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FY 2017 First Quarter Performance Metric: Implement and evaluate the impacts of irrigation on the hydrologic cycle in the ACME model

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1.0 Product Definition

Globally, around 70% and 90% of freshwater withdrawals and consumptions are used for irrigation purposes, respectively [*Döll*, 2009]. The large-scale water withdrawals from rivers, lakes, reservoirs, and aquifers have directly and substantially altered the terrestrial water and energy cycles [*Haddeland et al.*, 2006; *Kustu et al.*, 2010; *Wada et al.*, 2010; *Famiglietti et al.*, 2011; *Leng et al.*, 2014; *Pohkrel et al.*, 2015]. Irrigation impacts are expected to increase with growing world population and food demand, while production of bioenergy crops may further exacerbate irrigation water demands. Hence understanding the role of irrigation in human-Earth system interactions is important for adaptive planning of water, land, and energy use. During the last two decades, noteworthy progress has been made to represent irrigation in global hydrological models for assessing water resource availability and use, but there have been limited efforts in modeling irrigation in global land surface models and Earth system models (ESMs). From a modeling perspective, estimation of irrigation amount and choices of irrigation water sources and methods are key aspects in parameterizing irrigation water use and modeling its impacts. The most under-represented aspect of irrigation modeling is the irrigation method that determines how the extracted water is applied to the irrigated areas. Given the various approaches used to model irrigation, considerable discrepancy exists in simulating irrigation effects, especially at local/regional scales. To reduce such uncertainty, an interactive irrigation scheme has been developed and incorporated into the Accelerated Climate Modeling for Energy (ACME) Land Model (ALM) with consideration of the irrigation water sources (i.e., surface water and groundwater) and methods (i.e., drip, sprinkler and flood irrigation). The model has been used to investigate how the simulated irrigation effects are influenced by the water sources and methods for irrigation. By designing different irrigation scenarios, the pathways through which irrigation affects land surface water balance and how differences in irrigation water sources and methods affect irrigation water use efficiency are studied using numerical experiments. A set of numerical experiments with the new irrigation scheme in ALM showed that both different water sources (e.g., groundwater versus surface water) and methods of irrigation (e.g., sprinkler, flood, or drip) could lead to large differences in simulating the hydrological impacts of irrigation, suggesting that modeling of irrigation must consider those two factors to reduce uncertainty.

2.0 Product Documentation

The Accelerated Climate Modeling for Energy (ACME) is an ESM developed by the U.S. Department of Energy (DOE). To represent irrigation in the ACME Land Model (ALM), a groundwater pumping module has been added following *Leng et al.*, 2014 so that the estimated irrigation water demand can be met by withdrawing water from surface water storage (i.e., accumulated total runoff) and/or groundwater. The fraction of surface water withdrawal to the total water withdrawal is constrained by a global data set. The water table depth is updated after water is extracted for irrigation. In addition to the direct impacts on groundwater resources, changes in water table depth lead to subsequent changes in the subsurface drainage and recharge from the bottom soil layer to the aquifer, thus indirectly influencing soil water content through soil-aquifer interactions.

After the irrigation water is extracted, it can be applied to the irrigated areas using three distinct irrigation methods, i.e., drip, sprinkler, and flood irrigation. In practice, drip irrigation applies water directly to the root zone to reduce the wetted area, so it features the highest water use efficiency. Sprinkler

irrigation is less efficient because a large fraction of the water is sprayed into the air, which can result in wind drift and evaporation losses. In flood irrigation, less water is lost to evaporation than in sprinkler irrigation, but more water can be lost as runoff in the fields. The irrigation methods are parameterized mainly following the guidance of reflecting the distinct water use efficiencies among the three methods. For sprinkler irrigation, water is added directly to the canopy as precipitation. In drip irrigation, water is applied directly and slowly to the soil layers in the root zone to facilitate plant water use. In flood irrigation, water is poured directly and quickly to the ground surface in a period of 30 min. as precipitation falling on the ground surface, bypassing the canopy. The approach implemented in ALM can reflect the distinct irrigation water use efficiencies among the three irrigation methods, which is important for evaluating water use and hydrologic impacts driven by irrigation.

A series of sensitivity experiments were performed with ALM at 1-degree resolution driven by observed atmospheric forcing [*Qian et al., 2006*]. After cycling the atmospheric forcing for model spin-up, results for 1971-2005 were compared to contrast simulations with different irrigation water sources (surface water only, surface water and groundwater) and different irrigation methods (sprinkler with irrigation water applied to the canopy versus directly to the ground, flood, and drip) with water sources from both surface and groundwater. The impacts of water sources and irrigation methods were evaluated by comparing the effects of irrigation on water fluxes (e.g., evapotranspiration and runoff), soil moisture, groundwater table depth, and irrigation water use efficiency.

3.0 Results

An irrigation scheme has been added to the ACME Land Model (ALM) to study the effects of water sources and irrigation methods on the hydrological impacts of irrigation. The implementation of the irrigation scheme follows the details provided in Product Documentation. Building upon the Community Earth System Model (CESM) v1 [*Hurrell et al.*, 2013], ACME v0 couples the atmosphere, land, ocean, and sea ice components of CESMv1 with a target for high-resolution modeling. The ACME Land Model (ALM) v1 is an extension of the Community Land Model 4.5 (CLM4.5) [*Oleson et al.*, 2013]. Similar to CLM 4.5, ALM uses a subgrid hierarchy with multiple soil columns co-existing in a grid cell. Multiple plant functional types (PFTs) can exist in one soil column and compete for soil water, soil organic carbon, litter, etc. ALM v1 is coupled to an explicit representation of river transport based on the Model for Scale Adaptive River Transport (MOSART). ALM also includes a crop model [*Drewniak et al.*, 2013], with dynamic crop growth phenology coupled to carbon- and nitrogen-cycling processes. At present, three crops are considered in ALM, i.e., corn, soybean, and temperate cereals, each with its own soil column to avoid the competition for carbon and nitrogen and to facilitate crop-specific management practices. Irrigation is coupled with the crop model and can be activated when the crop model is turned on. To derive the managed crop PFTs, the gridded crop area from *Portmann et al.*, 2010 is used to provide the total and irrigated and non-irrigated harvested areas at 5 arc minutes worldwide. For irrigated croplands, irrigation is required when the crop leaf area index is > 0, and water is limiting photosynthesis. The irrigation amount is estimated as the soil moisture deficit between the irrigation target and the current soil water content in the root zone.

Accurate estimation of irrigation water amounts is crucial to assess the impacts of irrigation [*Leng et al.*, 2013; *Sorooshian et al.*, 2012]. Hence the irrigation scheme is calibrated to reduce the difference in the simulated and observed irrigation water amount based on data from *Siebert et al.*, 2010, which is a

global inventory of irrigation water use based on census reports or the FAO-AQUASTAT library. More details of the irrigation model are described in *Leng et al., 2016*.

Figure 1 shows the spatial distributions of the percentages of total irrigated areas and groundwater pumping intensity, respectively. About 70% of the irrigated area is located in Asian countries, followed by North America, Europe, South America, and Africa. At the country scale, the largest extent of irrigated areas is reported for China, India, the United States (US), and Pakistan, which together occupy about 56% of the global irrigated area. The largest irrigated areas fed by groundwater are located in India, followed by China, the US, Pakistan, Iran, Bangladesh, Mexico, Saudi Arabia, Turkey, and Spain (Figure 1b). At the regional scale, the highest groundwater pumping intensity is located in the Ganges and the upper Indus watersheds, Bangladesh, the North China Plain, and the High Plains aquifer and the alluvial aquifer along the Mississippi river in the US.

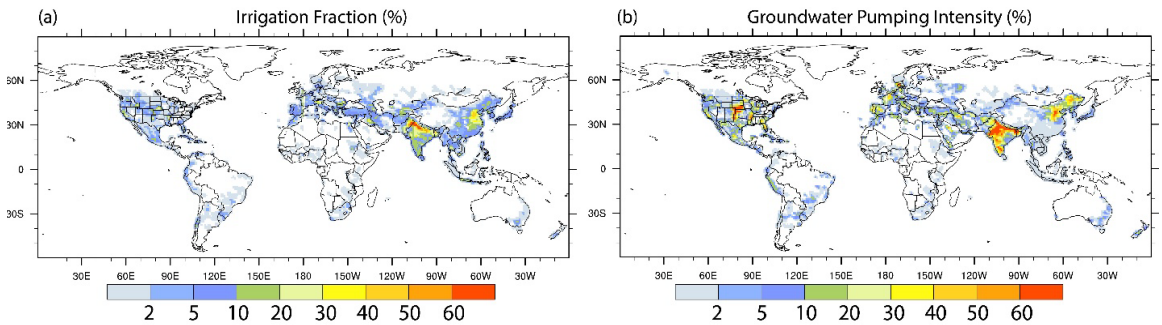

Figure 1. Spatial distribution of (a) gridded irrigation fraction (%), (b) gridded groundwater pumping intensity (%).

Six numerical experiments using ALM driven by observed atmospheric forcing were conducted at 1-degree resolution to investigate irrigation effects on terrestrial water budget terms with different irrigation water sources and irrigation methods. Table 1 summarizes the experiments conducted for 1971-2005. Specifically, the first three experiments, i.e., CTRL, SURF, and PUMP, are used to examine the irrigation effects using different irrigation water sources. In CTRL, the crop module was activated but with crops treated as rain-fed without considering irrigation. Both SURF and PUMP are the same as CTRL but with irrigation activated. In SURF, only surface water is used for irrigation while both surface water and groundwater can be used in PUMP. The last three experiments−PUMP_DRIP, PUMP_SPRINKLER, and PUMP_FLOOD−are the same as PUMP but with drip, sprinkler, and flood irrigation, respectively. Therefore, comparisons among PUMP_DRIP, PUMP_SPRINKLER, and PUMP_FLOOD are used to investigate irrigation effects using different irrigation methods. A comparison with the irrigation scheme in the CLM was also conducted. The CLM irrigation also uses the sprinkler method but water is added as precipitation directly to the ground instead of being sprayed from above the canopy. Before the simulations, an offline spin-up was performed by cycling the QIAN forcing data [*Qian et al.*, 2006] using the CTRL setup until equilibrium conditions were achieved for state variables including soil moisture and groundwater, following *Leng et al.*, 2015. The resulting state variables were then used as initial conditions for the irrigation experiments.

Table 1. Descriptions of simulations in this study. All experiments with irrigation used the same calibrated parameter for irrigation modeling.

Name	Irrigation	Irrigation Amount	Irrigation Source	Irrigation methods
CTRL	No	-	-	-
SURF	Yes	Calibrated	Surface water	From CLM
PUMP	Yes	Calibrated	Surface water and groundwater	From CLM
PUMP_DRIP	Yes	Calibrated	Surface water and groundwater	Drip
PUMP_SPRINKLER	Yes	Calibrated	Surface water and groundwater	Sprinkler
PUMP_FLOOD	Yes	Calibrated	Surface water and groundwater	Flood

Figure 2 shows the time series of growing season (June-July-August, JJA) runoff, evapotranspiration (ET), and water-table depth simulated by CTRL, SURF, and PUMP averaged over the global irrigated areas. Irrigation leads to significant decreases in runoff in SURF, but with smaller magnitudes in PUMP because part of the irrigation water pumped from the aquifer ends up as runoff. In regions with pumping intensity > 60%, runoff by PUMP could even be higher than that in CTRL because the large amounts of groundwater pumped may exceed the loss of runoff by surface-water withdrawals. ET increases significantly in both SURF and PUMP, compared to that in CTRL. Note that the ET changes do not depend on the water sources in the model because the simulations share the same irrigation targets for the soil water content calibrated by the observed irrigated amount. Water-table depth lowers with depletion of groundwater resources in PUMP, while elevated groundwater table depths are found in SURF as additional soil water due to irrigation could percolate and recharge the aquifer.

Increase in soil moisture induced by irrigation is found for all soil layers with the largest increase concentrated in the shallow soil layers or the root zone (Figure 3). This is reasonable given that additional water applied through irrigation would infiltrate and replenish the top soil layers, which would subsequently move to lower soil layers governed by the Richards equation. Importantly, compared to SURF, groundwater pumping in PUMP leads to smaller increase of soil moisture in the bottom soil layers. This is because groundwater-fed irrigation consumes water from the unconfined aquifer in the model [*Niu et al.*, 2007], which leads to a deeper water table and an enhanced recharge rate from the bottom soil layer to the aquifer. This suggests that groundwater pumping has a lower irrigation water use efficiency given the same irrigation target between SURF and PUMP. This important aspect of groundwater irrigation has received little attention, compared to the well-recognized negative impacts in groundwater depletion, land subsidence, deteriorated groundwater quality, etc. [*Aeschbach-Hertig and Gleeson*, 2012].

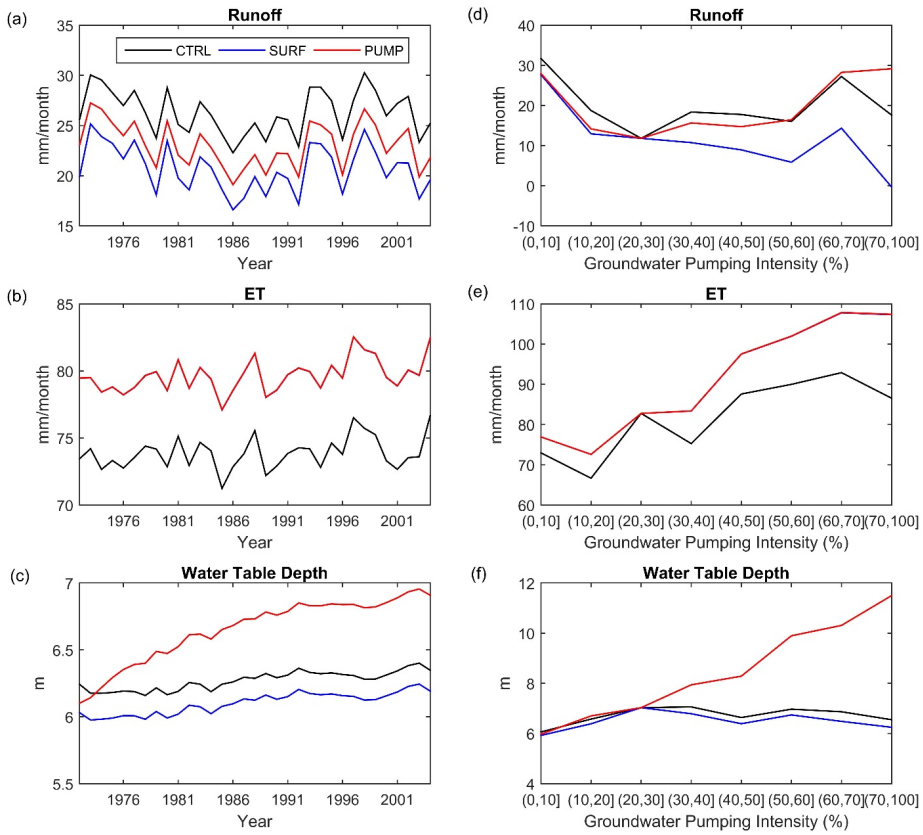

Figure 2. Annual time series of growing season (June-July-August) (a) runoff (mm/month), (b) ET (mm/month), and (c) water table depth (m) averaged over global irrigated areas, respectively, for simulations without irrigation (CTRL) and with surface water (SURF) and surface water and groundwater fed (PUMP) irrigation. (d),(e),(f) show the long-term mean values of growing season runoff, ET, and groundwater table depth, respectively, as a function of groundwater pumping intensity. Note that for ET, the red and blue curves overlap.

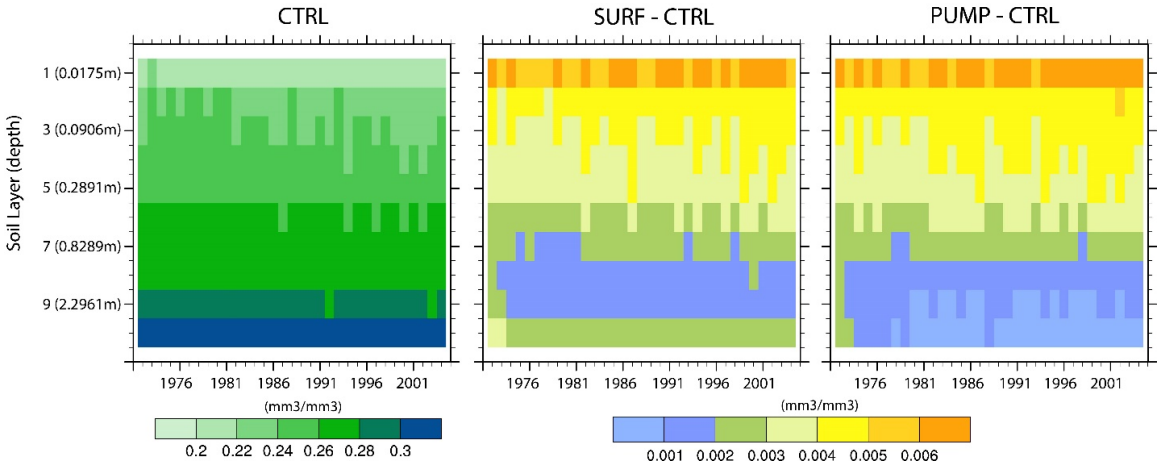

Figure 3. Irrigation effects on growing season (June-July-August) soil moisture content (mm^3/mm^3) for ten soil layers for the simulation period. (a) is for soil moisture content in CTRL, and (b) and (c) are for the changes in SURF and PUMP relative to CTRL.

Figure 4 shows the simulations of JJA runoff, ET, and water table depth with different irrigation methods. Moderate effects are simulated for sprinkler irrigation, with magnitudes lying between those of drip and flood irrigation. Specifically, in drip irrigation, much of the water is consumed efficiently with less loss to runoff; hence the largest reduction in runoff compared to CTRL as water is withdrawn for irrigation. With flood irrigation, water is applied in large volumes in a short time period so a large fraction of irrigation water becomes runoff, leading to a higher simulated runoff in PUMP_FLOOD than that in CTRL. Drip irrigation reduces groundwater depletion by enhancing infiltration, while flood irrigation amplifies groundwater depletions as a larger fraction of the irrigation water turns into runoff rather than recharge to the aquifers, resulting in deeper water table depths. With flood irrigation, a larger magnitude of increase in runoff is found over northern India and part of the North China Plain (not shown). ET increases substantially but the changes do not depend on the irrigation technique. Distinct impacts on water-table depths are found for the extensively irrigated regions among simulations with various irrigation methods (Figure 5). The distinct effects of irrigation methods on surface and subsurface water balances have great implications for modeling irrigation effects at the regional scale, which has not been explicitly considered in previous studies [*Haddeland et al.*, 2014; *Wada et al.*, 2014]. The results described here demonstrated that without explicit consideration of irrigation methods, previous estimates of irrigation water demand projections and irrigation effects could be significantly biased.

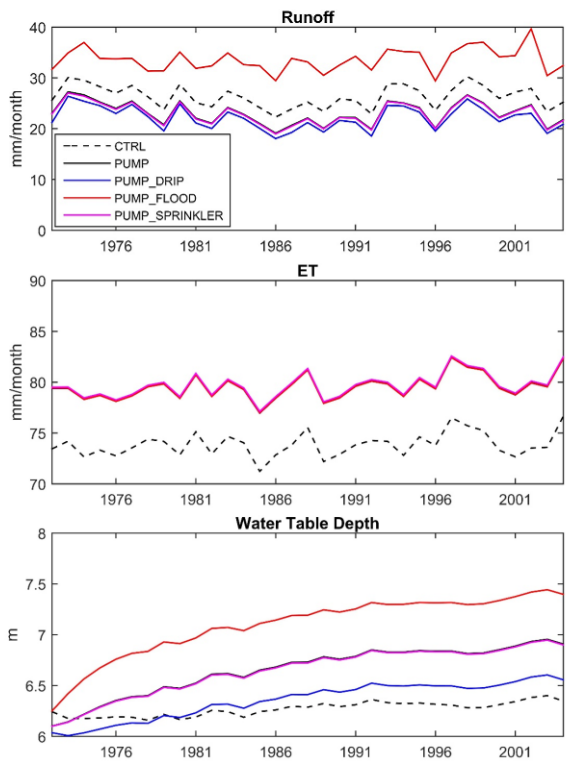

Figure 4. Temporal changes in growing season (June-July-August) (a) runoff (mm/month), (b) ET (mm/month), and (c) water table depth (m) in CTRL and simulations with different irrigation methods averaged over the global irrigated areas.

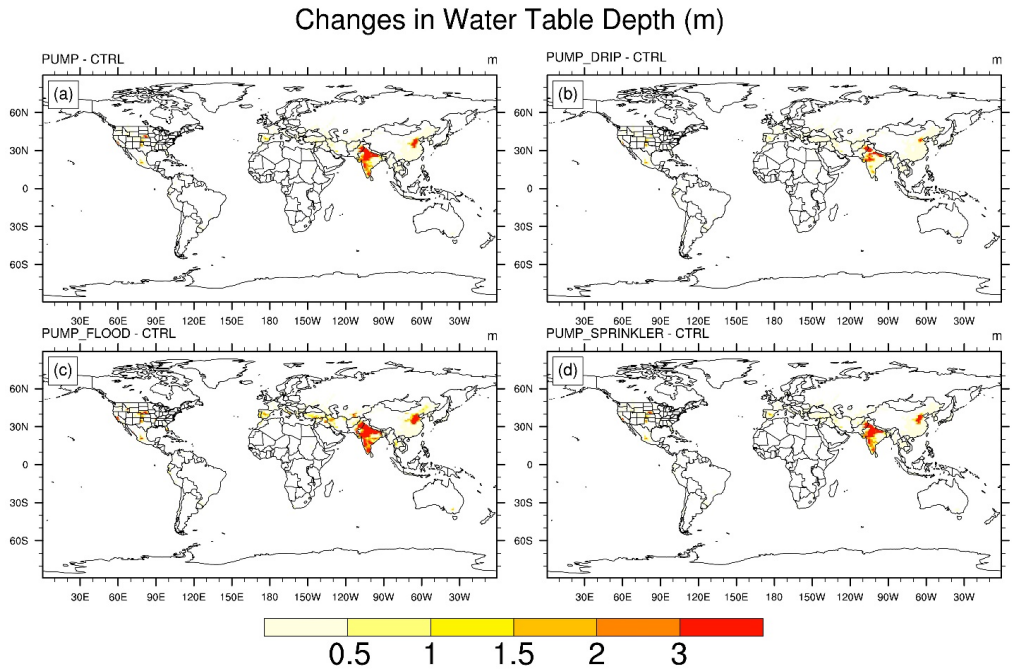

Figure 5. Spatial pattern of growing season (June-July-August) irrigation effects on groundwater table depth (in meters) using the (a) CLM, (b) Drip, (c) Flood, and (d) Sprinkler irrigation methods.

Figure 6 shows the simulated irrigation amount under various scenarios with different water sources and irrigation methods. The larger the irrigation water amount, the lower the irrigation water use efficiency and vice versa, since the irrigation target, i.e., reduction of crop water stress, is constrained to be the same among all simulations. Compared to surface-water-fed irrigation only, groundwater-fed irrigation leads to higher recharge rates as shown in Figure 2. The loss of soil water to aquifer leads to higher amounts of irrigation water withdrawals to maintain the same soil moisture level in the rooting zone as the SURF simulation in irrigated crop areas. Hence groundwater pumping lowers the irrigation water use efficiency compared to SURF. As for irrigation methods, drip irrigation has the highest water use efficiency while flood irrigation has the lowest, with sprinkler irrigation in between. The CLM irrigation method results in a similar irrigation amount as the sprinkler irrigation implemented in ALM. Since the CLM irrigation method is similar to sprinkler irrigation except that the irrigation water falls directly on the ground instead of from above the canopy, our results suggest that canopy interception has only minor effects on irrigation water use efficiency. Based on comparison of a suite of simulations, the simulated irrigation water use efficiency strongly depends on the water sources and irrigation methods, which has important implications for assessing and projecting irrigation water demands.

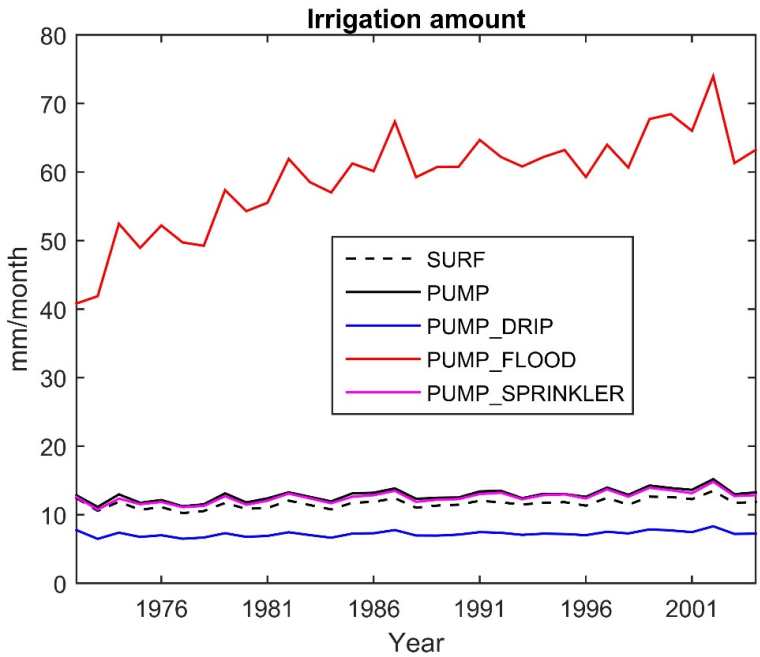

Figure 6. Temporal changes in simulated irrigation amount (mm/month) with different irrigation water sources and irrigation methods.

A growing body of literature uses numerical models to investigate irrigation impacts. However, a gap exists in holistic modeling of irrigation water amount, water source, and irrigation method in ESMs−factors that constitute key aspects of irrigation, with implications to how irrigation influences surface and subsurface water fluxes and water resources. An interactive irrigation scheme has been incorporated into the ACME Land Model. Compared to irrigation schemes in other large-scale models, the ALM approach represents several advancements in irrigation modeling by distinguishing irrigation water sources and, importantly, representing the least understood aspect of irrigation methods.

A set of sensitivity experiments using the ALM model indicates that irrigation water withdrawals can significantly alter land surface-water fluxes/states, with increase in soil moisture and ET constrained by observations of irrigation through parameter calibration for the irrigation target. Surface-water irrigation leads to decrease of runoff, but negligible changes in water-table depth. With groundwater pumping as an additional water source for irrigation, water-table depths increase and recharge rates are enhanced, but runoff may increase or decrease depending on the pumping intensity that influences the withdrawal and return of surface water. The magnitude of irrigation effects could be further altered when adopting specific irrigation methods, including drip, sprinkler, and flood irrigation. The largest increase of water-table depth is simulated when flood irrigation is used. The large amounts of water poured to the surface by flood irrigation could also become additional runoff, with much larger impacts than drip and sprinkler irrigation methods. By constraining the irrigation target, the simulations reported allow a meaningful comparison of irrigation impacts and irrigation water use efficiency associated with different water sources and irrigation methods. Importantly, the distinct irrigation effects on surface water balances are caused not only by where water is extracted (i.e., irrigation source) and how irrigation is applied (i.e., irrigation methods), but also indirectly through their impacts on the irrigation water use efficiency. Flood irrigation has the lowest irrigation water use efficiency, as reflected by the tripled irrigation water withdrawals to maintain the same soil water state compared to other irrigation methods, so it also

produces the largest impacts on surface water balances. This modeling effort represents a significant attempt toward enhancing irrigation scheme accuracy in an Earth system modeling framework. Its novelty lies in its explicit representation of irrigation water sources and irrigation methods. Realistically representing irrigation practices is crucial not only for projecting irrigation water demands and water scarcity, but also evaluating irrigation effects on land surface/subsurface hydrology and interactions with the atmosphere through exchanges of moisture and heat.

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