

Response to the reviewers

We thank the reviewer for the critical assessment of our work. Below is our response point by point. The comments by the reviewer are indicated in *italic*. The changes made to the manuscript are detailed in **red**. The referenced lines correspond to the updated version.

Reviewer 1

This study provides an analysis of observed and simulated surface solar irradiance (SSI) variability over land at small spatial scales for broken cloud conditions. After establishing the realism of the simulations, several sensitivity tests are applied to the simulations to explore the impact of cloud properties on the SSI variability. It is also proposed that a dense network of 10 surface-based pyranometers integrated over 10 mins can capture the main details of the SSI variability, providing useful guidance for sampling strategies targeted at future measurement campaigns. The manuscript is very well written. Figures are mostly clear. The references are mostly appropriate. I feel that the features of SSI variability that are discussed are largely already known and documented in other recent literature that has combined LES of shallow cumulus clouds with 3D radiative transfer. However, the observational focus of this study provides a somewhat different perspective that I think will still be of interest to the community. There are a few areas that would benefit from some further clarification and/or discussion, as outlined in my comments below. After addressing these minor comments, I recommend that the study be considered for publication in ACP.

Reply: We thank the reviewer for his/her positive assessment of our work. As pointed out in the introduction and stressed by the reviewer, the main contribution of this work with regards to the recent literature on the subject is the extensive use of observations from a dense network of pyranometers. However we also believe that the sensitivity studies (and related interpretations) based on the modified LES fields, as well as the preliminary discussion on instrument deployment, are complementary to what has been done before. In the following, we address the reviewer's concerns point by point.

Reviewer Point P 1.1 — *L20-22: It is a common misconception that 3D cloud effects vanish with spatial and temporal averaging. Systematic 3D biases can remain after averaging. For example, see Fig. 6a in Gristey et al., 2020b (already cited in the submitted paper).*

Reply: We thank the reviewer for this clarification. The corresponding sentence was adjusted as follows at l.20: "[...] this cloud enhancement has not been much investigated in the atmospheric science community, **primarily because it is thought to vanish with spatial and temporal averaging on scales relevant to energetic transfers in the Earth system, even though recent work has demonstrated that systematic biases could remain even on daily averages (Gristey et al., 2020)**".

Reviewer Point P 1.2 — *Section 2.1: It would be helpful to include some basic statistics such as the min/max/mean distances between the pyranometers. This will help with comparisons to the LES grid.*

Reply: We thank the reviewer for this suggestion. The information is added as follows at l.106:

"The minimum and maximum distances between any two pyranometers are 0.14 and 14.1 km, and the mean distance to the closest neighbour is 0.86 km"

Reviewer Point P 1.3 — *Are aerosols ignored in the simulations? It has been shown that aerosols, which are always present in reality to some extent, can have a substantial impact on the SSI PDF in such conditions (<https://doi.org/10.1029/2022JD036822>). This should at least be noted in the manuscript as a potential source of error assuming that aerosols are indeed excluded. It is interesting that the clear-sky PDFs (Fig. 3b) match quite well between the observations and simulations even without aerosols in the simulations. Perhaps this was a very pristine day. I recommend adding some discussion on this topic.*

Reply: This is an important point also raised by Reviewer 2. Indeed, the simulations have been performed without any aerosols, and this is now clearly stated l.148:

"Importantly, the simulations are performed without aerosols, although they can significantly alter the SSI distribution (Gristey et al., 2022)."

The potential impact of aerosols is now explicitly mentioned in the discussion (l.465):

"As pointed out before, we did not consider aerosols and instead focused on the impact of clouds only. In reality, aerosols are ubiquitous, but their detailed representation in atmospheric and radiative models is challenging because their optical properties depend on their size and composition, but also on their hygroscopicity and ambient humidity. Several physical processes have also been identified that can explain the increase of aerosol optical depth in the vicinity of cumulus clouds (Eck et al., 2014). Besides this complexity, we did not have observational data to properly account for their effects. Although aerosols were not accounted for in the simulations we believe that the qualitative results of the paper, along with the physical interpretations regarding the impact of cloud properties, would largely hold for real conditions. Yet, it is useful to discuss what impacts aerosols would have. According to Gristey et al. (2022), the presence of aerosols would typically shift the clear-sky mode to lower values due to increased absorption and the cloud-shadow mode to higher values due to extra radiation scattered laterally towards cloud shadows. Quantitatively, this impact could be as significant as those obtained from the sensitivity tests. In any case, accounting properly for aerosols would have required appropriate observations and a detailed optical module that are beyond the scope of the present paper. In view of making our understanding of the characteristics of surface flux distributions and their sensitivity to the overlying atmosphere more exhaustive, future work should strive to include aerosols in the simulations and perform additional sensitivity tests".

Besides these clarifications on the impact of aerosols, we have performed additional 3DRT simulations to study the impact of aerosols on the SSI pdf. The resulting simulations are the following:

- Control: without aerosol
- Case 0a: homogeneous concentration from the surface to cloud top such that total optical thickness ≈ 0.1 (which is close to the similar study in Gristey et al. (2022))
- Case 0b: homogeneous concentration from the surface to cloud top such that optical thickness ≈ 0.15
- Case 1: homogeneous concentration from the surface to cloud base, then 0 above, such that optical depth ≈ 0.1
- Case 2: homogeneous concentration from the surface to cloud base such that optical thickness ≈ 0.1 and homogeneous in the cloud layer such that optical thickness ≈ 0.05 . Total optical thickness ≈ 0.15

- Case 3: heterogeneous concentration which is proportional to the concentration of water vapour such that optical thickness ≈ 0.1 below the cloud base and optical thickness ≈ 0.05 in the cloud layer

Figure 1 shows the results of these simulations, in terms of SSI distributions and fields. It confirms that the aerosol optical depth plays an important role in shifting the two peaks of the SSI distribution. The clear peak is shifted to the left and the shadow peak is shifted to the right, correlated to what is found in Gristey et al. (2022). The aerosols below the clouds (Case 1) have more impact than those within the clouds (Case 0a). In contrast, the spatial variability of aerosol seems to have less impact on SSI pdf. These results suggest that the overall shape of the SSI distribution is not altered by the presence of aerosols, so our interpretations of the Control case remain relevant for real conditions.

Regarding the satisfactory match between the observed and clear-sky SSI pdfs, it probably comes from the fact that the conditions were relatively clean :

"They are both unimodal and symmetric, with approximately the same width and around the same mean value, suggesting that the impact of aerosols, which are not accounted for in the simulations, was rather limited for that particular day." (at l.271)

Note also that in dry conditions, the impact of aerosols is modest, compared to the very large AOD enhancement reported in the vicinity of clouds, and also simulated in Gristey et al. (2022) due to their hygroscopic growth. Hence the impact of aerosols is expected to be much larger in the presence of broken clouds due to what happens near cloud edges.

Reviewer Point P 1.4 — *L133: The spatial resolution of the 3DRT seems to be much finer than the LES, is that correct? If so, relatively coarsely resolved clouds are contributing to relatively finely resolved surface irradiance. Can a justification be provided that this is physically reasonable?*

Reply: The spatial resolutions of the 3DRT and LES are indeed different, the 3DRT resolution being much finer (5 m vs 25 m). Actually, even coarse clouds can result in fine features at the surface when considering rays passing near cloud edges, for instance, those contributing to cloud enhancement. Hence, to fully resolve the intensity and precise location of cloud enhancement, increasing the 3DRT resolution is crucial. To support this statement, Fig. 2 shows two simulated SSI maps and Fig. 3 shows the corresponding distribution with two 3DRT resolutions: 25 m (same as LES) and 5 m. Small differences can be noticed near cloud shadows' edges, and the distribution becomes smoother at a finer resolution. A short explanation is added at l.139:

"Each pixel of each field is a 5×5 m² square. Note that a finer resolution than the LES is used to accurately simulate what happens near cloud shadow edges, where variations occur at smaller scales than the cloud resolution. Such a fine resolution allows to correctly simulate the rapid transition from the shadow to the clear-sky areas, and to capture the value of the maximum cloud enhancement, which is essential to reproduce the SSI distribution."

Reviewer Point P 1.5 — *L177-178: The all sky images are a good check but are somewhat limited in spatial extent. The authors could also check satellite images from those days to confirm the presence of a widespread shallow cumulus cloud field at the location of interest.*

Reply: We thank the author for this kind advice. We did not find satellite images that precisely match the "golden cases" selected in our study. However, we did find a few satellite images with some spatial and temporal deviations (see Fig. 4). The information about the exact time when these satellite images are taken is lost in the database (Sentinel-Hub), but it can be inferred from Heinze et al. (2017).

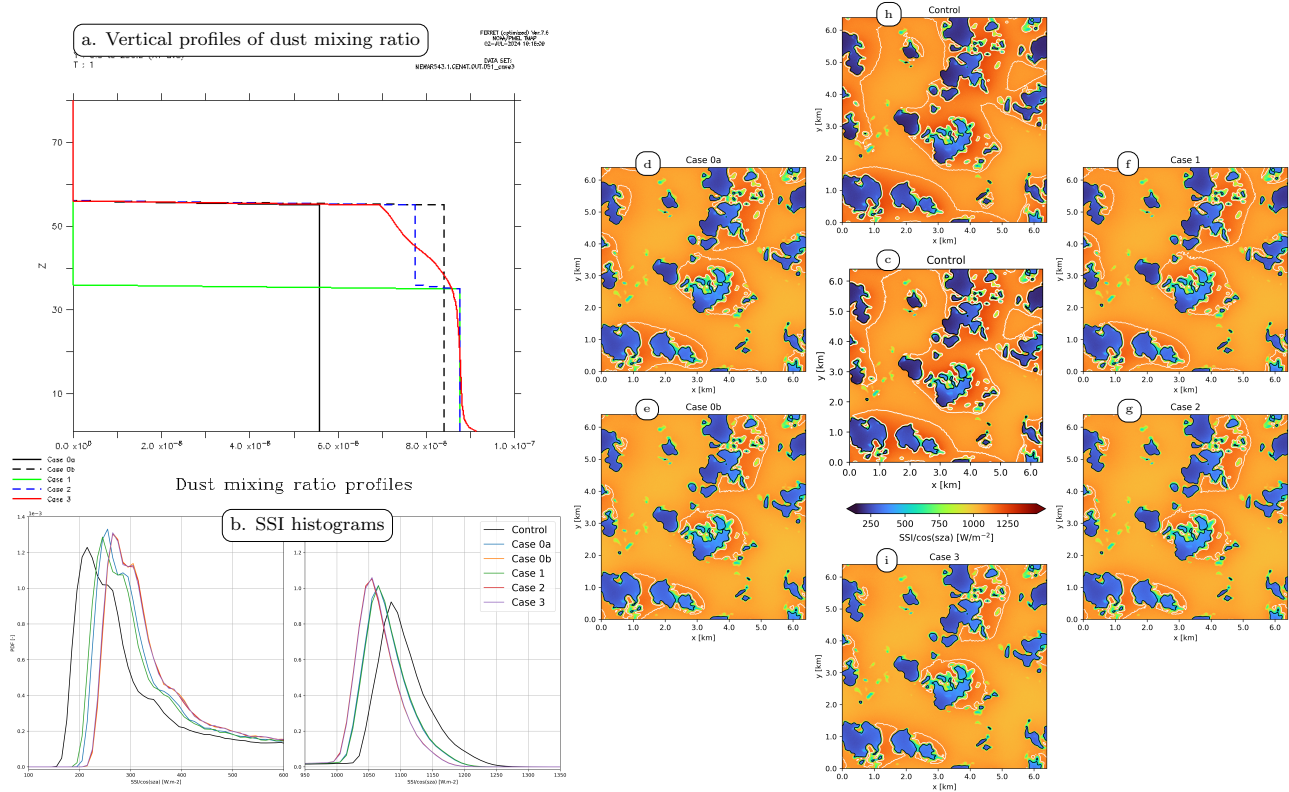


Figure 1: a preliminary study of aerosol's impact on the SSI pdf. (a) Vertical aerosol profile. (b) The SSI pdf with the presentation of aerosols. (c - i) The flux maps.

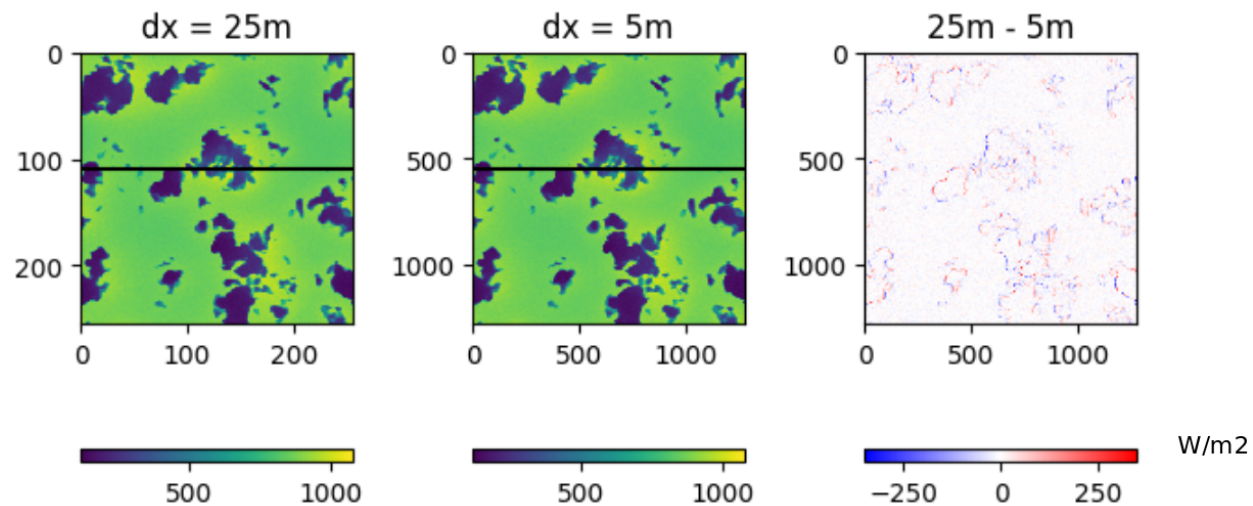


Figure 2: SSI map with different 3DRT resolution. Left: 25m. 3DRT uses the same resolution than it is used for LES. Middle: 5m. Right: Difference of the two SSI maps.

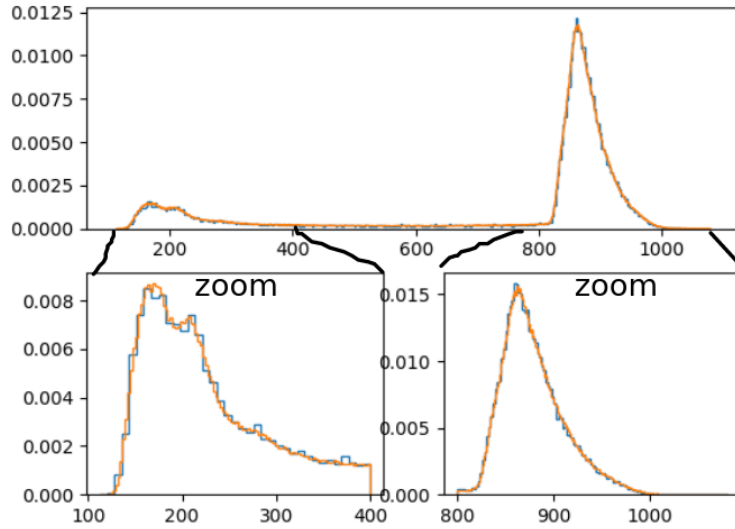


Figure 3: SSI pdf with different 3DRT resolution. blue: 25m. 3DRT uses the same resolution than it is used for LES. orange: 5m.

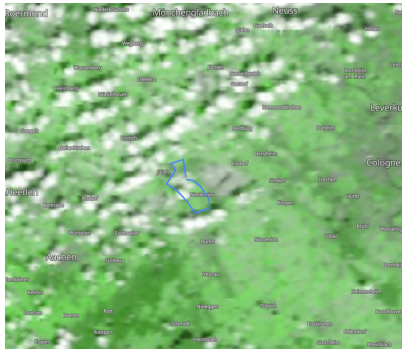
All satellite images are taken a few minutes to a few hours before the selected periods in this study (see caption of Fig. 4 for more details). Cumulus clouds can be clearly seen in P1, P3, P4 and P5 (Fig. 4(a,c-f)), but is not clearly shown in Fig. 4(b) for P2. Referring to Fig. 3 in the manuscript, P2 has a lower cloud fraction and lower SSI enhancement than other periods. We assume that the cumulus clouds at this period are smaller than the resolution of MODIS Terra ($1 \times 1 \text{ km}^2$), which is why they are not captured in the satellite image. This confirmation of cumulus presence is now specified (l.189): "Thanks to the all-sky images and to MODIS satellite images, it was verified that they indeed correspond to cumulus cloud situations, thereby validating our automatic selection procedure.

Reviewer Point P 1.6 — L214: *The choice of 500 W/m² and 900 W/m² seems rather arbitrary. Also, since the location of the two modes can vary from case to case or with different cloud properties (for example see Fig. 7), using fixed thresholds seems like it would incur some error because different portions of the PDFs will be represented. The authors could consider adjusting these thresholds depending on the PDF shape for a given case. Otherwise, I think a short discussion of this limitation in the manuscript is required.*

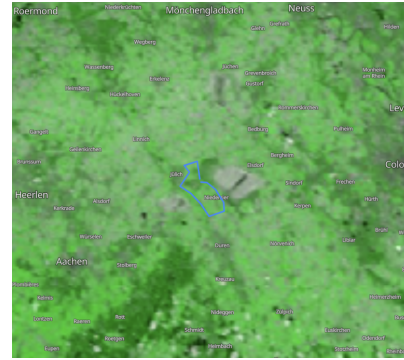
Reply: We thank the reviewer for this comment. This limitation is now pointed out at l.228:

"Although these two thresholds are arbitrary, the main objective was to qualitatively isolate both modes, which proved to be acceptable for the cases encountered. However, defining both modes in a more flexible way, which would depend on the actual distribution and would work for a larger variety of cloud properties, would be useful and should be considered for future studies."

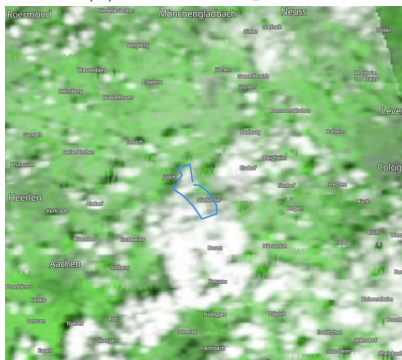
Reviewer Point P 1.7 — L221-222: *This approach assumes that the impact of different cloud properties on SSI can be linearly combined. Non-linearities are inherent in radiative transfer, especially 3D radiative transfer, so this might not be a great assumption. It should be noted that non-linearities are not accounted for, unlike the machine learning approaches used in other studies that are already mentioned.*



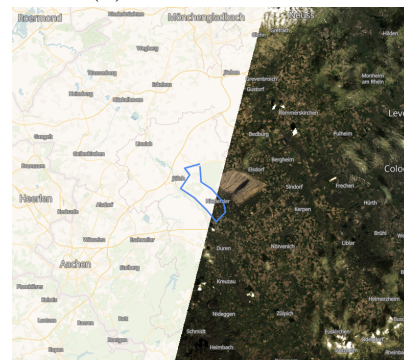
(a) MODIS Aqua, 2013-04-18



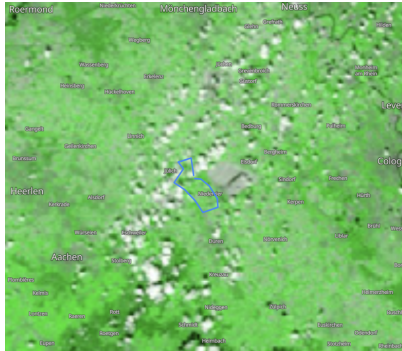
(b) MODIS Terra, 2013-04-20



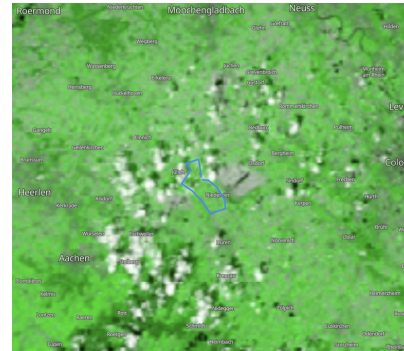
(c) MODIS Aqua, 2013-04-25



(d) Landsat8-9, 2013-04-25, 10:23



(e) MODIS Terra, 2013-05-05



(f) MODIS Aqua, 2013-05-05

Figure 4: The satellite images that are closed to the selected periods in our study in UTC from Sentinel-Hub: P1: 18 April 2013, 13:00-14:00; P2: 20 April 2013, 9:12-10:12; P3: 25 April 2013, 12:32-13:32; P4: 5 May 2013, 9:30-10:30; P5: 5 May 2013, 11:36-12:36. The blue contour indicates the pyranometer network. It is noted that the exact time when the images of MODIS Terra and Aqua were taken was missing in the database. However, we presume those images of MODIS Terra were taken around 11:30-12:45 and images of MODIS Aqua were taken around 8:30-9:30 based on Heinze et al. (2017).

Reply: We thank the reviewer for this clarification. It is true that the total response will not be the linear combination of individual responses, due to obvious non-linearities. This sensitivity study primarily aims to provide physical insight into how each cloud parameter influences the SSI. This is now more clearly stated l.234:

"Sensitivity tests are performed in Sect. 6 in order to gain physical insight on how various cloud characteristics drive SSI distributions. For each category of test, the 60 LES cloud fields of the one-hour-long simulation are modified, varying a single property at a time, among cloud LWC, cloud base height, cloud depth, or cloud fraction."

and l.434:

"Note also that due to strong non-linearities in the radiative transfer the impact of combined modifications of the cloud field cannot be estimated by the linear combination of the impacts of the individual modifications, making this sensitivity study primarily useful for the qualitative understanding of the impacts rather than their quantitative assessment in real situations."

Reviewer Point P 1.8 — *L254-255: I expect the enhancement increase with cloud cover is because the remaining clear-sky region is receiving scattered radiation from more surrounding clouds.*

Reply: We thank the reviewer for this suggestion. It is added at l.269:

"We believe that it is because the clear-sky region is receiving scattered radiation from more surrounding clouds (the sensitivity of the SSI distribution to cloud cover is investigated in Sect. 6)."

Reviewer Point P 1.9 — *Figure 3: The figure caption does not match what is plotted. I think b and c are swapped with d and e in the caption. I recommend revising the caption to improve clarity.*

Reply: We thank the reviewer for this careful comment. It is corrected in the revised version.

Reviewer Point P 1.10 — *Section 5: The discussion and conclusions from this section are broadly consistent with that found in Fig. 7 here: <https://doi.org/10.1175/BAMS-D-19-0227.1>. They found that, when averaging for 1 hour, the bimodal PDF was difficult to identify from a single site, but became much clearer when considering 10 sites. I recommend including this relevant comparison.*

Reply: We thank the reviewer for pointing to this reference, which is now mentioned at l.363:

"This result aligns with the findings of Riihimaki et al. (2021), who observed that for hourly averages the bimodal distribution was challenging to identify from a single site but became much clearer when cumulating data from 10 sites."

Reviewer Point P 1.11 — *L327: Cloud lifetime is only about 15mins for these clouds so the Taylor hypothesis probably does not hold very well in this environment.*

Reply: We agree with the reviewer and the Taylor hypothesis is removed in the revised version.

Reviewer Point P 1.12 — *L371-372: As well as the optically-thinner slant path, the wider footprint of scattering also means one cloud can be scattering more radiation into the shadow of a neighbouring cloud, therefore adding to the "brightening".*

Reply: We agree with the reviewer on this point and it is added at l.411:

"Shadows are also brighter, as clouds are overall optically thinner to slanted radiation because of the LWC scaling, and because more scattered radiation from the neighbouring clouds can reach the shadows thanks to the wider scattering footprint."

Reviewer Point P 1.13 — *L422: The suggestion that SSI observations could provide a constraint for LES cloud droplet effective radius heterogeneity is not related to any of the sensitivity tests performed in this study. It's an interesting suggestion but it comes a bit out-of-the-blue. If the authors would like to keep this statement, I think another sentence or two is required to provide some physical reasoning to support this claim.*

Reply: Indeed, the sensitivity studies performed in this paper are with respect to the liquid water content and cloud geometry. The heterogeneity of the droplet effective radius in LES is not explored these sensitivity studies. The corresponding statement is removed in the revised version.

Reviewer Point P 1.14 — *Cloud classifications that utilize SSI observations are already being developed. An appropriate reference to cite here is here: <https://doi.org/10.1175/JAMC-D-20-0153.1>.*

Reply: We thank the reviewer for this bibliographic complement. It is added at l.498:

"Relying on the objective determination of cumulus cloud conditions set up in this study, we also advocate the development of cloud classifications based on SSI observations using the metrics introduced in this study, in line with the random-forest classifier recently proposed by Sedlar et al. (2021)."

Reviewer Point P 1.15 — *L434-435: "It does not include Large Eddy Simulation 3D output fields but they will be provided on demand." I am not sure that a statement like this fits well with the journal data policy. Since the authors are providing the data needed to produce the plots, and the underlying tools are available (correct?), it might be est to remove this statement.*

Reply: We thank the reviewer for this careful comment. As mentioned, the LES simulation results can be obtained by running Meso-NH with the name lists provided in He et al. (2024) on Zenodo. The statement on LES (un)availability has been removed accordingly.

Other modifications

- The acknowledgements are adjusted. A new financial declaration for this work is added and highlighted in blue.
- We also adjusted some English expressions throughout the document. These corrections aim to enhance the overall readability and clarity of the text.

References

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