Response to Reviewers and Editor

Comments in black
Manuscript changes in **bold blue** at the line numbers of the revised draft.

Dear Dr. Christensen,

Thank you for the revised manuscript. The reviewers are generally satisfied with your document, however Reviewer 1 continues to be only marginally convinced by the ability of the model to resolve entrainment effects at cloud top. They also note some peculiarities in the physics of Figure 9 that I would agree are a bit difficult to understand. I suggest reconsideration of those profiles, but also at the very least add some further discussion of any prior studies that may help bolster an argument that a coarse resolution model is sufficient for application to aerosol cloud interactions in stratiform clouds with open cells.

Best regards,

Tim Garrett

Report #1
The authors have done a nice job responding to the reviewer comments. I recommend acceptance as-is. -MD

Report #2
I appreciate that the authors have addressed my previous comments comprehensively. I think the manuscript has significantly improved overall. The authors explained the important limitations about the model to minimize the confusion, but I am not sure my biggest concern was adequately addressed. The magnitude of LWP and cloud cover effects looks very large, and the LW heating rate does not match TKE and W' (Fig.9b, e, and d). Is it possible to say that the dynamic effects of cloud-top radiative cooling are adequately resolved in WRF? It would be nice to add some explanations and references if possible.

Dear Tim Garrett,

We appreciate the insightful feedback provided by Reviewer 2 and the opportunity to further refine our manuscript based on these comments. We understand the concerns raised by the reviewer and have made several key changes to Figure 9 to clear up confusion. First, we fixed a typo. The vertical velocity variance was inaccurately labeled as w' when it should have been w'^2. Second, we have added a shaded layer to each panel to represent the portion of the vertical profile with cloud so that it is easier to distinguish the location of the cloud top from the cloud base. Third, we now provide the TKE based on the subgrid parameterized output from MYNN3 as well as the resolved 3D wind field to account for turbulence by convective eddies at 800-m grid-spacing. The TKE computed based on the resolved winds show relatively larger values in the vicinity of the cloud top. Based on this feature as well as the evidence presented in Figure S10 and Figure R1 from our first round of revisions we are confident that turbulent kinetic energy production in the planetary boundary layer is connected to the cloud and radiation schemes. However, we agree with the reviewer that stronger liquid water path and cloud fraction adjustments to changes in aerosol concentration may arise if the parameterized entrainment rates are too weak in the MYNN scheme at relatively coarse resolution compared to LES. Therefore, we have tempered our language regarding these strong associations in the manuscript. We have also meticulously described our model configuration and setup, along with a thorough discussion of the model's strengths and limitations, to facilitate reproducibility and expansion of this analysis in future work.

Please see below the key points raised by the reviewer and the changes we have made to the manuscript.

Best regards,

Matthew Christensen

Editor Comment 1

Any prior studies that may help bolster an argument that a coarse resolution model is sufficient for application to aerosol cloud interactions in stratiform clouds with open cells.

>>The following has been added to the conclusions section:

Lines 487 – 497: As computation power increases, km-scale models employed with PBL schemes (similar to ours) will increasingly be used to quantify aerosol-cloud interactions at global-scales with increasing complexity (Terai et al. 2020). Kilometer scale models have been shown to successfully simulate the properties and mesoscale structure of stratocumulus. Chen et al. (2022) used WRF with 1-km grid spacing to simulate the roll structure and transition of stratocumulus and cloud streets by gradients in sea surface temperature. Saffin et al. (2023) utilize the Met Office Unified Model to simulate cloud transitions observed during the ATOMIC field campaign at similar scales. This transition shows the development of small shallow clouds into larger flower-type clouds with detrainment, triggered by increased mesoscale organization over several tens of kilometers. Beucher et al. (2022) utilized the French convection-permitting model AROME-OM at kilometer scales, successfully simulating four primary mesoscale patterns observed during the EUREC4A campaign. Despite the success of simulating the realism of the mesoscale structure of marine stratocumulus, further refinement may be needed to enhance connections between radiation, microphysics, and planetary boundary layer schemes for adequately simulating the complexity of aerosol-cloud interactions.

Reviewer Comment 1

Is it possible to say that the dynamic effects of cloud-top radiative cooling are adequately resolved in WRF? It would be nice to add some explanations and references if possible.

>> First, we have added a panel to Figure 9 which shows the resolved TKE. This quantity is described in section 4.2.2.

L322 – L329: To account for the turbulence of the convective eddies at 800-m grid spacing (in the so-called "gray-zone" where eddies in the PBL are partially resolved; Shin and Dudhia, 2016), TKE is also provided using the 3D resolved winds (Figure 9i) following the equation: $\boldsymbol{TKE = \frac{1}{2}(u'^2 + v'^2 + w'^2)}$, where u'^{2}, v'^{2} and w'^{2} are the variances of the winds computed over 3.2 x 3.2 km^2 regions. The resolved TKE is not very sensitive to changes in the averaging scale in which the 3.2, 6.4, and 12.8 km scales show similar magnitude within the cloud layer. While the TKE computed using the resolved winds shows a relative increase near cloud top hinting at a better connection to the cloud top radiative flux profile compared to the subgrid TKE output from MYNN3, this is a relatively weak relationship compared to large eddy simulations of stratocumulus (McMichael et al., 2019), and may suggest further refinement is needed in connecting these processes within the MYNN Eddy-Diffusivity Mass Flux (EDMF) scheme (Olson et al. 2019). Possible implications of the relatively weak mixing on the liquid water path and cloud fraction adjustments are discussed in further detail in the conclusions section.

Previous version Figure 9

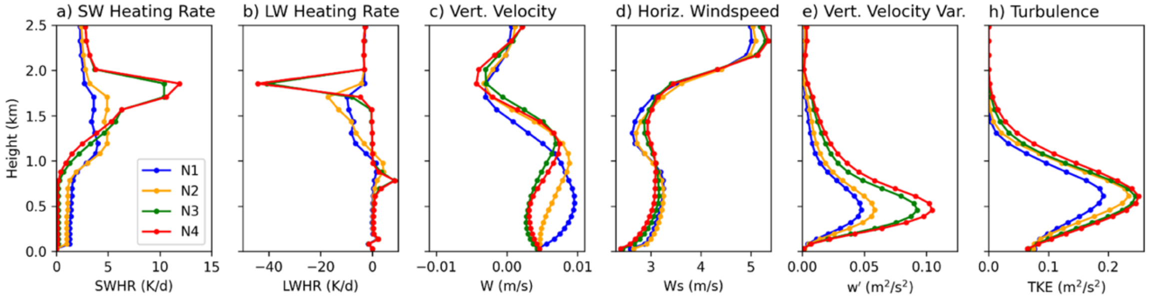
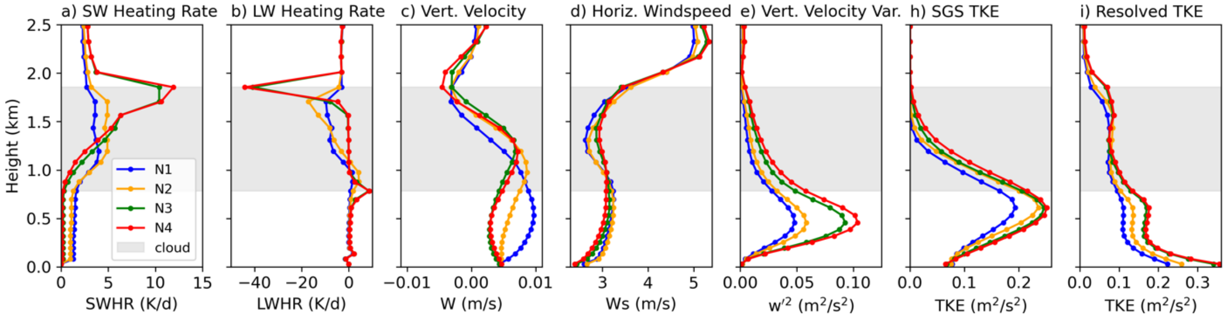


Figure 9. Vertical profile of the a) mean shortwave and b) longwave radiative heating rate, c) mean vertical velocity, d) mean horizontal wind speed, e) vertical velocity variance, and h) turbulent kinetic energy (TKE) for pristine (blue), unpolluted (orange), control (green), and polluted (red) WRF simulations on 07/15/2017 at 13:00 UTC.

Revised Figure 9



>> Next, the following has been added to the conclusions section:

Lines 516 – Lines 533: Ghonima et al. (2017) evaluated the MYNN scheme and other turbulence parameterization schemes using single-column model experiments showing that entrainment flux tendencies in stratocumulus tend to be underestimated compared to LES, resulting in cooler, moister stratocumulus-topped boundary layers. This discrepancy may imply a deficiency in representing strong turbulent mixing near the cloud top in our simulations. However, our simulations show an enhanced peak in the resolved TKE near the top of the stratocumulus cloud layer (Figure 9i). Also, when radiation is deactivated, TKE is much smaller and the cloud layer becomes significantly shallower (Figure S10), highlighting the role of radiative processes in driving stronger TKE throughout the boundary layer. WRF version 4.2 introduced scale-awareness, dynamically adjusting parameterized turbulent kinetic energy as resolution decreases, thus offering a more explicit representation of turbulent processes at finer scales (Olson et al. 2019). Subgrid-scale clouds produced by the MYNN-EDMF (section 3) are coupled to the longwave and shortwave radiation schemes (namelist parameter icloud_bl is set to 1). Despite these couplings, uncertainties may persist due to relatively coarse vertical resolution (compared to LES) and the ability to capture nonlocal production of TKE associated with cloud-top radiative cooling. Alternative approaches, such as explicit entrainment or employing the mass-flux method for downdrafts, may offer improved parameterization of destabilized parcels in stratocumulus environments (Olson et al. 2019). The impacts of model caveats

like these on cloud cell expansion due to increased aerosol concentration should be explored in subsequent research with higher resolution models including LES where the cloud-top entrainment interface can be modeled at finer spatial scale resolutions. Nevertheless, our model set up shows evidence that radiative cooling drives stronger turbulence in the marine boundary layer but it remains crucial to constrain such parameters based on observations (Suzuki and Stephens, 2009; Golaz et al. 2013; Christensen et al., 2023; Varble et al., 2023), where possible, to enhance model development and our understanding of aerosol-cloud interactions and radiative forcing.

Reviewers Comment 2

The magnitude of LWP and cloud cover effects looks very large.

>> The following have been added to the conclusions: Previous studies, such as Gryspeerdt et al. (2020) and Bellouin et al. (2020), have reported enhancement factors for radiative forcing attributable to aerosol-cloud interactions, when combined, reaching as high as 150% for adjustments in liquid and cloud fraction. **L392 – 396: Consequently, our findings approach the upper limits of these adjustments possibly due to a weak connection between entrainment mixing and cloud top radiation from the use of km-scale models (discussed further in the conclusions).**

Reviewers Comment 3

The LW heating rate does not match TKE and W' (Fig.9b, e, and d)

>> We agree, the TKE profile output from the MYNN scheme at the subgrid scale resolution *does not match* the 'spike' in the radiative cooling rates near the cloud top. In addition to the subgrid scale TKE provided by the MYNN scheme, the resolved TKE is now also computed from the grid-scale wind variances. This data has been added to Figure 9. At the typical gray-zone spatial resolutions (~1 km grid-spacings), the convective eddies are partly resolved (shown via our filtered resolved TKE) and partly parameterized (shown via the MYNN SGS TKE). The resolved TKE is part of the response to cloud-top radiative cooling which we observe as a maximum near the cloud tops. Hence, the relative increase in TKE near the cloud top indicates some coupling between the longwave heating rate and the TKE, although, as stated above (and in the manuscript) this connection may be relatively weak compared to finer-scale LES models.

Finally, it is noteworthy pointing out that in versions of WRF before V4.2, it was reported in Puhales et al. (2023) that the TKE budget terms were unbalanced. However, this artifact only affected the diagnostic output history files, not the actual TKE budget. Upon investigating this we discovered a typo in our original manuscript which we referenced WRF V4.2; we are actually using WRF V4.3. Nevertheless, the cited discrepancy in the WRF version is not relevant to the changes in the MYNN scheme which took place in prior versions of the WRF model.

References

Bellouin, N., Quaas, J., Gryspeerdt, E., Kinne, S., Stier, P., Watson-Parris, D., Boucher, O., Carslaw, K. S., Christensen, M., Daniau, A. L., Dufresne, J. L., Feingold, G., Fiedler, S., Forster, P., Gettelman, A., Haywood, J. M., Lohmann, U., Malavelle, F., Mauritsen, T., . . . Stevens, B. (2020). Bounding Global Aerosol Radiative Forcing of Climate Change. Reviews of Geophysics, 58(1). https://doi.org/ARTN e2019RG00066010.1029/2019RG000660

Beucher, F., Couvreux, F., Bouniol, D., Faure, G., Favot, F., Dauhut, T., & Ayet, A. (2022). Process-oriented evaluation of the oversea AROME configuration: Focus on the representation of cloud organisation. Quarterly Journal of the Royal Meteorological Society, 148(749), 3429-3447. https://doi.org/10.1002/qj.4354

Chen, J. Y., Wang, H. L., Li, X. Y., Painemal, D., Sorooshian, A., Thornhill, K. L., Robinson, C., & Shingler, T. (2022). Impact of Meteorological Factors on the Mesoscale Morphology of Cloud Streets during a Cold-Air Outbreak over the Western North Atlantic. Journal of the Atmospheric Sciences, 79(11), 2863-2879. https://doi.org/10.1175/Jas-D-22-0034.1

Christensen, M. W., Ma, P.-L., Wu, P., Varble, A. C., Mülmenstädt, J., and Fast, J. D.: Evaluation of aerosol–cloud interactions in E3SM using a Lagrangian framework, Atmospheric Chemistry and Physics, 23, 2789–2812, https://doi.org/10.5194/acp-23-2789-2023, 2023.

Golaz, J.-C., Horowitz, L. W., and Levy, H.: Cloud tuning in a coupled climate model: Impact on 20th century warming, Geophysical Research Letters, 40, 2246–2251, https://doi.org/10.1002/grl.50232, 2013.

Ghonima, M. S., Yang, H., Kim, C. K., Heus, T., & Kleissl, J. (2017). Evaluation of WRF SCM Simulations of Stratocumulus-Topped Marine and Coastal Boundary Layers and Improvements to Turbulence and Entrainment Parameterizations. Journal of Advances in Modeling Earth Systems, 9(7), 2635-2653. https://doi.org/10.1002/2017ms001092

Gryspeerdt, E., Mülmenstädt, J., Gettelman, A., Malavelle, F. F., Morrison, H., Neubauer, D., Partridge, D. G., Stier, P., Takemura, T., Wang, H., Wang, M., and Zhang, K.: Surprising similarities in model and observational aerosol radiative forcing estimates, Atmos. Chem. Phys., 20, 613–623, https://doi.org/10.5194/acp-20-613-2020, 2020.

McMichael, L. A., Mechem, D. B., Wang, S. P., Wang, Q., Kogan, Y. L., and Teixeira, J.: Assessing the mechanisms governing the daytime evolution of marine stratocumulus using large-eddy simulation, Quarterly Journal of the Royal Meteorological Society, 145, 845–866, https://doi.org/10.1002/qj.3469, 2019.

Puhales, F. S., J. B. Olson, J. Dudhia, D. L. de Bem, R. Maroneze, O. C. Acevedo, F. D. Costa, and V. Anabor, (2023), Turbulent Kinetic Energy Budget for MYNN-EDMF PBL Scheme in WRF model, Technical note UFSM/GruMA 001/2023, Universidade Federal De Santa Maria.

Olson, J. B., J. S. Kenyon, W. A. Angevine, J. M. Brown, M. Pagowski, and K. Suselj (2019), A Description of the MYNN-EDMF Scheme and the Coupling to Other Components in WRF-ARW, NOAA Technical Memorandum, https://doi.org/10.25923/n9wm-be49.

Saffin, L., Lock, A., Tomassini, L., Blyth, A., B.ing, S., Denby, L., & Marsham, J. (2023). Kilometer-scale simulations of trade-wind cumulus capture processes of mesoscale organization. Journal of Advances in Modeling Earth Systems, 15, e2022MS003295. https://doi.org/10.1029/2022MS003295

Shin, H. H. and Dudhia, J.: Evaluation of PBL Parameterizations in WRF at Subkilometer Grid Spacings: Turbulence Statistics in the Dry Convective Boundary Layer, Monthly Weather Review, 144, 1161–1177, https://doi.org/10.1175/Mwr-D-15-0208.1, 2016.

Suzuki, K. and Stephens, G. L.: Relationship between radar reflectivity and the time scale of warm rain formation in a global cloud-resolving model, Atmos. Res., 12.010, doi:10.1016/j.atmosres., 2009.

Terai, C. R., Pritchard, M. S., Blossey, P., & Bretherton, C. S. (2020). The impact of resolving subkilometer processes on aerosol-cloud interactions of low-level clouds in global model simulations. Journal of Advances in Modeling Earth Systems, 12, e2020MS002274. https://doi.org/ 10.1029/2020MS002274

Varble, A. C., Ma, P.-L., Christensen, M. W., Mülmenstädt, J., Tang, S., and Fast, J.: Evaluation of Liquid Cloud Albedo Susceptibility in E3SM Using Coupled Eastern North Atlantic Surface and Satellite Retrievals, EGUsphere, 2023, 1–39, https://doi.org/10.5194/egusphere-2023-998, 2023.