Introduction

Clouds are the most dominant feature of our weather and affect our daily activities and health in many ways. In contrast to their importance to our daily life stands our limited knowledge and the relatively poor representation of clouds in climate and weather prediction models. The extreme variability of clouds over large scales of ranges plus their dynamical nature complicate efforts to monitor and model clouds.

Solar radiation drives the weather and climate of the earth. Multiple scattering and absorption alter the incoming solar radiation on its path through the atmosphere and are dominated by clouds which cover large parts of the earth. The interaction of clouds and radiation plays an important role for the energy budget of the earth. The modelling of radiative heating rates is accompanied with significant uncertainties due to our limited understanding of multiple scattering and absorption in cloudy atmospheres. The description of the spatial structure of realistic clouds, their regional and large scale distribution, the regional and seasonal variation, and the efficient modelling of their radiative properties are urgent scientific issues to detect climate changes (*Rossow and Schiffer*, 1991). Climatologies of cloud layer amount, cloud layer thickness, cloud layer overlaps and the vertical distribution of water and ice should be taken into account in global circulation models but are investigated by a few studies only (*Poore et al.*, 1995). The layering of single cloud layers and their microphysical properties are crucial requirements for the parameterisation of clouds in global circulation models (*Brenguier et al.*, 2000).

The estimation of the net effect of the interaction of clouds and radiation has to consider many aspects: Clouds result in a cooling of the earth through the reflection of solar radiation. Simultaneously, they function as a trap for thermal radiation which decreases the amount of energy lost to space, and therefore, heat the earth. Another aspect is the absorption of the atmosphere with contributions from cloudfree and cloudy parts. An estimation of the short-wave heating and long-wave cooling effect is given by *Rossow and Zhang* (1995). The effect strongly depends on cloud height, surface characteristics, and geographic latitude. Especially the study of cloud absorption was studied intensively in the past, since a significant discrepancy between the calculated and measured absorption is found on a global scale. The measured absorption is systematically larger, by about 20 to 40 W m^{-2}, than the calculated one. This observation is referred to as the ”*anomalous absorption*” or ”*enhanced absorption*”. The work of *Kiehl et al.* (1995) initiated three basic papers which discuss the absorption of irradiance in cloudy atmospheres with net flux estimates measured either by satellites and ground based instruments (*Cess et al.*, 1995; *Ramanathan et al.*, 1995) or with two aircrafts flying spatially synchronised above and below cloud (*Pilewskie and Valero*, 1995). The reasons and the strength of the ”*anomalous absorption*” are controversially discussed and related to difficulties in either calculating or measuring the global absorption effect of cloudy atmospheres. A discussion of the difficulties related to the measurements can be found in, e.g. *Imre et al.* (1996), *Li et al.* (1999), and *Valero et al.* (2000). Absolute calibration uncertainties, deviation from an ideal cosine response of the instrument, and a horizontal displacement between aircrafts can be found among them. A recent overview of related papers is given by *Wendisch and Keil* (1999). The modelling of the global absorption may be biased due to oversimplified or missing physics (e.g. *Stephens and Tsay*, 1990): microphysical uncertainties, the impossibility of the consideration of cloud inhomogeneities, missing absorber, and incorrect modelling of

TABLE 1. Selected instruments and satellites relevant for cloud remote sensing. MERIS and Meteosat-8 (MSG) have a high resolution modus and channel, respectively. The spatial resolution of Meteosat-8 refers to nadir viewing. MERIS has programmable spectral channels.

Instrument / Satellite	Spatial Resolution	Spectral Characteristics
MERIS / Envisat	~300 m (high), 1 km (regular)	15 channels ranging from 400-900 nm
Modis / Terra, Aqua	250 m (vis), 500 m (vis, NIR), 1000 m (else)	36 channels ranging from 0.4-14.5 μm
Meteosat-8 (MSG)	1 km (high), 3 km (regular)	11 channels ranging from 0.6-13.4 μm

water vapour absorption. The latter is assumed to be the major uncertainty in the simulations. The effect of cloud inhomogeneities on cloud absorption gives reason to controversial discussions: depending on the considered scenario, decrease, increase and absence of cloud absorption in the presence of inhomogeneous cloud fields can be found (*Marshak et al.*, 1998 and references therein).

Satellites offer a great opportunity to monitor the current weather conditions on a global scale and with fairly high temporal frequencies on regional scales. Their potential for an improvement of weather forecast models is presumably high. Table 1 provides an overview of selected instruments on board satellites and their spatial resolutions and wavelength ranges. Measurements of reflected solar radiation in the visible and infrared are used for the retrieval of various cloud properties, like e.g. optical thickness, liquid water path, effective radius, albedo and cloud top height (e.g. *Twomey and Cocks*, 1982, 1989; *King*, 1987; *Nakajima and King*, 1990; *Nakajima et al.*, 1991; *Platnick and Twomey*, 1994; *Han et al.*, 1994; *Platnick and Valero*, 1995). The underlying idea of the retrieval of optical thickness and effective radius is that the reflection in a visible, non-absorbing channel is related to the optical thickness while the reflection in a liquid water absorption channel depends mainly on the droplet size. The cloud top height retrieval is based on several approaches: 1) brightness temperature differences, 2) $\mathrm{CO_2}$ slicing, and 3) absorption intensity by $\mathrm{O_2}$. The majority of retrieval schemes are based on multi-layer, plane-parallel and homogeneous solutions of the radiative transfer equation for the computation of radiance and flux databases as input for inversion techniques. In the recent past, numerical studies revealed that the plane parallel assumption may lead to significant uncertainties of the retrieval schemes. If the relation of the retrieved parameter, e.g. the optical thickness τ, is not a linear function of the reflectance R, the difference between the mean of the reflectance and the reflectance of the mean optical thickness can exceed 17% ($R(\bar{\tau}) \geq \overline{R(\tau)}$, see *Cahalan et al.*, 1994). In addition, the reflection of visible solar radiation depends not only on the local cloud properties but also on the interaction with neighbouring pixels. Exact 3-dimensional (3d) radiative transfer (RT) simulations and independent pixel approximations (1d RT model at local scale which neglects photon exchange between neighbouring pixels) agree within 1% of computed albedo for mesoscale simulations. An individual pixel comparison revealed differences, reaching as much as 50% (*Marshak et al.*, 1995a). The main reason for this is horizontal photon transport which results in a smoothed appearance of the reflectance, if compared to the optical thickness field (*Marshak et al.*, 1995a and *Davis et al.*, 1997a). Several other factors affect the interaction of clouds and radiation. Previous studies mainly focused on the horizontal variability of optical thickness and a varying observation geometry as well as different degrees of cloud fraction (*Barker and Davies*, 1992; *Loeb and Davies*, 1998; *Davis et al.*, 1997a,b; *Loeb and Coakley Jr.*, 1998). The effect of a variable horizontal optical thickness is generally less significant than cloud top height effects (*Loeb et al.*, 1997, 1998; *Varnai and Davies*, 1999; *Varnai*, 2000; *Iwabuchi* *and Hayasaka*, 2002). The vertical variation of cloud properties was investigated by, e.g., *Li et al.* (1994), *Brenguier et al.* (2000), and *Platnick* (2000). All studies mentioned are based on relatively simple cloud models which depend on a few parameters only and ease the interpretation of the results (e.g. *Barker and Davies*, 1992; *Marshak et al.*, 1994). More sophisticated cloud models mainly focus on case studies (e.g. *O'Hirok and Gautier*, 1998a,b). The physical frame of large eddy simulation (LES) models provide the most realistic cloud fields but the LES model is difficult to tune to produce certain cloud characteristics, sometimes difficult to interprete and time consuming. A cloud model, which produces cloud fields of pre-defined characteristics in combination with the exact representation of observed cloud properties is not available.

Several statistical approaches have been invented to characterise radiative transfer effects in cloudy atmospheres. Furthermore, the outcome could be related to physical processes which could not be drawn from the original data set: *Cahalan and Snider* (1989) observed a scale break in power spectra analysis of Landsat nadir radiances which can be explained by horizonal photon transport (*Marshak et al.*, 1995b; *Davis et al.*, 1997a). *Davis et al.* (1994, 1996) and *Marshak et al.* (1997) proposed the multifractal characterisation of geophysical data sets and its advantages over the power spectrum analysis. The first three moments (mean, standard deviation, and skewness) of computed reflectance are further parameters to study 3d effects (*Varnai*, 2000). Another question which arises from the 3d structure of cloud fields is the representativity of single measurements at different resolutions (remember the variable resolutions of satellite measurements given in Table 1). Is it possible to define optimal scales for cloud property retrievals and how can the results of different sensors be compared among each other?

This work provides a broad discussion of the effect of 3d cloud structure on solar radiation. The investigations are based on a measurement campaign and on 3d radiative transfer simulations. After the introduction of basic theory and tools, the utilised instruments and the campaign are presented (sections 2.1 and 2.2, respectively). A spatial high-resolution cloudmask for observations over land is developed which is needed for preprocessing of radiance measurements. The RT simulations are performed with a Monte Carlo model (section 4). After the implementation of a specific variance reduction technique, the model is validated by intercomparison to other models. To provide the model with input parameters a cloud generator is developed using Fourier transformations. It is used to characterise the noise behaviour of the model. Two other methods of cloud generation are introduced: The surrogate cloud generator and the large eddy scale model provide the cloud fields for the radiative smoothing and spatial averaging analysis. To obtain the required input parameters for the Monte Carlo model, microphysical properties are discussed and a specific mixing scheme is introduced. All the topics which concern the input of the Monte Carlo model are discussed in section 3. Two substantial aspects of the effect of 3d cloud structure on solar radiation are described in detail: cloud radiative smoothing (section 5) and spatial averaging (section 6). The effect of cloud radiative smoothing is dealt with by applying power spectra analysis to the measurements and simulations. The analysis focuses on the effects of water vapour absorption, surface albedo, and two layer cloud systems on cloud radiative smoothing: e.g. horizontal photon transport act as a filter for the high frequencies of the optical thickness field which is the reason for a smoother appearance of the nadir radiance at small scales. In this work, the terms large and small scale cloud radiative smoothing are introduced to emphasise their effectivity on different scales. The results are extracted from observations and validated by corresponding analysis of RT simulations. The effect of spatial averaging on cloud property retrievals is discussed by an artificial degradation of spatial high-resolution observations and simulations. While the discussion related to observations is fixed on 1d horizontal measurements, the analysis of the simulations is extended to two horizontal dimensions. The effect of vertical layering on nadir reflectance is described in the first part of section 6. This is followed by a parameterisation of the mean photon path length with optical thickness and effective radius which offers an improvement of remote sensing retrievals and the gas absorption scheme in global circulation models.