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Representative wavelengths absorption parameterization applied to satellite channels and spectral bands

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ABSTRACT

Accurate modeling of wavelength-integrated radiative quantities, e.g. integrated over a spectral band or an instrument channel response function, requires computations for a large number of wavelengths if the radiation is affected by gas absorption which typically comprises a complex line structure. In order to increase computational speed of modeling radiation in the Earth's atmosphere, we parameterized wavelength-integrals as weighted means over representative wavelengths. We parameterized spectral bands of different widths ($1\,\mathrm{cm}^{-1}$, $5\,\mathrm{cm}^{-1}$, and $15\,\mathrm{cm}^{-1}$) in the solar and thermal spectral range, as well as a number of instrument channels on the ADEOS, ALOS, EarthCARE, Envisat, ERS, Landsat, MSG, PARASOL, Proba, Sentinel, Seosat, and SPOT satellites. A root mean square relative deviation lower than 1% from a "training data set" was selected as the accuracy threshold for the parameterization of each band and channel. The training data set included high spectral resolution calculations of radiances at the top of atmosphere for a set of highly variable atmospheric states including clouds and aerosols. The gas absorption was calculated from the HITRAN 2004 spectroscopic data set and state-of-the-art continuum models using the ARTS radiative transfer model. Three representative wavelengths were required on average to fulfill the accuracy threshold. We implemented the parameterized spectral bands and satellite channels in the uvspec radiative transfer model which is part of the libRadtran software package. The parameterization data files, including the representative wavelengths and weights as well as lookup tables of absorption cross sections of various gases, are provided at the libRadtran webpage.

In the paper we describe the parameterization approach and its application. We validate the approach by comparing modeling results of parameterized bands and channels with results from high spectral resolution calculations for atmospheric states that were not part of the training data set. Irradiances are not only compared at the top of atmosphere but also at the surface for which this parameterization approach was not optimized. It is found that the parameterized bands and channels provide a good compromise between computation time requirements and uncertainty for typical radiative transfer problems. In particular for satellite radiometer simulations the computation time requirement and the parameterization uncertainty is low. Band-integrated irradiances at any level as well as heating and cooling rates below 20 km can also be modeled with low uncertainty.

1. Introduction

Modeling of wavelength-integrated radiative quantities is required frequently in atmospheric science, e.g. for simulating

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irradiances or radiances measured by remote sensing instruments. It requires the radiative transfer problem to be solved at a large number of wavelengths if the spectral range is affected by fine-structured absorption features of gases, making it computationally expensive. Fine-structured gas absorption features exist in large parts of the visible and infrared spectral range.

Different parameterization approaches are available for reducing the computational cost of such modeling problems. The most prominent general approach is the k-distribution approach. The basic idea of the k-distribution approach is to sort the wavelength grid such that the gas absorption coefficient on the reordered wavelength grid is smooth and monotonic; with the reordered grid, the spectral integration of radiative quantities requires much less wavelength grid points. The optimum ordering depends on pressure, temperature, and gas concentration. Many k-distribution methods use the assumption that the gas absorption spectra of the different atmospheric layers are correlated with the gas absorption spectrum of a reference layer [1]. Such correlated-k distribution methods are used for example by Kato [2] and Fu [3] for wide spectral bands, and by Kratz [4] for AVHRR satellite channels. A k-distribution method not employing the correlation assumption is described for example by Doppler et al. [5] which builds upon the so-called Spectral Mapping Transformation using k-distributions whose validity was tested at all atmospheric layers. Another parameterization approach employing k-distribution methods is LOWTRAN where the transmittance of the gases within 20 cm^{-1} wide bands is approximated by the sum of up to three exponential terms [6]. LOWTRAN7 is implemented in the uvspec radiative transfer model which is part of the freely available libRadtran toolbox [7] where it has been used frequently for spectral calculations and simulations of satellite channel responses. The gas absorption properties of LOWTRAN are based on HITRAN. Recent comparisons of measured thermal downward irradiances in the atmospheric window around 10 µm with LOWTRAN calculations have revealed some discrepancies, whereas high spectral resolution calculations using HITRAN 2004 [8] data show good agreement [9]. The commercially available MODTRAN code [10] also includes significantly improved spectral band parameterizations.

Buehler et al. [11] describe an approach for parameterizing gas absorption, where spectrally integrated radiances are approximated by weighted means of radiances at so-called representative frequencies or wavelengths. The representative wavelengths together with their weights are selected by an optimization method which minimizes the deviation from the accurate spectrally integrated radiances for a set of highly variable atmospheric states. Buehler et al. [11] focus on clear sky cases and parameterize thermal radiation channels of the HIRS satellite instrument. We developed a parameterization approach which is based on this work but includes adjustments to improve its applicability. For example, we added aerosols, water clouds, and ice clouds in the set of atmospheric states and increased the variability of the gas profiles. Furthermore, our approach determines automatically the number of representative wavelengths required to fulfill a parameterization accuracy threshold. Using this approach, we parameterized a large set of narrow spectral bands of different widths covering the thermal as well as the solar spectral range. Spectral response functions of many satellite channels were parameterized in addition (a list of channels is provided in Appendix A). We implemented the parameterized bands and channels, referred to as “REPTRAN” in the following, in the uvspec model [7]. The REPTRAN data files are available from the libRadtran webpage – http://libradtran.org.

In Section 2 we describe the representative wavelengths parameterization approach. After that, in Section 3, we apply the parameterization approach to spectral bands and satellite channels, investigate the spectral variability of the considered gas absorption, and compare results from parameterized bands and channels with results from exact high spectral resolution (HSR) calculations. We perform these comparisons for irradiances at the top of atmosphere, for which REPTRAN has been optimized, and also for irradiances at the surface and for heating rates as a function of height. We also consider the LOWTRAN parameterization for the comparisons because it has been one of the mostly used absorption parameterizations of the uvspec model.

2. Methodology

2.1. Parameterization approach for spectral integrals

We parameterized spectrally integrated radiative quantities by weighted means of these quantities at representative wavelengths, following the approach described by Buehler and coauthors [11] for broadband infrared radiometers. The basic idea of the parameterization approach is given by

$$I_{\text{int}} = \int_{\lambda_{\min}}^{\lambda_{\max}} I(\lambda)R(\lambda)\,d\lambda \approx I_{\text{int,para}} = R_{\text{int}} \cdot \sum_{i_{\text{rep}}=1}^{n_{\text{rep}}} I(\lambda_{i_{\text{rep}}})w_{i_{\text{rep}}}$$

$$\text{with } R_{\text{int}} = \int_{\lambda_{\min}}^{\lambda_{\max}} R(\lambda)\,d\lambda \qquad (1)$$

The spectrally integrated radiative quantity I_{int} is the integral of the spectral radiative quantity $I(\lambda)$ times the spectral weighting function $R(\lambda)$ (with $0 \le R(\lambda) \le 1$) from the limits $\lambda_{\min}$ to $\lambda_{\max}$ of the spectral interval. $R(\lambda)$ can describe, for example, an instrument channel response function or a wavelength band. I_{int} is approximated by $I_{\text{int,para}}$, which is the sum of the spectral radiative quantity I at n_{rep} representative wavelengths $\lambda_{i_{\text{rep}}}$ multiplied by their weights $w_{i_{\text{rep}}}$ and the term R_{int}. The sum over the weights $w_{i_{\text{rep}}}$ is equal to 1, thus the summation term of Eq. (1) is a weighted mean of the quantity I. The term R_{int} is a measure for the spectral width of the interval.

For each spectral interval, the set of representative wavelengths $\lambda_{i_{\text{rep}}}$ and weights $w_{i_{\text{rep}}}$ needs to be optimized. Our methodology is based on Buehler et al. [11] with some modifications as described below. The optimization approach uses spectrally high-resolved radiances of a set of different atmospheric states, the “training set of atmospheres”.

2.1.1. Training set of atmospheres

Our aim is developing a parameterization approach which approximates wavelengths integrals for any realistic