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Three-dimensional Monte Carlo calculation of atmospheric thermal heating rates

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ABSTRACT

We present a fast Monte Carlo method for thermal heating and cooling rates in three-dimensional atmospheres. These heating/cooling rates are relevant particularly in broken cloud fields. We compare forward and backward photon tracing methods and present new variance reduction methods to speed up the calculations. For this application it turns out that backward tracing is in most cases superior to forward tracing. Since heating rates may be either calculated as the difference between emitted and absorbed power per volume or alternatively from the divergence of the net flux, both approaches have been tested. We found that the absorption/emission method is superior (with respect to computational time for a given uncertainty) if the optical thickness of the grid box under consideration is smaller than about 5 while the net flux divergence may be considerably faster for larger optical thickness. In particular, we describe the following three backward tracing methods: the first and most simple method (EMABS) is based on a random emission of photons in the grid box of interest and a simple backward tracing. Since only those photons which cross the grid box boundaries contribute to the heating rate, this approach behaves poorly for large optical thicknesses which are common in the thermal spectral range. For this reason, the second method (EMABS_OPT) uses a variance reduction technique to improve the distribution of the photons in a way that more photons are started close to the grid box edges and thus contribute to the result which reduces the uncertainty. The third method (DENET) uses the flux divergence approach where – in backward Monte Carlo – all photons contribute to the result, but in particular for small optical thickness the noise becomes large. The three methods have been implemented in MYSTIC (Monte Carlo code for the phYSically correct Tracing of photons In Cloudy atmospheres). All methods are shown to agree within the photon noise with each other and with a discrete ordinate code for a one-dimensional case. Finally a hybrid method is built using a combination of EMABS_OPT and DENET, and application examples are shown. It should be noted that for this application, only little improvement is gained by EMABS_OPT compared to EMABS.

1. Introduction

Thermal radiation, emitted and absorbed by the surface and the atmosphere, plays a key role in the Earth's radiation budget. In contrast to solar radiation, scattering is generally of minor importance for infrared radiation, although not negligible. Absorption and emission are therefore the main

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interactions. Clouds absorb and emit infrared radiation at different height levels and therefore different temperatures which leads to different heating and cooling effects. Finite clouds show cooling at cloud tops and cloud sides as well as heating at the cloud bottom [23,16,9]. These effects have an impact on the development of the cloud and also on neighboring clouds [10,15,12,13]. The strongly simplified representation of these effects in climate models or numerical weather prediction models may cause huge uncertainties [8]. Radiation effects strongly depend on cloud geometry, cloud size, cloud shape [20,12,14] and microphysics [7]. For radiative transfer calculations in atmospheric models, the atmosphere is usually approximated as plane-parallel and one-dimensional, neglecting horizontal variability. It has been shown that this approximation causes considerable uncertainty [8,9,15,20,14,1,29,6]. Ellingson [8] showed that these uncertainties are in a range of 4% in the downward flux and 8% in the upward flux. Heidinger and Cox [17] found that about one-third of the radiative forcing at the surface may be due to cloud side effects. More relevant than these domain-averaged or surface effects, however, are local effects in or close to the cloud: former studies found thermal cooling rates up to -628 K/d in realistic 3d clouds [19] or about -816 K/d in cylindrical clouds [12] while there is modest warming at the cloud bottom. Guan et al. [12,13] also found that the cloud side and cloud top cooling might have a significant effect on cloud formation. They found that longwave cooling increases the liquid water content at cloud sides and tops as well as the total cloud water content. The additional condensation further increases the cooling rate – therefore a positive feedback takes place. In addition, the radiative cooling increases downward motion at the cloud sides, causing low level convergence which enhances vertical development in the cloud [12,13]. To study realistic interactions of thermal radiation and clouds, a three-dimensional radiative transfer model is required. 3D radiative transfer can be accurately simulated using the Monte Carlo method [24] where individual photons are traced on their random paths through the atmosphere. For calculations in the thermal spectral range, the absorption coefficient may be large in clouds and in the molecular absorption bands; a photon emitted at a random location in the atmosphere is very likely not to reach the location where the radiation is to be calculated because the mean free path of the photon is small. For this reason, backward photon tracing might be the method of choice. With backward Monte Carlo, where the photon is started at the detector, it is guaranteed that each photon contributes to the result. Atmospheric heating rates pose an extra challenge since, if absorption is strong, they are calculated as a small difference of two large numbers: the emission and the absorption of photons. The aim of this paper is to show methods to calculate thermal heating rates and to identify the fastest possible solution for a given problem. The methods were developed for the Monte Carlo code for the phYSically correct Tracing of photons In Cloudy atmospheres (MYSTIC, [25]). MYSTIC is one of the several solvers included in the libRadtran radiative transfer package by Mayer and Kylling [26]. The paper is structured as follows: we introduce theory and methodology in Section 2, including a detailed description of the methods and the optimizations. The performance of the methods is described in Section 3, and applications are shown in Section 4.

2. Theory

The source of thermal radiation in the Earth's atmosphere is emission by the Earth's surface as well as by molecules, droplets, and particles in the atmosphere. Planck's law describes the amount of electromagnetic energy that is emitted by a black body as a function of its temperature and wavelength [27]. The amount of radiation which is actually emitted or absorbed by the atmosphere is modified by the spectral absorption or emission coefficients which are equal to each other according to Kirchhoff's law [21]. Emission and absorption of radiation cause cooling or heating of the air which is described by the so-called heating or cooling rates, that is, the temperature change per unit time dT/dt of an atmospheric volume due to absorption and emission of radiation, usually specified in K/d. Emission and absorption can either be calculated directly or can be derived from the divergence of the net flux. In particular, the electromagnetic power $\dot{q}_{\text{em}} - \dot{q}_{\text{abs}}$ emitted minus absorbed per volume equals the divergence of the net flux vector $\vec{E}_{\text{net}}$:

$$\frac{dT}{dt} = -\frac{1}{\rho c_{\text{p}}}(\dot{q}_{\text{em}} - \dot{q}_{\text{abs}}) = -\frac{1}{\rho c_{\text{p}}}\nabla \vec{E}_{\text{net}}. \tag{1}$$

Here, $E_{\text{net},i}$ is defined as the difference of the irradiances in positive and negative i directions. ρ is the density and c_{p} the specific heat capacity of the medium, see, e.g. Liou [22]. For finite volumes this relationship translates to

$$\dot{q}_{\text{em}} - \dot{q}_{\text{abs}} = \sum_{i=1}^{3} \frac{1}{\Delta x_i}\left(E_{\text{net},i}(x_i + \Delta x_i) - E_{\text{net},i}(x_i)\right). \tag{2}$$

Emission, (multiple) scattering, and absorption of radiation are described by the radiative transfer equation, e.g. Chandrasekhar [5]:

$$\frac{1}{\beta_{\text{ext}}}\vec{s}\,\nabla L = -L + \frac{\omega_0}{4\pi}\int_{4\pi} p(\Omega', \Omega)L(\Omega')\,d\Omega' + (1-\omega_0)B(T). \tag{3}$$

L is the radiance in direction $\vec{s}$, β_{ext} is the volume extinction coefficient, ω_0 the single scattering albedo, $p(\Omega', \Omega)$ the scattering phase function, and $B(T)$ is the Planck function. The radiative transfer equation is usually evaluated monochromatically, that is, for a given wavelength or wavenumber. Often the scattering term (2nd term on the right side) is neglected in the thermal IR and the equation reduces to the Schwarzschild equation which is straightforward to solve numerically. In contrast to solar radiation, where the source of the radiation is the sun and the incoming radiation is incident at top of atmosphere (TOA) with a given solar zenith and azimuth angle, thermal radiation is emitted anywhere in the atmosphere and the amount of thermal radiation emitted depends on the temperature and the absorption coefficient $\beta_{\text{abs}} = (1-\omega_0)\beta_{\text{ext}}$. For the general concepts of Monte Carlo photon tracing and the implementation in MYSTIC, the reader is referred to the literature, e.g. [24,25]. In the following we concentrate on aspects relevant for the