Warm cloud study from ground-based remote sensing using different radiative transfer approaches

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Abstract — In this work, an analysis of radiation fields in cloudy atmospheres, as well as of cloud shape factor is presented based on results obtained from different radiative transfer models. The radiative transfer approaches include a plane-parallel approximation (1D), a three-dimensional radiative transfer model (3D) and an analytical model that has been developed and adjusted by the authors. The irradiances are obtained from simulations with the numerical radiative transfer models, considering only cumulus clouds. Furthermore, a shape factor related to cloud roughness is derived from the combination of the analytical model with the 3D numerical model, considering the same atmospheric conditions for all simulations.

Keywords — radiative transfer, cloud optical depth, geometrical shape factor, warm clouds

1 INTRODUCTION

Clouds play a significant role on the Earth's energy balance, exerting both a cooling effect on the surface by reflecting sunlight back to space, and a warming effect by trapping radiative heat emitted from the surface. Clouds represent one of the greatest areas of scientific uncertainty with respect to how much they influence climate on both regional and global scales. Consequently it is important to know their properties and understand how they interact with radiation. Clouds are principally distinguished by altitude and by shape. An important quantity for the characterization of clouds is the optical depth, a quantity that describes the cloud effects on the short and long wave radiation and depends on a variety of parameters such as: the cloud water content, cloud vertical extent and the distribution and shape of cloud particles. The cloud spatial structure may be extremely complex and this may strongly affect cloud radiative fields, therefore a detailed knowledge of cloud shape parameters is also of paramount importance. The aim of the present work is to evaluate and analyze the differences in the irradiance fields due to the use of two different radiative transfer approaches: the plane-parallel assumption and a three-dimensional (3D). It is also aimed here to address the cloud complex structure and in this framework, a cloud shape factor, related to the roughness of the cloud contours (cloud base and top), is proposed, obtained from the combination of the 3D radiative transfer numerical model and of an analytical radiative transfer model that takes into account the cloud complex three-dimensional shape.

2 METHOD

The purpose of the present work is twofold: analyzing the cloud irradiance fields and retrieving a cloud shape factor, from different radiative transfer approaches.

A 3D radiative transfer numerical model – Spherical Harmonics Discrete Ordinate Method for Three-Dimensional (3D) Atmospheric Radiative Transfer (SHDOM) [1] is adopted here and for comparison sake, the traditional radiative transfer assumption of plane-parallel atmosphere is also used, as an option of the 3D model (SHDOMPP). The use of both models is especially important to quantify the differences in cloudy conditions, which can hardly be considered horizontally homogeneous, especially in case of broken clouds.

The analytical model developed for cloudy atmospheres [3] allows for the calculation of the emergent solar irradiances at the cloud base and top, as a function of the incident solar irradiance at its top and bottom and of the optical and physical properties of the cloud. The model takes into account the cloud irregular shapes, admits that solar radiation is transferred only through scattering processes and that the radiometric cloud properties do not depend on the direction of the solar radiation [2]. The parameter that characterizes the geometrical properties of the clouds is the shape factor [4], F that allows determining, in an approximate form, the roughness of a surface. The shape factor varies between zero and one; if the surface is perfectly flat $F=0$, otherwise $F \neq 0$.

2.1 Numerical radiative Transfer Simulations

The downward global irradiance fields at the surface level were simulated with the 3D (SHDOM) radiative transfer numerical model and with the 1D

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version of the model (SHDOMPP). The simulations are done for cumulus clouds at the wavelength of 440 nm and for a surface albedo of 0.09, considering a Lambertian surface. The cloud optical depth values considered are shown in Fig. 1. The cloud properties distribution represents a layer of broken cumulus clouds that varies in x and z directions; in x there are 256 pixels where each pixel is spaced by 0.2 km and in z the clouds have their bottom fixed at 0.59 km and top fixed at 2.03 km.

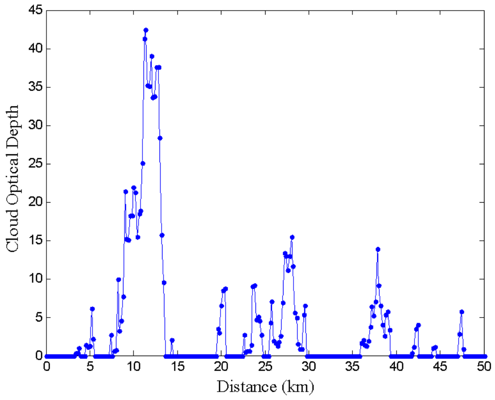

Fig. 1 Optical depth of the broken layer of cumulus clouds considered.

2.2 Shape Factor Retrieval

The irradiances calculated with the analytical model depend on a shape factor (F) that characterizes the roughness of the cloud contours. In this work, a cumulus cloud with a flatter bottom with respect to its top is considered and the parameter F may only take values according to this assumption. We assumed a constant value of 0.3 for the shape factor, F_{bb}, which characterizes the bottom of the cloud. The other input parameters necessary to the calculations with the analytical model, such as the incident irradiance at the top and bottom of the cloud, were taken from the simulations with the 3D numerical model. Then the shape factor value at the top of the cloud, F_{tt}, was determined for each x position, through the minimization of the differences between the downward irradiances obtained at the cloud base from the 3D numerical model and from the analytical model.

3 RESULTS

The irradiance at the surface level, obtained from simulations with SHDOMPP and SHDOM numerical models are represented in Fig. 2.The regions where the irradiances reaching the surface are strongly attenuated by the clouds can be clearly distinguished in this figure. These regions occur in correspondence with the higher values of cloud optical depth (see Fig. 1). To note also in Fig. 2 that the irradiance values simulated with the numerical 3D model are, in general, higher than the values obtained with the 1D approximation (plane-parallel atmosphere). In the 1D approximation it is assumed that the radiative properties of an individual pixel are independent of its neighbours [5]. In contrast, the 3D numerical model considers the radiative contribution of the neighbouring calculation points. The results from the 3D model constitute a better approximation of the actual conditions, because they are not based in the hypothesis that the clouds are constituted by plane and horizontal layers with uniform optical properties, as is the case of the 1D model. This permits a better simulation of the cloud edges effects where the cloudy and the clear sky exert important 3D radiative effects. These 3D effects are mostly pronounced and variable for cloud neighbouring pixels [6]. It is possible to see in Fig. 2, especially in the inner regions of the clouds that the irradiance values obtained with 1D model are lower than the values of the same quantities obtained with the 3D model; this is probably because of the contribution of the cloud neighbouring pixels. In Fig. 2 it is also possible to distinguish that as the distance from the clouds increases, the differences between the 3D and 1D model diminish, suggesting that 3D effects are then less important. Also the cloud shadow effects in clear sky pixels, in the vicinity of clouds, can be distinguished from the same figure. To note that from a distance of about 1000 m on, this effect becomes negligible (Fig 4).

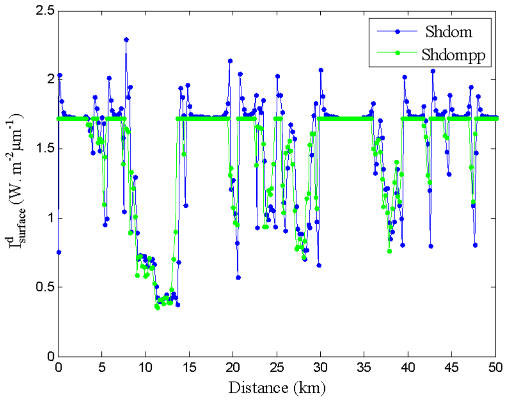

Fig. 2 Downward irradiance at the surface obtained from the 3D and 1D radiative transfer models, considering an atmosphere with cumulus clouds.

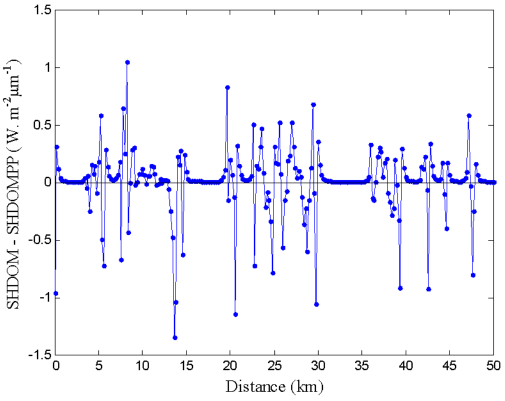

Fig. 3 Differences between the downward irradiances from the 3D and 1D radiative transfer models.

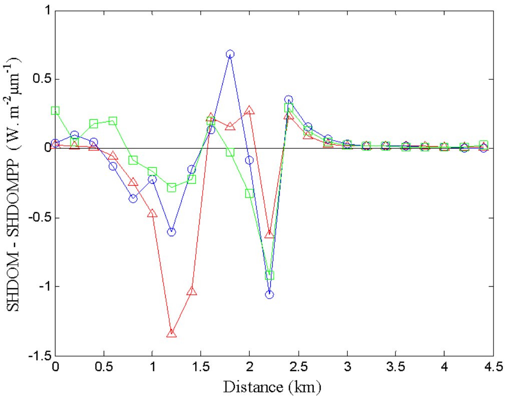

Fig. 4 Differences of the downward irradiances from the 3D and 1D radiative transfer models, considering a horizontal distance from the center of the clouds (0 km) to a distance of 2.2 km after cloud edges.

Fig. 3 shows the differences between the downward irradiance obtained from the 3D and the 1D radiative transfer models. To note that the differences between both models present higher values in the cloudy regions, with extreme values near the cloud edges. In Fig 4 the irradiance differences between the 3D and 1D radiative transfer models are represented, for three different clouds, starting in the center of the clouds, indicated as 0 km in the figure and up to a distance of 2.2 km after cloud edges. The graph shows a high variability within the cloud, with positive and negative differences, indicating the under and overestimations of the 1D radiative transfer results with respect to the 3D. The differences in the clear-sky regions can be observed from a distance of 2.4 km on in Fig. 4, which is zoomed and generalized for more clouds in the graph of Fig. 5. It is shown that as the distance to cloud edge increases, the differences become less important, tending to zero at about 1 km from the cloud edge. The negative differences found near the cloud border is related to the fact that the 3D model takes into account the cloud influence on the direct and diffuse irradiances and the direct downward irradiance at such a small distance is still strongly affected by the presence of the cloud, being attenuated. On the contrary, the 1D approximation considers only the clear sky column, reflecting a lower attenuation of the values and thus higher irradiances. As distance increases, the 3D direct irradiance is not affected anymore; nevertheless the 3D diffuse irradiance is amplified by the cloud scattering contributions, resulting in higher values with respect to the 1D model, which does not consider this effect, thus yielding positive differences.

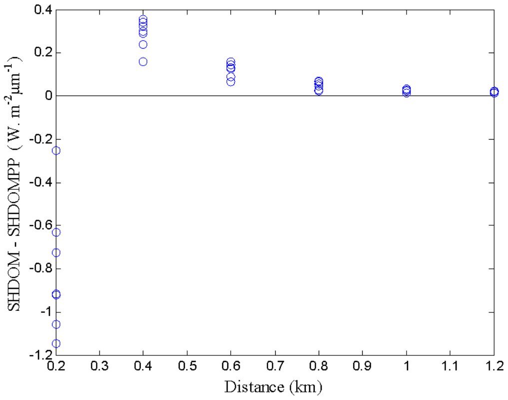

Fig. 5 Differences between the downward irradiances from the 3D and 1D radiative transfer models, for the clear sky regions as a function of the distance to the cloud edge.

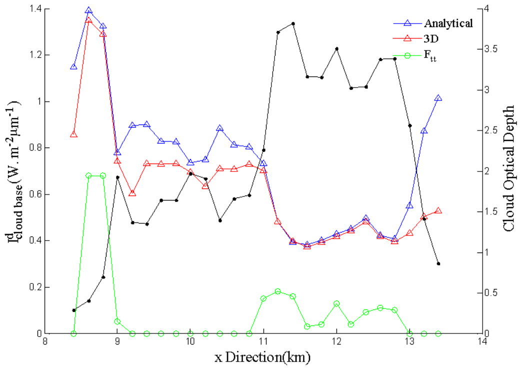

Fig. 6 Emergent downward irradiance at the bottom of a cumulus cloud, obtained with the 3D radiative transfer numerical model (red line) and with the analytical model (blue line). The cloud optical depth (black line) is represented in the right axis.

The simulations performed with the analytical model for a cumulus cloud are represented in Fig. 6. The same figure shows the values obtained for the shape factor at the top of the cloud (green line).

Considering the shape factor assumed for the base of the cloud, the irradiances obtained with the analytical model are adjusted to the irradiances of the numerical 3D model, by changing iteratively the cloud top shape factor. From the results obtained it is possible to conclude that the cloud shape factor is an important cloud parameter in the determination of the irradiances that emerge on the cloud base and reach the surface.

8 CONCLUSIONS

The 3D radiative transfer simulations of global irradiance at the surface, for atmospheres with clouds properties that are not horizontally uniform seem to be more appropriate than simulations done with the 1D radiative transfer numerical model. The differences between both models were quantified and it was shown that the importance of considering the 3D effects diminishes as distance to cloud increases. In this case it was found that at about 1km from the cloud border, this effect is negligible.

The results obtained with the numerical and with the analytical models allowed to verify the importance of cloud geometric parameters and to determine the shape factor for the cumulus cloud top.

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