Uncertainties in cloud-radiative heating within an idealized extratropical cyclone - Response to Reviewers

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We thank the reviewers for their evaluations, questions, and suggestions to improve our manuscript. Below, we respond to each of the reviewers' comments and describe how we plan to adapt the manuscript. We are confident that we can address the reviewers' comments in the revised manuscript, and we are hopeful that the revised manuscript will be acceptable for publication. The reviewers' comments are in bold, our answers are in normal font.

Reviewer 1

The authors argue that the uncertainty contributed by the 3D cloud radiative effect is generally small. However, in Section 4, the local uncertainty from the 3D cloud radiative effect is not quantified. 3D cloud radiative effect has been shown to affect less on domain-average flux quantities but more on the flux distribution (i.e., the flux gradient at the cloud boundary). It is expected that the effect is more dominant in the local uncertainty. The authors can mention the Monte Carlo noise as a caveat when interpreting the results, but it is not the reason to exclude this term from the analysis. Otherwise, it is difficult to argue that this uncertainty is small compared to other terms.

We thank the reviewer for the comment. We agree that we should include the local CRH uncertainty due to the 3D radiative effects in the analysis of the manuscript. We have now quantified the Monte Carlo noise of the MYSTIC solver in our radiation calculations. For this we calculated the relative standard deviation (RSD) of the radiative heating between two sets of MYSTIC calculations (please see our Monte Carlo noise analysis at the end of our response to this comment). The RSD analysis shows the relative variability of the radiative heating at each grid box between the two MYSTIC calculations. Our results show that the average RSD is less than 10 percent for almost all grid boxes in the LEM domains.

In addition, we would like to point out that our old notion of "small 3D cloud radiative effect" in the submitted manuscript was related to our expectation regarding the small impact of 3D cloud radiative effects on the large-scale dynamics of the cyclone. We calculated the average profile of the CRH to compare the magnitude of different CRH uncertainties at spatial scales of around 500 km. Our comparison of the mean profiles suggests that the large-scale changes in the dynamics of the cyclone may be more susceptible to CRH uncertainties due to cloud horizontal heterogeneity (assuming resolved clouds for the NWP model with a grid resolution of 2.5 km) and ice-optical parameterization than to 3D cloud radiative effects. Our expectation is in line with studies showing that perturbations on a larger spatial scale are more effective in changing the baroclinic error growth (e.g., Sun & Zhang, 2016). Recently, Lloveras et al., 2023 showed that small-scale perturbations, even with large amplitudes, have a negligible impact on the dynamics of the cyclone and the error-growth near the tropopause than larger-scale perturbations with smaller amplitudes. We believe that our analysis of CRH uncertainty at the domain mean and at the grid-scale speaks in this direction. To further elaborate on this point, we also quantified CRH uncertainties at different horizontal spatial scales (Fig. 1). For this, we coarse-grained CRH from different radiative transfer calculations at 300 m resolution to horizontal resolutions equivalent to 2.5, 5, 10, 50, 100 km, and the entire domain. We then derived the local CRH uncertainty (Equation 3 of the manuscript) for each of the coarse-grained CRH

Fig. 1 shows that the CRH uncertainty due to the 3D cloud radiative effects decreases with increasing horizontal scale, while the uncertainty due to the ice-optical parameterization is more or less constant as a function of horizontal scale. Although 3D radiative effects are large at small scales, their spatial extent is limited. However, the uncertainty due to the ice-optical parameterization exhibits a larger spatial extent, which could make it more relevant for the large-scale dynamics of the cyclone and the error growth near the tropopause.

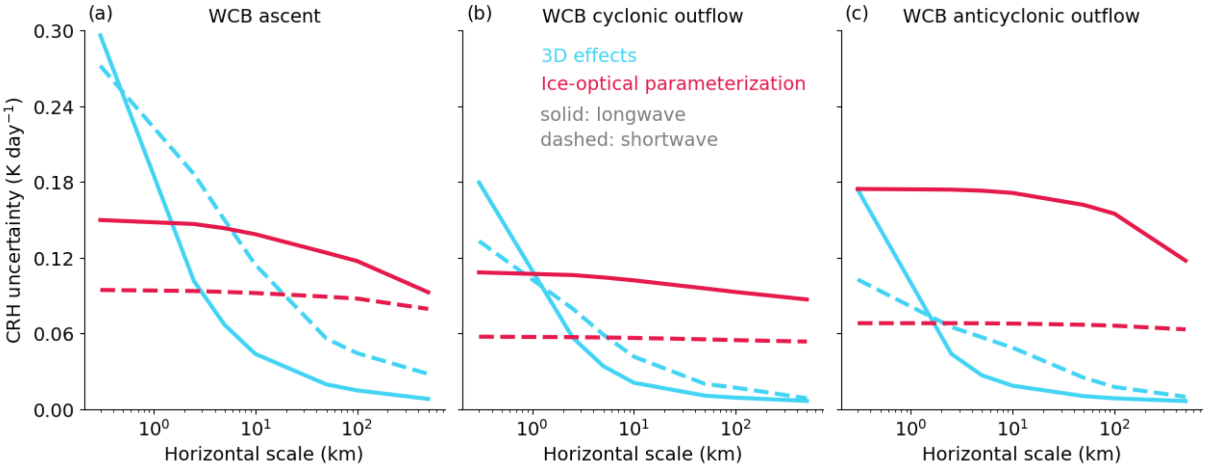

Fig. 1: *CRH uncertainty due to 3D cloud radiative effects (cyan lines) and ice-optical parameterization (red lines) as a function of horizontal scale (from 300 m to approximately 500 km) for domains over the (a) warm conveyor belt (WCB) ascent, (b) WCB cyclonic outflow, and (c) WCB anticyclonic outflow. CRH longwave and shortwave uncertainties are shown as solid and dashed lines, respectively. For the uncertainty due to ice-optical parameterization, the CRH difference between the ice scheme of Fu and Baum with the general habit mixture is used.*

We plan to revise the manuscript to clarify the above points. This will include adding details on the Monte Carlo noise of the MYSTIC solver in Section 2 and the analysis of the local CRH uncertainty due to 3D cloud radiative effects in Figure 11 in Section 4 of the manuscript. We will also add the complete analysis of CRH uncertainties as a function of horizontal scale, including the impact of cloud horizontal heterogeneity, in Section 4. In the revised manuscript, we will adjust the text in Section 4, the conclusion, and the abstract accordingly.

Quantifying the Monte Carlo noise of the MYSTIC solver

To make the 3D radiation calculation feasible, each LEM domain was divided into 36 subdomains. For each subdomain and time step, we used 72 million photons for each MYSTIC calculation. To increase the number of photons and reduce the noise, we repeated the MYSTIC calculations 10 times, resulting in a total of 720 million photons traced per subdomain. We then averaged over these 10 calculations and used the averaged heating rates in the analysis of the manuscript. To estimate the local Monte Carlo noise, we used the "jackknife" method. We split 10 MYSTIC calculations into two sets of 5 calculations and averaged the heating rates over the 5 calculations. The difference between the resulting two sets of calculations allowed us to estimate the Monte Carlo noise. This estimate is an upper bound, as the true Monte Carlo noise in our calculations with 720 million photons can be expected to be smaller.

We calculated the relative standard deviation (RSD) of radiative heating, which represents the relative variability of the radiative heating with respect to the mean values between the two sets of MYSTIC calculations at each grid box:

$$\mathrm{RSD} = \frac{100\ \times\ \text{standard deviation}}{|\text{mean}|}$$

Fig.2 shows the distribution of RSD values as box plots. The analysis shows that on average the Monte Carlo noise at the LEM grid boxes is less than 10 percent. We also repeated this analysis for the 3D radiation calculation with clouds in the warm conveyor belt anticyclonic outflow and came to a similar result. These values represent the noise estimation using 360 million photons. Thus, the noise should be even smaller when using 720 million photons.

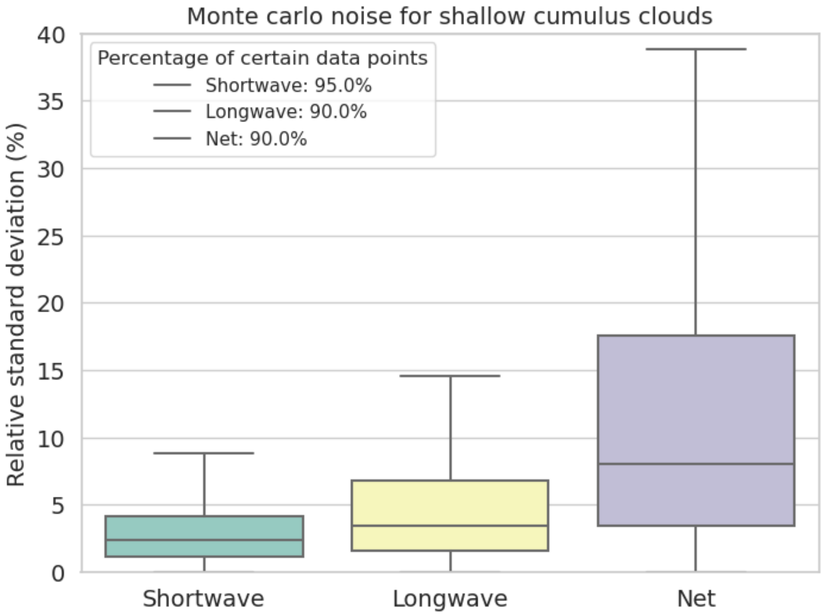

Fig. 2: *Distribution of the relative standard deviation of radiative heating at each grid box for shallow cumulus clouds between two radiative transfer calculations with MYSTIC solver using 360 million photons. The legend in the figure shows the percentage of data points fall within the upper and lower whiskers in the box plots.*

<u>Specific comments:</u>

Figure 1: Does the domain change in the nine snapshots that are used for analysis? If not, does it indicate that the extratropical cyclone is stationary within the 4-hour timeframe?

Thanks for the question. The positions of the LEM domains are fixed. The cyclone is not stationary, but the cyclone and the optical properties of the cloud do not change substantially during the 4-hour period.

Figure 5: I suggest adding another panel showing the net radiative heating difference between 3D and 1D calculations so as to be consistent with the following figures.

Thank you for your suggestion. We will change Figure 5 of the manuscript to include the net radiative heating and adjust the text accordingly in the revised manuscript.

Line 263: "There is a direct relationship between cloud-side illumination and solar zenith angle." Related to the question above, does the cloud field change significantly within the 4-hour timeframe?

The thin lines in Figure 2 of the manuscript show changes in the profiles of cloud properties. In the shallow cumulus and warm conveyor belt cyclonic and anticyclonic outflow domains, clouds do not change a lot. In the ascending region, however, cloud water changes more, yet the radiative heating rate in this region is more affected by ice clouds, and the cloud ice content does not vary much during the 4 hours.

Lines 273-275: "The stronger shortwave cloud-side illumination […] is most likely due to the higher solar zenith angle at higher altitudes […]" I think this argument can be verified from the flux output if the authors retain those outputs.

Unfortunately, we output only heating rates from the libRadTran calculations and we cannot further confirm this through analyzing fluxes. Črnivec & Mayer, 2019, also showed this direct relationship between cloud-side illumination and solar zenith angle. We will add more details in section 3.2 of the revised manuscript.

Figure 6: The time in the legend is confusing. I had thought it was local solar time, but the solar zenith angle is monotonically increasing from hours 10 to 14. I suggest explaining how these solar zenith angles are calculated or simply using the local solar time to avoid confusion.

Thanks for the comment and the suggestion. We used the solar zenith angle values provided by the ICON-LEM simulation output for these snapshots. To avoid confusion, we will use local solar time in figure 5 of the revised manuscript.

Lines 359-362: I am confused about these sentences. I don't understand why "the ice-optical parameterization has similar impacts on local and mean uncertainties" implies that "uncertainty due to the ice-optical parameterization is less important for km-scale circulations"? It sounds to me that the ice-optical parameterization is not necessary to be addressed in km-scale numerical models.

Thanks for this comment. We did not mean to imply that the uncertainties due to the ice-optical parameterization are not important; in fact, we believe they are a fundamental source of uncertainty even in km-scale models. The comparison of our "mean" and "local" CRH uncertainties is intended to show the magnitude of the uncertainties at different horizontal scales. The result showed that the uncertainty due to ice-optical parameterization is smaller compared to other sources of uncertainty at the 300 m resolution of the LEM domain, but larger at the 500 km scale of the LEM domain (also refer to Fig. 1 in this document and our response to the first Reviewer's comment). We will revise the text in the conclusion section of the manuscript to better clarify these points.

Line 411: The reference of Fan et al., 2022 is not up to date. Please use: Fan, C., Chen, Y.-H., Chen, X., Lin, W., Yang, P., & Huang, X. (2023). A refined understanding of the ice cloud longwave scattering effects in climate model. Journal of Advances in Modeling Earth Systems, 15, e2023MS003810. https://doi.org/10.1029/2023MS003810.

Thanks, we will update the reference.

Reviewer 2

3D cloud radiative effects versus cloud heterogeneity

Authors treats 3D cloud radiative effects and cloud heterogeneity (horizontal and vertical) as two distinguished uncertainty factors, but I think the terminology of 3D cloud radiative effects includes both. Horizontal photon transport (3D effects) occurs not only at clouds-to-clear-sky (what author refers to as 3D cloud radiative effects) but also at clouds-to-clouds (what author refers to as cloud heterogeneity). I would appreciate if authors can either 1) add more clarifications on why they sperate into two or 2) combine them into one.

We thank the reviewer for this comment. Within the framework of our study, the two sources of uncertainty can be separated. "Cloud horizontal heterogeneity" quantifies the uncertainty in CRH when we assume that clouds are resolved for the km-scale numerical weather prediction models, in other words neglecting the subgrid variability of clouds. "3D cloud radiative effects", however, quantify the horizontal gradient of radiative fluxes at the interfaces of clouds and clear sky, but also between the cloudy columns, which cannot be quantified with 1D radiation solvers. The latter is different from the impact of "cloud horizontal heterogeneity”. Thus, the components quantify different aspects of the CRH uncertainty. Overall, the CRH uncertainty assuming resolved clouds at the resolution of 2.5 km includes both the uncertainty of the cloud horizontal heterogeneity and the 3D cloud radiative effects.

We will adjust the text in the introduction section of the manuscript to better clarify the above points.

Resolution effect

The resolution effect (modeling grid size in x, y, and z) is a quite complex factor as it can alter cloud fraction, cloud structure (e.g., vertical overlap), and cloud heterogeneity etc. Can authors provide some comments/insights on which plays the most important role when speaking of resolution effect to the CRH uncertainty (discussion from L391 to L402)?

Thanks for the comment. In this study, we do not explicitly investigate the effect of model resolution on the simulation of clouds and hence CRH. Instead, our approach is to assume that the cloud field is known, i.e., is given by the LEM simulations at 300 m resolution. We then ask how CRH changes if the same cloud field was only known at 2.5 km horizontal resolution, and to what extent ignorance of the cloud variability at scales below 2.5 km affects CRH. To this end, we coarse-grained the LEM 300 m data to 2.5 km. We created two sets of NWP homogeneous clouds with and without cloud fraction, and our result shows that the coarse-graining or cloud horizontal heterogeneity affects the CRH for all clouds, especially for shallow cumulus clouds.

Regarding the effect of cloud fraction and vertical overlap, our result shows that accounting for vertical variability has a larger effect for shallow cumulus clouds than for stratiform clouds. For shallow cumulus clouds, the effect of cloud overlap is stronger than that of cloud horizontal heterogeneity. In contrast, for stratiform clouds in the WCB, vertical overlap has a weaker effect on the CRH compared to cloud horizontal heterogeneity.

We plan to adjust the text in the conclusion section of the manuscript to better clarify the above points.

Comments on “3D cloud radiative effects are overall small”

I don’t think with current results setup one can drew the conclusion of 3D cloud radiative effects are overall small not only because comment (1) but also because only limited solar geometries have been investigated. More importantly, since the paper only provides average profiles of CRH, the cloud 3D effects can potentially be “averaged out” (e.g., Figure 5c shows biases altering sign on the left and right of clouds). The realistic pattern of energetics (3D calculation) might play an important role in the convolution of cyclone, which cannot be captured by 1D even their averaged CRH seemingly the same. I would recommend adding standard deviation (or a selection of pixels) of the CRH profile in addition to the average value.

Thanks for the comment. We agree with the concern about the importance of local 3D cloud radiative effects. Reviewer 1 also expressed a similar concern. As addressed in our response to Reviewer 1's comment, we are going to include the analysis of local CRH uncertainty due to 3D cloud radiative effects and our new analysis in Section 4 of the revised manuscript.

Offline 3D radiative transfer calculations

Although might be technical, if authors can provide some information on the computational time along with computational resources that have been used, either in the manuscript or in the response to reviewers, would be much appreciated.

Thanks for the comment. The computational time can be characterized as follows.

For 3D radiative transfer calculations with the MYSTIC solver, the computational time depends on the distribution of clouds within the domain. The computational time and resources provided here are for the solar radiative transfer calculations with the MYSTIC solver for the LEM domain over the warm conveyor belt anticyclonic outflow.

A standard compute node of the Levante supercomputer at DKRZ is configured with 2x AMD 7763 CPUs: 128 cores, 256 GB memory and with a maximum run time of 8 hours. Using 1 compute node, it took between 1:30 and 4 hours to complete a 3D shortwave radiation calculation for a LEM domain, 1 time step and 1 iteration out of 10 calculations. We have no specific information regarding the memory usage.

The entire set of 3D calculations thus requires a total of 1440 hours on 1 node (i.e., 1440 node hours; 1440 hours = 4 LEM domains × 9 snapshots × 2 for longwave and shortwave × 10 iterations × an average of 2 hours for a single 3D radiation calculation).

We will include some of these details in Section 2 of the manuscript.

Minor comments:

LibRadtran: I think should be "libRadtran" with lower case "L".

Thanks, will change in the revised manuscript.

P1L21: I would appreciate if authors can expand cooling and warming from the radiative perspectives of shortwave and longwave.

We will add more information about the impact of shortwave and longwave radiation on cloud dynamics in the introduction of the manuscript.

P2L28: It would be better to add some specific numbers (e.g., "~1km", "~20km") when describing process scale and synoptic scale.

Thank you for bringing this point to our attention. As we discussed in our response for the importance of 3D cloud radiative effects, the horizontal and vertical scale of uncertainty play an important role in the forecast error growth (please also see our response to the first question of reviewer 1). We will include more information in the revised manuscript**.**

P2L50: To me, cloud-side illumination effect is the same as cloud-side radiation leakage. Please elaborate on the difference.

It has been shown that the cloud-side illumination leads to cloud warming, and the cloud-side shortwave leakage leads to cloud cooling. The magnitude of each effect depends on the solar zenith angle (Črnivec & Mayer, 2019; Jakub & Mayer, 2015). We will add more information on the difference between cloud-side illumination and cloud-side leakage in Section 3.2 of the revised manuscript.

P2L54: Suggest changing "might also lead to noticeable" to "can also lead to".

Thanks, will change it to "can also lead to".

P3L57: Please elaborate on “insufficient observations”. Aircraft in-situ observations have a decent amount of ice cloud observations for case studies.

Our notion of "insufficient observations" refers to the lack of observational data on the properties of cloud ice crystal shape and surface roughness for large-scale systems such as cyclones. We will better clarify these points in the revised manuscript.

P3L85: Please specify the vertical resolution after “75 model levels are used”.

The ICON model uses a hybrid sigma height. In the ICON-NWP simulation with 75 model levels, the layer thickness increases from 20 m near the surface to 400 m at 10 km. Above 10 km, the layer thickness increases from 400 m to 1200 m at 30 km. For ICON-LEM simulations with 150 model levels, the layer thickness increases from 20 m near the surface to 570 m at 30 km. We will include this information in Section 2 of the revised manuscript.

P4L103: “homogeneous solver” to “1D radiative transfer solver”.

The homogeneous solver is 1D, but it is different from other 1D radiation solvers. Other 1D radiation schemes can account for horizontal cloud heterogeneity, such as McICA or Tripleclouds. The homogeneous solver assumes "grid-box" clouds (all-or-nothing scheme) and does not require any assumption about vertical cloud overlap.

P5L124: “WBC” to “WCB”.

Thanks.

P6L147: “1.5 km” to “1km” (from readings on Figure 2b)

Thanks for noting this. We will change the text accordingly.

P8L204: What is the azimuthal direction? 0 at south (normally zero at north) and positive clockwise?

Thanks for the comment. It is correct that the azimuthal angle should be 180°, which directs the photons from the south to the domain. The zero value we mentioned represents a number for the default azimuthal direction in libRadTran, which is from the south. We will revise the text accordingly.

P9L205: Suggest changing “obtain low” to “reduce”.

Thanks for the suggestion.

P11L248, P11L251, and P18L376: “horizontal radiative transfer” to “horizontal photon transport” (or “horizontal radiation transport”).

Will change accordingly. Thanks

P11L250: The cloud shadowing in Figure 5a indicates a solar zenith angle of 25° instead of 65°, please double check.

The solar zenith angle in this analysis is 65°. The impression of a lower angle in the figure is due to the ratio of the length of the panel to the height, considering the actual distances represented by the axes. If we scale the length and height of the panels to a proportional value, one can clearly see the correct angle of incoming shortwave radiation. Fig. 3 shows that if we set the distance of latitude and height to 11 km and use a proportional scale for the length and height of the panels, the 65° angle of the incoming solar radiation becomes clear. We will add a note regarding this point in the caption of Figure 5 in the revised manuscript.

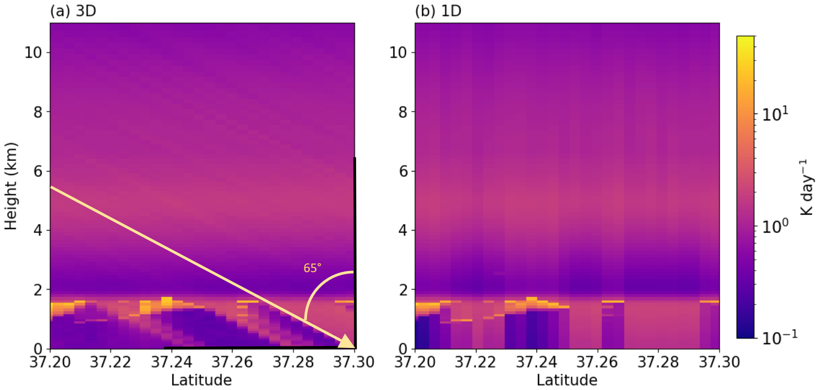

Fig. 3: *Comparison of shortwave radiative heating for shallow cumulus clouds between 1D and 3D radiation calculations at a solar zenith angle of 65°.*

P11L254: "southern sides" is difficult to infer from Figure 5 only, please reference to long-lat plot of Figure 1.

Thanks, we will include this information.

P18L386: Rephrase "who showed that … showed that …"

Thanks.

References

Črnivec, N., & Mayer, B. (2019). Quantifying the bias of radiative heating rates in numerical weather prediction models for shallow cumulus clouds. *Atmospheric Chemistry and Physics*, *19*(12), 8083–8100. https://doi.org/10.5194/acp-19-8083-2019

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