Reply to Anonymous Referee #1

We are grateful to referee #1 for carefully reading the manuscript and providing many helpful suggestions.

General comments

The paper compares 3D and 1D Monte Carlo simulations of a cirrus cloud field at four different MODIS wavelength channels in the thermal spectral range. The aim of the study is to investigate the difference in brightness temperature between 1D and 3D radiative transfer in an inhomogeneous cloud field from a nadir satellite perspective and to find the optimal horizontal resolution where the error between the realistic 3D radiative transfer and the commonly used 1D approximations are at a minimum.

Simulations of different horizontal resolutions (50m to 10km) have been performed and differences due to horizontal transport of radiation and the averaging/aggregation of high resolution pixels to coarser resolution, the plane parallel bias, have been addressed.

It was shown that the optimal horizontal resolution varies between 100 and 250m, depending on the wavelength channel. Even at this optimal resolution the difference in brightness temperatures between the 1D and 3D radiative transfer simulation can be up to 7K.

Additionally, sensitivity tests for varying optical properties have been performed. The off-nadir perspective was addressed by simulating one of the four MODIS channels of this study.

With this study, the authors extend former work in this field by showing the difference between 1D and 3D RT brightness temperatures at different horizontal resolutions.

The paper is suitable for publication after minor revision.

General Comments:

The optical thickness used in the paper is not always defined. In one figure, the optical thickness at 0.86m is shown, while most of the manuscript refers to the 12.03m optical thickness. It is not always mentioned which optical thickness is used for the comparisons. The authors might clarify which optical thickness is used where in the study. I would recommend using a single one. What is the reason for choosing that specific wavelength optical thickness?

This is an error in our labeling. Because part 2 of this study is dedicated to visible and near infrared wavelengths, we have kept the same labeling. But in the figure 5, the values are at 12.03 μm. We corrected the label and the caption.

The authors refer often to the mean path of a photon/FLIP when effects of the horizontal resolution are concerned. It might help readers to have a certain number associated with the mean path at the four different wavelengths considered in the work. Maybe the value of the mean path at a certain optical thickness (e.g. 1 or 1.4 as this seems to be the mean optical thickness of the cirrus cloud in this study) could be added.

Following the definition of the mean horizontal displacement given in Marshak and Davis (2005, chapter 12), for a homogeneous cloud, an optical thickness of 1, and wavelengths of 8.02μm, 11.01 μm, 12.03 μm and 13.36 μm we get an approximate mean horizontal transport of 3.34 km, 2.93 km, 2.68 km and 2.59 km, respectively.

Therefore, the mean horizontal displacement is larger than the pixel field of view, especially for 8μm radiances, leading to a stronger effect as seen in Figure 8. We have added this paragraph to page 7 after line 20: "Table 3 summarizes the number of scattering and photon mean path computed using Marshak and Davis, 2005 (chapter 12) for various optical thicknesses and for channels centered at 8.52 μm, 11.01 μm , 12.03 μm and 13.63 μm. Note the number of scatterings increases with optical thickness and is almost twice as large at 8.52 μm than at the other wavelengths. Obviously, the photon mean geometric path decreases with optical thickness (for the same cloud geometry) and is of about 3 km at 8.52 μm for an optical thickness of 1 and only about 0.5 km for an optical thickness of 10."

Some of the figures are hard to read. Especially the choice of red and pink in many of the line plots make it difficult to see the difference in the results. Please see the more specific comments below.

We agree that pink and red lines are difficult to discern especially when the plot is dense. We thus modified the color choice in the figures to improve the clarity. Pink was systematically changed to green.

Many abbreviations are introduced in the introduction. Sometimes the authors use capital letters to show the origin of the abbreviation, but not throughout the text. I recommend doing this throughout the text.

The first letters used for the abbreviation are capitalized only when this is a name (for instance MODIS).

How much different would results of a simulation of the 8.52m channel in the off nadir perspective be? As this channel has a stronger scattering, one might expect stronger 3D effects? I understand that these simulations are expensive, but it might be worth adding this channel to the analysis, or discuss possible differences in the results.

This is indeed an interesting question to assess but unfortunately, as we wrote page 14 lines 7 and 8, the required computational time to perform new off-nadir simulations is too

large. But, regarding the nadir results and differences between 8.52 μm and others channels we can anticipate the results as described below.
We moved line 7-8:"Computations for other channels were too computationally expensive and so a selection of a unique channel was preferred in order to highlight general behaviors related to off-nadir viewing geometries." to the end of the section
and added the following paragraph:

"These results were limited to the channel centered at 11.04 μm because computations for other channels were too computationally expensive. However, optical properties for channels at 11.01 μm, 12.03 μm and 13.36 μm are close, leading to similar $MAD(\overline{\Delta BT})$ for nadir view as seen in Fig. 8. $MAD(\overline{\Delta BT})$ for other view angles should therefore be equivalent to the one at 11.04 μm. Only the 8.52 μm channel may have a different behavior. However, considering $MAD(\overline{\Delta BT})$ differences between 11.04 μm and 8.52 μm in Fig. 8, we can expect that $MAD(\overline{\Delta BT})$ for 8.52 μm will be larger for a smaller pixel size due to the larger scattering and the greater horizontal radiative transport."

By the way, we corrected label in Fig. 11 where Θ_v was inserted instead of Φ_v for angles of 90 and 180°.

The 'Conclusion' in its current form is a summary of the shown work. An outlook and some discussion about the implications of the results is wanting. Please see the more specific comment below.

Specific comments

1) Page 2, Line 1: Delete "due"

Thank you for having seen this typo. We removed it.

2) Page 2, Line 6: Change "of their optical properties" to "cirrus cloud optical properties"

Done

3) Page 2, Line 15-18: This part is challenging to read and understand. I guess that the authors want to point out that the thermal infrared spectral range should (next to the retrieval of temperature/pressure and altitude) also be used for the retrieval of optical properties such as COD and CED? This is part of the motivation for the study and should be pointed out more clearly.

Yes indeed, we want to point out that several studies have shown the importance of thermal infrared channels for cirrus optical property retrieval. We have reformulated this sentence to: "cirrus optical properties may be retrieved with a better accuracy using a combination of TIR channels instead of VNIR channels, as long as the cirrus is optically thin

enough (with a visible optical thickness between roughly 0.5 and 3) and the CED smaller than 40 μm"

4) Page 2, Line 19: Comma is missing: "AVHRR, "

Done

5) Page 2, Line 20: delete brackets: ((Garnier et al., 2012, 2013))

Done

6) Page 2, Line 21: example concerning the capital letters mentioned above: "Optimal Estimation Method" (OEM)

Because Optimal Estimation Method is not a proper noun such as MODIS or AVHRR etc., we do not believe we should capitalize the first letter of "Optimal Estimation Method".

7) Page 2, Line 28: "etc.": The authors might add additional reasons or change the sentence to: "due to time constraints on 3-D forward radiative calculations and the lack of: : : "

We have modified the sentence as follow: "3-D forward radiative calculations, the lack of knowledge about the sub-pixel variability and the 3-D structure of the cloud"

8) Page 3, Line 1: Is longwave here the same as thermal IR?

In this study, longwave indeed includes thermal infrared but includes longer wavelengths into the infrared spectra.

9) Page 3, Line 1: Is the cooling rate in 1D too high or too low by 10%?

We have reformulated this sentence: "the broadband thermal cooling rates are increased by around 10% in 3-D RT by comparison to 1-D RT."

10) Page 3, Line 13: delete PPHB; it is already introduced at this point.
Done

11) Page 5, Line 27: optical thickness at which wavelength?

At 12.03 um as notified line 29.

12) Page 6, Line 10: Delete sentence "Note that TIR retrieval techniques are often limited to effective diameters between 5 and 50m." either here or in line 5/6 above.

We delete it in line 5/6.

13) Page 6, Line 30: ”cirrus 1” - There is only one cirrus case used in this study. I recommend deleting ”cirrus 1” in the whole manuscript. Otherwise one would expect more than one scene.

We agree. We have deleted the “1”.

14) Page 7, Line 18/19: The authors might mention the FLIP mean path as a second motivation for the 50m resolutions already at this point. I saw that it is mentioned later in the text, but it would already be worthy here.

Actually, the 50m spatial resolution is much finer than the mean horizontal displacement (see earlier comment). As mentioned, we were limited to 50m for computational time reason, but ideally, we would like to simulate up to 10m spatial resolution. At this spatial resolution, a much larger number of pixel can communicate through horizontal radiative transport.

We replaced lines 18/19 by: … “The choice of the native spatial resolution for 3-D computations should be much smaller than the photon mean path (distance travel before absorption or cloud escape) to account for horizontal radiative transport effects. However, 50 m is the finest spatial resolution that 3DMCPOL can achieve in a reasonable computational time for a 10 km domain.”

15) Page 7, Line 21: Mention the wavelength of the optical thickness here. From Figure I take that it is at 0.86m. Why? If the optical thickness is taken in the visible, the 550nm is a common wavelength to use. For the rest of the paper the authors use the 12.03m optical thickness. I suggest using the 12.03m here as well. Additionally, why is the 12.03m wavelength chosen? It is one of the channels of course, but how strong does the optical thickness vary for the wavelength of the other channels?

The optical thickness is at 12.03 μm, as mentioned earlier, and modified the figure accordingly. A wavelength around 12 μm is typically used as the reference channel in most studies concerning retrieval of cloud properties in the thermal infrared (Garnier et al., 2012, 2013, etc.). Since the extinction coefficients are quite similar between the thermal infrared channels (see Table 2), the difference between optical thickness defined at one channel or another does not have a significant impact.

16) Page 8, Line 26-28: Something about this paragraph is confusing and requires a better explanation. After reading it several times, I still cannot understand it in full. You point out that extreme values of the BT are smoothed out by the HRT effect. Therefore the difference between 1D and 3D BT should be smaller. As there is more scattering in channel 8.52m, one would expect smaller differences between 1D and 3D BT from the first conclusion. However, Figure 6 and your text show the opposite. This paragraph needs clarification. In addition, the choice of colors, the thickness of the lines and the scale of the y-axis makes this figure hard to read.

HRT makes the differences between 3-D and 1-D BT not smaller but higher. As mentioned, in 3-D, small BT values (associated with large optical thicknesses) are increased by the HRT and conversely, large BT values are decreased, resulting in a smoothing of the radiative field. Consequently, a 1-D radiative field (where no smoothing occurs) is always more heterogeneous than a 3-D field. Because the smoothing is stronger at 8.52 μm, the difference between 3-D (smooth) and 1-D (unsmooth) BT are larger for this wavelength.
We modified the sentence "This effect is stronger at 8.52 m, where the cloud scattering is significantly larger and cloud absorption smaller. As a result the BT differences between 3-D and 1D are larger at 8.52 μm than at 13.36 μm " to the following:
"The 3-D BT field looks more homogeneous than the 1-D BT field where no smoothing occurs. Because this difference is amplified with the number of scatterings, the differences between 3-D and 1-D for the channel at 8.52 μm are stronger than at 13.36 μm,…"

As previously mentioned, we have converted pink color into green to better contrast with the red in all the figures of the manuscript. We have also increased the linewidth for figure 6.

17) Page 9, Line 13: replace "smaller scattering" by "less scattering"
Done

18) Page 9, Line 19: typo: quite instead of quitte
Done

19) Page 11, Line 21: delete "(FLIP average distance before absorption or before leaving the cloud)" - this is explained a few times already
Done

20) Page 11, Line 22: typo: rapidly instead of rapidelly
Done

21) Page 12, Line 4: typo: Nevertheless instead of Netherless
Done

22) Page 12, Line 32: optical thickness at which wavelength?
At 12.03 μm. We now mentioned that in Page 12, Line 32.

23) Page 13, Line 12: "we chose to not show" – replace by "we chose not to show"
Done

24) Page 14, Line 7: I fully understand that Monte Carlo simulations are very expensive in terms of computational time. However, as scattering is stronger in the 8.52m channel and more horizontal transport of FLIPs between the column should occur, it might be worth adding this channel to the analysis? What result would be expected for the 8.52m channel?

Unfortunately, it would take too much time to add this channel to the analysis. So we are not able to do it. However, following others results of the paper, we were able to extrapolate the results as answered to your general comments above.

25) Page 14, Lines 20-22: Reformulate this sentence "In contrast, some lines of sight cross through small optical thicknesses... "

We rephrased it as: "In contrast, some lines of sight cross small optical thickness where photons emitted from the surface, warmer than the cloud, contribute to the TOA BT"

26) Page 14, Line 28: Remove "about"
Done

27) Page 15, Line 5: typo: lige
Done

28) Page 15, Line 24-26: Reformulate sentence: "In this study, we consider..."

We rephrased it as: "we assume that TOA brightness temperatures differences between computations assuming 1-D RT inside a homogeneous pixel and 3-D RT inside a heterogeneous pixel depend on two effects:"

29) Conclusion: An outlook concerning the presented work would be beneficial for this section. The authors briefly state what will be shown in a Part 2 paper, however different wavelength channels are involved there. As the choice of the cloud scene seems to have a larger impact on the off-nadir results, additional simulations (in future work) including different cirrus cloud fields might be one aspect. In addition, some discussion about the implications of the results for current cirrus cloud retrievals is wanting. How much would a satellite instrument with a resolution of 100-250m improve current retrievals? One might discuss that in the context of earlier studies (e.g. Fauchez et al., 2015) where the BT differences of 10K was related to ice crystal diameter and retrieved optical thickness. Is there a guess how much this improved resolution, with the following smaller differences in BT would improve the retrieval results? Currently, the conclusion section does not really show any conclusions. It only summarizes the presented work.

Thank you for this remark, indeed, the conclusion needed more details and perspectives.
The conclusion has been significantly modified in new version of the manuscript.

30) Figure 1, Caption: Delete "cirrus 1" and add "of the study"

Done

31) Figure 2: Is the potential temperature and the equivalent potential temperature really the same?

No, they are different. The equivalent potential temperature is the temperature a parcel of air would reach if all the water would condensate while the potential temperature is the temperature a parcel of air would reach if adiabatically brought to a standard pressure of 1bar.

32) Figure 3: Which optical thickness is shown in the figure?
We added 12.03 μm.

33) Figure 4: Delete "cirrus 1"
Done

34) Figure 5: Why do you use the optical thickness at 0.86m here and 12.03m in the following? The colors and especially the markers are hard to separate in this figure. One really has to zoom into the pdf.
We have corrected the label error. Now 12.03 μm is shown.

35) Figure 6: The difference between the lines is hard to see, especially the red and pink colors are hard to differentiate. Also, the scale of the y-axis makes it difficult to see the differences properly. The authors might also consider plotting thicker lines.

We have increased the line thickness and convert the pink lines into green lines to contrast better with the red.

36) Figure 7: The first sentence of the caption is challenging to understand.

We have modified this sentence as: "The contribution of photon horizontal transport to TOA brightness temperature differences between 3-D and 1-D RT at 50m ($\Delta BT = BT_{50m}^{3D} - BT_{50m}^{1D}$) seen from nadir as a function of the optical thickness at 12.03 μm (bottom axis). The proportion of pixel relative to each ΔBT is shown in the top axis."

37) Figure 8 and following: Please use a different color for the pink lines. Maybe green or orange?

We are converted pink to green

38) Figure 9: delete the "t" after "to" at the end of he third line.
Done

39) Figure 10: The lines in the upper row are hard to separate. I can see that you want to keep the values of the y-axis constant, but you might think of reducing it to 8 instead of 10? Maybe this would already help?

Yes, indeed the lines are very closed in this plot we have now rescale the y-axis up to 8.

40) Table 1: remove ”cirrus 1”

Done

Technical corrections
Please see the ”Specific Comments” section.