Reviewer 2

Sullivan et al. (2023) analyze cloud radiative heating (CRH) in the upper troposphere over the North Atlantic Ocean as simulated by the ICON model. They provide a comprehensive analysis of dependencies on model resolution and ice-cloud microphysics parameterizations. They also attribute model differences to different classes of clouds with different vertical structure and to different cloud-controlling environmental factors, which I found useful for understanding the model differences. The paper is well written and logically organized, and the figures are clear. I have one suggestion for generalizing the results and several minor comments. I recommend that the manuscript be accepted if these minor issues are addressed.

We thank the reviewer for their time and effort in evaluating our work and for their feedback.

General Comments:

The authors comprehensively discuss CRH in the upper troposphere, but they barely mention CRH in the lower troposphere. However, previous studies have shown that the CRH climatology and relationship of CRH to prominent modes of natural variability both have a peak magnitude in the lower troposphere (Haynes et al., 2013; Papavasileiou et al. 2020; Wall et al., 2022). I realize that the authors want to focus on ice microphysics, for which it makes sense to analyze upper tropospheric CRH. However, I think neglecting lower-tropospheric CRH from the discussion gives the (unintentionally) misleading impression that it is less important for the overall CRH throughout the troposphere. Could the authors add a section that analyzes CRH for the low-level cloud classes and some discussion that compares this analysis with the CRH for the upper-level cloud classes? I think this would generalize the findings and add value to the paper.

Thank you for this feedback. We recognize the importance of the low-level CRH; indeed, in the North Atlantic climatological profiles shown in Figure 3a, the overall maximum in cloud-radiative cooling occurs below 850 hPa. However, our motivation is large-scale circulation, and we provide three reasons throughout to focus on the upper tropospheric values:

1. (Sec. 3.1) We do not perform global warming simulations here, but +4-K simulations from Voigt and Shaw 2015 and Voigt et al. 2019 indicate that the largest CRH differences with warming are localized in the upper troposphere. This increased warming enhances the meridional temperature gradient and expands the Hadley cell poleward.
    - Additionally, these same studies show that upper tropospheric CRH is more influential on circulation than boundary layer CRH when sea surface temperatures are prescribed as they are here.
2. (Sec. 3.1) Radiative cooling from water vapor constrains the top of the troposphere, not only in the tropics but also in the midlatitudes (Thompson et al. 2017). Given this constraint of clear-sky cooling on cloud-top temperatures and approximate cloud fractions, if we constrain upper tropospheric CRH in the current climate, we can also constrain it under warming. The same is not true for boundary-layer CRH.
3. (Introduction) Variability in the upper tropospheric CRH (between different models and between models and observations) is especially large [Voigt et al. 2019, Cesana et al. 2019]. In the tropics, the upper tropospheric variability is much larger than the boundary layer variability. This is less true in the midlatitudes.

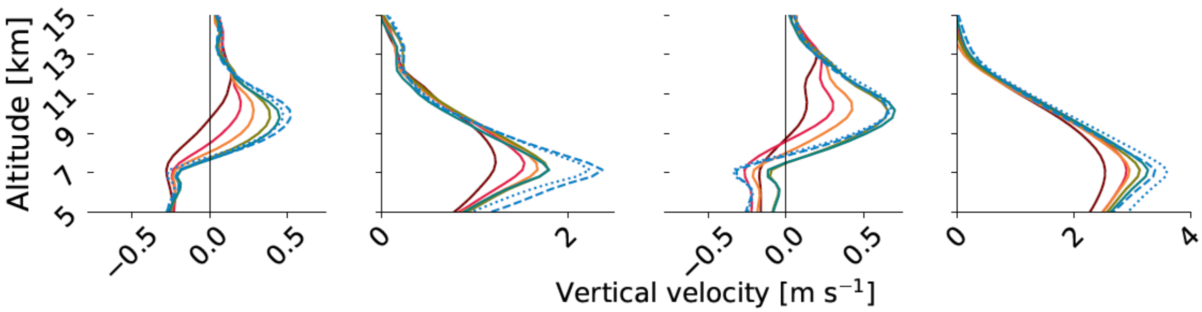
However, we do not want to give the impression that low-level CRH should be neglected. To Sec. 3.1, we add "*Radiative cooling from extratropical low-level clouds has non-negligible effects on circulation, for example enhancing baroclinicity* [*Li et al. 2015*]."

Specific Comments:

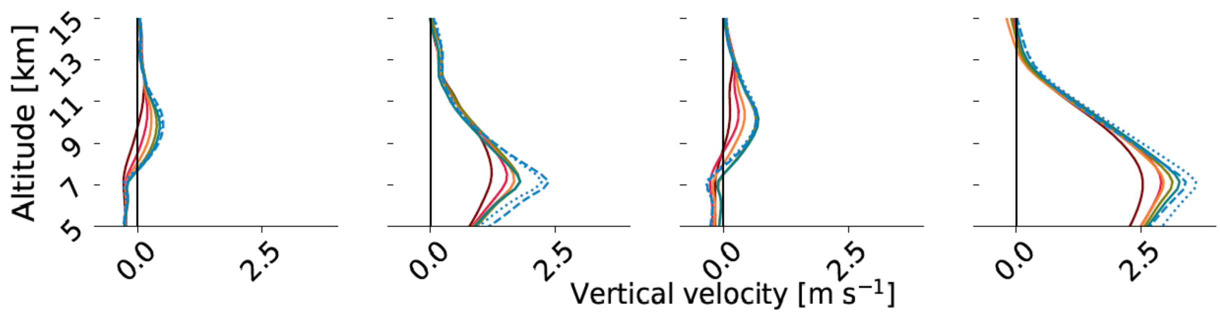
(1) Fig 12: It would help to plot all of the panels on the bottom row with the same range of vertical-velocity values.

Thank you for this suggestion, but we find that putting all the vertical velocity profiles on the same x-axis makes it somewhat more difficult to see the resolution dependence (panel 1 below). We do keep the x-axis limits uniform between the deeper (High-x-Middle *and* High-x-Middle-x-Low) and shallower (High *and* High-Low) cloud classes now, however (panel 2 below). We also note the different axis bounds in the caption now.

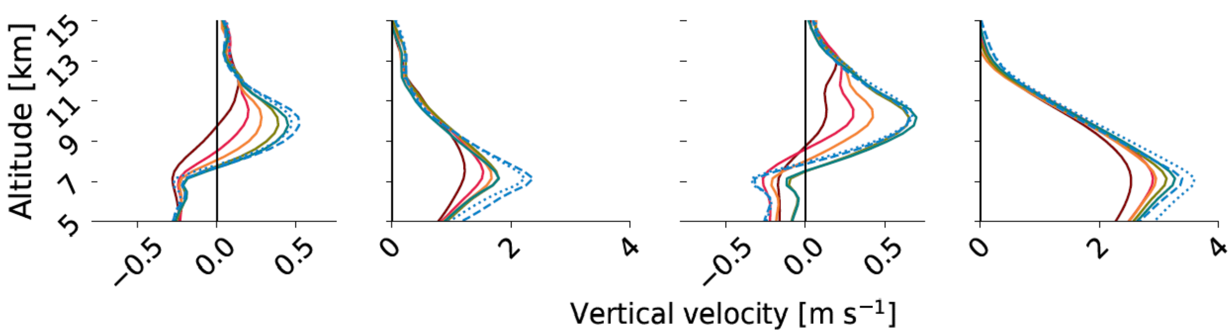
panel 0 – original version



panel 1 – all xlim = [-0.75, 4]



panel 2 – consistent xlim for deeper versus shallower classes



(2) Fig 13: Has the vertical velocity data been horizontally averaged to a common scale prior to computing these histograms? If not, then is such a comparison meaningful? I would expect finer horizontal resolution to have larger variance of resolved vertical velocity but perhaps a different treatment of unresolved subgrid-scale vertical velocity by the convective parameterization scheme. It might help to discuss this around line 350.

No, the vertical velocities shown in Figure 13 have not been averaged / interpolated to the same grid across the simulations. Because we want to explain the differing q_i profiles across grid spacings (among other factors), we also want to see the grid spacing dependence of these vertical velocities. Averaging or interpolating them to a uniform grid would be counterproductive. To the caption of Figure 13 we add "*Because we seek to explain the grid spacing dependence of q_i, these velocities are not averaged or interpolated to a uniform grid.*"

Then, as you say, finer horizontal resolution produces larger variance in the vertical velocity. The 5-km resolution simulations have the broadest spread in vertical velocities of the simulations with convective parameterization. We change wording in the description of Figure 13 to read "*the variance of these vertical velocity distributions becomes larger for finer grid spacing*." Finally, to the discussion of Figure 12, we add a "*note that the ICON model uses no representation of subgrid scale variability in vertical velocities.*"

(3) Line 376 states "Strong microphysical and convective sensitivity and weaker grid spacing sensitivity in the CRH profiles do not appear in distributions of cloud class occurrence and appear only weakly in cloud fraction profiles." Is this result a consequence of the fact that midlatitude synoptic weather systems are mostly resolved by all resolutions in the study? I'm just wondering if this result is specific to the midlatitudes or if it might generalize to the tropics. It would help to clarify this around line 376.

Yes, this is an interesting point. In looking through some previous studies of grid spacing sensitivity of extratropical cyclones, the general consensus seems to be that our coarsest resolution (80 km) is indeed sufficient to represent the macrostructure of the cyclone, i.e. its fronts and major airflows (e.g., Trzeciak et al. 2016, Flack et al. 2021, Priestly and Catto 2022). However, there is also substantial evidence that higher grid spacings produce stronger ascent rates, diabatic heating, and hence cyclone intensity (e.g., Willison et al. 2013, Flack et al. 2021, Choudhary and Voigt 2022). Whether increased intensity should generally imply increased cloud fraction or occurrence is another question.

Precisely because we trace the CRH dependencies back to differences in microphysical formulations, we do believe that these results are likely model-dependent. So we do not want to claim generalizability outside the midlatitudes, or even outside the ICON framework. To the paragraph in the Conclusions about robustness of findings, we add "*While our analysis method could be generalized to other regions or modeling frameworks, the role of q_i and specific microphysical processes or parameters in CRH sensitivity will not necessarily generalize.*"

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