Response to the Editor and Reviewers

Manuscript No.: egusphere-2026-1311

Title: Simulating the impacts of utility-scale photovoltaic installations with a physically based coupled WRF-PV model

Dear Topic Editor and Reviewers,

We sincerely thank the topic editor and the reviewers for their careful evaluation of our manuscript and for their valuable and constructive comments. We have revised the manuscript accordingly and provide detailed point-by-point responses below. The original reviewer comments are shown in *blue italics*, followed by our corresponding responses and the revised text. We hope that our revisions and responses have adequately addressed the reviewers' comments and concerns.

Thank you again for your time and valuable comments.

Yours sincerely,

Yiran Chen, Jiming Jin, and Yimin Liu

on behalf of all authors

Response to Reviewer 1

I have reviewed the revised manuscript and the authors' responses to both reviewers. I appreciate their efforts to address our comments. The revisions have notably improved the clarity of the methodology and the interpretation of the results. However, I still have concerns regarding a few issues from the initial review, as well as some specific points in the newly added content.

Response: We sincerely thank you for your valuable comments and constructive suggestions. We have revised the manuscript and conducted additional analyses to address the remaining concerns. First, we clarified the energy-balance residual reported in Table 2, particularly the treatment of GRDFLX in the Noah land surface model. Second, we assessed the link between PV installations and the simulated atmospheric and precipitation responses by conducting an additional sensitivity experiment with expanded PV coverage. Detailed responses to each comment are provided below.

L20: Phrasing like "by 0.51 °C" is vague, as it isn't clear how significant this change is without context regarding the baseline value. Please specify the absolute values instead (e.g., "from X.XX °C to Y.YY °C")

Response: Thank you for this comment. We have revised the sentence to report the absolute RMSE values.

The revised text reads:

> Evaluation against MODIS showed that WRF-PV improved the simulation of skin temperature over PV installations, reducing the RMSE from 3.071 °C in WRF_CTL to 2.560 °C in WRF_PV.

Location: Abstract, lines 19–20.

L21~22: "Additionally" and "moreover" are too wordy. Also, I think spatial redistribution of precipitation is part of the PV-induced atmospheric feedbacks the authors want to include (but see the specific comments below for my opinion). The full sentence can be: "Additionally, we identified PV-induced atmospheric feedback including an increase in cloud fraction, resulting in reduced downward SW radiation by about 1.2%, as well as a pronounced spatial redistribution of precipitation"

Response: Thank you for this suggestion. We have streamlined the sentence and incorporated the precipitation redistribution into the description of PV-induced atmospheric feedbacks.

The revised text reads:

> Additionally, we identified PV-induced atmospheric feedback including an increase in cloud fraction, resulting in a reduction in downward SW radiation of about 1.2%, as well as a pronounced spatial redistribution of precipitation.

Location: Abstract, lines 21–23.

L47~48: The first sentence is a bit too strong. I tend to be more conservative about the observations as they also suffer from uncertainties and are not necessarily the ground truth. Phrasing like the model "should be able to capture" based purely on observational studies sounds overly deterministic. How about: "Observational studies provide valuable insights into key microclimatic responses, including […]"?

Response: Thank you for this suggestion. We have revised the sentence to use more cautious wording regarding the observational evidence.

The revised text reads:

> Observational studies, including in situ field measurements and satellite-based remote sensing analyses, provide valuable insights into key microclimatic responses to utility-scale PV deployment.

Location: Section 1, lines 48–49.

L49: "consistent yet site-varying" may be a bit confusing. I think the meaning is that qualitatively the responses are consistent, yet the magnitude of changes may differ between sites.

Response: Thank you for this comment. We have revised the sentence to distinguish the consistent response patterns from the site-dependent magnitudes.

The revised text reads:

> Field measurements across multiple PV farms in semi-arid regions revealed qualitatively consistent microclimatic responses, although their magnitudes varied among sites.

Location: Section 1, lines 49–51.

L172~173: Saying the forcing is "modified according to the energy balance" makes it sound like a rule is modifying the forcing, while it is indeed caused by the presence of PV panels. Simply say that "The subsequent land surface model calculation uses the adjusted surface energy balance equation [Eq. (7)] to account for the presence of PV panels."

Response: Thank you for pointing this out. We have revised the sentence to state that the land surface model uses the adjusted surface energy balance to account for the presence of PV panels.

The revised text reads:

> The subsequent land surface model calculation uses the adjusted surface energy balance equation (Eq. 7) to account for the presence of PV panels.

Location: Section 2.3, lines 173–174.

L198~199: Regarding consistency between the three PV panel datasets, in addition to the consistency in spatial coverage and collocations, I am expecting to see data continuity examined (i.e., whether a location has PV panels should be consistent in the three datasets, assuming continuous PV deployment).

Response: Thank you for this comment. We evaluated the continuity of PV identification across years and datasets for each adjacent-year transition by classifying PV areas as retained, newly added, or lost. After applying a 100 m spatial tolerance, the lost PV area accounted for only 0–2.56% of the total PV area in each year, indicating that most previously identified PV areas were retained in subsequent years. These results support the temporal consistency of PV identification across the three datasets. This assessment was added to Section 3.2 in the previous revision.

L231~232: Given that the PV area is different across the years, did you find slightly different results when only looking at individual years? Say, assume that the PV area was increasing in these years, can I *expect that PV-induced effect also increased with time? If so, this could be a piece of evidence that the difference seen in the results is indeed caused by PV panels instead of other meteorological factors.*

Response: Thank you for this helpful suggestion. We examined the PV-induced responses separately for each year from 2018 to 2024. For T2, the response was calculated by averaging over the PV grid cells in each individual year. The annual results show a similar diurnal pattern, characterized by pronounced daytime warming and relatively weak nighttime changes (Fig. R1). The mean T2 response over PV grid cells did not increase monotonically with PV area. Moreover, the response of newly added PV farms may be affected by their latitude, elevation, and background circulation conditions. For precipitation, the median cumulative differences were generally comparable across years for both heavy precipitation and all precipitation intensities (Figs. R2 and R3). Among the seven years, 2024 showed a broader positive upper tail and comparatively large positive cumulative differences.

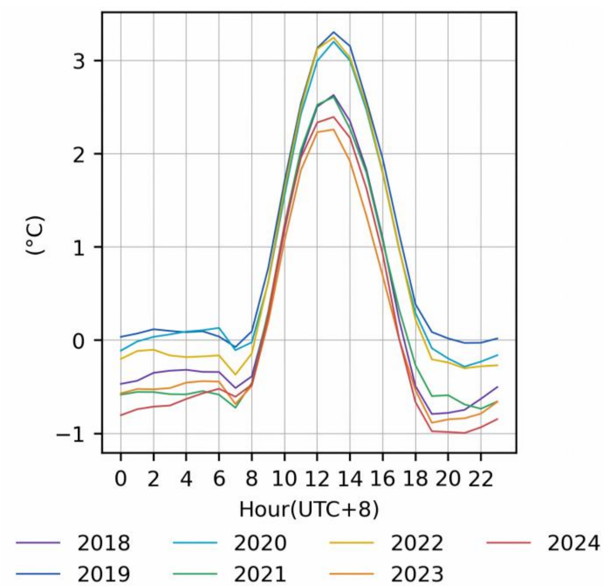

Figure R1: Annual diurnal cycles of the T2 difference between WRF_PV and WRF_CTL during 2018–2024, averaged over the PV grid cells in each year.

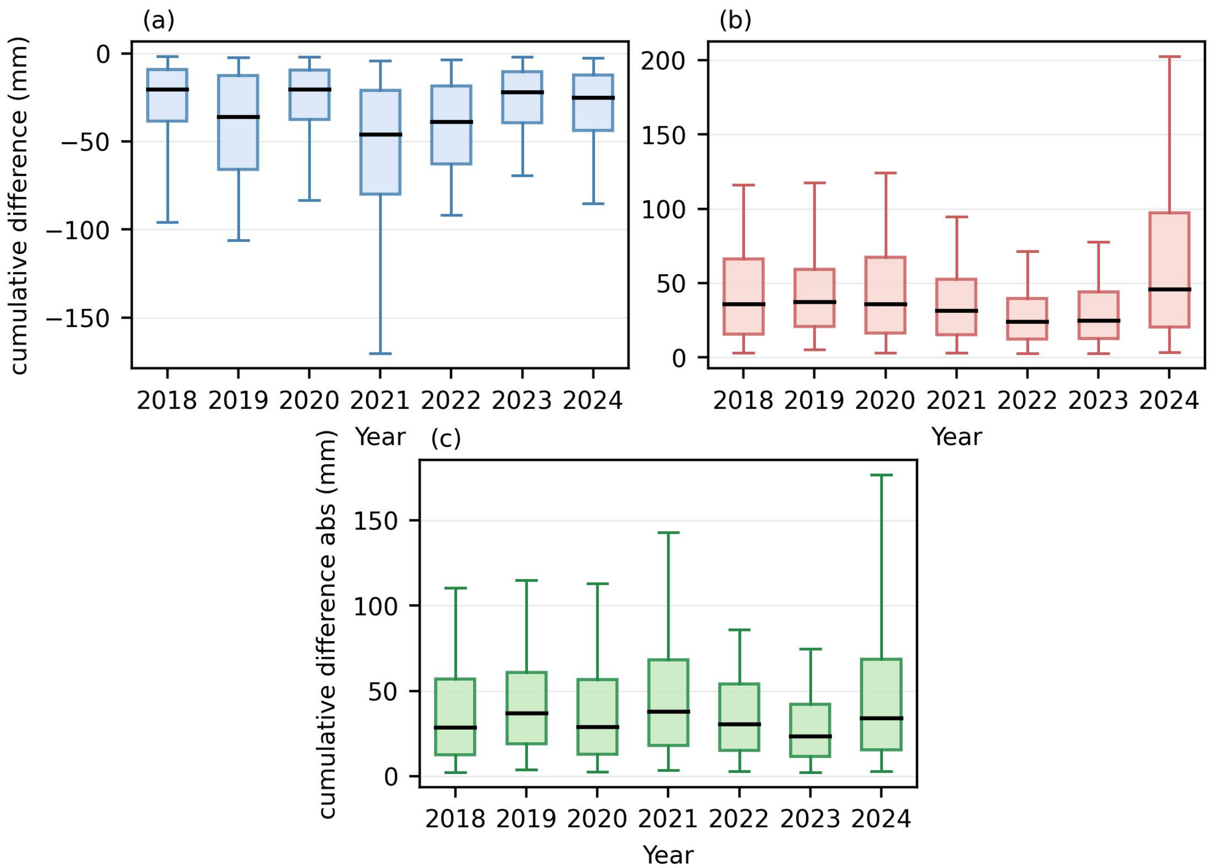

Figure R2: Annual distributions of cumulative precipitation differences between WRF_PV and WRF_CTL for individual years from 2018 to 2024. (a) negative cumulative differences, (b) positive cumulative differences, and (c) absolute cumulative differences. Boxes indicate the interquartile range, black lines indicate the median, and whiskers indicate the 5th–95th percentiles.

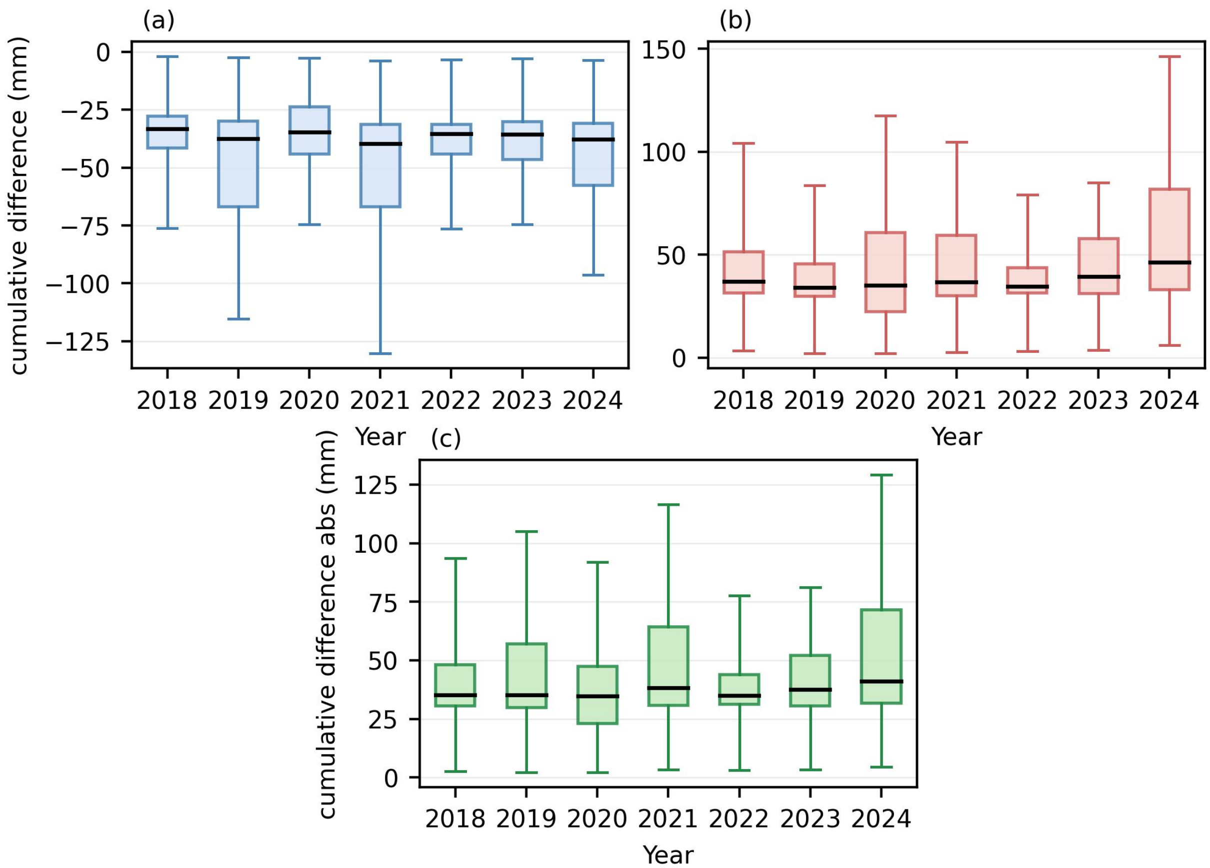

Figure R3: Annual distributions of differences in cumulative heavy precipitation amount (> 30 mm day^{-1}) between WRF_PV and WRF_CTL during 2018–2024. (a) negative cumulative differences, (b) positive cumulative differences, and (c) absolute cumulative differences. Boxes indicate the interquartile range, black lines indicate the median, and whiskers indicate the 5th–95th percentiles.

L295: Define "grid-cell ring". How wide the ring is?

Response: Thank you for this comment. The first grid-cell ring includes all non-PV WRF grid cells located one grid cell from the nearest PV grid cell, based on 8-neighbour connectivity. It is therefore one WRF grid cell wide, corresponding to approximately 3 km, and excludes all PV grid cells.

Figure 4: Related to the response to Reviewer #1, General Comment 1-2, what is specifically "refine the physical parameterization configuration"? Is it a bug fix? Why does it affect the MODIS-model comparison results?

Response: Thank you for this comment. By "refining the physical parameterization configuration," we specifically mean adopting the vegetation-dependent formulation for the surface thermal roughness length over land. This was a change in parameterization choice rather than a bug fix. Sensitivity tests showed that this formulation improved the CTL simulation of skin temperature. Because surface thermal roughness length affects the aerodynamic resistance to heat transfer and the partitioning of sensible heat, it directly influences simulated TSK and its comparison with MODIS. We therefore repeated both WRF_CTL and WRF_PV simulations using the same revised configuration. The revised configuration improved the baseline performance of WRF_CTL, while the PV coupling scheme further improved WRF_PV over PV installations.

Figure 5: MODIS TSK can be added to panel (a), and CLDAS 2m air temperature can be added to panel (b), so that we can also compare the diurnal cycle of simulated TSK and T2 to the references.

Response: Thank you for this suggestion. We did not add MODIS TSK to Fig. 5 because MODIS provides LST only at fixed satellite overpass times and under clear-sky conditions and therefore cannot represent a complete diurnal cycle. The comparison of the simulated T2 diurnal cycle with CLDAS is already presented in Fig. 2b. Moreover, Fig. 5b shows the differences between WRF_PV and WRF_CTL, for which CLDAS has no corresponding reference.

L322: Just to confirm, since daytime is defined as 08:00–19:00 and nighttime as 20:00–07:00, the transition hours (19:00–20:00 and 07:00–08:00) are excluded from the averages, correct?

Response: Thank you for checking. No transition hours were excluded. The analysis used discrete hourly records: daytime included 08:00, 09:00, …, 19:00, whereas nighttime included 20:00, 21:00, …, 07:00. Therefore, all 24 hourly records were included in the averages.

Table 2: I am very surprised to see that even the control simulations has a large residual in energy closure. 5 W/m^2 is not a small number. Based on my experience in another land model - Community Land Model (CLM), the energy balance is strictly enforced within a very small error (say 10^{-6} W/m^2) for each column. My understanding is that, given NetRad, SH, and LH are calculated independently, the remaining energy (NetRad – SH – LH) should go into the GRDFLX term [see https://escomp.github.io/CTSM/release-clm5.0/tech_note/Fluxes/CLM50_Tech_Note_Fluxes.html Eq. (2.5.149)]. Any idea why residual is so large in this model?

Response: Thank you for this comment. The treatment of ground heat flux in the Noah land surface model differs from that in CLM. In Noah, GRDFLX is not diagnosed as the remaining energy after subtracting the sensible and latent heat fluxes from net radiation. Instead, it is calculated independently from conductive heat transfer between the land surface and the uppermost soil layer, based on the soil thermal conductivity and the surface–soil temperature gradient (https://github.com/wrf-model/WRF/blob/release-v4.4.2/phys/module_sf_noahlsm.F#L2660-L2663). Therefore, the residual calculated from the independently diagnosed NetRad, SH, LH, and GRDFLX terms does not necessarily approach machine precision, as would be expected when the remaining energy is directly assigned to the ground heat flux.

Table 2: Also, it is more natural to define all terms positive downwards so that the sum of terms automatically gives the residual.

Response: Thank you for this suggestion. For clarity, we retained the original sign conventions of the individual energy terms: NetRad and GRDFLX are positive downward, SH and LH are positive upward, while Pout has no directional convention and is defined as positive for electricity generation.

L415~416 and L419~420: I don't understand the purpose of comparing these differences to the reanalysis data. This section analyzes the difference between two model simulations, which quantifies the effect of a physical process. Do you mean that the PV-induced effect is analogous to the long-term shift in atmospheric state? Instead, does this analogy imply that the PV-induced effect is actually just noise arising from interannual variability?

Response: Thank you for this comment. We agree that the comparison with reanalysis data was not sufficiently rigorous. Given the relatively short period of PV deployment, we have removed this analysis and the corresponding figure. The long-term atmospheric effects of PV deployment will be examined in future work using longer observational records.

Section 4.4: I still doubt whether the differences are significant relative to the noise from internal variability and whether they are really induced by PV panels. I think the key question to answer is whether the described atmospheric feedbacks can be linked to the PV installations. Maybe the authors can try some sensitivity experiments. For example, in an extremely idealized case, what if a more concentrated region or even the whole region is covered by the solar farms? Will we see the same consistent patterns in Figures 9 and 10?

Response: Thank you for this constructive suggestion. Following this suggestion, we conducted an additional idealized three-member ensemble experiment for summer 2024. A large contiguous area in the northern part of D03 was prescribed as PV-covered, while the model configuration, simulation period, and 2024 meteorological boundary forcing were kept consistent with the original experiments (Fig. R4). The ensemble-mean summer precipitation increased over the northern part of the plateau and the southern part of the domain, while precipitation decreased mainly in the far north and southwest (Fig. R5a). For heavy precipitation exceeding 30 mm day^{-1}, positive cumulative differences occurred over the northeastern part of the plateau and parts of the Hexi Corridor (Fig. R5b). The precipitation frequency distribution also showed a clear enhancement of heavy precipitation (Fig. R5c).

The associated atmospheric response followed the same mechanism identified in the original simulations. Enhanced sensible heat flux was concentrated over the expanded PV-covered area and was accompanied by a low-level convergence anomaly (Fig. R6). Both the sensible heating and the associated circulation response became more spatially extensive under the expanded PV coverage. These responses were spatially consistent with the enhanced precipitation, further supporting a link between the simulated precipitation response and PV forcing. For comparison, the corresponding precipitation and circulation responses from the original simulations are shown in Figs. R7 and R8.

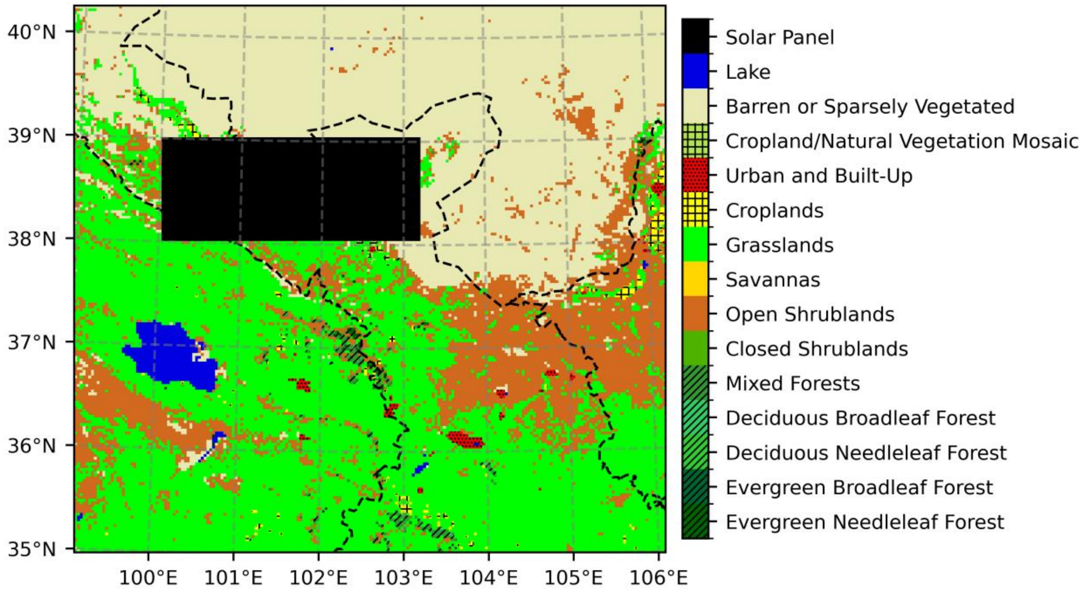

Figure R4: Land-use type of D03 in WRF_PV for the idealized experiment.

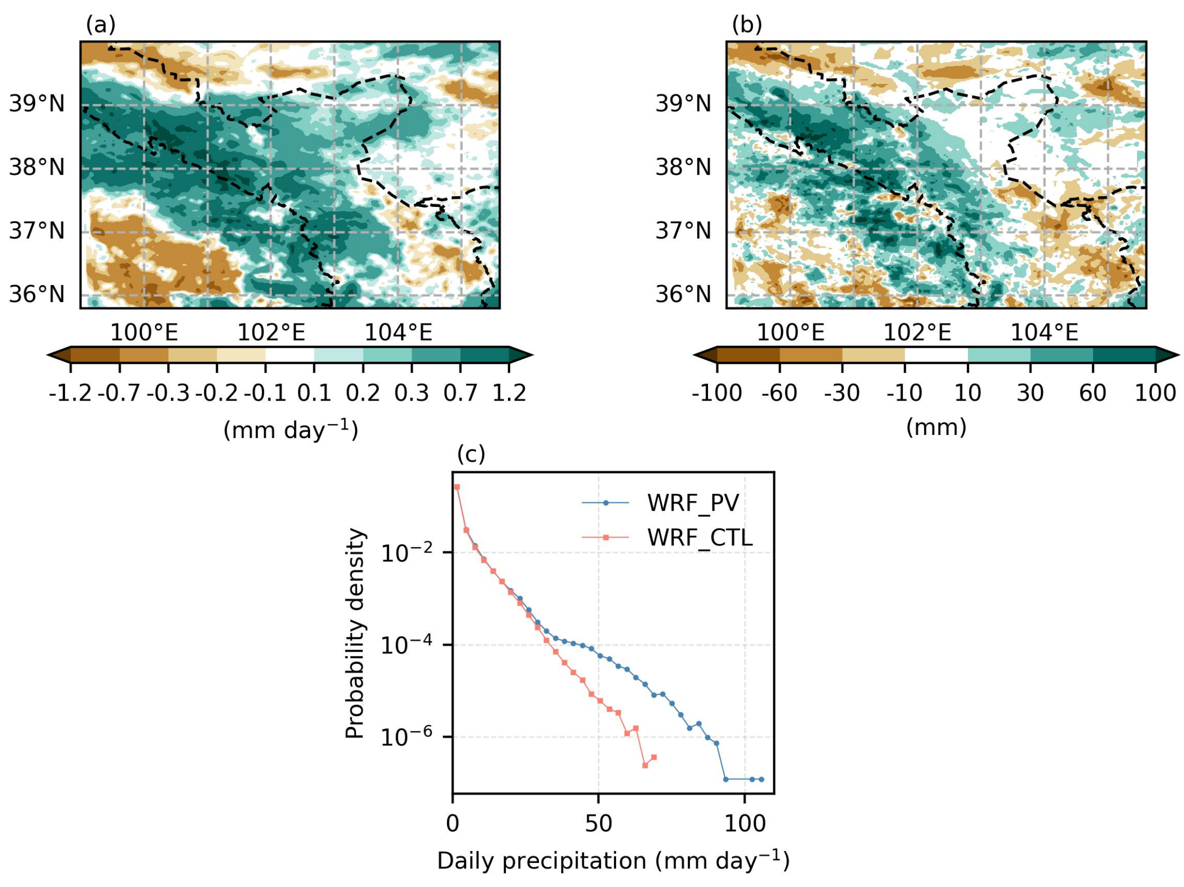

Figure R5: Spatial changes and probability density distributions of ensemble-mean summer precipitation in the 2024 idealized experiment. (a) Difference in mean daily precipitation between WRF_PV and WRF_CTL. (b) Difference in cumulative extreme precipitation (> 30 mm day^{-1}) amount between WRF_PV and WRF_CTL. (c) Probability density distributions of daily precipitation intensity in WRF_PV and WRF_CTL over D03.

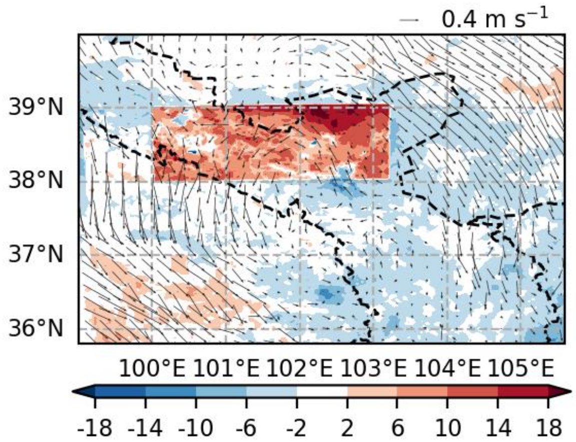

Figure R6: Ensemble-mean differences in sensible heat flux (shading) and low-level wind (vectors) between PV and CTL in the 2024 idealized experiment.

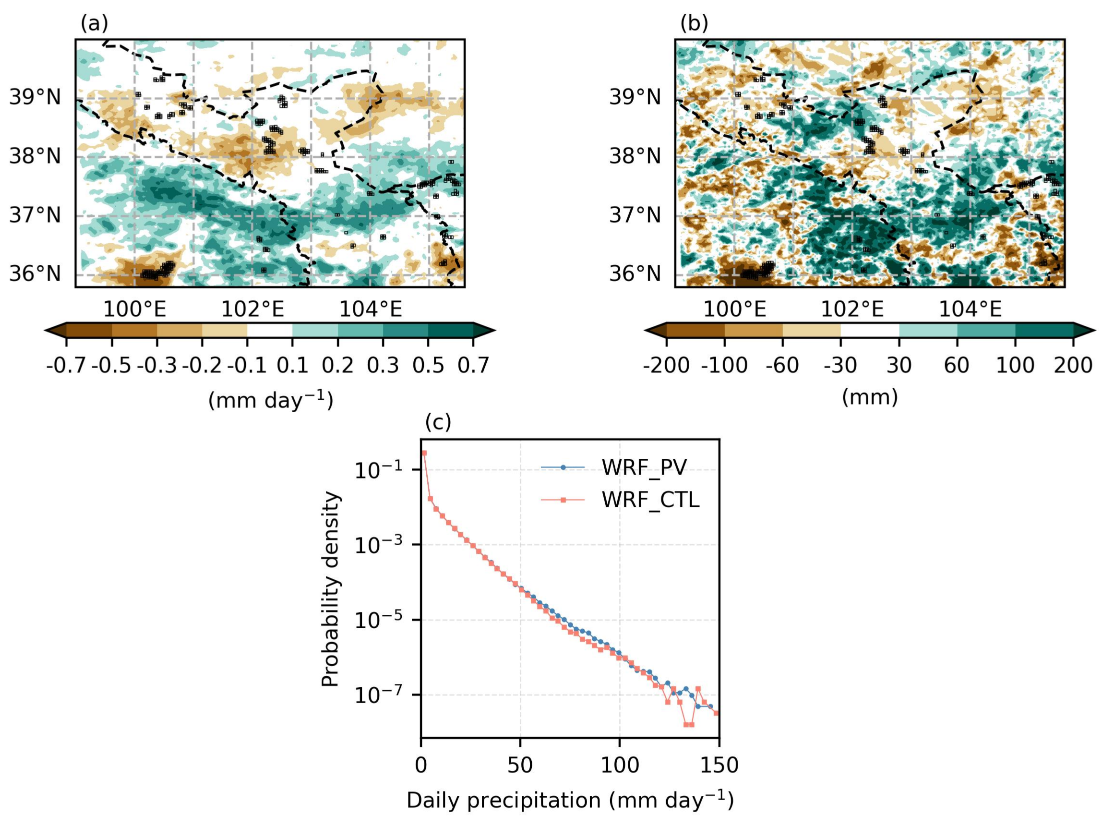

Figure R7: Spatial changes and probability density distributions of summer precipitation during 2018–2024. (a) Difference in mean daily precipitation between WRF_PV and WRF_CTL. (b) Difference in cumulative extreme precipitation (> 30 mm day^{-1}) amount between WRF_PV and WRF_CTL. (c) Probability density distributions of daily precipitation intensity in WRF_PV and WRF_CTL over D03. In (a) and (b), grey grid symbols denote PV grid cells. (Figure 9 in the revised manuscript)

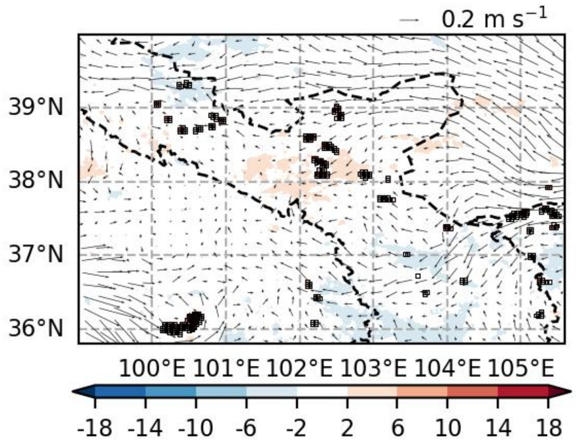

Figure R8: Differences in sensible heat flux (W m^{-2}, shading) and near-surface wind field (vectors) during the summers of 2018–2024. (Figure 10b in the revised manuscript)

L463: "The enhanced sensible heating arose from increased net radiation and reduced latent and ground heat fluxes." this attribution may confuse cause and effect. Is the increased sensible heat flux actually driven by the hot PV panels, which allows for more efficient convective heat transfer with the surrounding air?

Response: Thank you for this comment. We agree that the original attribution could confuse cause and effect. We have revised the sentence to clarify that the enhanced sensible heating was driven by convective heat transfer from the warm PV panels to the surrounding air.

The revised text reads:

> The enhanced sensible heating was driven by convective heat transfer from the warm PV panels to the surrounding air.

Location: Section 5, lines 461–462.

L467: Explain the full physical mechanisms behind the "PV-induced atmospheric feedbacks". Note that your results show reduced downward shortwave radiation is a consequence of increased cloud cover, so the explanation should focus on the cloud changes rather than the consequent radiation changes.

Response: Thank you for this comment. We have revised the text to clarify the full feedback mechanism.

The revised text reads:

> Additionally, the PV-induced increase in sensible heating weakened lower-atmospheric stability and promoted upward motion, which increased cloud fraction and thereby reduced SWdown by approximately 1.2%, with implications for local solar resources and PV yield estimation.

Location: Section 5, lines 466–468.

L470~479: This paragraph presents new findings and belongs in the results section, potentially supported by additional figures, rather than the conclusion section. In general, new results should not be introduced or analyzed in the conclusion. If manuscript length is a constraint, considering that the *experimental design is already in the Supplementary Materials, the authors could move these results there as well. From there, you could either: (1) integrate key findings from this comparison directly into the main Results section, or (2) focus this paragraph on the broader advantages of your modeling framework, briefly noting the limitations of the effective albedo method while citing the supplementary results.*

Response: Thank you for this suggestion. We have moved the detailed EA comparison to Supplementary Text S2 and Table S1 and revised the conclusion to focus on the broader advantages of WRF-PV and the limitations of the EA method.

The revised text reads:

> An additional comparison with the effective albedo (EA) method of Li et al. (2018) is presented in Supplementary Text S2 and Table S1. The EA method does not account for shading and the associated changes in ground heat storage, nor does it explicitly represent convective heat exchange between PV panels and the atmosphere. By contrast, WRF-PV explicitly represents panel coverage, panel thermal properties, panel–atmosphere convective heat exchange, and shading effects, and showed closer agreement with MODIS.

Location: Section 5, lines 470–474.

L478~479: "The EA method does not account for shading and the associated changes in ground heat storage." is it actually because the sensible heat transfer between PV panels and air is underestimated under this framework?

Response: Thank you for this comment. We have revised the text to clarify that, in addition to shading and ground heat storage effects, the EA method does not explicitly represent convective heat exchange between PV panels and the atmosphere.

The revised text reads:

> The EA method does not account for shading and the associated changes in ground heat storage, nor does it explicitly represent convective heat exchange between PV panels and the atmosphere. By contrast, WRF-PV explicitly represents panel coverage, panel thermal properties, panel–atmosphere convective heat exchange, and shading effects, and showed closer agreement with MODIS.

Location: Section 5, lines 471–474.