Cirrus Heterogeneity Effects on Cloud Optical Properties Retrieved with an Optimal Estimation Method from MODIS VIS to TIR Channels.

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Abstract. This study presents preliminary results on the effect of cirrus heterogeneities on top-of-atmosphere (TOA) simulated radiances or reflectances for MODIS channels centered at 0.86, 2.21, 8.56, 11.01 and 12.03 μm, and on cloud optical properties retrieved with a research-level optimal estimation method (OEM). Synthetic cirrus cloud fields are generated using a 3D cloud generator (3DCLOUD) and radiances/reflectances are simulated using a 3D radiative transfer code (3DMCPOL). We find significant differences between the heterogeneity effects on either visible and near-infrared (VNIR) or thermal infrared (TIR) radiances. However, when both wavelength ranges are combined, heterogeneity effects are dominated by the VNIR horizontal radiative transport effect. As a result, small optical thicknesses are overestimated and large ones are underestimated. Retrieved effective diameter are found to be slightly affected, contrarily to retrievals using TIR channels only.

INTRODUCTION

The understanding of cloud impacts on the Earth energy balance is one of the most important challenges pointed out in the Intergovernmental Panel on Climate Change (IPCC) report ([1]). The A-Train mission, which combines many instruments with a large temporal and spatial coverage, is particularly well suited to study clouds. However, current global operational algorithms assume that observational pixels are homogeneous and independent of their neighbors. This unrealistic representation inevitably leads to retrieval errors. Many studies have been conducted to understand retrieval biases due to cloud heterogeneities, but mainly focus on liquid clouds (e.g. [3]; [4], etc.). Concerning cirrus clouds, [5, 6] show that horizontal inhomogeneity effects at 1 km in the thermal infrared (TIR) on top of atmosphere (TOA) brightness temperatures (BT) can exceed +10 K resulting in an overestimate of the retrieved cloud effective diameter (CED) by several tens of percent and underestimate the retrieved cloud optical thickness (COT) by up to 25%. In addition, [7] show that VNIR/SWIR and TIR retrieval techniques based on the vertically homogeneous column assumption may lead to underestimate the COT and CED of thin cirrus.

In this work, we estimate how the retrieval of cirrus optical properties based on an optimal estimation method (OEM) with five channels from the VNIR to the TIR can be impacted by the wavelength dependence of cloud heterogeneity effects at the scale of the 1 km. We first present the modeling tools, namely the cloud generator 3DCLOUD ([8]), the radiative transfer (RT) code 3DMCPOL ([9], [5]) and the OEM retrieval algorithm ([2]) as well as the cirrus case of study. Then we discuss on the differences of cloud heterogeneity effects between solar and thermal infrared channels, followed by retrieval results using different combinations of channels. Conclusions and perspectives close this paper.

MATERIALS AND METHODS

The 10 × 10 km cirrus field used in this study is is generated by the 3DCLOUD code ([8]). Fig. 1 (a) presents the optical thickness field at 12.03 μm and (b) illustrates the vertical distribution of the ice water content (IWC)) along the red line shown in (a). The 2D horizontal distribution of the IWC follows, at each vertical level, a power law of constant -5/3 exponent, in agreement with observations (e.g. [5]; [8]).
The parameterization of ice crystal single-scattering properties follows that of MODIS collection 6 (MOD06, [10]). One crystal habit (aggregate column) and effective size ($CED = 20\ \mu m$) are used for the whole cirrus.

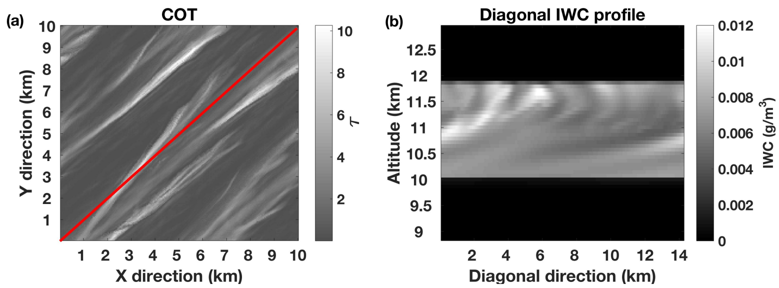

FIGURE 1. (a) 10 × 10 km cirrus cloud optical thickness (COT) field and (b) vertical profile of the ice water content (IWC) across the red line of (a). The mean COT is 1.4 at 12.03 μm, the heterogeneity parameter ($\rho_\tau = [\sigma_\tau / < \tau >] = 1.0$), the cloud top and base altitudes are 10 and 12 km, respectively and the spatial resolution is 50 m.

Radiative transfer (RT) computations are performed with the 3D Monte Carlo (MC) code, 3DMCPOL ([9], [5]). Atmospheric gases are parameterized using the correlated k-distribution ([11]). Fig. 2 shows the reflectance at 0.86 μm (a) and the BT at 12.03 μm (b) fields corresponding to Fig. 1. The RT is computed for 5 MODIS channels, centered at 0.86, 2.11, 8.52, 11.01 and 12.03 μm with the MC accuracy set up to the MODIS accuracy.

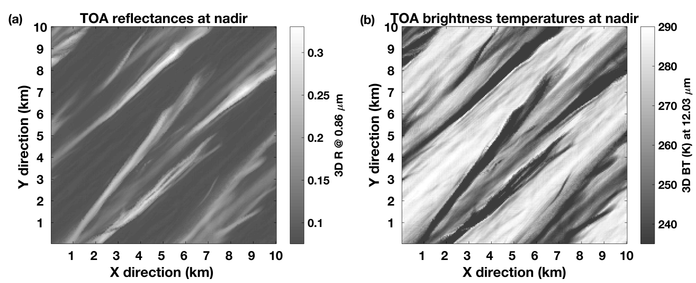

FIGURE 2. TOA nadir 3D reflectances (a) and brightness temperatures (b) estimated with 3DMCPOL for the cirrus of Fig. 1 (a)

Cloud optical properties (COT and CED) are retrieved by using the five-channels OEM code developed by [2] on 3D and 1D RT simulations by 3DMCPOL. The retrievals are obtained using either VNIR reflectances only (0.86 and 2.11 μm), TIR radiances only (8.52, 11.01 and 12.03 μm), or the 5 channels simultaneously (VNIR + TIR).

CLOUD HETEROGENEITY EFFECTS ON TOA RADIATIONS

The study by [5] show that, in the TIR, the plane parallel approximation bias (PPAB) on TOA radiances or BT are significantly larger than cloud vertical heterogeneities or horizontal transport of the Fictive Light Particle ([12]) between the cloudy columns. The PPAB comes from the non-linearity between radiative quantities according to the COT. Indeed, 3D radiative quantities computed for 3D heterogeneous optical property field and then averaged at a given scale are different from 1D radiative quantities of averaged 3D optical properties at the given scale. To highlight the impact of cirrus inhomogeneity effects we compare TOA simulated radiations from:

- 1D reflectances or radiances/BT computed directly at the 1 km MODIS spatial resolution (R_{1km}^{1D} and BT_{1km}^{1D})

- 3D reflectances or radiances/BT computed at 50 m and then averaged to 1 km ($R^{3D}_{50m-1km}$ and $BT^{3D}_{50m-1km}$)

R^{1D}_{1km}, $R^{3D}_{50m-1km}$ and BT^{1D}_{1km}, $BT^{3D}_{50m-1km}$ are plotted in Fig. 3 (a) and (b), respectively, as a function of the 1 km averaged optical thickness at 0.86 μm for a view at nadir. In Fig. 3 (a) we can see that for both channels (0.86 and 2.11 μm) $R^{3D}_{50m-1km} > R^{1D}_{1km}$ for optical thicknesses smaller than 1 and that $R^{3D}_{50m-1km} < R^{1D}_{1km}$ for optical thicknesses larger than 1.5. This effect is a consequence of the horizontal radiative transport (HRT, [3]). FLIPs scattered inside the optically thickest pixels of the cloud undergo a strong extinction decreasing their chance to escape the cloud from the top and do not contribute to the observed reflectance. But if they are horizontally transport to optically thinner columns then they have more chance to escape the cloud. As a result the reflectances of large optical thickness are reduced and those of small optical thicknesses increased. For viewing and solar geometries different from nadir and zenith, respectively, others effects may appear such as side illumination, shadowing, etc., but are not discussed here. In Fig. 3 (b) we can see that $BT^{3D}_{50m-1km} > BT^{1D}_{1km}$ due to the PPAB which increases with the optical thickness and depend on the wavelength. Heterogeneity effects between VNIR and TIR channels are thus very different. In the next section, we discuss how they may impact the cloud optical properties retrieved using a synergy of channels of different wavelength ranges.

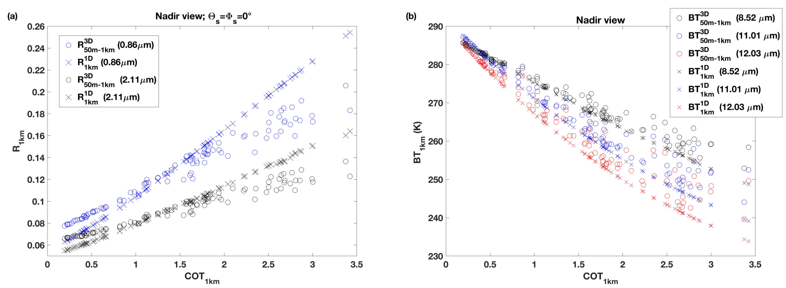

FIGURE 3. (a) Nadir reflectances for a sun at zenith at 0.86 μm and 2.11 μm and (b) nadir BT at 8.54 μm, 11.01 μm and 12.03 μm as a function of the 1 km optical thickness at 0.86 μm ($\tau^{0.86\mu m}_{1km}$) for 3D (circles) and 1D (crosses) computations.

HETEROGENEITIES EFFECTS ON OPTICAL PROPERTY RETRIEVALS

Cloud heterogeneities effects impact the TOA observed radiations and therefore the cloud optical property retrievals since operational algorithms assume the 1D homogeneous independent pixel approximation (IPA). Fig. 4 represents the COT ((a), (c) and (e)) and the CED ((b), (d) and (f)) retrieved from 1D and 3D RT as a function of the COT used for the RT. The top panel concerns TIR only retrievals, the middle panel concerns VNIR only retrievals and the bottom panel concerns retrievals using the five channels together ([2]). In the top panel, compared to 1D COT, 3D COT larger than 1 are strongly underestimated due to the PPAB ($BT^{3D}_{50m-1km}$ are larger than BT^{1D}_{1km}), and the effective diameter CED is overall overestimated and very scattered. Note that the 1D CED is also overestimated for small COT due to slight differences between atmospheric model used in the OEM and 3DMCPOL codes. For VNIR channels only, the HRT effect observed in Fig. 3 for 3D RT is also clearly present here (small COT are overestimated and the larges COT are underestimated). However, 3D CED are almost not affected, because heterogeneity effects impact similarly the bands at 0.86 and 2.11 μm at nadir (same arch of constant CED). Finally, the bottom panel (5 channels retrieval) is quite similar to the middle one and no significant improvements are observed. The COT is mainly impacted by the HRT effect and slightly by the PPAB increasing the underestimation for large COT. It can be noted that COT less than 1 are less impacted than in the VNIR case due to the TIR contribution. On the contrary, the 3D CED is much closer to the truth (20 μm) than for TIR retrievals only, thanks to the VNIR contribution. CED retrieval for small COT need however to be improved by a better constraint of the atmospheric profile.

CONCLUSIONS AND OUTLOOKS

Using a modeling approach, we have shown that cirrus cloud heterogeneity effects on TOA radiances and reflectances are very different between visible-near-infrared and thermal infrared wavelengths. For the 5 channel retrieval across

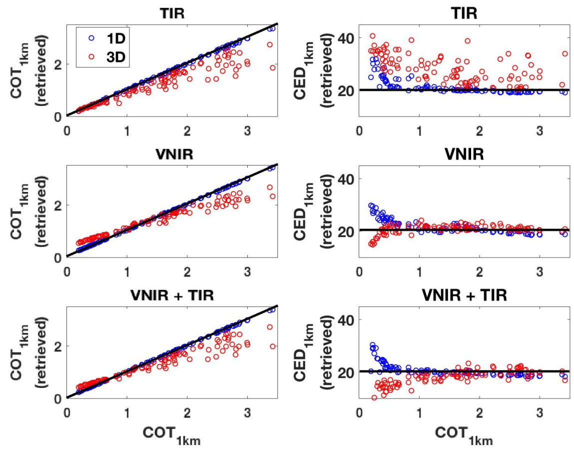

FIGURE 4. COT ((a), (c) and (e)) and effective diameter CED ((b), (d) and (f)) retrieved at 1 km from 1D and 3D RT as a function of the true COT at 0.86 μm. Top panel: retrievals using channels at 8.54 μm, 11.01 μm and 12.03 μm only, middle panel: retrievals using 0.86 μm and 2.11 μm channels only and bottom panel: retrievals combining the five channels together. Black lines correspond to the truths COT and CED values.

VNIR and TIR ranges at nadir, the VNIR HRT effect mainly dominates, leading to overestimate small COT and underestimate the large ones. CED are very affected by heterogeneities effects for retrievals using only TIR wavelengths but slightly affected when TIR and VNIR are combined. As a perspective, we will look at different viewing and solar geometries, spatial resolutions and study others cirrus cases where TIR heterogeneities could contribute relatively more (warmer surface, lower altitude).

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