Reply to Anonymous Referee #2

In principle, this manuscript will make a contribution because the 3D effects of cirrus have not been studied very extensively. It essentially seeks to translate findings of earlier studies by Zinner, Davis and others, which were done for low clouds, to thin, high clouds. The issue with the manuscript in its current state is that language shortcomings make it very hard to follow, particularly in section 4. The manuscript overall reads like a draft that has not been vetted by the co-authors. Some of the figures speak for themselves, but the text tends to confuse in many places, rather than guiding the readers' eyes. The interpretation of 3D effects is also questionable (see comments #1, #10, #11). Given the multitude of typos, grammatical errors, and non-idiomatic or semantically wrong use of the language (for which examples are provided below), I recommend to reconsider the manuscript after major revisions, or reject it to give the authors more time to edit. While it was not possible to give this a full review for the aforementioned reasons, the factual content does seem promising - with a few reservations listed below. The only major ones are #1, #2, and #10.

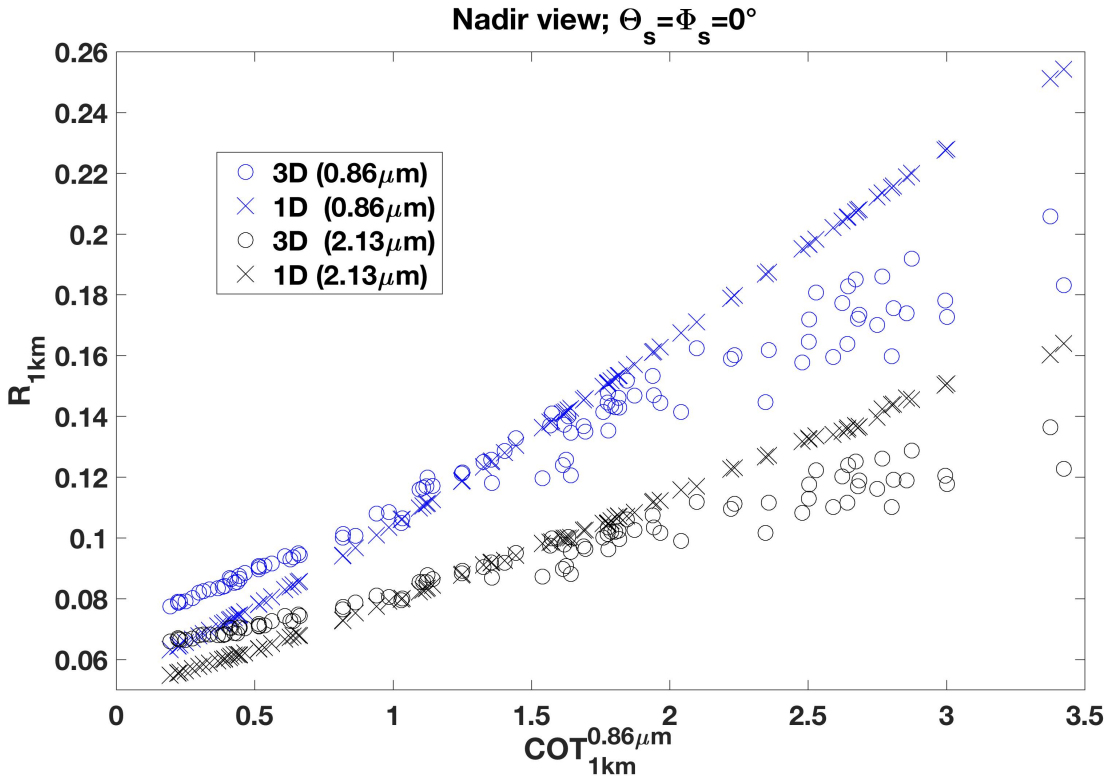
We would like to thank referee #2 for these very helpful comments who has widely contributed to improve the substance and the form of the paper. We also apologize for the numerous grammatical and typo errors. We greatly appreciate the time referee #2 spent for catching them. We ran a careful check through the whole manuscript and have corrected them in the updated version of the paper. Also, we changed the way to plot the figures, now the various effects showed in the manuscript are relative (in %) to the 3D reflectances (the truth) at the given spatial resolution. We have also over-imposed the MODIS reflectance accuracy ~3% to each of these plots in order to show when the impact of 3D and/or heterogeneity on the reflectances are significant or not.

In addition, to be clearer for explaining the cloud heterogeneity, we change the structure of the paper by first presenting the total differences between 3D and 1D reflectances and then the PPH bias, the THEAB and the 3D effects.
We also add Fig. 4 and Fig. 5 to illustrate the THEAB and 3D effects, respectively
We added a new section 4.4 on the 3D effects with a new figure (Fig. 14) and a table (Table 2).
The conclusion has been deeply re-written.

Also our manuscript has been proofreaded by a native English speaker.

1) p7, l11: "photons in thin columns have less chance to be absorbed" : : : "photons in neighboring columns with stronger scattering have more chance to leave the cloud if they are scattered toward a neighboring column with smaller extinction coefficient".
This seems to advocate for the flawed notion of photons moving along contrasts in extinction coefficients or optical thickness, a common misconception that does not pass muster upon closer examination. Perhaps a few figures showing the spatial distribution of some of the discussed biases would elucidate this issue.

We agreed that this sentence was confusing. What we mean is that real photons, of course, zigzag in all directions and some of them go from thin to thick areas and reverse; it is only the net flow that tends to go from thick to thin. As we can see in Varnai and Davis (1999) figure 5. We add this sentence to explain that this is the net flux:
"*Therefore, the net flux of photons tends to flow from thick to thin regions*."
And we have also added the new figure below to the manuscript in the section HRT to illustrate this effect
We can see that 3D reflectances are larger than 1D for small optical thicknesses while the opposite is true for large optical thicknesses.



2) p4, l31: Is a CER of 10 micron really representative? It's very small, although not outside the climatology. Even in collection 6, 30 micron is the median value of the global distribution of ice clouds.
We agreed with reviewer #2 that and effective radius of 10 microns is a small size for cirrus clouds.
The motivation behind the selection of the 10 microns effective radius is to be consistent with the Part I of this study which focuses on thermal infrared channels. Yet, the sensitivity of retrievals in the thermal infrared is often limited to CER below 20 μm. Therefore, for consistency reasons, we have also selected the same effective radius (10 μm) for this study and in the corresponding papers on cloud optical property retrievals (Fauchez et al., 2017b, 2018).
We have added this paragraph to the conclusion:
"Note that the results do not significantly change with a larger CER for 0.86 μm because the optical properties are fairly constant up to CER of 50 μm but at 2.13 μm the absorption increases with CER leading to stronger PPH and weaker 3D effects (because the mean free path is reduced by the absorption)."

3) p3,l34: ": : :because side illumination and shadowing almost cancel out each other, there is an overall agreement between CER retrieved using 2.1 or 3.7 micron."
This is unclear: is that relative to 1.6 micron? Why do "side illumination" and "shadowing" cancel each other? Does that refer to the domain average, and if so, over how large a domain does one need to average?
This is indeed unclear and we apologize for that. We rephrase it:

"3D radiative transfer effects, such as illumination and shadowing, can produce significant differences between CER retrievals based on 2.1 μm or 3.7 μm reflectances (along with 0.86 μm) for water cloud. Indeed, the authors showed that 3D effects have stronger impacts on CER retrievals based on 2.1 μm than 3.7 μm, leading to positive difference between the two from cloud side illumination and a negative difference from cloud shadowed. However, these two opposite

effects cancel each other out on the domain average, leading to an overall agreement between the CER retrievals."

4) p5,l21: At the beginning of this section, a more general description of 3D effects and their differences in the thermal and solar range would be in order. The "3D paths" that "radiation follow" [sic] are associated with fundamentally different physics, which deserves a thorough discussion. For example, scattering is much less important in the thermal wavelength range. This paper quickly dives into the details without providing a more general overview first. Furthermore, the observed dependencies on scale deserve a thorough justification.

We agreed with referee #2 that this section deserves a better explain of the 3D effects and their differences between wavelength ranges. We re-wrote the paragraph as follow:

"Clouds are complex 3D structures where solar and terrestrial radiations propagate in a three-dimensional space . However, in current retrieval algorithms, for simplification and/or computational reasons, the homogeneous independent pixel approximation (IPA, Cahalan et al. (1994)) is commonly applied: each portion of the observed cloudy scene is sampled in pixels, and each pixel is assumed to be horizontally homogeneous as well as radiatively independent of its neighbors (1D radiative transfer assumption). The sub-pixel horizontal heterogeneity leads to the plane-parallel and homogeneous bias (PPHB) because of the non-linearity between optical properties and radiance/reflectance. The 1D assumption leads to several effects describing below in terms of 3D radiative effects. Both effects (IPA and PPHB) are strongly dependent on the sensor spatial resolution. The sub-pixel heterogeneity effects increase for coarser spatial resolutions, while 3D effects linked to net horizontal photon transport between columns increase for finer spatial resolutions. The range of spatial resolutions for which either the IPA biases or the PPHB are dominant depends on the wavelength. Off course for thermal wavelength no illumination and shadowing effects are present and in addition cloud absorption is much larger for thermal infrared than for solar wavelengths leading to larger PPHB but smaller IPA effect (because of less scattering)."

5) [abstract] "This strong wavelength dependency [sic] of cirrus cloud radiative effects". Does this refer to the contrast between solar and thermal IR bands?

Yes it does and we agreed that it is more accurate and clear to rephrase the beginning of this sentence as:"
"The contrast of 3D radiative effects between solar and thermal infrared channels.."

6) p7,l15-17: The figure does not support this explanation. Isn't there a much simpler one? For lower sun elevation, satellites are more likely to pick up side scattering than for high sun elevation, especially for optically thin clouds. While this is in the realm of speculation, the explanation by the authors, finding different effects in different optical thickness ranges, is not supported by the figures. See also comment 1.

Thank you for pointing out that the figure did not support our reasoning clearly. To address this, we changed the color scheme of Figure 4 to make it easy to distinguish 1D and 3D results. We also added the following sentences to the end of the discussion on HRT in order to clarify that only Panel a is relevant to our argument about HRT:

We note that HRT, as described above, dominates only for overhead sun (Fig 4a and 4b). For oblique sun (Fig 4b and especially 4c) the trend reverses as 3D reflectances exceed 1D ones for optical thicknesses larger than about 5 and 3D reflectances are lower than 1D ones for smaller optical thicknesses. Increase of 3D reflectances oblique sun is caused by the side illumination discussed below.

7) In many places, the manuscript talks about an "increase" or "decrease" of reflectance without specifying the direction (e.g., p7,l21). It is important to include this information because 3D effects redistribute radiation differently - which can lead to a reflectance enhancement in one direction, and a decrease in another.

Good point! Accordingly, we replaced the sentence

This effect occurs when photons of the incoming sunlight travel obliquely which globally increases the reflectance of the cloud by comparison to what is expected in the 1D theory (Loeb and Davies, 1996) as we can see Fig.4 (c) for which most of the 3D reflectances are larger than 1D reflectances.

by the following text:

This effect occurs when photons of the incoming sunlight travel obliquely and enter a cloud through its side and top. In contrast to the HRT, side illumination tends to increase reflectance of thicker clouds (Loeb and Davies, 1996) as we can see Fig. 4c, where most of the 3D reflectances are larger than 1D reflectances. We note however, that side illumination can reduce reflectances in some forward scattering directions due to the "upward trapping process illustrated in Fig 5a of Várnai and Davies (1999).

8) Eq. 1: On the left hand side, there is a difference between a quantify with index "R" (reflectance) and a quantity with index "tau" (optical thickness). While not explained, it is assumed that the latter really means the reflectance calculated for a certain "tau", but the use of a retrieval parameter on par with a reflectance is a bit confusing, as is the nomenclature of the formulae in general. Simplifications would help tremendously.
We acknowledge that the formulae are difficult to read. To simplify we:

1. Remove the "tau" subscript
2. Remove the 50m subscript because the averaged reflectances are always averaged from 50m.

9) "PPHB increases as the spatial resolution increases": This is misleading throughout the manuscript. What is meant here is "aggregation pixel size", not spatial resolution. Higher spatial resolution actually means a smaller size of the individual pixels.
Thank you for pointing this out, this is indeed wrong and may lead to misinterpretation of the results. We have corrected this through the manuscript.

10) p8,l25: "Note that for sun at zenith : : : [sic]". When speaking about the PPHB in particular, it is hard to see why the sun angle would have an impact. Isn't the argument here that the optical thickness is small, which means that the retrievals are done in the linear (non-asymptotic) range of the LUT? PPHB is ultimately due to the morphology of the LUT, so it is hard to picture a role for SZA.

We do not agree with Reviewer #2 on this point. Indeed, the PPHB depend on the non-linearity between reflectance and optical thickness (Jensen inequality). The intensity of this non-linearity (and thus of the PPHB) depends on the optical thickness but also on viewing and solar angles. Also, the cirrus field has an average optical thickness of 1.5 with values going from 0.008 up to 12 at 0.86um. Therefore, for the largest value the PPHB can be very large.
"

11) "The THEAB is therefore a consequence of the PPHB for oblique view". The statement before does not support this assertion. The PPHB is fundamentally different from IPA/THEA; the latter two, on the other hand, are related.
We agreed that this sentence is at least confusing. We removed it.

12) p9,l16: This seems to be a somewhat unfortunate description of a version of TIPA. Would it be easier to just refer to one of the TIPA papers - for example, Várnai 99?

We do not agreed with referee #2. The TIPA refers to the oblique of sun radiation while the THEA (Tilted and Homogeneous Extinction Assumption) refers to the line of sight.
In order to highlight the relationship between THEAB and TIPA, we included the following sentences into the manuscript:

In essence ,the Tilted and Homogeneous Extinction Approximation (THEA) can be considered a variant of the Tilted Independent Pixel Approximation (TIPA) used in earlier studies (e.g., Várnai and Davies, 1999; Wapler and Mayer 2008; Frame et al., 2009), but with the tilting based on the view direction instead of the solar direction. A somewhat similar concept to THEA was used in Evans et al. (2008), where reflectances were related to cloud properties calculated along the slanted line of sight.

We also add in the end of section 4.3 :
Note that we choice to calculated the THEAB instead of the TIPA bias because only the former helps to understand why ΔR is positive for the small scales and negative for the larges, even when the Sun is at zenith (no TIPA bias). The TIPA bias is implicitly included in the 3D effects discussed in section 4.4.

References:
Evans, K.F., A. Marshak, and T. Várnai, 2008: The potential for improved cloud optical depth retrievals from the multiple directions of MISR. J. Atmos. Sci., 65, 3179-3196.
Frame, J. W., J. L. Petters, P. M. Markowski, and J. Y. Harrington, 2009: An application of the tilted independent pixel approximation to cumulonimbus environments. Atmos. Res., 91, 127–136.
Várnai, T., and R. Davies, 1999: Effects of cloud heterogeneities on shortwave radiation: Comparison of cloud-top variability and internal heterogeneity. J. Atmos. Sci., 56, 4206–4224.
Wapler, K., and B. Mayer, 2008: A fast three-dimensional approximation for the calculation of surface irradiance in large-eddy simulation models. J. Appl. Meteor. Climatol., 47, 3061–3071.

13) p10,l8: Why does "non-aggregated" have coarser resolution? Isn't it just the opposite?
Here the "non-aggregated" leads to confusion. What we mean is that 3D reflectances are aggregated while 1D reflectance are not because they are computed from the aggregated optical thickness..
We simply remover "non-aggregated" before 1D reflectance to avoid the confusion

Summarizing, the factual problems seem to lie in a rather superficial interpretation of the findings, and they could benefit from discussion with co-author Tamas Varnai and other experts in the field. The problems are compounded by many language errors, and I advise to run a spell and grammar check, and further to go through punctuation and semantic/idiomatic use of words. Such issues are not within the purview of manuscript reviewers. The time spent on this review is somewhat out of proportion with the current overall level of maturity of the manuscript.

We change the structure of the paper as follow:

- We now present the total bias in section 4.1
- The PPHB is presented in section 4.2
- The THEAB is presented in section 4.3
- And the 3D effects are presented in section 4.4.
- We add Fig. 4 and 5 to illustrate the THEAB and 3D effects, respectively.
- The analyze of Fig. 7, Fig. 8, Fig. 9, Fig. 10 and Fig. 12 has been improved and made more clear for the reader.

We apologize for the grammar and semantic errors. We have now check the all manuscript and hopefully corrected them.

Examples in no particular order:
Figure 8 caption: In 1D (top panel) [missing comma] the right column can be highlighted [should be "illuminated" - semantic error] by the photon coming from the Sun [missing comma] while in 3D, a [an optically] thick neighbor region intercept [intercepts?] first the photon [first intercepts ?] and scatted [scattered] it back to space. Aside from the errors, this statement is also hard to understand. Also, what is the difference between "intercept" and "scatter"? Physically accurate would be "scatter" or "attenuate".

Thank you, we have made the necessary change and rephrase the sentence: "*In 1D (top panel), the right column can be illuminated by the photon coming from the Sun, while in 3D (bottom panel), an optically thick neighbor region scatters first the photon, increasing the reflectance of the thick region, but reducing the reflectance of the thin region.*"

"the variety of voxel extinctions from a line of sight to another can be quite similar". (In this case, it's unclear what this means - perhaps that the extinction along the line of sight varies little from one tilted column to the next?)
Yes this is exactly what we mean and we rephrase it like you suggest.

"This is because of the THEAB which is a positive bias, stronger at high resolutions and large view angles." Not a sentence.
An "is" was missing there. Thank you.

"are more highlighted from the side" - this should be "illuminated" throughout the manuscript, unless the intention was to say "highlight", but that doesn't seem to make sense.
We agreed that in this context "highlighted" should be replaced by "illuminated". We apologize for the semantic error and make the necessary correction through the manuscript.
"depriving neighbor cloudy columns from [of] incoming photons" – aside from the wrong preposition, using "deprive" seems inappropriate for an inanimate object.
We removed the "of" and changed "depriving" in "blocking"
"an important factor that constrains the impact of these assumptions" - "determines" instead of "constrain"?
Yes, thank you.

"To compare reflectances issue from a 3D radiative transfer: : :" use of "issue" is unclear [as noun or verb]
We have removed "issue"
"conversevely" [sic] - several such typos that a spell checker would pick up
This has been corrected
"have an almost nil effect" - wrong semantic context for "nil"
"nil" has been changed by "no".

"which becomes almost null" - zero? idiomatic/semantic error
Corrected, thank you.

"since less different cloudy columns are crossed" - it should be "fewer" instead of "less"
Corrected, thank you.

"the PPHB increases as the spatial resolution increases" (the intended phrasing was probably: "the PPHB increases as the spatial resolution decreases (pixel size/aggregation level increases)".

Yes, we agreed, this is now corrected, thank you.

"the absolute 3D effects are slightly smaller and follow the same decreasing with coarsening spatial resolution" - "follow the same decreasing with coarsening" does not seem to work. Perhaps "also decreases with coarser resolution"?
Corrected, thank you.

"fallstreaks or not" - "whether fallstreaks are included or excluded"?
Corrected, thank you.

W.m-2: What is the meaning of the dot - found throughout the manuscript?
We are not sure to understand what referee #1 asks but instead of the dot we now

"can be extrapolated to other cirrus clouds" - "generalized" instead of "extrapolated"?
Corrected, thank you.

"spatial resolutions considered here are ranged from : : :" - spatial resolutions considered here range from : : :
Corrected, thank you.

"most of the figures shown [showed] the"
Corrected, thank you.

"THEAB and PPHB is [are] complicated"
Corrected, thank you.

"view zenith angle" - "viewing" instead?
Corrected through the manuscript, thank you.

"because of no THEAB" - because THEAB is turned off [or some qualifier instead of a "no"]
Corrected, thank you.

p2,l22-23: What is the difference between "information content" and "retrieval methods" in this case? They are two different categories.
This is indeed confusing, we rephrase it as:
"…but the number of retrievable cloud parameters is limited by the information content of the radiative measurements."
p4,l2: "LES domain" - was LES introduced before?
No it was not but we removed "LES" in the updated version of this sentence.

References:
Fauchez, T., S. Platnick, O. Sourdeval, K. Meyer, C. Cornet, Z. Zhang and F. Szczap: *Cirrus Heterogeneity Effects on Cloud Optical Properties Retrieved with an Optimal Estimation Method from MODIS VIS to TIR Channels.*, AIP Conf. Proc. 1810, 2017.