.17%)	3.55 (8.64%)
SHF (W m^{-2})	−23.85 (24.71%)	−2.90 (−3.41%)	−10.0 (−9.25%)	−2.17 (−2.21%)	−3.47 (−3.91%)
2-m mixing ratios (g kg^{-1})	0.74 (7.11%)	0.23 (3.52%)	0.41 (5.44%)	0.31 (2.66%)	0.28 (2.77%)
2-m air temperature ($^{\circ}\text{C}$)	−0.48 (−0.16%)	−0.30 (−0.10%)	−0.28 (−0.09%)	−0.22 (−0.08%)	−0.28 (−0.09%)
Vertical water vapor fluxes (mm day^{-1})	26.12 (86.93%)	2.30 (9.65%)	8.90 (43.34%)	3.43 (12.73%)	3.66 (13.82%)
Integrated precipitable water (mm)	0.75 (1.88%)	0.64 (2.73%)	0.74 (2.21%)	0.69 (1.63%)	0.65 (2.32%)
Divergence (mm day^{-1})	18.92 (226.10%)	0.75 (69.7%)	8.70 (18.90%)	4.33 (−50.38%)	3.40 (−42.46%)
MSE (J kg^{-1})	739.8 (0.22%)	395.23 (0.13%)	600.96 (0.18%)	264.92 (0.08%)	332.92 (0.10%)
CAPE (J kg^{-1})	52.85 (11.70%)	19.94 (9.10%)	43.90 (13.46%)	26.99 (4.98%)	22.58 (4.75%)
CIN (J kg^{-1})	12.59 (12.29%)	2.89 (5.87%)	8.42 (8.9%)	0.66 (0.52%)	2.31 (3.36%)
Total precipitation (mm day^{-1})	−0.153 (−8.25%)	0.200 (16.60%)	0.088 (7.20%)	−0.173 (−8.83%)	0.046 (2.11%)
Convective precipitation (mm day^{-1})	−0.084 (−7.70%)	0.150 (14.81%)	0.107 (10.6%)	−0.075 (−5.38%)	0.047 (3.25%)

New Mexico, and eastern Texas, although the magnitudes are different for different cases. However, rainfall changes due to irrigation depend on both climate conditions (e.g., rainfall variability) and locations, and no consistent changes are exhibited among dry, normal, and/or wet years. The physical mechanisms, which result in rainfall changes, are mainly due to CAPE changes over AZNM, NWMX, and CNMX (see CAPE changes in Figs. S2d–f in the supplemental material). Enhanced divergence/enhanced convergence over southwestern New Mexico and nearby areas and the Mexico mainland (see Figs. S2g–i in the supplemental material) also contribute to rainfall changes.

The changes of meteorological variables in AZNM and NWMX are shown in Table S1 in the supplemental material for selected dry, normal, and wet years. In most of the listed variables, changes of meteorological variables exhibit only slight differences among dry, normal, and wet years. However, some variables do show noticeable differences. For example, in the region of AZNM (shown in Fig. 1), changes of mixing ratios, precipitable water, and total rainfall show that irrigation-induced changes in dry years are similar to normal years, while irrigation-induced changes in wet years are different from either dry or normal years. On the other hand, in NWMX (location shown in Fig. 1), irrigation-induced changes in normal years are similar to wet years, while irrigation-induced changes in dry years are different from either wet or normal years, as indicated by changes of LHF, vertical water vapor fluxes, and total precipitation.

Figure S2 and Table S1 in the supplemental material indicate 1) that irrigation-induced rainfall changes depends on precipitation variability and location and 2) that it is difficult to conclude that consistent changes among the dry, normal, and/or wet years could be explained by irrigation, as indicated in other regions (e.g., [Harding and Snyder 2012](#); [Harding et al. 2015](#)).

c. Discussion

In its present model configuration, WRF highly underestimates the precipitation along the western slope of the SMO (see Figs. 2, 3) for two reasons. The first is SSTs in the Gulf of California (e.g., [Stensrud et al. 1995](#); [Mitchell et al. 2002](#); [Li et al. 2005](#)). In this study, model SSTs are prescribed and updated using FNL SSTs. We have examined SSTs from FNL and from NARR in the 2004 NAM season and found that SSTs from FNL over the Gulf of California are 1° – 2°C lower than those from NARR data (figure not shown). This could be one reason the model underestimates in the western slope of the SMO and western Arizona.

The second reason concerns model resolution ([Gao et al. 2007](#); [Li et al. 2008](#), [Garfin et al. 2013](#)). [Garfin et al. \(2013\)](#) have suggested that to reasonably simulate the short, intense monsoon storms, no larger than 6-km model resolution is required. [Li et al. \(2008\)](#) have compared model results with different resolutions in the 2004 monsoon and found that they were modestly better with 3-km resolution. For 13 years of simulations, considering the computation cost, we have used resolutions no finer than 10 km, which may contribute

to the underestimation along the western slope of the SMO.

Many other uncertainties about NAM rainfall simulations have been identified. In this study, the WRF was started on 1 May and the output for May was discarded. To reduce the effect of initial soil conditions, Vivoni et al. (2009) and Feng et al. (2013) have used an ensemble concept to investigate the effect of soil moisture forcing on 2004 monsoon precipitation. Previous studies also show that different physical schemes affect model results significantly (Gochis et al. 2002; Bright and Mullen 2002). In other words, using different physical schemes may produce results that differ from this study. Finally, Harding et al. (2015) have investigated the effects of irrigation on precipitation in the U.S. Great Plains based on WRF/CLM and a sprinklers irrigation concept. They found that using a dynamical vegetation model can capture the variation of transpiration and rainfall better than a static vegetation mode (used here). All of these uncertainties call for further investigations.

4. Conclusions

In this study, the impacts of agricultural irrigation in Mexico and the SWUS on NAM rainfall and other hydrometeorological fields are investigated using the WRF Model at 10-km resolution. The model is forced by the FNL data; the months of JJAS from 2000 to 2012 are examined to explore the hypothesis that agricultural and urban irrigation in this region impacts NAM rainfall. The simulations consist of a series of paired CTRL runs (running WRF as usual) with TEST runs (running WRF with irrigation being implemented). The simulations from both CTRL and TEST runs are first compared with gridded precipitation from NARR and satellite retrievals and then compared with observations from the 2002–04 NAME precipitation and sounding data. The simulations reasonably reproduced the precipitation's spatial distribution, as well as the sounding results at the three sites. However, the model exhibits dry biases over the western slope of the SMO and wet biases in southern Mexico compared with gauge and gridded precipitation. The model with irrigation performed slightly better than CTRL runs.

The following results are based on our simulations with the present model configuration:

- 1) Irrigation in Mexico and the SWUS affects hydrometeorological fields of the NAM at the regional scale. For a land-based domain average, our simulations show that irrigation increases 2-m LHF by 3.6 W m^{-2} (or 8.6%), 2-m mixing ratios by 0.28 g kg^{-1} (or 2.8%), and water vapor vertical fluxes by 3.7 mm day^{-1} (or

13.8%). The 2-m air temperatures affected by irrigation decrease by 0.29°C (or -0.1%), and planetary boundary heights decrease by 22.8 m (or -2.9%). Our results also show that irrigation increases the CAPE by 22.6 J kg^{-1} (or 4.76%), precipitable water by 0.65 mm (or 2.32%), and most importantly, precipitation by $0.046 \text{ mm day}^{-1}$ (2.11%) for a domain average, with the convective rainfall increase being dominant ($0.047 \text{ mm day}^{-1}$ or 3.23%).

- 2) The changes of irrigation-induced precipitation and other hydrometeorological fields are highly localized within the NAM region. Over the irrigated grids, irrigation increases ET, surface mixing ratios, and vertical water vapor fluxes but decreases 2-m air temperature by 0.48°C (or -0.16%), LHF, and PBL heights—all results consistent with other irrigated regions. Our results within irrigated grids show that both CAPE and CIN increase while precipitation decreases by $0.153 \text{ mm day}^{-1}$ (or -8.25%). The reason is that irrigation decreases surface temperature and therefore restrains the development of convection as shown by a decrease of convective rainfall of $0.084 \text{ mm day}^{-1}$ (or -7.7%).

In addition to the effects within irrigated areas, irrigation also affects hydrometeorology in non-irrigated areas, such as AZNM, NWMX, and CNMX. In AZNM and NWMX, irrigation increases CAPE by 19.94 (or 9.1%) and 43.9 J kg^{-1} (or 13.46%), respectively, and increases total rainfall by 0.205 and $0.075 \text{ mm day}^{-1}$, respectively. Furthermore, convective rainfall dominates the increases by $0.150 \text{ mm day}^{-1}$ in AZNM and by $0.107 \text{ mm day}^{-1}$ in NWMX. In other words, rainfall increases in these two regions because of the mean wind flow for the enhancement of CAPE in these downwind (of irrigation) areas and therefore increases convection through the positive soil moisture–rainfall feedback mechanism. On the other hand, irrigation decreases precipitation in central Mexico by $0.173 \text{ mm day}^{-1}$ (-8.8%), mainly due to the decrease of CAPE and large-scale water vapor flux horizontal convergence.

- 3) Irrigation decreases rainfall along the western slope of the SMO and in western Arizona by $0.01\text{--}0.1 \text{ mm day}^{-1}$ increased CIN and enhanced divergence.

Acknowledgments. This work has been partially supported by NSF Grant DMS 1419593, USDA NIFA Grant 2015-67003-23508, and NSF Sustainability Research Network (SRN) Cooperative Agreement 1444758. We are grateful to the two reviewers for the comments and suggestions.

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