Radiative Properties of 3-D Stratocumulus Clouds in the Near-IR Spectral Range

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Introduction

Measurements of vertical radiative fluxes in near infrared (IR) spectral range have been widely used to determine absorption in inhomogeneous clouds (Rawlins 1989). Neglect of horizontal radiative fluxes (horizontal transport) may introduce large errors in these estimations at small spatial scales (Marshak et al. 1997; Titov 1998). A method, which corrects for the effect of the horizontal transport, was proposed by Ackerman and Cox (1981). The method is based on simultaneous measurements of the net fluxes of visible and near IR radiation and consists of two steps. First, a value of the horizontal transport at a wavelength outside the absorption band (e.g., the visible range) is determined. Second, this value is used to estimate cloud absorption in the near IR spectral range (inside absorption band(s)). In other words, it is suggested that horizontal transport is relatively independent of wavelength. This method has been frequently used to determine the absorption in inhomogeneous clouds (Hayasaka et al. 1995; Marshak et al. 1997) but without any strict foundation.

In the present work, we try to address the following questions: How strongly does the horizontal transport depend on the wavelength? What factors responsible for the spectral dependence of the horizontal transport are most important? To what extent is it possible to ignore the spectral dependence of the horizontal transport for cloud absorption estimates?

Approach

In this paper, a three-dimensional (3-D) Large Eddy Simulation (LES) cloud model with explicit microphysics (Kogan 1991) and a 3-D Monte Carlo method have been used to study spectral dependence of the horizontal transport and its effect upon cloud absorption estimates. A marine low-level stratocumulus layer was simulated in the integration domain consisting of 40 x 40 x 51 grid points with horizontal and vertical resolution of 75 m and 25 m, respectively. Spatial (vertical and horizontal) distributions of water droplets and water vapor, as well as temperature and pressure, were predicted by the LES model. In each grid cell, we use drop size distribution to calculate optical properties at three wavelengths: 0.7 μm (pure scattering, no water vapor absorption); 0.94 μm (strong water vapor absorption); and 1.65 μm (strong water droplets absorption). We will use subscripts "0.7", "0.94", and "1.65" to denote radiative properties calculated for these wavelength.

The case of broken stratocumulus layer observed during the Atlantic Stratocumulus Transition Experiment (ASTEX) was considered. The absorption, vertical, and horizontal radiative fluxes were calculated using the Monte Carlo method and periodic boundary conditions. The influence of the underlying surface and the atmospheric aerosol was not considered. The calculations were done for the solar zenith angle of 60°. Computational error, using about 120 millions of photons, was less than 1%.

Results

There are two assumptions in the Ackerman and Cox method (1981): 1) the horizontal transport depends mainly on the scattering properties (extinction coefficient σ and scattering phase function g), and 2) the latter are wavelength independent.

The horizontal transport may depend both on the scattering and absorbing properties (co-albedo and absorption coefficient of atmospheric gases and water vapor). It has been found (Deirmendjian 1969; Goody 1964) that

- The extinction coefficient and asymmetry factor can vary by roughly 2% to 5% per micrometer of wavelength.

- The single scattering co-albedo and absorption coefficient of atmospheric gases and water vapor can vary by several orders of magnitude.

It might be expected, therefore, that the spectral behavior of absorbing properties has stronger influence on the spectral dependence of the horizontal transport than that of the scattering ones.

To estimate the influence of spectral variability of cloud scattering properties on horizontal transport E and absorption A, we calculated E using σ and g values corresponding to three wavelengths: 0.7 μm, 0.94 μm, and 1.65 μm. Only conservative scattering with no atmospheric gases and water vapor absorption was considered. The results of the calculations are presented in Figure 1.

As seen, the weak spectral variations of σ and g have little influence on E. Thus, the spectral dependencies of scattering properties can be neglected. We note that the absolute value of E may exceed 1. It means that the direct (unscattered) radiation may contribute considerably to E. Note that pixels with negative E values gain the radiative energy through their sides, while pixels with positive E values lose energy.

The vertical profiles of variance of horizontal transport Var(E), corresponding to the three wavelengths, are presented in Figure 2. Here we include the absorption by water vapor and droplets.

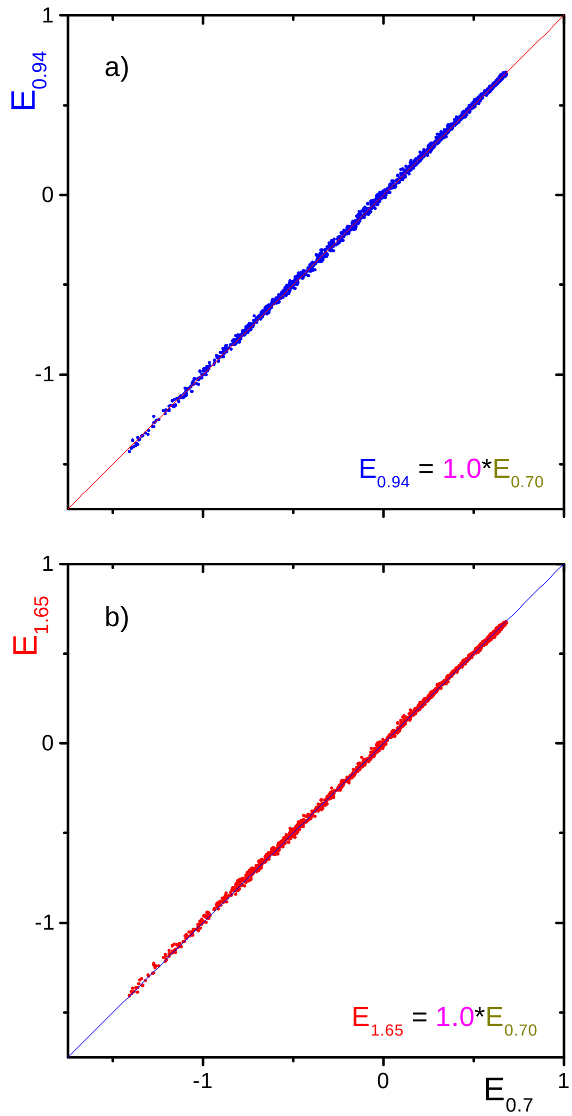

Figure 1. Linear regression of $E_{0.7}$ versus $E_{0.94}$ (a), and $E_{0.7}$ versus $E_{1.65}$ (b).

The water droplet absorption affects the diffuse radiation only. As scattering is most intense in the optically dense top portion of the cloud layer, the water droplet absorption affects Var(E) most significantly at cloud top (note the difference between Var($E_{0.7}$) and Var($E_{1.65}$) in Figure 2b, which is maximal at cloud top). The increase in Var(E) due to water droplet absorption is consistent with results obtained using a simpler model by Titov (1998).

The gaseous absorption, on the other hand, is important both for diffuse and direct radiation. As the mixing ratio is larger at cloud base (Figure 2a), the influence of water vapor on Var(E) is also the largest there (Figure 2b). In contrast to droplet absorption, gaseous absorption decreases Var(E), primarily by diminishing the relative contribution of direct radiation to Var(E).

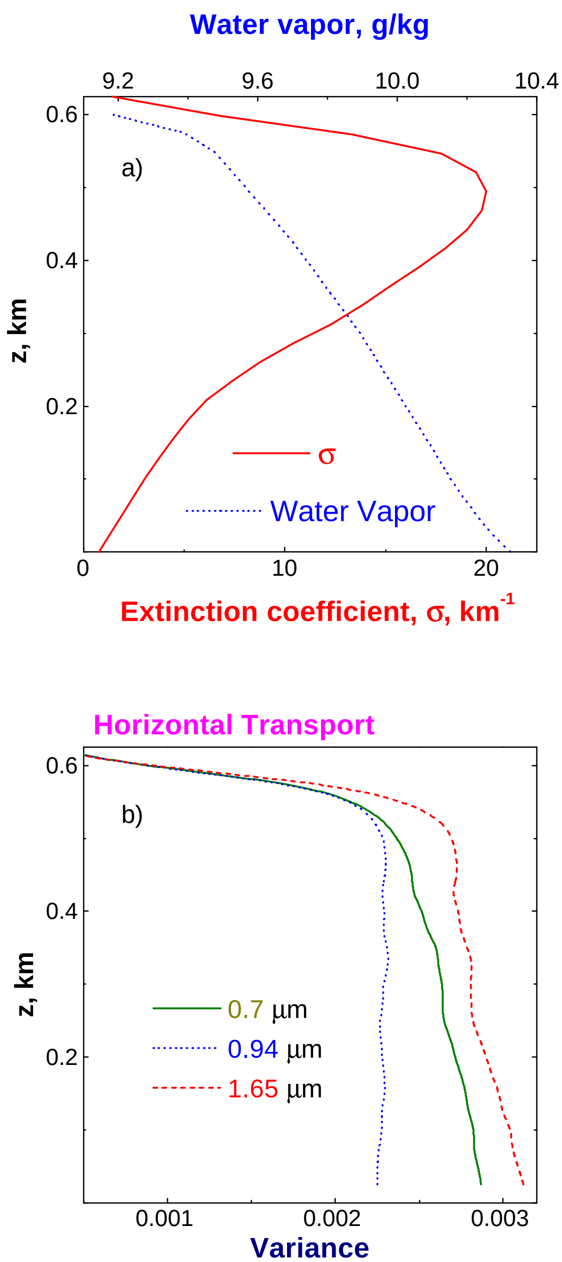

Figure 2. Vertical distribution of (a) the mean extinction coefficient (at 0.7 µm) and the mean water vapor concentration; (b) the variance of the horizontal transport at three wavelengths.

The water droplet absorption results in broadening of the probability density function of the total horizontal transport (between cloud top and bottom boundaries) (Figure 3). For the water vapor absorption the reverse is true. Due to droplet absorption, the variance of the total horizontal transport increases by 19% (from 0.295 to 0.35), alternatively; it decreases by 15% (from 0.295 to 0.25) due to vapor absorption.

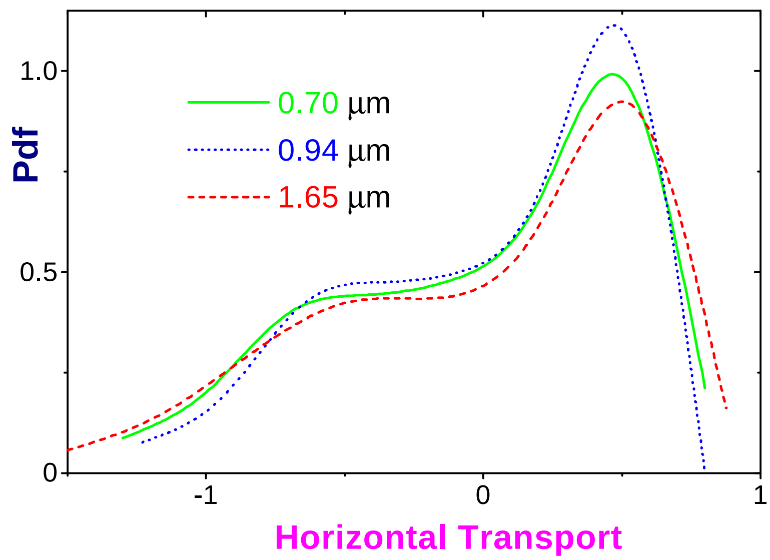

Figure 3. Probability density function of the total horizontal transport for three wavelengths.

How sensitive are absorption effects to the spectral dependence of E? We compared the real absorption A to the reconstructed one A′ = 1 - R - T - E, where R and T are albedo and transmittance, respectively (Figure 4). The reconstructed absorption may differ from the real one by as much as a factor of two if $E_{0.7}$ is used instead of $E_{0.94}$ (Figure 4a). This means, that at small scales (~100 m), the values of E for a weakly absorbing visible range cannot provide reliable absorption estimates for other wavelength intervals.

More reliable estimates can be obtained using the approach of Titov and Kasyanov (1997) based on

- additional spatial averaging of horizontal transport and other radiative parameters,
- liner regression between values of the horizontal transport in the visible and the near IR spectral range.

The approach is illustrated in Figure 5, where the values of horizontal transport, albedo, and transmittance are first averaged over a spatial scale of 0.6 km before applying the linear regression. This result demonstrates that an improved absorption estimate can be obtained at spatial scales of ~1.0 km.

Conclusions

The Cooperative Institute for Mesoscale Meteorological Studies (CIMMS) LES model of stratocumulus clouds with explicit liquid phase microphysics and a 3-D Monte Carlo method were used to study the spectral dependence of the horizontal transport and its effect on absorption estimates.

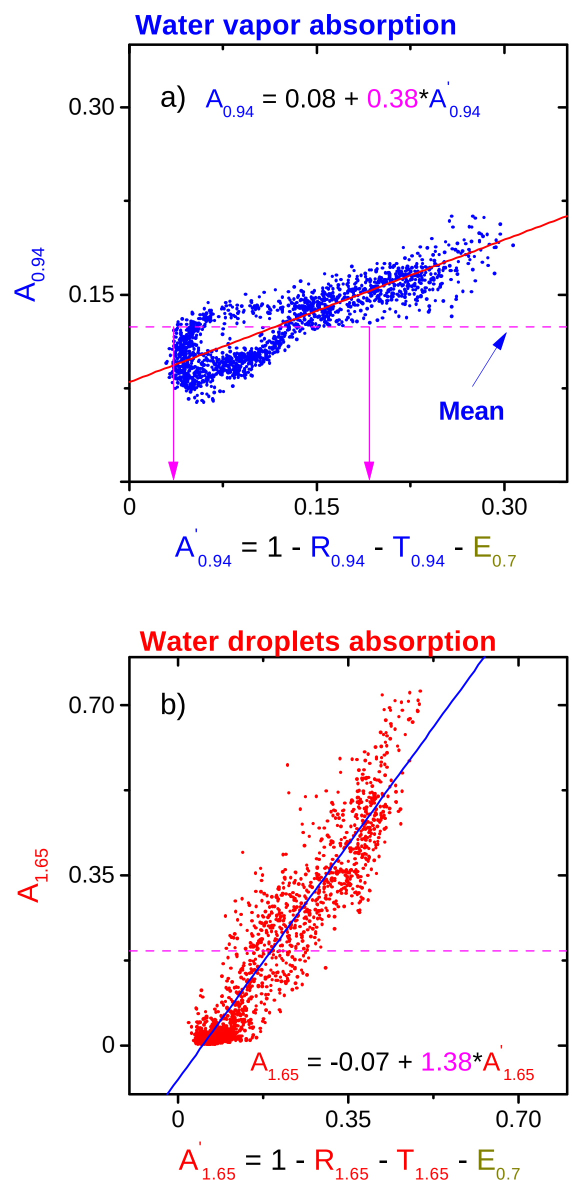

Figure 4. Real A absorption, plotted against reconstructed one A′: (a) 0.94 µm; (b) 1.65 µm.

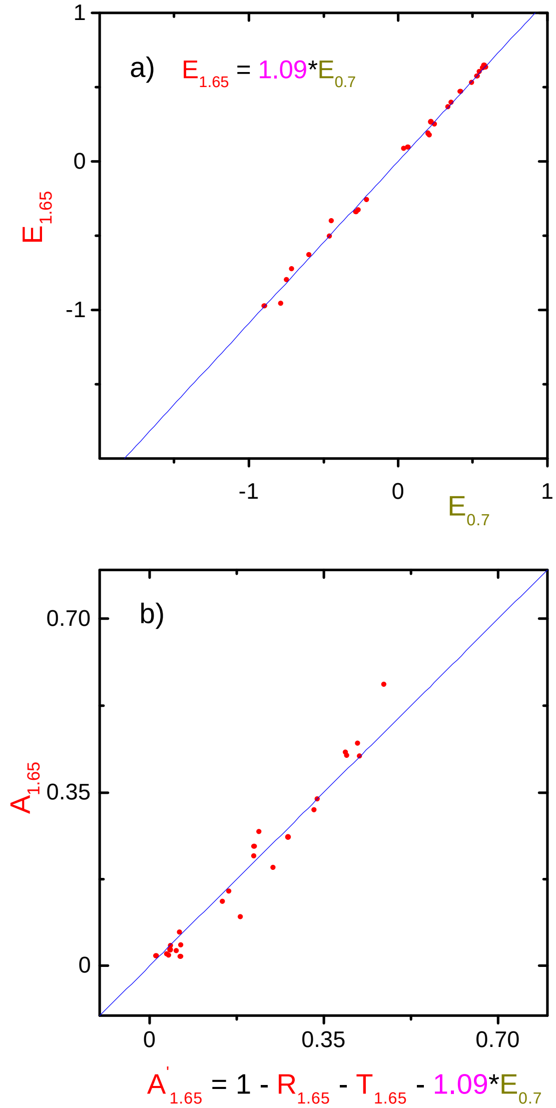

Figure 5. Linear regression of $E_{1.65}$ versus $E_{0.7}$ (a), and real absorption $A_{1.65}$ versus improved reconstructed one $A_{1.65}$ (b) for spatial resolution 0.6 km.

The mean, variance and spatial distribution of absorption, upward, downward, and horizontal radiative fluxes in the visible and near IR spectral range were calculated. It was shown that

- Horizontal transport depends markedly on wavelength. As wavelength changes by roughly 1 μm, the variance of the horizontal transport may change by 15% to 20%.
- The spectral dependence of the horizontal transport is primarily determined by spectral dependency of water droplets and water vapor absorption.
- The neglect of spectral dependency of the horizontal transport may lead to considerable (as large as a factor of two) errors in absorption estimates.

Acknowledgments

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References

Ackerman, S. A., and S. K. Cox, 1981: Aircraft observations of the shortwave fractional absorptance of non-homogeneous clouds. *J. Appl. Meteor*., **20**, 1510-1515.

Deirmendjian, D., 1969: *Electromagnetic Scattering on Spherical Polydispersions*. American Elsevier Publishing Company, Inc.

Goody, R. M., 1964: *Atmospheric Radiation. I: Theoretical Basis*, Oxford University Press (Clarendon), London and New York.

Hayasaka, T., N. Kikuchi, and M. Tanaka, 1995: Absorption of solar radiation by stratocumulus clouds: Aircraft measurements and theoretical calculations. *J. Appl. Meteor*., **34**, 1047-1055.

Kogan, Y. L., 1991: The simulation of a convective cloud in a 3-D model with explicit microphysics. Part I: Model description and sensitivity experiments. *J. Atmos. Sci*., **48**, 1160-1189.

Marshak A., A. B. Davis, W. J. Wiscombe, and R. F. Cahalan, 1997: Inhomogeneity effects on cloud shortwave absorption measurements: Two-aircraft simulations. *J. Geophys. Res.*, **102,** 16,619-16,637.

Rawlins, F., 1989: Aircraft measurements of the solar absorption by broken cloud fields: A case study. *Q. J. R. Meteorol. Soc*., **115**, 365-382.

Titov G. A., 1998: Radiative horizontal transport and absorption in stratocumulus clouds. *J. Atmos. Sci.*, **55**, 2549-2560.

Titov, G. A., and E. I. Kasyanov, 1997: Radiative characteristics of inhomogeneous stratocumulus with stochastic cloud top geometry. *J. Atmos. Ocean. Opt.*, **10,** 525-533.