Chapter 1

Introduction

Several aspects in atmospheric remote sensing and climatology evoke the interest in clouds in general and ice clouds in particular, which are known to permanently cover about 30 % of the Earth's surface (Wylie et al., 1994). First, clouds play an important role in the global balance of energy in the Earth-atmosphere system. They may have a cooling effect through avoiding solar radiation to penetrate and heat deeper parts of the atmosphere by reflecting it back into space. Terrestrial radiation emitted by the Earth's surface and by warm lower parts of the atmosphere may be absorbed or reflected back by the cloud. Thus, the radiation is "trapped" in the atmosphere which leads to a warming effect. Resulting net effects depend on microphysical properties as well as on location and extent of the clouds. Second, cloud properties, e.g. water content, have to be adequately represented in general circulation models (GCM) to allow for reasonable weather and climate prediction. For both, the estimation of the global energy budget and the maintenance of GCMs, global and comprehensive data of cloud occurrence and cloud properties would be desirable and helpful. Third, clouds "contaminate" molecular emission and absorption spectra and thus complicate trace gas retrievals.

Limb observations have been a common technique in thermal infrared and microwave passive remote sensing of the atmosphere for over 25 years. Starting with the Limb Radiance Inversion Radiometer (LRIR) on Nimbus-6 in 1975, a number of instruments for the measurement of limb emission spectra have been launched. The latest of these missions include MIPAS (Fischer and Oelhaf, 1996) on ENVISAT and TES (Beer et al., 2001), MLS (Waters et al., 1999), and HIRDLS (Remedios et al., 2001) on EOS-Aura.

Compared to nadir and slant observation geometries limb sounding is almost independent of surface properties and provides a better vertical resolution of measurements and derived data products, but requires the consideration of the sphericity of the Earth-atmosphere system in forward modeling. "Classical" models for thermal infrared and microwave radiative transfer solve the Schwarzschild equation, i.e. do only consider thermal emission as source term, with extinction determined by molecular absorption solely. Contribution of atmospheric particles, especially the scattering source term, is neglected.

Limb measurements by thermal emission and microwave sounders have primarily been used for retrieval of temperature and trace gas profiles. Only at the beginning of the 21st century, the potential of limb sounders concerning observation of high altitude clouds had been examined (Spang et al., 2002b). While clouds at first were only accounted as emitting radiation, Höpfner et al. (2002) demonstrated, that certain features in high resolution infrared limb spectra can only be explained by scattering of radiation into the instrumental line of sight. During the last years, several models have been developed for modeling terrestrial radiative transfer including scattering in spherical atmospheres, e.g. ARTS (Emde, 2005), KOPRA (Höpfner, 2004), FM2D (Kerridge et al., 2004) and McClouds_FM (Ewen et al., 2005).

In parallel, the limb observation technique was also adapted to the ultraviolet and visible spectral region. Instruments like OSIRIS (Llewellyn et al., 2004) on Odin, SCIAMACHY (Bovensmann et al., 1999) on ENVISAT as well as the Shuttle-borne SOLSE/LORE mission (McPeters et al., 2000), which measure limb scattering radiances, have been designed primarily for ozone monitoring with high vertical resolution. Observation of clouds by these instruments just recently has come into focus (Bourassa et al., 2005). For being able to access the data acquired by UV limb scattering instruments, a number of radiative transfer models considering scattering in a spherical atmosphere have been developed, e.g. LIMBTRAN (Griffioen and Oikarinen, 2000), VECTOR (McLinden et al., 2002) and SCIATRAN (Rozanov et al., 2003).

Although limb observations still are primarily applied to the retrieval of trace gas profiles, their high potential for cloud observation has been recognized. They may serve well, in particular for the derivation of properties of thin and subvisible ice clouds, that can hardly be detected by nadir and slant looking instruments like MODIS (King et al., 1992) and MERIS (Rast and Bezy, 1999). While there are no tangible limb missions planned and a "limb gap" is menacing (Bernath and Kyrölä, 2006), currently several instruments at all spectral regions used in passive remote sensing are operating and acquire data. With EOS-Aura and ENVISAT, two platforms exist that carry multiple limb sounding instruments at a time. Beside the mere development of cloud retrieval methods for separate instruments, this provides the opportunity to evaluate the potential of multispectral data analysis. The simultaneous use of data, measured at diverse spectral regions, may allow for combining the specific strengths and to overcome the weaknesses of the individual spectral intervals. In the future the emphasis concerning the development of new methods and algorithms will certainly be more evidently placed on the exploration of synergies among instruments. However, for being able to analyze data measured from the ultraviolet to the microwave spectral region, appropriate radiative transfer models are required.

The new radiative transfer model SARTre ([Approximate] **S**pherical **A**tmospheric **R**adiative **Tr**ansf**e**r model), that is presented in this work, might satisfy those needs. It has been developed to provide a consistent model, that is capable to consider emitted and scattered radiation from solar and terrestrial sources in a spherical atmosphere.

An overview of the theoretical background of radiative transfer modeling in the atmosphere is given in chapter 2. The basic quantities and equations are introduced, that are used to describe emission, absorption, and scattering of radiation originating from solar and terrestrial sources. Furthermore, the composition and structure of the Earth's atmosphere is described and optical properties of its constituents are discussed.

The structure and principles of the SARTre model are presented in chapter 3. The approach used to solve the radiative transfer equation is described in detail. An overview of the line-by-line algorithms for calculation of molecular absorption cross sections, that are adapted from the radiative transfer package MIRART (Schreier and Böttger, 2003), is provided. The local planarity assumption for the derivation of the multiple scattering contribution is introduced and a comprehensive explanation of the implementation of the plane-parallel radiative transfer solver DISORT for the calculation of the incident radiation field is given.

The following chapters 4 – 6 deal with the verification and validation of the SARTre model. In this context, the term "verification" is used according to Boisvert et al. (2005) and in compliance with the IEEE Standard Terminology given in IEEE (1990). Verification is the confirmation, that the implementation of the underlying models – i.e. the mathematical methods as well as the computational means – is correct, or in other words verification ensures that a product “is built right”. Validation on the other hand evaluates, whether “the right product is built” concerning a certain purpose (Calder et al., 2004).

Verification of SARTre is done by a set of successive and complementary model intercomparisons. Since SARTre is the first model, that is able to model limb radiances in the shortwave and the longwave spectral region, these two aspects of the SARTre model have to be verified separately. In chapter 4 the verification of the terrestrial radiative transfer modeling will be presented, while chapter 5 deals with the intercomparison of the solar radiative transfer simulations.

In chapter 6 the effect of thin and subvisible cirrus clouds on mid-infrared limb spectra is studied. For validation of the SARTre model, simulated spectra are set in contrast to cirrus features observed in MIPAS data. Cloud properties are estimated from comparison of modeled and measured spectra, and examined concerning their plausibility. Deviations between simulations and measurements are discussed.

Chapter 7 summarizes the results presented in this work and gives an outlook to potential future applications of the SARTre model.