Response to Reviewers' Comments

We greatly appreciate the editor and the reviewer for providing valuable and constructive comments on our manuscript (egusphere-2024-4093). We seriously considered each comment and revised the manuscript accordingly. The individual comments are addressed in the following response letter and the manuscript has been revised to accommodate the changes. Below are our detailed responses, with the comments from the editor and the reviewer in black followed by our responses in blue. Please note that the comments are marked with codes for brevity, such as R1C2 (Comment 2 from Reviewer 1).

R2C1: This study contributes to the field of irrigation modeling by incorporating an irrigation scheme into the Common Land Model (CoLM) by building upon established methodologies from existing literature. I believe this article has the potential for publication in Hydrology and Earth System Sciences (HESS). However, there is still much room for improvement in model validation. My comments are outlined below.

Response: We greatly appreciate the time and effort you have spent on our manuscript, as well as your encouraging feedback and constructive comments, which have been highly helpful in improving the overall quality of our work. We have provided a point-to-point response to each comment and made corresponding changes in the revised manuscript.

R2C2: Before introducing the "Two-way coupled irrigation water use module," it would be beneficial to provide a brief overview of the Common Land Model (CoLM)'s water and energy processes related to irrigation. This will help readers better understand CoLM's key mechanisms and how the new module integrates with them.

Response: As per your suggestion, we have added a detailed description of the water and energy processes in CoLM to provide better context for the integration of the two-way coupled irrigation module. Please see the Lines 173-199 in revised manuscript and Figure S1 in the revised supplement.

Lines 173-199: *"In CoLM2024, the 'patch' serves as the fundamental computational unit to account for land surface heterogeneity (Figure S1). Based on land type, patches are divided into five types: vegetation (including bare soil), urban, wetlands, glaciers, and water bodies. The vegetation patch is further classified into natural vegetation and crops, represented using the Plant Functional Type (PFT) approach. Under this framework, all natural vegetation within a grid cell is treated as a single* *patch, sharing common soil thermal and moisture conditions while radiative and photosynthesis processes are simulated independently. When the crop model is activated, each crop type (distinguishing between rainfed and irrigated crops) is treated as an independent patch. This means that the calculations of soil moisture and thermal processes for each crop patch remain independent, without shared water and heat dynamics.*

At each patch, the primary thermal processes include precipitation phase change, radiation transfer, temperature calculations for leaves, snow, and soil, turbulent exchange, etc. The key hydrological processes include canopy interception, evapotranspiration, surface runoff, infiltration, soil water vertical movement, subsurface runoff, groundwater, river routing, etc. Specifically, the two-big-leaf scheme is employed to compute radiation transfer, leaf temperature, photosynthesis and transpiration (Dai et al., 2004; Yuan et al., 2017). Surface turbulent exchange is simulated using similarity theory (Liu et al., 2022; Zeng and Dickinson, 1998). Soil and snow temperature are determined using the heat diffusion equation, considering only vertical exchange (Dai and Yuan, 2014). Canopy interception is calculated same as CoLM2014 with considering the leaf angle and precipitation phase (Dai and Yuan, 2014; Sellers et al., 1996). Soil water vertical movement is simulated by the Richards equation and Buckingham-Darcy's law with using the Campbell soil water characteristic curve scheme to close the Richards equation (Buckingham, 1907; Campbell, 1974; Richards, 1931). Surface and subsurface runoff are estimated using the SIMTOP approach (Niu et al., 2005). When the irrigation scheme is activated, irrigation water is applied to the canopy or top soil according to predefined irrigation methods and simulated irrigation amounts, thereby influencing the soil moisture and thermal processes within the irrigated patches."

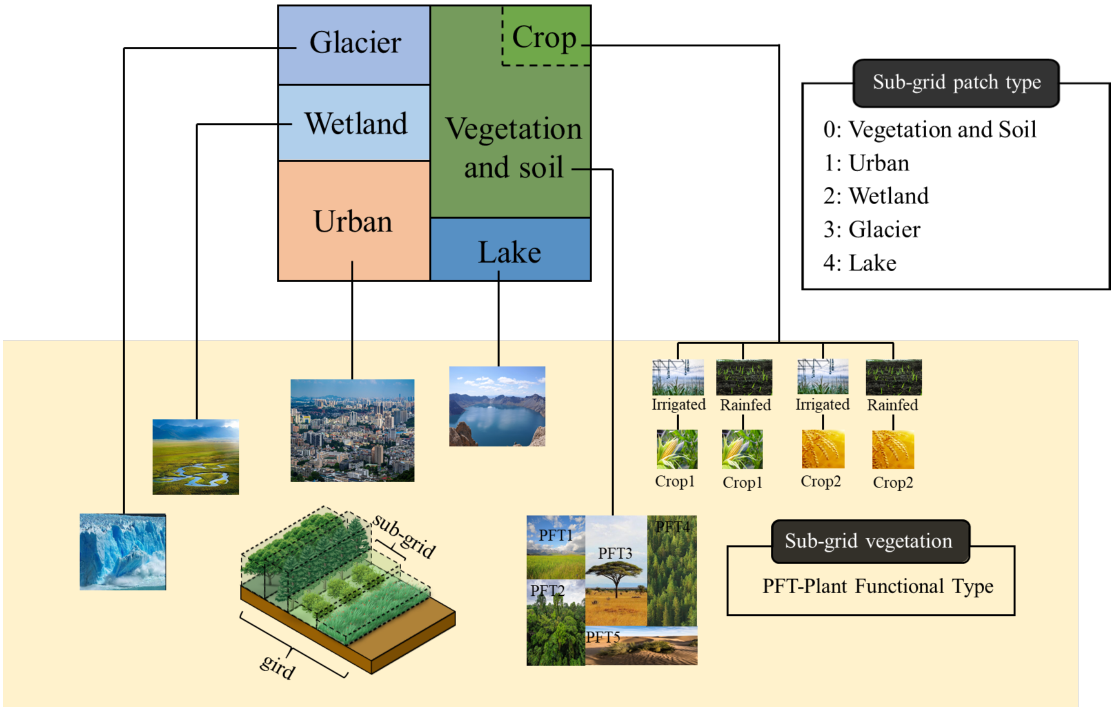

Figure S1. Diagram of the sub-grid structure in the Common Land Model.

R2C3: The irrigation system employed in this study is based on the soil moisture deficit method. The authors need to explain how this strategy is appropriate for the study region. Specifically, are the parameters f_{irrig} and f_{thresh} set to their default values? If so, using field capacity or saturation water amount as the target and threshold values for the root zone (1m) may be impractical, as it would theoretically demand an excessively large volume of water (as illustrated in Figure 3). While subsequent limitations might arise due to water availability constraints, this process remains inherently passive, as it is predicated on an initially overestimated assumption. If not, I suggest listing the value of the parameters.

Response: Yes, the parameters f_{irrig} and f_{thresh} were set to their default values in this study, as now stated in Line 241 of the revised manuscript.

We understand your concerns regarding the potential overestimation of irrigation demand due to parameter choices, including the target value, threshold value, and root zone depth. The soil moisture deficit method is a widely used approach for estimating irrigation requirements. We reviewed parameter settings in other hydrological and land surface models (Table R1) and found that most, like our study, adopt a uniform soil moisture threshold—either field capacity or saturation—while a few models (e.g., ORCHIDEE) account for crop-specific variations. As noted in our discussion, incorporating crop-specific thresholds is an important direction for future improvement (Lines 825-829). Regarding root zone depth, CoLM does not simulate dynamic root growth, so we set a fixed depth of 1 m for all crops, consistent with the median crop root depth reported in previous studies (Table R1). While this assumption may not be realistic for shallow-rooted crops such as rice and soybean, large-scale root depth data remain scarce and are beyond the scope of this study. To avoid introducing additional uncertainties, we adopted the simplified approach commonly used in other models. We acknowledge this as a potential source of uncertainty and have revised the manuscript to discuss its implications (Lines 829-832).

Lines 825-832: *"However, the parameterization of certain key variables (e.g., target and threshold soil moisture levels) is overly simplified and does not account for variations among crop types. These parameters are adjustable, and their calibration could further enhance the model's accuracy in reproducing irrigation water use. Similarly, the fixed root depth of 1 m for all crops introduces additional uncertainty, potentially leading to overestimation or underestimation of irrigation demand. Incorporating dynamic root growth could better represent actual root zone depth based on crop-specific characteristics."*

Table R1. Review of scheme of irrigation in the literature.

Model	Irrigation demand method*	Root depth	Target threshold
WaterGAP (Müller et al., 2014; 2021)	PET	--	--
PCR-GLOBWB (Sutanudjaja et al., 2018; Wada et al., 2014)	SMD	0.5m-1.5m	no paddy: field capacity paddy: ponding 0.05m
H08 (Hanasaki et al., 2008;2018)	SMD	0.15m	no paddy: 0.75* field capacity paddy: saturation
WBMplus (Grogan et al., 2022; Wisser et al., 2010)	SMD	0.5m-1.5m	no paddy: field capacity paddy: ponding 0.05m
VIC (Haddeland et al., 2006; Zhou et al., 2016)	PET	--	--
MATSIRO (Pokhrel et al., 2012; 2015)	SMD	1m	no paddy: 0.75* field capacity paddy: saturation
LPJmL (Jägermeyr et al., 2015)	SMD	0.5m	saturation
ORCHIDEE (Arboleda-Obando et al., 2024)	SMD	0.65m	saturation*crop coefficient

ELM (Zhou et al., 2020)	SMD	0.6m	between field capacity and saturation
CLM (Leng et al., 2014; Yao et al., 2022)	SMD	0.6m	between field capacity and saturation
Noah-MP (He et al., 2023; Nie et al., 2018; Ozdogan et al., 2010)	SMD	1m	field capacity or saturation

* PET: potential evapotranspiration method; SMD: soil moisture deficit method.

R2C4: Model evaluation. Terrestrial Water Storage (TWS) anomaly is a crucial variable for model evaluation. Comparing this variable with GRACE satellite data would enhance the study's robustness and provide additional validation for the model's performance.

Response: Thank you for your valuable suggestion. We have incorporated an evaluation of the model's performance in simulating terrestrial water storage anomalies by comparing the results with GRACE satellite data. A detailed description of the GRACE dataset has been added (see Lines 439-442), and the validation results are presented in the revised manuscript (see Lines 656–683, Figure 9 and Figure S13).

Lines 439-442: *"For terrestrial water storage (TWS) validation, we utilized monthly terrestrial water storage anomaly data from the Gravity Recovery and Climate Experiment (GRACE) mission for the period 2002-2016, with a spatial resolution of 0.5 degree, provided by the NASA Jet Propulsion laboratory (Watkins et al., 2015; Wiese et al., 2016)."*

Lines 656-683:

"3.2.3 Evaluation of simulated terrestrial water storage anomalies

To assess the model's ability to simulate the impact of irrigation on terrestrial water storage (TWS) dynamics, we compared the simulated monthly TWS anomalies with those derived from GRACE satellite products provided by the NASA Jet Propulsion laboratory. The results showed that incorporating the irrigation module, particularly under the irrig-lim scheme, improved the model's ability to capture both the interannual variability (Figure 9a) and seasonal patterns (Figure 9b) of TWS anomalies. Under the noirrig scheme, the simulated monthly TWS anomalies from 2002 to 2016 had a Pearson correlation of 0.25 with GRACE data and an RMSE of 6.75. In contrast, the irrig-lim scheme increased the correlation to 0.75 and reduced the RMSE to 5.13 (Figure 9a). The spatial distribution of Pearson correlation *coefficients between the simulations and GRACE data (Figure S13) further demonstrated a widespread improvement across the U.S., particularly in the Corn Belt.*

The enhancement was even more pronounced in the simulation of seasonal TWS anomaly patterns. Without irrigation, the model underestimated seasonal variations, resulting in a pattern that deviated substantially from GRACE observations. This bias was effectively corrected in the irrig-lim scheme, where the Pearson correlation coefficient increased to 0.92 and the RMSE decreased to 3.44 (Figure 9b). However, none of the simulations captured the decline in GRACE-derived TWS anomalies during 2012 to 2016, likely due to groundwater depletion from irrigation (Rodell and Reager, 2023). This suggests that the model may require further validation and improvements in simulating irrigation-induced groundwater storage changes."

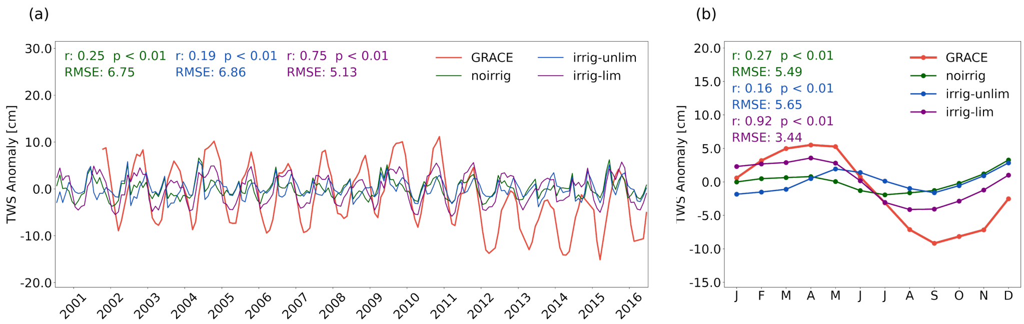

Figure 9. Evaluation of simulated terrestrial water storage anomalies in irrigated region. (a) Time series of monthly terrestrial water storage anomalies from 2001 to 2016, simulated by CoLM (under the noirrig, irrig-unlim, and irrig-lim schemes) and derived from GRACE (JPL dataset). The Pearson correlation coefficient (r) and root mean square error (RMSE) between the simulations and GRACE data are indicated in the panel. (b) Climatological monthly terrestrial water storage anomalies averaged over 2001–2016, simulated by CoLM and derived from GRACE.

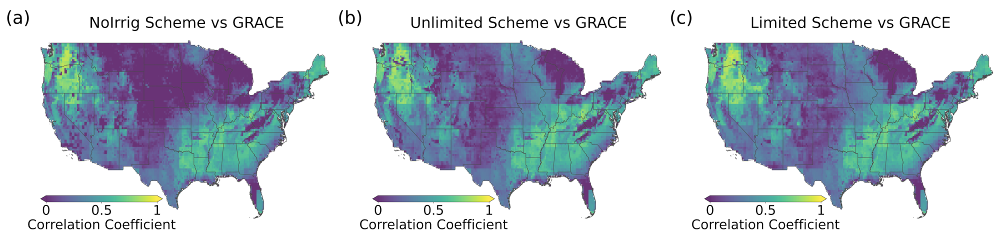

Figure S13. Comparison of observed and simulated monthly terrestrial water storage anomalies in the United States. (a) Spatial distribution of the Pearson correlation coefficient (r) between GRACE-derived TWS anomalies (JPL dataset) and CoLM simulations under the noirrig scheme. (b–c) Same as (a) but for the irrig-unlim and irrig-lim schemes, respectively.

R2C5: Experimental Design. Consider creating a table that clearly delineates the differences between each experiment. Specifically, the table should highlight the scheme-specific variations in surface water and groundwater supply between the two irrigation experiments. This would help improve clarity and facilitate comparisons.

Response: Thanks for your suggestion. We have added a table to clearly delineate the differences between the experiments. Please see Table 1 in the revised manuscript.

Table 1. Experiment Configurations.

Experiment	Management	Water limitation	Water sources
noirrig	Rainfed	NA	NA
irrig-unlim	Irrigated	No	NA
irrig-lim	Irrigated	Yes	Surface water and groundwater

R2C6: Figure 7. Although the simulations of latent heat flux and sensible heat flux have improved, there is still a discrepancy compared to FLUXCOM data. Additionally, the fact that irrigation leads to an underestimation of temperature from June to September needs further discussion.

Response: Thank you for your insightful comments. We fully agree with your observations. While CoLM has improved the simulations of latent and sensible heat fluxes, it still exhibits notable uncertainties, particularly a systematic underestimation of evapotranspiration, even in non-cropland or non-irrigated areas (Figure S7). This issue reflects inherent limitations in CoLM itself, which are beyond the scope of this study. We have discussed the potential uncertainties introduced by CoLM's parameterization, including those related to evapotranspiration simulations, in the revised manuscript (see Lines 890–906).

We also acknowledge that incorporating irrigation led to a pronounced cooling effect, resulting in an underestimation of temperature from June to September, when irrigation volumes are highest. The impact of irrigation on land surface temperature is complex, as previous studies have shown that irrigation can induce both cooling and warming effects (Hu et al., 2019; McDermid et al., 2023; Thiery et al., 2017). The cooling effect primarily arises from increased evapotranspiration. However, irrigation can also enhance atmospheric water vapor content, leading to increased absorption of longwave radiation and potential impacts on cloud formation, which may contribute to a warming effect (Dessler and Sherwood, 2009; Hu et al., 2019). Since this study employs offline land simulations, it does not account for irrigation-induced atmospheric feedbacks, which likely leads to an overestimation of the cooling effect and, consequently, an underestimation of temperature. This limitation is now explicitly discussed in the revised manuscript (Lines 753-762).

Lines 753–762: *"It is important to note that this study employs offline land simulations, which do not capture land-atmosphere interactions, potentially introducing biases in the estimated climate impacts. Previous studies have demonstrated that irrigation can induce both cooling and warming effects. While increased evapotranspiration contributes to cooling, irrigation can also enhance atmospheric water vapor content, leading to greater absorption of longwave radiation and potential cloud formation, resulting in warming (Dessler and Sherwood, 2009; Hu et al., 2019). These processes cannot be adequately represented in offline simulations, likely leading to an overestimation of irrigation-induced cooling and a subsequent underestimation of temperature (Figure 11g). Future studies should incorporate coupled land-atmosphere simulations to provide a more comprehensive assessment (Cook et al., 2015; Puma and Cook, 2010; Sacks et al., 2009)."*

R2C7: References. Some citations share the same author surname and publication year, which may cause linking issues. To resolve this, distinct labels (e.g.,2024a, 2024b) should be added, or additional author names can be included to differentiate them.

Response: Thanks for your suggestion. We have revised the references and citations accordingly by adding distinct labels. Please see Lines 96, 213, 348, and 509 in the revised manuscript.

R2C8: Figure S1. (1) Please confirm that the units in the figure (km3 -> km2 ?); (2) The color bar range needs to be adjusted. Due to at mid-latitudes (around 40°N), a 0.25°×0.25° grid cell covers approximately 770 km². Alternatively, you could use percentages to present the data for better clarity.

Response: Thank you for pointing out the unit error in the figure and for your constructive suggestion on improving the visualization. Following your suggestion, we have updated Figure S2 to present the data in percentages for better clarity.

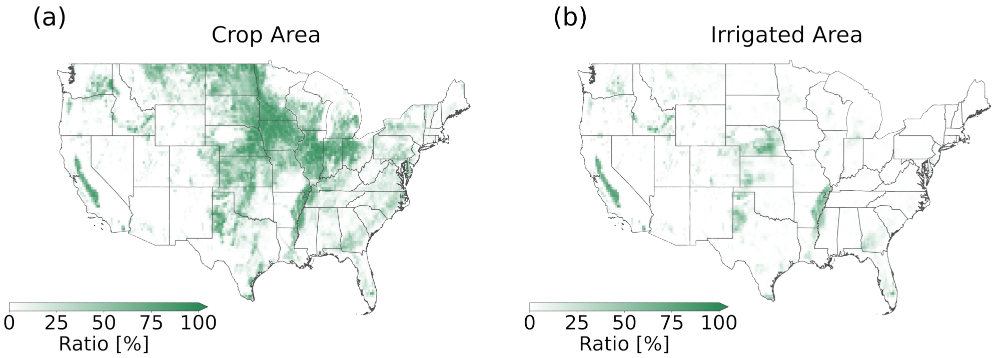

Figure S2. Spatial distribution of crop and irrigated area percentages within the study region. (a) Percentage of crop area. (b) Percentage of irrigated area.

R2C9: Since the validation of simulated irrigation is obtained from the USGS. I suggest including some supporting text related to USGS and show total irrigation water withdrawals and categorized by surface and groundwater sources in Table format as a supplementary text.

Response: As per your suggestion, we have expanded the description of USGS irrigation water withdrawal data in the revised manuscript (Lines 479-481) and added a table in the supplementary materials (Table S3) to show total irrigation water withdrawals along with withdrawals from surface and groundwater sources.

Table S3. Observed and simulated irrigation water withdrawals ($km^3\ yr^{-1}$).

Sources	USGS	irrig-unlim	irrig-lim
Total	166.23	290.94	120.81
Surface	92.60	NA	37.78
Groundwater	73.63	NA	81.43

Reference:

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