THE INDIRECT EFFECT OF AEROSOLS ON CLIMATE: OBSERVATIONS WITH AN AIRBORNE RADIOMETER

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1. INTRODUCTION

The indirect effect of aerosols on climate, also referred to as the Twomey Effect, is related to changes in cloud radiative properties due to aerosols acting as cloud condensation nuclei (CCN), via changes in cloud microphysics. This anthropogenic forcing is estimated with global climate simulations supplemented by satellite survey. It is thus crucial to develop techniques for the retrieval of cloud microphysical and optical parameters from space.

The measurement of the reflected solar radiation in the visible (VIS) and near infrared (NIR) spectral regions has been used to retrieve the cloud optical thickness and the effective droplet radius assuming vertically homogeneous clouds (e.g. Twomey and Seton, 1980, Nakajima and King, 1990, King, 1993). The relationship between droplet concentration as derived from CCN properties and the droplet radius is still missing. In actual clouds of stratocumulus type, the droplet effective radius is in fact dependent on both the droplet concentration and the altitude above cloud base: a negative correlation between remotely sensed cloud optical thickness and effective radius thus reflects the Twomey Effect, while a positive correlation illustrates the cloud geometrical thickness dependence.

A conceptual cloud model with an adiabatic profile of the microphysics has been used in radiative transfer calculations instead of the plane-parallel vertically uniform model. The conceptual model is parameterised with cloud geometrical thickness *H* and cloud droplet number concentration (CDNC) *N*, and reflectances in the VIS and NIR are calculated. The inverse procedure is then used to derive *H* and *N* from measurements of the reflectances. The statistical analysis of the results and the comparison with in situ data is presented in this paper.

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2. MEASUREMENTS DURING ACE-2

During the ACE-2 Cloudy-Column campaign, the FUB-WeW operated a high spectral resolution downward looking radiometer OVID (Schüller et al. 1997) onboard the DLR-Do228. The OVID instrument consists of two detection units (telescope, fibre cable, spectrometer and CCD detector). The VIS part covers the spectral range between *700 nm* and *1000 nm* with 1024 spectral channels (spectral resolution *0.8 nm*) and the NIR (near infrared) part has 256 channels for measurements between *1000 nm* and *1700 nm*. The spectral resolution is *6 nm*. The sampling frequency during ACE-2 was *10 Hz*, that corresponds to a spatial resolution of approximately *10 m*.

A number of 8 flight missions were flown by the Do-228 in close co-ordination with the Météo-France M-IV instrumented aircraft, equipped with in situ measurements of cloud microphysical properties (Pawlowska and Brenguier, 2000). Observations were made above marine stratocumulus clouds that were affected by different levels of pollution. A more detailed description of the project can be found in Brenguier et al., (2000-a).

3. RADIATIVE TRANSFER SIMULATIONS AND ALGORITHM DEVELOPMENT

Radiative transfer calculation are the basis of retrieval algorithms, that usually compare the measured radiation to simulated ones. The cloud reflectance in a VIS channel is mainly dependent upon cloud optical thickness, while the reflectance in the liquid water absorption bands (NIR) shows more sensitivity to the droplet size. Due to large multi-scattering effects, photons at wavelengths, where absorption occur, carry information from the top-most cloud layer only. A remotely sensed droplet radius refers therefore to the upper cloud layer and it is not necessarily representative of the whole cloud.

Stratocumulus clouds usually show a very pronounced vertical profile of the droplet size, that depends on CDNC. The interpretation of remotely sensed droplet sizes is therefore problematic, since natural variations of cloud geometrical thickness will result in variations of the droplet sizes at cloud top. On the contrary CDNC is more uniform through the cloud layer and it is thus more suited for characterizing the microphysical properties of stratocumulus and their relationship with the aerosol background. Therefore, stratified cloud models are more realistic than vertically uniform models for radiative transfer simulations.

3.1 The adiabatic model

The adiabatic model describes the vertical profile of the microphysics in a closed ascending cloud parcel. The liquid water content increases linearly with height:

$$LWC_{ad}(h)=C_w\, h.$$

In addition, N_{ad} is constant in the adiabatic model. Hence, the droplet mean volume diameter expresses as:

$$r_{v,\,ad}(h) = (A\, h)^{1/3}\, (N_{ad})^{-1/3} \text{ with } A= C_w/(4/3\, \pi\, \rho_w).$$

The effective radius can be derived from $r_{v,\,ad}$ with the factor $k = r_e^3 / r_v^3$. The optical thickness of an adiabatic cloud layer can thus be calculated as a function of H and N (Brenguier et al. 2000-b):

$$\tau = 3/5\, \pi\, Q_{ext}\, A^{2/3}\, (kN)^{1/3}\, H^{5/3}.$$

In the adiabatic model, droplet effective radius and optical thickness are both functions of N and H:

$$r_e = r_e(N,H)$$
$$\tau = \tau\, (N,H).$$

This relation is used to simulate the radiative transfer of vertically stratified clouds.

3.2 Radiative transfer simulations

For the calculation of the radiative transfer a Matrix-Operator Model has been applied (Fischer and Graßl, 1991). The single scattering properties (extinction and scattering coefficient, scattering phase function) are calculated by Mie theory. Upward directed radiances at flight level have been calculated and converted to reflectance values.

Vertical stratification of the simulated clouds were realized by combining homogeneous sub-layers of *25 m* thickness as indicated in Fig. 1. The layer averaged values of τ and r_e are determined by the adiabatic model (previous section). The reflectances at two wavelength (*754 nm* and *1535 nm*) were calculated for different combinations of H (from 0 to *500 m*) and N (from *10* to *800 cm*$^{-3}$). Figures 2 and 3 show the result of the radiative transfer simulations as iso-lines of N and H together with the statistics of the measured reflectances.

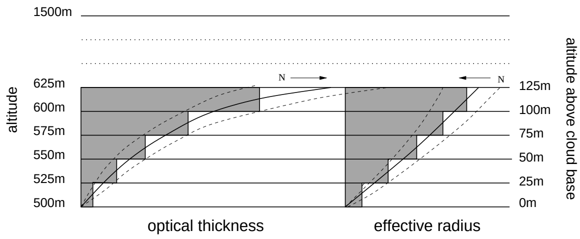

***Figure 1**: Optical thickness and effective radius of the homogeneous sub-layers for radiative transfer simulations with the adiabatic stratified cloud model.*

3.1 Inversion technique

The data set of simulated reflectances for different combinations of N and H is inverted by means of artificial neural network training. A number of 1000 learning patterns were used for the training, where each learning pattern consists in the three input values for solar zenith angle, reflectance at *754 nm* and reflectance at *1535 nm*, and the corresponding output values for N and H. The test patterns have the same structure and are used to control and estimate the quality of the inversion.

A back-propagation type of network training was applied to the learning patterns. The resulting neural network is implemented in the OVID processing system.

4. STATISTICAL ANALYSIS

The *754 nm* and *1535 nm* reflectances of the solar radiation were extracted from the OVID spectra and the algorithm for the retrieval of N and H was applied to the OVID measurements performed during ACE-2. Fig. 2 and 3 show the statistics of two flight legs that were flown above clouds in a clean (Fig. 2) and in a polluted (Fig. 3) environment.

There is a remarkable increase of reflection in the polluted case in contrast to the clean case. The comparison of measured data with the radiative transfer simulations (iso-lines) indicates that the largest variation in reflectance is due to variations of cloud thickness while N is rather constant. Generally, the measured data show similar behaviour as predicted by the radiative transfer simulations with the adiabatic stratified cloud model.

The statistics of reflectance can be assigned to typical iso-lines of droplet concentration, such as N*=25 cm*$^{-3}$ for the clean case (26 June, 1997, Fig. 2) and *100 cm*$^{-3}$ for the polluted case (9 July, 1997, Fig. 3). Since the adiabatic model describes the maximum possible liquid water that can be condensed, it is expected, that the high reflective parts of a flight leg correspond to adiabatic conditions and that the retrieval is more accurate for those samples. For the statistical analysis and comparison with in situ data, we therefore selected samples corresponding to samples with reflectance values in the upper *p %* of the distribution.

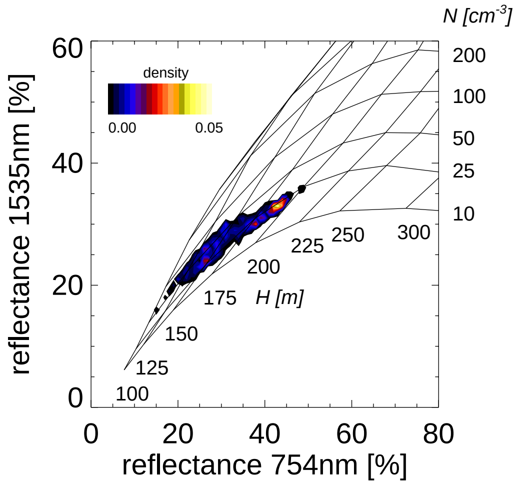

***Figure 2**: Two-dimensional histogram of measured reflectances at two wavelengths during a flight mission in a marine environment (26 June, 1997). The results of the corresponding radiative transfer simulations are indicated as iso-lines of N and H.*

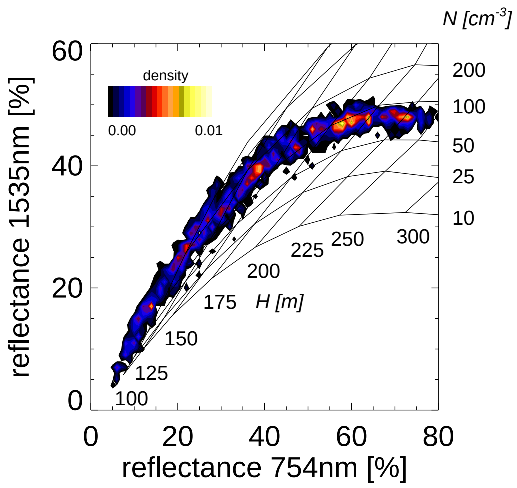

***Figure 3:** Same as Figure 2 in a polluted environment (9 July, 1997).*

An example of the resulting *N* histograms is displayed in Fig. 4 (polluted case 9 July, 1997, for *p= 0* (all values), *40, 60* and *80 %.*

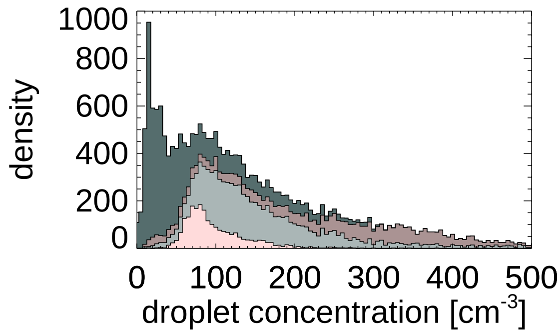

***Figure 4**: Histograms of the retrieved droplet concentration for the Cloudy-Column mission in a polluted environment (9 July, 1997).*

5. COMPARISON WITH IN SITU MEASUREMENTS

The retrieval of *N* and *H* has been performed for 8 Cloudy-Column missions. After selection of the most reflective parts (*p=80 %*) of the flight legs, the mean droplet concentration of the histogram (N_{OVID}) is compared (Fig. 5) to the mean droplet concentration, derived from in situ measurements with the Fast-FSSP, after selection of samples that are not affected by mixing with dry air and drizzle scavenging (N_{mean}) (Pawlowska and Brenguier, 2000-a and –b). Fig. 5 demonstrates, that the new remote sensing procedure is able to retrieve correctly the variations of N_{mean}, from the pure marine case to the most polluted one. The figure also shows, that there is a significant bias between in situ derived and remotely retrieved *N* values. The retrieved values are underestimated by a factor of about 2. The reason for this deviation is not clear. It is probably related to the sub-adiabaticity of microphysics in the cloud layer and to its spatial heterogeneity.

The comparison between remotely sensed and in situ observed cloud geometrical thickness is reported in Fig. 6. N_{max} is first derived as the value at 99 % probability of the cumulated distribution of the measured *N* values. The typical *H* value for each case is then derived from the cumulated distribution of the measured values of altitude above cloud base, after selection of samples with $N > 0.2\ N_{max}$. It is calculated as the value at *97 %* probability of the distribution and it is referred to as H_{max} (Pawlowska and Brenguier, 2000-a and –b). Fig. 6 shows also a good correlation but with an overestimation by the radiation measurements.

6. CONCLUSION

A new remote sensing technique, based on a realistic cloud model for radiative transfer simulations, has been developed for the retrieval of cloud geometrical thickness and droplet concentration. The anthropogenic Twomey Effect as well as the natural variation of cloud geometrical thickness both affect optical thickness and the effective radius at cloud top. In contrast, using *N* and *H* as co-ordinates, dynamical variations can be separated from the possible modifications of cloud microphysical properties.

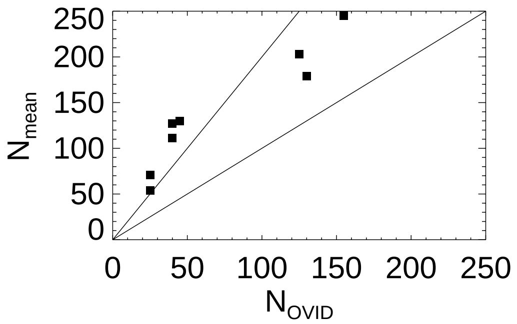

Figure 5: *Comparison of the remotely retrieved (N_{OVID}) and in situ measured (N_{mean}) droplet concentration values, for 8 Cloudy-Column missions.*

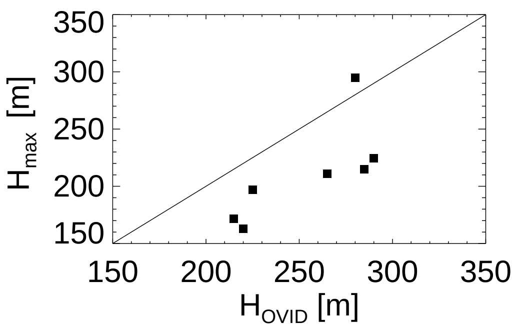

Figure 6: *Comparison of the remotely retrieved (H_{OVID}) and in situ measured (H_{max}) geometrical thickness values for 8 Cloudy-Column missions.*

Simultaneous measurements of the reflected radiation and microphysical properties with two instrumented aircraft have been used to validate the new remote sensing technique. Qualitatively, the validity of the algorithms has been demonstrated by the correlation between the in situ measured and retrieved values of *N* (Fig. 5) and *H* (Fig. 6). The next step will be focused on the analysis of the influence of non-adiabadicity and spatial heterogeneity of the microphysical field on the retrieval method. This might lead to a better parameterization of the aerosol-cloud-radiation interaction processes for the development of remote sensing algorithms as well as for climate models.

7. ACKNOWLEDGEMENTS

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