Response to Reviewer 1

We thank the reviewer for the positive appraisal of the manuscript and for providing great comments to improve the clarity of the paper. A point-by-point response to the reviewer's comments is given below.

Reviewer #1:

Major comments

1) "11298, line 25: I am not convinced that 3-D effects are minimal except for cloud edges. It would seem important to show this by including into the paper some test retrievals based on radiances from 3-D radiative transfer simulations. Alternatively, the wording should clarify that 3-D effects being minimal away from cloud edges is only the authors' guess, and that the issue still needs to be explored."

Response: Thank you for this comment; it helped illustrate the ambiguity in this section. What this section was meant to highlight is that most 3-D effects are minimal 'far' away from cloud edges. We acknowledge that the term 'far' is unclear so a more thorough discussion has been included as follows.

"Although the RRBR method is developed from overcast scenarios, we also apply this method to broken clouds to analyze the errors associated with 3-D effects. Two main types of errors are expected when applying the RRBR method to partial cloud cover. The largest 3-D effect is the geometric difference in a broken cloud's optical path (τ_p) compared to an overcast cloud's τ_p (Hinkelman et al., 2007). Fig. 8 illustrates the definition of τ_p as the optical thickness along the path of the direct solar beam, while τ_c is the optical thickness integrated along the vertical direction. For overcast clouds the τ_p is simply related to the τ_c as,

$$\tau_c = \tau_p \cos(\theta_0). \quad (7)$$

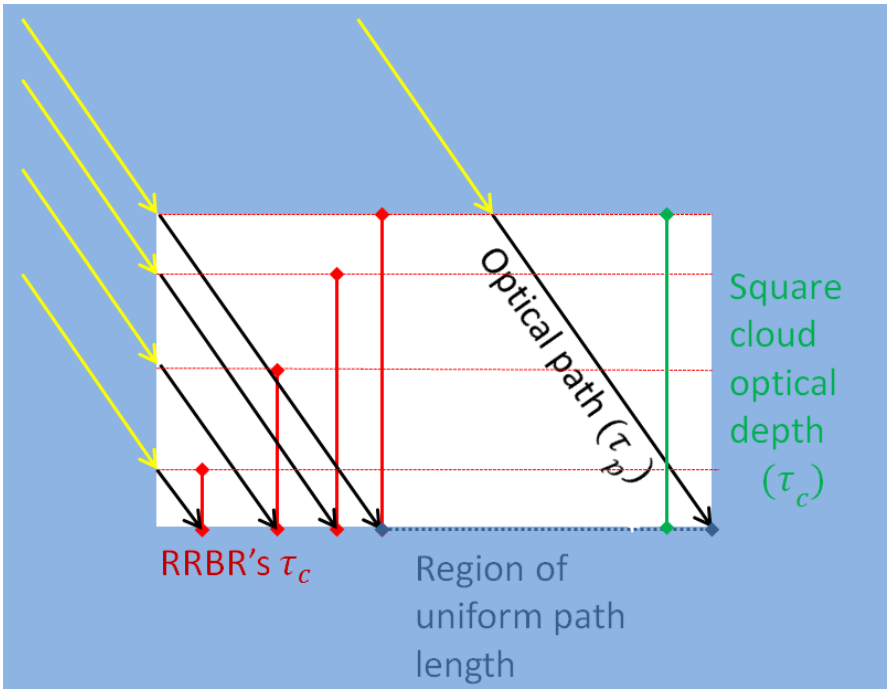

Fig. 8 Illustration demonstrating differences between RRBR measured cloud optical depth, cloud optical depth and cloud optical path.

But for partial cloud cover the optical path changes along the cloud and as a result it affects I_λ, which in turn affects the RRBR retrieval. Ignoring horizontal photon transport, the RRBR's τ_c is then a function of the τ_p as in equation 7, which unlike the actual τ_c changes across the square cloud. Fig. 9 demonstrates how the RRBR method retrieves τ_c for a 1 km x 1 km square cloud with a 0.2 km cloud geometric thickness. τ_c is observed to increase in the same way that τ_p increases. Therefore differences between the actual τ_c and the RRBR's τ_c will occur based on the geometry of the cloud. Again ignoring horizontal photon transport, in ideal cases, such as a cubic cloud, the region of uniform path length where the actual τ_c and the RRBR's τ_c are similar are limited to $\theta_0 << 45°$. For square clouds with a small vertical extent, the region of uniform path length is increased while for a square cloud of large vertical extent the region of uniform path length is decreased compared to the cubic cloud. For a parallelogram cloud aligned with the solar beam, the local homogeneity is extended to include most of the cloud base. The specifics of defining when clouds can be considered locally homogeneous will be left for future work. When horizontal photon transport is included it would be expected to decrease the area of homogeneity.

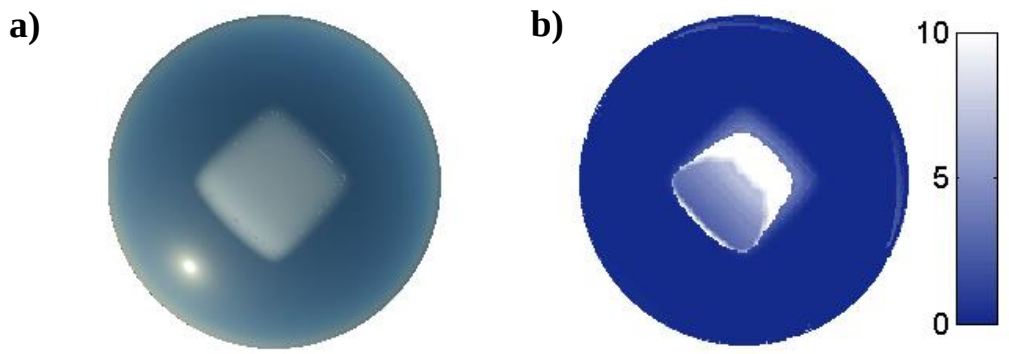

Fig. 9(a) SHDOM simulated sky image of a 1km x 1km square cloud with cloud geometric thickness of 0.2 km and τ_c =10 (b) and RRBR τ_c retrieval.

The second major 3-D effect is that heterogeneous clouds are brighter than homogeneous clouds under the same τ_c. This is caused by the unobscured part of the sky illuminating the cloud from below through surface reflection. This is demonstrated in Fig. 10 where overcast and square clouds where compared for two different spectral surface reflectance (R) for $\tau_c = 10$. The results demonstrate that the cloud bottom radiance increases 5% due to a spectral surface reflectance of 0.08 at a wavelength of 620 nm.

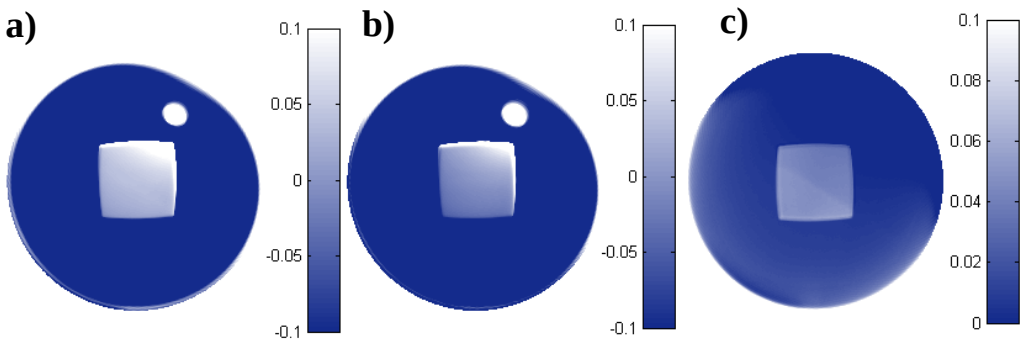

Fig. 10 Relative difference in red radiance [-] between square and overcast clouds $(\frac{I_{\lambda=620}^{overcast}-I_{\lambda=620}^{square}}{I_{\lambda=620}^{overcast}})$, (a) for surface reflectance R = 0.08 and (b) R =0 (c) difference between (a) and (b), i.e. $((\frac{I_{\lambda=620}^{overcast}-I_{\lambda=620}^{square}}{I_{\lambda=620}^{overcast}})_{\mathrm{R=0.08}} - (\frac{I_{\lambda=620}^{overcast}-I_{\lambda=620}^{square}}{I_{\lambda=620}^{overcast}})_{\mathrm{R=0}})$

2) "Page 11298, lines 26-29: I recommend expanding the discussion on the impact of uncertainties in aerosol properties. For example, sample calculations could alleviate the concern that variations in aerosol optical depth, absorptivity, and particle size (all of which affect the spectral dependence of radiances) could impact cloud optical thickness retrievals by modifying the used red-blue ratios."

Response: The section was expanded to include results for various aerosol optical depths.

"The chosen τ_a is an additional source of error in the reference SHDOM simulations. Higher actual τ_a values than those in the simulations may lead to τ_a being classified as τ_c, while smaller τ_a lead to a reduced τ_c estimate. This error is small since most τ_c are much larger than the variations in τ_a in the US. Furthermore, this error is not important for solar forecasting as – spectral effects aside – only the total atmospheric optical depth is of interest to estimate ground irradiance, not the partition between τ_a and τ_c. As demonstrated in Fig. 10 variations in AOD from 0 to 0.2 lead to changes in I_λ and RBR of less than 5%.

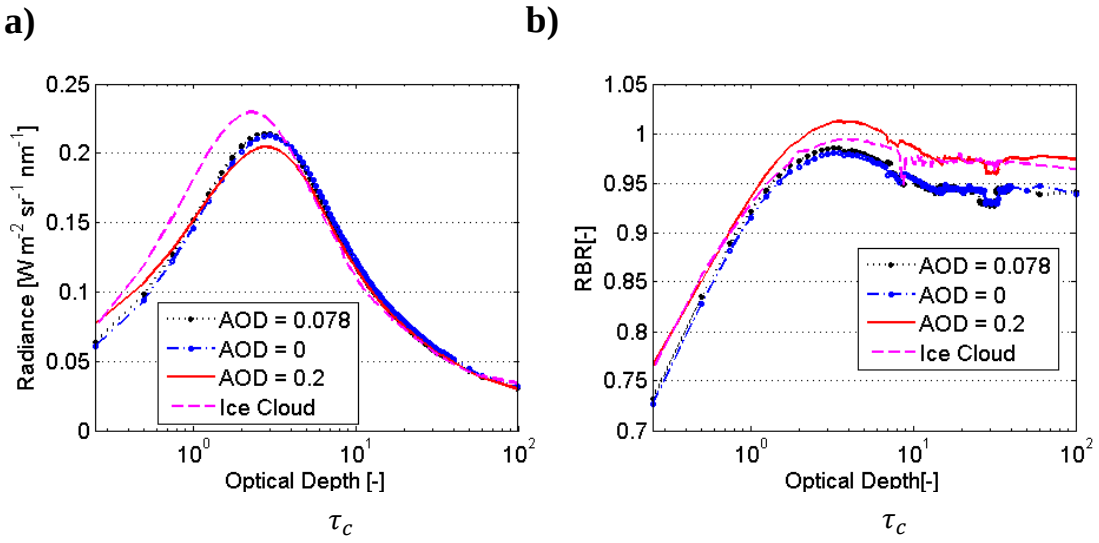

Fig. 10 (a) Red radiance and (b) RBR for liquid clouds with τ_a= 0, 0.078, and 0.2, and ice clouds with τ_a= 0.078 versus τ_c for $\vartheta_s = 45°$, $\theta_0 = 60°$ and $\vartheta_z = 45°$."

3. "Page 11301, lines 22-26: It would be interesting to see how retrieval accuracy improves when clouds brighter than the radiance peak are not assigned the maximum value (e.g., tau_c=7.25), but instead are excluded as "unreliable" retrievals."

Response: We investigated removing clouds brighter than the radiance peak, but found that this occurs only 5.4% of the time and does not have a large impact on the results. The following sentence was added to the manuscript:

"Clouds brighter than the SHDOM radiance peak were found to occur only 5.4% of the time."

4. "Page 11321: The figure should be clarified, for example by expanding the caption. What do the red and black diamonds represent, and what is the difference between them? What is a "small DNI" mentioned in the caption? Results from USI are compared to results from which other method(s)? The caption says that the figure shows results from the DNI method, but the horizontal axis label says that it shows results from the MWR method. I guess the red diamonds represent DNI results and black diamond represent MWR results, but this is only a guess."

Response: Apologies for using the wrong captions in Fig.8-11. We have posted the correct captions in a previous short comment. We will make sure that the correct captions are used for the revised and final paper.

5. "My impression is that the described approach works only for single-layer liquid phase clouds. I recommend discussing the issue of applicability somewhere in the manuscript, perhaps by also mentioning some possibilities for identifying the situations where the approach can or cannot be applied."

Response: More discussion was added at the end of section 5 to address this concern.

"The RRBR method was derived based on SHDOM results for liquid clouds but the model could be extended to ice clouds with additional SHDOM runs. Fig. 10 demonstrates results from ice cloud simulations, with an effective radius of 100 μm. Ice clouds are not assessed in this paper as none of the methods used for validation provide information for ice clouds. In the presence of multiple-layer clouds the RRBR method represents the additive τ_c of all cloud layers."

Minor Comments

1. "Page 11288, line 2: Part of the text seems to be missing right after "Pincu". "

Response: The sentence has been corrected:

"To analyze this relation, the Spherical Harmonic Discrete Ordinate Method (SHDOM) (Evans et al., 1998; Pincus et al., 2009) is used to produce synthetic overcast sky images (Section 3) and analyze the determinants of sky imager radiances (Section 4)."

2. "Page 11288, line 20: I suggest changing the word "between" to something like "for all". I think this could help because my initial (incorrect) guess in reading the text was that the sentence was about the clear-sky gaps that lie between nearby contrails."

The wording has been changed in the manuscript.

"A fixed RBR threshold between clear sky and cloudy sky (Koehler et al. 1991) led to successful identification of opaque clouds but consistently failed to distinguish thin and clear skies."

3. "Page 11294, line 2: I suggest deleting the word "are". "

Response: The wording has been changed in the manuscript:

"Stray light leads to brighter pixel values than expected, which in turn can lead to misclassifications of clear sky as thin clouds (τ_c<3)."

4. "Page 11295, line 8: There are two equal signs at the solar zenith angle. "

Response: The wording has been changed in the manuscript.

"Note that all of the statements in Section 4 strictly only apply for the θ_0 and ϑ_z shown in the figure, but Figs. 4-6 indicate that the conditions θ_0= 60°, ϑ_s = 60°, ϑ_z = 60° are representative for a wide range of conditions."

5. "Page 11295, line 19: The phrase "consistent to" should be replaced by "consistent with". "

Response: The wording has been changed in the manuscript.

"The effects of θ_0 are intuitive and consistent with what is observed during a sunset and therefore not graphically presented; the red and blue radiance is observed to decrease with increasing θ_0."

6. "Page 11298, line 1: For consistency, I suggest including the index theta_0 for I_620_meas, or excluding it for I_620. The same applies lower in the page. "

Response: θ_0 was added for consistency throughout the paper.

"The algorithm begins by comparing $I_{620}^{meas}(\theta_0, \vartheta_s, \vartheta_z)$ against $\max\left(I_{620}(\tau_c, \theta_0, \vartheta_s, \vartheta_z)\right)$ (e.g 0.19 W m^{-2} sr^{-1}, nm^{-1} in Fig. 6a), where $I_{620}^{meas}(\theta_0, \vartheta_s, \vartheta_z)$ is the measured radiance in the camera's red channel."

7. "Page 11299, line 24: I suggest adding the word "sites" between "ARM" and Min". "

Response: Sentence was corrected as suggested.

"At the ARM site the Min τ_c is sampled and reported every 20 sec."

8. "Page 11300, Equation (9); I suggest replacing the symbols "[" and "]" by "" or perhaps using overbars, as these are more often used to indicate averaging. "

Response: The brackets have been replaced with overbars:

$$\tau_c = \exp(\overline{\log(\tau_c)}) .$$

9. "Page 11301, line 18: I suggest spelling out the acronym "MBE", which is not as widely used as the RMSE mentioned a few lines earlier. "

Response: The acronym definition has been added.

"A mean bias error (MBE) of -10.5% is observed demonstrating a tendency for the RRBR method to under predict τ_c."

10. "Page 11301, line 24: I suggest replacing the word "thicker" by "brighter", because the discussion suggests that clouds get outside the look-up table range due to 3-D effects rather than large thicknesses."

Response: The word "brighter " was added but "thicker" was also left since this is referring specifically to clouds that are thicker.

"For cloud that are brighter and thicker than the radiance peak (τ_c =7.25) this increased radiance along the sun-facing edge of the cloud results in an under prediction of τ_c."

11. "Page 11311: I suggest specifying in the table caption what RMSE[-], RMSE[%], MAE[%], and MBE[%] mean, and perhaps mentioning that the MWR and DNI data is for both overcast and partly cloudy skies."

Response: The table caption was changed to include the meaning of RMSE.

"Table 2. Statistics of RRBR validation against the Min method in overcast skies, microwave radiometer measurements, and DNI measurements from the MFRSR. RMSE[-] is the absolute root mean square error, RMSE[%]is the relative root mean square error, MAE[%]is the relative mean average error, and MBE[%]is the mean bias error."

12. "Page 11316: The caption or axis label of Figure 5 should say what PZA stands for."

Response: PZA was changed to ϑ_z which was previously defined.

13. "Page 11316: I recommend making the curves for various optical thicknesses easier to distinguish. The tau=0 and tau=10 curves are especially difficult to distinguish."

Response: The markers where changed on graphs,

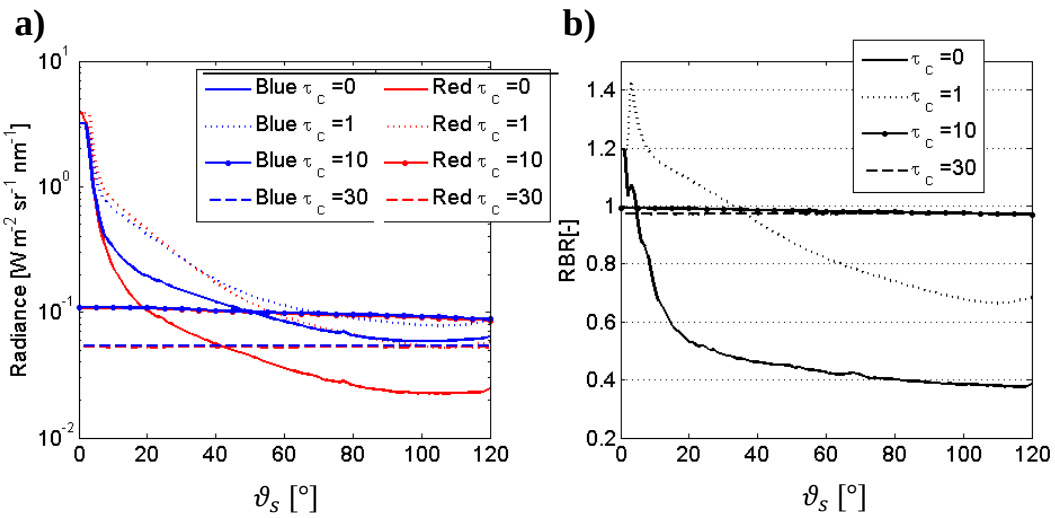

Fig. 4a) SHDOM red channel radiance over various sun pixel angles (ϑ_s) at ϑ_z = 60°, and θ_0= 60° (Pixels used for Fig. 4 are highlighted as a red line in Fig. 2c). Results are shown for different cloud optical depths from clear (τ_c = 0) to thick clouds. b) RBR as a function of ϑ_s at constant ϑ_z = 60° and θ_0= 60°.

14. "Page 11319: The caption should describe what each of the four panels show."

Response: The corrected caption is as follows:

"Fig. 8 (a) USI image for 25 March 2013, 22:10:00 UTC, (b) τ_c retrieval from RRBR method, Pixels inside the black ring are the pixels used for averaging and comparison with the MWR (Section 6.4) (c) $RBR^{meas}(\vartheta_s, \vartheta_z)$ and (d) $I_{620}^{meas}(\theta_0, \vartheta_s, \vartheta_z)$. For this scene, the MWR measured a τ_c of 0.56 and the USI measured a τ_c of 0.20, the highest τ_c within 10 minutes of this is 19.4 and 15.3 for the MWR and USI respectively."