Incorporating irrigation effects into high-resolution daily land evaporation estimates over the Iberian Peninsula

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Response to the Editor and Reviewers

Dear Editor (Elham R. Freund), Reviewer 1 (Stefanie Fischer), and Anonymous Reviewer 2,

We would like to sincerely thank you for your careful evaluation of our manuscript and for your constructive comments and suggestions. We greatly appreciate the positive assessment of our work and the valuable feedback, which has helped us improve the clarity of the methodology, strengthen the discussion of the results and limitations, and substantially improve the overall quality of the manuscript. We have carefully considered all comments and revised the manuscript accordingly. Please see our full responses below. For ease of reading, the following colour scheme is used throughout this response letter:

- Original reviewer comments in **black**
- Our responses in blue
- New or revised text in the manuscript in green

Sincerely,

The authors

Reviewer 1 | Stefanie Fischer

R1-C1: The study under review ("Incorporating irrigation effects into high-resolution daily land evaporation estimates over the Iberian Peninsula") evaluates the GLEAM4 version at a 1 km spatial resolution over the Iberian Peninsula, comparing two approaches: (1) the default GLEAM4 framework, which implicitly accounts for irrigation through soil moisture and vegetation dynamics, and (2) an enhanced version that explicitly incorporates irrigation by integrating spatial information on irrigation extent and crop phenology (used to infer agricultural management timing) and by increasing soil water content to field capacity in the irrigated areas.

The model first computes potential evaporation (Ep) using the Penman equation, which is then reduced by a stress factor (S, ranging from 0 to 1). This stress factor is derived via a machine learning approach that accounts for environmental controls on evaporation (i.e. soil moisture, vapor pressure deficit, air temperature, global radiation, wind speed), particularly their influence on stomatal conductance.

The analysis covers the period 2018–2022, selected primarily because the underlying irrigation extent data (Meier et al., 2018) are static and based on 2018. Similarly, the crop phenology data (FAO, 2018) are also from 2018 and used to derive a daily irrigation mask. While the authors likely assume that irrigation practices remained relatively stable over this 5-year window, the rationale for choosing this specific time period is not explicitly stated in the manuscript. A key innovation lies in the dynamic application of this static irrigation mask: irrigation is only applied when the irrigation area intersects with short vegetation (as captured by the fraction of absorbed photosynthetically active radiation, fAPAR), thereby introducing a dynamic, biologically informed constraint on irrigation timing. Additionally, the model incorporates surface soil moisture data assimilation to improve soil moisture estimates.

Model performance is evaluated against daily evaporation observations from eight eddy covariance stations. Time series of modeled and observed evaporation are presented for two representative irrigated sites, with particular emphasis on the physical behavior of the stress factor and soil moisture dynamics under both irrigated and non-irrigated conditions. This allows for a meaningful assessment of the model's ability to represent the physical mechanisms governing evaporation.

Accurate estimation of evaporation is crucial for understanding the energy balance and hydrological cycle, as it directly influences other components such as runoff, soil moisture, and groundwater storage. In agricultural regions, especially in water-scarce environments and under climate change, capturing the impact of irrigation is essential for effective water resource management. The study addresses this need by developing a method to incorporate irrigation into the GLEAM4 framework, enabling the derivation of temporally continuous, high-resolution evaporation estimates at regional scales (with potential for extension to global applications).

The main limitation of the study is the use of static information on irrigation extent and timing, which is critically addressed. The method of soil moisture assimilation using the climatology from the irrigated GLEAM4 version is not entirely clear, nor is the rationale for running the non-irrigated GLEAM4 version without soil moisture data assimilation. This needs to be explained and justified more precisely in the methods chapter. In the results chapter, certain

regions of the study area are mentioned without a description of their location, which may hinder understanding for readers unfamiliar with the Iberian Peninsula or with limited background in European geography. Further details are provided in the comments attached.

Overall, the study is well designed, well structured, and clearly written. The results are presented in a clear manner and are supported by an appropriate number of figures that are well integrated into the text. I recommend the manuscript for publication after minor revisions.

We thank Stefanie Fischer for the careful reading of our manuscript and for the positive assessment of the study, its scientific approach, and the presentation of the results. We greatly appreciate the constructive comments, which have helped us improve the clarity and overall quality of the manuscript.

The rationale for selecting the study period has now been explicitly stated in the manuscript and reads: "The 2018–2022 period was selected based on the consistent availability of the datasets required by the proposed framework and because it encompasses contrasting hydroclimatic conditions, ranging from wet to dry years, providing a suitable period to evaluate the irrigation representation under different water-availability conditions."

The soil moisture data assimilation scheme and the rationale for excluding data assimilation from the benchmark experiment have also been clarified in the Methods, as detailed in our responses to R1-C6–R1-C9. The geographical context of the regions mentioned in the Results has also been improved, as addressed in R1-C12 and the related specific comments. The remaining specific comments are addressed individually below. We thank the reviewer once again for her constructive feedback.

R1-C2: L112: These rivers should be indicated in the map of the study area (e.g. in Figure 1), which helps the reader to keep track of the described areas (particularly those being not familiar with the region).

We agree that adding the rivers will help readers follow the text more easily. The rivers are now indicated in Panel *a* of Figure 1, which is reproduced below.

R1-C3: L150: Some variables are abbreviated, others are not... please first introduce the variable and give abbreviation in brackets: e.g. vegetation optical depth (VOD), air temperature (Ta) ...

We thank the reviewer for this comment. We have revised the manuscript to ensure that the variables vegetation optical depth (VOD), net radiation (R_n), transpiration (E_{t}), and bare soil evaporation (E_{b}) are properly defined at their first occurrence in the main text without considering Table 2. For variables such as precipitation (P) and air temperature (T_a), whose symbols are introduced in Table 2, we prefer to use their full names in the main text to improve readability. To make this distinction clear to readers, we have added the following note to the caption of Table 2: "Some variable symbols are used only within this table and are not adopted in the main text."

R1-C4: L193: Irrigated areas are represented on static information based on the year 2018 assuming these are still representative for 2019 - 2022... this needs to be considered in the discussion.

We agree with the reviewer. The irrigation extent used in this study is based on the static map of Meier et al. (2018), representative of 2018, and therefore assumes that the spatial distribution of irrigated areas remained relatively stable throughout 2018–2022. We note, however, that the spatial patterns of irrigation-induced increases in E broadly agree with those in the more recent ECIRA dataset over the Iberian Peninsula (Zhu et al., 2025), providing some support for the spatial representa-

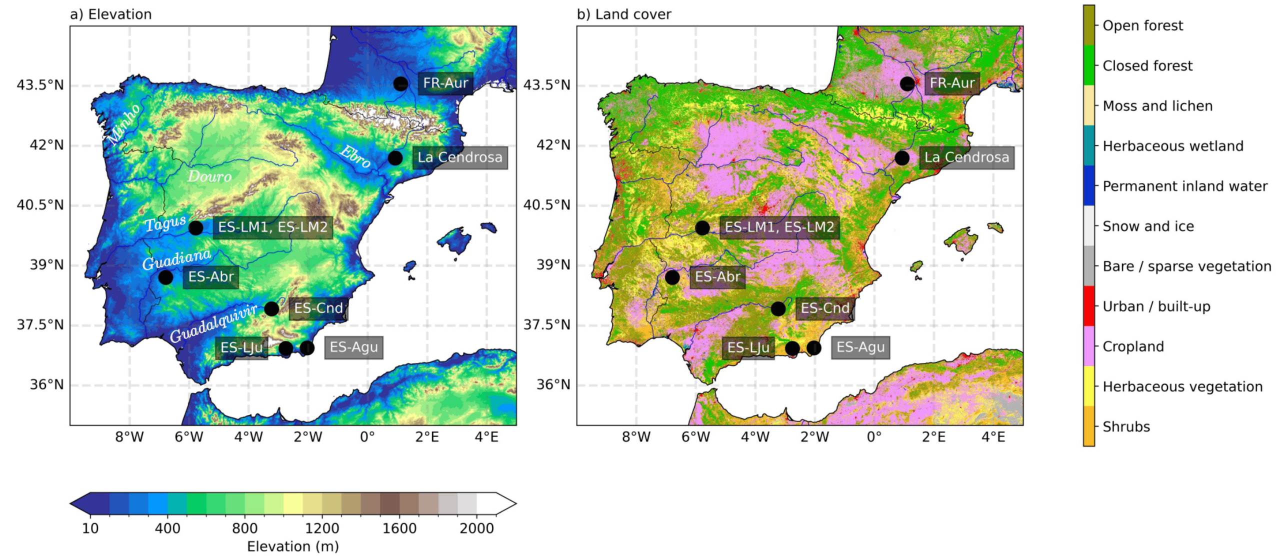

Figure 1. The Iberian Peninsula showing (a) elevation from the ETOPO Global Relief Model (NOAA, 2022), and (b) land cover from the CORINE Land Cover dataset (Bossard et al., 2000). Eddy-covariance stations are shown as black dots and river names in white text. For a detailed description of the sites, see Table 1.

tiveness of the irrigation mask. Nevertheless, potential changes in irrigation extent during 2019–2022 are not represented and remain a source of uncertainty. We have clarified this limitation in the Section *Contribution of irrigation in E estimates* as follows:

"It is also worth noting that the irrigation extent used in this study, based on the static map of Meier et al. (2018), is representative of 2018 and therefore assumes that the spatial distribution of irrigated areas remained relatively stable throughout 2018–2022. This assumption is reasonable over the relatively short study period, as changes in irrigation infrastructure at the kilometre scale generally occur over longer timescales, although regional exceptions may occur (Mehta et al., 2024). Nevertheless, potential changes during the study period are not represented and remain a source of uncertainty. The broad agreement with the more recent ECIRA dataset over the Iberian Peninsula (Zhu et al., 2025) further supports the spatial representativeness of the irrigation mask, although this comparison is not fully independent because both datasets incorporate information from GMIA."

R1-C5: L216: Grid-cells

Thanks! The typo has been corrected and now the text reads: "... applied. Grid-cells are flagged..."

R1-C6: L234: This is not clear to me. What is the baseline climatology for the anomalies?

Thank you for pointing this out. We have clarified that the anomalies are computed on a daily basis using the same period as the GLEAM4 simulation and are subsequently scaled to match the corresponding daily climatology of the GLEAM4 open-loop soil moisture estimates. The daily climatology is calculated as the multi-year mean soil moisture for each day of the year over the simulation period and smoothed using a 31-day moving window. This part has been substantially revised and now reads: "Soil moisture assimilation follows the sequential approach of Martens et al. (2017) and Miralles et al. (2025). GLEAM4 is first run over the full 2018–2022 period including the irrigation strategy but without data assimilation. The resulting soil moisture estimates are used to derive a daily soil moisture climatology, calculated as the multi-year mean soil moisture for each day of the year over the simulation period and smoothed using a 31-day moving window. Observed Sentinel-1 soil moisture anomalies are calculated over the same time frame, scaled to the corresponding GLEAM4 climatology, and subsequently assimilated through a Newtonian nudging scheme."

R1-C7: ... GLEAM4 soil moisture estimates including irrigation are based on static information of 2018 (despite the modulation through short vegetation fraction)... are these used to calculate the baseline climatology? Please justify

We thank the reviewer for this comment. The soil moisture climatology used for rescaling the Sentinel-1 observations is calculated over the full 2018–2022 simulation period, rather than from 2018 alone (see also our response to R1-C6). Specifically, GLEAM4 is first run over 2018–2022 with the irrigation strategy active but without soil moisture data assimilation, and the resulting soil moisture estimates are used to derive the daily climatology for scaling the Sentinel-1 soil moisture anomalies. Although the spatial extent of irrigation is based on a static map representative of 2018, the resulting irrigation inputs are not static: they vary dynamically with the simulated soil moisture state and meteorological forcing, with less water added under wetter conditions and more under drier conditions. The irrigation signal is further modulated by crop phenology and the dynamic short-vegetation fraction. We have clarified this point in the Methods section describing the assimilation scheme.

The text follows the additions made in response to R1-C6 and reads: "Although the spatial extent of irrigation is based on a static map representative of 2018, irrigation water inputs vary dynamically with the simulated soil moisture state and meteorological forcing, and are further modulated by crop phenology and the dynamic short-vegetation fraction."

R1-C8: Caption Figure 2: "(a) the model run without irrigation and soil moisture data assimilation". This is not clear to me... without irrigation and without soil moisture data assimilation?

Thanks for pointing out this ambiguity. The corresponding caption now reads: "...(a) the model run excluding both irrigation and soil moisture data assimilation, ...".

R1-C9: The original GLEAM4 Model without irrigation (Miralles et al. 2025) includes soil water assimilation, why omitting data assimilation here?

We thank the reviewer for pointing this out. Soil moisture observations over irrigated areas can implicitly capture the effects of irrigation on soil moisture dynamics. We therefore considered soil moisture data assimilation as part of the irrigation strategy, as it constrains the soil moisture dynamics (not the amounts, see R2-C2), and thus can help constrain the timing of irrigation-induced soil moisture changes. Consequently, our benchmark simulation excludes both the explicit irrigation scheme and soil moisture data assimilation, whereas the irrigation experiment includes both. We agree that this experimental design was not sufficiently clear in the manuscript and have revised the Methods and figure captions accordingly.

We modified point number three when introducing the data and methods, and it now reads: "...(iii) executing GLEAM4 at high resolution with two configurations: an irrigation experiment including both the explicit irrigation strategy and soil moisture data assimilation, and a benchmark experiment excluding both components; and...". Additionally, we explicitly explained why the data assimilation scheme is considered part of the irrigation strategy, and the modified text now reads: "Therefore, soil moisture assimilation is considered part of the irrigation strategy in this study, as observed soil moisture can implicitly capture the effects and timing of irrigation. Consequently, soil moisture assimilation is not applied in the benchmark open-loop simulation."

R1-C10: L320: The argumentation for the limited effect of false positives on soil moisture dynamics is plausibly explained but requires further analysis, as only two stations are used as a reference (discussion).

We agree with the reviewer that the limited number of stations was insufficient to support a general assessment of the effect of false positives. We therefore performed an additional spatial analysis over the Ebro irrigation system, comparing the global irrigation mask with an independent local irrigation dataset and evaluating the temporal correlation between E estimates from the benchmark and irrigation experiments in agreement areas and potential false-positive areas. This analysis provides a more spatially comprehensive assessment and shows that the irrigation implementation has a relatively smaller influence on the temporal dynamics of E in potential false-positive areas. The corresponding analysis and figure have now been included in the Results and Discussion. The text added to the manuscript and further details of this analysis are provided in our response to R2-C12.

R1-C11: L337: I understand that this paragraph aims to first introduce total E, before evaluating its components, but it's a bit hard to navigate, as it introduces Figure 6 but actually describes Figure 3b.

We agree that the original paragraph was difficult to navigate because it introduced Figure 6 while initially describing the spatial distribution of total E shown in Figure 3b. We have therefore reorganised the paragraph to first describe the spatial patterns of total E and then introduce Figure 6 to discuss its partitioning into E_t, E_i, and E_b.

The first paragraph describing E now starts as follows: "Figure 3b shows the spatial distribution of mean annual E for 2018–2022 based on the experiment that includes irrigation.", while the following paragraph, which describes the contributions of the individual components, starts with: "Figure 6 shows the spatial distribution of the main components of E (E_t, E_i, and E_b) for 2018–2022."

R1-C12: L340: Readers from outside the Iberian Peninsula or those without a strong background in European geography might struggle to visualize or locate the mentioned regions (e.g., Aragon, Andalusia). Please use a more descriptive language (in northern and southern Spain, respectively).

Thank you for this helpful suggestion. We have revised the paragraph to provide geographical context for the regions mentioned, making their locations more accessible to readers who may not be familiar with the geography of the Iberian Peninsula. In particular, we now indicate the approximate locations of the regions (e.g., northern, north-eastern, central-northern, and southern Spain) in the revised text:

- "... along the Mediterranean coast of Catalonia and Valencia in north-eastern Spain."

– "... Central System in central-northern Spain (Castile and León), ..."

– "... Iberian System in north-eastern Spain (Aragon), ..."

– "... and Sierra Morena in southern Spain (Andalusia), ..."

R1-C13: L343: The placement of the reference Miralles et al. (2025) is confusing, as it may be interpreted as a dataset, whereas Miralles et al. (2025) conducted a comparative analysis of GLEAM4 against other state-of-the-art evaporation datasets.

We would like to clarify that Miralles et al. (2025) is the reference presenting the GLEAM4 dataset. In addition to introducing GLEAM4, the study evaluates it against its previous version (GLEAMv3.8) and other state-of-the-art evaporation datasets, including ERA5-Land and FLUXCOM. We therefore consider the reference appropriate in this context.

R1-C14: L347: Please also add the range of Ei.

The range of E_i has been included in the sentence, and we have also added a geographical locator to help readers better identify the regions mentioned. The sentence now reads: "In relative terms, E_i generally contributes up to 20% of total E, mainly in forested areas of northern Spain, particularly Galicia, the Cantabrian Coast, and the Pyrenees, with values typically ranging from 0 to 180 mm yr^{-1}."

R1-C15: Caption Figure 5: The location of ES-Cnd (analogous to La Cendrosa) should be specified for clarity.

The geographical context for ES-Cnd has been added for consistency. The caption now reads: "Time series of E (top), S (middle), and soil moisture (bottom) at the La Cendrosa site (left panel), located within the Ebro Basin, and ES-Cnd (right panel), located in southern Spain. The blue line represents observed E, while the green and yellow lines depict estimates for the irrigated and non-irrigated experiments, respectively."

R1-C16: L357: In addition, is the fraction of bare soil increasing in winter (due to dormancy or agricultural practices), area corresponds to the cropland extent?

We agree with the reviewer that the higher winter E_b is also related to the seasonal increase in the bare soil fraction, particularly over cropland areas where vegetation cover decreases outside the growing season. We have revised the text accordingly and now reads: "In contrast, E_b reaches higher values during winter in the sparsely vegetated regions of central-western Spain, partly associated with the seasonal increase in the bare soil fraction, particularly over cropland areas; while remaining relatively low in summer due to strong water limitations during the dry season."

Reviewer 2

R2-C1: The paper entitled "Incorporating irrigation effects into high-resolution daily land evaporation estimates over the Iberian Peninsula" shows how the inclusion of irrigation in the GLEAM framework can improve the estimates of evaporation (E). The manuscript is well written and well structured, and I think it is a useful contribution. However, some aspects lack clarity, especially related to the workflow to include irrigation. I asked for minor revisions because I believe most comments can be answered via in-text clarifications. They come from my own background in irrigation and data assimilation, so they are somewhat focused on that part of the workflow. I hope that this helps to improve and strengthen the manuscript.

We sincerely thank the reviewer for the careful reading of our manuscript, the positive assessment of our work, and the constructive comments. We particularly appreciate the reviewer's expertise in irrigation and data assimilation, which provided valuable suggestions for improving the clarity of the irrigation workflow and strengthening the manuscript. We have addressed all specific comments below and incorporated the corresponding clarifications into the revised manuscript.

R2-C2: The connection between the "irrigation scheme", i.e. bringing the SM to FC, and the subsequent S1-SSM DA is not entirely clear. The anomalies are rescaled to the climatology of the open loop, which already contains the irrigation (SM to FC) (L233-235), so does the SM end up hovering around FC during the growing season? If that is the case, the DA can likely only adjust the timing and not the irrigation amounts. Related to this, if there is consistent irrigation (S1-SSM consistently higher), the anomalies would lose the irrigation signal. Could the authors clarify what the DA actually adds here? Did the authors perform any experiments of irrigation (back to FC) without DA to better clarify the impact of the DA?

Bringing soil moisture to field capacity represents an irrigation update rather than a constraint that subsequently maintains soil moisture at field capacity. Following this update, the normal GLEAM4 water balance operates, and soil moisture can decrease through transpiration, and drainage. This behaviour can be observed in Fig. 5, where soil moisture remains generally higher when irrigation is included but does not systematically remain close to field capacity. We have clarified this point in the *Irrigation representation* Section as follows: "Increasing soil moisture to field capacity represents an irrigation update rather than a constraint that maintains soil moisture at field capacity. Following this update, soil moisture evolves according to the GLEAM4 water balance and can decrease through transpiration, and drainage."

Soil moisture data assimilation subsequently provides an observational constraint on the simulated soil moisture trajectory. This is particularly relevant because the FAO phenology data define a broad potential irrigation period, from the start to the end of the growing season, rather than the actual timing of irrigation events. Assimilation of Sentinel-1 observations can therefore correct deviations of simulated soil moisture from the observed evolution within this period, thereby constraining the timing and persistence of the simulated irrigation signal.

We nevertheless agree with the reviewer that assimilating anomalies has implications for the information provided by the observations. Because Sentinel-1 soil moisture anomalies are rescaled against the climatology of the irrigation-active simulation, the assimilation primarily constrains departures from this climatological state rather than the absolute irrigation-induced soil moisture increase. Consequently, a persistent systematic soil moisture offset associated with irrigation may be partly removed by the anomaly calculation. Data assimilation therefore does not directly determine irrigation amounts, which remain controlled by the modelled soil water deficit to field capacity, but instead provides an observational constraint on the resulting soil moisture dynamics. We have clarified this distinction in the revised manuscript by adding the following text:

"In this framework, data assimilation does not directly determine irrigation amounts, which are controlled by the modelled soil water deficit to field capacity, but instead constrains the resulting soil moisture dynamics. This is particularly relevant because the FAO phenology data define a broad potential irrigation period rather than the actual timing of irrigation events. Sentinel-1 assimilation can therefore correct deviations from the observed soil moisture evolution within this period, constraining the timing and persistence of the simulated irrigation signal. However, because soil moisture anomalies are rescaled against the climatology of the irrigation-active simulation, the assimilation primarily constrains departures from this climatological state, and persistent irrigation-related soil moisture offsets may be partly removed."

Finally, although an irrigation simulation without data assimilation is generated as an intermediate step to derive the GLEAM4 soil moisture climatology used for rescaling the Sentinel-1 observations, we did not evaluate this simulation as a separate experiment. The experiments presented in this study were designed to compare the benchmark configuration with the complete irrigation framework, in which soil moisture assimilation is considered an integral component.

R2-C3: The distinction between which soil depth is meant is not always clear. Is the surface soil moisture set to FC, or the entire profile, or the root zone? The manuscript never mentions rooting depth, so it is not clear whether a constant root zone is assumed or something dynamic. This matters more than usual here, because L141–143 states that GLEAM4 runs a multi-layer water balance that also accounts for plant access to groundwater (Hulsman et al., 2023), but this component is not mentioned again anywhere in the paper. Could the authors clarify which layers are reset to FC, whether FC is layer-specific, and how the groundwater access module behaves in the irrigated run? In general, the authors should clarify which soil depth they are talking about throughout the manuscript.

We thank the reviewer for this comment. We agree that the soil depth affected by the irrigation scheme was not sufficiently clear in the original manuscript. Irrigation is applied to the entire soil profile associated with the short-vegetation fraction, i.e., the first and second soil layers, which together represent the 0–100 cm root zone in the fraction of short vegetation. The soil moisture in these layers is increased to their corresponding field-capacity values when the irrigation conditions are met. We have revised the manuscript to explicitly clarify this point as follows: "For grid-cells and periods identified as irrigated, root-zone soil moisture is increased to field capacity within the short-vegetation fraction of each grid-cell before the computation of S."

Additionally, we have also expanded the general description of the GLEAM4 soil water balance (*GLEAM4 baseline* Section) to specify the soil and rooting depths associated with the different land-cover fractions and to explain how the effective root-zone depth varies with the dynamic vegetation fractions. These additions are described in our response to R2-C5. Finally, the role of plant access to groundwater and its treatment in the irrigation experiment are clarified in our response to R2-C4.

R2-C4: GLEAM4 accounts for plant access to groundwater (L141–143), but this is not discussed further. Since plants may already be sustaining E through groundwater in the benchmark run, the difference in E between the two runs may not be fully representative of irrigation. Could the authors discuss this?

We thank the reviewer for raising this point. Plant access to groundwater is represented consistently in both the benchmark and irrigation experiments. Therefore, the differences in E between the two experiments represent the additional effect of the irrigation framework relative to a baseline in which groundwater-sourced transpiration is already considered. We agree, however, that groundwater access can reduce the incremental response of E to irrigation in areas where groundwater already compensates for water limitation. In GLEAM4, the contribution of groundwater to transpiration increases under dry soil conditions when groundwater is accessible to the root zone, whereas it decreases as root-zone soil moisture approaches field capacity (Hulsman et al., 2023). Consequently, groundwater and irrigation should not be interpreted as independent or additive contributions to E: irrigation can partly replace groundwater as a source of water for transpiration. We have clarified this interaction and its implications for the interpretation of the differences between the two experiments in the revised manuscript (L297-303), and now the explanation reads as follows:

"It should also be noted that plant access to groundwater is represented in both experiments and can therefore influence the magnitude of the estimated irrigation effect. In areas where accessible groundwater already reduces plant water stress, the additional response of E to irrigation may be smaller. Moreover, groundwater and irrigation are not independent water sources in GLEAM4, as the contribution of groundwater to transpiration decreases as root-zone soil moisture approaches field capacity (Hulsman et al., 2023). Consequently, the differences between the experiments represent the additional effect of the irrigation strategy given the groundwater contribution already represented by GLEAM4."

R2-C5: The propagation of the DA updates from the surface to the deeper layers is said to be done via process-based modelling (L237). Could the authors clarify which processes (Richards equation, other)? It might be defined in the description of GLEAM v4 but it would be useful to have it here. Also, is the added water conserved, i.e. could it drain?

We thank the reviewer for this comment. We have expanded the description of the GLEAM4 soil water balance to explain that vertical water transfer between soil layers is represented through a simplified formulation of Darcy's law, and we now explicitly specify the soil and rooting depths considered for the different land-cover fractions. Drainage depends on the relative saturation of the soil layers and the difference in soil moisture between adjacent layers (Martens et al., 2017). Consequently, the soil moisture update introduced by data assimilation in the surface layer becomes part of the modelled soil water balance and can subsequently drain towards deeper layers. This information has been added to the revised Methods and reads as follows:

"GLEAM4 uses a multi-layer running water balance accounting for plant access to groundwater, which plays an important role in sustaining vegetation during dry conditions (Hulsman et al., 2023). The water balance considers precipitation and snowmelt as inputs and E and drainage as outputs. The model assumes a constant soil depth for the bare-soil fraction (0–5 cm), and constant rooting depths for short vegetation (0–100 cm) and tall vegetation (0–250 cm) fractions. However, because the relative land cover fractions vary dynamically in space and time, as described by Zhong et al. (2022), the effective rooting depth at the grid-cell level varies according to the evolving land-cover composition. Water is transferred between soil layers through a simplified representation of Darcy's law, in which vertical drainage is parametrised based on the relative saturation of adjacent soil layers and the soil moisture gradient between them (Martens et al., 2017; Miralles et al., 2025)."

R2-C6: If I read L219-220 correctly, SM is increased to FC only within the short vegetation fraction. But ES-Cnd is described in Table 1 as a woody savanna with irrigated olives, and L115-116 lists olives, grapes and fruit trees among the irrigated crops of the Ebro, is that defined as short? If not, how does irrigation then reach the tall vegetation fraction, which is actually irrigated?

We thank the reviewer for highlighting this important limitation. In the current implementation, irrigation is applied only to the short-vegetation fraction. At ES-Cnd, this means that irrigation is not explicitly assigned to the tall-vegetation fraction representing the irrigated woody crops. Extending irrigation indiscriminately to the tall-vegetation fraction could improve the representation of irrigation at this and other irrigated woody-crop sites, but at the expense of introducing irrigation in many areas where tall vegetation is not irrigated. We have therefore clarified this limitation in the manuscript (*Limitations and future work* Section) as follows:

"As reliable information on irrigation practices and irrigated crop types is not consistently available at the global scale, irrigation is currently applied only to the short-vegetation fraction in our implementation. Consequently, irrigated crops represented within the tall-vegetation fraction may be misrepresented. Addressing this limitation would require crop-specific information on irrigation. However, because most crops are shorter than 2 m, which is the height threshold used in GLEAM4 to distinguish short from tall vegetation, indiscriminately extending irrigation to the entire tall-vegetation fraction would likely improve the representation of a limited number of irrigated woody-crop sites at the expense of introducing false positives across non-irrigated woody ecosystems."

Additionally, we highlight the need for improved irrigation datasets capable of distinguishing between irrigated short- and tall-vegetation crops, as follows: "Future work should therefore focus on developing methods that combine multiple complementary data sources (e.g., land surface temperature, vegetation dynamics, microwave backscatter, gravimetric observations, census information, and local irrigation statistics) to produce long-term, global, dynamic irrigation datasets capable of distinguishing between irrigated short- and tall-vegetation crops."

R2-C7: At La Cendrosa the irrigated run still underestimates E quite strongly (Fig 5a: observations up to about 8 mm/day against about 4 mm/day simulated). Even with SM at FC the model does not reach the observed fluxes, which points more towards the stress module than towards water availability. Were irrigated croplands part of the training data of the S model? On a related note, γ going from 1.63 to 0.52 is described as moving closer to one, but it flips from over- to underestimation of the variability, so I would phrase this more carefully.

We agree with the reviewer that the remaining underestimation of E at La Cendrosa cannot be attributed solely to water availability. Irrigated croplands were not explicitly represented in the training of the S model, which may limit its response to increased plant-available water. We have therefore expanded the discussion to acknowledge three potential sources of the remaining discrepancy. The text now reads as follows: "Despite the improved performance at this site, the remaining underestimation of E may arise from several factors: (i) irrigation is not applied to the bare-soil fraction, which may be particularly relevant under flood irrigation or at the beginning of the growing season when irrigation is applied but crops haven't grown yet; (ii) irrigated croplands were not explicitly represented in the training of the S model, potentially limiting its response to increased plant-available water; and (iii) uncertainties in the input datasets used as predictors of S may propagate into the estimated stress. Future developments could therefore target both the representation of irrigation over bare soil and the response of S over irrigated croplands."

Additionally, we have also revised our interpretation of γ and now state that it "switches from overestimating (1.63) to underestimating (0.52) the observed variability, indicating that the model still does not fully capture it."

R2-C8: Areas with flood irrigation have (1) a different evaporation and (2) high uncertainty in the retrievals, and La Cendrosa, which shows the largest improvement, is exactly a flood or gravity irrigated site (Table 1). Could the authors acknowledge this?

We agree with the reviewer that the characteristics of flood irrigation and the associated uncertainty in soil moisture retrievals should be considered when interpreting the results at La Cendrosa. We have therefore added the following text where we discuss the improvements in E associated with the inclusion of irrigation: "La Cendrosa is managed using flood (gravity) irrigation, which can produce abrupt increases in surface soil moisture and E following irrigation events. These very wet surface conditions may also increase uncertainty in Sentinel-1 soil moisture retrievals due to reduced radar sensitivity at high soil moisture levels."

R2-C9: In general, the S1-SSM uncertainties and limitations could be better acknowledged. The manuscript mentions subsurface scattering over dry soils (L300, L368), but not the other end, i.e. saturation and canopy attenuation over denser crops such as maize.

We have included additional uncertainties associated with the use of backscatter-based soil moisture retrievals. We have revised the text in the *Ability to capture E dynamics* Section and added relevant literature. The text now reads: "Additionally, backscatter–based products, such as the 1 km S1-DPA soil moisture product (C-band SAR), are affected by subsurface scattering over dry soils, signal saturation under wet conditions, vegetation attenuation (particularly relevant for dense irrigated crops such as maize), changes in surface roughness, and limited revisit frequency. These factors can reduce the sensitivity of backscatter to soil moisture variations and limit the temporal continuity and accuracy of the resulting soil moisture retrievals (McNairn and Shang, 2016; Wagner et al., 2022; Busschaert et al., 2024)."

R2-C10: The KGE numbers in the abstract do not match the results. The abstract reports increases of 0.40 and 0.70, while L305-310 give -0.48 to 0.19 at La Cendrosa (an increase of 0.67) and 0.21 to 0.40 at ES-Cnd (an increase of 0.19). The 0.40 looks like the final KGE of ES-Cnd rather than the increase.

The numbers in the abstract have been corrected, and the text now reads: "... irrigation of 0.19 and 0.67, respectively."

R2-C11: Fig 3 c): does the delta truly stop at 0? Are there any negative values? Since run (a) also lacks the DA there could be some, so please explain.

Indeed, negative differences occur in Fig. 3c because the benchmark experiment does not include soil moisture data assimilation, whereas the irrigation experiment does. However, these negative differences are generally small, with a mean daily value of approximately -0.15 mm day^{-1} across the Iberian Peninsula. The standard deviation of the daily negative differences ranges from 0.18 to 0.28 mm day^{-1} depending on the year. Values below zero were already represented by the lower extension of the colour bar in Fig. 3c, but we agree that this was not sufficiently clear. We have therefore explicitly clarified the occurrence and origin of these negative differences in the revised manuscript as follows: “Small negative differences also occur locally over non-irrigated locations (mean of approximately -0.1 mm day^{-1} when considering only pixels and times with negative differences), reflecting the additional effect of soil moisture data assimilation in the irrigation experiment.”

R2-C12: The claim that the approach is relatively robust to false positives (abstract and L407) rests on three sites, of which two (ES-LM1 and ES-LM2) are almost co-located, and the KGE decreases at both. Only FR-Aur improves slightly. I would soften this. False negatives, i.e. irrigated areas missed by the mask, are not assessed at all.

We thank the reviewer for this comment. We agree that three sites were insufficient to support a general claim of robustness to false positives. We therefore added a spatial assessment comparing the global irrigation mask with an independent local irrigation dataset over the Ebro irrigation system. Areas identified as potential false positives showed substantially higher temporal correlations between the benchmark and irrigation experiments than areas classified as irrigated by both datasets (median difference = 0.33; mean difference = 0.27; $p < 0.001$). This indicates that the irrigation implementation has a smaller influence on the temporal dynamics of E in potentially misclassified areas. The new analysis and corresponding figure have been included in the Results and Discussion. We have added the following text and figure to the end of the *Contribution of irrigation in E estimates* Section:

Figure 4 assesses the sensitivity of the irrigation strategy to spatial misclassification, particularly false positives, over the Ebro irrigation system in north-eastern Spain. First, Figure 4a shows the spatial distribution of the temporal Pearson correlation between daily E estimates from the benchmark and irrigation experiments over 2018–2022. To identify potential false positives in the irrigation mask, we then compared the global irrigation map of Meier et al. (2018) with an independent local irrigation dataset at 1.1 km spatial resolution, derived from the 1:50,000 map sheets of the *Mapa de Usos y Aprovechamientos de España* (https://sig.mapama.gob.es/). Based on this comparison, Figure 4b distinguishes grid-cells classified as irrigated by both datasets (agreement areas, shown in blue) from those classified as irrigated by Meier et al. (2018) but as non-irrigated in the local dataset (potential false positives, shown in red). Finally, Figure 4c compares the distributions of the temporal correlations shown in Figure 4a between these two classes. Correlations were substantially higher in potential false-positive areas than in agreement areas, with a median difference of 0.33 and a mean difference of 0.27. The distributions differed significantly (two-sided Mann–Whitney U test, $p < 0.001$; KS statistic = 0.602). Higher correlations indicate greater agreement between the temporal dynamics of E in the benchmark and irrigation experiments, and therefore a smaller influence of the irrigation implementation. Conversely, lower correlations in agreement areas indicate that irrigation produces stronger changes in the temporal dynamics of E where both datasets consistently identify irrigation.

R2-C13: Fig 4: the text boxes on the map are difficult to read. Would it be possible to increase the fontsize? Alternatively, a table with KGE, r, β and γ for all sites and both experiments could also help.

We thank the reviewer for this suggestion. We have increased the font size of the text boxes in Fig. 4, which substantially improves their readability. We considered adding a table with the performance metrics for all sites and both experiments but opted to retain the figure only to keep the presentation of the results concise. In particular, at the three non-irrigated sites that are also correctly classified as non-irrigated by the irrigation mask (ES-Abr, ES-Lju, and ES-Agu), the performance remains

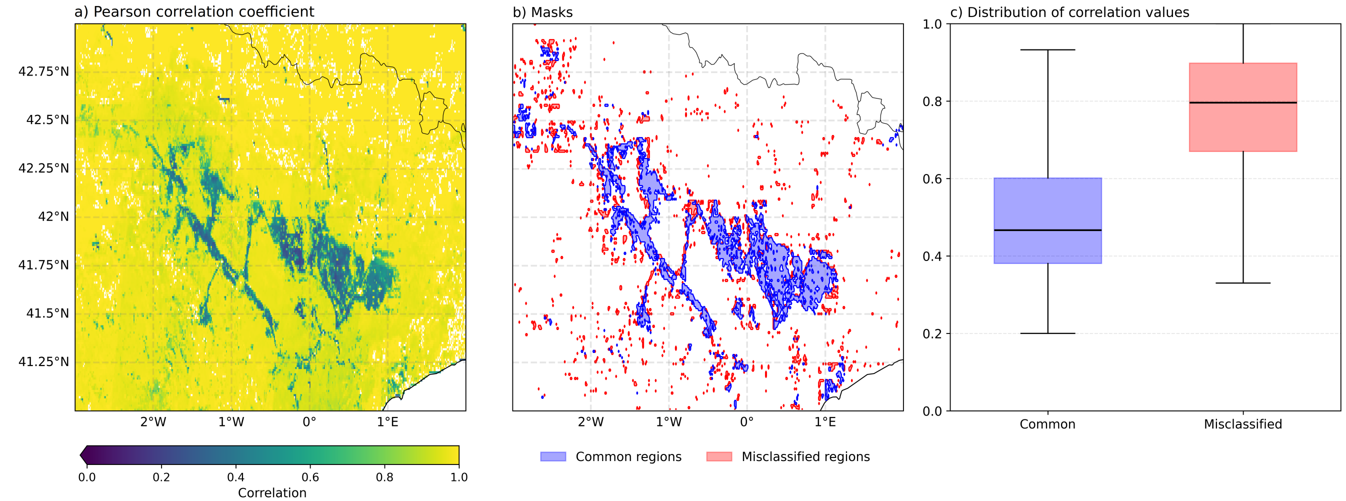

Figure 2. Assessment of the sensitivity of the irrigation strategy to potential false positives in the irrigation mask over the Ebro irrigation system. (a) Spatial distribution of the temporal Pearson correlation between daily E estimates from the benchmark and irrigation experiments over 2018–2022. (b) Comparison between the global irrigation map of Meier et al. (2018) and an independent local irrigation dataset derived from the 1:50,000 map sheets of the *Mapa de Usos y Aprovechamientos de España* (https://sig.mapama.gob.es/). Blue indicates areas classified as irrigated by both datasets (agreement areas), while red indicates areas classified as irrigated by Meier et al. (2018) but as non-irrigated by the local dataset (potential false positives). (c) Distribution of the temporal correlations shown in panel (a) for the two classes identified in panel (b).

practically unchanged between the two experiments, as the main difference between them at these locations arises from soil moisture data assimilation. We have clarified this point in the revised figure caption. Please note that, for consistency with our responses to R1-C9 and R2-C2, we use the terms “irrigation experiment” and “benchmark experiment”. The updated figure and caption are provided below:

R2-C14: L401: missing space after the comma in “transpiration,thereby”

Thanks. The typo has been corrected, and the text now reads: “... transpiration, thereby ...”.

R2-C15: L216: “grid-cells” ⟶ “Grid-cells”

Thanks! The typo has been corrected and now the text reads: “... applied. Grid-cells are flagged...”

R2-C16: L407: “constrained by fractional-vegetation approach” ⟶ “constrained by the fractional-vegetation approach”

The text now reads: “... constrained by the fractional-vegetation approach...”

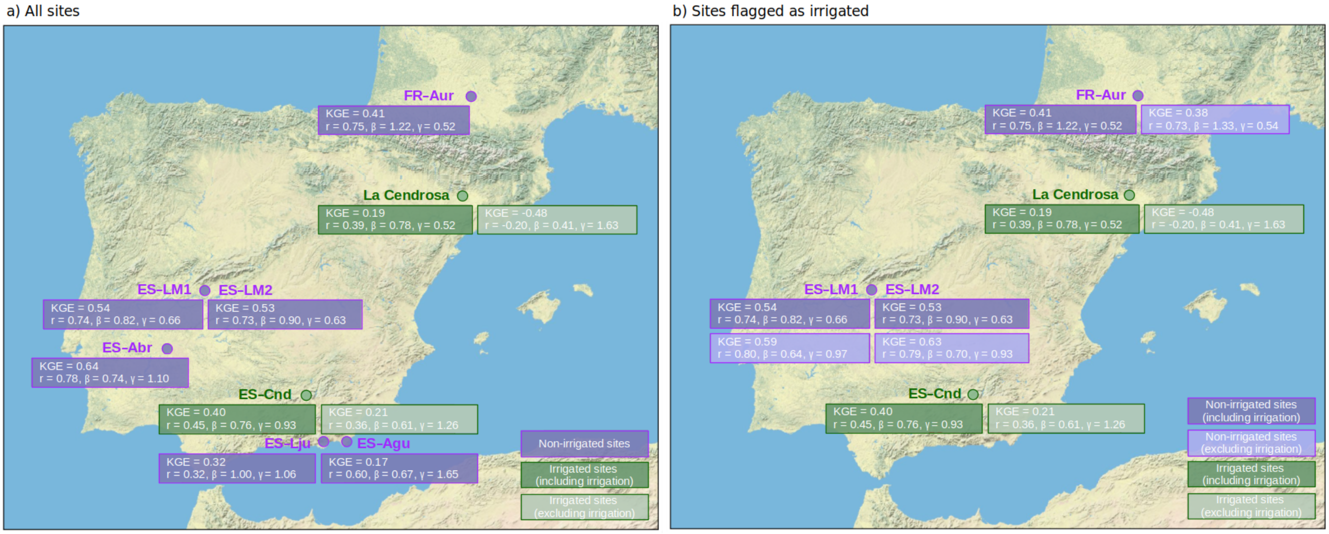

Figure 3. Performance of GLEAM4 E estimates at eddy-covariance sites using the KGE and its components. (*a*) All evaluated sites, distinguishing non-irrigated (purple) and irrigated (green) locations. For irrigated sites, results are shown for both the irrigation (dark green) and benchmark (light green) experiments. (*b*) Subset of sites classified as irrigated by the dynamic mask, including three non-irrigated sites incorrectly identified as irrigated (purple). Results are shown for both the irrigation (darker colours) and benchmark (lighter colours) experiments. Results from both experiments are not shown separately for the three non-irrigated sites correctly classified as non-irrigated (ES-Abr, ES-Lju, and ES-Agu), as their performance remains practically unchanged between the two experiments.

References

Bossard, M., Feranec, J., Otahel, J., et al.: CORINE land cover technical guide: Addendum 2000, vol. 40, European Environment Agency Copenhagen, 2000.

Busschaert, L., Bechtold, M., Modanesi, S., Massari, C., Brocca, L., and De Lannoy, G. J.: Irrigation quantification through backscatter data assimilation with a buddy check approach, Journal of Advances in Modeling Earth Systems, 16, e2023MS003 661, https://doi.org/https://doi.org/10.1029/2023MS003661, 2024.

Hulsman, P., Keune, J., Koppa, A., Schellekens, J., and Miralles, D. G.: Incorporating plant access to groundwater in existing global, satellite-based evaporation estimates, Water Resources Research, 59, https://doi.org/https://doi.org/10.1029/2022WR033731, 2023.

Martens, B., Miralles, D. G., Lievens, H., Van Der Schalie, R., De Jeu, R. A., Fernández-Prieto, D., Beck, H. E., Dorigo, W. A., and Verhoest, N. E.: GLEAM v3: Satellite-based land evaporation and root-zone soil moisture, Geoscientific Model Development, 10, 1903–1925, https://doi.org/https://doi.org/10.5194/gmd-10-1903-2017, 2017.

McNairn, H. and Shang, J.: A review of multitemporal synthetic aperture radar (SAR) for crop monitoring, Multitemporal remote sensing: Methods and applications, pp. 317–340, https://doi.org/https://doi.org/10.1007/978-3-319-47037-5_15, 2016.

Mehta, P., Siebert, S., Kummu, M., Deng, Q., Ali, T., Marston, L., Xie, W., and Davis, K. F.: Half of twenty-first century global irrigation expansion has been in water-stressed regions, Nature Water, 2, 254–261, https://doi.org/https://doi.org/10.1038/s44221-024-00206-9, 2024.

Meier, J., Zabel, F., and Mauser, W.: A global approach to estimate irrigated areas–a comparison between different data and statistics, Hydrology and Earth System Sciences, 22, 1119–1133, https://doi.org/https://doi.org/10.5194/hess-22-1119-2018, 2018.

Miralles, D. G., Bonte, O., Koppa, A., Villanueva, O. B., Tronquo, E., Zhong, F., Beck, H., Hulsman, P., Dorigo, W., Verhoest, N. E., et al.: GLEAM4: global land evaporation dataset at 0.1 resolution from 1980 to near present, Scientific Data, https://doi.org/https://doi.org/10.1038/s41597-025-04610-y, 2025.

NOAA: ETOPO 2022 15 arc-second global relief model, https://doi.org/https://doi.org/10.25921/fd45-gt74, 2022.

Wagner, W., Lindorfer, R., Melzer, T., Hahn, S., Bauer-Marschallinger, B., Morrison, K., Calvet, J.-C., Hobbs, S., Quast, R., Greimeister-Pfeil, I., et al.: Widespread occurrence of anomalous C-band backscatter signals in arid environments caused by subsurface scattering, Remote Sensing of Environment, 276, 113 025, https://doi.org/https://doi.org/10.1016/j.rse.2022.113025, 2022.

Zhong, F., Jiang, S., Dijk, A. I. J. M. v., Ren, L., Schellekens, J., and Miralles, D. G.: Revisiting large-scale interception patterns constrained by a synthesis of global experimental data, Hydrology and Earth System Sciences, 26, 5647–5667, https://doi.org/https://doi.org/10.5194/hess-26-5647-2022, 2022.

Zhu, W., Baumert, J., Storm, H., Heckelei, T., and Siebert, S.: ECIRA-European crop-specific irrigated area at 1 km resolution annually from 2010 to 2020, Scientific Data, 12, 1349, https://doi.org/https://doi.org/10.1038/s41597-025-05628-y, 2025.