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

Behrooz Keshtgar, Aiko Voigt, Bernhard Mayer and Corinna Hoose

We thank the reviewers for their evaluations, questions, and suggestions to improve our manuscript. Below, we respond to each of the reviewers' comments and include the revised parts in the manuscript according to each reviewers' comments. We are hopeful that the revised manuscript will be acceptable for publication. The reviewers' comments are in bold, our answers are in normal font, and the revised parts are written in gray italics.

We have also made some minor editorial changes for clarification and better readability. These changes are purely editorial and are not highlighted here. Figures 5, 6, 10, 11 have been revised and a new figure has been added to the revised manuscript. The abstract has been also slightly changed.

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 identical MYSTIC calculations (please see our Monte Carlo noise analysis at the end of our response and highlighted revised sections 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 for 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. 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 CRH uncertainties (Equation 4 of the revised manuscript) from the coarse-grained CRH.

Here we include the new figure (Fig. 12) and the new and revised texts from the revised manuscript:

Revised (L227:225)

"… To reduce the Monte Carlo noise, we run MYSTIC and MYSTIC-ICA with 72 million photons for each subdomain in the LEM domains at each time step and repeat the calculations 10 times, resulting in a total of 720 million photons traced per subdomain (nearly 5000 photons per LEM column). We then average over these 10 calculations to derive the radiative heating in each LEM domain."

Revised (L227:235)

"To estimate the Monte Carlo noise of the MYSTIC solver in our setup, we split 10 MYSTIC calculations for the shallow cumulus domain at a single time step into two sets of 5 calculations and average the heating rates over these two sets of 5 calculations. We then calculate the relative standard deviation of the radiative heating between these two sets at each grid box. The relative standard deviation represents the relative variability of the radiative heating to the mean values calculated from the two sets of MYSTIC calculations. The median relative standard deviations in the shortwave, longwave, and net are less than 10 percent for almost all grid boxes (not shown). 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. The low Monte Carlo noise of our radiation calculation allows us to calculate the CRH uncertainty due to 3D cloud radiative effects locally at the scale of the horizontal grid resolution of the LEM domains (Sect. 4)."

Revised (Figure 11; L393:401)

"… In contrast to the mean uncertainties, the impact of 3D cloud radiative effects is much stronger at the scale of the horizontal grid resolution of 300 m. Except for the WCB anticyclonic domain, cloud horizontal heterogeneity dominates local uncertainties at the boundary layer between 0-2 km and mid-levels between 2-8 km in all regions of the cyclone. As for the mean uncertainties, taking into account the vertical overlap assumption reduces the local uncertainties for shallow cumulus clouds, but slightly increases them for stratiform clouds in the WCB regions. Local uncertainties due to 3D cloud radiative effects, cloud horizontal heterogeneity, and vertical overlap are much larger compared to their mean uncertainties in all four regions of the cyclone. However, the ice-optical parameterization has similar impacts on local and mean uncertainties. This shows that 3D cloud radiative effects and cloud horizontal heterogeneity and vertical overlap have a much stronger impact on CRH locally than on the domain mean."

Revised (L402:425)

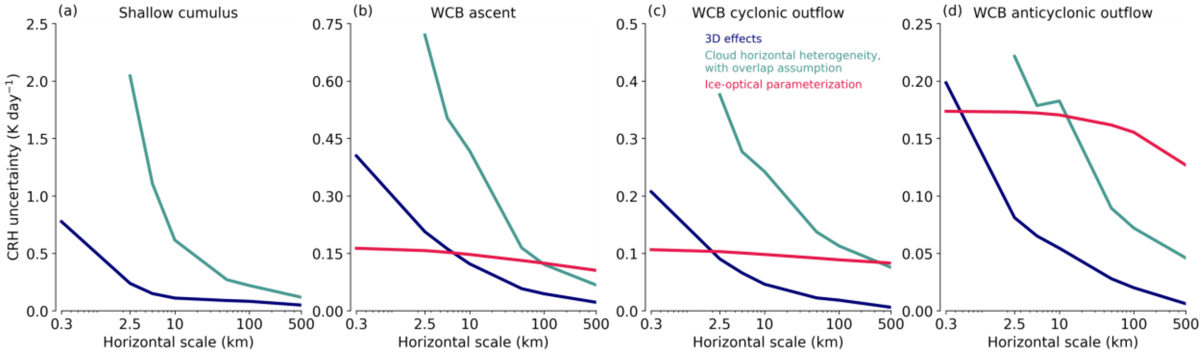
"To understand the relative importance of CRH uncertainties at different horizontal spatial scales and for the dynamics of extratropical cyclones, we coarse-grain CRH from different radiative transfer calculations from their original horizontal resolution to horizontal resolutions equivalent to 2.5, 5, 10, 50, 100, and 500 km, which is approximately the spatial extent of the LEM domains. We calculate the CRH uncertainty at different spatial scales x by computing the mean absolute difference of net CRH between different radiative transfer calculations from different sets of coarse-grained CRH and average over time and domain,

Eq. 4

Here, x is the horizontal resolution of the coarse-graining, the subscripts a and b indicate different radiative transfer calculations, n is the number of horizontal grid points i at each vertical layer for different resolutions, and t is the number of time steps j. The CRH uncertainty we calculate from Eq. 4 is an intermediate between the mean and the local CRH uncertainties described earlier such that at the *horizontal resolutions of 300 m and 2.5 km this equation is equivalent to Eq. 3 and at the resolution of 500 km, the equation is equivalent to Eq. 2. For the shallow cumulus domain, where clouds are present only in the boundary layer, we apply a mass-weighted vertical average to the CRH uncertainties between 0-2 km altitude interval but for the WCB domains, we apply the averaging between 0-12 km altitude interval (Fig. 12).*

Fig. 12 shows that in all regions of the cyclone, the net CRH uncertainty due to 3D cloud radiative effects and cloud horizontal heterogeneity with overlap assumption decreases with increasing the horizontal scale. In the WCB regions, these uncertainties decrease more rapidly than the uncertainty due to the ice-optical parameterization (cf. green and dark blue lines with red lines in panels b, c, and d of Fig. 12). This analysis indicates that while the CRH uncertainty due to 3D cloud radiative effects is large at horizontal resolutions of hundreds of meters, its spatial extent is limited and becomes less relevant at larger spatial extents. The uncertainty due to cloud horizontal heterogeneity shows a similar pattern but is larger than the uncertainty due to 3D cloud radiative effects. In contrast, the uncertainty due to the ice-optical parameterization is more or less constant as a function of horizontal scale in the WCB regions and dominates the uncertainty at spatial scales of 100 km and larger. This is due to the large-scale stratiform ice clouds that cover the entire domains in the WCB region of the cyclone, and therefore nearly the same level of uncertainty occurs over the entire domains."

<u>Revised (New figure)</u>



*"**Figure 12**: Net CRH uncertainties as a function of horizontal scale from 300 m to approximately 500 km for all LEM domains. Uncertainties are computed as mass-weighted vertical averages between 0-2 km and 0-12 km altitude intervals for shallow cumulus and WCB regions, respectively. For the uncertainty due to the ice-optical parameterization, the CRH difference between the ice schemes of Fu and the ice scheme of Baum with the general habit mixture is used. Note the different y-axes in the panels."*

<u>Revised (L445:446)</u>

"…We find that 3D cloud radiative effects are large at the scale of the horizontal grid resolution of 300 m but negligible on larger spatial scales of hundreds of kilometers."

<u>Revised (L461:464)</u>

"… Our expectation is in line with studies showing that perturbations on a larger spatial scale are more effective for baroclinic error growth (e.g., Sun and 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."

Revised (L479:482)

"… for the baroclinic error growth the spatial scale of the uncertainty is more important than the amplitude of the uncertainty (e.g., Lloveras et al., 2023). Although 3D cloud radiative effects are large at the scales of LEM model grid resolution and have been shown to affect the organization of subtropical low-level clouds, their spatial extent is limited."

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:

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

Figure 1 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.

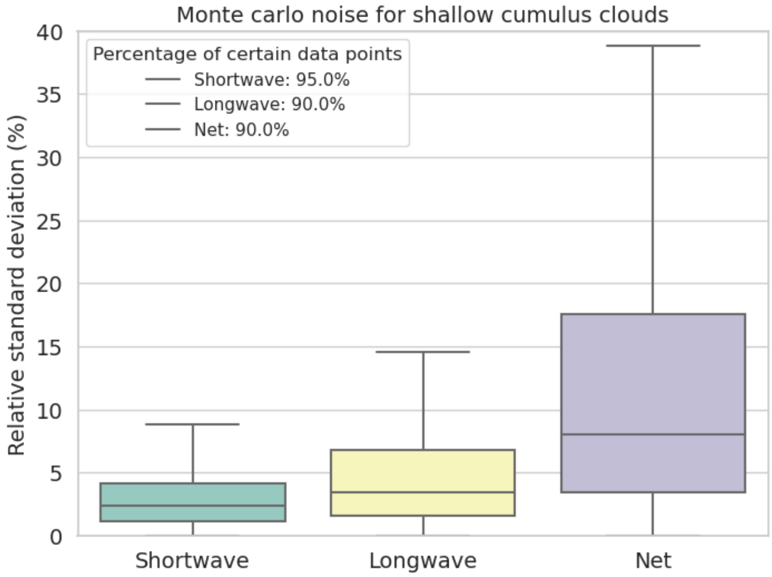


Figure 1: *Distribution of the relative standard deviation of radiative heating at each grid box for shallow cumulus clouds between two radiative transfer calculations with MYSTIC solver using 360 million photons. The legend in the figure shows the percentage of data points fall within the upper and 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 changed Figure 5 to include the net radiative heating and adjusted the text accordingly in the revised manuscript.

<u>Revised (L287:295)</u>

"… In the longwave spectrum, cloud "shadows", visible as white areas below clouds (panels d and e of Fig. 5), are weaker in the 3D calculation than in the 1D calculation due to the horizontal photon transport between model columns. However, the largest differences between the 3D and 1D calculations occur at the cloud-clear sky boundaries, where horizontal emission of longwave radiation from the cloud tops and cloud sides leads to stronger radiative cooling in the 3D calculation (blue colors around 1.5 km height in Fig. 5 f).

In the net, most features of cloud radiative heating and cooling within the atmosphere are present in both 3D and 1D calculations (Fig. 5 g, and h). However, due to the shortwave cloud-side illumination and horizontal longwave cloud absorption and emission, large differences exist at the interface of clouds and clear sky regions around 1.5 km height in Fig. 5 i and in the position of cloud shadows."

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 added this information in section 3.2 of the revised manuscript.

<u>Revised (L300:301)</u>

"… Črnivec & Mayer, 2019 also showed this direct relationship between cloud-side illumination and solar zenith angle."

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. In the revised manuscript we used the local solar time in figure 6.

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 (please also refer to our response to the first Reviewer's comment). We have revised the text in section 4 of the revised manuscript.

Revised (L422:429)

"… the uncertainty due to the ice-optical parameterization is more or less constant as a function of horizontal scale in the WCB regions and dominates the uncertainty at spatial scales of 100 km and larger. This is due to the large-scale stratiform ice clouds that cover the entire domains in the WCB region of the cyclone, and therefore nearly the same level of uncertainty occurs over the entire domains.

Our analysis suggests that the large-scale changes in the dynamics of the cyclone are more susceptible to CRH uncertainties due to cloud horizontal heterogeneity (assuming resolved clouds at the horizontal resolution of the NWP model) and ice-optical parameterization than to 3D cloud radiative effects."

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 updated 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. In the revised manuscripts, we have added more detail to make the distinction between the two terms clearer.

<u>Revised (L57:65)</u>

“ … the largest differences between 3D and 1D radiative transfer calculations are expected to occur between cloudy and clear model grid boxes, where the gradient of cloud optical properties is large. Strong horizontal variability of in-cloud and subgrid cloud optical properties can also lead to horizontal radiative transfer that is neglected in 1D radiative transfer schemes. Since we can assume that the clouds from the large eddy model simulations are perfectly known and no further subgrid cloud variability exists, 3D cloud radiative effects here are only attributed to the horizontal gradient of radiative fluxes between model columns and not within model grid boxes. For model grids with coarser horizontal resolution, the horizontal radiative exchange caused by the horizontal subgrid variability of cloud optical properties needs to be parameterized as part of the 3D cloud radiative effects.”

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 data to the resolution of 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.

<u>Revised (L439:444)</u>

“… This provides a framework to for the first time assess and compare uncertainty in CRH due to four factors within an extratropical cyclone: 3D cloud radiative effects, ice-optical parameterization, cloud horizontal heterogeneity, and cloud vertical overlap. Since we can assume that clouds from the LEM simulations are perfectly known for the purpose of radiative transfer calculation, we quantify the last two factors by coarse-graining the LEM clouds to the horizontal resolution of 2.5 km of the NWP model.

We create two sets of NWP homogeneous clouds with and without cloud fraction. By doing so, we quantify to what extent ignorance of the cloud subgrid variability at scales below 2.5 km affects CRH."

Revised (L467:473)

"… Including the vertical overlap assumption significantly improves the simulation of CRH for shallow cumulus clouds, but in fact slightly degrades CRH for clouds in the WCB since the maximum-random overlap assumption misrepresents the vertical arrangement of cloud layers in sheared flows and a more complex form of the overlap assumption would be needed (e.g., Giuseppe and Tompkins, 2015). The comparison between the impact of cloud horizontal heterogeneity and cloud vertical overlap shows that for shallow cumulus clouds, vertical overlap has a stronger impact on CRH than 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."

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 included the analysis of local CRH uncertainty due to 3D cloud radiative effects and a new figure and analysis in Section 4 of the revised manuscript. Please refer to our response and the highlighted revised parts in page 1, 2, 3 and 4 of this document.

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).

Revised (L225:226)

"… Overall, the total computational time required to perform the entire set of 3D radiative transfer calculations amounts to about 1500 hours on a single node of the Levante DKRZ supercomputer."

Minor comments:

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

Thanks a lot, we corrected this in the revised manuscript.

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

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

Revised (L21:25)

"… Within the atmosphere CRH results from the interaction of clouds with radiation in different parts of the electromagnetic spectrum. In the shortwave spectrum, clouds absorb the incoming shortwave radiation, which warms clouds and contributes to their stabilization. In the longwave spectrum, clouds absorb outgoing longwave radiation at their base and re-emit it at colder temperatures at their top, leading to substantial cooling. This pattern of cloud top cooling and the modest warming from below promotes convective instability within the cloud."

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 of the uncertainty play an important role in the forecast error growth. Please see our response to the first question of reviewer 1.

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 added more information on the difference between cloud-side illumination and cloud-side leakage in the introduction of the revised manuscript.

Revised (L51:56)

"… 3D cloud radiative effects arise from horizontal photon transport that is not taken into account in 1D radiation schemes, as currently operational in weather and climate models. The main 3D cloud radiative effects are shortwave cloud-side illumination (Jakub and Mayer, 2015, 2016), shortwave cloud-side radiation leakage (Hogan and Shonk, 2013), and longwave cloud-side absorption and emission (Klinger et al., 2017). At high solar zenith angles, shortwave cloud-side illumination increases the shortwave absorption at the cloud sides facing the sun. At low solar zenith angles, however, photons can escape through cloud sides and lead to the reduction of shortwave cloud absorption."

P2L54: Suggest changing “might also lead to noticeable” to “can also lead to”.

Thanks, we changed 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.

Thanks for the comment, we revised the text accordingly to convey the message about the complexity of ice crystals better in the manuscript.

Revised (L67:70)

“The representation of ice-optical properties in models is challenging due to the complexity of ice crystals, especially with assumptions regarding their shape and surface roughness. The lack of a consolidated understanding of the ice crystal shapes and how they should be represented in models creates an important source of uncertainty for simulating CRH.”

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

The ICON model uses a terrain-following hybrid vertical coordinate. 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.

Revised (L100:102)

“…ICON applies a terrain-following hybrid vertical coordinate, and we use 75 model levels in the vertical direction. The layer’s 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.”

Revised (L146:147)

“…We use 150 model levels with layer thicknesses increasing from 20 m near the surface to 570 m at 30 km.”

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 cloud horizontal heterogeneity, such as the operational McICA or RRTM schemes and the 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 changed 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 revised the text accordingly.

Revised (L221:222)

"…The azimuth angle is set to a constant value of 180 degrees, which directs the solar radiation from south to north."

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").

Thanks. We revised the texts accordingly.

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.

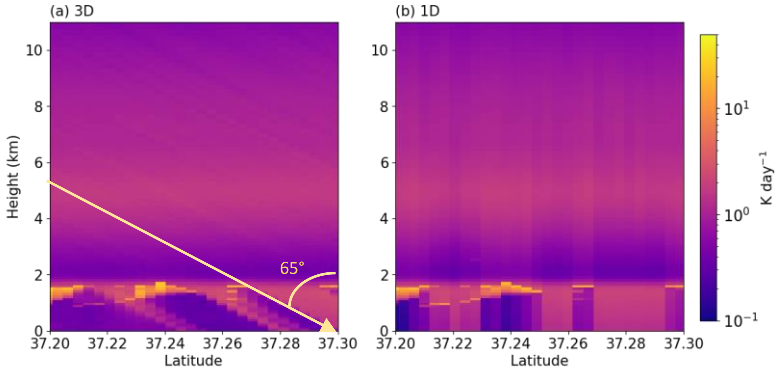


Fig. 3: *Comparison of shortwave radiative heating for shallow cumulus clouds between 1D and 3D radiation calculations at a solar zenith angle of 65°.*

Revised (Caption of figure 5)

"…Note that the impression of a lower solar zenith angle in the figure is due to the aspect ratio of the figures."

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

Thanks, we included 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

Jakub, F., & Mayer, B. (2015). A three-dimensional parallel radiative transfer model for atmospheric heating rates for use in cloud resolving models—The TenStream solver. *Journal of Quantitative Spectroscopy and Radiative Transfer*, *163*, 63–71. https://doi.org/10.1016/j.jqsrt.2015.05.003

Lloveras, D. J., Durran, D. R., & Doyle, J. D. (2023). The Two- to Four-Day Predictability of Midlatitude Cyclones: Don’t Sweat the Small Stuff. *Journal of the Atmospheric Sciences*, *80*(11), 2613–2633. https://doi.org/10.1175/JAS-D-22-0232.1

Sun, Y. Q., & Zhang, F. (2016). Intrinsic versus Practical Limits of Atmospheric Predictability and the Significance of the Butterfly Effect. *Journal of the Atmospheric Sciences*, *73*(3), 1419–1438. https://doi.org/10.1175/JAS-D-15-0142.1