

Response to referee comments

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Title: “EarthCARE reveals details on the role of rain in closed-to-open cell transitions”

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Dear Referees,

We thank both referees for taking the time to review our manuscript. Your feedback is greatly appreciated and was helpful to further improve the manuscript. We carefully considered your suggestions and incorporated them into the revised manuscript, as specified in the following (referee comments in blue; our answers in black).

Response to main comments

Main comment of Referee 1: This manuscript describes an investigation of transitions from closed-cell stratocumulus to open-cell stratocumulus cloud fields. The paper shows convincingly how microphysical properties change over a long period before transitions occur, support a precipitation-linked transition pathway. The manuscript is well-written. It makes excellent use of EarthCARE data as well as other data and several analysis methods. I recommend acceptance of the paper after considering a few minor comments listed below. In general, the authors may consider trimming the paper a bit by removing some figures and maybe some text.

Main comment of Referee 2: The paper is well-written, but is slightly longer than required. It would enhance readability if the authors trim portions of the paper. For instance, transition from closed to open-cell stratocumulus is a well explored topic. So, there is no need to provide too many details about known results/statistics. Instead, it would be better if the focus is on the new or relatively under-explored ideas.

We thank the referees for their positive evaluation and agree that the manuscript benefits from some trimming. We have therefore shortened the manuscript in several places:

- We removed several passages on details of established results that were already covered in the Introduction, allowing the Results section to focus more clearly on the new findings.
- We shortened the Discussion by removing both the text and figure on cold-pool detection in SAR, as it was not essential to the main conclusions and was somewhat off-topic to the scope of the manuscript.
- We shortened the Implications section by removing the discussion of stratocumulus-to-cumulus transitions, which was likewise somewhat outside the main focus of the study.
- We removed two subpanels from Fig.13 and revised the corresponding text to focus more directly on the decomposition of RWP into rain fraction and rain intensity.

We believe these changes improve the focus and conciseness of the manuscript. Overall, the manuscript is shortened by a bit more than one page.

Response to minor comments of Referee 1

Line 68: This part of the sentence is unclear to me: “and improved identification of light precipitation occurrence”. Should this be something like ““and CPR has an improved identification of light precipitation occurrence compared to Cloudsat”. Please rephrase the sentence to make it more clear.

Thanks for pointing this out; we changed the sentence to:

“Using the first year of CPR observations, Xu et al. (2025) show that surface clutter is effectively suppressed above approximately 0.5 km, and that CPR detects substantially more stratocumulus and has an improved identification of precipitation compared to CloudSat's radar instrument in key subtropical regions.”

Line 163: By filtering for scenes with $BT < 273$ K also super-cooled liquid clouds are removed, not only cirrus. I guess this is not a limitation here.

As the referee mentions, we believe that supercooled liquid clouds do not play a role in the considered regions. Manual inspection of BT values in the considered regions showed that stratocumulus clouds do not reach low temperatures (< 273 K) for all inspected cases.

Line 170: Please give a reference or explanation for the “F1 score”

We added a short explanation of the F1 score in the text: “... the CNN shows substantially improved classification skill with an F1 score (a performance metric balancing precision and recall) ...”

Line 255: The authors might want to consider to look if larger effective radii are also found by the MSI bi-spectral retrievals, comparable to MODIS.

The referee raises a good point; we followed the suggestion and conducted a short analysis comparing effective radii from ACM-CAP and M-COP for closed and open cells. The results are briefly described in the main text of the manuscript, and in an additional appendix section:

Main text:

A comparison with collocated M-COP retrievals shows that also EarthCARE's passive imager retrieves larger r_e in open cells, and that small r_e values in ACM-CAP occur mainly in optically thin parts of the open cells (Appendix C). These optically thin cloud layers are more readily detected by the ACM-CAP active-sensor synergy than by passive imagers, which preferentially sample the optically thicker parts of open cells and therefore retrieve larger average r_e .

Appendix C: Comparison with M-COP effective radius

To investigate where the discrepancies between our findings of similar average r_e for closed and open cells and previous findings of larger r_e in open cells originate, we compare ACM-CAP with collocated M-COP retrievals for June-August 2025. For each ACM-CAP profile, the M-COP pixel with the closest longitude-latitude position along track is selected. When all cloud profiles are included, ACM-CAP

shows similar scene-mean r_e for open and closed cells, whereas M-COP retrieves larger r_e in open cells, consistent with previous studies using passive imagers (Fig. C1(a)).

The absolute r_e values are also shifted between ACM-CAP and M-COP. This offset can partly arise from differences between the retrieval methods of the still-maturing products. In addition, passive bispectral retrievals are weighted toward the upper part of the cloud, whereas the ACM-CAP values considered here are averaged over the cloud column. Since r_e generally increases with height in approximately adiabatic clouds, this difference in vertical sampling is expected to contribute to larger r_e from M-COP.

When only profiles with ACM-CAP optical thickness >1 are retained before scene averaging, the open-cell ACM-CAP distribution shifts toward larger r_e , while M-COP changes comparatively little (Fig. C1(b)). This suggests that the small ACM-CAP r_e values occur predominantly in optically thin parts of open-cell scenes that are less readily detected by passive imagers. Consequently, passive retrievals preferentially sample the optically thicker parts of open cells, where r_e is larger. Three-dimensional radiative effects and sub-pixel inhomogeneity, which are stronger for heterogeneous open-cell scenes, may additionally affect the retrieved r_e and contribute to differences between closed and open cells, as well as to retrieval differences between the two products (Zhang et al., 2012).

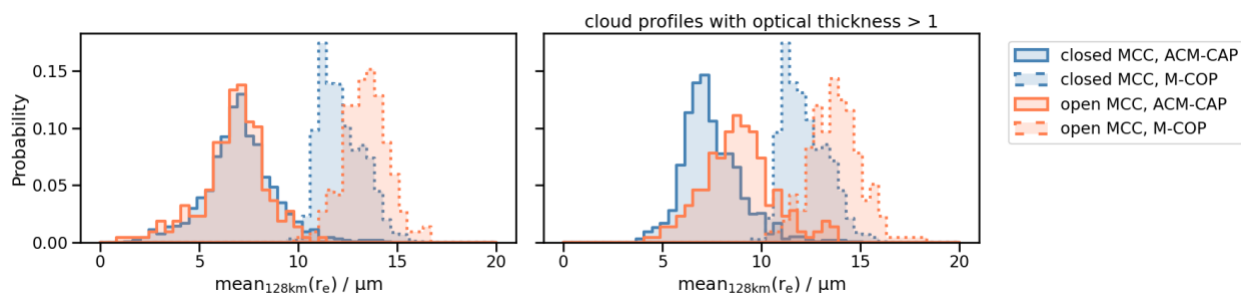


Figure C1: Probability distributions of scene-mean r_e for closed and open cells from ACM-CAP and collocated M-COP retrievals for June-August 2025. (a) All cloud profiles. (b) Taking only profiles with ACM-CAP cloud optical thickness >1 into account for the scene-means.

Line 257: The Nakajima-King (bi-spectral) retrievals are also affected by cloud inhomogeneity, 3D-radiative transfer effects and influence of rain. I suggest adding that to the discussion, possibly referring to Zhang et al. (2012) and/or other literature. In addition, the passive retrievals get effective radius at cloud top, whereas the ACM-CAP effective radii are averaged over the cloud column, which in an adiabatic case should lead to larger values for the bi-spectral retrievals.

Zhang, Z., A. S. Ackerman, G. Feingold, S. Platnick, R. Pincus, and H. Xue (2012), *Effects of cloud horizontal inhomogeneity and drizzle on remote sensing of cloud droplet effective radius: Case studies based on large-eddy simulations*, *J. Geophys. Res.*, 117, D19208, doi:10.1029/2012JD017655.

We address this point, including the suggested citation, in the discussion on r_e from synergy and passive retrievals in the answer above.

Figure 7: I suggest to make it clearer what the different panels show.

We rewrote the caption of Figure 7 to make it more clear:

Figure 7. Examples of two typical closed-cell (a,b) and two typical open-cell (c,d) cloud scenes. Larger subplots show M-COP LWP and r_e for the four 128 km×128 km scenes. The smaller subplots show the corresponding ACM-CAP profiles along-track (black dashed line in M-COP images) for several cloud and rain variables, namely liquid water content, r_e , N_d , RWC and D_0 . The bottom right subplot shows the CPR reflectivity for each scene. The orbits and mid-points of the four scenes are specified in the titles. Numbers at the top left in ACM-CAP subplots are the mean and CV taken over the 128 km along-track scenes.

Line 265: Could the variation in effective radius also be caused by variations in cloud physical thickness, which clouds at the edges having slightly higher tops? With cloud size adiabatically increasing with height, a higher top would lead to larger (vertically-averaged) effective radius.

Thank you for this suggestion. In principle, variations in cloud geometrical thickness could affect the retrieved r_e , since droplet size generally increases with height in an approximately adiabatic cloud and passive r_e retrievals are weighted toward the upper part of the cloud. However, we do not expect this effect to explain the observed pattern. In non-precipitating closed cells, the broad updraft regions at the cell centres are generally associated with larger optical depth, whereas the downdraft regions at the cell edges have reduced optical depth (e.g. Kazil et al., 2017). Moreover, stratocumulus cloud tops tend to be relatively flat because they are constrained by the capping inversion (as also shown in the closed-cell examples in our Fig. 7), while cloud-base height varies more strongly; updrafts tend to have lower cloud bases and downdrafts higher cloud bases (e.g. Wood, 2012). Thus, if anything, we would expect the cloud to be somewhat thinner rather than thicker at the cell edges. We therefore do not think that systematically higher cloud tops at the cell edges are the main explanation for the observed r_e pattern, although local variations in cloud-top height cannot be excluded.

Line 295 and Figure 8: I find Figure 8 rather interesting and informative, but I am surprised that there is only one single sentence on it in the paper. Could the figure be described and discussed more, or if not, maybe the authors should consider removing it.

Thank you for pointing out that the references to Fig. 8 were not sufficiently clear in Section 3.1. Throughout this section, Figs. 7 and 8 are discussed jointly, with Fig. 7 showing representative examples and Fig. 8 the corresponding statistics. However, Fig. 8 was referenced only rarely in the original text. We have therefore added several explicit references to Fig. 8 at the relevant points to make this connection clearer.

Figure 10: This figure does not add much compared to figure 7. Maybe consider removing it.

We appreciate this suggestion and agree that Fig.10 is similar in format to Fig.7. However, we would prefer to retain it because it shows closed cells shortly before their transition to open cells and therefore illustrates the contrast with the more typical closed-cell example in Fig.7. In addition, the example helps place the statistical results of Section 3.2 into context by showing the spatial scales over which the statistics are computed, and the variability within individual scenes. We therefore believe that Fig.10 provides useful complementary information despite the similarity in presentation.

Lines 393 and further: This section on Sentinel-1 observations does not add much in my view. The picture in figure 15 is not very clear and, frankly, I do not know what I am looking at/for. I think this part can be removed or reduced to a sentence or two.

We agree that the discussion about cold pools from Sentinel-1 opens up a new topic and might be a bit out of place in this manuscript. We removed the paragraph and figure.

Line 414: This discussion on stratocumulus to cumulus transitions is a bit out of place in my view. It does not add much and the mentioned role of the development of open cells in this transition is speculative. If the authors want to keep such an discussion in, I suggest moving it to the introduction or conclusions and possibly reducing it.

We agree that the discussion on stratocumulus-to-cumulus transitions may be a bit off topic. We removed the paragraph and concentrate on the implications on closed-to-open cell transitions.

Appendix B and C: Please point to the figure numbers that are related to these appendices.

Thanks for pointing this out. We added the missing Figure references.

References:

Kazil, J., Yamaguchi, T., Feingold, G.: Mesoscale organization, entrainment, and the properties of a closed-cell stratocumulus cloud, doi:10.1002/2017MS001072, 2017.

Wood, R.: Stratocumulus clouds, doi:10.1175/MWR-D-11-00121.1, 2012.

Zhang, Z., A. S. Ackerman, G. Feingold, S. Platnick, R. Pincus, and H. Xue, Effects of cloud horizontal inhomogeneity and drizzle on remote sensing of cloud droplet effective radius: Case studies based on large-eddy simulations, doi:10.1029/2012JD017655, 2012.

Response to minor comments of Referee 2

1. Can you define how LWP and RWP are defined?

The definition of LWP and RWP on a profile basis can be found in Section “2.1 EarthCARE ACM-CAP for detailed cloud and rain observations”:

“For cloud microphysics, we use ACM-CAP retrievals of liquid water content, [...], rain water content, [...]. In this study, we focus on column-integrated or averaged values: Liquid water content, and rain water content are vertically integrated to obtain liquid water path (LWP) and rain water path (RWP).”

A revised definition of LWP and RWP as scene-averages, is described in Section “2.6 Putting it all together: Dataset of closed and open cell properties with transition information”:

“For LWP and RWP, means and CVs are computed over all cloudy profiles; thus, they represent values conditional on cloud occurrence.”

2. EarthCARE provides a snapshot. How was the time to transition defined and how was it determined (Figs 11 and 12)? Was it using GOES? It would be good to specify that in the Fig captions.

Thanks for the suggestion. We specified that time-to-transition comes from the combination of GOES with trajectories in the caption:

“Cloud properties of all cloud scenes in which closed-to-open cell transitions were identified, as a function of their time to transition (= time of EarthCARE overpass - time of transition; determined from GOES morphology along trajectories)....”

Additionally, we made this point more explicit in the introductory sentences of Section 3.2.

3. Lines 406-407: Mechanisms behind moisture increase? Could there be changes in SST playing a role?

Yes, to our understanding, increased SST could increase the surface moisture flux and therefore increase moisture and LWP. We modified the relevant sentence in the implications section to make this more explicit: “This implies that changes in environmental conditions that increase boundary-layer moisture, for instance stronger surface winds and higher sea-surface temperatures, could lead to more open cell occurrences, decreasing the albedo and cooling effect of the stratocumulus decks.”

4. Lines 380-383: If not Na, what are the potential mechanisms that are responsible for this breakup? Sandu & Stevens 2011 and Yamaguchi et al 2017 explored the role of SST.

We thank the referee for raising this point. We did not intend to argue that aerosol number concentration (N_a) is unimportant for breakup. Rather, our interpretation is that aerosol depletion may be an important part of the transition feedback, but not necessarily the first trigger.

In our timelines, N_d is initially close to climatological values, while LWP and precipitation increase earlier. Once precipitation becomes sufficiently strong, wet scavenging can reduce N_a and consequently N_d increase droplet size, and further enhance precipitation. We therefore interpret aerosol scavenging as an important positive feedback that can amplify rain and promote breakup, even if the initial perturbation originates elsewhere.

One possible upstream mechanism is enhanced boundary-layer moisture, consistent with the stronger winds preceding transitions reported by Eastman et al. (2022). We agree that changes in SST and associated surface forcing, as explored by Sandu & Stevens (2011) and Yamaguchi et al. (2017), are also plausible contributors to this initial evolution. Determining which environmental factors trigger the

increase in moisture and precipitation was beyond the scope of the present study, but we agree that this is an important next step. We have revised the manuscript to clarify both the important role of aerosol in the feedback and ultimately breakup, and the distinction between this feedback and the possible initial trigger.

References:

Eastman, R., McCoy, I. L., and Wood, R.: Wind, Rain, and the Closed to Open Cell Transition in Subtropical Marine Stratocumulus, <https://doi.org/10.1029/2022JD036795>, 2022.

Sandu, I. and Stevens, B.: On the Factors Modulating the Stratocumulus to Cumulus Transitions, <https://doi.org/10.1175/2011JAS3614.1>, 2011.

Yamaguchi, T., Feingold, G., and Kazil, J.: Stratocumulus to Cumulus Transition by Drizzle, <https://doi.org/10.1002/2017MS001104>, 2017.