

Scale dependence of cirrus heterogeneity effects. Part II: MODIS vNIR and SWIR channels

Thomas Fauchez^{1,2}, Steven Platnick², Tamás Várnai^{3,2}, Kerry Meyer², Céline Cornet⁴, and Frédéric Szczap⁵

¹Universities Space Research Association (USRA), Columbia, MD, USA

²NASA Goddard Space Flight Center, Greenbelt, MD, USA

³University of Maryland Baltimore County: Joint Center for Earth Systems Technology and the Department of Physics, Baltimore, MD, USA

⁴Laboratoire d'Optique Atmosphérique, UMR 8518, Université Lille 1, Villeneuve d'Ascq, France

⁵Laboratoire de Météorologie Physique, UMR 6016, Université Blaise Pascal, Clermont Ferrand, France

Correspondence to: Thomas Fauchez (thomas.j.fauchez@nasa.gov)

Abstract. In a context of global climate change, the understanding of the radiative role of clouds is crucial. ~~Ice clouds such as cirrus have, on average,~~ On average, ice clouds such as cirrus, have a significant positive radiative effect, ~~while in~~ but under some conditions ~~the effect~~ may be negative. However, many uncertainties remain ~~on~~ regarding the role of ~~this type of~~ ice clouds on Earth's radiative budget and in a changing climate. Global satellite observations are particularly well suited to monitor clouds, retrieve their characteristics and infer their radiative impact. To retrieve ice cloud properties (optical thickness and ice crystal effective size), current operational algorithms assume that each pixel of the observed scene is plane-parallel and homogeneous, and that there is no radiative connection between neighboring pixels. Yet, this retrieval representation is ~~these~~ retrieval assumptions are far from ~~the reality, where the~~ accurate, as real radiative transfer is 3D. This leading to the plane parallel and homogeneous bias (PPHB) ~~and~~ plus the independent pixel approximation bias (IPAB) ~~impacting~~ which impacts both the estimation of top of the atmosphere (TOA) radiation and the retrievals. An important factor that ~~constrains~~ determines the impact of these assumptions is the sensor spatial resolution. High spatial resolution pixels can better represent cloud variability (low PPHB), ~~but~~ though the radiative path through the cloud can involve many pixels (high IPAB). In contrast, low spatial resolution pixels poorly represent the cloud variability (high PPHB) but the radiation is better contained within the pixel field of view (low IPAB). In addition, the solar and viewing geometry (as well as cloud optical properties) can modulate the magnitude of the PPHB and IPAB. In this Part II of our study, we ~~have~~ simulated TOA 0.86 μm and 2.13 μm solar reflectances over a cirrus uncinus scene produced by the 3DCLOUD model. Then, 3D radiative transfer simulations are performed ~~by~~ with the 3DMCPOL code at spatial resolutions ranging from 50 m to 10 km, for twelve viewing geometries and nine solar geometries. It is found that, for simulated nadir observations taken at resolution higher than 2.5 km, horizontal radiation transport (HRT) dominates biases between 3D and 1D reflectance calculations, but ~~it is~~ these biases are mitigated by the side illumination and shadowing effects for off-zenith solar geometries. At resolutions coarser than 2.5 km, PPHB dominates. For off-nadir observations at resolutions higher than 2.5 km, the effect that we call THEAB (Tilted and Homogeneous Extinction Approximation Bias) due to the oblique line of sight passing through many cloud columns contributes to a large increase of the reflectances, but ~~other~~ 3D radiative effects such

as shadowing and side illumination for oblique Sun are also important. ~~Similar to nadir simulations, side illumination effects mitigate the HRT.~~ At resolutions coarser than 2.5 km, the PPHB is again the dominant effect. The magnitude and resolution-dependence of PPHB and IPAB is very different for visible, near-infrared, and shortwave infrared channels compared with the thermal infrared channels discussed in Part I of this study. ~~This strong wavelength dependency of cirrus cloud 3D radiative effects~~ The contrast of 3D radiative effects between solar and thermal infrared channels may be a significant issue for retrieval techniques that simultaneously use radiative measurements across a wide range of solar reflectance and infrared wavelengths.

1 Introduction

Clouds cover between 60% to 70% of the Earth's surface and are one of the principal actors in the Earth's radiative budget (Intergovernmental Panel on Climate Change (IPCC) assessment report 5 Boucher et al. (2013)). On average, they lead to a net radiative effect of about $-20 W \cdot m^{-2}$ (Ramanathan et al., 1989) but this estimation depends on the global circulation model (GCM, Lane et al. (2000); Dufresne and Bony (2008)). It is therefore necessary to better understand clouds and their interaction with radiation. As part of the wide diversity of clouds, high altitude clouds such as cirrus play an important role in the climate and ~~on~~ the Earth's radiation budget (Hartmann and Short (1980); Ohring and Clapp (1980); Liou (1986); Stephens (2005); Eguchi et al. (2007)). ~~They~~ Cirrus cover a large part of the Earth's surface (15 % to 40 %, Sassen et al. (2008)) and their high altitude implies a large temperature difference between the cloud top and Earth's surface temperature. Such large difference produces an efficient greenhouse effect by trapping part of the infrared radiation emitted by the surface. Meanwhile, part of the incident solar radiation is reflected to space due to the albedo effect, particularly when the optical thicknesses is large (greater than 10 (Choi and Ho, 2006)). Most of the cirrus clouds are optically thin (optical thickness less than 3 at 532 nm, Sassen et al. (2008)), leading to an average positive radiative effect (e.g., a greenhouse effect) of about $+28 W \cdot m^{-2}$ (Boucher et al., 2013). However, their radiative impact depends on numerous factors, such as cloud altitude (Corti and Peter, 2009), cloud thickness (Jensen et al., 1994), crystal shape and size parameter (Min et al., 2010) and temperature (Katagiri et al., 2013). Furthermore, in contrast to the light scattering by spherical water droplets which can be solved using the Mie theory, there is no exact solution for ice crystal scattering due to the multiplicity of crystal sizes and shapes (Lynch et al. (2002)).

Passive satellite sensors are well suited for global temporal and spatial observations of clouds, but the number of retrievable cloud parameters is limited, ~~on the one hand,~~ by the information content of the radiative measurements ~~and, on the other hand, by the retrieval methods.~~ Cloud optical thickness (COT) and cloud effective particle radius (CER) can be retrieved from space-based radiometric measurements using dedicated operational algorithms. Most algorithms are developed for solar-reflectance bands, like the operational algorithm of the Moderate Resolution Imaging Spectroradiometer (MODIS, Platnick et al. (2017)) for the MOD06 product; Minnis et al. (2011) for the CERES product). Currently, operational constraints such as time constraints or the lack of information regarding the 3-three-dimensional (3D) structure of clouds necessitate the use of a simplified cloud when operationally retrieving cloud properties. In one approach for processing the observations from an area, clouds are considered flat and homogeneous over the entire area. This hypothesis is named known as the homogeneous plane parallel approximation

(PPHA, Cahalan et al. (1994)). If each cloudy pixel is considered flat, homogeneous and independent of its neighbors, this is called the homogeneous independent pixel approximation (IPA, Cahalan et al. (1994)) or homogeneous independent column approximation (ICA, Stephens et al. (1991)). Such representation implies that no interaction between pixels or cloudy columns is taken into account between the assumed homogeneous pixels. This is often far from the reality, where clouds have complex
5 three-dimensional and heterogeneous structures and where the radiative transfer occurs in 3D, and this can lead to errors in cloud property retrievals.

Therefore, a means for quantifying the impact of realistic cloud heterogeneities is necessary to begin to understand potential cirrus retrieval errors. Numerous studies have examined this issue for cloud products derived from solar spectral reflectance
10 measurements, but mainly for warm liquid water clouds (e.g. stratocumulus clouds). Indeed, Varnai and Marshak (2001); Zinner and Mayer (2006); Kato and Marshak (2009) and Zhang and Platnick (2011) (and references therein) have shown that neglected cloud horizontal and vertical inhomogeneities can lead to ~~an~~ erroneous albedo ~~of~~On top of the atmosphere (TOA) reflectances estimates, depending on numerous factors such as sensor spatial resolution, the wavelength range, observation geometry, and cloud type, etc. ~~Concerning~~Regarding cirrus clouds in the solar spectral range, Buschmann et al. (2002) found
15 that, for cirrus clouds with mean optical thicknesses smaller than 5 and with relative optical thickness variances smaller than 0.2, retrieval errors due to the cloud homogeneous assumption are smaller than $\pm 10\%$. Carlin et al. (2002) showed that, due to horizontal cirrus inhomogeneity, both solar albedo and outgoing long wave radiation biases could reach $15 \text{ W} \cdot \text{m}^{-2}$ in magnitude. Using spectral irradiance measurements below and above tropical cirrus, Schmidt et al. (2009) showed that solar radiation in the visible wavelength range is significantly decreased due to net horizontal radiation transport, especially near cloud edges.
20 Zhang et al. (2010) showed that the vertically homogeneous column assumption used in solar reflectance bi-spectral and thermal infrared retrieval techniques may lead to underestimates of COT and CER of thin cirrus due to the non-linear dependence of ice crystal scattering properties on the effective size. More recently, Fauchez et al. (2012, 2014) showed that 3D thermal infrared (TIR) brightness temperatures (BT) at TOA can be up to 15 K greater than those computed from a 1D radiative transfer code. (Fauchez et al., 2016) have also showed that, at nadir, 3D radiances are larger than their 1D counterparts for direct
25 emission but smaller for scattered radiation. They have also developed a hybrid model based on exact 3D direct emission, the first scattering order from 1D in each homogenized column, and an empirical adjustment which is linearly dependent on the optical thickness to account for higher scattering orders to drastically reduce the 3D RT computational time. Concerning cirrus cloud optical property retrievals, Fauchez et al. (2015) showed that cirrus heterogeneity effects can significantly ~~influence cirrus optical property retrievals~~impact them (up to 20% for COT and 100% for CER retrievals) at the 1 km scale of MODIS TIR
30 observations while Zhou et al. (2016) have found similar values for COT retrieved from solar reflectance-based retrievals. In the TIR, TOA BT differences and retrieval errors due to cloud inhomogeneities and 3D effects ~~are mainly dependent~~depend mainly on the standard deviation of optical thickness within a 1 km pixel. ~~Thus~~. At the 1 km scale, the differences between 3D TIR radiative transfer from heterogeneous pixels and 1D radiative transfer from homogeneous pixels are mainly dominated by ~~the failure of~~ the PPHB.

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Most of these previous studies have been performed at the typical 1 km nadir spatial resolution of polar orbiting imagers. H: however, the impact of the cloud homogeneous assumption depends on the scale at which the cloud is considered homogeneous. For liquid water clouds Davis et al. (1997) have examined cloud heterogeneities as a function of scale for stratocumulus clouds. They ~~highlighted~~found that the impact of the cloud inhomogeneities on the optical thickness retrieval is at a minimum around 1 km - 2 km resolution. ~~Indeed,~~ On the one hand, the 3D radiative impact increases at finer spatial resolutions because the photon mean path becomes as large or larger than the pixel size. ~~On the other hand,;~~ conversely, at coarser spatial resolutions, the plane parallel and homogeneous bias (PPHB) is enhanced because the pixel becomes larger than the homogeneity scale. In addition, Zhang et al. (2012) showed that at 100 m spatial resolution, ~~3-D radiative transfer effects on CER retrieval, such as side illumination and shadowing, are much larger at 2.1 than 3.7 μm but because side illumination and shadowing effects almost cancel out each other, there is an overall agreement between CER retrieved based on 2.1 or 3.7 μm .~~ 3D radiative transfer effects, such as side illumination and shadowing, can produce significant differences between CER retrievals based on either 2.1 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 than on 3.7 μm , leading to positive difference between the two from cloud side illumination and a negative difference from cloud shadowed side. However, these two opposite effects cancel each other out on the domain average, leading to an overall statistical agreement between the CER retrievals. ~~However~~ Yet, at resolutions similar to MODIS, while ~~both~~ the two 3D effects cancel each other out, CER retrieved at 2.1 μm is systematically larger than the CER retrieved at 3.7 μm when averaged over the ~~LES~~ domain because of cloud horizontal inhomogeneity (PPHB). These results are important for assessing the overall retrieval errors from various space-borne imagers having different spatial resolutions and determining, if possible, which resolution is better to mitigate the effects of cloud heterogeneities on radiance measurements.

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In Part I of our study, Fauchez et al. (2017a) discussed the impact of ice cloud (cirrus) heterogeneities as a function of pixel size by simulating MODIS thermal infrared channel measurements. It was shown that the spatial resolution range where the combination of heterogeneity and 3D effects is at its minimum falls between 100 m and 250 m. In Part II of this study, we focus our attention on simulating MODIS visible-near-infrared ($\forall\text{NIR}$) and shortwave infrared (SWIR) reflectance measurements in ~~the~~ the 0.86 μm and 2.13 μm MODIS channels, respectively; these channels are currently used to retrieve cloud optical properties over water surfaces in the operational MODIS cloud product MOD06 (Platnick et al., 2017). ~~Effects~~ The effects of cloud heterogeneity are studied for different viewing and solar angles as a function of spatial resolutions ranging from 50 m to 10 km.

In the next section, we briefly describe the cloud generator model 3DCLOUD (Szczap et al. (2014)) and the 3D radiative transfer model 3DMCPOL (Cornet et al. (2010), Fauchez et al. (2012, 2014)) used to simulate ~~the~~ 3D radiative transfer for heterogeneous cirrus clouds. In Section 3 we describe the cloud heterogeneity effects for solar reflectance channels. ~~In~~ and in section 4, we study the dependence of horizontal heterogeneity effects on spatial resolution and observation geometry. Our summary and conclusions are given in Section 5.

2 Simulation of 3D radiative transfer through a realistic 3D heterogeneous cirrus field

The single cirrus field modeled in this paper is identical to the one presented by Fauchez et al. (2017a) in Part I. This allows comparisons of ~~those~~ TIR results presented in Part I (Fauchez et al., 2017a) with the ~~v~~NIR/SWIR results in this Part II. The cirrus field is modeled with the 3DCLOUD (Szczap et al. (2014); Alkasem et al. (2017)) ~~model that simulates 3D cloud structures~~
5 ~~by assimilating meteorological profiles and by solving simplified basic atmospheric equations~~code for a mid-latitude summer atmosphere profile (see Fauchez et al. (2017b) Fig. 2) . The scale invariant properties observed for clouds are ~~then~~ constrained by 3DCLOUD using a Fourier filtering method to follow a -5/3 spectral slope (Hogan and Kew (2005), Szczap et al. (2014)) ~~using a Fourier filtering method~~. This method ensures that the horizontal variation of the ice water content (IWC) is consistent with observations (Hogan and Kew (2005); Fauchez et al. (2014)).

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The radiative transfer simulations are then performed using the 3DMCPOL Monte Carlo radiative transfer (RT) code (Cornet et al. (2010), Fauchez et al. (2014)) assuming cyclic boundary conditions are imposed at the edges of the domain. Cirrus optical properties are parameterized using the same microphysical model assumed by the MODIS Collection 6 (MOD06) cloud product, namely the severely roughened single-habit column aggregate from Yang et al. (2013). The domain mean optical thickness
15 of the 3DCLOUD cirrus is 1.5 at 0.86 μm , and the cloud is assumed to have a constant CER of 10 μm . Note that while the microphysical properties are homogeneous, the extinction coefficient varies horizontally and vertically. The optical properties of the assumed ice crystals used at two MODIS channels are shown in Table 1.

Solar reflectances are computed with 3DMCPOL for MODIS channel 2 (centered at 0.86 μm) and 7 (centered at 2.13 μm).
20 Five solar geometries are considered: ($\Theta_s = 0^\circ$; $\Phi_s = 0^\circ$), ($\Theta_s = 30^\circ$; $\Phi_s = 0^\circ$, 90° and 180°) and ($\Theta_s = 60^\circ$; $\Phi_s = 0^\circ$) with Θ_s and Φ_s corresponding to solar zenith and azimuth angles, respectively. For each of these ~~angle~~solar directions, reflectances are computed for twelve viewing geometries~~are computed~~: three viewviewing zenith angles ($\Theta_v = 0^\circ$, 30° and 60°) withand four viewing azimuth angles each: ($\Phi_v = 0^\circ$, 45° , 90° and 180°). The azimuths of viewing angles relative to the cirrus field are represented in Figure 1. This figure shows the cirrus cloud field simulated by 3DCLOUD based on the mid latitude summer
25 meteorological profiles already used in Fauchez et al. (2017b). No aerosol is added and the surface is Lambertian with a constant albedo of 0.05. Top panels show the vertical profiles of ice water content (IWC) along the red lines in the optical thickness field, which is shown in the bottom panels for different viewing angles. Note that the cirrus vertical profile looks very different ~~as a function of the viewing geometry~~along different azimuths. The wind direction is following the $\Phi_v = 45^\circ$ arrow leading to clearly visible virga features at this angle. Note that the azimuth view angles $\Phi_v = 225^\circ$ and 270° are shown on this figure~~for comparison~~
30 ~~to other angles~~, but reflectances are not computed for these viewing azimuths due to computational time reasonslimitations.

Figure 2 (a) shows the cirrus optical thickness field at 0.86 μm at 50 m spatial resolution, and Fig. 2 (b) shows the corresponding 3D reflectance field at nadir. ~~100~~One hundred billions of fictive light particles (FLIPs (Pujol, 2015), referenced hereafter as photons) are computed in ~~13 hours~~3.5 days on 2048 parallel cores of the NCCS discover supercomputer (see ac-

knowledgements) for 3D computations of solar reflectances within an accuracy of about 0.1%.

3 Decomposition of the effects of cloud heterogeneity and 3D radiative transfer on simulated reflectances

Clouds are complex 3D structures where solar and terrestrial radiation follow 3D paths propagate in a three-dimensional space.

5 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 and vertically 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 bias 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).

15 To study cirrus heterogeneities that can affect solar reflectances, we simulate 1D solar reflectances with 3DMCPOL following the common homogeneous IPA retrieval assumption. COT is first averaged from the highest spatial resolution (50 m) to the spatial resolution of interest (up to 10 km) before performing the 1D RT calculations. Conversely In turn, 3D reflectances are always computed at 50 m resolution and are then aggregated to a given spatial resolution (from 50 m to 10 km). The difference ΔR between 3D and 1D reflectances obtained this way corresponds to the combined impact of cloud heterogeneities and 3D RT total bias including sub-pixel cloud heterogeneities and IPA biases on the TOA reflectances.

25 However To go further, it is useful to distinguish the following the amplitude and scale of the different effects and radiative processes that impact cloud-top reflectances when 3D RT inside heterogeneous pixels are compared to 1D RT inside homogeneous pixels the homogeneous and IPA assumption are used:

1. The Plane-Parallel and Homogeneous Bias assumption (PPHB);
2. Optical property Radiative impact of vertical inhomogeneity (not considered here);
3. The Tilted and Homogeneous Extinction Approximation Bias (THEAB); and
4. 3D radiative effects due to the non-radiative non-independence of the pixels.

30 **Plane-parallel and homogeneous assumption bias (PPHB):** In current operational satellite retrieval algorithms, the scene within each observed pixel is assumed to be horizontally homogeneous. The impact of the sub-pixel horizontal heterogeneity

clearly depends on the sensor spatial resolution (Oreopoulos and Davis, 1998). In Fig. 3 we plot the reflectances R_{50m}^{1D} estimated with a 1D RT calculation at 50 m for 0.86 μm and 2.13 μm channels, respectively, as a function of the 50 m optical thickness at 0.86 μm at 50 m. We see that the relation between reflectance and optical thickness is increasing (the thicker is the cloud, the more light is reflected) but is non-linear. Indeed, ~~between two reflectances R_{1D_1} and R_{1D_2} , the averaged reflectance, $\overline{R_{1D}}$ corresponds to a smaller optical thickness than the averaged optical thickness corresponding to the two reflectances~~ the reflectance of the averaged optical thickness $R_{\overline{COT}}$ is larger than the average reflectance of the optical thicknesses $\overline{R_{1D}}$. This is the Jensen's inequality (Newman et al., 1995), usually called the plane-parallel and homogeneous bias (PPHB, Cahalan et al. (1994); Cahalan et al. (1995), Oreopoulos and Davis (1998)). Note that we plot 1D but not 3D reflectances ~~and not 3D ones only~~ specifically to highlight the effect of the PPHB.

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Vertical inhomogeneity (not considered here): For the same optical thickness, the vertical distribution of the ice crystal CER and IWC may have an impact on TOA reflectances and ~~retrieved CER~~ cloud retrievals. For instance, Zhang et al. (2010) showed that the vertically homogeneous column assumption used in solar reflectance bi-spectral and thermal infrared retrieval techniques may lead to underestimates of COT and CER of thin cirrus due to the non-linear dependence of ice crystal scattering properties on the effective particle size. However, ~~because in this study since~~ we are interested in the impact of the space sensor horizontal spatial resolution on TOA ~~v~~NIR/SWIR reflectances, we do not consider the vertical heterogeneity.

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Tilted and homogeneous extinction approximation bias (THEAB): This effect concerns off-nadir viewing geometries. At the spatial resolution of a spaceborne imager, the tilted line of sight ~~can~~ cross several atmospheric columns above the surface for a single observed cirrus pixels, while in the operational algorithms, each cloudy column is assumed horizontally infinite and homogeneous. More detailed explanation will be given on section 4.3 but this effect can lead to a smoothing of the radiative field from an sideview because each line of sight encounters many cloudy columns and voxels (pixel in volume) of various optical properties. This is shown in Fig. 4 where we can see the oblique line of sight crossing voxels of various extinction while the IPA considers only the column underneath the observe pixel. The THEAB column, which is then uprighted, is therefore different from the IPA column. Note that both column has the same vertical extension, but for the THEAB the extinction in each voxel has been adjusted to account for the longer oblique path. ~~and overall the total optical path along each line of sight is equivalent leading on average, to a more homogeneous view~~ Statistically, each line of sight will cross voxels with a wide range of extinction along its path leading to similar total optical paths between each of these line of sight. ~~See for example~~ (e.g. Várnai and Davies (1999); Varnai and Marshak (2003), Kato and Marshak (2009)).

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3D radiative effects: In addition to the impact of the heterogeneity in the cloudy column, the IPA can lead to significant retrieval errors due to the horizontal photon transport between nearby columns (Várnai and Davies (1999); Varnai and Marshak (2001, 2003); Marshak and Davis (2005), Oreopoulos and Cahalan (2005), Kato and Marshak (2009), etc.). Indeed, for 3D radiative transfer, photons can cross several cloudy columns having different optical properties, though horizontal transport depends strongly on particle absorption and ~~so~~ can vary widely between ~~v~~NIR and SWIR imager channels for the same pixel

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(e.g., Platnick (2001)). ~~Several~~Three distinct categories of 3D effects are worth mentioning:

1. **Horizontal radiation transport (HRT)** (Davies (1978), Kobayashi (1993), Davis and Marshak (2001), Várnai and Davies (1999); Varnai and Marshak (2003)): photons can be transported from one cloud column to another. Marshak et al. (1995) ~~have~~ determined that the radiative smoothing scale L due to photon horizontal transport (or photon diffusion) is expressed by $L = H \times \sqrt{(1-g)COT}$ where H is the cloud geometrical thickness, COT the optical thickness and " g " the asymmetry parameter of the phase function. ~~It has been found that~~Horizontal transport leads to the escapes of photon's escapes from the cloud (leakage effect) ~~are concentrated~~ where the optical thickness is the thinnest because first, photons in thin columns have less chance to be absorbed or scattered toward another column, and second, because photons in neighboring columns with stronger scattering have ~~more~~a higher chance to leave the cloud if they are scattered toward a neighboring column with a smaller extinction coefficient. Therefore, the net flux of photons tends to flow from thick to thin regions. This is illustrated in Fig. 5 where are plotted 3D and 1D Nadir reflectances at 1 km as a function of the optical thickness and where we can see that the 1 km reflectances are smaller in 3D than in 1D for large COT while the opposite is true for small COT. This increases the reflectance of optically thin pixels and decreases the reflectance of optically thick ones. This is confirmed by Fig. 6 (a) that shows nadir reflectances at 50 m (R_{50m}) as a function the optical thickness $\tau^{0.86 \mu m}$ in 3D and 1D for channels centered at $0.86 \mu m$ and $2.13 \mu m$ for a solar zenith angle of $\Theta_s = 0^\circ$. For zenith sun we can see that, due to the HRT, for small $\tau^{0.86 \mu m} (\leq 2)$, 3D reflectances are larger than 1D reflectances while for larger $\tau^{0.86 \mu m}$, 3D reflectances are smaller than 1D reflectances ~~due to the HRT~~. We note that HRT, as described above, dominates only for not too tilted sun ($\Theta_s = 0^\circ$ for Fig 6a and $\Theta_s = 30^\circ$ for 6b). For oblique sun (Fig 6c), 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.
2. **Side illumination effect** (Wendling (1977), Varnai and Marshak (2003), Zhang et al. (2012)): ~~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.6 (c) for which most of the 3D reflectances are larger than 1D reflectances.~~This effect occurs when photons of the incoming sunlight travel obliquely and enter a cloud through its side, rather than the top. In contrast to the HRT, side illumination tends to increase the reflectance of thicker clouds for backward and overhead viewing directions (Loeb and Davies, 1996) as we can see in Fig. 6 (c), where most of the 3D reflectances are larger than 1D reflectances.
3. **Shadowing effect** (L. H. Chambers (1997), Zuidema and Evans (1998), Varnai and Marshak (2003), Zhang et al. (2012)): ~~As for~~Similarly to side illumination, this effect occurs when sunlight incoming solar photons traveled slantwise diagonally, but this time, photons first reach a cloudy column with a large extinction, depriving which blocks neighbor cloudy columns from incoming photons from reaching the thinner columns behind it ("upward trapping" process illustrated in Fig 5a of Varnai

and Davies (1999)). ~~Note that 3D reflectances are closer to 1D reflectances values for $\Theta_s = 60^\circ$ (Fig. 6c) than for an overhead sun (Fig. 6a) for this range of optical thickness.~~

The first 3D effect acts to smooth the radiation field structure, whereas the second and the third effects lead to a roughening effect of the radiation field. Smoothing is an isotropic effect accounting for large scattering orders, whereas roughening ~~acts~~ occurs mainly in the solar plane by affecting direct and low order scattered sunlight (Zuidema and Evans (1998); Varnai and Marshak (2003); Oreopoulos and Cahalan (2005)). Also, the side illumination effect is usually larger than the shadowing effect (Varnai and Marshak (2003)). ~~On average, columns with large optical thickness are more highlighted from the side but they also block part of the photons from reaching the neighboring columns.~~

Note that all of these effects are dependent on the cloud optical thickness heterogeneity, the vertical inhomogeneity of the volume extinction, the variation of the cloud top and base altitude (always considered flat in our study) as well as the solar and viewing angles. ~~All combined together,~~ The total effect due to cloud inhomogeneity and 3D radiative transfer ~~are~~ is therefore very complex and dependent on the spatial resolution.

4 Cirrus horizontal inhomogeneity and 3D effects as a function of the observation scale

4.1 ~~Horizontal heterogeneity and 3D effects~~ Overall differences between 3D and 1D reflectances

In nature, radiative transfer occurs in 3D not in 1D. ~~Therefore, in addition to the PPHB,~~ 3D radiative effects influence the spectral reflectance of a given pixel due to its radiative connection between to its neighbors. These 3D effects includes ~~various effects such as~~ the HRT between cloudy columns or side illumination and shadowing effect for oblique Sun illumination. To compare reflectances ~~issue~~ from a 3D radiative transfer through a heterogeneous pixel with reflectances from the 1D homogeneous pixel assumption, we estimated the arithmetic mean difference between aggregated 3D at x km and ~~non-aggregated (coarser resolution)~~ 1D reflectances of the mean optical thickness at x km, with respect to the 3D aggregated reflectance in percentage, as follows:

$$\frac{\Delta R(\overline{3D} - 1D)}{\overline{R^{3Dxkm}}} (\%) = \frac{100}{\overline{R^{3Dxkm}}} \times \left[\sum_{i=1}^N (\overline{R^{3D}xkm} - R^{1Dxkm}) \right] / N, \quad (1)$$

~~with where~~ $\overline{R^{3D}xkm}$ is the averaged of 3D radiances reflectances computed at 50 m resolution, R^{1Dxkm} is the 1D radiances reflectances computed at for the optical thickness averaged over x km and N is the number of pixels at the spatial resolution x km. Note that ~~because the PPHB is already included in Eq. 3,~~ the comparison here shows the total bias including how the nonlinearity of the relationship between reflectance and optical thickness, ~~combined with and the~~ 3D radiative effects ~~and solar geometries,~~ affects TOA reflectances for a given view angle and spatial resolution.

Some effects such as the HRT may have almost ~~nil effect~~ no impact on average reflectances but locally, at the pixel scale, they may have large positive and negative ~~magnitudes~~ effects. We therefore estimate the mean absolute magnitude of the total

effect by calculating the absolute mean difference between aggregated 3D and ~~non-aggregated~~ 1D reflectances, relative to the 3D aggregated reflectance in percentage, as follows:

$$|\overline{\Delta R(3D - 1D)}| (\%) = \frac{100}{R^{3Dxkm}} \times \left[\sum_{i=1}^N (|R^{3Dxkm} - R^{1Dxkm}|) \right] / N, \quad (2)$$

Figure 8 shows $\overline{\Delta R(3D - 1D)}$ (panels (a), (b) and (c)) and $|\overline{\Delta R(3D - 1D)}|$ (panels (d), (e) and (f)) at $0.86 \mu m$ as a function of the spatial resolution (ranging from 50 m to 10 km), for various viewing and solar angles. First of all, we see that $\overline{\Delta R(3D - 1D)}$ is on-average negative for most of the spatial resolutions, viewing and solar angles and is larger than the 3% MODIS reflectance measurement uncertainty, mainly due to the HRT (see Fig. 6) and PPHB for optical thicknesses larger than 5 (see Fig. 3). However, at $\Theta_v = 60^\circ$ we see that $\overline{\Delta R(3D - 1D)}$ changes sign. This is because the THEAB, which is a positive bias, is stronger at high resolutions and large view angles (see Fig. 13). Indeed, as previously stated, in 3D RT the HRT acts mostly by moving photons from thick to thin areas leading to an increase of reflectances for small optical thicknesses and a decrease of reflectances for large optical thicknesses in comparison to 1D RT. Furthermore, $|\overline{\Delta R(3D - 1D)}|$ is, on average, decreasing with Θ_s (except at $\Theta_v = 60^\circ$; $\Phi_v = 180^\circ$), because the PPHB is stronger (at coarser resolutions, cf. Fig. 11 (d), (e) and (f)) and because the HRT from thick to thin areas is mitigated by the side illumination effect (at higher spatial resolutions). In 3D, the side illumination effect leads many photons to be first intercepted by thick regions, without reaching thin regions, contrary to cases with an overhead Sun. In turn, this leads to a larger reflectance in thick regions and to a smaller reflectance in thin regions, but on average, 3D reflectances at $\Theta_s = 60^\circ$ are closer to 1D reflectances than for an overhead Sun (see Fig. 7 for illustration). For nadir view, $\overline{\Delta R(3D - 1D)}$ and especially $|\overline{\Delta R(3D - 1D)}|$ tend to be the smallest for nadir view because of no THEAB see explanation in section 4.3, and they are almost constant over the wide ranges of spatial resolutions and Θ_s . For oblique views, the larger the viewing zenith view angle Θ_v , the larger is $\overline{\Delta R(3D - 1D)}$ and $|\overline{\Delta R(3D - 1D)}|$ (see THEAB in section 4.3), except for $\Phi_v = 45^\circ$. This view is directly parallel to the fallstreaks of the cirrus, where the variability along the line of sight is the smallest (see Fig. 1 (b) and (e)). We can also see that due to the THEAB, $\overline{\Delta R(3D - 1D)}$ is positive for $\Theta_v = 60^\circ$ for several Φ_v for the highest finest spatial resolutions (see section 4.3 on the THEAB). Indeed by comparing these results with those of Fig. 13, we can see that, for spatial resolutions below 1 km, the THEAB is the dominant effect for large solar zenith angles. The absolute THEAB effect $|\overline{\Delta R(1D.o.e - 1D)}|$ is even larger than the total effect $|\overline{\Delta R(3D - 1D)}|$ which is reduced by the radiative smoothing.

Figure 9 is the same as Fig. 8 but for $2.13 \mu m$ reflectances, shows $\overline{\Delta R(3D - 1D)}$ (panels (a), (b) and (c)) and $|\overline{\Delta R(3D - 1D)}|$ (panels (d), (e) and (f)) at $2.13 \mu m$ as a function of the solar zenith angle Θ_s for and for various viewing angles. Comparing with Fig. 8 for $0.86 \mu m$ reflectances we can see that the amplitude of $\overline{\Delta R(3D - 1D)}$ and $|\overline{\Delta R(3D - 1D)}|$ are smaller at $2.13 \mu m$ for low solar zenith angles ($\Theta_s = 0$ and 30°) very similar. Indeed, because of the larger cloud absorption in the SWIR channel, the HRT is reduced. But at $\Theta_s = 60^\circ$ the cloud extinction is also strong at $0.86 \mu m$, leading to similar $\overline{\Delta R(3D - 1D)}$ and $|\overline{\Delta R(3D - 1D)}|$ amplitudes. Because the effects are similar between the VNIR and SWIR channels of this similarity between the effects on NIR and SWIR reflectances, in the later figures we only focus on the VNIR channel centered $0.86 \mu m$ to avoid overloading the manuscript.

In Fig. 10, we can see the influence of the solar azimuth angle on $\overline{\Delta R}$ and $|\overline{\Delta R}|$. For this particular cloud geometry, the largest $\overline{\Delta R}$ and $|\overline{\Delta R}|$ is for a solar azimuth angle $\Phi_s = 180^\circ$ because the side illumination effect is the strongest in forward scattering. The weakest absolute effect

$\overline{|\Delta R|}$ is for a solar azimuth angle $\Phi_s = 0^\circ$. However, the differences are relatively small over the solar azimuth angles because each of the three angles highlights the cirrus fallstreaks obliquely (see Fig. 1 to compare with viewing angles). Indeed, while cirrus clouds with fallstreaks are particularly heterogeneous as highlighted/illuminated from different solar azimuth angles, the relative small optical thickness of cirrus does not lead to large azimuthal dependency.

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~~Like other effects, the importance of 3D effects is dependent on the spatial resolution. It is complicated to represent their relative effect since they can either increase or decrease the reflectances (smoothing by HRT or roughening by side illumination and shadowing). However, the mean deviation due to 3D effects at each spatial resolution can be obtained by subtracting the absolute value of PPHB ($|\overline{\Delta R}(\overline{1D}_{50m} - 1D)|$), the THEAB being already included in the PPHB) from the total absolute mean difference $|\overline{\Delta R}(\overline{3D} - 1D)|$ such as 3D effects = $|\overline{\Delta R}(\overline{3D} - 1D)| - \text{PPHB}$. Figure ?? represents the absolute values |3D effects| as a function of the spatial resolution for solar angles Θ_s from 0 to 60° with the solar azimuth angle set at $\Phi_s = 0^\circ$ and for a various view angles. In contrast to the PPHB, 3D effects are large for small pixel sizes and then decrease with coarsening spatial resolutions. Indeed, at small pixel sizes, photons with a given mean free path can cross a lot of pixels. Comparing with the absolute THEAB in Fig. 13, the absolute 3D effects are slightly smaller follow the same decreasing with coarsening spatial resolutions. Note that the dependence on the view azimuth angle is due to the fall streak structure of this particular cirrus field.~~

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15 4.2 Plane parallel and homogeneous bias

When all the various effects relative to pixel optical property inhomogeneity, radiation transport, and oblique viewing geometry act together, it is difficult to separate their relative contributions. Following Varnai and Marshak (2003), the horizontal inhomogeneity effects due to the PPHB can be isolated from 3D effects by using 1D radiative transfer calculations. Nadir 1D reflectances aggregated from the native spatial resolution (50 m) can be compared to reflectances computed at a given spatial resolution following the homogeneous pixel assumption. This difference, relative to the 3D aggregated reflectance in percentage, is expressed by Eq. 3, and is shown in Fig. 11.

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$$\overline{\Delta R}(\overline{1D} - 1D) (\%) = \frac{100}{R^{3Dxkm}} \times \left[\sum_{i=1}^N (\overline{R^{1D}xkm} - R^{1Dxkm}) \right] / N, \quad (3)$$

where $\overline{R^{1D}xkm}$ and $\overline{R^{3D}xkm}$ denotes the averaged 1D and 3D reflectances, respectively, computed at 50 m and R^{1Dxkm} is the 1D radiance computed for the averaged optical thickness of x km-size areas.

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The finest spatial resolution for this figure is at 100 m because at 50 m (native spatial resolution) there are no aggregated reflectances. As we can expect $\overline{\Delta R}(\overline{1D} - 1D)$ is negative, the PPHB increases overall as the spatial resolution/pixel size increases with the largest $\overline{\Delta R}(\overline{1D} - 1D)$ occurring at 10 km spatial resolution, i.e. when the entire cloud field is assumed homogeneous. As we have already seen in Fig. 3, in most of the optical thickness range (≥ 2), the PPHB leads to averaged reflectances smaller than the reflectances computed for the averaged optical thickness, such that, on average, $\overline{\Delta R}(\overline{1D} - 1D) < 0$. The PPHB is the dominant effect at coarse spatial resolutions, explaining while the total bias $\overline{\Delta R}(\overline{3D} - 1D)$ in Fig. 8 is negative for every viewing and solar angles at resolutions coarser than 1 km. Also, we can see that for an overhead sun (panel (a)), the PPHB $\overline{\Delta R}$ is smaller than the MODIS

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reflectance measurement uncertainty of $\pm 3\%$ (Xiong et al., (2005, 2017)) represented by the horizontal dash lines, except for $\Theta_v = 60^\circ$ (blue lines) from 500 m spatial resolution and beyond. Therefore, for this particular scene and an overhead sun, the PPHB is not significant except for very large viewing angles. Also, we can see that the PPHB increases with increasing solar zenith angle (moving from (a) to (c)). ~~Indeed, it~~ because of the increasing of the non-linearity of the reflectance vs. COT relation (compare the blue or ~~green~~magenta curves of 1D reflectances in Fig. 6 (a) and (c)) making the PPHB (which arises from this nonlinearity) ~~much~~ stronger. But again, the PPHB becomes significant for spatial resolutions coarser than 250 m for a very large viewing zenith angle ($\Theta_v = 60^\circ$) at low solar zenith angle, or at very high solar zenith angle ($\Theta_s = 60^\circ$) at any viewing angle. Note that for sun at zenith, the PPHB effect is tiny, almost 0 except for large viewing zenith angles ($\Theta_v = 60^\circ$, blue lines) where the extinction is very large along the line of sight. ~~This conclusion is different from Varnai and Marshak (2003) because cirrus optical thickness is, on average, smaller than~~ stratocumulus optical thicknesses leading to a weaker PPHB, which is overall very weak for nadir views at all spatial resolutions. In addition, this conclusion is also drastically different from that of Fauchez et al. (2017a) for thermal infrared wavelengths, where the PPHB dominates beyond about 250 m. Indeed in the TIR, the cloud absorption is larger and the source of radiative emission is not the Sun but the atmosphere, the cloud and the surface. Furthermore, the large temperature difference between the cirrus and the surface leads to large brightness temperature inhomogeneities and therefore large PPHB. This conclusion is different from that of Fauchez et al. (2017a) for thermal infrared wavelengths, where the PPHB dominates for Nadir view beyond ~~about~~ ~ 250 m. Indeed in the TIR, the cloud absorption is larger and the source of radiative emission is not the Sun but the atmosphere, the cloud and the surface. Furthermore, the large temperature difference between the cirrus and the surface leads to large brightness temperature inhomogeneities and therefore large PPHB.

4.3 Tilted and homogeneous extinction approximation bias (THEAB)

When the ~~view~~viewing zenith angle is large, the bias due to the tilted view of the cloudy scenes called THEAB may also significantly impact the difference between TOA reflectances estimated with the 1D horizontal homogeneous cloud assumption and those corresponding to the reality of ~~the~~ 3D radiative transfer. For cloud observations from TOA, an oblique line of sight may cross many different cloudy columns, while the 1D plane parallel and homogeneous assumption considers only a single cloudy column above the observation pixel, assumed horizontally infinite with vertically heterogeneous extinction coefficient (see Fig. 4). ~~The THEAB is therefore a consequence of the PPHB for oblique view. 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), Wissmeier et al. (2013)), 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. Overall, Each of them~~ tilted line of sight crosses large, medium and small extinctions through many different columns leading to an average optical paths similar between each tilted columns and therefore ~~a more homogeneous field of view; for the 1D plane parallel assumption, where only a unique homogeneous column is crossed and each of them are different.~~ the field of view appears more homogeneous than the one with independent cloudy columns (1D assumption) with small optical thickness juxtaposed to large optical thickness. This effect is shown in Fig. 12 where we can see that the optical thickness field at 50 m spatial resolution view from 60° zenith angle is much smoother

than the one see from nadir. We can also see that the extinction plumes are stretched out, spreading and smoothing the cloud extinction over the columns. Indeed, for a voxel horizontal and vertical sizes of 50 m and 72 m, respectively, and a $\Theta_v = 60^\circ$, the line of sight reaching the top of a given voxel from its center (see Fig. 4) then cross horizontally $72 \times \tan(60) \sim 125$ m, i.e. two adjacent voxels before reaching the underneath cloud layer. To highlight only the THEAB without considering the horizontal radiative transport effect we compared 1D reflectances computed with the homogeneous, independent and infinite pixel assumption (named 1D) to those computed with the independent but non-infinite pixel assumption (named $1D_{o.e}$ for oblique extinction). In the latter situation, the line of sight ~~allowed to~~ cross neighboring cloudy columns, but the columns ~~are~~ still radiatively independent (i.e., this is not 3D RT). For each pixel, we ~~have~~ re-created a 1D cloud for which the optical thickness per layer corresponds to the oblique optical thickness of the 3D heterogeneous extinction field but keeping the cell dimension constant. ~~In other words,~~ We have ran 1D RT using the oblique columns crossed as adjacent vertical cloud layers (i.e., tilted the oblique columns crossed to a vertical column). The relative and absolute differences, with respect to the 3D aggregated reflectance in percentage, are estimated following equations 4 and 5, respectively, and are also represented in Fig. 13 (a), and (b), respectively.

$$\overline{\Delta R}(1D_{o.e.} - 1D) (\%) = \frac{100}{R^{3Dxkm}} \times \left[\sum_{i=1}^N (R_{o.e.}^{1Dxkm} - R^{1Dxkm}) \right] / N, \quad (4)$$

$$|\overline{\Delta R}(1D_{o.e.} - 1D)| (\%) = \frac{100}{R^{3Dxkm}} \times \left[\sum_{i=1}^N (|R_{o.e.}^{1Dxkm} - R^{1Dxkm}|) \right] / N, \quad (5)$$

In Fig. 13, we see that for a viewing zenith angle of $\Theta_v = 30^\circ$, the relative value $\overline{\Delta R}$ is, on average, equal or below the MODIS reflectance measurement uncertainty, while locally the absolute value of THEAB ($|\overline{\Delta R}|$) can reach few tens of percents. ~~as expected, that for oblique sun and off-nadir view the THEAB is the largest for the finest spatial resolutions, because the pixel size is small and thus an oblique line of sight can cross many different columns during its paths through the cloud. There is a small dependence on the view azimuth angle with the largest effect at $\phi_v = 180^\circ$.~~ The THEAB is more important for large viewing zenith angles because the number of columns crossed by the line of sight increases with the viewing zenith angle. The THEAB also increases with the solar zenith angle from 30° to 60° for much of the same reasons. There is a small dependence on the viewing azimuth angle with the largest effect at $\phi_v = 180^\circ$. Because the optical thickness field from the $1D_{o.e.}$ appears more homogeneous than for 1D for the finest spatial resolutions, the difference $R_{o.e.}^{1Dxkm} - R^{1Dxkm}$ is positive. This explain why for the finest spatial resolution and viewing zenith angle the total bias $\overline{\Delta R}(3D - 1D)$ in Fig. 8 ($0.86 \mu m$) and Fig. 9 ($2.13 \mu m$) is positive. By comparing these results with those of Fig. 8 we can see that, for spatial resolutions below 1 km, the THEAB is the dominant effect for large solar zenith angles. The absolute THEAB effect $|\overline{\Delta R}(1D_{o.e} - 1D)|$ is even larger than the total effect $|\overline{\Delta R}(3D - 1D)|$ which is reduced by the radiative smoothing. At a pixel size of 2.5 km, the large pixel size reduces the THEAB, which becomes almost nullzero, since less different cloudy columns are crossed as when observation pixel resolution increases, differences between tilted and vertical optical thicknesses logically reduce. ; Thus, the PPHB thus becomes the dominant effect. Note that the spatial resolution from which the THEAB becomes almost null will depend on the horizontal extent and geometrical thickness of the cloud. The horizontally longer and/or geometrically thicker the

~~cloud, the coarser the spatial resolution at which the THEAB becomes insignificant.~~ Note that we choice to calculated the THEAB instead of the TIPA bias because only the former helps to understand why $\overline{\Delta R}$ 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

5 Like other effects, the importance of 3D effects is dependent on the spatial resolution. 3D effects refer to both radiative (HRT, side illumination and shadowing) and geometric (THEAB) 3D effects. In Fig. 14 we can see the relative difference due to 3D effects calculating from the total difference minus the PPHB (in percentage relative to the 3D reflectances) for a Sun at zenith and for viewing angles of $\Theta_s = 0^\circ$, 30° and 60° . The difference, averaged over the field, for each spatial resolution is represented by the solid line and the 10th and 90th percentiles of the difference are represented by the shaded area. Note that

10 Fig. 14 is for sun at zenith, consequently only HRT are present with no shadowing and illumination effects. We can see that, at the pixel scale, HRT can have a positive or negative impact on the reflectance but that the average value (averaged over the entire field) is constant over the spatial resolutions. Also, as expected, we see that the amplitude of HRT is much larger for fine (up to +150 %, down to -200 %) and decrease with the decrease of the spatial resolutions. Note that negative differences are larger than positive differences. Negative reflectance differences are associated with a darkening of the radiation because the

15 HRT reduces the reflectances of large optical thicknesses (see Fig. 5). To not overload Fig. 14 with too many viewing and solar angle we have summarized the relative 3D effects averaged over the 10 km field in Table 2. The interpretation of Table 2 is not easy and further study need to be conducted to give consolidated conclusions but some clues can still be given. In this table, we can see that for a Sun at zenith (no side illumination nor shadowing effects) and a view from nadir (no THEAB), 3D effects correspond to HRT only and the averaged difference is negative. However, for a Sun at Zenith (first line) and for the largest

20 viewing zenith angles $\Theta_v = 60^\circ$, the differences are less negatives and are even positives for viewing azimuths $\Phi_v = 90^\circ$ and $\Phi_v = 180^\circ$. This is due to the THEAB which increase the reflectances (see Fig. 13). This effect is less strong at $\Phi_v = 0^\circ$ and is weak at $\Phi_v = 45^\circ$ because the line of sight is parallel to the fallstreaks leading to i) a similar extinction through the crossed columns and ii) a reducing of the fallkstreaks reflectances due to HRT. For a Sun off-zenith, the effects of shadowing and side illumination are added to those of the HRT. At $\Theta_s = 30^\circ$, we can see that the negatives differences dominate because of the

25 HRT, except again for for $\Theta_v = 60^\circ$ with $\Phi_v = 0, 90$ and 180° . For $\Theta_s = 60^\circ$, two effects can reduced the negative differences and even lead to positive differences. The illumination effects that increase the 3D reflectances and the THEAB, in particular for the $\Theta_v = 60^\circ$.

5 Conclusions

In this work, we have modeled a typical cirrus cloud ~~with~~field, with a constant $CER = 20 \mu m$ using the 3DCLOUD model ~~with~~

30 ~~typical~~characteristics. Only one cirrus structure has been modeled for computational time reasons, but many spatial resolutions, viewing and solar angles have been considered. However, the radiative processes discussed here can be ~~extrapolated~~generalized to other cirrus clouds, with ~~some~~ differences depending on cirrus structure (whether fallstreaks are included or excluded), solar and view geometries, average optical thickness etc. ~~Simulation of the radiative transfer through this scene have been performed with the 3DMCPOL code for~~ 0.86 and $2.13 \mu m$ reflectances have been simulated for this scene using the 3DMCPOL code for various

configurations: 1) Full 3D radiative transfer at high spatial resolution, 2) 1D radiative transfer at various spatial resolutions, ~~for~~ which taking into account the extinction variability along the oblique line of sight ~~is take into account (like in 3D),~~ and 3) Vertically homogeneous 1D radiative transfer at various spatial resolutions. The spatial resolutions considered here ~~are ranged~~ range from 50 m to 10 km. By comparing the results of these simulations, the paper examined three types of effects: the plane-parallel and homogeneous approximation bias (PPHB) due to the non-linear relationship between optical thickness and reflectance, the tilted and homogeneous extinction approximation bias (THEAB) ~~due to the fact that~~ that arises because in 1D, the line of sight is assumed to remain in a single vertical column, while in reality, it can cross many different cloudy columns and the 3D effects due to 3D radiative effects such as the horizontal transport of photons between pixels (HRT) or (for oblique sun) side illumination and shadowing effects, associated with the 3D geometrical effect of the THEAB. The relative contribution of these

10 three effects onto the TOA reflectances is strongly dependent on spatial resolution but also on cloud structure. No particular differences have been noticed between 0.86 and 2.13 μm channels (except in the magnitude of the effects); therefore, for clarity, most of the figures show results for the 0.86 μm channel only. For the particular configuration of a cirrus uncinus, we have emphasized the following points:

- For nadir observations:
 - 15 – Below 2.5 km spatial resolution, 3D effects are dominant.
 - For overhead Sun, HRT is the only 3D effect and can reach +20 % and –60 % in a 50 m spatial resolution pixel.
 - For oblique Sun, ~~side illumination effect mitigates the HRT from thick to thin regions, leading to smaller~~ 3D radiative effects such as side illumination and shadowing modify the differences between 3D and 1D reflectances which can reach +120 % and –170 % ($\Theta_s = 30^\circ$) and +150 % and –200 % ($\Theta_s = 60^\circ$) in a 50 m spatial resolution pixel.
 - At spatial resolution coarser than 2.5 km, the PPHB is the dominant effect.
- For ~~an observation off nadir~~ Off-nadir observations:
 - Similar conclusion to nadir observations except that below 2.5 km spatial resolution and for a very large viewing zenith angle of $\Theta_v = 60^\circ$ and an viewing azimuth not parallel to the fallstreaks, ~~the dominant effect is THEAB, rather than~~ 3D In addition to illumination effects, the THEAB leads to increase the 3D reflectances (radiative) effects.

For off-nadir observations, the THEAB is ~~very~~ large mostly for $\Theta_s = 60^\circ$ and for high spatial resolutions (small pixels, roughly below about 250-m 1 km), especially for a line of sight crossing perpendicularly the fallstreaks of cirrus uncinus. This bias is difficult to evaluate from observations, as this would need an active sensor, such as a lidar, looking at an oblique view

30 angle. For low spatial resolutions (large pixel sizes, roughly > 2.5 km) the PPHB is the largest effect when compared to higher spatial resolutions. Note that this spatial resolution is ~~different from~~ slightly larger than ~~that~~ the roughly > 1 km estimated by Davis et al. (1994) for stratocumulus clouds; ~~of roughly > 1 km~~ the difference is certainly due to ~~the larger optical thickness of those clouds~~ the

weaker optical thickness of the studied cirrus cloud. Between ~~this~~these two ranges, competition between 3D effects, THEAB and PPHB ~~is~~are complicated and will depend on the cloud structure and the viewing and solar geometries. It is therefore difficult to generalize the conclusions for this intermediate range to other cirrus clouds. ~~It is also important to notice~~Concerning 3D effects, the relative influence of the HRT (leading to a net flux of photons mostly from thick to thin regions), ~~occurring regardless of the solar geometry~~versus side illumination and shadowing effects which (mostly increasing the reflectance of large optical thicknesses, but blocking the photons from eventually reaching thinner neighbor regions) is dependent on the Sun zenith angle. At moderate Sun zenith angles (0° and 30° in our simulations), the HRT is dominant over the side illumination effects leading overall to a negative 3D effect. However when the Sun is very low (60° in our simulations), the side illumination mitigate the effects of both, HRT and shadowing leading to weaker 3D effects. Note that, 3D effects, when averaged over the entire field, are constant whatever the spatial resolutions. Overall, the total difference between 3D and 1D reflectances are mitigated when increases with the solar zenith angle because of the increase of PPHB with the solar zenith angle increases which is different from the conclusions of as already shown by Loeb and Davies (1996) on thicker stratocumulus clouds. The overall predominant effect will therefore depend on the cloud optical thickness and viewing/solar geometries. Note that the results do not significantly change with a larger CER than 20 μm 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 PPHB and weaker 3D effects (because the mean free path is reduced by the absorption).

In Part I of this study, which focused on the impact of cloud inhomogeneity and 3D effects in thermal infrared channels, the PPHB ~~has been~~was found to be larger than 3D effects at resolutions coarser than 100-250 m. This is because the cloud absorption is much larger in the thermal infrared (TIR), leading to a larger PPHB even at relatively small pixel sizes. The differences between horizontal inhomogeneity and 3D effects at TIR and \forall NIR/SWIR channels pose a problem for retrieval techniques such as the optimal estimation method (OEM, Rodgers (2000)) that use multiple channels from these wavelength ranges (Fauchez et al., 2017b). In a future study, the impact of such differences in the retrieval of cirrus optical properties will be investigated using an OEM at five channels across the \forall NIR/SWIR/TIR ranges and at spatial resolutions ranging from 50 m to 10 km.

25 *Code availability.* The simulated data used in this study were generated by the 3DCLOUD (Szczap et al. (2014)) and 3DMCPOL (Cornet et al. (2010); Fauchez et al. (2014)) closed-source codes. Please contact the authors for more information.

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Figures

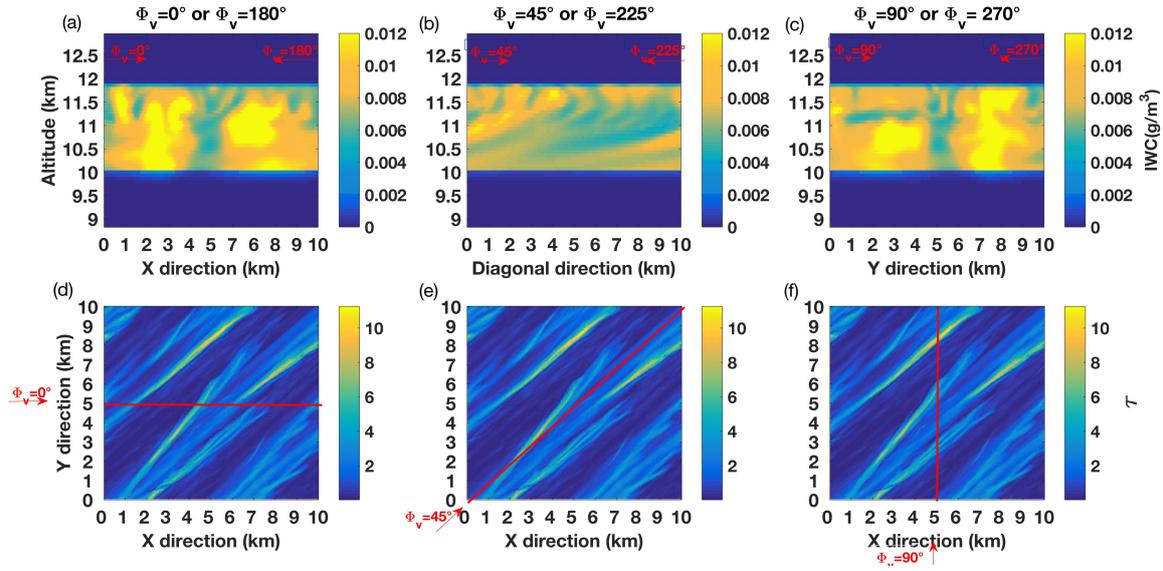


Figure 1. Top panels ((a), (b) and (c)) vertical distribution of the ice water content (IWC (g/m^3)) following the red lines of the through the 50 m spatial resolution optical thickness field shown in the bottoms panels ((d), (e) and (f)) along the red line as a function of the azimuth viewing angle Φ_v .

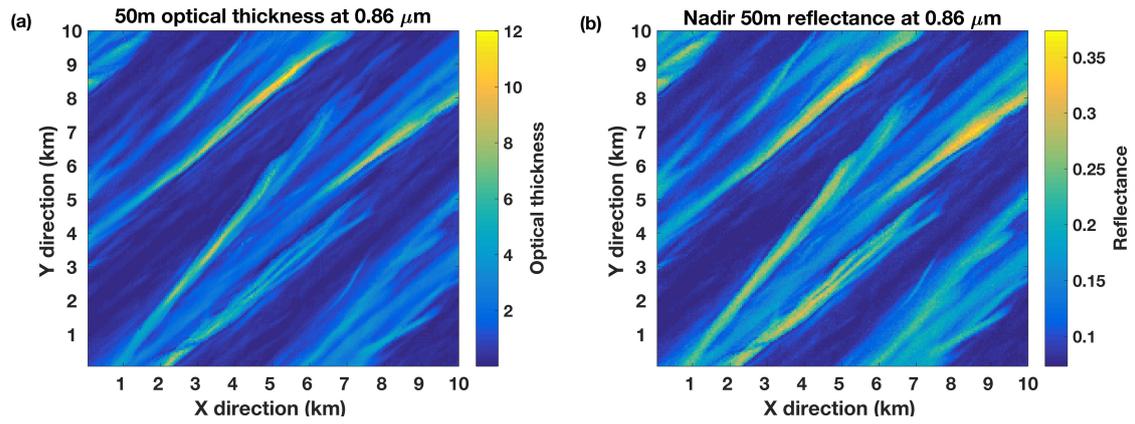


Figure 2. (a) Optical thickness field at 0.86 μm and (b) solar reflectance field at 0.86 μm at a spatial resolution of 50 m, with nadir view and overhead Sun.

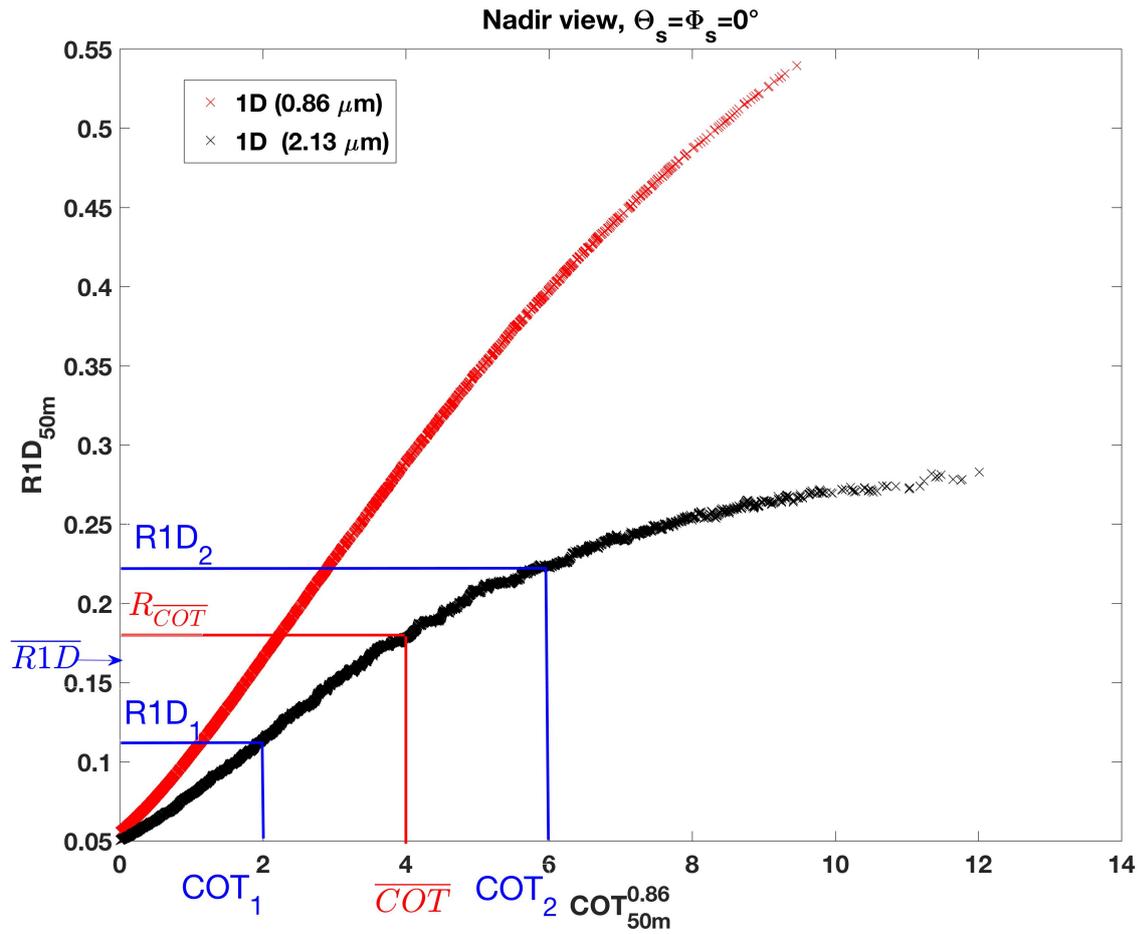


Figure 3. 1D reflectances ($R1D_{50m}$) as a function of the 50 m optical thickness at $0.86 \mu\text{m}$ ($COT_{50m}^{0.86\mu m}$) for channels centered at $0.86 \mu\text{m}$ (red) and $2.13 \mu\text{m}$ (black) for nadir view and overhead Sun. $\overline{R1D}_1$ and $\overline{R1D}_2$ represent the average of the two $2.13 \mu\text{m}$ reflectances between reflectances $R1D_1$ and $R1D_2$ for which reflectances corresponding to the optical thicknesses are COT_1 and COT_2 , respectively, and \overline{COT} is their averaged value. τ is the optical thickness associated with $\overline{R1D}$. Because of the non-linearity between $R1D$ and COT , the average reflectance $\overline{R1D}$ is smaller than the reflectance of the average optical thickness R_{COT} .

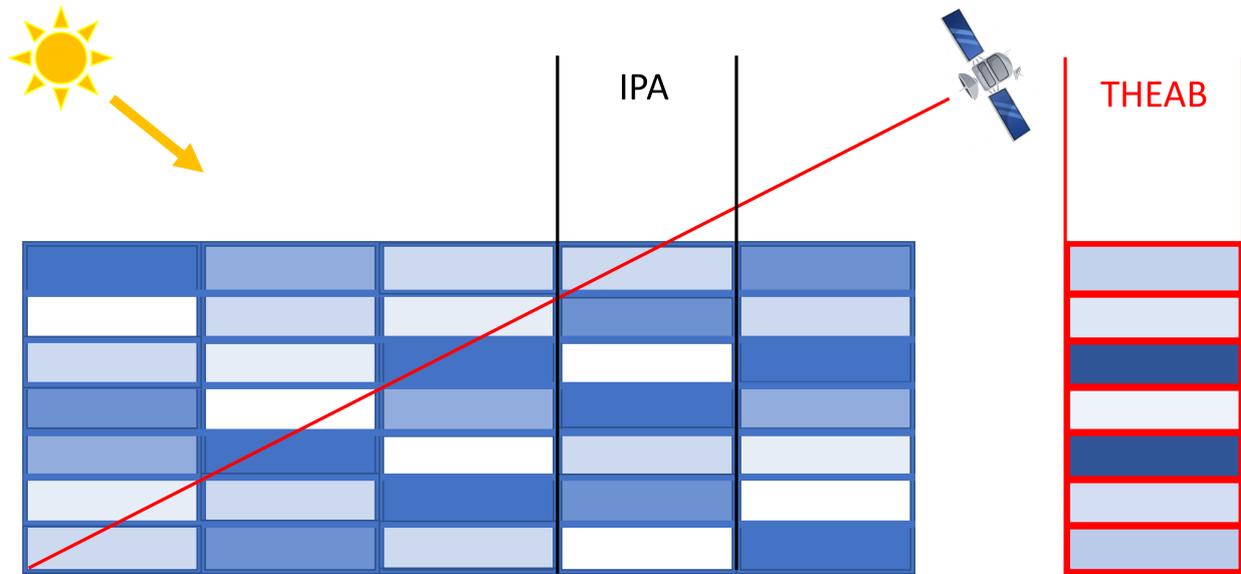


Figure 4. Schematic illustration of the Tilted Homogeneous Extinction Approximation used for calculating the Tilted Homogeneous Extinction Approximation Bias (THEAB). The line of sight crosses various cloudy columns with variable extinctions while the Independent Pixel Approximation (IPA) considers only the cloudy column directly under the observed pixel at the top of the cloud. Note that each cell in the THEAB looks darker than in the IPA because we account for the longer path through the cell while keeping the cell size constant which implies to increase the extinction.

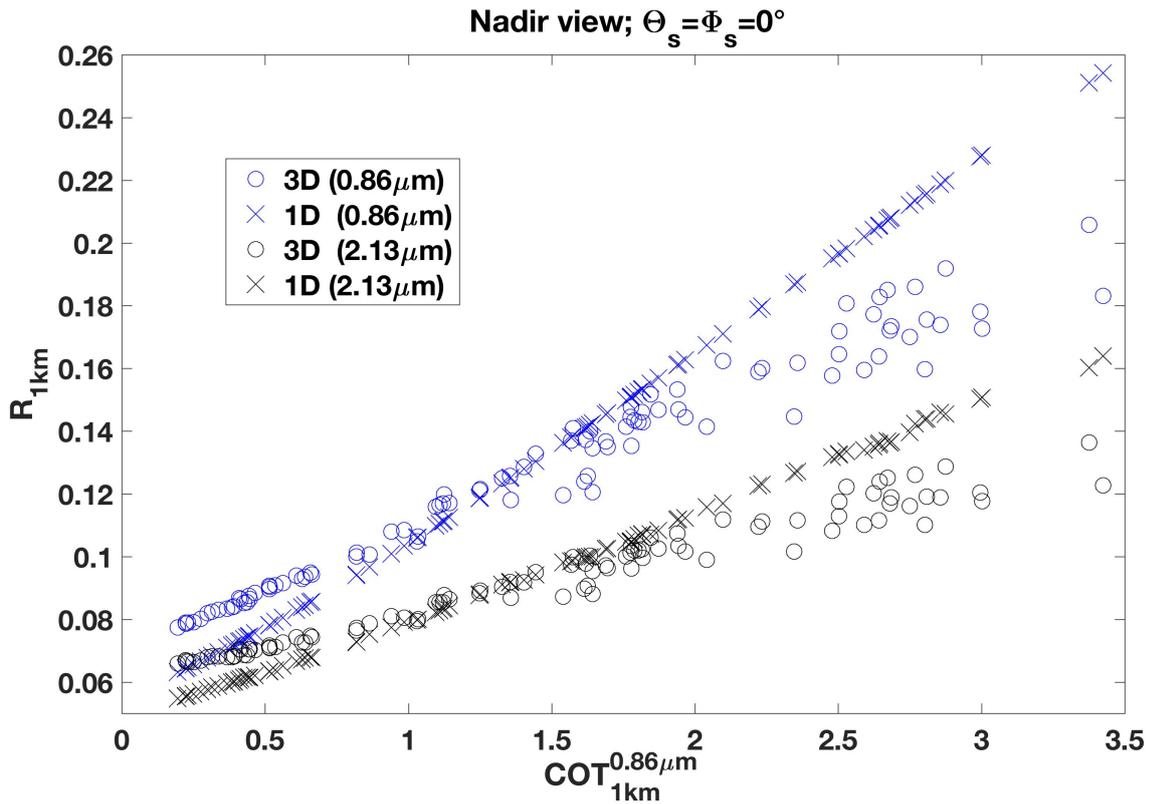


Figure 5. Solar reflectances at 0.86 μm (blue) and 2.13 μm (black) at 1 km spatial resolution computed in 3D (circles) and in 1D (crosses). We choice to show these reflectances at 1 km to not overload the plot with too many points at finer spatial resolutions but the effect is the same.

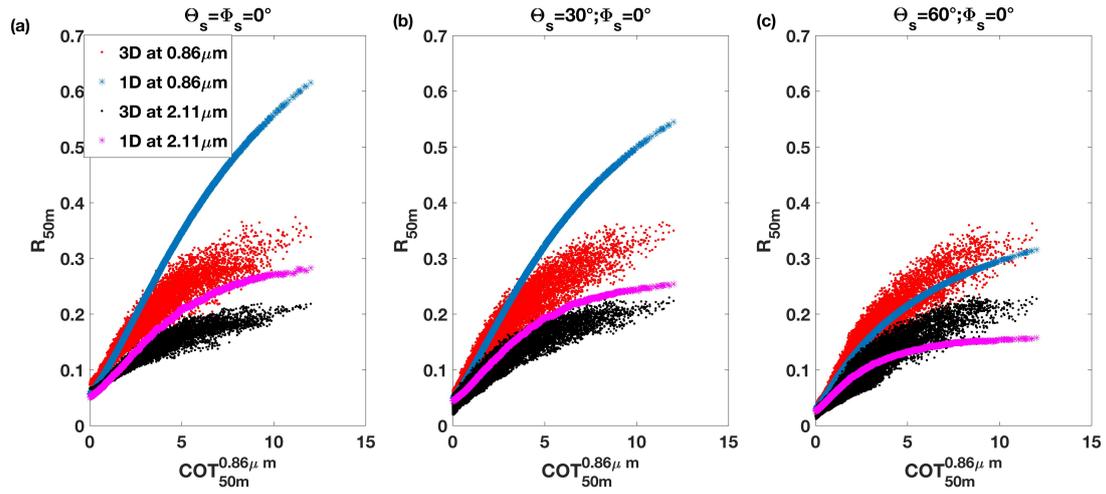


Figure 6. Reflectances (R_{50m}) for nadir view, as a function of 50 m optical thickness the solar zenith angle Θ_s and 50 m optical thickness, at $0.86\mu m$ ($COT_{50m}^{0.86\mu m}$) for channels centered at $0.86\mu m$ (in red and blue colors for 3D and 1D computations representing by star and dot markers, respectively) and $2.13\mu m$ (in black and magenta colors with for 3D and 1D computations representing by star and dot markers, respectively) and as function of the plotted separately for the three solar zenith angles Θ_s .

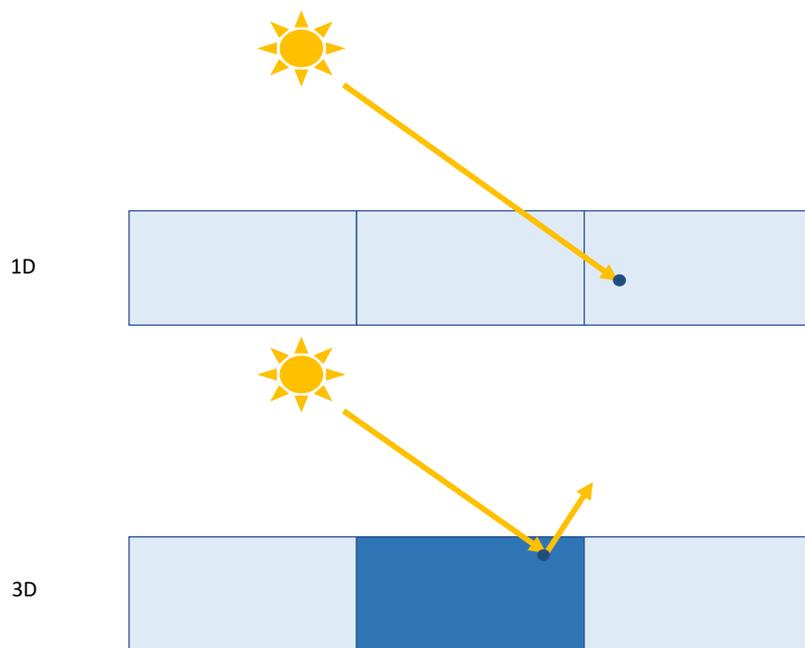


Figure 7. Illustration of the side illumination shadowing effect. In 1D (top panel), the right column can be highlighted illuminated by the photon coming from the Sun, while in 3D (bottom panel), an optically thick neighbor region intercepts scatters the photon first and scatted it back to space, increasing the reflectance of the thick region, but reducing the reflectance of the thin region.

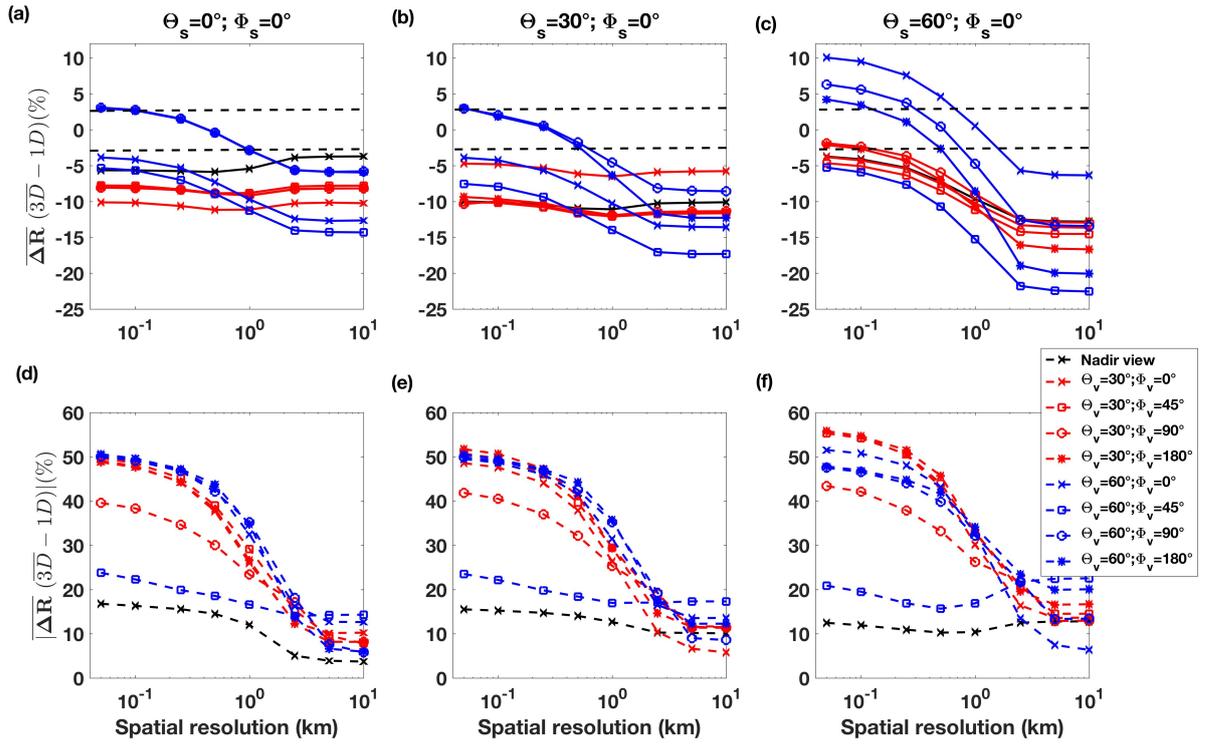


Figure 8. Arithmetic ($\overline{\Delta R}$) and absolute ($|\overline{\Delta R}|$) differences between 3D and 1D reflectances at $0.86 \mu m$ relative to the 3D reflectances in percentage, estimated with equations 1 (panel (a), (b) and (c)) and 2 (panel (d), (e) and (f)), respectively, as a function of the spatial resolution. Each line is for a different pair of viewviewing zenith and azimuth angles Θ_v and Φ_v , respectively, and as a function of the and each panel is for a different solar zenith angles Θ_s . The horizontal dashed lines represent the MODIS reflectance measurement uncertainty of 3% (Xiong et al., (2005, 2017)).

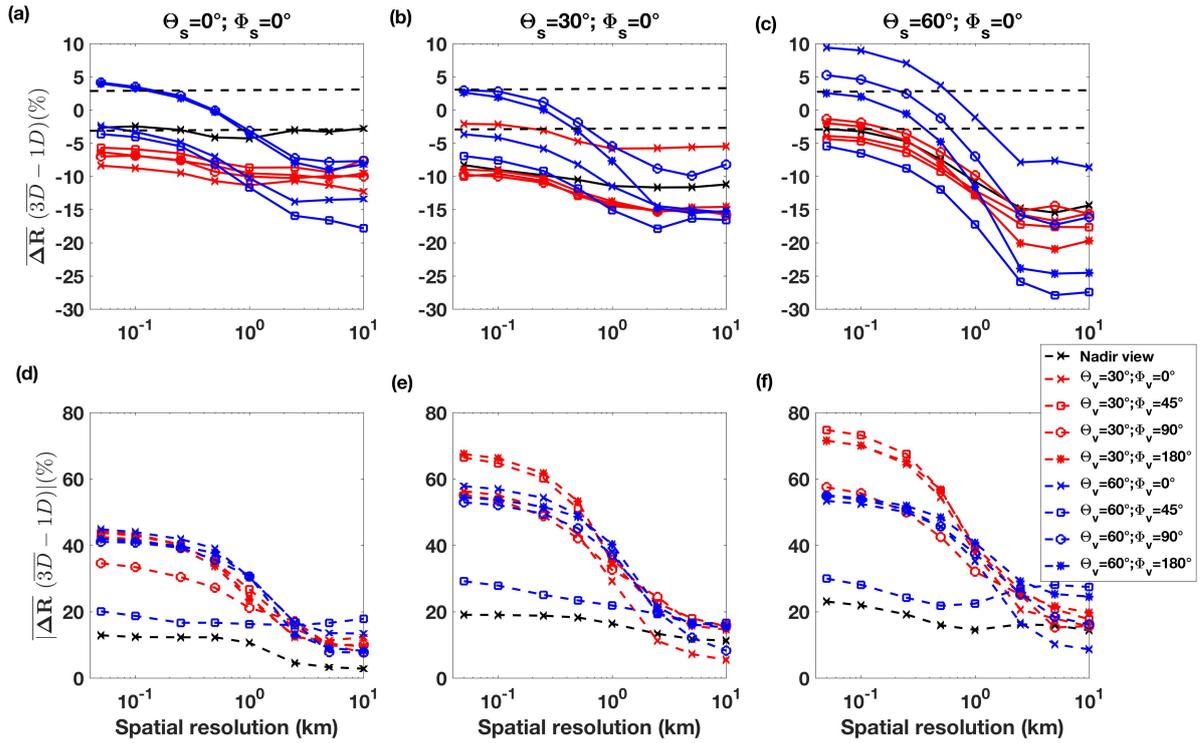


Figure 9. Arithmetic ($\overline{\Delta R}$) and absolute ($|\overline{\Delta R}|$) differences between 3D and 1D reflectances at $2.13 \mu\text{m}$, relative to the 3D reflectances in percentage, estimated with equations 1 (panel (a), (b) and (c)) and 2 (panel (d), (e) and (f)), respectively, as a function of the spatial resolution. Each line is for a different pair of viewing zenith and azimuth angles Θ_v and Φ_v , respectively, and as a function of the and each panel is for a different solar zenith angles Θ_s . The horizontal dashed lines represent the MODIS reflectance measurement uncertainty of 3% (Xiong et al., (2005, 2017)).

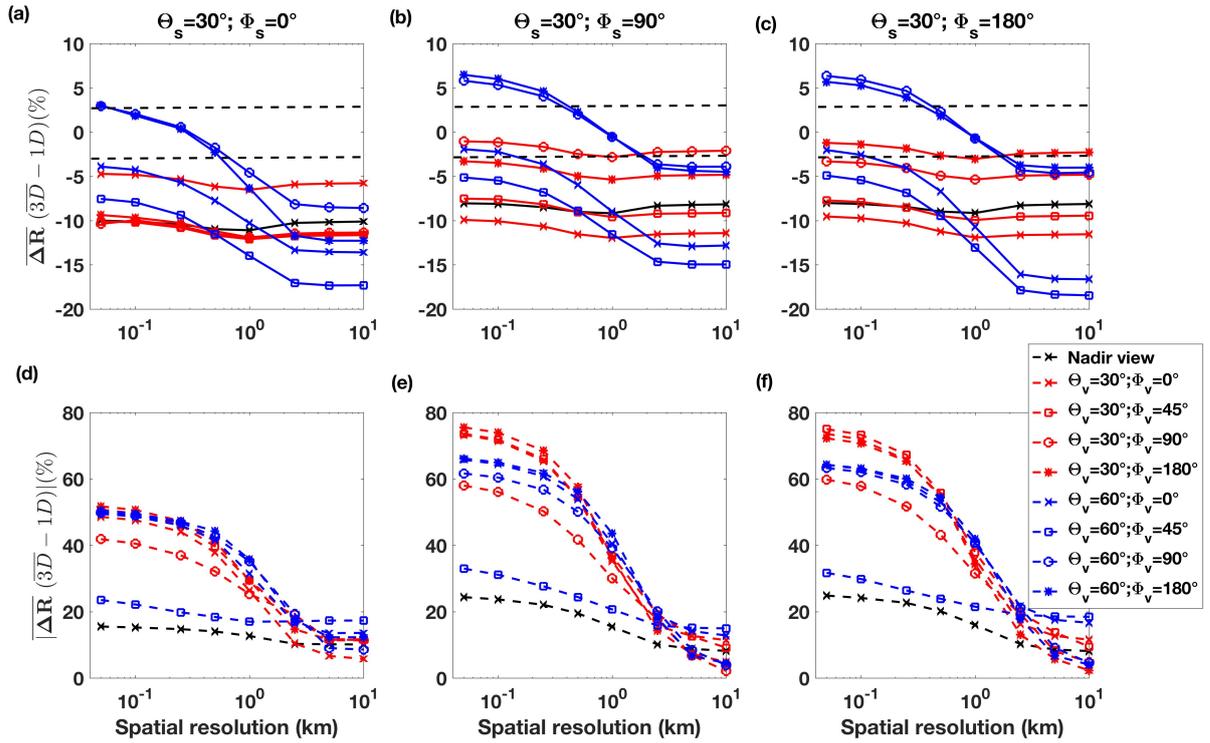


Figure 10. Mean arithmetic ($\overline{\Delta R}$) and absolute ($|\overline{\Delta R}|$) differences between 3D and 1D reflectances at $0.86 \mu m$, relative to the 3D reflectances in percentage, estimated with equations 1 (panel (a), (b) and (c)) and 2 (panel (d), (e) and (f)), respectively. Each line is for a different pair of viewing zenith and azimuth angles Θ_v and Φ_v , respectively, and as a function of the and each panel is for a different solar azimuth angles Φ_s for solar zenith angle $\Theta_s = 30^\circ$. The horizontal dashed lines represent the MODIS reflectance measurement uncertainty of 3% (Xiong et al., (2005, 2017)).

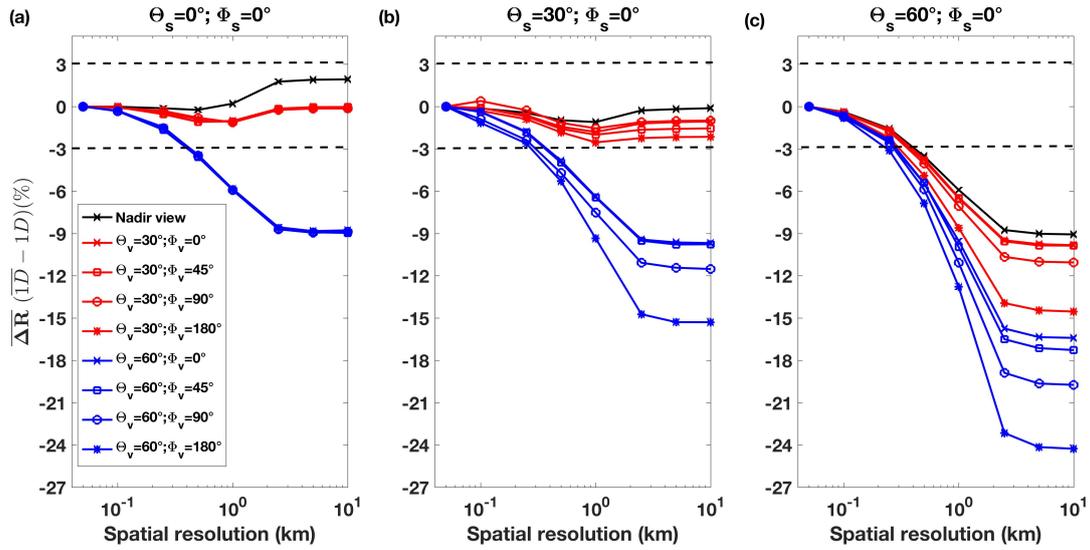


Figure 11. Plane-Parallel and Homogeneous Bias (PPHB) representing by the arithmetic ($\overline{\Delta R}(\overline{1D} - 1D)$) and absolute ($|\overline{\Delta R}|$) differences in percentage between 1D reflectances at $0.86 \mu m$ relative to the 3D reflectances in percentage, estimated with Eq. 3 as a function of the spatial resolution for various viewviewing zenith and azimuth angles Θ_v and Φ_v , respectively (black, red and blue colors), and solar zenith angles Θ_s (from the left to the right panels). The horizontal dashed lines represent the MODIS reflectance measurement uncertainty of 3% (Xiong et al., (2005, 2017)).

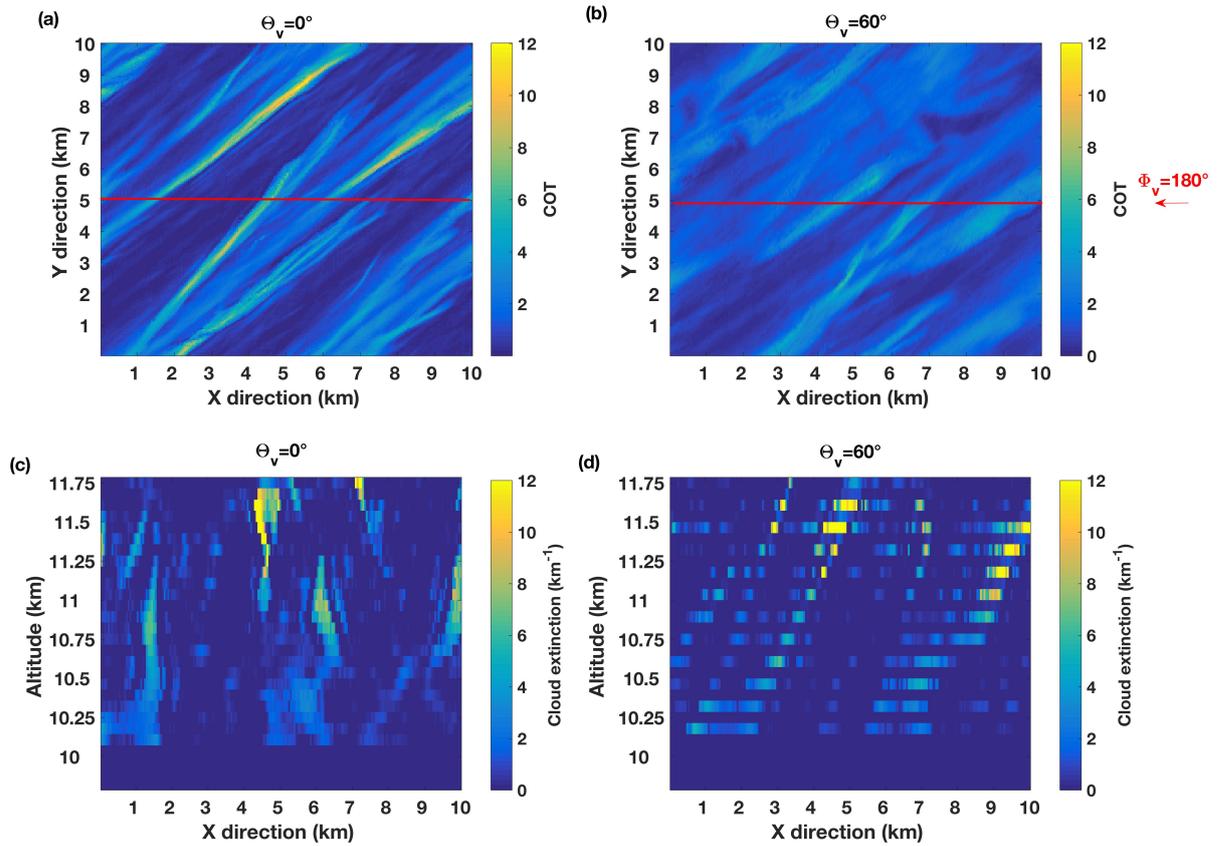


Figure 12. Optical thickness (COT) field view from nadir (a) and from a view zenith angle $\Theta_v = 60^\circ$ and vertical profile of the cloud extinction coefficient view from nadir (c) and from $\Theta_v = 60^\circ$ (d) along the red line of the COT field in (a) and (b), respectively for a viewing azimuth angle $\Phi_v = 180^\circ$.

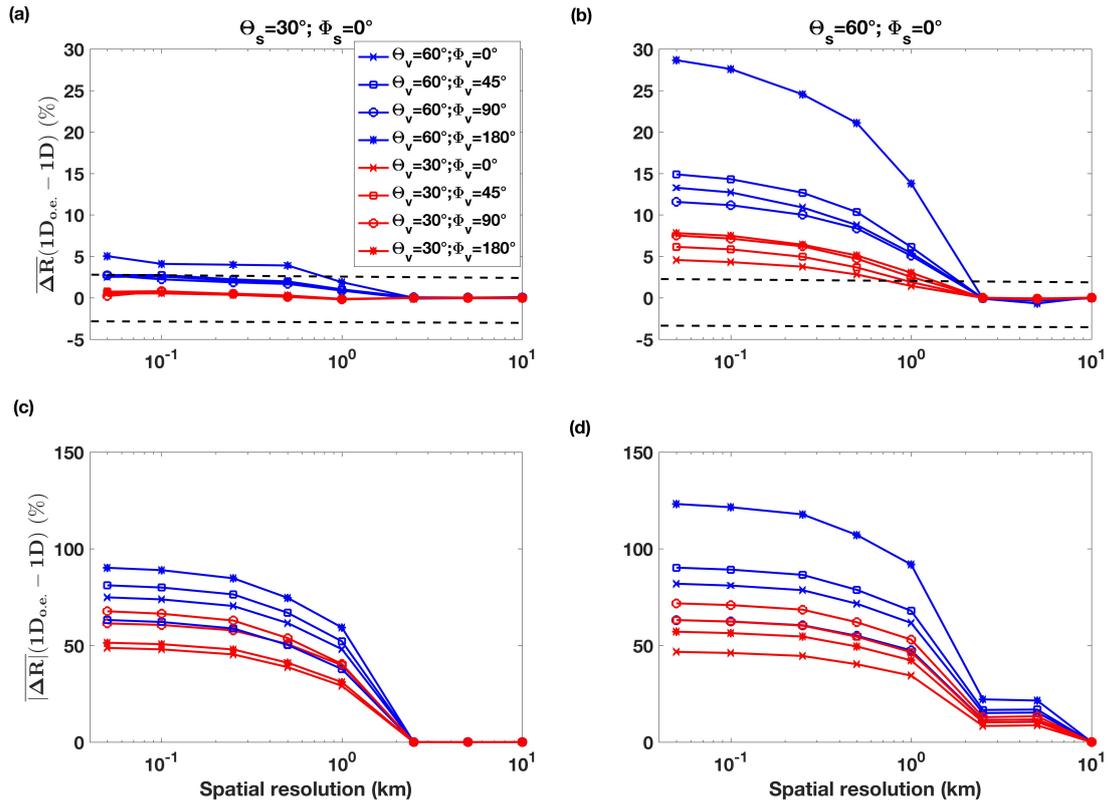


Figure 13. Tilted and homogeneous extinction approximation bias (THEAB) relative to the 3D reflectances in percentage, estimated with by equations Eq. 4 (panels (a) and (b)) and 5 (panels (c) and (d)) for solar zenith angles of $\Theta_s = 30^\circ$ and $\Theta_s = 60^\circ$ and $\pm 180^\circ$ solar azimuth angle, as a function of for several viewing zenith and azimuth angles Θ_v and Φ_v . The horizontal dashed lines represent the MODIS reflectance measurement uncertainty of 3% (Xiong et al., (2005, 2017)).

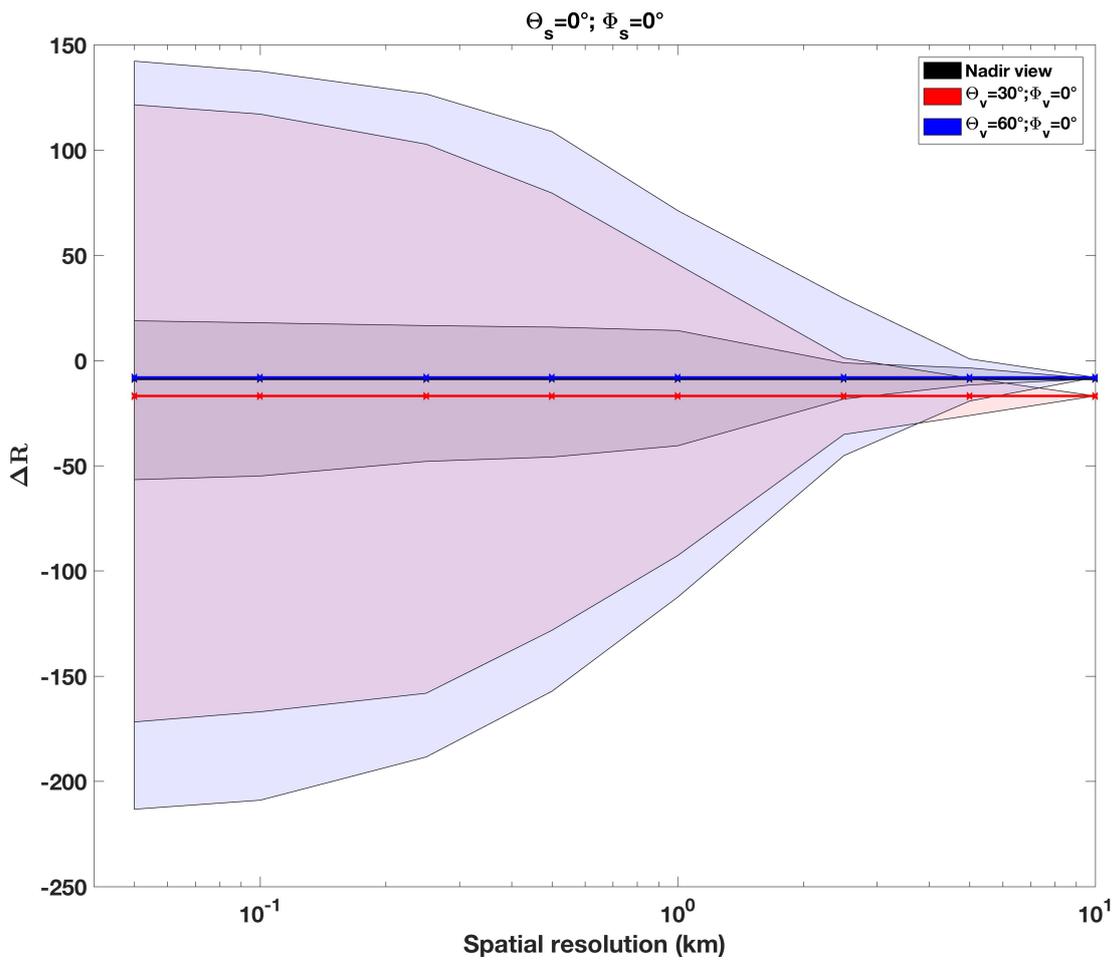


Figure 14. 3D effects as a function of the spatial resolution relative to the 3D reflectances in percentage. The shade areas correspond to the range of relative reflectance differences estimated for the 10th and 90th percentiles and the solid lines correspond to the average differences for different pair of viewing zenith and azimuth angles Θ_v and Φ_v .

Tables

Table 1. ~~MOD06-o~~Optical properties (extinction coefficient σ_e , single scattering albedo ϖ_0 and asymmetry parameter of the phase function g) of the ice crystal ~~with~~distribution used in this study, which assumes an effective radius of $10 \mu m$ and an aggregate column shape provided by the Yang et al. (2013) model ~~for the four channels use in this study.~~

	σ_e	ϖ_0	g
MODIS channel 2 ($0.86 \mu m$)	2.0855446	0.9999855	0.7526803
MODIS channel 7 ($2.13 \mu m$)	2.100443	0.9621367	0.7898260

Tables

Table 2. 3D effects, in percentage relative to the 3D reflectance, averaged over the 10 km field for various viewing zenith and azimuth angles (resp. Θ_v and Φ_v) and solar zenith and azimuth angles (resp. Θ_s and Φ_s).

	Nadir	$\Theta_v = 30^\circ$ $\Phi_v = 0^\circ$	$\Theta_v = 30^\circ$ $\Phi_v = 45^\circ$	$\Theta_v = 30^\circ$ $\Phi_v = 90^\circ$	$\Theta_v = 30^\circ$ $\Phi_v = 180^\circ$	$\Theta_v = 60^\circ$ $\Phi_v = 0^\circ$	$\Theta_v = 60^\circ$ $\Phi_v = 45^\circ$	$\Theta_v = 60^\circ$ $\Phi_v = 90^\circ$	$\Theta_v = 60^\circ$ $\Phi_v = 180^\circ$
Zenith	-8.7	-16.9	-12.9	-13.4	-13.4	-8.1	-11.1	6.4	6.2
$\Theta_s = 30^\circ$									
$\Phi_s = 0^\circ$	-14.9	-7.2	-15.7	-16.0	-14.6	-7.6	-14.6	5.8	7.0
$\Phi_s = 90^\circ$	-11.6	-15.3	-11.7	-1.6	-5.1	-3.8	-10.0	11.3	12.9
$\Phi_s = 180^\circ$	-11.5	-14.8	-11.9	-5.1	-1.9	-4.7	-10.9	12.7	11.1
$\Theta_s = 60^\circ$									
$\Phi_s = 0^\circ$	-3.9	-4.3	-5.2	-2.2	-2.9	15.2	-8.0	10.5	9.8

Reply to Anonymous Referee #1

1 General Comments

In this paper, the authors performed a set of 3D and 1D radiative transfer simulations with varying solar and measurement viewing angles. The goal of the study is to characterize and disentangle the various effects, problems and shortcoming that stem from 1D compared to 3D radiative transfer. The simulations seem appropriate for this endeavor, the results seem reasonable and I liked the review of possible 3D effects. However, I think the manuscript falls a bit short on the discussion and future implications of the results. The manuscript could include the following two key points before I would want to recommend to publish it.

We would like to thank the anonymous referee #1 for his careful look at our paper. In the text below we answer point by point to anonymous referee #1 comments and questions. We have also included the necessary changes in the manuscript. 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 $\sim 3\%$ 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 conclusions has been deeply re-written.

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

1. Could you please discuss the magnitude of errors that you find in reflectances compared to current satellite observations? I guess that today's reflectance measurements are on the order of 5 to 10%? How does that relate to or impact your findings?

This is a very pertinent remark, indeed we agreed that it would be valuable for the reader to compare the impact of 3D and heterogeneity effects to the reflectance measurements accuracy.

Currently for MODIS, such accuracy is estimated at 3% (Xiong et al., 2005; 2017). All the figures discussion about the amplitude of 3D and heterogeneity effects are now in percentage in order to be compared to the retrieval accuracy and some discussions are added comparing the measurements accuracy and the magnitude of cloud heterogeneity impacts.

2. I think the manuscript would greatly benefit from a short discussion or sensitivity test regarding the impact of your findings on actual retrievals. Could you for example provide estimates for errors in retrieved effective radius. I know you promise a future study grounded

on optical estimates with spectral information from all ranges but could you not provide or discuss first estimates for a retrieval like Nakjima-King?

We agreed with referee #2 that this is an important point to show the impact on the optical property retrieval, however these results have already published in (Fauchez, T., Platnick, S., Sourdeval, O., Meyer, K., Cornet, C., Zhang, Z., and Szczap, F. Cirrus heterogeneity effects on cloud optical properties retrieved with an optimal estimation method from MODIS VIS to TIR channels. AIP Conference Proceedings, 1810(1): 10 040002, 2017b.) at a 1km spatial resolution and submitted in (Fauchez, T., Platnick, S., Sourdeval, O., Wang, C., Meyer, K., Cornet, C., and Szczap, F. *Cirrus horizontal heterogeneity and 3D radiative effects on cloud optical property retrievals from MODIS near to thermal infrared channels as a function of spatial resolution*) in the upcoming JGR special issue: “3D Cloud Modeling as a Tool for 3D Radiative Transfer”.

In this study we have shown that when only considering cloud horizontal heterogeneity effects, the largest retrieval errors are associated with TIR retrievals due to the PPH bias. However, when both cloud 3D and heterogeneity effects are considered, the solar reflectance-based retrievals have the largest error for spatial resolutions less than 500–1000 m, while the TIR-based retrievals have the largest error above this resolution due to PPH bias.

COT and CER retrieval errors using SWIR/VNIR reflectance measurements are of the order of 10 % for a Sun at zenith but they can be up to 20 % [at 10 km spatial resolution] and 100% [at 50 m spatial resolution] for COT and CER retrievals, respectively, for an oblique Sun.

1.0.1 Specific Comments

• p.4 l.20-26 Please state if the domain has cyclic boundary conditions. I guess this is important because the interaction radius may be quite far?

Yes the domain has cyclic boundary conditions.

We add in the revised manuscript, line 24 page 4 the following sentence: “... *assuming cyclic boundary conditions are imposed at the edges of the domain*”

• p.4 l.28-33 Please give a more detailed description of the simulation so that one could reproduce your setup. What is the surface albedo? Was aerosol used? Water vapor background profile?

The detailed description of the simulations are already presented in the Part I of the paper. However, we agreed that it is valuable to be presented in this second part too. Ocean surface albedo values for NIR/SWIR channels are set at 0.05, there is no aerosol and the mid-latitude summer atmospheric profile is presented in Fig 2 of Fauchez et al., 2017a.

We add line 9, page 5: “*No aerosol is added and the surface is Lambertian with a constant albedo of 0.05. No aerosol and atmospheric absorption are considered.*”

• p.5 l.24 IPA does not necessarily mean that the scene is vertically homogeneous. 1D RT is very well capable of simulating vertically inhomogeneous atmospheres numerically. This phrasing of yours kept me wondering till the end of the manuscript if you actually averaged the ice water content vertically or not. Please make that more clear.

You are right, the IPA implies the horizontal inhomogeneity and pixel independence not the vertical inhomogeneity. However, for the retrieval of optical properties from space radiometers

only one crystal size/shape is retrieved regardless the vertical extension and inhomogeneity of the cloud column. In our study the cloud extinction is vertically inhomogeneous, however only one crystal size and shape is assumed in the whole cloud domain for simplification of the problem and assess the extinction coefficient variability effects only. The impact of the vertical variability of ice crystal size/shape is very interesting to study but out of the scope of this paper.

We have remove the “*vertically inhomogeneous*” of L24, P5.

We have added this sentence in the section presenting the microphysical model: “Note that while the microphysical properties are homogeneous, the extinction coefficient varies horizontally and vertically.”

• **p.9 l.4 I think a schematic would be very helpful for the tilted part. I am wondering which slanted path you used, i.e. did you take the optical properties along the sun angle or from viewing geometry. Out of the two, which one would you think is better? Also, did you use an interlaced grid like for example Wissmeier2013 <https://doi.org/10.1175/JAMC-D-12-0227.1>?**

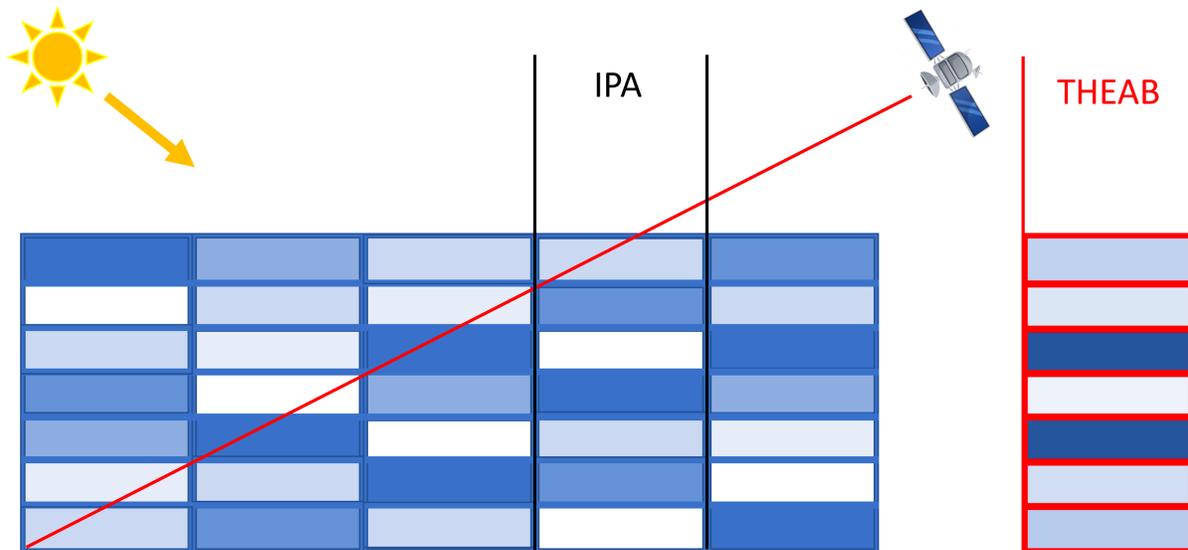
We take the optical properties along the viewing geometry, this is different from the Tilted Independent Pixel Approximation (TIPA, Varnai et al. 1999), which have computed the optical properties along the sun angle.

Thank you for providing us this reference that we did not have. The TICA approach (i.e. paNTICA, parameterized nonlocal tilted independent pixel approximation) described in this paper (Wissmeier et al., 2013) is similar to the TIPA of Varnai et al., (1999). In our study we only account for the tilted view of the line of sight crossing various extinction through different cloudy columns while the ice crystal size and shape are constant. We explain our method in page 9, line 13 to 16:” For each pixel we have re-created a 1D cloud for which the vertical extinction is the averaged oblique extinction of the 3D heterogeneous field. In other words, we have run 1D RT using the oblique columns crossed as adjacent vertical cloud layers (i.e., tilted the oblique columns crossed to a vertical column).”

In order to highlight the relationship between THEAB and TIPA, we included the following sentences into the manuscript:

In essence, THEAB 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; Wissmeier et al., 2013), but with the tilting based on the view direction instead of the solar direction. A somewhat similar concept to THEAB was used in Evans et al. (2008), where reflectances were related to cloud properties calculated along the slanted line of sight.

Also, as you mentioned, a figure will be very helpful, we add it in the manuscript and refer it as Fig. 4 in the new version.



The computation of the THEAB was helpful to understand why the sign of $\Delta R(3D-1D)$ depends on the spatial resolution (for Sun at zenith and off-zenith). We explain the change of sign due to the THEAB in section 4.3 Tilted and homogeneous extinction approximation bias (THEAB) :

“A somewhat similar concept to THEAB was used in Evans et al. (2008), where reflectances were related to cloud properties calculated along the slanted line of sight. Each tilted line of sight crosses large, medium and small extinctions through many different columns leading to an average optical paths similar between each tilted columns and therefore the field of view appears more homogeneous than the one with independent cloudy columns (1D assumption) with small optical thickness juxtaposed to large optical thickness. This effect is shown in Fig. 11 where we can see that the optical thickness field at 50 m spatial resolution view from 60° zenith angle is much smoother than the one see from nadir. We can also see that the extinction plumes are stretched out, spreading and smoothing the cloud extinction over the columns. Indeed, for a voxel horizontal and vertical sizes of 50 m and 72 m, respectively, and a $\Theta_v = 60^\circ$, the line of sight reaching the top of a given voxel from its center (see Fig. 4) then cross horizontally $72 \times \tan(60) \sim 125$ m, i.e. two adjacent voxels before reaching the underneath cloud layer. “

Because this effects occurs also for the Sun at zenith it is not due to the TIPA, therefore we had no need to compute new time expensive computation for TIPA which is implicitly included in the 3D radiative effects.

• **p.10 l.21-26 Would it not make sense to have a look at 45° and 45°+90°? Is there a particular reason you did not examine that?**

There is no particular reason to not look at these angles except that for computational time reasons we had to select a small number of viewing geometries. Indeed, at 45° the line of sight is parallel to the fallstreaks, at 45°+90° the line of sight will be perpendicular to the fallstreaks that would not differ too much to the other viewing azimuth of 90° and 180°.

- **p.12 l.19-21** *Isn't that particularly interesting for retrievals that use both channels? Wouldn't Nakajima King for example suffer from this even if there would be a linear relationship between the errors in those two channels?*

This is an interesting question, both are solar channels (0.86 and 2.13 μm) and they produce similar 3D effects (shadowing, side illumination and horizontal transport). However, because the absorption is different between these two channels the amplitude of the effects is also different. Obviously, because the amplitude of the 3D heterogeneity effects is different between 0.86 and 2.13 μm this will impact the cloud optical property retrieval through a Nakajima and King method (or other similar method using a combination of NIR/SWIR channels, see for instance Zhang et al., (2012, 2013), Marshak et al., (2006)). Note that those differences are much smaller than between TIR and NIR/SWIR channels (see Fauchez et al. 2017b). Also, Fauchez et al., (2017a) have shown that for TIR MODIS channels (centered at 8.52, 11.01, 12.03 and 13.36 μm), the difference of cloud absorption (and scattering) between those channels leads to different 3D and heterogeneity effects, which later impact the cloud optical property retrieval using thermal infrared channels such as the split-window technique (see also Fauchez et al, 2017b and 2018).

Marshak, A., S. Platnick, T. Várnai, G. Wen, and B. Cahalan (2006), Impact of three-dimensional radiative effects on satellite retrievals of cloud droplet sizes, *J. Geophys. Res.*, *111*, D09207, doi:10.1029/2005JD006686.

Zhang, Z., Ackerman, A. S., Feingold, G., Platnick, S., Pincus, R., and Xue, H. Effects of cloud horizontal inhomogeneity and drizzle on remote sensing of cloud droplet effective radius: Case studies based on large-eddy simulations. *Journal of Geophysical Research: Atmospheres*, *117*(D19), 2012. D19208.

Zhang, Z. (2013), On the sensitivity of cloud effective radius retrieval based on spectral method to bi-modal droplet size distribution: A semi-analytical model, *J. Quant. Spectros. Radiat. Transfer*, *129*, 79–88, doi:10.1016/j.jqsrt.2013.05.033.

1.0.2 Minor remarks

- **p.1 l.15** *“by” should be with?*

Yes, done

- **p.2 l.12** *“thicknesses” should be singular*

Yes, done

- **p.5 l.01** *shown “in” table*

Yes, done

- ***p.5 l.16 I assume you meant 100e9 for all simulations? This is impressive if that is a single core performance which would be 2e6 photons per sec. Or was that parallelized on multiple cores/nodes? If so please state the number of core hours.***

Thank you for pointing this out, it was a mistake, the computational time is about 3.5 days for 100 billions of photons for each simulations (spread on 2048 batches). Below is a detail of one of the simulations.:

Total time = 3 days, 13 hrs, 14 mins, 2 secs
Mean time per trial = 0.80 millisecs
Mean time per scatter = 145.60 microsecs
Mean time per batch = 149.83secs
102400.00 Mtrials completed with 2048batches

We have corrected the computational time in the manuscript and explain that those simulations have been parallelized on 2048 core each.

- ***p.5 l.27 Conversely?***

Yes, done

- ***p.7 l.12 “more” should be “higher”?***

Yes, done

- ***p.7 l.16 + fig.2 Please change the color of the 1D markers and put them on top, I could not see your claims.***

We assume that you mean Fig. 4 and we made the change in the figure.

- ***p.7 l.20 effects should be singular?***

Yes, done

- ***p.8 l.24 green? . . . and I thought I am not colorblind. . .***

No, you are not! That was a mistake, we have corrected it according to the color change you asked for this figure.

- ***p.9 l.02 temperatures should be singular***

Yes, done

- ***p.10 l.7 remove “issue”?***

Yes, done

- ***p.11 l.6 remove “view”?***

Yes, done

- ***p.11 l.34 remove the “a” in “for a various view”***

Yes, done

- ***p.12 l.08 process should be plural***

Yes, done

- **p.12 l.09 Simulation should be plural?**

Yes, done

- **p.12 l.12 take should be taken**

Yes, done

- **p.12 l.13 maybe change “here are ranged to” “here range from”**

Yes, done

- **p.12 l.21 “shown” should be “show”?**

Yes, done

- **p.13 l.06 “this” should be “these”?**

Yes, done

- **p.13 l.20 insert “from” after “ranging”**

Yes, done

- **f fig.1 Error in caption, reference to (f) is (e)**

Yes, done

- **f fig.2 if you mention 50m here I am wondering was it something else in fig1?**

No, both are at 50 m spatial resolution so we now mention it too in Fig.1.

- **f fig.3 I would like it very much if you could provide short conclusions here already in the caption**

We add: “Because of the non-linearity between R1D and τ , the τ retrieved from averaged $\overline{R1D}$ is smaller than the averaged $\bar{\tau}$ retrieved from the two R1D.”

- **f fig.4 As mentioned earlier, please update the colors so that a reader can distinguish the markers**

Done, thank you.

- **f fig.5 please add the idea of the panels and colors to the caption. I.e. left to right are zenith angles, colors are view zenith angles**

Done, thank you

- **f fig.6 put brackets around equation references? Change null to $_s = 0$**

We changed equations 2 to Eq.2 and changed null to 0.

- **table 1 MOD06 optical properties please write out the names and symbols**

Done, thank you

- **table 1 why use diameter here when you use radius everywhere else?**

We changed it to effective radius of 10 micron

- **table 1 _ for channel 2 differs. . . is .83 micron correct?**

No it should be 0.86 micron, thank you.

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- Fauchez, T., Platnick, S., Sourdeval, O., Wang, C., Meyer, K., Cornet, C., and Szczap, F. *Cirrus horizontal heterogeneity and 3D radiative effects on cloud optical property retrievals from MODIS near to thermal infrared channels as a function of spatial resolution. JGR 2018, in review*
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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 proofread by a native English speaker.

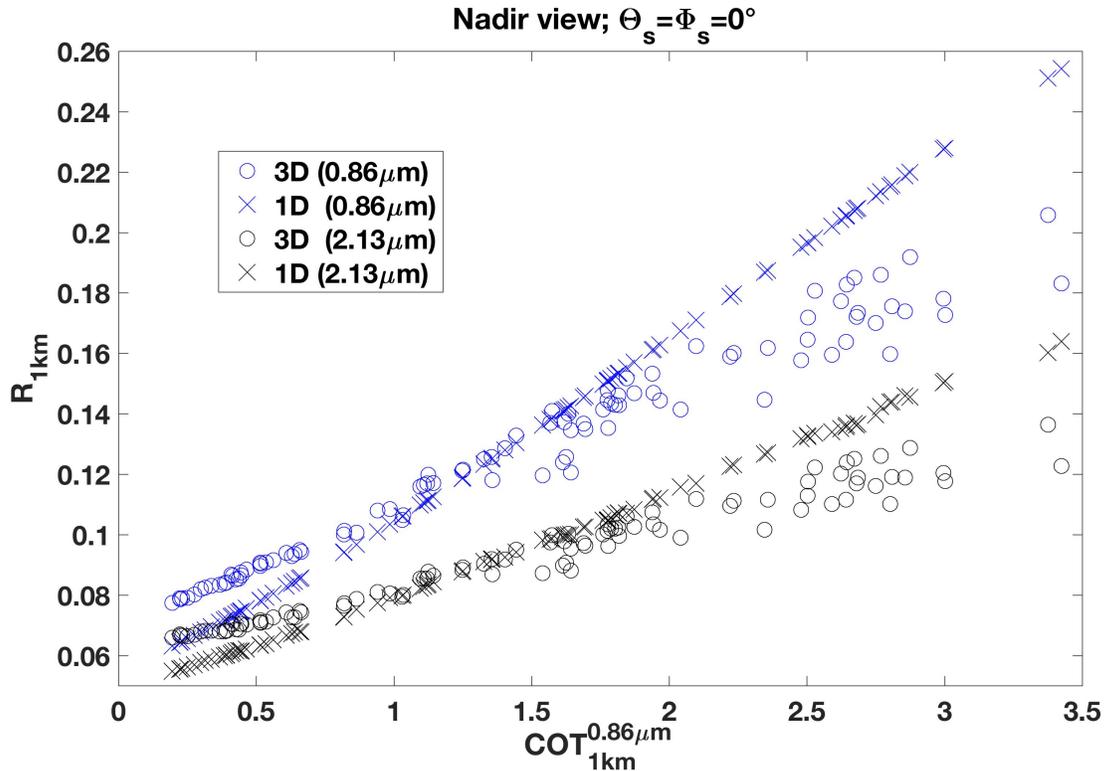
1) p7, l11: "photons in thin columns have less chance to be absorbed" : : : "photons in neighboring columns with stronger scattering have more chance to leave the cloud if they are scattered toward a neighboring column with smaller extinction coefficient".

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 an 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) p5,121: 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) p7,115-17: 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., p7,121). 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) p8,125: “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) p9,116: 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 agree 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 chose to calculate 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 large, 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:

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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.

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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 remove “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.

p2,122-23: 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.”

p4,12: “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.