Summary

The central subject of this work is to improve the understanding of multiple scattering and absorption in the presence of 3d cloud fields. A systematic investigation of the effect of 3d cloud structure on the atmospheric radiation field is carried out. The discussion focuses on cloud radiative smoothing and the analysis of horizontal and vertical averaging and layering.

The investigations within this work are based on two different data sets: The first one relies on radiance observations taken during the BBC campaign in The Netherlands in September 2001. The second data set is computed with (3d) radiative transfer simulations of reflectances. In this way, the experimentally retrieved results and conclusions could be verified, and their combination led to a better understanding of the processes affecting the results and enhances the reliability of the outcome.

The Freie Universität Berlin participated in the BBC campaign with its research aircraft, a Cessna 207T. The Cessna was equipped with a variety of remote sensing instruments and performed several flight missions over broken, closed, and multi-layer clouds. Two of the instruments, *casi* and FUBISS, supply radiance measurements in the visible and near-infrared and form the basis of the analysis of the interaction of 3d cloud fields with radiation. The construction of the instruments is introduced, and the calibration procedures are outlined in detail. During the introduction of the BBC campaign a spectral and time series verification of both observations is presented and demonstrated the reliability of the measurements and calibrations.

During the BBC campaign a large variety of ground based instruments participated and provided information about observed cloud fields. These measurements are statistically analysed to identify a few characteristics of the clouds. The slope of liquid water path, retrieved from a power spectrum analysis, is found to be approximately 8/3 which significantly differs from the value given in literature (5/3). Additionally, the determination of the standard deviation of cloud top and base height revealed a larger variability of cloud base than cloud top height. It is argued that the cloud base height changes are related to fluctuations in thermodynamic parameters while large cloud top heights are disabled by strong inversions. It can be assumed that cloud base height inhomogeneities have no significant effect on nadir observations if the cloud optical thickness is relatively large. However, this argument needs to be verified, and it would be worthwile to identify a critical optical thickness, where inhomogeneities of the cloud base height become relevant. A possible effect in case of thin clouds should be quantified in future studies. Another open issue is the difference of clouds characterised with spectral slopes of 8/3 and 5/3 in terms of radiative aspects. The statistical analysis of cloud properties is currently a topic of the author and project partners. The outcome of the investigation of observed cloud fields by ground based instruments is used as input variables to artificial cloud generators which provide the radiative model with input parameters. The cloud generators produce geometrical cloud information or LWC what is completed by microphysical schemes. In particular, a mixing scheme is introduced which allows the handling of non-adiabatic LWC. The radiative transfer is computed with a Monte Carlo model. Its basic principles are introduced, and great effort was spent to validate the model using I3RC. The radiation field, weighting functions, and photon statistics are determined and allow the application of the equivalence theorem,

a powerful tool to calculate the radiance in absorbing channels using a single computation only.

Based on the radiance observations and corresponding Monte Carlo simulations, the effect of gas absorption, surface albedo, and two layer clouds on nadir radiances is investigated by applying the power spectrum analysis. In a conservative medium horizontal photon transport results in a scale break at scales proportional to the cloud thickness and an increase in the small scale slope. Here, this phenomenon is denoted as small scale cloud radiative smoothing in order to emphasise its occurrence at small scales. The horizontal movement of photons blurs the optical thickness: The locally measured radiance is not only related to the corresponding optical thickness but also to a large amount of neighbouring optical thicknesses. Gas absorption prevents horizontal photon transport and reduces the mean free photon path. In consequence, the scale break and the small scale slope decrease, if the intensity of gas absorption increases. In contrast to the small scale effect of gas absorption, significantly large surface albedos and two layer clouds lead to a decrease of the large scale slope what is identified as large scale cloud radiative smoothing. Large albedos of the lower cloud layer or of the surface increase the brightness of optically thin cloud parts while optically thick cloud parts remain almost unchanged in brightness. In this way, spectral energy is removed from scales proportional to the diameter of typical cloud cells. If large surface albedos and gas absorption occur simultaneously, the gas absorption prevents multiple scattering between cloud and surface and therefore cancels the surface albedo effect. The results from the observations and the computations are in excellent agreement. However, the analysis of the simulations revealed that the occurrence of large scale cloud radiative smoothing depends on the relative distribution of the optical thickness of two layer cloud systems. If the maxima and minima of the optical thickness of the upper and lower layer coincide, the effect cannot be observed. It is left open to future studies how large optical thicknesses of the upper or small optical thicknesses of the lower layer, variable degrees of coverage of the upper and lower layer, and the vertical separation between both layers affect cloud radiative smoothing. The fraction and the optical thickness, the spatial distribution of optically relevant cloud properties and the vertical separation of both layers should be well-defined for the interpretation of the result. Similar arguments are appropriate, if the effect of the surface albedo is studied. It is of great advantage to carry out measurements with increased spectral resolution in order to avoid spectral averaging over regions with highly variable absorption intensities. Alternatively, line-by-line calculations using the equivalence theorem can be used. Eventually, an empirical relationship between the strength of the gas absorption and the scale break can be established. The absolute results of the power spectrum analysis have to be considered with care, since they depend on the pixel size, the sampling frequency, and the interpolation range. Longer flight legs or larger input fields and a higher spatial resolution will help to consolidate the results.

The exact knowledge of the scale break is a valuable information for remote sensing. If the resolution of the instrument is smaller than the scale break, a retrieval of the optical thickness is not reliable while at resolutions larger than the scale break the application of the retrieval scheme is uncritical: The resolution of the high resolution channels of Modis and MERIS are in the order of scale breaks which can be expected for stratus clouds while Seviri's resolution is certainly large enough to avoid problems related to horizontal photon transport. Since increasing gas absorption reduces the scale break, retrieval schemes, which rely on gas absorption, can be applied to data from sensors with correspondingly higher resolution. It becomes obvious that surface albedo effects on nadir observations are effective even in completely overcasted cases. Therefore, the retrieval of cloud properties over surfaces with significant albedo should be carried out with care. A similar argument holds if two layer clouds are considered. Here, it is often not an easy task to decide about the amount of layers. The presented analysis may offer a way to identify multi-layer clouds in some cases. If the energy budget of the earth is considered with respect to horizontal photon transport, surface albedo, and multi-layer clouds, effects on scales below the scale break are probably neglectable. The large scale effects related to large suface albedos and multi-layer clouds are assumed to influence the energy budget of cloudy atmospheres significantly. In both cases, the albedo of the sytem increases, and multiple scattering between surface and cloud as well as between cloud layers enhances the probability of absorption, thus decreasing the transmission.

In the second part, the effect of horizontal and vertical averaging and layering is analysed, again based on measurements and computations but with a stronger emphasis on the latter. Utilising realistic cloud profiles, the effect of vertical layering and averaging is investigated. It could be shown that non-absorbing media do not depend significantly on the cloud profile (The optical thickness was constant for all profiles). As soon as absorption is effective, large effects are observed, and the intensity of the absorption and the volume extinction at cloud top are the dominant dependencies. The mixing scheme and the layer thickness are of minor importance. Since the vertical profile of volume extinction is in general unknown, the retrieval of cloud properties should be carried out at pixels where the likelihood of adiabaticity reaches its maximum: It is in the core of convective cells, where the reflectance is at its largest. Horizontal averaging is studied with the help of *casi* data and 3d RT simulations. If reflectances are considered, the averaging needs large ranges to reach its large scale mean. In the case of absorption to window channel ratios closed single layer clouds reach their large scale mean at small scales, hardly reaching the significance level. In contrast, complex cloud fields, e.g. broken or two layer clouds, may not reach their large scale mean below scales of 25 km. The results for the closed single layer clouds are found in observations and simulated reflectance fields while the complex cloud cases are studied based on measurements only. If 2d, and not 1d averaging is carried out, the averaging is much less problematic, since the amount of pixels is significantly increased. Great care is required, if satellite observations of different resolution are compared. A simple adjustment of the resolution must be accompanied by an exact allocation of both measurements, especially, if broken or multi-layer clouds are observed.

The last topic of the second part, is the parameterisation of the mean photon path length with the optical thickness and the effective radius utilising adiabatic profiles. The parameterisation offers a way to improve the retrieval of atmospheric properties which rely on gas absorption: Either, the additional absorption through enhanced photon path length in the cloud can be estimated with the help of the mean photon path length, if scattering within the cloud was neglected in the development of the original retrieval algorithm, or the mean photon path can be utilised as additional input parameter for a retrieval scheme. In terms of GCMs, the inclusion of a second parameter, the effective radius, is an extension of usually used parameterisations of photon path length, since they rely on optical thickness only. The dependence of the mean photon path length on the effective radius is found to be significant, especially at high optical thicknesses. E.g., if the optical thickness is fixed at 50, an increase of the effective radius from 6.5 to 15.5 μm results in an increase of the mean photon path length from 0.6 to 1 km, almost a doubling. While the effect of photon path length enhancements is significant, if airborne remote sensing from low altitudes is considered, its effect on the gas absorption of the whole atmospheric column is assumed to be of lower degree because the geometrical path above cloud can be significantly larger than the path length within and below cloud. However, the extension of the parameterisation to the effective radius may enhance the quality of the computation of heating rates in GCMs.

Furthermore, the sun zenith angle strongly affects the mean photon path length. An exemplary study revealed an increase at low and a decrease at high optical thicknesses. A more intense analysis of the influence of the sun zenith angle will be subject of future studies. The investigation of the mean photon path length and its effect on transmission should be extended to cumulus cloud fields (cloud fraction less than 100%). On the one hand multiple scattering between neighbouring cumulus clouds may enhance gas absorption. On the other hand the transmitted solar radiation through cloud edges is characterised by large intensities which can be larger than the incoming radiation. The net effect of both processes has not been investigated in full detail so far. These findings and future plans are related to gas absorption. If liquid water absorption is considered, the analysis is far more complicated: First, the absorption and the scattering cannot be separated, as it was possible during the application of the equivalence theorem. Second, the absorption properties cannot assumed to be constant with height above ground, what was another assumption during the analysis.

The investigation of cloud radiative smoothing and the analysis of horizontal and vertical averaging and layering led to a significant increase of the understanding of multiple scattering and absorption, as well as interactions between both processes. Moreover, the results and conclusions are even helpful for the improvement of retrieval schemes of atmospheric cloud properties and their validation and for the improvement of the estimation of gas absorption in GCMs.