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Spectra of polarized thermal radiation in a cloudy atmosphere: Line-by-Line and Monte Carlo model for passive remote sensing of cirrus and polar clouds

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ABSTRACT

A polarized high-resolution 1-D model has been presented for TIR (Thermal Infrared) remote sensing application. It is based on the original versions of MC (Monte Carlo) and LbL (Line-by-Line) algorithms, which have shown their effectiveness when modelling the thermal radiation atmospheric transfer, taking into account, the semi-transparent Ci-type and polar clouds scattering, as well as the direct consideration of the spectra of molecular absorption. This model may be useful in the planning of satellite experiments and in the validation of similar models, which use the "k-distribution" or other approximations, to account for gaseous absorption.

The example simulations demonstrate that, the selective gas absorption does not only significantly affect the absorption and emission of radiation, but also, its polarization in the Ci-type clouds. As a result, the spectra of polarized radiation contain important information about the clouds, and a high-resolution polarized limb sounding in the TIR, seems to be a useful tool in obtaining information on cloud types and their vertical structures.

1. Introduction

It is known that the Arctic and Antarctic regions are the most susceptible to climate change. In the polar regions, the climate is particularly sensitive to the presence of clouds due to their strong radiative influence on the surface energy balance which might change the ice melting rate. Also, the polar clouds have an impact on the atmospheric radiation budget. Cooling the lower stratosphere radiatively (and/or adiabatically) by deep-tropospheric clouds, may lead to the formation of Polar Stratospheric Clouds (PSCs) [1], and PSCs, in turn, play a central role in the polar ozone depletion due to heterogeneous chlorine activation reactions [2]. Although, polar clouds are important subjects to study, it is a rather challenging task to deploy ground-based observations in such a remote destination with severe weather conditions. In the present work, for the investigation of polar clouds by polar-orbiting satellites, we accept the fact that clouds polarize radiation and simulate the measurements of polarimetric instruments on-board.

The main objective of our work was to study the capabilities of passive remote sensing using the spectra of the Stokes vector $\mathbf{J}=(I,Q,U,V)$ measurements in obtaining information on cirrus (Ci), and polar clouds from satellites. There are several radiative transfer models that takes polarization into account, for example, MYSTIC [3], 3DMCPOL [4], ARTS [5] and others, participating in the International Polarized Radiative Transfer (IPRT) intercomparison [6,7]. Majority of

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these models either use different approximations to account for gaseous absorption (k-distribution methods), or they are only applicable when modelling the solar radiation, and therefore, cannot be applied for remote sensing at polar night. The crucial role played by a high-resolution line-by-line treatment of gaseous absorption is shown in our work. We have found that the ARTS (Atmospheric Radiative Transfer Simulator) model could as well, simulate the high-resolution limb measurements of the polarization of thermal radiation. That model uses the precalculated accurate PT-tables of absorption coefficients as well as a combination of discrete ordinate and the Monte Carlo methods. But the implementations of ARTS mainly focus on microwave radiometry. In contrast to works [8,9], where the microwave region (MW) was also considered, our work considers the Thermal Infrared Region (TIR). A paper by Takano and liou [10] shows that the polarization of TIR radiation caused by scattering in the cirrus clouds, is detectable towards the limb, where the degree of linear polarization is represented by the value of $D=Q/I\sim 1\%$. Hence, it can be concluded that it is possible to obtain information on such clouds, using ground-based and aircraft measurements of radiation polarization. However, in this work, the gaseous absorption that is absolutely essential for considering the limb "cloud-satellite" directions, was not taken into consideration. Also, gaseous absorption significantly affects the polarization of radiation in the cloud. In the case of strong absorption, there is no polarization, whatsoever, since the value of D for the blackbody is equal to zero. And in the TIR region, this occurs in many strong spectral lines. That is why in this study, we have given special consideration to gaseous absorption and calculated the Stokes vector spectra of the outgoing radiation in a spherical atmosphere, using the Line-by-Line (LbL) method. At this point, it should be noted that these high-resolution spectra are necessary to simulate any experimental spectra, because in each sensor channel, a signal is a convolution of the spectrum with the response function.

In order to efficiently account for the radiation scattering processes, such studies have commonly used the models based on the Monte Carlo (MC) method (refers to a review of models presented in work [8]). But these models were not intended for spectra modelling. However, such modelling requires fast repeat solutions of the vector radiative transfer equation at multiple spectral points, as well as the application of a procedure for the reduction of the "statistical noise" in the calculated spectra. This prompted us to improve our 1-D forward MC+LbL model for solar radiation [11], in order to make it applicable to thermal radiation. We also considered the fact that the subject of our research (a Ci or a polar cloud) is a relatively thin, semi-transparent layer in which the role of multiple scattering in the process of radiation transfer is minor. As a result, in this study, we adopted the method which was previously and successfully used for a scalar long wave model [12]. It involves dividing radiation into "primary" and "scattered" radiation.

The "primary" radiation comes from the emission of the atmosphere and surface. It consists of the pure thermal photons (not yet scattered by the atmospheric particles). Due to the first scattering in the cloud, the "primary" radiation becomes the "source" of the "scattered" radiation. In the presented MC model, this very cloud-localized "source", and not the entire atmosphere and surface as it usually occurs in nature and in other MC models, emits the photons which, being scattered and absorbed in the atmosphere, forms the "scattered" radiation. Let us denote this cloud-localized "source" by "Effective Source" (ES) as distinct from the "Natural Source" (NS), which simulates emission of the thermal photons in nature. In this research, the contribution of "primary" radiation is generally the main one, and it is calculated using the standard spatial integration (Eq. (13)) similar to the clear-sky, Line-by-Line models. The contribution of single scattering is also calculated without statistical errors using spatial integration (Eq. (16)), and the MC method is used only to account for the multiple scattering (details presented below).

Initially, the thermal radiation is unpolarized ($I\neq 0$, $Q=0, U=0, V=0$). After single scattering by cloud particles $I, Q\neq 0$, whereas $U, V=0$ (see below). Thus, in the case of the optically thin clouds, where the single scattering contribution usually dominates the multiple scattering contribution in radiation, only the I and Q Stokes parameters seem detectable. Therefore, in our vector MC model, we take into account all the I, Q, U and V Stokes parameters, but discussed only I and Q.

In numerical experiments, we used the ice cloud optical models from work [13], Ci '010' (effective diameter of particles 10 μm), and the "75% Sulphuric Acid (H_2SO_4) Droplets" model from WCP-112 [14]. These models have been chosen as characteristic models for polar clouds [15], as well as for typical representations of acid-droplet and crystal clouds. It is known that the optical properties of clouds vary much more smoothly with the wave number compared to the gas absorption. However, in our calculations, these properties are constant in the spectral range and not wider than $10\ \mathrm{cm}^{-1}$. For subsequent intervals, these properties are recalculated by means of the linear interpolations between the wave number points defined in the above cloud optical models.

In Section 2, we describe some characteristic features of the developed MC technique: the modeling of thermal photon trajectories and MC estimations in Section 2.1, modeling emission of thermal photons in Section 2.1 and a validation of this technique in Section 2.3. In Section 3, we elucidate this technique for the calculation of the spectra of polarized thermal radiation in a spherical atmosphere: accounting for gaseous and cloud absorption of radiation in Section 3.1, the simulation of polarized thermal radiation inside a cloud, and at TOA, in Sections 3.2-3. In teaching Section 3, it was enough to consider only one cloud+atmospheric model and the spectral interval. Furthermore, in Section 4, we consider several numerical experiments that may be interesting for remote sensing. Here, we used the above cloud models and a pair of the standard atmospheric models, which, in our opinion, ably represents the atmospheric conditions. Their optical properties are described in Section 4.1. Section 4.2 reviews the polarized radiation being affected by those observation parameters, which are the target of remote sensing: the optical depth, composition and height of the cloud. In our