

Comparing the Impacts of Irrigation Patterns on the Near-surface Climate

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Abstract – Previous studies have shown that irrigation can impact the near-surface climate, but none refer to the differences in the impacts of irrigation types such as flooding and spraying. In this study, we add a novel irrigation module to the recently released community land model 4.0 and simulate irrigation in two ways: first, by spraying water above a canopy similar to precipitation to simulate spray irrigation; second, by directly adding water on the ground to simulate flood irrigation. Differences between coupled irrigation and control runs and differences between two irrigation patterns are analyzed globally and in three heavily irrigated countries: the USA, India, and China. Our results show that spray irrigation has greater impacts than flood irrigation on near-surface climate. Spray and flood irrigation respectively increase evapotranspiration by 4.33 w/m² and 3.36 w/m² and 2 m relative humidity by 0.36% and 0.14%. In addition, spray and flood irrigation respectively decrease sensible heat flux by 2.86 w/m² and 2.43 w/m², ground temperature by 0.13 K and 0.12 K, daily maximum of average 2 m temperature by 0.1 K and 0.04 K, soil temperature in top 10 cm of soil by 0.22 K and 0.12 K, and vegetation temperature by 0.12 K and 0.06 K averaged over irrigated land. Among the above three heavily irrigated countries, impacts of both flood and spray irrigation are greatest in India.

Keywords: Agriculture, Climate, Crop, Spray irrigation, Flood irrigation

1. INTRODUCTION

Some studies have simulated irrigation impact by numerical modeling. For example, de Rosnay et al. (2003) estimated that intensive irrigation increased annual mean latent heat fluxes by 3.2 w/m² over India during 1987–1988 by combining an irrigation scheme with the land surface model ORCHIDEE (Organizing Carbon and Hydrology In Dynamic Ecosystems) and pointed out that irrigation can strongly impact the partitioning of energy between sensible and latent heat fluxes. Boucher et al. (2004), using an atmospheric general circulation model, reported that irrigation caused water vapor to increase by 0.12–0.18% and net radiative forcing to increase by 0.03–0.1 w/m² globally for 1990. Gordon et al. (2005) reported that vapor flows increased around 2600 km³/yr globally during 1961–1990 owing to irrigation and suggested that expanding irrigation in the Indian subcontinent will increase the risk of changes in the behavior of the Asian monsoon. Their model is relatively simple: It calculates evapotranspiration for actual vegetation and potential vegetation, and then multiplies the values by a global irrigation map. Haddeland et al. (2006) evaluated the effects of irrigation on water and energy balances in the Colorado and Mekong river basins by using a variable infiltration capacity (VIC) macroscale hydrological model. Their

result shows that irrigation caused mean annual latent heat flux to increase by 1.2 and 1.3 w/m², respectively, and correspondingly, mean annual temperature decreased by 0.04°C in the study areas during 1979–1999. Douglas (2006) reported a 17% increase in mean annual vapor fluxes owing to change in land cover compared with pre-agriculture, and estimated, using a coupled land surface–atmosphere boundary layer model, that two thirds of the increase was due to irrigation in India. In his model, potential evapotranspiration (PET) and actual evapotranspiration (AET) were assigned as vapor fluxes from irrigated and rainfed cropland, respectively. Lobell et al. (2009) modified a community land model (CLM 3.0) by adding irrigated agriculture to data on land cover type and coupled it with a community atmosphere model (CAM 3.3) to evaluate regional differences in effects of irrigation on near-surface air temperature in eight heavily irrigated areas (California, Nebraska, Mississippi, Spain, Turkey, Aral Sea Basin, Indo-Gangetic Plains, and northeast China). Their result shows that from a global perspective the cooling effect of irrigation varies across regions and that temperature may decrease by as much as 10°C. Ozdogan et al. (2010) simulated the effects of irrigation over the USA by using satellite-derived agricultural data and a land surface model. In their model, irrigation was used when soil moisture falls below 50% of field capacity during the growing season. Irrigation amount was determined by the ratio of irrigated area to total crop coverage in a grid cell and the difference between current root zone soil moisture and the field capacity. They reported that irrigation contributed to a 12% increase in evapotranspiration and a corresponding decrease in sensible heat flux over all irrigated areas of the USA during the 2003 growing season.

Previous studies have shown that irrigation can impact the near-surface climate, but thus far, none refer to the different impacts of irrigation types such as flood irrigation and spray irrigation. In this study, we add a novel irrigation module to the recently released CLM 4.0 model and simulate both flood and spray irrigation. The differences between coupled irrigation and control runs and the differences between two irrigation patterns are analyzed globally and in three heavily irrigated countries: the USA, India, and China.

2. DATA AND METHODOLOGY

2.1 Community Land Model and Irrigation Simulation

Our irrigation simulation was performed with CLM 4.0. The total water balance in CLM is

$$\Delta W_{can} + \Delta W_{snow} + \sum_{i=1} (\Delta W_{liq,i} + \Delta W_{ice,i}) + \Delta W_a = (P_{rain} + P_{sno} - E_{veg} - E_g - P_r - P_{drain} - P_{rlgwl} - P_{rsgwl}) \Delta t \quad (1)$$

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where ΔW_{can} , ΔW_{snow} , $\Delta W_{liq,i}$, $\Delta W_{ice,i}$, ΔW_a are changes in canopy water, snow water, soil water, soil ice, and water in the unconfined aquifer, respectively (all in kg m^{-2}). The variable P_{rain} denotes the liquid part of precipitation; P_{sno} is the solid part of precipitation; E_{veg} is evapotranspiration from vegetation; E_g is ground evaporation; P_r is surface runoff; P_{drain} is sub-surface drainage; P_{rsgwl} and P_{rsgwl} are liquid and solid runoff (respectively) from glaciers, wetlands, lakes, and from other surface types due to snow capping (all in $\text{kg m}^{-2} \text{s}^{-1}$); n is the number of soil layers; and Δt denotes the time step (s). After adding irrigation, the formula is revised as below.

$$\Delta W_{can} + \Delta W_{snow} + \sum_{i=1}^n (\Delta W_{liq,i} + \Delta W_{ice,i}) + \Delta W_a = (P_{rain} + P_{sno} + IRR - E_{veg} - E_g - P_r - P_{drain} - P_{rsgwl} - P_{rsgwl}) \Delta t \quad (2)$$

where IRR is irrigation water ($\text{kg m}^{-2} \text{s}^{-1}$).

In our scheme, irrigation is triggered when transpiration wetness factor (β) is below a prescribed threshold. Here, β is between 0 (dry soil) and 1 (wet soil) and is determined by the soil water potential of each soil layer, the root distribution of the plant functional type, and a plant-dependent response to soil water stress. Transpiration is the engine that pulls water up from the roots to supply photosynthesis and bring minerals from the roots for biosynthesis within the leaf. A plant cannot continue rapid transpiration if its water loss is not compensated by replacement from the soil. When absorption of water by the roots fails to keep up with the rate of transpiration, loss of turgor occurs, and the stomata close. The important environmental factors that affect the rate of transpiration include light, temperature, humidity, wind, and soil water.

$$\beta = \sum_i w_i r_i \quad (3)$$

$$w_i = \begin{cases} \frac{\varphi_c - \varphi_i}{\varphi_c - \varphi_o} \left[\frac{\theta_{sat,i} - \theta_{ice,i}}{\theta_{sat,i}} \right] & T_i > T_f - 2 \\ 0 & T_i \leq T_f - 2 \end{cases} \quad (4)$$

$$\varphi_i = \varphi_{sat,i} s_i^{-B_i} \geq \varphi_c \quad (5)$$

$$s_i = \frac{\theta_{liq,i}}{\theta_{sat,i} - \theta_{ice,i}} \geq 0.01 \quad (6)$$

$$\theta_{ice,i} = \frac{w_{ice,i}}{\rho_{ice} \Delta z_i} \leq \theta_{sat,i} \quad (7)$$

$$\theta_{liq,i} = \frac{w_{liq,i}}{\rho_{liq} \Delta z_i} \leq \theta_{sat,i} - \theta_{ice,i} \quad (8)$$

$$r_i = \begin{cases} 0.5(e^{-r_a z_{h,i-1}} + e^{-r_b z_{h,i-1}} - e^{-r_a z_{h,i}} - e^{-r_b z_{h,i}}) & i \leq 1 < N \\ 0.5(e^{-r_a z_{h,i-1}} + e^{-r_b z_{h,i-1}}) & i = N \end{cases} \quad (9)$$

Here, w_i is a plant wilting factor for layer i , r_i is the fraction of roots in layer i , φ_i is the soil water matric potential (mm), and φ_c

and φ_o are the soil water potential (mm) when stomata are fully closed or fully open, respectively. $w_i = 0$ when the temperature of the soil layer is below -2°C or when there is no liquid water in the soil layer. s_i is the soil wetness for layer i with respect to the effective porosity, $\varphi_{sat,i}$ is the saturated soil matric potential (mm), and B_i is the Clapp and Hornberger parameter. $w_{ice,i}$ and $w_{liq,i}$ are the ice and liquid water contents (kg m^{-2}), respectively, and $\theta_{sat,i}$ is the saturated volumetric water content. ρ_{ice} and ρ_{liq} are the densities of ice and liquid water, respectively (kg m^{-3}). Δz_i is the soil layer thickness (m), $z_{h,i}$ is the depth from the soil surface to the interface between layers i and $i+1$, and r_a and r_b are plant-dependent root distribution parameters.

The irrigation scheme initially checks whether the current column is cropland and whether the grid is irrigated, then evaluates β each day at 6:00 a.m. If β is below 0.5, then irrigation is applied at the rate of 0.005 mm/s for the next 4 hours. Irrigation is applied in two ways: above a canopy similar to precipitation, and directly on the ground. The former pattern allows water to be intercepted by the canopy, evaporated from leaves and stems, and drip off the vegetation (canopy drip).

2.2 Data and Experiments

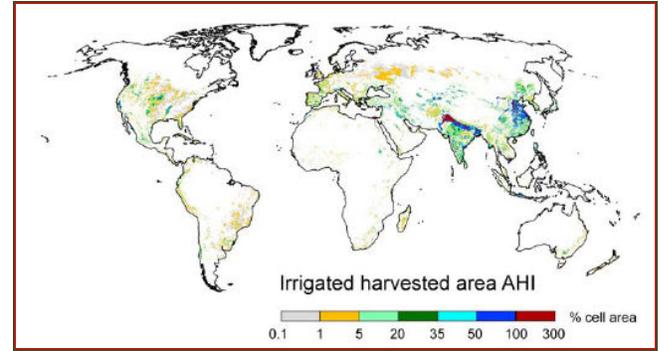


Figure 1. Globally irrigated harvested areas (F.T. Portmann, et al. 2010)

The irrigation map used here is a global dataset of monthly irrigated and rainfed crop areas for around the year 2000 (MIRCA2000). This dataset describes monthly growing areas of 26 irrigated and rainfed crops, including wheat, rice, maize, barley, rye, millet, sorghum, soybeans, sunflower, potatoes, cassava, sugar cane, sugar beet, oil palm, rape seed/canola, groundnuts/peanuts, pulses, citrus, date palm, grapes/vine, cocoa, coffee, as well as related crop calendars for 402 spatial units. The spatial resolution of this map is 5 arc-minutes by 5 arc-minutes. Figure 1 is an example of the MIRCA dataset showing globally irrigated harvested areas. The forcing data used are CLM 4.0 offline forcing data. The initial data come from an existing initial condition dataset. Both of the above are available when a case is set up via the input data archive of the SVN repository. The model resolution is 96 by 144.

Three experiments were conducted in this study to evaluate the irrigation impact: a control test without irrigation information (control test), irrigation simulation by applying water above a canopy to simulate spray irrigation (experiment 2), and irrigation

simulation by applying water directly on the ground to simulate flood irrigation (experiment 3).

3. RESULTS

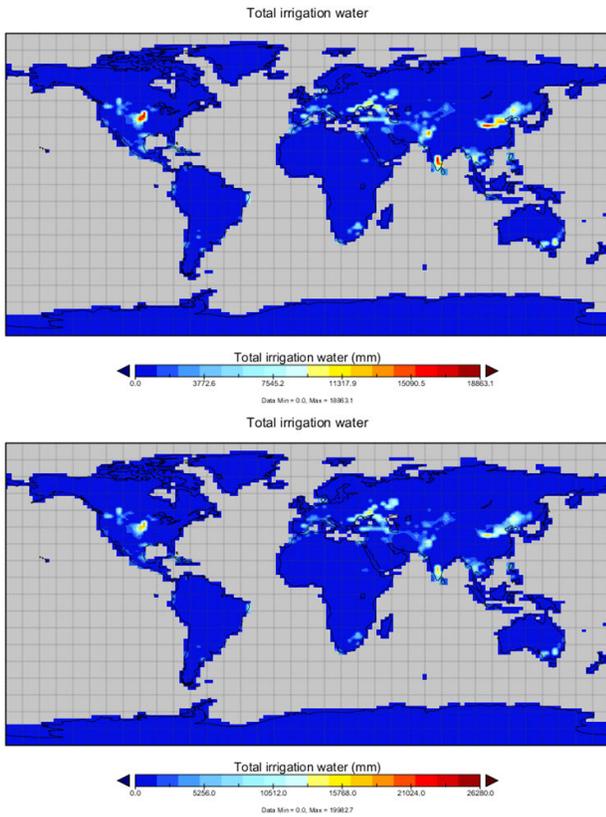


Figure2. Total irrigated amount (top: flood irrigation simulation; bottom: Spray irrigation simulation)

Total irrigation amounts after a one-year run of experiments 2 and 3 are shown in Figure 2. The latitude-based average irrigation amount in irrigated cells for experiment 2 and 3 are shown in Figure 3. Here, the irrigated cells are those cells that accepted irrigation water in the model and do not correspond to the irrigated area shown in MIRCA dataset. The figure shows that areas with latitude between 35°N and 46°N and around 35°S exhibit the highest irrigation demands. Some places equipped with irrigation systems based on the MIRCA dataset were not irrigated in the simulation year, such as southeast Asia, eastern USA, and central India. More irrigation water was applied with spray irrigation than

in the flood irrigation simulation. Moreover, the biggest difference in irrigation amount occurred in the areas with latitude between 35°N and 56°N.

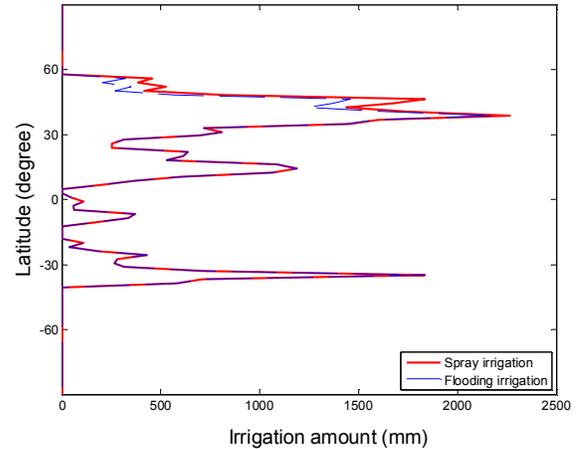


Figure3. Latitude-based average irrigation amount in irrigated cells for experiment 2 and 3

We compared the differences between coupled irrigation and control runs globally and in three heavily irrigated countries—the USA, India, and China—and list the results in Table A. Spray and flood irrigation respectively increased evapotranspiration by 4.33 w/m² and 3.36 w/m² and 2-m relative humidity by 0.36% and 0.14%. Further, spray and flood irrigation respectively decreased sensible heat flux by 2.86 w/m² and 2.43 w/m², ground temperature by 0.13 K and 0.12 K, daily maximum of average 2 m temperature by 0.1 K and 0.04 K, soil temperature in top 10 cm of soil by 0.22 K and 0.12 K, and vegetation temperature by 0.12 K and 0.06 K averaged over irrigated land. Among the above three heavily irrigated countries, the impacts of both flood and spray irrigation are greatest in India and smallest in China. The impact in China is complex: absorbed solar radiation in China decreased and the reflected solar radiation increased in the spray irrigation simulation, which is different to that found in the simulation of spray irrigation in the other two heavily irrigated areas, and also different to the results obtained from the simulation of flood irrigation in China. This difference may be because spray irrigation in China leads to more clouds in the atmosphere. More clouds cause more solar radiation to be reflected; therefore, less solar radiation reaches the ground surface.

Table A. Differences between coupled irrigation and control runs, average over irrigated area

	Flooding irrigation				Spray irrigation			
	China	USA	India	Global	China	USA	India	Global
Evapotranspiration (ET, w/m ²)	1.07	2.66	11.52	3.36	2.59	3.20	13.47	4.33
Photosynthesis(Ph0, umol/m ² s)	0.03	0.08	0.20	0.09	0.03	0.08	0.24	0.09
Absorbed solar radiation(ASA, w/m ²)	0.25	0.23	1.01	0.32	-0.09	0.09	1.01	0.07

Sensible heat(SH, w/m ²)	-0.51	-1.84	-8.14	-2.43	-0.64	-1.74	-9.52	-2.86
Reflected solar radiation(RSA, w/m ²)	-0.25	-0.23	-1.01	-0.32	0.09	-0.09	-1.01	-0.07
Volumetric soil water(VSW, mm ³ /mm ³)	0.04	0.03	0.06	0.03	0.04	0.03	0.06	0.03
2m relative humidity (RH, %)	0.06	0.14	0.65	0.19	0.47	0.30	0.75	0.36
Soil liquid water(SLW, kg/m ²)	0.51	0.42	0.98	0.46	0.41	0.41	0.98	0.43
Ground temperature(GT, K)	-0.01	-0.09	-0.42	-0.12	-0.02	-0.08	-0.45	-0.13
Daily minimum of average 2-m temperature(DT _{MIN} , K)	0.05	0.03	0.01	0.02	0.09	0.04	0.01	0.05
Daily maximum of average 2-m temperature(DT _{MAX} , K)	-0.04	-0.04	-0.12	-0.04	-0.20	-0.08	-0.14	-0.10
2m air temperature(T, K)	0.01	0.00	-0.06	-0.01	-0.02	-0.02	-0.07	-0.02
Soil temperature in top 10cm of soil(ST, K)	0.00	-0.08	-0.43	-0.12	-0.22	-0.14	-0.46	-0.22
Vegetation temperature (VT, K)	0.03	-0.04	-0.30	-0.06	-0.03	-0.05	-0.42	-0.12

4. CONCLUSION AND DISCUSSION

In this study, we added a novel irrigation module to the recently released CLM 4.0 model and simulated irrigation in two ways: first, by spraying water above a canopy similar to precipitation to simulate spray irrigation, and second, by directly adding water on the ground to simulate flood irrigation. The differences between coupled irrigation and control runs and the differences between two irrigation patterns were analyzed globally and in three heavily irrigated countries: the USA, India, and China. Our results show that irrigation increases the evapotranspiration, photosynthesis, soil water, relative humidity, and reduces the daily temperature, soil temperature, vegetation temperature, and sensible heat. In sum, spray irrigation has a greater impact than flood irrigation, because more irrigation water was applied in the spray irrigation than in the flood irrigation simulation. The irrigation impact is greatest in India, followed by the USA, and China has the smallest influence. Moreover, the impact in China is complex, which may be because of cloud increase due to irrigation application in this location. Further evidence must be gathered in order to better understand this issue.

Some locations equipped with irrigation systems based on the MIRCA dataset were not irrigated in the simulation year. There may be several reasons for this. First, our simulation is a one-year run, which is too short. Second, the threshold of β is fixed at 0.5 in this study for different crop types and different regions. This may be low for some crops such as paddy rice, which may result in a lower irrigation amount in irrigated paddy fields. In contrast, it is too high for some drought-resistant crops. In future studies, the threshold of β should be adjusted according to crop type.

In this study, we did not control the total irrigation amount, which may cause over- or under-estimation of the water consumption. However, our objective in this study was to compare the impacts of various irrigation patterns on the near-surface climate, because differences in impacts between spray and flood irrigation are more important than the absolute impact caused by each of these methods. In future work, ancillary data, such as a census of irrigation amounts, should be used to control the water amount and combine key crop growth and development periods with the transpiration wetness factor in order to control irrigation dates and times.

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