Global Irrigation Characteristics and Effects Simulated by Fully Coupled Land Surface, River, and Water Management Models in E3SM

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Abstract Irrigation supports agricultural production, but widespread use of irrigation can perturb the regional and global water cycle. The one-way coupled irrigation scheme used in some land surface models and Earth system models assumes that surface water demand is always met and ignores the surface water constraints, leading to overestimation of surface water usage, underestimation of groundwater pumping, and unrealistic simulation of their seasonal variability. To better represent the irrigation processes, a two-way coupled irrigation scheme is developed within the Energy Exascale Earth System Model (E3SM). The new irrigation scheme simulates irrigation water demand and applies irrigation water in E3SM Land Model (ELM), which is coupled to a river routing model and a water management model (MOSART-WM) that simulate streamflow, reservoir operations, and irrigation water supply. With two-way coupling, surface water irrigation is constrained by the available runoff, streamflow, and reservoir storage. Simulations were performed for 1979–2008 at 0.5° spatial resolution to estimate irrigation surface water and groundwater use and their seasonality in global and large river basin scales. Compared to one-way coupling, the two-way coupling scheme (1) estimates less surface water withdrawal and less return flow due to the surface water constraint; (2) better represents groundwater recharge and groundwater level decline at global scale; and (3) is able to capture the seasonal dynamics of irrigation water allocations which reflect the local water conditions. The new development is an important step to more realistically account for the interactions between human water use and the terrestrial water cycle in an Earth system model.

Plain Language Summary A novel method is developed in the Energy Exascale Earth System Model (E3SM) to better represent the irrigation processes. The old method applies the irrigation water by assuming there is no limitation on the water availability. This will lead to overestimation of irrigation withdrawal in dry conditions. The new development, however, constrains the irrigation withdrawal by evaluating river water availability every computational time step. It is an important step to more realistically represent the interactions between water management and natural hydrologic processes. Compared to the old method, the new method (1) estimates less surface water withdrawal and less return flow due to the surface water constraint; (2) better represents groundwater recharge and groundwater level decline at global scale; and (3) is able to capture the seasonal dynamics of irrigation water allocations which reflect the local water conditions. The new development is an important step to more realistically account for the interactions between human water use and the terrestrial water cycle in an Earth system model.

1. Introduction

Irrigation accounts for about 70% of the total water withdrawal globally (Shiklomanov, 2000; Wada et al., 2013). It alters the water cycle through many hydrological processes such as evapotranspiration, runoff generation, streamflow, and soil water drainage (Hooke et al., 2012). These processes would in turn perturb the climate, ecology, and human systems at local to global scales (Vörösmarty & Sahagian, 2000). With rapid growth of the global population and the Gross Domestic Product (GDP) in the twentieth century, global
agriculture land area equipped for irrigation has increased from $0.5 \times 10^6$ to $3 \times 10^6$ km$^2$ (Freydank & Siebert, 2008). Therefore, assessing the irrigation water use is very important in water resource allocation, trading, and policy making at scales ranging from small watersheds to continental basins. Understanding the impact of irrigation in the water cycle is also critical in future projection and planning for sustainable development of the human society.

Assessment of the irrigation water use is difficult due to the complex dynamics of the natural hydrological processes and the anthropogenic activities and their interactions. Since the 1960s, many studies have attempted to estimate and project global water use in irrigation and other sectors. Their approaches can be summarized in two categories: accounting-based and modeling-based (Zhou et al., 2016). Before the 21st century most studies used accounting-based approaches to estimate water use for different sectors by linearly projecting the water needs per person per year to the entire population group. Future projections were then based on the growth of the population, crop land, and GDP (Falkenmark & Lindh, 1974; Lvovich, 1974; Nikitopoulos, 1967; Postel et al., 1996; Shiklomanov, 1997, 1998). Due to limited data availability from administrative agencies and various overly simplified assumptions adopted in these

| Studies                        | Time     | Withdrawal (km$^3$/yr) | Consumption (km$^3$/yr) | Model                                      | Notes                                      |
|-------------------------------|----------|------------------------|-------------------------|--------------------------------------------|--------------------------------------------|
| Döll and Siebert (2002)       | 1961–1990| 2,452                  | 1,092                   | WaterGAP v2, 0.5° × 0.5°                    | CRU climate, FAO irrigation               |
| Hanasaki et al. (2006)        | 1987–1988| 2,254                  | 1,127                   | Modified TRIP, 0.5° × 0.5°                 | ISLSCP climate, ICOLD reservoir           |
| Oki and Kanae (2006)          | not specified | 2,660                  | not specified           | CRU climate, w/o nonlocal water            |                                            |
| Rost et al. (2008)            | 1971–2000| 1,161                  | 636                     | LPjML                                      | CRU climate, w/nonlocal water             |
| Wisser et al. (2008)          | 1963–2002| 3,100                  | 1,364                   | WBM$\_\text{plus}$                         | CRU climate, FAO irrigation               |
|                               | 3,800    | 2,200                  | 2,700                   |                                             |                                            |
| Döll (2009)                   | 1998–2002| 2,900                  | 1,200                   | WaterGAP2.1 g                              | CRU and GPCC climate, GMIA irrigation     |
| Hanasaki et al. (2010)        | 1985–1999| 3,128                  | 1,530                   | H08                                        | NCC climate, FAO irrigation               |
| Siebert et al. (2010)         | around 2000 | 1,277                  | 1,277                   | GCWM                                       | GMIA irrigation                           |
| Sulser et al. (2010)          | 2000     | 2,528                  | 1,098                   | IMPACT                                     | CRU climate, MIRCA 2000 irrigation        |
| Wada et al. (2011)            | 1958–2001| 2,057                  | 1,176                   | PCR-GLOBWB                                 | CRU climate, FAO irrigation               |
| Döll et al. (2012)            | 1998–2002| 3,185                  | 1,231                   | WaterGAP2.1                                | CRU climate, Freydank and Siebert (2008) irrigation |
| Pokhrel et al. (2015)         | 1983–2007| 2,158                  | 906                     | LSM MATSIRO                                 | Climate based on JCDAS                    |
|                               | 2000     | 2,462                  | 1,021                   | TRIP routing model                         | FAO irrigation                            |
| Wada et al. (2013)            | 1980–2010| 2,945                  | 1,098                   | ISI-MIP ensemble                           | WATCH climate                             |
| Wada et al. (2014)            | 2000     | 2,572                  | 1,098                   | PCG-GLOBWB                                 | Averaged results CRU, ERA-Interim, and MERRA climates, FAO irrigation |
| Pokhrel et al. (2015)         | 1998–2002| 3,028                  | 1,238                   | HIW-MAT                                    | Climate based on JCDAS, FAO irrigation    |
| Hanasaki et al. (2018)        | 2000–2015| 2,544                  | 1,368                   | Enhanced H08                               |                                            |
| Sutanudjaja et al. (2018)     | 2000–2015| 2,735                  | 1,170                   | PCG-GLOBWB                                 |                                            |
| This study                    |          | 2,253                  | 1,140                   | E3SM                                       | 30 arcmin resolution                      |
|                               |          | 1,571                  | 1,053                   |                                            | 5 arcmin resolution                       |
|                               |          | 2,006                  | 1,170                   |                                            |                                            |
|                               |          | 2,549.5                | 1,170                   |                                            |                                            |
| Median                        |          | 2,549.5                | 1,170                   |                                            |                                            |
approaches, the resulting estimations of irrigation water use varied widely from –50% to 100% of the average (Gleick, 2003). In the early 21st century, Döll and Siebert (2000) published the first digital global irrigation map at 0.5° spatial resolution by synthesizing and digitizing information obtained from governments, archived drawings, and international agencies. With booming computational power and the global irrigation map, global hydrology models (GHMs) and land surface models (LSMs) have been developed and improved to estimate the global water use in irrigation and other sectors (de Graaf et al., 2014; Döll & Siebert, 2002; Haddeland et al., 2006; Hanasaki et al., 2006, 2018; Leng et al., 2014; Nazemi & Wheater, 2015; Oki & Kanae, 2006; Pokhrel et al., 2015; Rost et al., 2008; Siebert & Döll, 2010; Sutanudjaja et al., 2018; Wada et al., 2010, 2013; Wisser et al., 2008). Estimations of irrigation withdrawals from modeling-based approaches have a smaller range compared to that of accounting-based approaches, with the global irrigation water withdrawal estimated as 2,000 to 3,000 km³/year around year 2000 (Zhou et al., 2016).

Representation of the irrigation processes in GHMs and LSMs has been approached using different assumptions and simplifications in three categories. First is the estimation of irrigation water demand (IWD). Some models (e.g., Döll & Siebert, 2002; Hanasaki et al., 2006) calculate IWD based on the difference between the effective precipitation (the part of precipitation that reaches the root zone of the crops) and the potential evapotranspiration of the cropland (PET), while some models use the soil-moisture-deficit approach to estimate IWD (e.g., Haddeland et al., 2006). In the latter case, at every modeling step, IWD is calculated as the moisture deficit between the soil moisture level at the crop root zone layers and a moisture target (e.g., a fraction of the field capacity). Second is the representation of irrigation water constraints. Most of the PET-based irrigation models assume that irrigation water is freely available and IWD can always be met (Döll & Siebert, 2002; Hanasaki et al., 2006). In some soil moisture deficit-based models IWD can be met by surface water, shallow groundwater, and sources not explicitly modeled, with surface water constrained by available streamflow and/or storages such as reservoirs (Haddeland et al., 2006; Pokhrel et al., 2015; Rost et al., 2008; Wada et al., 2014). Third is the representation of irrigation water allocation to surface and groundwater sources. Some studies (e.g., Leng et al., 2015, 2017) assumed a fixed irrigation allocation such as Siebert et al.’s (2010) global irrigation data set in which the irrigation sources were modeled at administrative unit level at annual time scale. Wada et al. (2014) inferred the groundwater allocation using an empirical method by comparing the base flow condition with the long-term historical climatology. Table 1 summarizes a number of LSMs commonly used in irrigation studies with estimated irrigation withdrawal and consumptive use. Note that some of the LSMs also serve as the land components within an Earth system model (ESM) framework (e.g., CLM is the land model of CESM).

The Energy Exascale Earth System Model (E3SM, previously known as the Accelerated Climate Modeling for Energy, ACME) is an Earth system model supported by the United States Department of Energy (DOE) (https://e3sm.org) (Golaz et al., 2019). It consists of six major components: an atmosphere model, an ocean model, a sea ice model, a land model, a land ice model, and a river model, as well as a coupler that synchronizes the time steps and exchanges information among the components. The E3SM Land Model (ELM) was built from the Community Land Model Version 4.5 (CLM4.5), with a few changes that synchronizes the time steps and exchanges information among the components. The E3SM Land Model (ELM) was built from the Community Land Model Version 4.5 (CLM4.5), with a few changes including a new soil hydrology solver called Variably Saturation Flow Model (VSFM) (Bisht et al., 2018) and two new biogeochemistry (BGC) frameworks to represent plant and soil carbon-nutrient mechanisms. One of the two BGC approaches, Converging Trophic Cascade (CTC) (X. Yang et al., 2014) is the default BGC configuration in ELM and therefore is activated in this study. The other approach, Equilibrium Chemistry Approximation (ECA) (Zhu et al., 2019) and VSFM are not activated in this study.

Another difference between ELM and CLM4.5 is the irrigation scheme in the crop model. The ELM crop model is originally inherited from CLM4.5 with a simple irrigation scheme to allow freely available water to be added to the cropland based on demand calculated from soil moisture deficit (Oleson et al., 2013). Recent improvements allow the irrigation demand to be fulfilled by surface water withdrawal and groundwater pumping following a prescribed allocation ratio (Leng et al., 2014). This improved irrigation scheme aims to more realistically represent the irrigation water allocations based on the observational data as well as the impact of groundwater pumping on the water table. However, it is still relatively simple compared to some LSMs and GHMs. It lacks a representation of the dynamics in the irrigation water constraint and source allocations. More importantly, water is not strictly conserved because the surface water added in ELM to fulfill the irrigation demand is not deducted from other water storages to...
ensure a water balance. While this is not an issue in offline simulations, which have been the only mode of simulations reported in previous studies, maintaining a water balance is critical in coupled ESMs for ensuring integrity of modeling the water balance in other Earth system components. For example, even a small water imbalance in the land-river components may lead to significant errors in modeling sea level rise on decadal time scale.

To improve the representation of irrigation in E3SM for modeling the coupled Earth system, we develop a two-way coupled modeling capability for integrating the land model, the river model, and a water management model, to represent irrigation processes. More specifically, the new development allows the land model to dynamically allocate irrigation sources based on the river water availability estimated by the river and water management models. The hydrologic effects caused by the two-way coupled irrigation scheme are evaluated by comparing it with the one-way coupled scheme through a number of modeling experiments. Also, given that human effects on the terrestrial water cycle are widely underrepresented or even ignored in many ESMs (Gleick et al., 2013; Nazemi & Wheater, 2015), this development can be further used to enhance human-water interactions in a coupled ESM framework.

In summary, the objective of this study is to implement a two-way coupled irrigation scheme (i.e., surface water irrigation withdrawal is constrained by water availability) in E3SM and address some technical challenges in ensuring water conservation. By evaluating a historical 30-year period simulation with different irrigation configurations, we aim to answer the following research questions: (1) what are the impacts of the two-way irrigation scheme on representing hydrological and irrigation processes in contrast with the original one-way coupling scheme (i.e., surface water irrigation withdrawal is independent of water availability); and (2) how does surface water constraint alter the seasonal allocation of irrigation at global scale.

2. Method

2.1. Model Descriptions

The hydrological processes represented in ELM include precipitation interception by the vegetation canopy, throughfall, evapotranspiration, infiltration, snow effects, surface and subsurface runoff, and soil water content dynamics. Activating the irrigation scheme in the model allows an extra irrigation water flux to be added to the canopy top, soil surface, or root zone, over the irrigated crop plant functional types (PFTs) in each grid cell depending on the selected irrigation method (Leng et al., 2017).

The ELM irrigation scheme performs a daily evaluation at 6 am local time to determine whether irrigation is needed for each grid cell. If the crop leaf area index is >0 and the soil moisture is dry enough to limit photosynthesis, irrigation is required. In ELM, soil moisture is distributed in each grid cell following the modified 1-D Richards equation in the vertical direction (Zeng & Decker, 2009). The soil depth of each soil layer is determined by an exponential equation

\[ z_i = f_s \{ \exp[0.5(i - 0.5)] - 1 \} \]  

Where \( z_i \) is the node depth (center) of soil layer \( i \), \( f_s = 0.025 \) as a scaling factor. Soil water is tracked in 10 soil layers (about 3.8 m deep) before entering an unconfined aquifer lying below the soil layers. The water table depth is updated every time step using different solutions depending on the position of the water table (i.e., within the soil layer or in the unconfined aquifer). Note that the water table is not connected with the neighboring grid cells and subsurface lateral flow is not represented in ELM. The readers are referred to (Niu et al., 2007) for details about the groundwater simulations.

The model calculates the irrigation demand for each day based on the deficit between the current soil moisture level and the target soil moisture level summed over the root zone soil layers. The deficit is then converted to a demand flux (\( D \), mm/s) for an irrigation period from 6 to 10 a.m. local time. The 4-hr irrigation period mimics common irrigation operations that start in the early morning and end before the middle of the day to reduce evaporative loss. The target soil moisture level is defined by a calibratable dimensionless parameter \( F_{\text{irrig}} \) (ranging from 0 to 1) that varies between the minimum level to prevent water stress and the fully saturated level for each crop PFTs. \( D \) is satisfied by surface water (\( D_{\text{surf}} \)) and groundwater (\( D_{\text{gmd}} \)) sources with the ratio between these sources determined by a modeled data set from the FAO.
AQUASTAT library (Siebert et al., 2010), where the surface water fraction ($F_{surf}$) and groundwater fraction ($F_{grnd}$) were derived based on reported irrigation water use statistics:

$$D = D_{surf} + D_{grnd}$$  

(2)

where

$$D_{surf} = D \times F_{surf}$$  

(3)

and

$$D_{grnd} = D \times F_{grnd}$$  

(4)

The one-way coupling scheme assumes $D$ is completely satisfied, that is, the irrigation water applied (IRR) is always equal to $D$ regardless of water availability:

$$IRR = I_{surf} + I_{grnd}$$  

(5)

where $I_{surf}$ and $I_{grnd}$ are irrigation water withdrawn from surface water and groundwater resources, which are equal to $D_{surf}$ and $D_{grnd}$, respectively. $I_{surf}$ is taken from the runoff of the local grid cell. The unmet portion of $I_{surf}$ (if $I_{surf} > 0$) is assumed to be filled by other external sources such as interbasin water transfer that are not explicitly represented by the model. The groundwater level at each grid cell is updated to reflect groundwater pumping. The readers are referred to Leng et al. (2013, 2015) for a detailed description of the crop and irrigation schemes.

ELM generates runoff ($Q$) through surface processes ($Q_{surf}$) and drainage ($Q_{drai}$) from the soil layer and/or unconfined aquifer. $Q_{surf}$ includes excess water from soil saturation ($Q_{over}$), and an outflow term ($Q_{h2osfc}$) from surface water storage such as pond and wetland. $Q_{h2osfc}$ is a highly dynamic variable as the volume and area fraction of the surface water storage is updated every time step, which further affects the outflow from the storage and the infiltration to soil layers at the bottom of the storage (Oleson et al., 2013). The complexity of the hydrological processes represented in ELM suggests that the linkage between irrigation and runoff is a nonlinear mechanism which depends on multiple factors such as the intensity of the irrigation, local topography, antecedent conditions of soil moisture, unconfined aquifer, and surface water storage. The runoff ($Q$) generated by ELM is sent to the E3SM river model, the Model for Scale Adaptive River Transport (MOSART) for river routing (Li et al., 2013, 2015) through a flux coupler. MOSART uses a...
kinematic wave approach to route the runoff through hillslope to subnetwork and then to main channel. For main channel routing, MOSART uses either kinematic wave method for steep channels or diffusion wave method for flat channels (Luo et al., 2017). MOSART is also fully coupled with a Water Management (WM) model (referred to as MOSART-WM) to simulate natural and regulated river streamflow based on the ELM runoff (Voisin, Li, et al., 2013). The WM model regulates the river streamflow through the representation of spatially distributed water extractions for irrigation as well as flow regulations at dams. Each dam's operating rules are determined based on historical long-term mean monthly inflow simulated by the models, reservoir characteristics, and reservoir purpose (flood control, irrigation, combination of flood control and irrigation, and others).

As mentioned above, the one-way coupling scheme and associated lack of water availability constraint can significantly overestimate irrigation water supply. In our newly developed two-way coupling scheme, surface water supply to irrigation is constrained daily by the surface water availability simulated by MOSART-WM. At 6 a.m. local time every day during the crop growing season, $D_{surf}$ from ELM is passed to MOSART-WM, which evaluates how much of the surface demand can be met sequentially by local runoff, local streamflow (routed from upstream), and upstream reservoirs. The total surface water irrigation withdrawal ($I_{surf}$), which is the sum of the withdrawal from local runoff, local streamflow, and upstream reservoirs, is subtracted from the water budget in MOSART-WM and sent back to ELM at the same time step to maintain an overall water balance. Then the constrained $I_{surf}$ ($I_{surf} \leq D_{surf}$) (Figure 1) is applied on the cropland PFTs together with $I_{grnd}$, which is equal to $D_{grnd}$ calculated in Equation 3. The irrigation water is applied as additional precipitation to the cropland surface (bypassing the crop canopy) to mimic a drip irrigation system. Note that this irrigation scheme does not consider the conveyance loss. In other words, the water applied in the field is equal to the water diverted from rivers, reservoirs, and local groundwater if needed.

In the default E3SM configuration (Golaz et al., 2019), ELM adopts the cubed-sphere spectral element grid system identical to that used in the E3SM atmosphere model (EAM), to simplify the exchange of fluxes between ELM and EAM. The cubed-sphere spectral element grid is a spatial discretization approach used in some atmosphere models to provide a quasi-uniform resolution grid, thus removing the need for polar filters to address numerical issues associated with the decreasing grid spacing toward the pole in regular latitude-longitude grid. However, similar to most of hydrologic models, MOSART-WM runs on a latitude-longitude grid system to facilitate river routing using an eight-direction river network. In this implementation, fluxes exchanged between the land and river models are spatially interpolated from the land grid system to the river grid system and vice versa, which can lead to erroneous irrigation demand and supply. Using the spectral element grid at 1° resolution in ELM and the 0.5° latitude-longitude grid in MOSART-WM, up to 15% of the total irrigation supply from the river model is assigned to land grids that do not
need irrigation and results in irrigation efficiency that is too low compared to observations. To address this modeling issue, a new model configuration is developed to allow ELM and MOSART-WM to run on an identical 0.5° latitude-longitude grid system to ensure that irrigation fluxes are correctly assigned between the models. The modeling time step is 30 min for ELM. For MOSART-WM, the time step ranges from 12 min (for relatively fast processes such as main channel flow) to 60 min (for relatively slow processes such as hillslope flow). Given the different time steps between the two models, a 3-hr coupling time step is adopted in the simulations (i.e., information exchange between the two models occurs every 3 hr). Also because of the coupling time step, the surface water irrigation supplied by the river model has a 3-hr delay in response to the irrigation demand simulated by the land model. Overcoming the technical issue of flux exchange between ELM and MOSART-WM and implementing two-way coupling between these models to properly account for the irrigation water supply and maintain a water balance are important for modeling irrigation and its effects in fully coupled Earth system models.

2.2. Data Sets

ELM is driven by the atmospheric forcing data set developed by Getirana et al. (2014), who combined the Global Precipitation Climatology Centre (GPCC) full data product version 6 (Schneider et al., 2014) and the global meteorological forcing data set developed by Sheffield et al. (2006) for land surface modeling. This atmospheric forcing data set includes 6-hourly air temperature, specific humidity, wind speed, surface pressure, precipitation, and incoming solar radiation at 0.5° latitude-longitude resolution. It is considered more accurate for modeling runoff than using the QIAN meteorological forcing data (T. Qian et al., 2006) in the official release of CLM4 as part of the benchmarking configuration (Li et al., 2015). The cropland in ELM is represented by crop functional types (CFTs) based on MIRCA2000 (Portmann et al., 2010). Five irrigated CFTs are represented in ELM including corn, temperate cereals, winter cereals, soybean, and other C3 crop. The crop calendar in ELM is estimated based on the simulated local climate conditions (i.e., precipitation and temperature) following Waha et al.’s (2013) algorithm. The surface water and groundwater withdrawal fractions are based on the gridded maps created by Siebert et al. (2010). The MOSART-WM model requires topographic parameters to simulate the river flow, which include flow direction, channel length, as well as terrain and channel slopes. These parameters are at 0.5° resolution derived using the Dominant River Tracing (DRT) algorithm (Wu et al., 2011), which was produced based on the combined 1-km resolution (HYDRO1k) and 3 arcsec hydrological data and maps (HydroSHEDS, Lehner et al., 2006). Dam and reservoir parameters were obtained from the Global Reservoir and Dam (GRanD) database (Lehner et al., 2011), which includes dam location, reservoir capacity, and major functions for more than 4,200 dams worldwide. The location of the dams and the spatial distribution of the cropland equipped for irrigation are presented in Figure 2.

2.3. Model Calibration and Experimental Design

ELM is calibrated against Huang et al. (2018) in which global water withdrawal was simulated by four widely used large scale hydrologic models (WaterGAP, H08, LPIML, and PCR-GLOBWB) from 1971 to 2010 and bias-corrected with the FAO-AQUASTAT and USGS data sets at the administrative unit scale. Our calibration follows the method used in Leng et al. (2015), in which only the dimensionless parameter \( F_{\text{irrig}} \) was calibrated between 0 and 1 to represent the target soil moisture for irrigation. Note that \( F_{\text{irrig}} \) is an empirical parameter which is constant over the simulation period and may lump the effects of several processes that are not explicitly represented in the model, such as conveyance losses, different irrigation technologies, and underrepresented crop types. Calibration was performed based on the two-way coupled scheme with irrigation deficit removed by extra groundwater pumping (the 2SGM scenario explained below). Given that \( F_{\text{irrig}} \) and \( IRR \) have a monotonic relationship at each grid cell, our calibration used a simple bisection root finding approach to minimize the difference between the ELM-simulated \( IRR \) and the mean \( IRR \) from the four models reported in Huang et al. (2018). The calibration was performed at 408 administrative units across the globe from 1981 to 1985 and evaluated for 1986–1990. An administrative unit is normally a country, but for the seven largest countries (i.e., Australia, Brazil, Canada, China, India, Russia, and United States), the administrative unit is defined at the state or province level. All grid cells within one administrative unit share the same \( F_{\text{irrig}} \) and \( IRR \) is aggregated over the administrative unit during the calibration.
After model calibration, we conducted a series of modeling experiments to quantify the impact of the two-way coupling scheme to the irrigation and water budget variables. These experiments include a simulation at natural condition (NAT) in which all cropland is assumed rain-fed, without irrigation and dam regulations. Other experiments include two commonly configured one-way coupled experiments, with irrigation water fulfilled by surface water only (1SO) and by both surface water and groundwater (1SG). Correspondingly, we included 2 two-way coupled experiments, 2SO and 2SG with constrained surface water irrigations. We also included one additional two-way coupled experiment, 2SGM in which unmet surface water irrigation demand is fulfilled by unlimited groundwater resources (Table 2). Given that 2SG and 2SGM assume that groundwater pumping is either determined by a fixed source fraction or unlimited, we expect the “real world” to fall between these two scenarios, with regional differences reflecting water use policy and surface water availability, among other factors. An offline spin-up run was performed by cycling the 30-year simulation multiple times using the NAT setup until the soil moisture and groundwater table reached a stable state. The resulting state variables were used as initial conditions for an extra 30-year spin-up under each experimental setup.

The results from these experiments are evaluated and compared, with a focus on two aspects: (1) the hydrological processes, which include the water budget variables such as runoff, evapotranspiration, and groundwater level; and (2) the irrigation processes, which include surface water and groundwater allocations and irrigation efficiency. These analyses are carried out at annual to seasonal time scales and global to basin spatial scales.

3. Results

3.1. Model Evaluation

The model (2SGM) simulated mean monthly irrigation withdrawal is compared with Huang et al. (2018) at the global administrative unit level (Figure 3) from 1986 to 1990. With calibration, our model captures the general pattern and magnitude of Huang et al. (2018) very well with the total global irrigation withdrawal about 2,000 km$^3$/year. Note that the ELM simulation does not reflect the agricultural expansion over the simulation period because cropland area was held constant, which leads to underestimation of current irrigation withdrawal in regions that experienced a rapid increase of cropland area. To confirm this, we compare the annual irrigation withdrawal from 1979 to 2008 in the United States where the change in irrigated area is relatively small, and in India where the irrigated area experienced a significant expansion (Figure S1 in the supporting information). The comparison shows a good agreement in the United States with long-term averaged annual irrigation withdrawal around 180 km$^3$/year. In India ELM maintains the estimation around 450 km$^3$/year but the Huang et al. estimate shows a secular trend that reaches 600 km$^3$/year in the early 21st century due to agriculture expansion. Although ELM does not represent the evolution of irrigated cropland area, comparison among simulations with irrigation area held constant still allows us to isolate the impacts contributed from the coupling scheme only.

3.2. Impacts of the Irrigation Scheme on Hydrological Processes

We compare the annual mean irrigation water applied ($IRR$), evapotranspiration ($ET$), and runoff ($Q$) at grid level among the scenarios over the simulation period. Changes of these water budget terms due to different irrigation configurations are determined by subtracting the terms in the baseline simulation (NAT) from the
terms in the irrigated simulations. As expected, $\text{IRR}$ (Figure S2) and $\text{ET}$ increases due to irrigation (Figure S3) are concentrated in highly irrigated area such as northern India, eastern China, and the western United States. The 1SO, 1SG, and 2SGM simulations produce a similar magnitude of $\text{IRR}$ as the irrigation demands are fully met in these scenarios. 2SO has the least $\text{IRR}$ as the irrigation water comes from the constrained surface water source only, so irrigation demand is not always met. $\text{IRR}$ of 2SG is greater than in 2SO but is less than the one-way coupled scenarios. The reason is that 2SG has less surface water irrigation demand than 2SO but the surface water irrigation demand still cannot be fully satisfied in some regions due to the surface water constraint. The $\text{ET}$ increases relative to NAT ($\text{ET}_{\text{irr}}$) can be viewed as the effective irrigation or consumptive use of the irrigation water (Figure S3). All five scenarios have a similar spatial pattern of $\text{ET}_{\text{irr}}$ with the magnitude corresponding to the irrigation applied (i.e., greater $\text{IRR}$ leads to higher $\text{ET}$). The runoff change caused by irrigation ($Q_{\text{irr}}$) is essentially the return flow, which is the irrigation water excess returned as runoff (Figure S4). Interestingly, irrigation does not always increase runoff. In 1SG, 2SG, and 2SGM, small negative $Q_{\text{irr}}$ are observed in northern India where heavy groundwater pumping occurs. This is because intense groundwater pumping increases groundwater recharge, so less water enters the surface runoff. In surface water only scenarios (1SO and 2SO), there are no negative $Q_{\text{irr}}$ as the groundwater storage remains the same as the NAT condition.

To evaluate the impact of the two-way coupling scheme, we further compare the water budget terms of 2SG and 2SGM relative to 1SG (Figure 4). Compared to 1SG, the $\text{IRR}$ in 2SG is reduced in most irrigated areas due to the constraint on surface water supply. In some arid river basins such as Amu Darya, Colorado, Yellow, and Shatt al Arab, the reductions in $\text{IRR}$ are greater than 50% (Figure 4). In these basins, the impacts of the reduced $\text{IRR}$ are reflected in the reduced $\text{ET}_{\text{irr}}$ (Figure 4c) and the greatly reduced $Q_{\text{irr}}$ (Figure 4e). In 2SGM, as the irrigation demand is met by additional groundwater pumping, the $\text{IRR}$ is closer to the 1SG scenario. However, in some areas with heavy pumping such as central Asia, the $\text{IRR}$ in 2SGM is slightly higher (about 10%) than in 1SG (Figure 4b) because more irrigation is needed to maintain the same soil moisture level, as the additional groundwater pumping increases groundwater recharge at the expense of soil moisture. The $\text{ET}_{\text{irr}}$ in 2SGM is generally the same compared to 1SG (Figure 4d) but the $Q_{\text{irr}}$ experienced a decrease because additional water enters the groundwater storage as recharge (Figure 4f).
From a water budget point of view, the IRR is sourced from surface water and groundwater at different ratios and contributes to \( ET_{irr} \), \( Q_{irr} \), and recharge to the soil layers \( R_{irr} \) following the equation below:

\[
IRR = ET_{irr} + Q_{irr} + R_{irr}
\]

The global-averaged water budget terms (Figure 5) suggest that the global IRR is about 15 mm/year in one-way coupled scenarios (i.e., 1SO and 1SG), followed by 13 mm/year in 2SGM, 10 mm/year in 2SG and 6 mm/year in 2SO. The 4 mm/year irrigation increase from 2SO to 2SG results in a 3 mm/year increase in \( ET_{irr} \), suggesting that about 75% of the irrigation from groundwater pumping is consumed by the crops. However, the 3 mm/year IRR increase from 2SG to 2SGM only results in about 1 mm/year \( ET_{irr} \) increase, which is about 30%. A majority of the increase in irrigation in 2SGM contributes to the return flow to soil and groundwater recharge. With the highest groundwater pumping rate, 2SGM has the highest groundwater table depletion rate over the simulation period (4 mm/year), followed by 3.1 mm/year in 2SG, which is comparable to the global water storage decreasing rate (~2.6 mm/year) estimated from the Gravity Recovery and Climate Experiment (GRACE) mission data sets (assuming other long-term water storage terms such as snow water equivalent, channel storage, soil moisture are constant). By synthesizing the global water budget comparisons between 1SG, 2SG, and 2SGM.

**Figure 4.** Change of annual mean irrigation water applied (IRR) (a, b), evapotranspiration due to irrigation (ETirr) (c, d), and runoff due to irrigation (Qirr) (e, f) of 2SG (left) and 2SGM (right) relative to the 1SG scenario. Experiment configurations of 2SG and 2SGM are defined in Table 2.
we found that the one-way coupling scheme estimates similar evapotranspiration compared to the two-way coupling scheme, but it tends to overestimate the return flow, and underestimate the groundwater recharge and water table decline. The estimated global water withdrawal are 2,253, 1,571, and 2006 km$^3$/year for the 1SG, 2SG, and 2SGM scenarios, which are among the lower end values reported in previous studies (Table 1). Note that these values largely depend on the calibration of $F_{irrig}$. Although the calibration of $F_{irrig}$ can be improved by allowing more spatial variability, the main focus of this study is not to accurately estimate the global irrigation water withdrawal. Rather, we focus on the impact of the surface water constraint on the irrigation behaviors and the implications to a coupled system.

3.3. Impacts of the Irrigation Scheme on Irrigation Characteristics

Water availability has a strong seasonality in many regions around the world. For example, precipitation predominantly falls during summer in monsoon regions (e.g., China, India) and in winter in the Mediterranean climate regions (e.g., California). Constraining surface water irrigation by available water may alter the seasonal irrigation water allocation globally and across different river basins. We first investigate the global irrigation allocation in two seasons (MAM and JJA) across the 1SG, 2SG, and 2SGM scenarios (Figure 7). In 1SG, most of the irrigation is dominated by surface water with about 76% of the irrigated land mainly supplied by surface water and 24% by groundwater pumping. Given that the allocation fraction is fixed in 1SG, no difference is observed between the two seasons. In 2SG, the fraction of surface water in the total

Figure 5. Simulated global averaged water budget terms: Evapotranspiration (ETirr) (a), streamflow (Qirr) (b), total irrigation water applied (IRR) (c), irrigation water from surface water (Isurf) (d) and groundwater (Igrnd) (e), and groundwater table depth (f) across six experiments denoted by different colors and symbols.

Figure 6. Partitioning of the global irrigation withdrawal among different water budget terms (in percentage of the irrigation withdrawal) for the 1SG, 2SG, and 2SGM scenarios. Experiment configurations of 1SG, 2SG, and 2SGM are defined in Table 2.
irrigation withdrawal is reduced due to the surface water constraint. Area dominated by groundwater irrigation is increased to about 37% and 35% in MAM and JJA seasons, respectively. From MAM to JJA, the surface water fraction is reduced by 10–20% in some arid and semiarid areas such as Western United States, West Asia, and South Africa, suggesting that more irrigation demand and/or more constraints for the surface water occurred during JJA. In southern India, the fraction of surface water increases in JJA by more than 20% which may be due to the larger surface water available from the Indian monsoon rainfall. In 2SGM, given that groundwater pumping is allowed in all grid cells to fulfill unmet irrigation demand, area that is mainly supplied by groundwater is increased to about 43%. The dynamics of water allocation change from MAM to JJA are similar to 2SG.

The impact of the two-way coupling scheme on the irrigation allocation is also investigated in 14 basins where irrigation is relatively intense. We first evaluated the river discharge against the Global Runoff Data Centre (GRDC) database (http://www.bafg.de/GRDC/EN/Home/homepage_node.html), at the most downstream gauge with data available in each basin (Figure 8). The comparisons show that the model adequately captured the overall water availability at annual time scale (scatter plot) with R² = 0.86 for both 1SG and 2SG. Discrepancies are found at seasonal scales in some basins. For example, in Amu Darya and Indus, the simulated discharge is largely underestimated, which may lead to underestimation of the surface water irrigation and over pumping. These discrepancies may be introduced by biases in the climate forcings and input parameters of the models as well as uncertainties in representing the land and/or river processes in the models. We also notice that the two-way coupling scheme slightly lowers the streamflow in most basins due to irrigation water withdrawal from the river. Large decrease is observed in dry basins with relatively small discharge and heavy irrigation demand such as Yellow and Colorado River basins. In some basins, although the irrigation is intense (e.g., Shatt Al Arab and Indus), discharge differences between 1SG and 2SG are still negligible. The reason is that the hydrographs are compared at upstream locations on tributaries where irrigation has yet to take place.

The seasonality of the irrigation allocation is investigated at basin scale (Figure S5) and global scale (Figure 9). From a global perspective, at least 2/3 of the irrigation water is supplied by the surface water sources each month in 1SG. In high demand seasons (JJA), irrigation from surface water can be more than twice higher than from groundwater with 65% and 35% of the annual total allocation contributed by surface water and groundwater, respectively. In 2SG, due to the surface water constraints, the allocations are
partitioned more evenly, with 55% from surface water and 45% from groundwater. The ratio of the two sources of irrigation water varies seasonally, depending on the local water conditions. From February to June, groundwater plays a leading role in the allocation but after June when the river discharge starts to increase in many major basins dominated by the monsoons, the main source switches to surface water. The allocation simulated in 2SG is comparable to Wada et al.’s (2014) estimates of 60% from surface water and 40% from groundwater. In 2SGM, the dominant source is groundwater all year round, which accounts for about 65% of the total irrigation withdrawal. This is an overestimation because groundwater pumping is unlimited in every grid cell. From a basin perspective (Figure S5), for basins located in humid areas (e.g., Amur, Brahmaputra, Danube, and Mekong) or for irrigated area confined along the main stem of the river network (e.g., Nile), the difference in water allocation between simulations with and without surface water constraint is small. In some arid basins with high irrigation demand (e.g., Amu Darya and Indus), the difference appears to be relatively large and exaggerated due to underestimation of the discharge as explained above. We compared the simulated irrigation allocations with the United States Geological Survey (USGS) observed

Figure 8. Line plots show the simulated river discharge (blue) compared with GRDC observed discharge (red) at seasonal time scale in 16 river basins. The scatter plot at the lower right panel shows the simulated against observed annual river discharge in these basins. The gauges are located at the most downstream locations of each basin available in the GRDC database.

Figure 9. Global averaged seasonal surface (surf) and groundwater (grnd) irrigation allocation in the 1SG, 2SG, and 2SGM scenarios. Experiment configurations of 1SG, 2SG, and 2SGM are defined in Table 2.
water use statistics in 2015 (Maupin, 2018) for the Mississippi river basin, where the simulated discharge was reasonably good compared to other basins. The reported allocation is 44% from surface water and 56% from groundwater, close to our 2SG estimate of 41% and 59%, respectively.

Irrigation efficiency is defined as the water consumption (essentially the evapotranspiration caused by irrigation, \( ET_{irr} \)) divided by the irrigation applied (IRR). It can be affected by several factors such as water delivery method, irrigation rate, irrigation technique, and local climatology. By comparing 1SG, 2SG, and 2SGM across 14 basins (Figure 10), we note that in all basins, 2SG, with the lowest irrigation rate among the three scenarios due to the least water withdrawal, has the highest irrigation efficiency. We also notice that in some basins the irrigation efficiencies were quite low (<20%). This might be due to model limitations or climate forcing biases. For example, in the Yangtze and Amur basins, a large portion of the irrigation withdrawal is contributed by the rice paddy, which is not considered in ELM. By calibrating \( F_{irrig} \) using the observed irrigation withdrawals that provide water for the rice paddy, the model likely overestimates the irrigation demand in these basins, leading to a low irrigation efficiency. For the Danube basin, the simulated discharge is about 30% higher than the observed values, possibly due to climate forcing bias (see Figure 8). Since the irrigation demand was calibrated against the observed condition, which is drier than that simulated by the model, the model is expected to simulate excessive irrigation demand and hence a low irrigation efficiency. Using the Mississippi river basin as another example, the irrigation efficiencies are estimated to be 31%, 38%, and 27% for 1SG, 2SG, and 2SGM. According to the USGS statistics, the irrigation efficiency is about 55% in the Mississippi river basin, which is higher than all three estimates. The discrepancy partly reflects the simplifications in representing the irrigation target and the lack of renewable groundwater in the model.

4. Discussion

In this study we presented a two-way coupled irrigation scheme to represent irrigation that accounts for the interactions between land and river in the E3SM framework. The two-way coupled scheme allows the irrigation model to adjust the surface water supply and groundwater pumping automatically based on the water demand and water availability. To achieve this, a new grid configuration has been developed and the time management scheme has been improved to ensure mass conservation when passing fluxes between the land and river components through the flux coupler. Although the new development has improved the ability of the model to simulate certain irrigation processes in a more realistic way, it also comes with several limitations and uncertainties. Here we discuss two aspects as future directions of model improvements.
(1) Representation of the irrigation application. According to Jägermeyr et al. (2015), irrigation efficiency generally includes two parts: the conveyance efficiency and the field application efficiency. In this study, the conveyance loss is ignored, that is, the irrigation water diverted from the rivers, reservoirs, and groundwater is equal to the irrigation water applied in the field. This might lead to an overestimation of the effective irrigation efficiency. The field application efficiency, on the other hand, is dependent on the irrigation methods (Leng et al., 2017). In this study irrigation is modeled as a drip system and evaporation from the irrigation water applied in the field is simulated by the land surface model. Modeling irrigation as a drip system may lead to underestimation of the irrigation withdrawal and thus overestimation of the irrigation efficiency in flood irrigation areas such as rice paddy dominated regions. The order of the water withdrawal from different sources is also important. In this study irrigation water demand is met sequentially by local surface runoff, local streamflow, upstream reservoirs, and shallow groundwater. The irrigation allocation could vary significantly when this order is changed (Wada et al., 2014). In addition, water allocation could also be different in areas with local regulations such as water laws (e.g., Colorado and Columbia river basins) and interbasin water transfer contracts (e.g. Colorado river and Indo-Gangetic basins). The fraction of the surface water withdrawal might be relaxed in wet seasons to reduce the cost of groundwater pumping and constrained in dry seasons to accommodate water laws and inter-basin water transfers. In current model these applications are not represented due to data availability.

(2) Estimation of water demand. Modern large-scale hydrologic models still have large uncertainties in estimating irrigation water demand (Nazemi & Wheater, 2015) which could cascade into water resources management and redistribution of water resources in space and time (Voisin et al., 2017). Voisin, Liu, et al. (2013) and Hejazi et al. (2015) demonstrated that accounting for water demand uncertainty and the resulting unmet demand is essential to understand stresses on water resources. In the current E3SM, water demand is estimated by a soil moisture deficit method which largely depends on the representation of soil hydrology (i.e., groundwater table dynamics and the saturated and unsaturated flows). The model uses a simple volumetric water content based Richards equation in the unsaturated zone and an unconfined aquifer to represent the saturated zone (Oleson et al., 2013). To better simulate the coupled soil moisture and shallow groundwater dynamics, a newly developed Variably Saturated Flow Model (VSFM) that unifies the treatment of soil hydrologic processes in both saturated and unsaturated zones has been incorporated into ELM (Bisht et al., 2018) and is expected to improve the irrigation water demand estimation and irrigation water infiltration modeling in future simulations. In addition, irrigation water demand is affected not only by climate but also local agricultural practices such as crop type, crop calendar, cropping intensity, etc. These agricultural practices might play an important role in estimating the irrigation demand and water allocations.

5. Summary and Conclusion

In this study, a major enhancement has been introduced in E3SM to replace the one-way coupled irrigation scheme with a two-way coupled scheme to better capture the interactions between the river and the land models that influence irrigation. The two-way coupling scheme alters hydrological and irrigation processes in many ways. First, compared to the one-way scheme, the two-way coupling scheme with surface water constraints results in less surface water withdrawal as well as less return flow. In some arid river basins, surface water withdrawal is reduced by more than 50%, resulting in 5–10% reduction in evapotranspiration and up to 60% reduction in return flow. In areas with intense groundwater pumping (e.g., northern India), increase in groundwater recharge reduces irrigation water contribution to runoff and thus leads to reduced return flows. These changes further lead to an increase in the irrigation efficiency. In the Mississippi river basin, two-way coupling brings the irrigation efficiency closer to the observed value, although the simulated value is still lower than observed.

Second, globally, the representation of water availability constraints on irrigation supply reduces the irrigation water withdrawal by about 30% if both surface water and groundwater are used. Our model estimated an irrigation withdrawal of 2,253 km³/year if surface water withdrawal is not constrained. With surface water constraint, this estimate is reduced to 1,571 and 2,006 km³/year in simulations with irrigation water supplied by limited and unlimited groundwater pumping, respectively. Furthermore, if surface water and groundwater are used with constraint, 66% of the irrigation is consumed by the crop which is highly
efficient (summarized in Figure 6). With unlimited groundwater pumping to meet the demand, the efficiency is reduced to 58%, with the irrigation water not used by the crops contributing to return flow and groundwater recharge.

Third, the two-way coupled scheme is able to capture the seasonal dynamics of irrigation water allocations. Globally, groundwater contributes more to irrigation allocation from February to June but the main source of irrigation water switches to surface water after June, reflecting the increase in summer river discharge in major basins dominated by the monsoons. Regionally, the changes in seasonal allocation due to surface water constraints are highly dependent on the local climate conditions. Representing the seasonal dynamics of irrigation water allocations is important for more realistic simulations of the impacts of irrigation on surface hydrology and land-atmosphere interactions. We also note that compared to the one-way coupled scheme, the two-way coupling scheme reports greater groundwater allocation increase in dryer river basins with over 20% and 40% in 2SG and 2GM scenarios, respectively.

Despite the inherent limitations and uncertainties, the new development is an important step to better account for the interactions between human water use and the terrestrial water system. By ensuring mass conservation associated with irrigation in the land-irrigation coupled system, the new development lays a foundation for future global water cycle studies using fully coupled E3SM simulations. For example, the irrigation modeling scheme developed in this study can be used in coupled land-atmosphere simulations to evaluate the impact of the irrigation on clouds and precipitation (Qian et al., 2013; Yang et al., 2016). This motivates the need to further examine the various assumptions of irrigation modeling as changes in evapotranspiration and surface temperature have important implications for regional precipitation and storm activities, changes in streamflow amount and timing have important effects on riverine and coastal processes, and groundwater pumping has nonnegligible contributions to sea level rise and important implications for energy use.

The new development can also be coupled with socioeconomic models such as the Global Change Assessment Model (GCAM) (Edmonds et al., 1997) to include water demand from sectors other than irrigation. These improvements would enhance the representation of anthropogenic impacts in modeling the integrated water cycle. Understanding the social, environmental and economics drivers of water allocation to the groundwater and surface water systems is an emerging research topic that allows better understanding and mitigation of environmental tipping points in vulnerable regions such as Aral Sea, Lake Urmia and Lake Chad, which have displayed drying trends in the recent decades.

**Data Availability Statement**

The source code from this study will be publicly available through the E3SM webpage at https://e3sm.org.

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