

In their manuscript, the authors run a convection-permitting simulation of MCB over the Great Barrier Reef and show that a dense network of sprayers using moderate emission rates is substantially more effective at dispersing aerosol and brightening clouds than a sparse network of high-emission sprayers. The core idea is important and worthy of publication. Unfortunately, much of the supporting commentary requires major revisions before I can recommend the manuscript be published.

**Major comments:**

A) Interpretation of aerosol “scavenging”: As the authors show elsewhere, precipitation (and therefore wet deposition) is not particularly high in their simulations. Increasing aerosol would also tend to decrease precipitation. Denser aerosol plumes therefore would not be expected to result in greater wet scavenging; this explanation for the differences between EXP20 and EXP100 is implausible. More likely, the aerosols are coagulating more in the sparser-but-denser plumes, reducing number but not necessarily mass. An easy way to check this would be to look at the total or average mass concentration of aerosol between the experiments in addition to number concentration.

We agree with the reviewers that our previous interpretation overemphasised precipitation scavenging. Given the non- to weakly precipitating nature of the simulated case, wet scavenging by precipitation is unlikely to be the dominant mechanism explaining the lower domain-mean aerosol enhancement in EXP100. We have therefore revised the manuscript to avoid attributing this behaviour primarily to precipitation scavenging efficiency.

Instead, we interpret the results as arising from enhanced aerosol processing within concentrated emission plumes in the sparse-source configuration, which may lead to more efficient domain-wide dispersion and aerosol loss. Multiple processes may contribute to this behaviour, including cloud processing, dilution, possible coagulation, turbulent mixing, and deposition. In particular, processes such as coagulation may reduce aerosol number concentration without necessarily reducing aerosol mass, which could partially explain the differences between experiments.

However, the current model output does not fully resolve or diagnose the relative contributions of wet scavenging, dry deposition, coagulation, and transport. This limitation has now been explicitly acknowledged in the revised manuscript.

Lines 239-244 have now been revised to

“This behaviour arises from the nonlinear response of aerosol processing and removal pathways to local aerosol number concentration in the WRF Thompson aerosol-aware microphysics scheme (Wang et al., 2010; Weston et al., 2022). In the sparse-source configuration (EXP100), aerosol emissions are concentrated into fewer locations, leading to enhanced aerosol processing within these concentrated plumes. Multiple processes may contribute to this behaviour, including cloud processing, dilution, possible coagulation, and deposition. Given the non- weakly- precipitating nature of the simulated case, coagulation within the highly concentrated aerosol plumes is likely an important, and potentially dominant, contributor, as it can efficiently reduce aerosol number concentrations near the source regions and thereby limit the enhancement of domain-mean aerosol concentrations. However, it should be noted that the current model output does not fully resolve or diagnose the relative contributions of wet scavenging, dry deposition, coagulation, and transport.”

B) Overinterpretation of aerosol-cloud interaction results: The novelty of the current work lies in the exploration of the denser versus sparser sprayer setup, not in exploring ACI under shallow cumulus conditions. The general finding that adjustments to the Twomey effect would tend to promote cloudiness under moist and precipitating conditions and decrease cloudiness under dry and non-precipitating conditions is very well established at this point. The results and discussion should be rewritten to better highlight which areas of the study are a novel contribution versus which are reinforcing the preexisting consensus. The abstract already does a nice job of this!

Thank you for this helpful comment. We fully agree that the primary novelty of this study lies in examining the impact of spatial variability in aerosol injection (i.e., denser versus sparser sprayer configurations), rather than in establishing the general behaviour of ACI under shallow cumulus

conditions. Our intention was not to present these behaviors as novel findings, but rather to provide context for interpreting the sensitivity of cloud responses to aerosol forcing configurations.

In response, we have revised the Results and Discussion sections to more clearly distinguish between:

- (1) well-established ACI mechanisms that are consistent with previous studies, and
- (2) the novel aspects of this work, namely the sensitivity of cloud and radiative responses to the spatial distribution of aerosol injection in a convection-permitting framework.

We have also reduced interpretative emphasis on well-known processes and instead highlight how different sprayer configurations modulate the magnitude, spatial extent, and efficiency of these responses. We appreciate the reviewer's suggestion, which has helped improve the clarity and positioning of the manuscript.

C) Analysis of cloud and radiation variables: A number of issues arise with the treatment of cloud properties, including an inappropriate means of calculating cloud fraction. See specific comments below. I would also encourage the authors to consider evaluating cloud radiative effect (CRE; all sky minus clear sky net fluxes) directly.

We thank the reviewer for this thoughtful and constructive comment. Following this comment, and in conjunction with the Specific Comment 12, we have now added analysis of the shortwave cloud radiative effect (CRE) associated with the aerosol perturbation experiments. In addition, the cloud mask methodology has been updated following reviewer recommendations (Specific Comment 10) to define cloudy conditions using cloud optical depth (COD)  $> 1$ , which represents optically significant clouds and is commonly used to improve robustness in cloud detection and radiative analyses (Heidinger et al., 2020). The corresponding analyses in Figures 7 and 8 have been updated accordingly, although the overall statistical behaviour and conclusions remain largely unchanged.

As shown in the Figures R1 and R2 (updated Figures 7 and 8 in the revised manuscript), the aerosol-seeding sensitivity experiments exhibit enhanced shortwave cloud radiative effects relative to the control simulation, indicating increased reflection of incoming solar radiation due to aerosol-induced cloud brightening. The largest CRE enhancement occurs during periods of smaller solar zenith angle near local midday, when incoming solar radiation is strongest. While the simulated case study covers only a limited daytime period, the results consistently demonstrate measurable increases in cloud reflectivity and shortwave radiative cooling associated with additional aerosols.

However, we agree with the reviewer that our simulations alone are insufficient to determine whether these radiative perturbations would be large enough to produce meaningful ocean cooling or mitigate marine heat stress over the GBR. Such conclusions would require substantially broader analyses, including coupled atmosphere–ocean modelling, longer temporal integrations, and regional energy budget assessments, all of which are beyond the scope of the present study.

Accordingly, we have revised the manuscript to avoid overstating the implications of the results. The conclusions now focus specifically on the demonstrated process-level sensitivity of cloud microphysical and radiative responses to aerosol seeding configuration and meteorological conditions, rather than asserting direct mitigation of extreme heat exposure over the GBR.

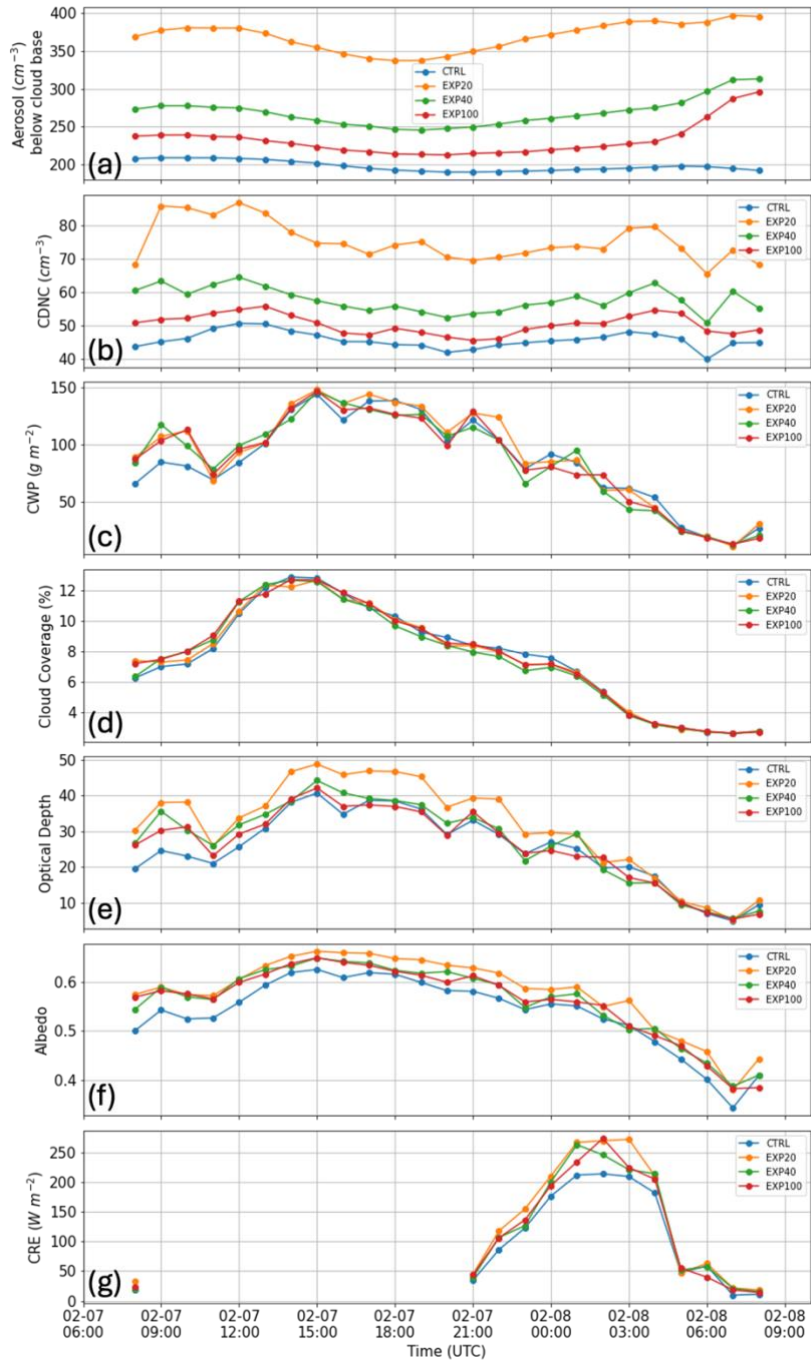


Figure R1: Time series of domain-averaged (a) aerosol number concentration below cloud base, (b) CDNC, (c) cloud water path, (d) Cloud Coverage, (e) Optical depth, (f) synthetic cloud albedo, and (g) cloud radiative effect over the Cairns Region. Note that all variables are averaged over cloudy grid points.

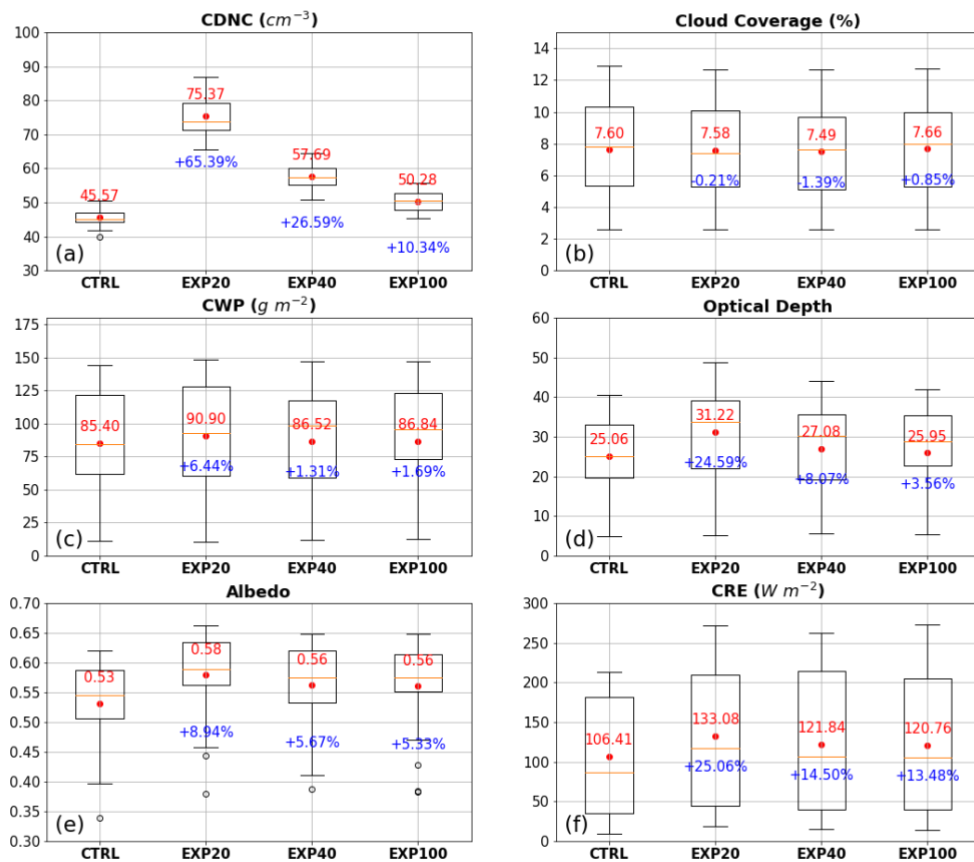


Figure R2: Boxplots of cloud properties over Cairns Region from CTRL and sensitivity experiments. Time period for analysis is 08UTC 07 Feb to 08 UTC 08 Feb 2022. Red numbers are mean values of each experiment, and blue numbers are differences with respect to CTRL experiment.

**Specific comments:**

1. Title: “A Case Study using a Convection-Permitting Model”

Revised as suggested.

2. Line 46: The most current review of MCB science is: Feingold, G., Ghate, V. P., Russell, L. M., Blossey, P., Cantrell, W., Christensen, M. W., Diamond, M. S., Gettelman, A., Glassmeier, F., Gryspeerd, E., Haywood, J., Hoffmann, F., Kaul, C. M., Lebsock, M., McComiskey, A. C., McCoy, D. T., Ming, Y., Mülmenstädt, J., Possner, A., Prabhakaran, P., Quinn, P. K., Schmidt, K. S., Shaw, R. A., Singer, C. E., Sorooshian, A., Toll, V., Wan, J. S., Wood, R., Yang, F., Zhang, J., and Zheng, X.: Physical science research needed to evaluate the viability and risks of marine cloud brightening, Science Advances, 10, eadi8594, doi:10.1126/sciadv.adi8594, 2024.

Thank you for this reference. It has now been cited properly in the revised manuscript.

3. Line 52: As the authors note elsewhere, secondary indirect effects/cloud adjustments can also decrease cloudiness by increasing dry air entrainment

Thank you for this helpful comment. We agree that aerosol-induced cloud adjustments are not unidirectional. While increased CCN can suppress precipitation and potentially enhance cloud lifetime (the so-called cloud lifetime effect), previous studies have also shown that enhanced entrainment of dry air may reduce cloud liquid water and cloud fraction under certain conditions.

We have added the text as follows to acknowledge this:

“However, aerosol-induced cloud adjustments are complex and may also act in the opposite direction: enhanced entrainment of dry air can reduce cloud liquid water and cloud fraction under certain environmental conditions.”

4. Section 2.1: Please clarify if the nesting is one-way or two-way

The simulations were conducted using one-way nesting, in which the parent domain provides boundary conditions to the nested domain without feedback. This configuration ensures that the large-scale environment remains unaffected by the inner-domain processes. The manuscript has been revised to clarify this.

5. Line 195: Can the authors elaborate on the “key features of maritime shallow clouds, visible in the true-color imagery” here? In my read of Figure 4, the agreement is not at all obvious

Thank you for this comment. Specifically, the “key features of maritime shallow clouds” is referring to the spatial distribution characteristics of scattered and broken cloud structures visible from true-color image and the cloud top temperature range indicated by brightness temperature proxy, which are reasonably well captured by the model. We acknowledge that the model underestimates the total cloud fraction and does not fully reproduce the observed spatial organization when compared with Himawari-8 observations. In particular, much of the high-level cloud cover within the domain is underestimated or missing, leading to discrepancies in the representation of fine-scale cloud structures. Such differences are expected given the inherent difficulty in reproducing the exact realization of convective cloud fields. We have clarified this in the revised manuscript and avoided overstating the level of agreement in cloud morphology as follows:

“Overall, the model underestimates the cloud fraction and does not fully reproduce the observed spatial organization when compared with Himawari-8 observations. In particular, much of the high-level cloud cover within the domain is underestimated or missing, leading to discrepancies in the representation of fine-scale cloud structures. Such differences are expected given the inherent difficulty in reproducing the exact realization of convective cloud fields. However, the model captures the key characteristics of the maritime shallow cloud regime visible in the true-color imagery (Figure 4c and 4f) and brightness temperature proxy, which is the primary focus of this study. In particular, the lower-tropospheric thermodynamic structure (Figure 3c and 3d) is reasonably well represented, providing a physically consistent boundary layer environment for shallow cloud formation. Therefore, although the detailed cloud morphology is not fully reproduced, the simulation is considered suitable for investigating aerosol–cloud interaction processes under shallow cumulus conditions.”

6. Lines 241-242: Precipitation scavenging efficiency increasing nonlinearly with aerosol concentration is not what I would expect... presumably this is referring to scavenging by impaction of aerosol on raindrops? Nucleation scavenging should be a much larger sink and will decrease in efficiency with increasing aerosol.

Please see response to major comment A.

- Line 242: What is meant by “self-scavenging” here? Dry scavenging? Are the aerosol truly being lost (in terms of mass)? This sounds more like coagulation to me.

Please see response to major comment A.

- Figure 6: What are the “-C” and “-U” after EXP40 and EXP100, respectively?

These were typos, which have now been revised.

- Line 274: It does not seem like you have shallow stratocumulus cloud regimes here... cumulus?

This was a typo. It has now been revised.

- Lines 296-297: This is an inappropriate way to define cloud fraction, if I’m correctly interpreting this as dealing with 3D outputs, and results in values that seem wrong on their face (e.g., Figure S2 definitely shows cloud fraction is much higher than 7%!). The fraction of columns with cloud optical thickness or liquid water path about a given threshold (e.g.,  $COT > 1$  or  $COT > 3$ ) would be a better choice here.

We thank the reviewer for this helpful comment. We agree that the previous definition of cloud fraction based on 3-D cloud fields was not ideal for this analysis. Following the reviewer’s suggestion, we have revised the cloud coverage calculation using a column-based approach. Specifically, a grid column is now classified as cloudy when the cloud optical depth (COD) exceeds 1, and cloud coverage is calculated as the fraction of such cloudy columns within the analysis domain (Figure R3).

Using this revised definition, the domain-mean cloud coverage remains relatively low, generally around 8-12% (Figure R1). As an example in Figure R3, although the cloud field appears spatially widespread, the clouds are highly scattered and broken, with many small cloud elements. As a result, the visual impression of broad cloud occurrence does not directly translate into a large fractional area of optically significant cloud.

We have updated the corresponding analyses and figures using this revised cloud-mask method. The manuscript has also been revised to clarify the definition of cloud coverage and to avoid confusion between visually apparent cloud occurrence and quantitatively defined cloud fraction.

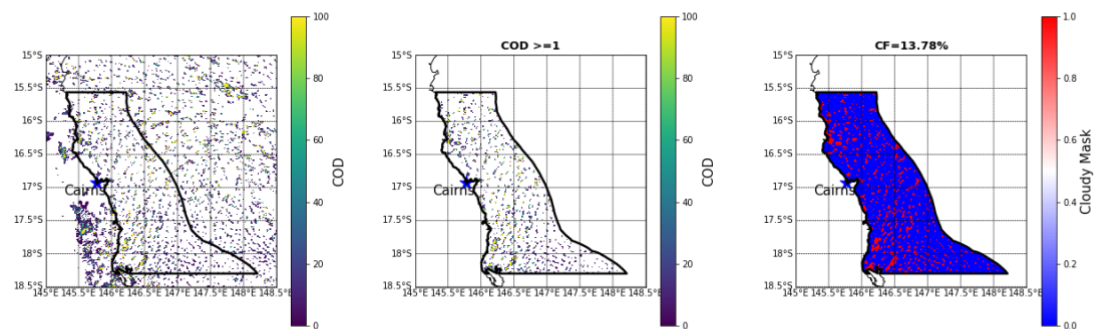


Figure R3: (Left) Example of spatial distribution of cloud optical depth (COD) at 1400UTC 07 Feb 2022 derived from WRF, (middle) Threshold of 1 and Cairns region applied to COD distribution, and (right) cloudy mask defined by  $COD > 1$  over the Cairns Region.

- Lines 313-315: I’m surprised COT needs to be estimated instead of output directly by WRF... it probably doesn’t matter, but you do have the information required to calculate COT explicitly

We agree that WRF provides the necessary variables to calculate cloud optical thickness (COT) explicitly using cloud liquid water content and effective radius. However, effective radius and/or COT are not a standard WRF output and was not archived in this study. In this study, COT is diagnosed using a bulk parameterisation based on cloud water path (CWP) and cloud droplet number concentration ( $N_c$ ), following a commonly used approximation derived from adiabatic cloud assumptions (Zhang et al., 2005).

This formulation provides a consistent estimate of COT from the available model outputs and is appropriate for assessing relative changes in optical thickness associated with aerosol-induced changes in CWP and  $N_c$ . We have revised the manuscript to clarify that COT is diagnosed from CWP and  $N_c$ , rather than output directly by WRF.

12. Lines 329-330: Why not calculate CRE and show this?

Please see response to major comment C.

13. Figure 8: Something seems off in this figure. For example, in (f), the EXP100U

The labels have been revised now.

14. Figure 8: Why are EXP40 and EXP100 given U's in their names?

These were typo, which have now been revised.

15. Figure 9 and related discussion: This figure does not show your results very clearly, at least in my read. Figure 10 is much easier to interpret and there doesn't seem to be anything Figure 9 is doing that Figure 10 doesn't already show more clearly. Consider removing Fig. 9; perhaps you can add a third bin to Fig. 10 if you wanted to show finer-grained variability?

We appreciate this suggestion. However, Figures 9 and 10 are intended to convey different aspects of the analysis and therefore we prefer to keep them separate. Figure 9 is used to illustrate the density distribution and methodology underlying the regime classification thresholds, while Figure 10 presents the resulting statistical characteristics based on the thresholds identified in Figure 9. To improve readability, we will revise the captions and strengthen the cross-reference between the two figures in the main text.

16. Section 3.4: I would hesitate to use words like "marked" and "clear" here, these results really are not that dramatic... which makes sense, given elsewhere you discuss how the aerosol is not changing the cloud macrophysics much!

The manuscript has been carefully reviewed throughout and revised accordingly.

17. Lines 438-440: I don't disagree here, but the results in this paper alone suggest the meteorology/cloud adjustments really don't matter much here...

We agree that the potential for marine cloud brightening over the GBR depends not only on aerosol loading and composition, but also strongly on the prevailing meteorological conditions. In fact, one of the key findings of this study is that the cloud response varies substantially under different humidity, wind shear, and lower-tropospheric stability regimes. For example, CWP responses were found to differ markedly between moist and dry free-tropospheric environments, highlighting the important role of meteorological control on aerosol–cloud interactions. We acknowledge the limitation of case studies, however this result is physically consistent with the mechanism proposed by Ackerman et al. (2004).

18. Line 471: “Our work extends this understanding to shallow maritime cumulus” is greatly overstated. There is an extensive literature at this point on cloud adjustments outside the core stratocumulus regimes. Chen et al. (2024) is one recent, prominent example that has essentially identical findings about cloud adjustments as those presented here: Chen, Y., Haywood, J., Wang, Y., Malavelle, F., Jordan, G., Peace, A., Partridge, D. G., Cho, N., Oreopoulos, L., Grosvenor, D., Field, P., Allan, R. P., and Lohmann, U.: Substantial cooling effect from aerosol-induced increase in tropical marine cloud cover, *Nature Geoscience*, 17, 404-410, 10.1038/s41561-024-01427-z, 2024.

Thank you for this important comment. We have revised the text accordingly to avoid overstating the novelty and to clarify the specific contribution of this work as follows.

“Our results are consistent with previous studies based on satellite data demonstrating aerosol-induced cloud adjustments in tropical marine cloud regimes (e.g., Chen et al., 2024). Building on this understanding, we investigate the sensitivity of these responses to the spatial variability of aerosol forcing using convection-permitting simulations, emphasizing that MCB will be most efficient when timed with supportive weather regimes.”

19. Lines 478-479: My read of the state of the ACI literature is that there’s a general consensus that LWP adjustments on net are relatively small and offset a fraction of the Twomey effect but cloud fraction adjustments are potentially quite large, maybe even rivaling or surpassing Twomey in importance. The revised Rosenfeld et al. (2019) paper does show limited LWP changes, but what they originally attributed to LWP are actually cloud fraction increases (at least in their revised analysis).

We thank the reviewer for this important clarification and agree that the broader aerosol–cloud interaction (ACI) literature suggests a more complex picture regarding cloud macrophysical adjustments. While aerosol-induced changes in liquid water path (LWP) are often found to be small and may partially offset the Twomey effect, cloud fraction (CF) adjustments can be substantial in some cloud regimes.

However, it is important to note that the present study examines a weakly precipitating shallow trade-cumulus regime over the Great Barrier Reef, which differs from many previous studies that focused on marine stratocumulus or more extensive marine cloud fields. Rosenfeld et al. (2019) showed that aerosol-induced responses occur in both marine stratocumulus and cumulus regimes, but that the magnitude of the response weakens when transitioning from marine stratocumulus to cumulus clouds. They further showed that cloud fraction responses are strongest in deeper clouds and become weaker in shallower cloud fields.

In our simulations, aerosol perturbations resulted in clear increases in CDNC, cloud optical depth, and cloud albedo, but only minor changes in both LWP and CF. This suggests that the radiative response in this case is primarily associated with the Twomey effect. We also acknowledge that the present modelling framework is not designed to explicitly assess cloud lifetime effects, which may contribute substantially to CF adjustments. The simulations focus on the short-term response of clouds to aerosol perturbations during a single case study and therefore do not provide a robust basis for quantifying aerosol impacts on cloud persistence or cloud lifetime adjustments. Consequently, while cloud lifetime effects may be important in other cloud regimes, our simulations neither provide strong evidence for nor rule out their importance in the present trade-cumulus case.

Our original wording may have overly emphasized the relatively weak LWP response without sufficiently acknowledging the potential importance of cloud fraction and cloud lifetime adjustments. Accordingly, we have revised the manuscript text to avoid overstating the role of weak LWP responses alone and to more accurately reflect the current understanding of ACI processes and their associated uncertainties.

20. Line 529: Do the authors consider local MCB to be “geoengineering”? I don’t necessarily disagree, but the “intervention” phrasing used in the introduction is perhaps more accurate.

The “geoengineering” has now been revised to “climate intervention”.

21. Data availability statement: Where can readers find the model outputs needed to reproduce the analyses in the text?

WRF outputs of all model simulations in this study have been uploaded to figshare for public access. References and Data Availability sections have now been updated accordingly in the revised manuscript to include follows:

Wenhui Zhao, Huang, Y., Siems, S. T., Harrison D.: WRF outputs of CTRL simulation [Dataset]. University of Melbourne. <https://doi.org/10.26188/30071935>, 2026a.

Wenhui Zhao, Huang, Y., Siems, S. T., Harrison D.: WRF outputs of EXP20 simulation [Dataset]. University of Melbourne. <https://doi.org/10.26188/32592879>, 2026b.

Wenhui Zhao, Huang, Y., Siems, S. T., Harrison D.: WRF outputs of EXP40 simulation [Dataset]. University of Melbourne. <https://doi.org/10.26188/32593914>, 2026c.

Wenhui Zhao, Huang, Y., Siems, S. T., Harrison D.: WRF outputs of EXP100 simulation [Dataset]. University of Melbourne. <https://doi.org/10.26188/32593482>, 2026d.

22. Supplemental figures: Consider bringing these into the main text

All figures in main text and supplementary have now been updated.

#### References:

- Zhang, Y., Stevens, B., and Ghil, M.: On the diurnal cycle and susceptibility to aerosol concentration in a stratocumulus-topped mixed layer, *Quart. J. Roy. Met. Soc.*, 131, 1567–1583, s2005.
- Heidinger, A. K., Foster, M. J., Walther, A., and Zhao, X.: NOAA Enterprise Cloud Mask Algorithm Theoretical Basis Document (ATBD), NOAA/NESDIS, 2020.