Authors' reply to comments by referee #2 (James Manners)

We thank the referee for carefully reviewing the manuscript, providing the valuable comments and suggestions, which helped improving the original manuscript version. We incorporated the majority of suggested improvements. In the following the referee comments are presented in blue and the authors' reply in black. Please note that the line and figure numbers refer to those in the original manuscript. Changes in the revised manuscript are marked with quotation marks and additional indent.

Specific comments:

1) Introduction: I would suggest that one disadvantage of the tripleclouds method, compared to the other cloud heterogeneity methods described, is the computational cost of the tripleclouds solver. Lines 72-74 mention that the value of the tripleclouds scheme would be increased if fewer spectral intervals were used. Perhaps the main point to mention here is that in order to limit MCICA noise when there are a small number of spectral intervals, oversampling of each interval would be required, which would increase the cost of MCICA to a similar level as the tripleclouds solver.

Thank you for this advice. We extended the relevant paragraph as you suggested and additionally emphasized that the current operational McICA is computationally more efficient than the Tripleclouds:

> "In contrast to the McICA, which is still operational also at EMCWF due to ist higher computational efficiency, the TC scheme does not produce any radiative noise. As suggested by Hogan and Bozzo (2016) this superiority could become even more valuable in the future if an alternative gas optics model with fewer spectral intervals than the current RRTM-G (Mlawer et al., 1997) will be developed, since this would increase the level of the McICA noise, but it would not affect the Tripleclouds. In other words, in order to limit the McICA noise in this case, oversampling of each interval would be required, which could increase the computational cost of the McICA to a similar degree as that of the Tripleclouds scheme."

2) Lines 77-78: the initial implementation of the "tripleclouds" scheme from Shonk and Hogan 2008 was in the Edwards-Slingo (now "Socrates") model that is also a delta-Eddington two-stream scheme. I would suggest the novel focus of this paper is the implementation and adaptation of the method in the libRadtran package in particular.

Thank you for pointing this out. We changed the text accordingly:

> "To that end, building upon the Tripleclouds idea of SH08, the classic δ-Eddington two-stream method with maximum-random overlap assumption for partial cloudiness was extended to incorporate an extra cloudy region at each height (Fig. 1, bottom right). The prime focus of this paper is to document the present Tripleclouds implementation in the comprehensive radiative transfer package libRadtran (Mayer and Kylling, 2005; Emde et al., 2016)."

3) Section 2.3.2 conventional GCM representation: did you have an optical depth threshold to determine the cloudy part of the domain? Might the results improve if you did? The determination of cloud fraction in a GCM is quite model dependent I imagine and possibly tuned to give the best emergent cloud properties. It probably doesn't represent the total cloud fraction down to the very thinnest cloud.

Yes, we applied a standard LWC threshold of 10^{-3} g/m^3 to define a cloudy pixel on the LES grid. This should give reasonable LES cloud representation as well as reasonable derived GCM cloudiness, and consequently also the heating rate.

4) Section 3.1: thermal emission is neglected in these equations and could be simply added as an extra source term in equation 4 and 6, even if it is to be neglected in the further equations.

Thank you for this suggestion. We added an extra paragraph within Section 3.1 briefly explaining the thermal emission treatment. As our current version of the two-stream radiation scheme is only capable of separately performing the solar and thermal calculations, we prefer not to simultaneously include the thermal emission term in Eqs. (4) and (6). The added paragraph is the following:

> "The preceding formulation considered solar radiative transfer in the absence of thermal emission. As solar and thermal spectra are separated and can be therefore conveniently treated independently, the solar source is merely replaced with the terrestrial emission term when addressing thermal radiation. The vertical temperature variation is thereby taken into account by allowing the Planck function to vary in accordance with the Eddington type linearization: $B_{Planck}(\tau) = B_0 + B_1 \tau$, where B_0 and B_1 are constants. The equation system for a single layer is constructed in a similar manner, accounting for both upward and downward thermal emission contributions. For a more comprehensive explanation the reader is referred to Zdunkowski et al. (2007), as in the rest of this section we will focus on solar radiation."

5) Line 249: As a suggestion, I think the overlap (transfer) coefficients should correspond to a level rather than a layer as they determine the transfer across the boundary between layers. It would then be useful to add the level being referred to for each T in equations 10, 11, and 12. Note then that eg. T_upˆck,cn(i) = T_downˆcn,ck(i), so the up and down arrows are perhaps redundant and the notation could simply indicate the upper cloud region, lower cloud region.

The overlap coefficients could be expressed as level quantities and hence presumably without distinguishment between up and down arrows. For consistency, however, we would like to preserve the same indexing in the paper as in our coded Tripleclouds implementation, where the overlap coefficients are defined per layer (this is further consistent with our recently implemented "twomaxrnd" solver following Zdunkowski et al., 2007). We have further emphasized this in the text:

> "The coefficients starting with T appearing in Eqs. 10, 11, 12 are referred to as the overlap (transfer) coefficients and correspond to the layer under consideration (j)."

As they all correspond to the same layer (j) we omitted this in Eqs. 10, 11, 12 - consistently with the omission of the j-index for the Eddington coefficients. In this case the upward and downward arrows are necessary in Eqs. 10, 11, 12, since T_down^a,b(j) = function(C(j),C(j-1)) and T_up^a,b(j) = function(C(j),C(j+1)). We have further emphasized the latter:

> "The transmission of upward radiation is managed via overlap coefficients T_up^{a,b}(j) in an equivalent manner, except that these are dependent on the cloud fraction in the layer under consideration and that in the layer underneath [C(j), C(j+1)]."

6) Section 3.3: While the formulation of the overlap rules is fairly clearly outlined here I think it would be better to provide the generalised formulas for the overlap between different regions rather than just the example case given. Especially as I think this method might be one of the key novel developments in this scheme. It would be particularly interesting to see how this new overlap scheme performs in comparison to a standard maximum-random approach which does not follow a core-shell model (i.e. a scheme where each region is maximally overlapped with itself but the overhang randomly overlapped with the other regions).

As the referee #1 also suggested that the initial description of overlap rules including only one cloud geometry case is not sufficient, we added an extra overlap section in the Appendix. This section contains the overlap coefficients for the four possible geometries as well as their generalized formulas. We agree that comparison of this overlap scheme with the standard maximum-random approach for three regions would be interesting, but it is out of the scope of the present study.

7) Section 3.4: I think this section requires further explanation with regard to how exactly your solver is implemented. Ideally, this should be explained in relation to the concept of entrapment explained in Hogan et al 2019. The method implemented in Shonk and Hogan 2008 corresponds to zero entrapment whereas the original Edwards and Slingo / Socrates method described in eqn 15 of Shonk and Hogan 2008 corresponds to maximum entrapment. It looks to me like your method also corresponds to maximum entrapment. It would be useful to indicate how your method differs from this.

Thank you for this suggestion, we agree that Section 3.4 was not adequately formulated. From the various entrapment possibilities presented in Hogan et al. (2019) [“zero”, “explicit” and “maximum” entrapment; their Fig. 1] it might seem that our version corresponds best with the maximum entrapment. Nevertheless, Fig. 1 of Hogan et al. (2019) illustrates the “entrapment” as a mechanism occurring between two randomly overlapped layers of a multilayered cloud scene, whereas our Fig. 9 (right panel, present implementation) illustrates the division of radiative fluxes between two adjacent maximally overlapped cloudy layers. This division is managed according to the assumed overlap: whereas our overlap treatment follows the core-shell model, their does not. The exact comparison of both solvers (in theory and in practice) should be a topic of a future study. We therefore removed Section 3.4 from the current version and rather briefly clarified the differences in the initial introductory part of Section 3:

> “The underlying δ-Eddington two-stream framework employed in the present Tripleclouds implementation differs from that applied by SH08 and subsequent studies (e.g., Shonk et al, 2010; Hogan et al., 2019), whereby the latter is based on the Adding Method (Lacis and Hansen, 1974) as originally included in the Edwards and Slingo (1996) radiation scheme. Therefore we first present the δ-Eddington two-stream method (Zdunkowski et al., 2007), already previously contained in *libRadtran*, and introduce the terminology in Sect. 3.1. We focus only on those aspects of the method, important to understand its extension to multiple (three) regions, explained in subsequent Sect. 3.2. The novel overlap formulation based on the core-shell model is established in Sect. 3.3. Further technical instructions regarding the Tripleclouds usage within the scope of *libRadtran* are provided in Appendix A.”

8) Figure 9: This schematic is not entirely clear: I think the large downward radiation arrow should actually indicate the flux coming from just the upper dark blue region.

We removed Section 3.4 and thereby this figure in the revised version, therefore the details might not be relevant anymore. Nevertheless, in our Tripleclouds implementation the large downward arrow represents the entire downward radiative flux that is entering the region of optically thick cloud in the layer (j) under consideration. This flux component stems from all three regions in the upper layer and not only from the optically thick cloudy region.

9) Section 5.1: At large zenith angles your TC schemes tend to approximate the 3D heating better than the ICA: could this be due to your effective treatment of "maximum entrapment" in your TC solver, whereas the ICA effectively treats "zero entrapment" (from Hogan et al. 2019)? The effective treatment of 3D effects in your method should be discussed, otherwise the improved treatment of TC over ICA can only be interpreted as a cancellation of errors.

This is indeed an interesting note. We extended the discussion within Section 5.1 accordingly:

> “Finally, it should be noted that at low Sun (SZA of 30° and 60°) the TC is generally even more accurate than the ICA, which could be partially due to effective treatment of solar 3-D effects in the TC scheme.”

We as well added an extra sentence comparing the TC and the ICA in the thermal spectral range:

> “Noteworthy, the TC performs similarly well as the ICA also in the thermal spectral range, implying that the realistic subgrid cloud variability can be adequately represented by a two-point PDF.”

10) Section 5.1: The use of a constant FSD of 0.75 in these experiments muddies the comparison a bit as you are convoluting the error in using the constant FSD with the error introduced by the method to generate the LWC pair. You could repeat the experiments using the actual FSD in each layer to isolate error in the LWC pair method.

We repeated the experiments using the actual FSD in each layer as you suggested. We additionally repeated the experiments with the parameterization of Boutle et al. (2014) for liquid cloud inhomogeneity. We have eventually decided to include the results of the latter, which is of practical interest for the application in weather and climate models, pointing out limitations of current FSD parameterizations. We added an extra figure panel within Section 5.1 and extended the corresponding discussion in Section 5.1 and 5.2 as well as slightly changed the summary and conclusions in Section 6.

The added paragraph in Section 5.1:

> “Based upon these considerations, we additionally evaluated the parameterization of Boutle et al. (2014) for liquid cloud inhomogeneity, which takes into account that variability is cloud fraction dependent. Although solar RMSE slightly reduces when FSD is represented following Boutle et al. (2014), the TC experiment with global FSD constant assuming Gaussian distribution remains the most accurate during both nighttime and daytime (Fig. 13, right). To that end, the development of improved parameterizations is highly desired in the future.”

The added comment in Section 5.2:

> “Similar findings are obtained if the FSD is parameterized according to Boutle et al. (2014), which does not bring desired improvements (not shown).”

The changed sentence in Section 6:

> “The validity of global estimate of fractional standard deviation (a common measure of cloud horizontal variability) as well as of more sophisticated inhomogeneity parameterization was tested along with different assumptions for subgrid cloud condensate distribution (Gaussian, gamma, lognormal), which are frequently applied when representing clouds in weather and climate models.”

11) Section 5.2: The performance of the TC scheme for surface thermal flux should probably be compared with the ICA as the achievable benchmark as the entrapment implicit in your scheme would not have a large effect in the thermal and you scheme is effectively approximating the ICA.

The performance of the Tripleclouds should always preferably be compared with the 3-D calculation as a benchmark.

12) Appendix A: this looks like something that would be better left to a user manual rather than a journal paper - with development of the package I suspect these instructions would change and the user manual could be updated accordingly.

We shortened the appendix by removing the instructions for “twomaxrnd” solver, which is not the main focus of this paper. We however kept the Tripleclouds instructions in order to additionally highlight the simple usage of the solver. Otherwise yes – similar guidance will be provided in the user manual accompanying the next libRadtran release.

Technical corrections:

1) Line 184: stemms -> stems

Changed.

2) Line 434: Hill 2015 is referenced but is not in the reference list (Hill et al 2015: A regime-dependent parametrization of subgrid-scale cloud water content variability). This paper could also be referenced at line 480/481 in the conclusions.

Corrected, we included Hill et al. (2015) in the reference list. We also added this reference within the conclusions section, together with similar studies of Hill et al. (2012) and Boutle et al. (2014).

Additional remark: *We have further added a brief preface at the beginning of Section 2 (introducing subsections 2.1-2.3; to make it consistent with prefaces in Sections 3, 4, 5):*

> *"We first introduce the core-shell model for convective clouds as well as the shallow cumulus case study in Sect. 2.1. The radiative transfer models and experimental setup are outlined in Sect. 2.2. The results of preliminary radiation experiments demonstrating the importance of representing cloud horizontal heterogeneity are presented in Sect. 2.3."*

Consequently, we could shorten/reformulate the last paragraph of the Introduction as follows:

> *"The manuscript is organized as follows: in Sect. 2 the cloud data and methodology is introduced. In Sect. 3 our version of the TC radiation scheme is presented. In Sect. 4 existing approaches for generating cloud condensate pairs are revised. The TC performance is evaluated in Sect. 5. A brief summary and concluding remarks are given in Sect. 6."*