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Impacts of cirrus clouds heterogeneities on TOA thermal infrared radiation

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Abstract

This paper presents a study on the impact of cirrus cloud heterogeneities on the thermal infrared brightness temperatures at the Top Of Atmosphere (TOA). Realistic 3-D cirrus are generated by a cloud generator based on simplified thermodynamic and dynamic equations and on the control of invariant scale properties. The 3-D thermal infrared radiative transfer is simulated with a Monte-Carlo model for three typical spectral bands in the infrared atmospheric window. Comparisons of TOA brightness temperatures resulting of 1-D and 3-D radiative transfer show significant differences for optically thick cirrus ($\tau > 0.3$ at 532 nm) and are mainly due to the Plan-Parallel Approximation (PPA). At the spatial resolution of 1 km × 1 km, two principal parameters control the heterogeneity effects on brightness temperatures: (i) the optical thickness standard deviation inside the observation pixel, (ii) the brightness temperatures contrast between the top of the cirrus and the clear sky atmosphere. Furthermore, we show that the difference between 1-D and 3-D brightness temperatures increases with the view zenith angle from two to ten times between 0° and 60° due to the Tilted Independant Pixel Approximation (TIPA).

1 Introduction

Cirrus clouds cover from 15 % to 40 % of the Earth's surface (Sassen et al., 2008). The temperature difference between the cloud top and the surface leads to a warming of the atmosphere by capturing a part of the infrared radiation emitted by the Earth's surface. On the contrary, a part of the solar incident radiation is reflected to the space by the parasol effect, but this is generally slight for high clouds. Therefore, cirrus clouds lead to a positive radiative forcing (e.g. a greenhouse effect) and their knowledge and evolution are crucial in the understanding of the Earth's radiative budget (Hartmann and Short, 1980; Ohring and Clapp, 1980; Stephens, 2005; Eguchi et al., 2007).

Global observations are well adapted to follow and better understand cloud evolution and characteristics. With this aim, many satellites are dedicated to their observations from visible to infrared wavelengths. Algorithms usually used to retrieve cloud parameters from passive instruments, such as optical thickness and effective diameter of ice crystals, assume that clouds are homogeneous and infinite between two planes. This assumption is called the homogeneous *Independent Pixel Approximation* (IPA, Cahalan et al., 1994) or *Independent Column Approximation* (ICA, Stephens et al., 1991). However, real clouds can be far from this idealized model and this assumption may lead to bias on the retrieval of clouds properties.

In this context, radiative transfer modelling is very useful to study the 1-D bias in function of the cirrus structure and composition. Many studies have been conducted on the impact of cloud heterogeneities in the visible range and principally for warm clouds (Marshak and Davis, 2005). However, only few studies have been performed on cirrus cloud heterogeneities in the thermal infrared and they concern mainly the fluxes or heating/cooling rates. Concerning the fluxes, Hogan and Kew (2005) showed that radiative transfer calculations using IPA can change the mean TOA radiative fluxes of about $45\,\mathrm{W\,m^{-2}}$ in the shortwave and $15\,\mathrm{W\,m^{-2}}$ in the longwave. Furthermore, Chen and Liou (2006) showed that significant impact exists on the broadband thermal cooling rates (around 10 %) when the 3-D radiative transfer is compared to 1-D radiative transfer.

As far as we know, no study has been made concerning the heterogeneity bias on the infrared radiative quantities measured by space sensors. However, satellites, such as the Imaging Infrared Radiometer (IIR, Garnier et al., 2012, 2013) or the Moderate Resolution Imaging Spectroradiometer (MODIS, Cooper et al., 2007; Wang et al., 2011), use TOA Brightness Temperatures (BT) in the thermal infrared window to retrieve cloud parameters. In this paper, we study the impact of cirrus heterogeneities in this spectral domain. In Sect. 2, we present the model 3DCloud (Szczap et al., 2013) used to generate realistic cloud scenes and the Monte-Carlo 3-D radiative transfer code named 3DMCPOL (Cornet et al., 2010) used to simulate the radiative transfer inside

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three dimensional (3-D) atmospheres. We simulate BT for several cirrus generated from realistic conditions as well as from measurements made during the CiRus CLoud Experiment-II (CIRCLE II) airborne campaign. In Sect. 3, the biases due to heterogeneities are quantified by comparing the 3-D and 1-D BT at the IIR spatial resolution (1 km × 1 km). Summary and conclusions are given in Sect. 4.

2 Cirrus cloud generation

In order to simulate the impact of cirrus heterogeneities on the TOA BT, realistic 3-D cirrus need to be generated. Firstly, 3-D cirrus Ice Water Content (IWC) was simulated with a cloud generator based on basic atmospheric equations as well as Fourier transform framework to constrain invariant scale properties. Then, the optical properties are parametrized with two different models described hereafter.

2.1 3-D Ice Water Content generation

Cirrus clouds are generated by the 3DCloud model (Szczap et al., 2013). Firstly, basic atmospheric equations with idealized meteorological profiles are resolved in order to simulate the 3-D IWC. Secondly, scale invariant properties are constrained by the iterative Fourier framework. Hogan and Kew (2005) have shown that the IWC or 3-D extinction are characterized by a power spectra with a $-5/3$ spectral slope. Generally, this spectral slope is delimited by a large scale limit L_{out} and a smaller scale limit corresponding to the cloud pixel spatial resolution. Hogan and Kew (2005) estimated from radar reflectivity and cirrus temperature that the IWC spectral slope is equal to $-5/3$ from scales of the order of a meter to a L_{out} of 50 km at the top of the cirrus, but it can decrease with the optical depth. Hogan and Kew (2005) have supposed that this decrease can be due to the coupled action of the wind shear with a spread of particle fall speeds leading to a homogenization of the IWC preferentially at smaller scales. With this behaviour, the cirrus must be old enough for that an important sedimentation

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of crystals to appear. However, as we show later on LIDAR measurements, we do not observe a change in the spectral slope with the altitude (see at the end of the section). Therefore, in our cirrus simulations, the spectral slope is assumed to be equal to $-5/3$ at all scales and altitudes.

For this study, two different cloud structures are generated. The first cirrus field (Fig. 1) is based on meteorological profiles to form a cirrus cloud as presented by Starr and Cox (1985), with the addition of a wind profile to form virgas. From this first realisation, the influence on TOA BT of the cirrus mean optical thickness τ_c, the cirrus heterogeneity parameter ρ_τ, the ice crystal effective diameter D_{eff} and the cirrus altitude are easily tested. The heterogeneity parameter is defined by Szczap et al. (2000) as $\rho_\tau = \sigma_\tau/\tau_c$, with σ_τ the standard deviation of the optical thickness. Eight cirrus with different mean cloud parameters are generated (see Table 1). The cirrus mean optical thickness τ_c increases from 0.45 to 1.8, the cirrus heterogeneity parameter ρ_τ from 0.7 to 1.5, the ice crystal effective diameter D_{eff} from 9.95 µm to 40.58 µm and the altitude from 7.97 km to 11.06 km. These macrophysical parameters cover the characteristics of usual cirrus clouds (Sassen and Cho, 1992; Szczap et al., 2000; Carlin et al., 2002; Lynch et al., 2002), as well as the values of D_{eff}. Figure 1a shows an example of a 10 km × 10 km optical thickness field at 12.05 µm with a spatial resolution of 100 m and Fig. 1b the x-z view of the Ice Water Content (IWC).

The second cirrus is generated from measurements obtained on 25 May 2007 during the CIRCLE II campaign (Mioche et al., 2010). CIRCLE II was an airborne campaign dedicated to the study of the cirrus optical properties and the validation of space measurements made by the LIDAR CALIOP and the Infrared Imaging Radiometer IIR on board CALIPSO. This campaign consists of two Falcon 20 aircraft with several complementary on-board instruments to study cirrus cloud. In order to simulate the cirrus observed during this campaign in a realistic way, we used in input of 3DCloud the in situ measurements provided by the aircraft as well as IIR and MODIS radiometric measurements. The cirrus mean IWC is determined by the combination of the CPI (Cloud Particle Imager), more sensitive to small particles, and the PMS (Particle Measuring

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System) FSSP 300 probes, more sensitive to large particles. The extinction coefficient is obtained by the Polar Nephelometer (PN) and the cirrus mean optical thickness by IIR measurements. In addition, the meteorological profiles (wind speed and orientation, temperature, humidity etc.) are set in the model (Fig. 2) using the meteorological data provided by the European Center for Medium-Range Weather Forecasts (ECMWF) with adaptations of the potential temperature and relative humidity profiles necessary to form cirrus (Starr and Cox, 1985).

The scale invariant properties are controlled by a $-5/3$ constant spectral slope at all the scales and altitude levels according to the cirrus backscattering coefficient at 532 nm measured at different altitudes by the LIDAR CALIOP/CALIPSO (Fig. 3), and the extinction coefficient measured by the Polar Nephelometer at the aircraft altitude.

To compare real measurements and 3DCloud simulations, the MODIS "true color RGB" picture of the cirrus is presented in Fig. 4a. Figure 4b corresponds to the CALIOP/CALIPSO vertical profile of the cirrus attenuated backscattering coefficient. Figure 4c represents the 20 km × 20 km optical thickness field at a spatial resolution of 100 m generated by 3DCloud inside the black rectangle of Fig. 4a and Fig. 4d the IWC profile with a vertical resolution of 58 m. On Fig. 4a and Fig. 4c, the lines in the cirrus have the same orientation. It illustrates that the cirrus generated by 3DCloud and that one observed on 25 May 2007, during the CIRCLE II campaign, have a similar geometry. The mean optical thickness is set $\tau_c = 0.41$ in the model as that retrieved from the IIR measurements in the black rectangle area. Furthermore, the comparison of Fig. 4b and 4d allows us to see that the vertical profiles of the simulated and observed cirrus present the same cloud top and base altitudes. Three different simulations were done from the cirrus field observed during CIRCLE II and their properties are summarized in Table 1. The cirrus CII-1 corresponds to the simulation of the cirrus observed on 25 May. The cirrus CII-2 is the same with the IWC increased twofold. The cirrus CII-3 has the same distribution of IWC but with optical properties of the cirrus 8. Their properties are resumed in Table 1.

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2.2 Cirrus optical property parametrization

Cirrus microphysical and optical properties are particularly difficult to apprehend because of the variability of shapes, sizes and orientations of ice crystals that can exist. Numerous studies have treated this problem and used different methods to compute the optical properties of cirrus clouds for visible and infrared wavelengths (Magono, 1966; Labonnote et al., 2000; Yang et al., 2001, 2005; Baum et al., 2005, 2011; Baran and Labonnote, 2007; Baran et al., 2009, 2011a, b). Among all the available methods, we choose for the cirrus 1 to 8 to use the ice crystals model developed by Yang et al. (2001, 2005). This model allows us to supply an extinction coefficient, a single scattering albedo and an asymmetry factor for seven forms of crystals having an effective diameter from 1 µm to 10 000 µm. In our simulations, the aggregate shape with a monodisperse distribution is selected because it is one of those used in the IIR retrieval algorithm (Garnier et al., 2013). Furthermore, in the thermal infrared, the forward peak is weak and the particle phase functions are smooth enough to be approximate in a correct way (Yang et al., 2001) by phase functions of Henyey-Greenstein type (Henyey and Greenstein, 1940) that is assumed in the Yang et al. (2001, 2005) model. Values of the extinction coefficient efficiency, the single scattering albedo and the asymmetry parameter are presented in Table 2.

For the CII-1 and CII-2, the parametrization developed by Baran et al. (2009, 2011a, b) is used to study the impact of the optical property variabilities on the TOA BT. This parametrization consists in obtaining the extinction coefficient σ_e, the single scattering albedo ϖ_0 and the asymmetry factor g from the couple (IWC, Temperature). The relations between the optical properties and the couple (IWC, Temperature) were obtained from more than 20 000 Particle Size Distributions (PSD) provided by in situ measurements (Field et al., 2005, 2007). Therefore, from a realistic 3-D profile of IWC and temperature, we employed this parametrization to generate the 3-D heterogeneous optical property field for the CII-1 and CII-2 cirrus. Their vertical optical property distributions are presented in Fig. 5.

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2.3 Radiative transfer modelling

Thermal radiative transfer computations are made with the 3-D Monte-Carlo code, 3DMCPOL, initially developed in the visible range by Cornet et al. (2010) and extended for this study to the Thermal InfraRed (TIR). In 3DMCPOL, the atmosphere is divided into voxels (3-D pixels), with a constant horizontal size (dx, dy) and a variable vertical size dz. Each of the voxels is described by the cloud optical properties: the extinction coefficient σ_e, the single scattering albedo ϖ_0, the phase function and the cloud temperature T_c. 3DMCPOL is a forward Monte-Carlo which used the Local Estimate Method (LEM, Marshak and Davis, 2005; Mayer, 2009). It was first developed for the visible range where the initial direction of photon packages is given by the solar direction. The extension of the code to the TIR conserved the forward method, even if the source of emission can be the atmosphere, the surface or the cloud.

Monte-Carlo methods consist in following photon packages, which undergo some scattering and absorption processes in the atmosphere and surface reflections. At each scattering event, the LEM is used and consists to compute the contribution of emission, scattering or reflection events into the detector direction, attenuated by the medium optical thickness crossed between the interaction and the detector. The LEM weight W_{le} attached to the photon is thus defined as:

$$W_{le} = \frac{W_{\varpi_0} P_{11}(\theta_s) \exp(-\tau_m)}{\cos(\theta_v)}, \tag{1}$$

with P_{11} the first element of the scattering matrix which gives the probability of a photon to be scattered in the direction of the detector, θ_s the scattering angle between photon direction and the detector, τ_m the medium optical thickness from the interaction to the detector and θ_v the view zenith angle. W_{ϖ_0} is the weight due to the cloud absorption and it corresponds at each interaction to the product of the single scattering albedo ϖ_0 for cloud scattering (or of the surface albedo α for surface reflection). When W_{ϖ_0} is less

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than 10^{-6}, the contribution of the photon package is considered to be neglectful and a new one is launched.

To include the gaseous absorption in 3DMCPOL, we use the correlated k-distribution method (Lacis and Oinas, 1991; Kratz, 1995). This technique allows us to take into account the absorption variations in each spectral band by dividing the range of absorption coefficient values into bins using a sum of weighted exponentials. To each bin, a weight a_{ib} is associated whose sum is equal to 1. However, to avoid running radiative transfer for every bin which is very time consuming, we use the Equivalence Theorem (Partain et al., 2000; Emde et al., 2011). It consists in attaching an absorption vector W_g to the photon package, with a size corresponding to the bin number n_{bin} of the correlated k-distribution. $W_g(\text{ib})$ is expressed by Eq. (2).

$$W_g(\text{ib}) = \exp\left(-\int_0^l k_g(\text{ib}, z)\,\mathrm{d}l'\right), \tag{2}$$

with ib the number of correlated k-distribution bin, l the photon package path and $k_g(\text{ib}, z)$ the absorption coefficient for bin ib and altitude z.

With the gaseous absorption, the LEM weight W_{le} becomes a vector of size n_{bin} as:

$$W_{\text{le}}(\text{ib}) = \frac{W_g(\text{ib})\,W_{\varpi_0}\,P_{11}(\theta_{\text{s}})\exp(-\tau_{\text{m}})}{\cos(\theta_{\text{v}})}. \tag{3}$$

With this method, it is possible to compute the reflectance for a spectral band with variable gaseous absorption with one Monte-Carlo RT simulation, as long as the medium optical properties are homogeneous. The other important modification concerns the sources of emission. The total number of emission processes (or photon packages) is fixed in input by the user and a fraction of the total number of photon packages corresponds to each source (cloud, surface and gases). This fraction is obtained in function of the emission characteristics (emissivity, temperature) of all the corresponding voxels. We compute a quantity called source flux F, defined as the energy

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emitted in every direction by each cell of the emission source. As emission processes are isotropic, the direction of emission is chosen randomly. The sum of the source flux of the cloud, the surface and the gases ($F_c + F_s + F_g$ respectively) over all the cells gives the total emitted energy. The number of photons emitted by a source type is then the proportion of energy of this source to the total energy. A random choice determines the spatial location where the emission takes place.

The source flux F is computed from the radiance R. For cloud cell, the source flux F_c is defined as:

$$F_c = 4\pi R_c = 4\pi \tau_a B(T_c) = 4\pi(1-\varpi_0)\tau_e B(T_c), \tag{4}$$

with R_c the cloud radiance emitted by the cell, τ_a and τ_e the absorption and extinction optical thicknesses respectively, $B(T_c)$ the Planck function at the temperature T_c and ϖ_0 the single scattering albedo. In the same way, the source flux F_s emitted from the surface is defined as:

$$F_s = \pi R_s(\theta,\phi) = \pi \epsilon_s B(T_s), \tag{5}$$

with R_s, ϵ_s and T_s the surface radiance, the emissivity and the surface temperature respectively. Finally, the source flux F_g emitted by the gases in function of bin ib is expressed by:

$$F_g(\mathrm{ib}) = 4\pi R_g(\mathrm{ib}) = 4\pi a_{\mathrm{ib}} \tau_g(\mathrm{ib}) B(T_c), \tag{6}$$

with a_i, the weight associated to bin ib, $\tau_g(\mathrm{ib})$ the gaseous optical thickness.

Validation of the 3DMCPOL modifications was done by inter-comparisons with SHDOM simulations (Evans, 1998). An example of comparison between 3DMCPOL and SHDOM is illustrated in Fig. 6 at the scale of $100\,\mathrm{m} \times 100\,\mathrm{m}$, for the cirrus 3 and for $\theta_v = \phi_v = 0°$. Three and half billion photon packages are launched, which lead to a statistical accuracy of about $10^{-3}\,\mathrm{W\,m^{-2}\,sr^{-1}}$. Figure 6a shows the 3DMCPOL radiance field view at the nadir, Fig. 6b presents the comparison of 3DMCPOL and SHDOM

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radiances along the X-axis for $Y = 5$ km, Fig. 6c shows the relative difference (%) field between 3DMCPOL and SHDOM radiances and Fig. 6d represents the correlation plot between 3DMCPOL and SHDOM radiances. The relative error between 3DMCPOL and SHDOM simulations is generally under 2 % and the correlation between the two models is 0.998. The small remaining differences can be explained by the different treatment of the medium properties as 3DMCPOL considers the medium properties homogeneous in each voxel while SHDOM interpolates the properties in a voxel. Comparisons were also been made for several cases of cirrus and spectral bands and give similar results.

3 Heterogeneity effects on the brightness temperatures simulated at TOA

3.1 Description of the heterogeneity effects

Clouds present many variabilities at different scales. In retrieval algorithms, for simplifications and computational reasons, the Independent Column Approximation (ICA, Stephens et al., 1991) is commonly applied: the cloud layers are assumed to be vertically and horizontally homogeneous and independent of each other. At the scale of IIR (or MODIS) observation pixel (1 km × 1 km), the radiative transfer is supposed to be 1-D without horizontal transport between columns. Cloud properties are assumed to be homogeneous in each cloudy layer. To study the cirrus heterogeneity effects that can affect the BT observed in the thermal infrared at TOA, we made 3-D and 1-D simulations with 3DMCPOL. 3-D BT are simulated at the spatial resolution of 100 m × 100 m and then averaged to 1 km × 1 km ($BT3D_{1\,km}$). For 1-D BT, cloud properties are first averaged at 1 km × 1 km before simulating BT ($BT1D_{1\,km}$). Note that the spatial resolution is an important parameter in the study of the impact of cirrus heterogeneities on BT and our results are, thus, only applicable for a spatial resolution close to 1 km × 1 km.

To describe the heterogeneity effects, we plot in Fig. 7 the variation of the BT at 100 m ($BT3D_{100\,m}$) in function of the optical thickness at 100 m ($\tau_{100\,m}$) for the cirrus 5 and for

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the three IIR channels (8.65 µm, 10.60 µm and 12.05 µm). We see that the relation is non-linear and the averaging of BT leads to Jensen inequality, usually called the Plan Parallel Approximation (PPA). The width of the $BT3D_{100\,m}$ distribution, which is about 4–5 K, is due, on the one hand, to the vertical variability of the extinction coefficient and, on the other hand, to the photon horizontal transport between cloud columns (Varnai and Marshak, 2001). The PPA thus causes the average of BT ($\overline{BT3D}$) to be higher than the BT of the average of the optical thicknesses $\bar{\tau}$.

In Figs. 8 and 9, we plot the absolute value of the BT differences at the scale of 100 m ($|\Delta BT_{100\,m}|$) and 1 km ($|\Delta BT_{1\,km}|$) respectively for a case of a very inhomogeneous cirrus (cirrus 5). Note that, for 3D brightness temperatures at 100 m × 100 m ($BT3D_{100\,m}$), the extinction coefficient varies vertically, and not for the 1-D brightness temperatures at 100 m × 100 m ($BT1D_{100\,m}$). Several effects contribute to the differences between 3-D and 1-D BT and are described below for the 100 m spatial resolution (Fig. 8):

- In green, we plot the absolute value of the extinction vertical heterogeneity effect $|BT1Dvhe_{100\,m} - BT1D_{100\,m}|$, with $BT1Dvhe_{100\,m}$ corresponding to 1-D radiative transfer with independent column and vertically heterogeneous extinction coefficient.
- In red, we plot the absolute value of the BT difference due to the horizontal transport which is computed with the calculation of $|BT3Dvho_{100\,m} - BT1D_{100\,m}|$ with $BT3Dvho_{100\,m}$ corresponding to 3-D radiative transfer with vertically homogeneous extinction.
- In blue, we plot the absolute value of the difference $|\Delta BT_{100\,m}|$ obtained with the calculation of $|BT3D_{100\,m} - BT1D_{100\,m}|$. Note that $|\Delta BT_{100\,m}|$ is not the sum of the two effects described above, because some of them can be opposing.

In addition, we also plot the absolute value of the statistical error (black line) due to the statistical approach of the Monte-Carlo algorithm which is about 0.5 K.

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We see that at 100 m, the $|\Delta BT_{100\,m}|$ for the band at 8.65 µm is larger and dominated by the horizontal transport effect because the scattering is higher for this band than the two others. On the contrary, the vertical extinction variability, which is also associated to the vertical emissivity variability, is larger at 10.60 µm and at 12.05 µm than for the band at 8.65 µm. For these two bands, the horizontal transport effect and the vertical extinction variability are of the same order and thus, contribute with equal prominence to the total differences $|\Delta BT_{100\,m}|$. The results are similar for the other cirrus cases and they are not presented here.

At the scale of 1 km × 1 km (Fig. 9) the horizontal transport (red) and the extinction vertical heterogeneity (green) effects are slight. That means that the absolute difference $|\Delta BT_{1\,km}|$ (blue) between $BT3D_{1\,km}$ and $BT1D_{1\,km}$ are strongly dominated by the PPA. It reaches more than 12 K for the largest optical thicknesses in the three bands. Horizontal transport in the band at 8.65 µm is larger than in the other bands, but remains low compared to the total difference $|\Delta BT_{1\,km}|$. The extinction vertical inhomogeneity appears also negligible at the 1 km × 1 km scale. In summary, Fig. 9 shows that, at the scale of IIR and MODIS, the most important difference between $BT3D_{1\,km}$ and $BT1D_{1\,km}$ is due to the PPA. During the retrieval process, the cloud properties retrieved from brightness temperatures at the 1 km × 1 km pixel will thus be different from the mean cloud properties.

3.2 Heterogeneity effects due to optical thickness variabilities

This section focuses on the impact of the optical thickness variabilities on TOA BT, all the other parameters being constant (atmospheric profile, altitude, geometrical thickness, surface temperature, particles size and shape). Figure 10 presents the heterogeneity effects on the brightness temperatures ($\Delta BT_{1\,km}$) for the band at 12.05 µm in function of the optical thickness $\tau_{1\,km}$ (Fig. 10a), the standard deviation of the optical thickness $\sigma_{\tau_{1\,km}}$ computed from the 100 pixels of 100 m × 100 m (Fig. 10b), and the heterogeneity parameter $\rho_{\tau_{1\,km}}$ at 1 km × 1 km (Fig. 10c). We see that the difference $\Delta BT_{1\,km}$ is better correlated with $\sigma_{\tau_{1\,km}}$ ($R = 0.95$). Indeed, as discussed previously, the

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PPA is the most important effect at this scale and the larger $\sigma_{\tau_{1\,\mathrm{km}}}$ is, the greater the averaging effect is and, thus, the difference $\Delta\mathrm{BT}_{1\,\mathrm{km}}$. Furthermore, as the increase in the $\tau_{1\,\mathrm{km}}$ is not totally correlated with the increase in the sub-pixel heterogeneity $\sigma_{\tau_{1\,\mathrm{km}}}$, the correlation between $\Delta\mathrm{BT}_{1\,\mathrm{km}}$ and $\tau_{1\,\mathrm{km}}$ is smaller, as well as the correlation between $\Delta\mathrm{BT}_{1\,\mathrm{km}}$ and $\rho_{\tau_{1\,\mathrm{km}}}$. The $\sigma_{\tau_{1\,\mathrm{km}}}$ appears, therefore, to be the best parameter to highlight the heterogeneity effects and it will always be used afterwards to represent the field heterogeneity.

The $\Delta\mathrm{BT}_{1\,\mathrm{km}}$ in function of the standard deviation $\sigma_{\tau_{1\,\mathrm{km}}}$ for the different cirrus of Table 1 and for the three channels of the IIR are presented in Fig. 11. The first remark on this figure is that correlation coefficient R is better than 0.80 for all the cirrus, except for cirrus 1. For this cirrus, the lowest optical thickness (0.45) associated to the strong scattering at 8.65 µm lead to smoothing of the variability due to the photon transport. The five cirrus have similar characteristics with different mean optical thickness τ_c and heterogeneity parameter ρ_τ. For each of these cirrus, we computed $\mathrm{BT3D}_{1\,\mathrm{km}}$ and $\mathrm{BT1D}_{1\,\mathrm{km}}$ for 100 pixels of 1 km × 1 km. We see that the relation between $\Delta\mathrm{BT}_{1\,\mathrm{km}}$ and $\sigma_{\tau_{1\,\mathrm{km}}}$ is almost linear. This figure shows that, for the same altitude, geometrical thickness and optical properties, $\Delta\mathrm{BT}_{1\,\mathrm{km}}$ depends mainly on the optical thickness sub-pixel heterogeneity, the optical thickness sub-pixel distribution being almost insignificant. Note that, similar results were obtained in the visible (Szczap et al., 2000; Cornet et al., 2004) where heterogeneity effects depend mainly on $\tau_{1\,\mathrm{km}}$ and $\sigma_{\tau_{1\,\mathrm{km}}}$.

We now study the impact of heterogeneities for different ice crystal effective diameters D_{eff}. In Fig. 12, we present $\Delta\mathrm{BT}_{1\,\mathrm{km}}$ in function of $\sigma_{\tau_{1\,\mathrm{km}}}$ for $D_{\mathrm{eff}} = 9.95\,\mu\mathrm{m}, 20.09\,\mu\mathrm{m}$ and 40.58 µm. The crystal model used is the P. Yang model (Yang et al., 2001, 2005, Table 2), for an aggregate shape. This figure shows that $\Delta\mathrm{BT}_{1\,\mathrm{km}}$ decrease with the increase in D_{eff} for the three TIR bands. For the bands at 10.60 µm (Fig. 12b) and at 12.05 µm (Fig. 12c), the single scattering albedo ϖ_0 and the asymmetry parameter g increase with D_{eff} (Table 2), that lead to a decrease in the absorption inside each 1 km × 1 km pixel and an increase in energy in the forward peak respectively. Therefore, photons emitted from the surface cross easier the cloud, leading to a decrease in the contrast between high and low optical thicknesses. The radiative field heterogeneities appear thus smoothed. Concerning the band at 8.65 µm, ϖ_0 decreases with D_{eff} but the asymmetry parameter g increases. Between D_{eff} = 9.95 µm and D_{eff} = 20.09 µm, the increase in g dominates and, as previously explained, the $\Delta BT_{1\,\text{km}}$ decrease. But between D_{eff} = 20.09 µm and D_{eff} = 40.58 µm, g increases slightly and ϖ_0 decreases. These two effects are opposite and the $\Delta BT_{1\,\text{km}}$ do not change significantly between these two effective sizes.

In summary, the amplitude of heterogeneities effect depends on the particle effective size when a constant size is supposed in the cloud. Indeed, in this situation, the optical properties can be very different from one crystal size to another and, thus, lead to different values. For example, the mean value of $\Delta BT_{1\,\text{km}}$ for the cirrus 3 is 3.12 K (band at 12.05 µm), while for cirrus 7 the mean value is 0.99 K. However, a unique crystal size and shape as supposed in these simulations is not realistic. It just allows us to give information on the crystal size influence on TOA BT. In reality, a large variety of particle sizes and shapes are present in a cirrus and, therefore, a more complex parametrization of the optical properties is necessary to study the impact of the optical property variabilities on TOA BT.

3.3 Heterogeneity effects due to optical and microphysical property variabilities

To study the effects of three dimensional optical property heterogeneities on TOA BT and simulate more realsitic clouds, we employed the parametrization developed by Baran et al. (2009, 2011a, b) (see Sect. 2.2). The cirrus simulated from the CIRCLE II campaign are used to generate a heterogeneous macrophysical field (Fig. 4 and Table 1) and optical property field (Fig. 5).

Before studying the heterogeneities' effect, we look at the effects of vertical variabilities of the extinction coefficient σ_e, the single scattering albedo ϖ_0 and the asymmetry factor g (Fig. 13). The 1-D RT with homogeneous columns ($BT1D_{1\,\text{km}}$) is compared with the 1-D RT with heterogeneous columns ($BT1Dhe_{1\,\text{km}}$) for the cirrus CII-2. We see that the difference is, on average, lower than 0.5 K for the three channels and it is maximum for the band at 8.65 µm. Indeed, because the scattering is higher in this band and thus the absorption lower, the vertical optical property variabilities have, therefore, a more significant impact on BT.

$\Delta BT_{1\,km}$ in function of $\sigma_{\tau_{1\,km}}$ are presented in Fig. 14 in the three IIR channels for cirrus CII-1 and CII-2 with variable optical properties and for cirrus CII-3 with homogeneous optical properties. This last cirrus has been generated in order to compare, on the one hand, the two optical property models and, on the other hand, the influence of the cirrus vertical extension (see Sect. 3.4). In this figure, the mean correlation coefficient R averaged on the three channels between $\Delta BT_{1\,km}$ and $\sigma_{\tau_{1\,km}}$ is larger again than 0.80. The low value of R (0.88) for cirrus CII-1 is due to the band at 8.65 µm. Indeed, in this case, the PPA bias is close to zero, firstly because the $\sigma_{\tau_{1\,km}}$ values are quite small the cirrus CII-1 and, secondly, because there is more scattering which tends to smooth the field heterogeneity and, thus, decorrelates the relation between $\Delta BT_{1\,km}$ and $\sigma_{\tau_{1\,km}}$. For this cirrus, which is the result of the realistic simulation obtained from the cirrus observed during the CIRCLE II campaign, the heterogeneities' effect on the TOA BT are, on average, lower than the instrumental precision of the IIR (1 K). The PPA and IPA bias have, thus, a limited impact in this case. Concerning the cirrus CII-3 with homogeneous optical properties, the $\Delta BT_{1\,km}$ is lower than for other cirrus for the band at 8.65 µm, but this difference decreases for the band at 10.60 µm and becomes positive for the band at 12.05 µm. Indeed, cirrus CII-3 contains only small aggregate crystals ($D_{eff} = 9.95$ µm). As explained in Sect. 3.2, the PPA is larger for the band at 12.05 µm because small particles are highly absorbing in this band (Table 2). For the band at 8.65 µm, ϖ_0 is more important for small particles leading to more scattering which, thus, smooth the heterogeneities. We can, thus, conclude that the optical property model has a weak influence on the heterogeneity effects on BT (in average inferior to 1 K).

3.4 Influence of altitude and geometrical thickness of the cirrus cloud

In the troposphere, the temperature decreases with altitude. A cirrus with a high altitude emits, therefore, at a lower temperature than a cirrus with the same optical properties at a lower altitude. Figure 15 presents $\Delta BT_{1\,km}$ in function of $\sigma_{\tau_{1\,km}}$ for cirrus 2 with the top altitude of 7.97 km, the cirrus 8 and CII-3 with the top altitude of 11.06 km. We note that $\Delta BT_{1\,km}$ is greater for the higher cirrus. Indeed, for a higher cloud, the BT contrast between the cloud top and the clear sky is larger and, thus, the PPA bias is also larger.

To study the influence of the vertical extension, we then compare the cirrus 8 and CII-3. They have the same optical characteristics, the same cloud top altitude but a different vertical extension involving a different cloud base at 9.06 km for cirrus CII-3 and at 10.60 km for cirrus 8. Note that, the cirrus optical thickness distribution is also different but, as seen previously, it does not influence the $\Delta BT_{1\,km}$ much. Figure 15 shows slight differences between the two clouds at 8.65 µm and at 10.60 µm but a greater difference at 12.65 µm. At this wavelength, the absorption is strong, leading to a large contrast between the cloud top and clear sky brightness temperatures. However, the cloud base of cirrus CII-3 is at a lower altitude, meaning that the emission temperature is higher and, thus, closer to the surface temperature. The average temperature of cirrus CII-3 is, thus, less contrasted with the surface temperature than for cirrus 8, leading to a lower PPA bias. To conclude, for two identical cloud top altitudes, if the band is strongly dominated by the absorption (as the band at 12.05 µm), the PPA bias decreases with the increase in the vertical extension, but this effect is, on average, in the order of tenths of a Kelvin.

3.5 Influence of the observation geometry on cloud heterogeneity effects

The previous results were presented for nadir view as measured by IIR/CALIPSO. In this section, heterogeneity effects for other view directions are investigated. In the framework of a 3-D radiative transfer for tilted geometry, photons cross different inhomogeneous columns (TIPA, Várnai and Davies, 1999) contrary to the 1-D framework which assumes infinite layers. Figure 16 shows the $\Delta BT_{1\,km}$ averaged over all the pixels of the field ($\overline{\Delta BT_{1\,km}}$) in function of the zenith view angle Θ_v for cirrus 1 to 5 and for CII-1, CII-2 and CII-3 cirrus. For the band at 8.65 µm, the $\overline{\Delta BT_{1\,km}}$ increases with Θ_v. For cirrus 1 to 5, its value is twice as high for $\Theta_v = 60^\circ$ than for $\Theta_v = 0^\circ$. For CII-1, CII-2 and CII-3 cirrus, the difference is approximately 10 times as large because they present more important 3-D extinction coefficient variability. In the band at 12.05 µm, we note for cirrus 3, cirrus 4 and cirrus 5 that the $\overline{\Delta BT_{1\,km}}$ does not change in function of Θ_v. This is due to a saturation effect. These three cirrus have a large mean optical thickness ($\tau_c = 1.8$), with optical thicknesses superior to 6 for some pixels. As we can see in Fig. 7, the PPA tends to zero for these pixels as the surface emission is not visible any more. We also note that, for $\Theta_v \neq 0^\circ$, $\overline{\Delta BT_{1\,km}}$ is no longer correlated with $\sigma_{\tau_{1\,km}}$ which is computed for integrated vertical cloud column and, thus, does not represent the heterogeneity perceived from an oblique view zenith angle. Concerning view azimuth angle Φ_v, we see no real tendency, except differences due to different crossed optical properties.

4 Summary and conclusions

This paper presents results concerning the impact of cirrus cloud heterogeneities on the top-of-atmosphere brightness temperatures ($\Delta BT_{1\,km}$). Spatial radiometers such as IIR/CALIPSO and MODIS/AQUA measure top-of-atmosphere brightness temperatures at 1 km × 1 km and their operational algorithms use the Independent Pixel Approximation (IPA) and the Plan-Parallel Approximation (PPA) to retrieve cirrus cloud properties. Different effects can result from this assumption. We have shown that the larger effect at the 1 km scale is the PPA. It depends on the absorption properties and therefore on the observation channel with larger effects for bands at 10.60 µm and 12.05 µm. We have also shown that $\Delta BT_{1\,km}$ depend mainly on the optical thickness standard deviation inside the observation pixel and on the brightness temperature contrast between the cloud top and the clear sky atmosphere.

To summarize the different results presented in this paper, Fig. 17 shows the brightness temperature differences $\Delta BT_{1\,km}$ simulated to the nadir in function of the optical thickness at $1\,km \times 1\,km$ ($\tau_{1\,km}$). The two red lines correspond to the instrumental precision of IIR. The different cases of cirrus are superimposed to obtain 2, 000 pixels with different optical thicknesses. For these cirrus, the contrast between the cloud top and clear sky brightness temperatures are between −46 K to −67 K and we observe that the heterogeneity effects start to be significant ($\Delta BT_{1\,km}$ higher than the IIR instrumental precision of 1 K) around $\tau_{1\,km} \sim 0.4$ at 12.05 µm. This is equivalent to $\tau_{1\,km} \sim 0.3$ at 532 nm, corresponding to the limit of optically thick cirrus defined by Sassen and Cho (1992). In term of $\sigma_{\tau_{1\,km}}$, heterogeneity effects are superior to 1 K for $\sigma_{\tau_{1\,km}} \sim 1$.

Furthermore, we have also shown that the impact of heterogeneity effects increases strongly with the zenith view angle except for cirrus with large mean optical thickness ($\tau_c = 1.8$), where a saturation effect is observed for the band at 12.05 µm due to the strong absorption.

The next step will be the estimation of the impact of cirrus heterogeneities on the cloud properties retrieved from IIR thermal infrared measurements with the 1-D approximation (Fauchez et al., 2013).

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Table 1. Cirrus simulated by 3DCloud. "OP" corresponds to the optical properties parametrization, "CTA" corresponds to the Cirrus Top Altitude, "Yal" represents the model of ice crystals developed by Yang et al. (2001, 2005) for aggregates ice crystals and "Bal" represents the parametrization of ice crystals optical properties developed by Baran et al. (2009, 2011a, b).

Cirrus	τ_c	ρ_τ	Deff (µm)	OP	CTA (km)
1	0.45	0.7	9.95	Yal	7.97
2	0.90	0.7	9.95	Yal	7.97
3	1.80	0.7	9.95	Yal	7.97
4	1.80	1.1	9.95	Yal	7.97
5	1.80	1.5	9.95	Yal	7.97
6	1.80	0.7	20.09	Yal	7.97
7	1.80	0.7	40.58	Yal	7.97
8	0.90	0.7	9.95	Yal	11.06
CII-1	0.41	0.77	variable	Bal	11.06
CII-2	0.81	0.77	variable	Bal	11.06
CII-3	0.90	0.70	9.95	Yal	11.06

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Table 2. Optical parameters for aggregates ice crystals of the P. Yang model (Yang et al., 2001, 2005) used in cirrus 1 to 8 and CII-3.

D_{eff}(µm)	band at 8.65 µm			band at 10.60 µm			band at 12.05 µm		
	σ_e	ϖ_0	g	σ_e	ϖ_0	g	σ_e	ϖ_0	g
9.95	1.704	0.771	0.879	0.951	0.317	0.880	1.716	0.410	0.860
20.09	2.460	0.748	0.938	1.480	0.439	0.961	1.951	0.471	0.925
40.58	2.054	0.603	0.944	1.838	0.499	0.979	1.966	0.494	0.944

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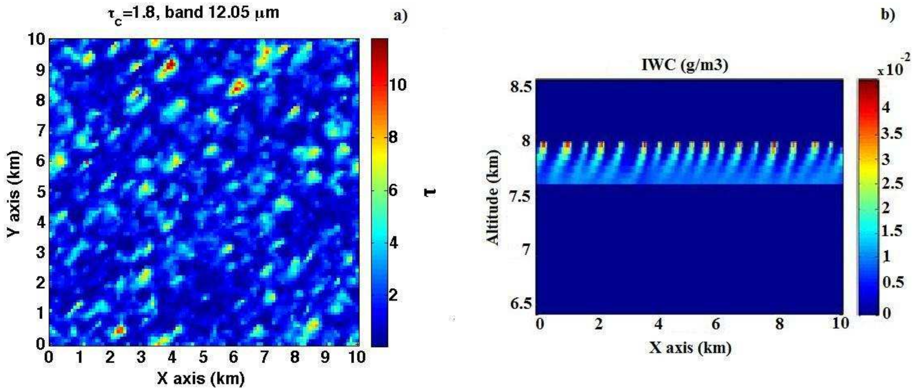

Fig. 1. **(a)** 10 km × 10 km optical thickness field at 12.05 µm with a horizontal spatial resolution of 100 m, **(b)** x-z view of the cirrus Ice Water Content (IWC) with a vertical spatial resolution of 58 m.

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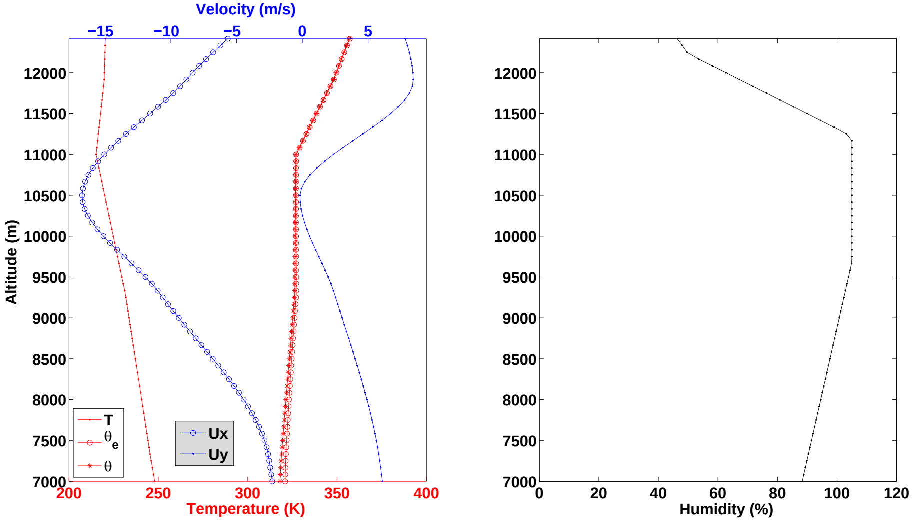

Fig. 2. Basic state thermodynamic and moisture structure initialy specified for cirrus CII-1, with T the thermodynamical temperature, θ the potential temperature, θ_e the equivalent potential temperature, Ux and Uy the wind profil on the x and y axes respectively, and the relative humidity (%).

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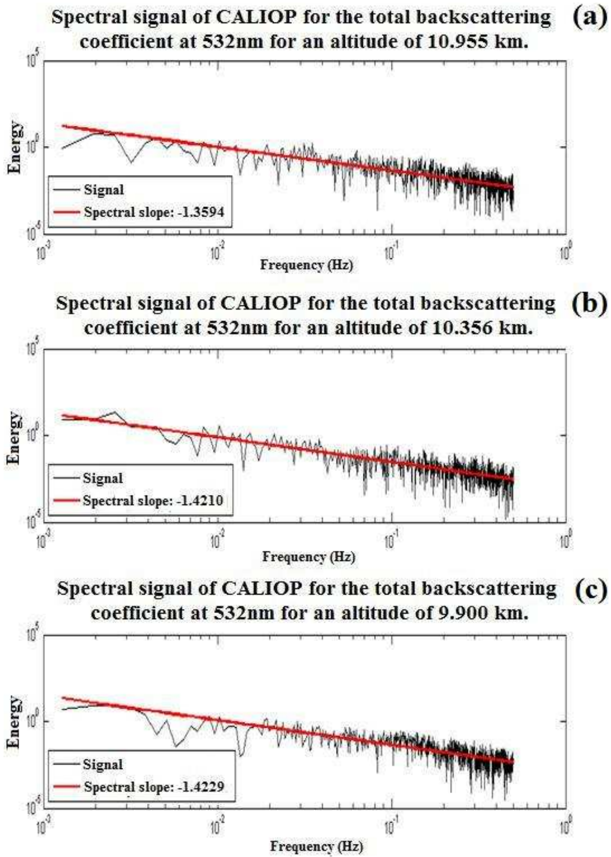

Fig. 3. Spectral slopes of the CALIOP/CALIPSO backscattering coefficient at 532 nm observed at 10.955 km **(a)**, 10.356 km **(b)** and 9.900 km **(c)** in function of the frequency in Hz.

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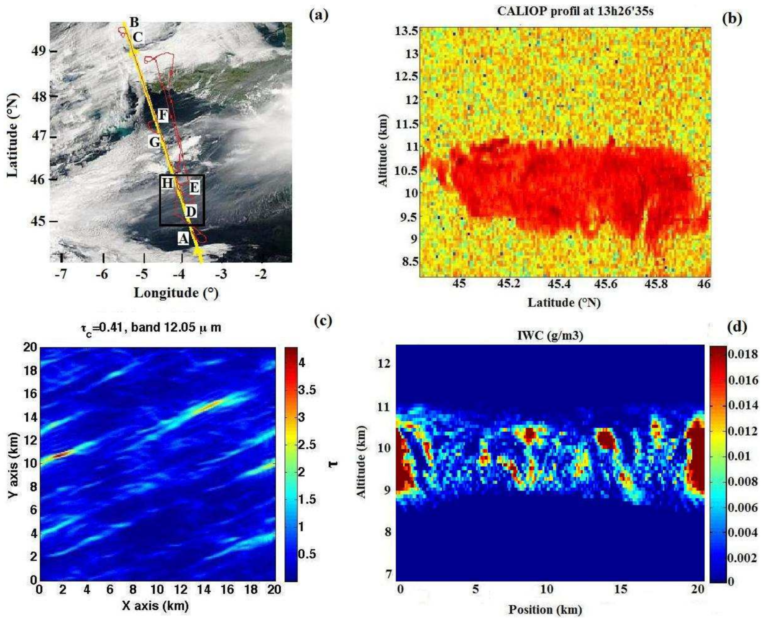

Fig. 4. Observed **(a)**, **(b)** and simulated **(c)**, **(d)** cirrus cloud on 25 May 2007 during the CIRCLE II campaign. **(a)** shows the MODIS "true color RGB" picture of the cirrus. The yellow bold line represents the CALIOP track and the red line the French Falcon 20 flight. Measurements start from point A to finish at point H. The black rectangle represents the cirrus area without any low water cloud below. **(b)** represents the vertical profile of the attenuated backscattering coefficient of the cirrus observed by the LIDAR CALIOP/CALIPSO inside the black rectangle in **(a)**. **(c)** represents the 20 km × 20 km optical thickness field generated at 12.05 μm with a horizontal spatial resolution of 100 m and with the mean optical thickness $\tau_c = 0.41$ observed by IIR at 12.05 μm. **(d)** represents the x-z view of the cirrus IWC genereted by 3DCloud with a vertical resolution of 58 m.

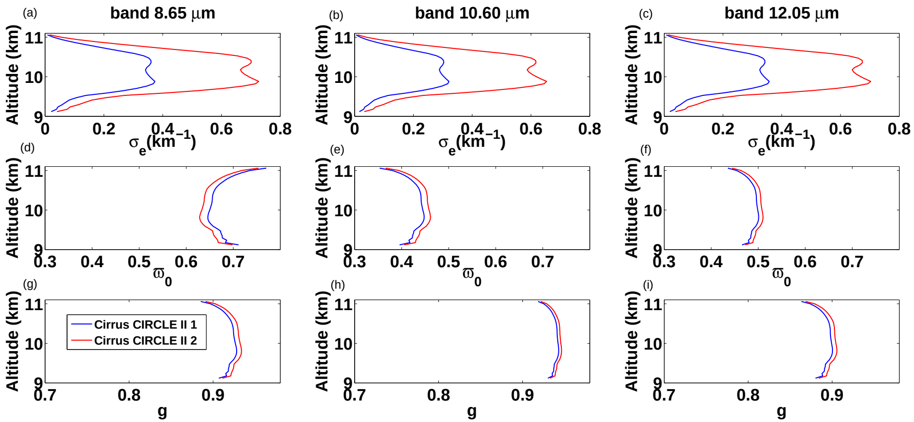

Fig. 5. (a), **(b)** and **(c)**: vertical variation of the mean extinction coefficient σ_e, **(d)**, **(e)** and **(f)**: vertical variation of the single scattering albedo ϖ_0 and **(g)**, **(h)** and **(i)**: vertical variation of the asymmetry factor g for the 3 channels at 8.65 µm, 10.60 µm and 12.05 µm and for the cirrus CII-1 (blue curves) and CII-12 (red curves).

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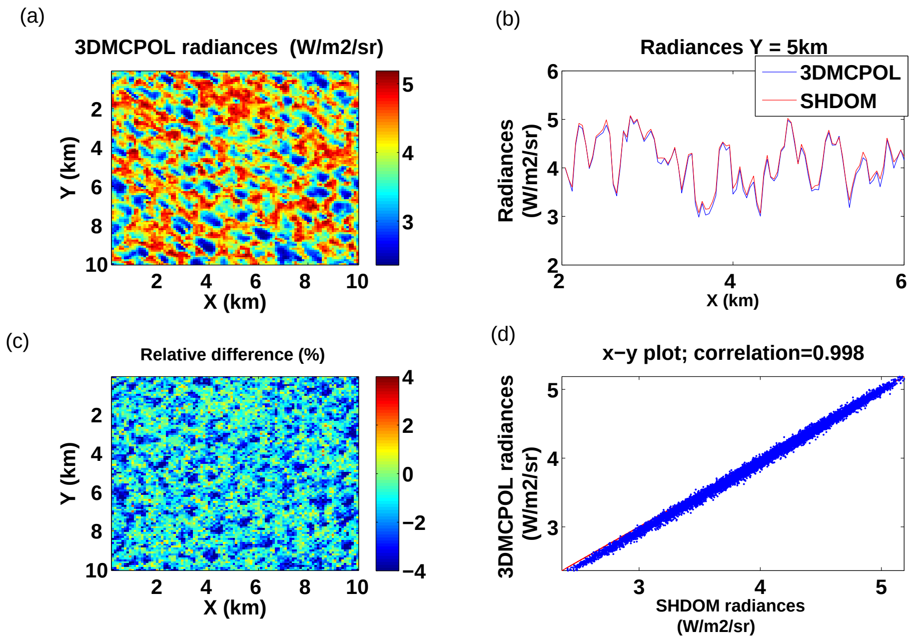

Fig. 6. Comparisons of 3DMCPOL and SHDOM radiance simulations at 10.60 µm for $\varpi_0 = 0.5$, $\tau_c = 1.8$ and for $\theta_v = \phi_v = 0°$. **(a)** 3DMCPOL TOA radiance field simulate at the nadir, **(b)** 3DMCPOL and SHDOM radiances along the X-axis for Y = 5 km, **(c)** relative differences 3DMCPOL – SHDOM/3DMCPOL) × 100 (%) between 3DMCPOL and SHDOM radiances, **(d)** 3DMCPOL-SHDOM correlation plot.

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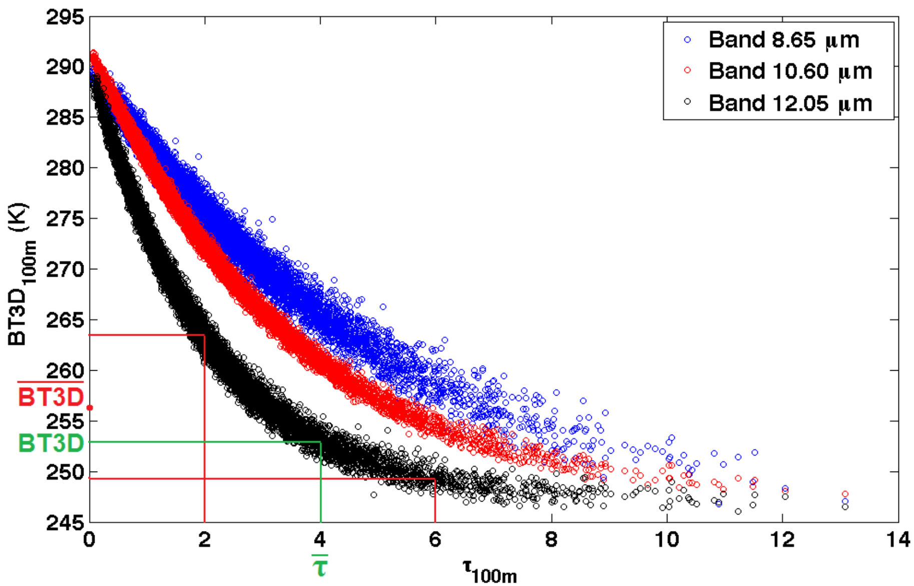

Fig. 7. Variation of the 3-D brightness temperatures $BT3D_{100\,m}$ in function of the optical thickness at 100 m × 100 m $\tau_{100\,m}$ for the three IIR channels and for cirrus 5. $\overline{BT3D}$ represents the average of $BT3D_{100\,m}$ corresponding to two $\tau_{100\,m}$, BT3D represents the 3-D brightness temperature corresponding to the mean optical thickness $\bar{\tau}$. The mathematical formulation of the PPA due to the Jensen inequality is expressed by: $\overline{BT3D} > BT3D(\bar{\tau})$.

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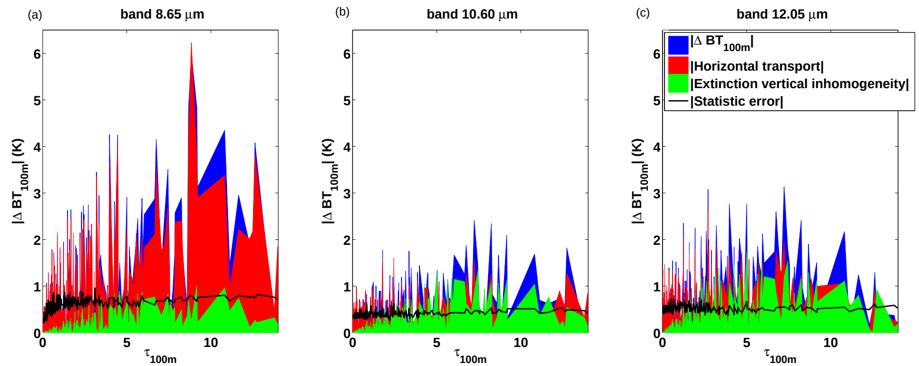

Fig. 8. Absolute brightness temperature differences at 100 m × 100 m $\Delta BT_{100\,m}$ (in blue) due to the horizontal transport (in red), the extinction vertical variability (in green) and the statistical error of the code (black line) for cirrus 5. Results are presented for the bands at 8.65 µm, 10.60 µm and 12.05 µm.

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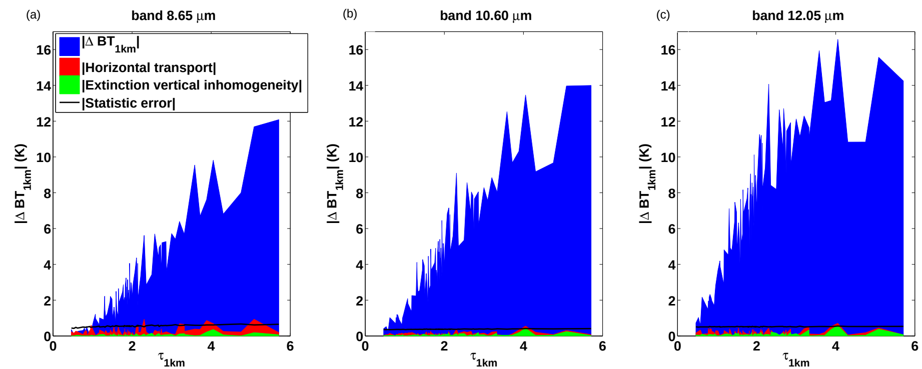

Fig. 9. Absolute brightness temperature differences at 1 km × 1 km $\Delta BT_{1\,km}$ (in blue) due to the horizontal transport (in red), the extinction vertical variability (in green) and the statistical error of the code (black line) for cirrus 5. Results are presented for the bands at 8.65 µm, 10.60 µm and 12.05 µm.

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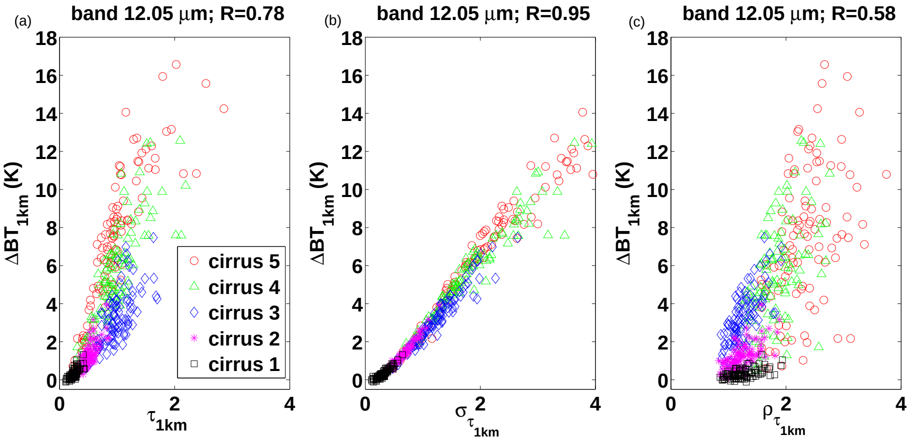

Fig. 10. Brightness temperature differences $\Delta BT_{1\,km}$ in function of the optical thickness $\tau_{1\,km}$, the optical thickness standard deviation $\sigma_{\tau_{1\,km}}$ and the heterogeneity parameter $\rho_{\tau_{1\,km}}$ for different cirrus presented in Table 1 and for the band at 12.05 µm. R represents the correlation coefficient computed for the five cirrus.

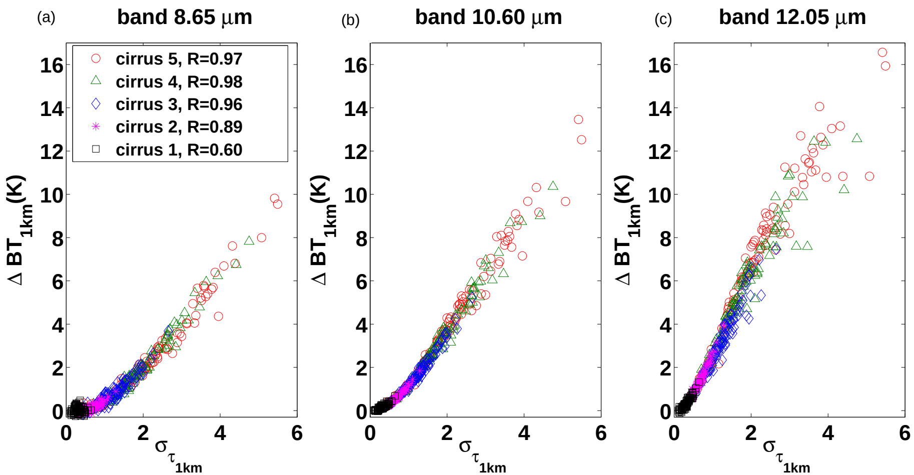

Fig. 11. Brightness temperature differences $\Delta BT_{1\,km}$ view at the nadir in function of the optical thickness standard deviation $\sigma_{\tau_{1\,km}}$ for different cirrus presented in Table 1. *R* represents the average correlation coefficient over the three bands.

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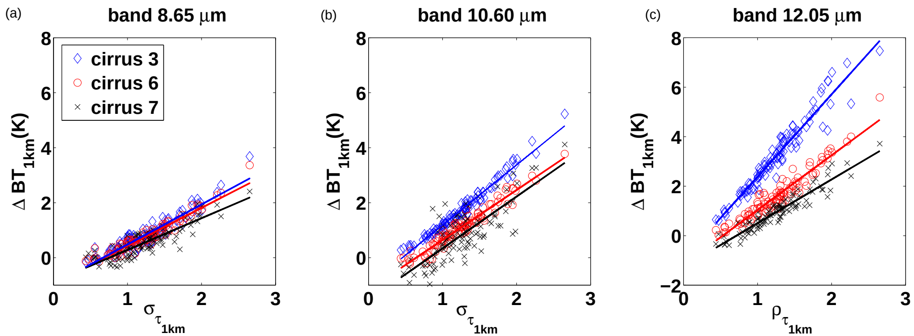

Fig. 12. Brightness temperature differences $\Delta BT_{1\,km}$ view at the nadir in function of the optical thickness standard deviation $\sigma_{\tau_{1\,km}}$ for same three cirrus fields with different ice crystal effective diameters: cirrus 3 (D_{eff} = 9.95 µm), cirrus 6 (D_{eff} = 20.09 µm) and cirrus 7 (D_{eff} = 40.58 µm).

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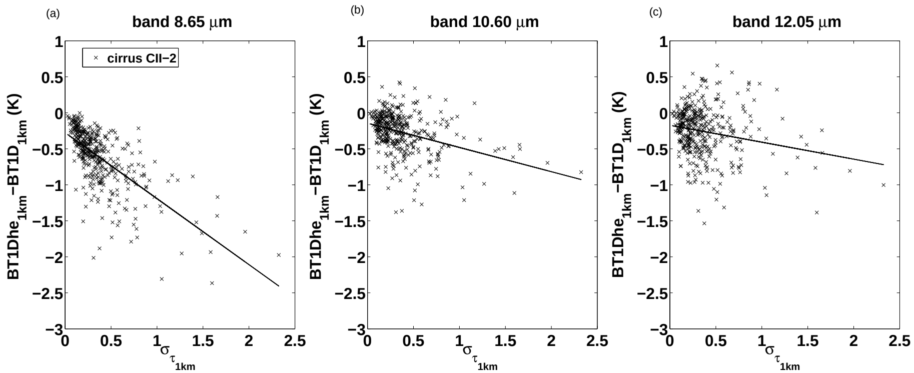

Fig. 13. Differences between brightness temperatures view at the nadir between a 1-D radiative transfer with vertically heterogeneous columns ($BT1Dhe_{1\,km}$) and with homogeneous columns ($BT1D_{1\,km}$) in function of the optical thickness standard deviation $\sigma_{\tau_{1\,km}}$ for cirrus CII-2 and for the bands at 8.65 µm, 10.60 µm and 12.05 µm.

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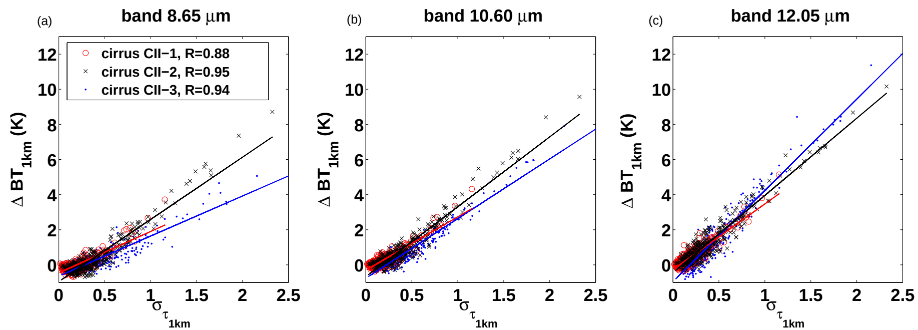

Fig. 14. Brightness temperature differences $\Delta BT_{1\,km}$ view at the nadir in function of the optical thicknesss standard deviation $\sigma_{\tau_{1\,km}}$ for cirrus CII-1, CII-2 and CII-3 and for the bands at 8.65 µm, 10.60 µm, 12.05 µm.

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Cirrus heterogeneities in the thermal infrared

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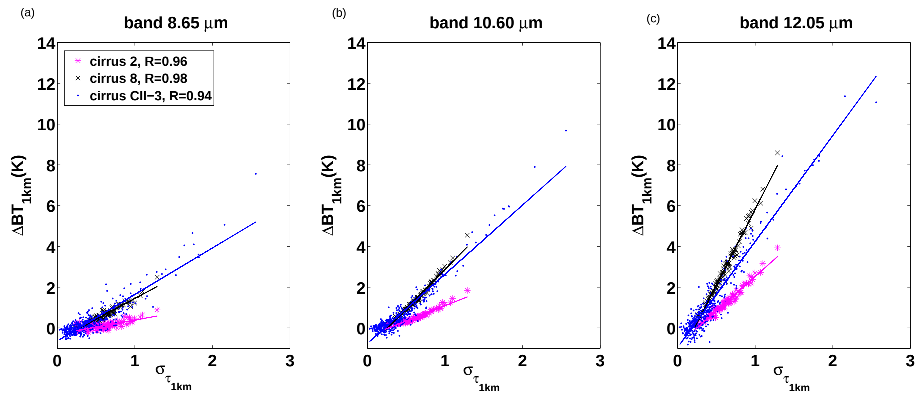

Fig. 15. Brightness temperature differences $\Delta BT_{1\,km}$ view at the nadir in function of the optical thicknesss standard deviation $\sigma_{\tau_{1\,km}}$ for cirrus 2, cirrus 8 and CII-3 and for the bands at 8.65 µm, 10.60 µm, 12.05 µm. The cloud top of cirrus 2, cirrus 8 and cirrus CII-3 are 7.97 km, 11.06 km and 11.06 km respectively and cloud base at 7.60 km, 11.06 km, and 9.06 km respectively.

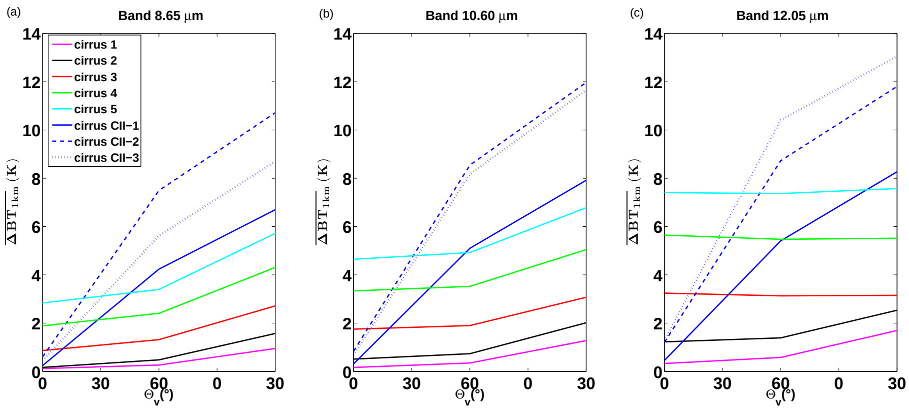

Fig. 16. Mean difference $\overline{\Delta BT_{1\,km}}$ in function of the view zenith angle Θ_v(°) for the cirrus 1 to 5 and cirrus CII-1 & CII-2 for the bands at 8.65 µm, 10.60 µm, 12.05 µm.

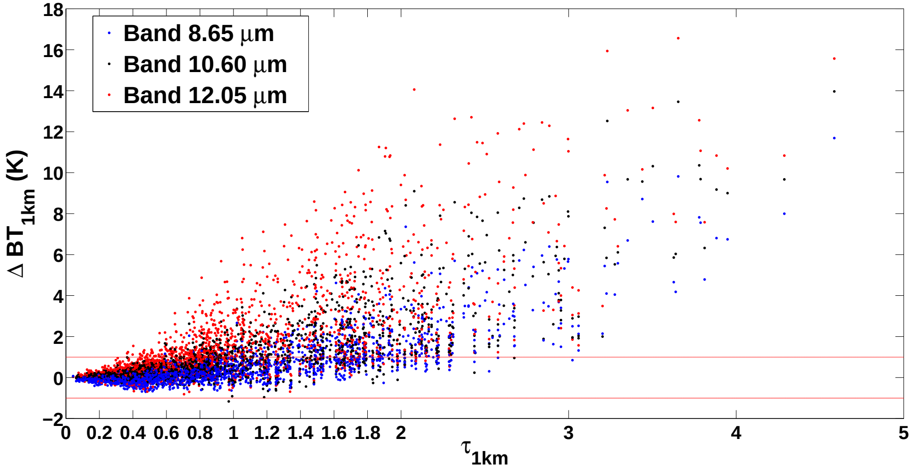

Fig. 17. Brightness temperature differences $\Delta BT_{1\,km}$ view at the nadir between $BT3D_{1\,km}$ and $BT1D_{1\,km}$ in function of the optical thickness at 1 km ($\tau_{1\,km}$) for the three channels of the IIR and for 2000 pixels per band. The two red lines correspond to the instrumental precision of the IIR of about ±1 K.

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