Response to reviewers' comments on egusphere-2026-4199

We would like to thank Dr Pierre Tiengou and an anonymous reviewer for their comments. We are very grateful for their constructive feedback, which has helped us clarify several important aspects of the manuscript and strengthen both the methodology and discussion. In the following document, we provide a point-by-point response to their comments. Our responses are shown in blue.

Comments by Anonymous Referee #1

This manuscript investigates the impacts of irrigation on the top-of-atmosphere (TOA) radiative budget, a topic that has received sustained attention over the past decades. The primary novelty of this study lies in the use of seven models from the Irrigation Model Intercomparison Project (IRRMIP), which substantially reduces the model dependence. In addition, the authors compare clear-sky and all-sky radiation-related variables to indirectly assess the impact of cloud-related variables on the TOA radiative budget. Finally, they employ a fully coupled Earth system model (CESM2) to investigate the future evolution of irrigation-induced radiative forcing (Rn,TOA). Overall, this study focuses on a well-defined scientific question. Although the analytical framework is relatively straightforward, the results are presented in considerable detail. I have several comments that I hope will help further improve the manuscript.

We thank the reviewer for these very constructive comments. We have addressed the reviewer's comments in this response and have made modifications to the manuscript.

1. Model dependence in future projections. One of the major strengths of this study is the use of a multi-model ensemble to reduce model dependence in the historical analysis. However, this advantage is largely lost in the future projections, where only a single model (CESM2) is employed. As a result, the projected future changes may be strongly influenced by model-specific characteristics, weakening one of the manuscript's main innovations. The authors should either justify this choice more clearly or discuss the associated uncertainty more explicitly.

Response:

We thank the reviewer for highlighting this important limitation. At present, CESM2 is the only model for which future irrigation experiments under the selected scenarios are available within the IRRMIP framework; no other participating groups have performed the corresponding future simulations. We therefore use CESM2 to provide an initial assessment of the potential future evolution of irrigation-induced radiative effects, while acknowledging that these projections may be influenced by model-specific characteristics. The following statement is added in the revised manuscript:

L501: "In addition, the future projections are currently available only from CESM2, as no other IRRMIP modelling groups have performed the corresponding future irrigation experiments. Consequently, the magnitude and regional patterns of the projected responses may be influenced by CESM2 specific characteristics and should be interpreted as preliminary rather than as a robust multi-model projection."

2. Uncertainty associated with cloud parameterization. Cloud-related processes form one of the primary mechanisms used to interpret the TOA radiative responses throughout the manuscript. However, cloud representation remains one of the largest sources of uncertainty in current climate models. Consequently, the inferred cloud contributions should be interpreted with caution. I recommend that the authors explicitly acknowledge this uncertainty, particularly in the Conclusions.

Response:

We thank the reviewer for highlighting this important point. We fully agree that uncertainties in the representation of clouds and cloud-radiation interactions are an important source of uncertainty when interpreting ERF.

The following text is added in the revised manuscript to acknowledge this limitation:

L296: "Several models also show isolated positive (> +1 W m^{-2}) and negative (< -1 W m^{-2}) ERF patches over the oceans. Under clear-sky conditions, most of these oceanic features disappear, with ERF values generally remaining between -1 and +1 W m^{-2} (Fig. 4). This contrast indicates that the oceanic anomalies in the all-sky fields may be associated with cloud-related radiative effects. This contribution should, however, be interpreted with caution, given structural uncertainties in cloud representation across models. At the same time, the multi-model consistency of several key spatial patterns and physical relationships provides confidence that the main features of the irrigation-induced radiative response are not specific to a single model formulation. All-sky versus clear-sky comparison provides a diagnostic estimate of the net cloud contribution rather than a process attribution, and its magnitude remains model dependent.".

3. Mechanistic interpretation of regional heterogeneity. The manuscript provides detailed descriptions of the spatial heterogeneity of irrigation-induced radiative effects. However, the interpretation is largely qualitative, relying on spatial coincidence with potential controlling variables and previous literature. A more mechanistic explanation is needed to explain why different regions exhibit markedly different responses and why the dominant controls vary geographically. For example, in Line 373, the authors state that "EAS is distinct in showing a sign reversal under clear-sky conditions, with ΔRn,TOA transitioning from weakly positive to weakly negative after approximately 2030-2040 under both scenarios.". This behavior is particularly interesting but is not adequately explained. Likewise, why do the clear-sky and all-sky responses remain so similar over East Asia? More detailed physical interpretation would substantially improve the manuscript.

Response:

We thank the reviewer for this important comment. The following text:

"EAS is distinct in showing a sign reversal under clear-sky conditions, with ΔRn,TOA transitioning from weakly positive to weakly negative after approximately 2030-2040 under both scenarios"

Is replaced by:

L415: "East Asia exhibits a distinct radiative regime in which the competing longwave and shortwave effects of irrigation are more closely balanced. Irrigation-induced moistening tends to increase atmospheric longwave trapping, producing a positive clear-sky contribution, but this effect is relatively weak compared with the strong positive response over SAS and WCA. At the same time, the historical analysis shows a consistent negative relationship between low- and medium-level cloud changes and ERF over EAS, indicating that cloud-related shortwave reflection can offset part of the longwave effect. Under the future CESM2 simulations, the clear-sky ΔRn,TOA in EAS changes from weakly positive to weakly negative around 2030-2040 in both scenarios, suggesting that the balance between the competing radiative components evolves as the background climate and irrigation-induced hydrological response change. In addition, the small difference between the all-sky and clear-sky responses over EAS suggests that the net cloud contribution is insufficient to substantially modify the already weak clear-sky signal, indicating that non-cloud processes also contribute to the negative radiative response. Overall, across all regions, clear-sky ΔRn,TOA is consistently equal to or larger than all-sky ΔRn,TOA, indicating that cloud adjustments exert a systematic damping influence on the ΔRn,TOA response to irrigation in the future projections, mirroring the all-sky/clear-sky relationship found for the historical ERF"

4. Line 91: The manuscript states that IRRMIP contains eight participating models. Why were only seven models included in the analysis.

Response:

We thank the reviewer for pointing this out. We confirm that eight models participated in the IRRMIP protocol, including IPSL-CM6. However, the atmospheric variables required for the present analysis were not available for IPSL-CM6. Consequently, IPSL-CM6 could not be included in the multi-model analysis, and the results presented here are based on the seven models for which the required atmospheric and radiative variables were available.

We now include the following text in Section 2.1:

L143: "Although eight models so far contributed simulations to IRRMIP, the present analysis includes seven models (CESM2, CESM2_GW, CNRM, E3SM, MIROC, NASA-GISS, and NorESM), as the atmospheric variables required for our analysis were not available for IPSL-CM6."

5. Figure 1A: Global cropland area has expanded substantially over the past century. Why, then, does the irrigation-induced ERF exhibit no trend? Is this because changes in shortwave and longwave radiation largely compensate each other? A brief discussion would be helpful.

Response:

We thank the reviewer for highlighting this point. The absence of a clear global trend, despite the AEI expansion since 1901, reflects the spatial cancellation shown in Fig. 3H and Table 1: the strengthening positive ΔERF trend in South Asia and West Central Asia is offset by a comparably negative signal over East Asia and mixed/near-zero signals elsewhere, so global-mean ΔERF stays flat even as the regional forcing intensifies.

We now include the following text in the revised manuscript:

L200: "Despite the expansion of irrigated areas since 1901 (Fig. 1H), the strengthening positive ERF over SAS and WCA is offset by a negative response over EAS, together with mixed or near-zero responses elsewhere. Thus, the global-mean ERF remains small and shows no clear long-term trend."

6. Lines 205–206: The statement "The rate of ΔERF change accelerates after approximately 1950, consistent with the rapid post-war expansion of irrigation infrastructure in Asia." appears to relate Asian irrigation development to a globally averaged ERF. Please clarify whether this discussion refers to the global mean or only to the Asian contribution.

Response:

We fully agree that the sentence is ambiguous as written. The statement is intended to describe the multi-model mean ΔERF (Fig. 1B) over SAS (South Asia), with the post-1950 acceleration attributed to Asian irrigation expansion (shown in Fig. 1I).

To remove the ambiguity, we rephrase it to:

L225: "The rate of ERF change over SAS accelerates after approximately 1950, consistent with the rapid post-war expansion of irrigation infrastructure in Asia. South Asia (SAS; Fig. 1B) shows the strongest and most coherent positive ERF signal, rising progressively from near zero in the early 20th century to values approaching 0.5 W m^{-2} by the 1980s for NorESM, with a historical MMM of +0.22 W m^{-2}."

7. Line 310: The statement "However, reductions in albedo can also trigger rapid atmospheric adjustments." requires supporting references. Relevant studies include, but are not limited to:

Laguë, M. M., Swann, A. L., & Boos, W. R. (2021). Journal of Climate, 34, 6651–6672. https://doi.org/10.1175/JCLI-D-20-0883.1IF: 4.3 Q2

Tang, S. et al. (2025). Geophysical Research Letters, 52, e2025GL117253. https://doi.org/10.1029/2025GL117253IF: 5.0 Q1

Response:

We thank the reviewer for the references. We have included them in the revised manuscript.

L353: Regarding surface albedo, the models show negative correlations globally and across most regions, indicating that decreases in albedo linked to surface wetting are generally associated with higher ERF through enhanced absorption of solar radiation. However, reductions in albedo can also trigger atmospheric adjustments (Laguë et al., 2021; Tang et al., 2025). For example, Laguë et al. (2021) showed that lower land surface albedo increases cloud cover, accompanied by enhanced precipitation, leading to greater reflection of TOA incoming shortwave radiation and enhanced longwave trapping over land. These opposing radiative effects may partially offset one another, thereby moderating the net ERF.

L443: This ocean signal may indicate cloud radiative adjustments driven remotely by irrigation-induced moisture and circulation changes rather than a direct local forcing (Laguë et al., 2022). Under the clear-sky (Fig. 8C, D), over the major irrigated regions including the Indo-Gangetic Plain and WCA, a consistent positive $\Delta R_{n,TOA}$ of +1 to +3 W m^{-2} emerges clearly in both scenarios. The strong ocean anomalies in Fig. 8A, B under all-sky conditions are almost absent under clear-sky conditions (Fig. 8C, D), confirming they are cloud-mediated responses rather than direct water vapor forcing (Laguë et al., 2021). The clear-sky signal is also more spatially coherent between SSP3-7.0 and SSP1-2.6, with SSP3-7.0 producing somewhat larger positive values over SAS and Central Asia, consistent with greater irrigation water application under the higher-emission scenario.

8. Line 404: The manuscript states that "while over Central Asia and China, the shortwave reductions from enhanced cloud cover drive an overall decline." However, Figure 6F shows that clear-sky $\Delta R_{n,TOA}$ over East Asia is also negative. This suggests that factors other than cloud changes also contribute to the radiative response. The authors should discuss these additional mechanisms.

Response:

We thank the reviewer for pointing this out. As this issue has already been addressed earlier in the manuscript (see our response to Comment 3), we have omitted this sentence here to avoid repetition.

Comments by Dr. Pierre Tiengou

This paper examines the impact of irrigation on the Earth's radiative budget in Earth System Models (ESMs). It first uses land-atmosphere simulations of historical climate, conducted within the framework of IRRMIP, to quantify the Effective Radiative Forcing (ERF) induced by irrigation, at the global scale and in several various regions of interest for irrigation. An analysis of multiple physical processes possibly contributing to irrigation's ERF is then conducted to identify the main drivers of the radiative response through correlations and formulate explanations relevant for each region. Finally, one ESM is used to run fully coupled simulations of future climate and study the evolution of the radiative impacts of irrigation identified previously, under two distinct SSP-RCP scenarios.

The paper relevantly addresses an important yet often overlooked impact of irrigation with multiple climate model runs that cover the entire historical period. It provides much more reliable and complete analysis than previously done thanks to ensemble runs and multi-model means and comparisons. Overall, it is well structured and the three sections make clear distinct points that complement each other. I have several questions and comments listed below to help improve the manuscript for the reader.

We thank the reviewer for these very constructive comments.

1. l.62-71.

I am not fully familiar with radiative metrics and therefore have some questions. You mention RF (and RF at the TOA but I believe they are the same thing), and then ERF.. It is not fully clear to me why previous studies used RF ? Is it only that ERF was introduced later or that they had distinct objectives ? The paper also later uses TOA radiative imbalance with a clear justification. Assuming the orders of magnitude are directly comparable, it could be worth giving an idea of how do the values given for irrigation RF compare with estimated RF (and associated uncertainty) and/or radiative imbalance associated to major processes such as anthropic GHG emissions, aerosols, or clouds feedbacks under climate change. A mention of the uncertainty on estimates from the literature for irrigation (E)RF would also be useful in my opinion.

Response:

We thank the reviewer for highlighting this point. The reviewer is correct that RF and RF at the TOA (same for ERF and ERF at the TOA) refer to the same thing. We have revised the manuscript to make this consistent throughout the manuscript. RF at the TOA and RF are replaced to RF_{TOA}, in the revised manuscript.

ERF was formally introduced into the IPCC assessment framework in AR5 and is now the preferred metric for comparing the climate effects of different forcing agents because it is more closely related to the subsequent temperature response. This was already mentioned in the revised manuscript:

L66: "The traditional stratospherically adjusted RF metric is not well suited to fully assess near-surface water vapor perturbations in climate models because it requires the tropospheric state (including humidity)

to remain fixed (Forster et al., 2016). As a result, tropospheric radiative adjustments, which have been shown to play an important role in the response to irrigation forcing (Sherwood et al., 2018), are not accounted for (Sherwood et al., 2015). The Intergovernmental Panel on Climate Change (Myhre et al., 2013) adopted Effective RF (ERF), which includes rapid tropospheric adjustments and is a better predictor of long-term temperature change than RF (Ramaswamy et al., 2018). Since then, ERF has become widely used to quantify radiative forcing and adjustments across climate models (Smith et al., 2020). To our knowledge, global estimates of irrigation-induced ERF still rely on a limited number of modelling frameworks or single-model studies (e.g., Boucher et al., 2004; Gormley-Gallagher et al., 2022; Sherwood et al., 2018). Consequently, the global-scale magnitude of irrigation-driven greenhouse forcing remains highly uncertain (Li et al., 2022)."

We also add in the revised manuscript:

L204: "The global irrigation-induced ERF (+0.023 W m^{-2}) is smaller in magnitude than the total anthropogenic ERF over 1750-2019 at 2.72 [1.96 to 3.48] W m^{-2}, the ERF of greenhouse gases at 3.84 [3.46 to 4.22] W m^{-2}, and the aerosol ERF at -1.3 [-2.0 to -0.6] W m^{-2} over 1750-2014 (Forster et al., 2023)."

We also agree that uncertainty in previous irrigation estimates should be stated explicitly. Published studies have produced estimates ranging from negative to positive values, including approximately +0.03 to +0.1 W m^{-2} in the idealized simulations of Boucher et al. (2004), approximately +0.02 W m^{-2} in Cook et al. (2015), approximately −0.026 W m^{-2} in Sherwood et al. (2018), and approximately +0.05 W m^{-2} in Gormley-Gallagher et al. (2022).

We now include in the revised manuscript the following text:

L63: "This spread reflects both structural model uncertainty and differences in the representation of irrigation and its associated atmospheric adjustments, rather than a formal uncertainty range from a single statistical distribution."

2. I assumed this was studied within IRRMIP, and think the introduction might be the good moment to justify the relevance of these ESMs to simulate impacts of irrigation compared to previous studies. Have they improved simulated irrigated volumes or been shown to perform better in irrigated regions maybe ?

Response:

We thank the reviewer for pointing this out. We agree that the motivation for using IRRMIP should be clarified in the Introduction. The purpose of IRRMIP is not primarily to determine which model is better than another, but rather to provide a consistent multi-model framework in which the agreement and disagreement among models can be evaluated and the uncertainty associated with different model structures

and irrigation representations can be quantified. Previous irrigation studies have often relied on a single ESM and/or static irrigation distribution. In contrast, IRRMIP represents the transient historical expansion of irrigation and uses model-specific irrigation schemes to simulate water application. This provides a more systematic framework for assessing the robustness of irrigation-induced climate responses and the associated structural uncertainty.

We now clarify this in the revised manuscript as follows:

L85: "To address these structural uncertainties and consolidate our understanding of irrigation-climate interactions, the Irrigation Model Intercomparison Project (IRRMIP) was established (Yao et al., 2025a, 2025c, 2025b). IRRMIP provides a multi-model framework involving state-of-the-art Earth System Models (ESMs), including the Community Earth System Model version 2 (CESM2; Danabasoglu et al., 2020), CESM2 with groundwater withdrawal and flow representation (hereinafter referred to as CESM2_GW; Felfelani et al., 2021), the Centre National de Recherches Météorologiques Climate Model version 6 (hereinafter referred to as CNRM; Colin et al., 2023), the Energy Exascale Earth System Model Version 2 (hereinafter referred to as E3SM; Golaz et al., 2022) with active two-way coupled irrigation scheme (Zhou et al., 2020), the Model for Interdisciplinary Research on Climate INTEGrated LAND surface model version 1 (hereinafter referred to as MIROC; Yokohata et al., 2020), the NASA Goddard Institute for Space Studies (GISS) ModelE2.1G model (hereinafter referred to as NASA-GISS; Kelley et al., 2020), the Norwegian Earth System Model version 2 (hereinafter referred to as NorESM; Seland et al., 2020), and the Institute Pierre-Simon Laplace Climate Model version 6 (IPSL-CM6; Boucher et al., 2020) with a newly developed irrigation scheme (Arboleda-Obando et al., 2024). Although IRRMIP has already been used to assess the thermal and hydrological impacts of irrigation, its multi-model ensemble has not yet been used to quantify irrigation-induced ERF. Initial IRRMIP results led by Yao et al. (2025a) have demonstrated that while irrigation reduces dry-heat extremes, it can amplify moist-heat stress and aggravate land water depletion (Yao et al., 2025c), emphasizing the complex trade-offs of irrigation as an adaptation strategy. In this study, we leverage the IRRMIP multi-model ensemble to provide the first quantification of irrigation-induced ERF across multiple model structures"

3. l.119. Why have you used 7 out of the 8 IRRMIP models mentioned in the introduction and not all ?

Response:

We thank the reviewer for pointing this out. The eighth IRRMIP model, IPSL-CM6, was not included because the required atmospheric TOA radiative flux variables needed to calculate ΔERF consistently were not available in the dataset used for this analysis. We now include the following text in the revised manuscript:

L143: "Although eight models so far contributed simulations to IRRMIP, the present analysis includes seven models (CESM2, CESM2_GW, CNRM, E3SM, MIROC, NASA-GISS, and NorESM), as the atmospheric variables required for our analysis were not available for IPSL-CM6."

4. l. 189 …whereas Gormley-Gallagher et al. represented irrigation interactively through the land model. Unsure that I understand the point of this sentence correctly. I see how that is different from Sherwood et al. but it seems similar to what is done in IRRMIP models, right ?

Response:

We thank the reviewer for pointing this out. The transient irrigation in Gormley-Gallagher et al. (2022) was not implemented and thus different from the IRRMIP models, where irrigation expansion is transient throughout the simulation period. The following text is added:

L193:"Sherwood et al. imposed an idealized near-surface water-vapor source without accounting for the associated surface evaporative cooling, whereas Gormley-Gallagher et al. represented irrigation interactively through the land model but ignored irrigation expansion. The IRRMIP models, in contrast, represent transient irrigation extent throughout the simulation period, thereby accounting for the strong irrigation expansion from 1901 to 2014 concentrated in hot spots like South Asia (SAS), East Asia (EAS), and Central North America (CNA)"

5. Fig. 1 (and associated section)

To understand the trends in ERF, I would be curious to see a variable that shows simulated irrigation, unless it can be considered as behaving directly like irrigated areas (which I think would then be worth mentioning).

Response:

We thank the reviewer for this suggestion. The simulated irrigation is already presented and discussed extensively in Figure 1 of Yao et al. (2025a), which shows the historical evolution and spatial distribution of irrigated areas and the associated irrigation water withdrawal across the IRRMIP models. To avoid duplicating a figure that has already been published, we have chosen not to reproduce this figure in the present manuscript. Instead, we now refer to Figure 1 of Yao et al. (2025a) in the relevant sections and clarify that the simulated irrigation follows the historical expansion of irrigated areas, while inter-model differences remain in the magnitude of irrigation water withdrawal. We include the following text in the revised manuscript:

L197: "The IRRMIP models simulate a broad range of global irrigation water withdrawal (IWW; 900-4000 km3/yr during the post-2000 period), but the temporal trend of simulations with transient irrigation extent generally aligns with that of AEI, as illustrated in Yao et al. (2025a). This broad range of IWW simulated by the IRRMIP model may be explained by the different representations of irrigation in these models."

And

L230: "According to Yao et al. (2025a), SAS has the highest simulated IWW across all IRRMIP models, accounting for approximately one-third of global IWW after 2000 (32.4-35.8% in CESM2, 31.4-35.1% in CESM2_GW, 27.5-41.8% in E3SM, and 32.8-35.1% in NorESM). The large positive ERF (i.e., warming influence) here may reflect reduced TOA outgoing longwave from increased atmospheric moisture, which outweighs the shortwave cooling effect of enhanced cloud cover, a pattern noted for northern India in earlier single-model studies (Cook et al., 2015). West central Asia (WCA; Fig. 1G) displays a similarly rising positive historical ERF MMM of +0.24 W m^{-2}, associated with extensive irrigation in Central Asian river basins. Despite having a smaller area equipped for irrigation than EAS, WCA has the second-highest IWW consumption, highlighting that simulated IWW depends not only on irrigated area but also on factors such as background climate conditions (Yao et al., 2025a)"

6. Fig. 1 (and associated section)

I also wondered if seeing a graph of the evolution of irrigation for each region might be more helpful than the share (which is quite easy to grasp from subfigure H) to compare it with trends in ERF shown for each regions. For example, there seem to be decreasing trends from the 1930s in North America and the 1960s in MED, is that associated with similar trends in irrigation ?

Response:

We thank the reviewer for this suggestion. The purpose of Figure 1 in our manuscript is to show the spatial contribution and relative importance of the different regions, rather than to reproduce the detailed temporal evolution of irrigation already presented in Yao et al. (2025a) in Figure 1 (the historical evolution of irrigated areas and irrigation water withdrawal differs among regions). We now add a reference to this figure and clarify this point in the revised manuscript. We do not interpret the decreasing ERF trends in regions such as North America and the Mediterranean as being directly caused by corresponding decreases in irrigation. The regional ERF reflects not only changes in irrigation extent or water application, but also the associated surface and atmospheric responses and their evolution over time. Therefore, a direct correspondence between the temporal trend in irrigation and the ERF trend should not necessarily be expected. The following text is included in the revised manuscript:

L230: "According to Yao et al. (2025a), SAS has the highest simulated IWW across all IRRMIP models, accounting for approximately one-third of global IWW after 2000 (32.4-35.8% in CESM2, 31.4-35.1% in CESM2_GW, 27.5-41.8% in E3SM, and 32.8-35.1% in NorESM). The large positive ERF (i.e., warming influence) here may reflect reduced TOA outgoing longwave from increased atmospheric moisture, which outweighs the shortwave cooling effect of enhanced cloud cover, a pattern noted for northern India in earlier single-model studies (Cook et al., 2015). West central Asia (WCA; Fig. 1G) displays a similarly rising positive historical ERF MMM of +0.24 W m^{-2}, associated with extensive irrigation in Central Asian river basins. Despite having a smaller area equipped for irrigation than EAS, WCA has the second-highest IWW

consumption, highlighting that simulated IWW depends not only on irrigated area but also on factors such as background climate conditions (Yao et al., 2025a)"

7. Fig. 1 (and associated section)

There is a white band in Fig1 H at the bottom which is not associated with any region

Response:

We thank the reviewer for noticing this. The white band at the bottom of Fig. 1H corresponds to SEA (Southeast Asia). It is now clarified in the revised figure caption.

8. Fig. 1 (and associated section)

I am surprised by the lack of evolution of ERF at the global scale. Although this is partially commented on later by comparing with clear-sky ERF, I think it deserves more details. I am particularly curious of wether that there is a significant ERF in the beginning of the century where irrigation is supposedly quite small (at least compared to the rest of the period). More generally, I wonder about the uncertainty or statistical significance associated with the ERF values mentioned, since 0 often seems to be in the MM-spread. I am not fully familiar with the usual methods to assess significance in such a study but maybe additional details could be useful here.

Response:

We thank the reviewer for this suggestion. The absence of a pronounced global trend does not imply an absence of irrigation-induced radiative responses. Rather, the global mean is strongly affected by cancellation among spatially heterogeneous positive and negative responses. The regional responses, particularly in South Asia and West Central Asia, become much larger as irrigation expands during the second half of the twentieth century. We now include the following text in the revised manuscript:

L200: "Despite the expansion of irrigated areas since 1901 (Fig. 1H), the strengthening positive ERF over SAS and WCA is offset by a negative response over EAS, together with mixed or near-zero responses elsewhere. Thus, the global-mean ERF remains small and shows no clear long-term trend."

The confidence intervals reported in Table 1 are based on a t-distribution across the models. We now add in the caption of Table1 the following text: "The confidence intervals (CI) values are based on a t-distribution across the seven models.".

9. l.262. 80% of the models

That means 6 out of 7 right ? It might be clearer to state it this way, unless a more complex calculation accounting for ensemble members is used?

Response:

Yes. We replace "≥80% of models" with "at least six of the seven models" in the revised manuscript (**L284**).

10. Fig 3

Hatches are barely visible, I would suggest exploring other visualisation, either only showing coloured data where the condition is verified, or maybe dots on grid cells that verify it rather than the hatches

Response:

We thank the reviewer for this suggestion. Instead of the current hatching, we use dots.

11. Fig. 3

There are strong patches in oceans in CESM, NorESM, E3SM, what is the statistical significance of these changes ? How much do they contribute to the mean global ERF ? Have you checked the share of global ERF impact coming from land versus oceans ?

Response:

We thank the reviewer for raising this important point. In our analysis, ERF is calculated as a global mean, including both land and ocean areas, rather than being calculated separately for land and ocean. This approach is consistent with the conventional calculation of global-mean ERF and allows direct comparison with globally averaged radiative forcing estimates reported in the IPCC assessments. To further investigate the pronounced patches over the oceans in some models, we repeated the analysis using the models that provide the required clear-sky radiative variables (CESM2-GW, CNRM-CM6-1, and E3SM). The oceanic patches largely disappear under clear-sky conditions. This indicates that the spatial patterns over the oceans are strongly influenced by cloud-related processes and radiative adjustments. We now include a new figure (Fig.4) and the following text in the manuscript:

L296: "Several models also show isolated positive (> +1 W m^{-2}) and negative (< -1 W m^{-2}) ERF patches over the oceans. Under clear-sky conditions, most of these oceanic features disappear, with ERF values generally remaining between -1 and +1 W m^{-2} (Fig. 4). This contrast indicates that the oceanic anomalies in the all-sky fields may be associated with cloud-related radiative effects. This contribution should, however, be interpreted with caution, given structural uncertainties in cloud representation across models. At the same time, the multi-model consistency of several key spatial patterns and physical relationships provides confidence that the main features of the irrigation-induced radiative response are not specific to a single model formulation. All-sky versus clear-sky comparison provides a diagnostic estimate of the net cloud contribution rather than a process attribution, and its magnitude remains model dependent.".

12. l. 288 Interestingly, this correlation reverses in CNA and WNA, suggesting that in these regions, other components of the TOA energy balance (likely SW changes) dominate the ΔERF response.

I would add that it's also not clearly present for MED and EAS, and maybe relate it in more details to opposite behaviours of SW and near-surface T (possibly merging some of the next paragraph to examine the variables conjointly ?)

Response:

We agree. The following text is included in the revised manuscript:

L324: "The relationship between ERF and outgoing longwave radiation is not uniform across all regions. For instance, MED and EAS do not show the same clear relationship as SAS and WCA. In EAS and MED, the models show contrasting relationships between ERF and outgoing LW, with some exhibiting negative correlations and others positive relationships. This inter-model spread likely reflects differences in the relative contributions of longwave water-vapor effects and shortwave radiative effects associated with cloud and surface changes, as well as differences in the representation of cloud processes and parameterizations across models.".

13. Fig 5, 6

I feel the need to visualise irrigation (or irrigated areas if it is sufficient as mentioned earlier) in both scenarios to understand the differences in the magnitude of the changes involved here.

Response:

We thank the reviewer for this suggestion. Please see our reply to comments # 5.

14. Fig 7

Although responses over the ocean are discussed here, the large values at the pole still raise the question of statistical significance of the impacts of irrigation since these regions are also very sensitive to climate change

Response:

Please see our reply to comment # 11.

15. (Generic comment)

I wondered about the relevance of considering mean values over the entire historical period since irrigation is evolving rather quickly in a century, have you considered looking into distinct 20- or 30-year periods (like for analysis under climate change) ?

Response:

Thank you for this suggestion. In addition to showing the temporal evolution of irrigation and its effects in Figures 1, 2, 5, and 7, we also analyze distinct periods. Specifically, Figure 3 focuses on the 1981-2014 period (34 years), while Figure 7 examines the 2050-2070 period (21 years). These analyses complement the historical-period mean values and allow us to assess how irrigation and its associated effects evolve over time.

16. (Generic comment)

Particularly because of the remote impacts observed on Fig 3, 7, I also am unsure about the physical meaning of local ERF (I admit do not know how common it is to look into this variable in that way). I understand the relevance of regional surface energy balance for instance since it is directly related to boundary layer conditions at the regional scale, but ERF is integrated over the entire atmospheric column which is supposedly very well mixed (I cannot think of studies linking irrigation with changes of cloud

cover above the ABL and would be interested to know about any). Do you consider that the different regional behaviours could be an indicator of different regimes piloting interactions with general circulation patterns well above the ABL ?

Response:

We appreciate this important point, and we also agree with the reviewer that different regional responses may reflect different background hydroclimatic regimes and interactions between local irrigation effects and large-scale atmospheric circulation. The spatially heterogeneous response can arise from several processes, including local surface energy partitioning, atmospheric moisture changes, cloud adjustments, and remote circulation and moisture transport. This is particularly important because irrigation can modify atmospheric humidity and latent heating, which can influence atmospheric circulation beyond the irrigated region. We therefore include the following in the revised manuscript:

L260: "Globally, the clear-sky forcing exhibits a systematic upward trajectory, particularly after the mid-20th century. This amplification, also true over SAS, WCA, and CNA, when moving from all-sky to clear-sky diagnostics, indicates that cloud-related adjustments contribute negatively to the all-sky ERF. The larger clear-sky ERF suggests that irrigation-induced cloud changes partially offset the positive clear-sky radiative effects of water vapor. These cloud-related effects may involve enhanced shortwave reflection and changes in cloud amount or distribution associated with enhanced surface evaporation and latent heat flux, which can modify atmospheric stability and cloud formation. In particular, increased partitioning of available energy into latent rather than sensible heat flux may reduce atmospheric boundary layer (ABL) warming and alter its vertical development, stability or moisture conditions, potentially favoring low-cloud formation and thereby contributing to the cloud-mediated cooling response (Qian et al., 2013; Rappin et al., 2022; Tiengou et al., 2026). In EAS, the clear-sky signal is weakly positive or near zero while the all-sky signal is negative, suggesting that cloud-associated effects may regulate or even reverse the sign of the regional ERF.".

17. (Generic comment)

To what extent have you considered the impact of modelling choices for parameterisations on the radiative response to irrigation ? I am particularly thinking of irrigation representation, clouds, deep convection, and radiative schemes, which all have rather large uncertainties. More specifically, is the diversity of modelling approaches a good way of assessing uncertainty in the responses in this study ? Could the presence of several models from the same family affect the relevance of a multi-model mean ? Have distinct models been found to consistently agree/disagree and could that be explained by differences in modelling choices ?Although listing the modelling approaches for each in the Methods might be too much, I think this should be at least discussed in the final part of the paper.

Response:

We thank the reviewer for this important point, and we agree that this is an important limitation. Several elements relevant to this question are already present in the manuscript, though not yet drawn together into a dedicated paragraph.

L124: "Here, we analyze simulations from seven models: CESM2, CESM2_GW, MIROC, CNRM, NorESM, NASA-GISS, and E3SM. The irrigated experiment (IRR) prescribes the transient historical evolution of irrigation extent and applies dynamically computed irrigation amounts to the land surface, whereas the experiment without irrigation expansion (NOIRR) uses identical boundary conditions but maintains irrigation conditions at their 1901 levels. The difference between the two experiments isolates the climate response to irrigation expansion, with SST and sea ice prescribed in both simulations. CESM2 is a state-of-art ESM, with the Community Land Model version 5 (CLM5) as the land model, the Community Atmosphere Model version 6 (CAM6) as the atmosphere model, and the Model for Scale Adaptive River Transport (MOSART) as the routing mode (Yao et al., 2025a). In CESM2_GW, parameterizations for aquifer pumping and an intercell lateral groundwater interaction are implemented (Yao et al., 2025c). NorESM shares with CESM2 the same land system model (CLM5) and atmosphere model (CAM6), except for additional developments including, but not limited to, updated chemistry, aerosol, and cloud modules. Furthermore, the irrigation schemes themselves differ across models: CNRM and NASA-GISS use external irrigation forcing, whereas the other models use soil moisture-based irrigation schemes with different triggers, timing, and amounts. However, with only seven models in total, three of which share a land component and four of which are structurally distinct, the current ensemble is too small to meaningfully partition into "shared" and "independent" subsets and statistically compare their behaviors."

References

Arboleda-Obando, P.F., Ducharne, A., Yin, Z., Ciais, P., 2024. Validation of a new global irrigation scheme in the land surface model ORCHIDEE v2.2. Geosci. Model Dev. 17, 2141–2164. https://doi.org/10.5194/gmd-17-2141-2024

Boucher, O., Myhre, G., Myhre, A., 2004. Direct human influence of irrigation on atmospheric water vapour and climate. Clim. Dyn. 22, 597–603. https://doi.org/10.1007/s00382-004-0402-4

Boucher, O., Servonnat, J., Albright, A.L., Aumont, O., Balkanski, Y., Bastrikov, V., Bekki, S., Bonnet, R., Bony, S., Bopp, L., Braconnot, P., Brockmann, P., Cadule, P., Caubel, A., Cheruy, F., Codron, F., Cozic, A., Cugnet, D., D'Andrea, F., Davini, P., de Lavergne, C., Denvil, S., Deshayes, J., Devilliers, M., Ducharne, A., Dufresne, J.-L., Dupont, E., Éthé, C., Fairhead, L., Falletti, L., Flavoni, S., Foujols, M.-A., Gardoll, S., Gastineau, G., Ghattas, J., Grandpeix, J.-Y., Guenet, B., Guez, E., Lionel, Guilyardi, E., Guimberteau, M., Hauglustaine, D., Hourdin, F., Idelkadi, A., Joussaume, S., Kageyama, M., Khodri, M., Krinner, G., Lebas, N., Levavasseur, G., Lévy, C., Li, L., Lott, F., Lurton, T., Luyssaert, S., Madec, G., Madeleine, J.-B., Maignan, F., Marchand, M., Marti, O., Mellul, L., Meurdesoif, Y., Mignot, J., Musat, I., Ottlé, C., Peylin, P., Planton, Y., Polcher, J., Rio,

C., Rochetin, N., Rousset, C., Sepulchre, P., Sima, A., Swingedouw, D., Thiéblemont, R., Traore, A.K., Vancoppenolle, M., Vial, J., Vialard, J., Viovy, N., Vuichard, N., 2020. Presentation and Evaluation of the IPSL-CM6A-LR Climate Model. J. Adv. Model. Earth Syst. 12, e2019MS002010. https://doi.org/10.1029/2019MS002010

Colin, J., Decharme, B., Cattiaux, J., Saint-Martin, D., 2023. Groundwater Feedbacks on Climate Change in the CNRM Global Climate Model. J. Clim. 36, 7599–7617. https://doi.org/10.1175/JCLI-D-22-0767.1

Cook, B.I., Shukla, S.P., Puma, M.J., Nazarenko, L.S., 2015. Irrigation as an historical climate forcing. Clim. Dyn. 44, 1715–1730. https://doi.org/10.1007/s00382-014-2204-7

Danabasoglu, G., Lamarque, J.-F., Bacmeister, J., Bailey, D.A., DuVivier, A.K., Edwards, J., Emmons, L.K., Fasullo, J., Garcia, R., Gettelman, A., Hannay, C., Holland, M.M., Large, W.G., Lauritzen, P.H., Lawrence, D.M., Lenaerts, J.T.M., Lindsay, K., Lipscomb, W.H., Mills, M.J., Neale, R., Oleson, K.W., Otto-Bliesner, B., Phillips, A.S., Sacks, W., Tilmes, S., van Kampenhout, L., Vertenstein, M., Bertini, A., Dennis, J., Deser, C., Fischer, C., Fox-Kemper, B., Kay, J.E., Kinnison, D., Kushner, P.J., Larson, V.E., Long, M.C., Mickelson, S., Moore, J.K., Nienhouse, E., Polvani, L., Rasch, P.J., Strand, W.G., 2020. The Community Earth System Model Version 2 (CESM2). J. Adv. Model. Earth Syst. 12, e2019MS001916. https://doi.org/10.1029/2019MS001916

Felfelani, F., Lawrence, D.M., Pokhrel, Y., 2021. Representing Intercell Lateral Groundwater Flow and Aquifer Pumping in the Community Land Model. Water Resour. Res. 57, e2020WR027531. https://doi.org/10.1029/2020WR027531

Forster, P.M., K, A., T, S., W, C., Dufresne, J.-L., D, F., D.j, L., T, M., M.d, P., M, Watanabe, M, Wild, H, Z.A., 2023. The Earth's Energy Budget, Climate Feedbacks and Climate Sensitivity. Cambridge University Press, p. 923. https://doi.org/10.1017/9781009157896.009

Forster, P.M., Richardson, T., Maycock, A.C., Smith, C.J., Samset, B.H., Myhre, G., Andrews, T., Pincus, R., Schulz, M., 2016. Recommendations for diagnosing effective radiative forcing from climate models for CMIP6. J. Geophys. Res. Atmos. 121, 12,460-12,475. https://doi.org/10.1002/2016JD025320

Golaz, J.-C., Van Roekel, L.P., Zheng, X., Roberts, A.F., Wolfe, J.D., Lin, W., Bradley, A.M., Tang, Q., Maltrud, M.E., Forsyth, R.M., Zhang, C., Zhou, T., Zhang, K., Zender, C.S., Wu, M., Wang, H., Turner, A.K., Singh, B., Richter, J.H., Qin, Y., Petersen, M.R., Mametjanov, A., Ma, P.-L., Larson, V.E., Krishna, J., Keen, N.D., Jeffery, N., Hunke, E.C., Hannah, W.M., Guba, O., Griffin, B.M., Feng, Y., Engwirda, D., Di Vittorio, A.V., Dang, C., Conlon, L.M., Chen, C.-C.-J., Brunke, M.A., Bisht, G., Benedict, J.J., Asay-Davis, X.S., Zhang, Y., Zhang, M., Zeng, X., Xie, S., Wolfram, P.J., Vo, T., Veneziani, M., Tesfa, T.K., Sreepathi, S., Salinger, A.G., Reeves Eyre, J.E.J., Prather, M.J., Mahajan, S., Li, Q., Jones, P.W., Jacob, R.L., Huebler, G.W., Huang, X., Hillman, B.R., Harrop, B.E., Foucar, J.G., Fang, Y., Comeau, D.S., Caldwell, P.M., Bartoletti, T., Balaguru, K., Taylor, M.A., McCoy, R.B., Leung, L.R., Bader, D.C., 2022. The DOE E3SM Model Version 2: Overview of the Physical Model and Initial Model Evaluation. J. Adv. Model. Earth Syst. 14, e2022MS003156. https://doi.org/10.1029/2022MS003156

Gormley-Gallagher, A.M., Sterl, S., Hirsch, A.L., Seneviratne, S.I., Davin, E.L., Thiery, W., 2022. Agricultural management effects on mean and extreme temperature trends. Earth Syst. Dyn. 13, 419–438. https://doi.org/10.5194/esd-13-419-2022

Intergovernmental Panel on Climate Change (IPCC) (Ed.), 2023. The Earth's Energy Budget, Climate Feedbacks and Climate Sensitivity, in: Climate Change 2021 – The Physical Science Basis: Working Group I Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, pp. 923–1054. https://doi.org/10.1017/9781009157896.009

Kelley, M., Schmidt, G.A., Nazarenko, L.S., Bauer, S.E., Ruedy, R., Russell, G.L., Ackerman, A.S., Aleinov, I., Bauer, M., Bleck, R., Canuto, V., Cesana, G., Cheng, Y., Clune, T.L., Cook, B.I., Cruz, C.A., Del Genio, A.D., Elsaesser, G.S., Faluvegi, G., Kiang, N.Y., Kim, D., Lacis, A.A., Leboissetier, A., LeGrande, A.N., Lo, K.K., Marshall, J., Matthews, E.E., McDermid, S., Mezuman, K., Miller, R.L., Murray, L.T., Oinas, V., Orbe, C., García-Pando, C.P., Perlwitz, J.P., Puma, M.J., Rind, D., Romanou, A., Shindell, D.T., Sun, S., Tausnev, N., Tsigaridis, K., Tselioudis, G., Weng, E., Wu, J., Yao, M.-S., 2020. GISS-E2.1: Configurations and Climatology. J. Adv. Model. Earth Syst. 12, e2019MS002025. https://doi.org/10.1029/2019MS002025

Laguë, M.M., Quetin, G.R., Boos, W.R., 2022. Downwind control of oceanic air by land: the land wake and its sensitivity to CO2. Environ. Res. Lett. 17, 104045. https://doi.org/10.1088/1748-9326/ac9702

Laguë, M.M., Swann, A.L.S., Boos, W.R., 2021. Radiative Feedbacks on Land Surface Change and Associated Tropical Precipitation Shifts. J. Clim. 34, 6651–6672. https://doi.org/10.1175/JCLI-D-20-0883.1

Li, H., Lo, M.-H., Ryu, D., Peel, M., Zhang, Y., 2022. Possible Increase of Air Temperature by Irrigation. Geophys. Res. Lett. 49, e2022GL100427. https://doi.org/10.1029/2022GL100427

Myhre, G.D., Shindell, D., Bréon, F.M., et al, 2013. Anthropogenic and Natural Radiative Forcing Supplementary Material. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. 2013.

Qian, Y., Huang, M., Yang, B., Berg, L.K., 2013. A Modeling Study of Irrigation Effects on Surface Fluxes and Land–Air–Cloud Interactions in the Southern Great Plains. J. Hydrometeorol. 14, 700–721. https://doi.org/10.1175/JHM-D-12-0134.1

Ramaswamy, V., Collins, W., Haywood, J., Lean, J., Mahowald, N., Myhre, G., Naik, V., Shine, K.P., Soden, B., Stenchikov, G., Storelvmo, T., 2018. Radiative Forcing of Climate: The Historical Evolution of the Radiative Forcing Concept, the Forcing Agents and their Quantification, and Applications. Meteorol. Monogr. 59, 14.1-14.101. https://doi.org/10.1175/AMSMONOGRAPHS-D-19-0001.1

Rappin, E.D., Mahmood, R., Nair, U.S., Sr, R.A.P., 2022. Land–Atmosphere Interactions during GRAINEX: Planetary Boundary Layer Evolution in the Presence of Irrigation. J. Hydrometeorol. 23, 1401–1417. https://doi.org/10.1175/JHM-D-21-0160.1

Seland, Ø., Bentsen, M., Olivié, D., Toniazzo, T., Gjermundsen, A., Graff, L.S., Debernard, J.B., Gupta, A.K., He, Y.-C., Kirkevåg, A., Schwinger, J., Tjiputra, J., Aas, K.S., Bethke, I., Fan, Y., Griesfeller, J., Grini, A., Guo, C., Ilicak, M., Karset, I.H.H., Landgren, O., Liakka, J., Moseid, K.O., Nummelin, A., Spensberger, C., Tang, H., Zhang, Z., Heinze, C., Iversen, T., Schulz, M., 2020. Overview of the Norwegian Earth System Model (NorESM2) and key climate response of CMIP6 DECK, historical, and scenario simulations. Geosci. Model Dev. 13, 6165–6200. https://doi.org/10.5194/gmd-13-6165-2020

Sherwood, S.C., Bony, S., Boucher, O., Bretherton, C., Forster, P.M., Gregory, J.M., Stevens, B., 2015. Adjustments in the Forcing-Feedback Framework for Understanding Climate Change. Bull. Am. Meteorol. Soc. 96, 217–228. https://doi.org/10.1175/BAMS-D-13-00167.1

Sherwood, S.C., Dixit, V., Salomez, C., 2018. The global warming potential of near-surface emitted water vapour. Environ. Res. Lett. 13, 104006. https://doi.org/10.1088/1748-9326/aae018

Smith, C.J., Kramer, R.J., Myhre, G., Alterskjær, K., Collins, W., Sima, A., Boucher, O., Dufresne, J.-L., Nabat, P., Michou, M., Yukimoto, S., Cole, J., Paynter, D., Shiogama, H., O'Connor, F.M., Robertson, E., Wiltshire, A., Andrews, T., Hannay, C., Miller, R.,

Nazarenko, L., Kirkevåg, A., Olivié, D., Fiedler, S., Lewinschal, A., Mackallah, C., Dix, M., Pincus, R., Forster, P.M., 2020. Effective radiative forcing and adjustments in CMIP6 models. Atmos. Chem. Phys. 20, 9591–9618. https://doi.org/10.5194/acp-20-9591-2020

Tang, S., Piao, S., Cai, W., Wang, T., Li, L.Z.X., Wang, K., Kan, F., Gui, Y., Yao, T., Li, X., 2025. Tropical Pacific Zonal Temperature Gradient Intensified by the Tibetan Plateau Surface Darkening. Geophys. Res. Lett. 52, e2025GL117253. https://doi.org/10.1029/2025GL117253

Tiengou, P., Ducharne, A., Cheruy, F., 2026. Regional impacts of irrigation on the atmospheric and terrestrial water cycle of the Iberian Peninsula in a climate model. Earth Syst. Dyn. 17, 843–876. https://doi.org/10.5194/esd-17-843-2026

Yao, Y., Ducharne, A., Cook, B.I., De Hertog, S.J., Aas, K.S., Arboleda-Obando, P.F., Buzan, J., Colin, J., Costantini, M., Decharme, B., Lawrence, D.M., Lawrence, P., Leung, L.R., Lo, M.-H., Devaraju, N., Wieder, W.R., Wu, R.-J., Zhou, T., Jägermeyr, J., McDermid, S., Pokhrel, Y., Elling, M., Hanasaki, N., Muñoz, P., Nazarenko, L.S., Otta, K., Satoh, Y., Yokohata, T., Jin, L., Wang, X., Mishra, V., Ghosh, S., Thiery, W., 2025a. Impacts of irrigation expansion on moist-heat stress based on IRRMIP results. Nat. Commun. 16, 1045. https://doi.org/10.1038/s41467-025-56356-1

Yao, Y., Satoh, Y., van Maanen, N., Taranu, S., Keune, J., De Hertog, S.J., Lampe, S., Lawrence, D.M., Sacks, W.J., Wada, Y., Ducharne, A., Cook, B.I., Seneviratne, S.I., Liu, L., Buzan, J.R., Jägermeyr, J., Thiery, W., 2025b. Compounding future escalation of emissions- and irrigation-induced increases in humid-heat stress. Nat. Commun. 16, 9326. https://doi.org/10.1038/s41467-025-64375-1

Yao, Y., Thiery, W., Ducharne, A., Cook, B.I., Ding, A., De Hertog, S.J., Sieber, P., Aas, K.S., Arboleda-Obando, P.F., Colin, J., Costantini, M., Decharme, B., Lawrence, D.M., Lawrence, P., Leung, L.R., Lo, M.-H., Devaraju, N., Wu, R.-J., Zhou, T., Jägermeyr, J., McDermid, S.S., Pokhrel, Y., Satoh, Y., Yokohata, T., Gudmundsson, L., Seneviratne, S.I., 2025c. Irrigation-induced land water depletion aggravated by climate change. Nat. Water 3, 1424–1435. https://doi.org/10.1038/s44221-025-00529-1

Yokohata, T., Kinoshita, T., Sakurai, G., Pokhrel, Y., Ito, A., Okada, M., Satoh, Y., Kato, E., Nitta, T., Fujimori, S., Felfelani, F., Masaki, Y., Iizumi, T., Nishimori, M., Hanasaki, N., Takahashi, K., Yamagata, Y., Emori, S., 2020. MIROC-INTEG-LAND version 1: a global biogeochemical land surface model with human water management, crop growth, and land-use change. Geosci. Model Dev. 13, 4713–4747. https://doi.org/10.5194/gmd-13-4713-2020

Zhou, T., Leung, L.R., Leng, G., Voisin, N., Li, H.-Y., Craig, A.P., Tesfa, T., Mao, Y., 2020. Global Irrigation Characteristics and Effects Simulated by Fully Coupled Land Surface, River, and Water Management Models in E3SM. J. Adv. Model. Earth Syst. 12, e2020MS002069. https://doi.org/10.1029/2020MS002069