Microphysical and radiative properties of inhomogeneous stratocumulus: Observations and model simulations

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SUMMARY
Detailed microphysical observations made from aircraft during the Atlantic Stratocumulus Transition Experiment are used to examine the optical properties of marine stratocumulus. Special attention is given to the relationship between the droplet size distribution (droplet-number concentration, effective radius, and liquid-water content) and the optical extinction parameter. The extinction parameter calculated with measurements from the forward-scattering spectrometer probe (FSSP) differs only slightly from the extinction parameter obtained from the total droplet spectrum (measured with two optical probes, FSSP and 260X). In contrast, the results for the effective radius and the liquid-water content show differences up to 40% between the two spectra. A Monte Carlo radiative-transfer model is initialized with optical properties calculated from the observed microphysics. Monte Carlo simulations of radiative fluxes are in good agreement with observations for well-mixed boundary-layer cloud fields.

KEYWORDS: Inhomogeneous clouds Microphysics Monte Carlo model Optical parameters Solar radiation Stratocumulus clouds

1. INTRODUCTION
A considerable fraction of the earth’s global energy budget is attributed to cloud radiative forcing (Wielicki et al. 1995). Highly reflective stratocumulus make the solar radiation balance of the planet strongly sensitive to variations in cloud amount and cloud coverage. For example, mid-latitude oceanic stratocumulus occurs in all seasons, the cloud amount being larger than 50% and the values of cloud radiative forcing in the summer being lower than $-100 \text{ W m}^{-2}$ (Klein and Hartmann 1993). With this amount of cloud radiative forcing, uncertainties of several tenths of a percent in the modelled cloud radiative fluxes may lead to arbitrary offsets in the energy balance of global circulation models (GCMs). However, in climate modelling grid boxes with resolutions of several hundreds of kilometres are insensitive to cloud parameters on subgrid scales.

The impact of horizontal cloud inhomogeneities on modelled cloud albedo has been clearly demonstrated by, for example, Cahalan et al. (1994) and Barker (1992). Parametrizations of cloud albedo as a function of cloud fraction (Stephens 1994; Slingo 1989) allow the inclusion in GCMs of the radiative effects of cloud inhomogeneities. Nevertheless, in situ measurements of cloud albedo are difficult to reproduce with radiative-transfer simulation models. The limited representation of realistic three-dimensional cloud optical properties in radiative-transfer simulation models may explain the discrepancy that arises because of the difficulty of accurately prescribing cloud optical properties in inhomogeneous cloud fields. Therefore, we not only compare model simulations with observations but also use the difference between model results based on three-dimensional cloud optical properties and model results based on the plane-parallel cloud assumption. The difference between inhomogeneous cloud albedo and plane-parallel cloud albedo, under the assumption that both cloud fields have the same cloud optical depth, is called plane-parallel cloud albedo bias. It is a well accepted method that allows the assessment of the impact of cloud inhomogeneities on radiative fluxes independently of special circumstances during observations.

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We investigate the effect of realistic cloud optical properties on radiative fluxes in inhomogeneous cloud fields with a Monte Carlo radiative-transfer model. The cloud field for the three-dimensional Monte Carlo model is derived from the thermodynamical properties of stratocumulus. To ensure that the cloud statistics of the real cloud field are reproduced in the model, we initialized the model with cloud optical properties calculated from observed microphysics and macrophysics. The observations were performed during the 'First Lagrangian' experiment of the Atlantic Stratocumulus Transition Experiment (ASTEX).

The study by Hignett and Taylor (1996) presented the plane-parallel cloud albedo bias and observations in a comparable way, as in the present study. The most important differences between this study and that of Hignett and Taylor (1996) can be summarized as follows. In the present study we use a theoretical derivation based on the thermodynamical properties of stratocumulus to obtain the cloud field for the Monte Carlo model, i.e. we define the cloud field without using empirical relations. Special emphasis is put on the interpretation of cloud microphysical and macrophysical properties to derive the statistical properties that are used to initialize the Monte Carlo model. We present the solar broad-band cloud albedo, transmission, and absorption obtained from models and observations. As in the present study, Hignett and Taylor (1996) used different flights performed during the same 'First Lagrangian' experiment of the ASTEX campaign. They used observed microphysical and macrophysical properties to build their cloud field, and derived the cloud geometrical thickness variability from the in-cloud vertical-velocity time series. They presented the observed cloud albedo as well as the narrow-band and broad-band albedos and the narrow-angle and hemispheric albedos, transmittions, and absorptions. They considered separately the effects of cloud gaps and (especially) cloud-gap distribution on radiative fluxes.

Microphysical and thermodynamical properties of marine and continental stratocumulus have been investigated by Slingo et al. (1982a,b), Nicholls (1984), and Nicholls and Leighton (1986). Duynkerke et al. (1995, 1999) and de Roode and Duynkerke (1996, 1997) presented turbulence and thermodynamical properties of the stratocumulus observed during the 'First Lagrangian' experiment of the ASTEX campaign. Observed microphysical properties of stratocumulus have been related to optical properties by Stephens and Platt (1987), Duda et al. (1991), Taylor (1994), and Taylor and McHaffie (1994). In the present approach the Monte Carlo model is initialized by combining the horizontal time series with vertical profiles of optical properties deduced from observed microphysics.

In the next section the instruments and observations are presented, including the cloud microphysical and optical properties of the cloud layer. In section 3 the Monte Carlo model is presented and model results based on the initialization with observed horizontal and vertical cloud microphysics are shown. Section 4 contains the summary and conclusions.

2. Observations

(a) Flights

During the ASTEX campaign the NCAR* Electra participated in the 'First Lagrangian' experiment (Albrecht et al. 1994; de Roode and Duynkerke 1997) between 12 and 14 June 1992. Measurements of the turbulence, microphysical and radiative properties of the boundary-layer clouds were collected on board the aircraft. Figure 1

* National Center for Atmospheric Research.
shows the aircraft heights as a function of time for flights RF06 and RF07 conducted on 13 June 1992.

Bretherton and Pincus (1995) and de Roode and Duynkerke (1997) described the flight trajectory of the ‘First Lagrangian’ experiment. Briefly, on flights RF06 and RF07 straight-and-level runs were flown throughout the boundary layer at various heights (Duynkerke et al. 1999). At each height two runs were performed along and across the mean wind direction. Each run had a length of approximately 60 km. According to the Lagrangian strategy the flight pattern drifted with the mean southward flow of the air mass.

The papers by Duynkerke et al. (1995), Bretherton and Pincus (1995) and de Roode and Duynkerke (1997) presented a detailed analysis of the mean and turbulent properties observed during the ‘First Lagrangian’ experiment. De Roode and Duynkerke (1997) reported that, during flight RF06, a stratocumulus cloud deck with occasional small cumulus clouds developed beneath the stratocumulus. The boundary layer, which was well-mixed, generated cloud inhomogeneities in the horizontal direction. During flight RF07, the boundary layer was partially decoupled and (larger) cumulus clouds formed below the stratocumulus. The cumulus clouds then penetrated the stratocumulus. Consequently, the cloud fraction at lower cloud levels was most probably due to cumuli. Drizzle was observed throughout the experiments; drizzle was able to develop because of low droplet-number concentration and the presence of large droplets. Drizzle was also evident in the effective radius and liquid-water content values presented later in this paper.

(b) Instruments

For a detailed description of the Electra instrumentation the reader is referred to the ASTEX operational plan (ASTEX 1992a). A short description of the instruments used
in the present study is given here. Two optical probes measured the droplet-size spectra. A forward-scattering spectrometer probe (FSSP) was used to measure particles in the diameter range 4.35–64.25 μm (15 intervals, maximum sample rate 10 Hz) and a 260X probe was used to measure particles in the diameter range 0–620 μm (62 intervals of 10 μm, maximum sample rate 1 Hz). A PMS King probe (hot-wire probe) was used for measurements of liquid-water content. The liquid-water content calculated from the full measurement size range of the FSSP was systematically higher (about 20%) than the liquid-water content observed with the PMS King probe. When large droplets were detected, e.g. near cloud top there was almost a 40% difference between the liquid-water content of the PMS King probe and the sum of liquid-water contents calculated from the two optical probes (FSSP and 260X). According to the ASTEX project documentation summary (ASTEX 1992b) the PMS King probe had a reduced sensitivity to droplets larger than 30 μm, which explains the observed discrepancy. For the best estimate of liquid-water content we decided to use the sum of the measurements made with the two optical probes (FSSP and 260X); the particles larger than 70 μm were measured with the 260X probe only.

The radiation measurements used in the present analysis were made with broad-band hemispheric radiometers (Eppeley Laboratory Inc.) and infrared radiation thermometers (type Barnes PRT-5). One instrument from each set was mounted below and on top of the fuselage to measure the upwelling and downwelling fluxes, respectively. The broad-band hemispheric radiometers had a 180° field of view and measured solar radiation between 0.285 and 2.80 μm. The infrared-radiation thermometers had a narrow field of view (2°) and were sensitive to long-wave radiation between 9.5 and 11.5 μm. The measurement frequency of the radiometers was 1 Hz.

(c) Microphysical and optical properties

The cloud microphysical properties are related to the cloud optical properties by the scattering and extinction parameters, β, and β_e, respectively. From detailed droplet-size spectra one obtains β_s and β_e by means of Mie theory (see, for example, Mie (1908), Liou (1980), and Goody and Yung (1989)). For consistency reasons we use β_e and the single-scattering albedo \( \tilde{\omega}_0 = \beta_s / \beta_e \) to describe the cloud optical properties.

The definition of β_e is

\[
\beta_e(\lambda) = \pi \int_0^\infty Q_e(\lambda, r) r^2 n(r) \, dr,
\]

where \( r \) is the droplet radius and \( n(r) \) is the size distribution of the droplets. The extinction coefficient, \( Q_e = Q_e(\lambda, r) \), which is defined by Mie theory, is a function of wavelength, \( \lambda \), and droplet radius, \( r \), both expressed in terms of the size parameter \( a = (2\pi r / \lambda) \). However, the extinction coefficient \( Q_e \) can be approximated by a value of 2 when a mixture of particles of various sizes is used in Mie theory, provided the particles are large enough such that the size parameter \( a \) exceeds about 10 (van de Hulst 1957). The uncertainty introduced with the approximation \( Q_e \approx 2 \) is less than 5%. To obtain \( \beta_e \) for the solar spectral region we used a four-band scheme and the interpolation and weighting method presented by Slingo et al. (1982a) (for details on the derivation of the four-band scheme and the wavelength intervals see appendix A). The four-band scheme and the approximation \( Q_e \approx 2 \) apply to the remaining part of the article.

The profiles of the mean extinction coefficient, \( \beta_e \), are given in Fig. 2 for flights RF06 and RF07. The cloud-top and cloud-base heights are given in relative height units, defined as \( z' = (z - h_b) / (h_t - h_b) \), i.e. cloud top and cloud base are equal to \( z' = 1 \) and
Figure 2. Vertical profiles of the mean extinction parameter, \( \beta_e \), for (a) flight RF06 and (b) flight RF07. The filled diamonds represent mean values of observations made on horizontal runs. The error bars indicate the standard deviations and are slightly shifted either up or down inside the filled diamond for better visibility. The least-squares linear fit (dashed lines) shows the vertical gradient of \( \beta_e \) in the cloud layer.

\[ z' = 0, \] respectively. The fitted functions are used to determine the volume-integrated mean cloud optical depth, \( \langle \tau \rangle \), defined as

\[ \langle \tau \rangle = \int_{h_b}^{h_1} \beta_e(z) \, dz. \]  \hspace{1cm} (2)

With the fitted function, say \( \beta_e = z'/\alpha \), and Eq. (2) we get

\[ \langle \tau \rangle = \frac{H}{\alpha} \int_0^{1} z' \, dz' = \frac{H}{2\alpha}, \]  \hspace{1cm} (3)

where \( H = h_1 - h_b \) is the cloud geometrical thickness, and \( \alpha \) is the slope of the fitted function. With the values for \( H = h_1 - h_b \) given in Table 1 we obtain \( \langle \tau \rangle = 18 \) for flight RF06 and \( \langle \tau \rangle = 11 \) for flight RF07. The uncertainty in the mean cloud optical depth \( \langle \tau \rangle \) stems from the measurement and computation errors in the extinction parameter, the standard error in the least-squares linear fit of the \( \beta_e \)-profile, and the uncertainty in the cloud geometrical thickness. The resulting uncertainty in \( \beta_e \) (and hence in \( \langle \tau \rangle \)) is estimated to be 20%.

With the approximation of \( \beta_e \) presented by, for example, Stephens and Tsay (1990), the extinction parameter \( \beta_e \) can be written as

\[ \beta_e = \frac{3}{2} \frac{q_1 \rho_{air}}{r_{eff} \rho_l}, \]  \hspace{1cm} (4)

where \( q_1 \) is the specific liquid-water content in kg liquid water per kg air and \( \rho_{air} \) is the dry air density. The effective radius, \( r_{eff} \), of the cloud droplets is defined as the ratio between the third and second moment of the droplet distribution, \( n(r) \),

\[ r_{eff} = \frac{\int_0^{\infty} n(r) r^3 \, dr}{\int_0^{\infty} n(r) r^2 \, dr}. \]  \hspace{1cm} (5)

The observations of \( q_1 \) in Fig. 3 are based on the FSSP and 260X probe measurements. From the fitted function for \( q_1 \) the cloud-base height, \( h_b \), was defined as the
height at which the linear fit to the measured $q_1$ data gives a value of $q_1 = 0 \text{ g kg}^{-1}$. The cloud-top height, $h_t$, has been calculated from the ‘porpoising’ runs (Duynkerke et al. 1999). Table 1 contains the cloud geometrical dimensions observed during flight RF06 and flight RF07.

The cloud droplet-number concentration, $N$, is depicted in Fig. 4 for flights RF06 and RF07. Inside the cloud layer the droplet-number concentration shows little variation with height. At the cloud edges the entrainment and cloud morphology reduce the number concentrations. The vertically constant ensemble-average droplet-number concentration is a consequence of the fast transition of water vapour to cloud droplets in a supersaturated regime. According to the diffusional droplet growth rate presented by Rogers (1976), a supersaturation of only a few percent is enough to initialize cloud droplet formation within a few tenths of a second. On this timescale virtually all the potential cloud droplet nuclei are transformed into water droplets.

Many studies have reported similar constant droplet-number concentration profiles and increasing specific liquid-water content profiles inside stratocumulus clouds (Slingo et al. 1982a,b; Nicholls 1984; Nicholls and Leighton 1986; de Roode and Duynkerke 1996, 1997; Duynkerke et al. 1999). Profiles of nocturnal marine stratocumulus have been reported by Duynkerke et al. (1995) for ASTEX ‘First Lagrangian’ observations, and by Slingo et al. (1982a) for JASIN observations. Slingo et al. (1982b) showed that $q_1$
Figure 4. Profiles of the mean cloud droplet-number concentration, \( N \), for (a) flight RF06 and (b) RF07. The labels and symbols are the same as in Fig. 2 except the vertical dashed line which represents the ensemble-averaged droplet-number concentration of in-cloud flights with a relative cloud height, \( z' \), between 0.1 and 0.9.

Figure 5. Vertical profiles of effective radius, \( r_{\text{eff}} \), for (a) flight RF06 and (b) flight RF07. The filled diamonds represent the effective radius \( r_{\text{eff}} \) of the total droplet spectrum (FSSP+260X) and the open diamonds represent \( r_{\text{eff}} \) based on the observations made with the FSSP probe only. The least-squares linear fits (dashed lines) are calculated with the values of the open diamonds. Note the rescaled \( x \)-axis at \( r_{\text{eff}} = 25.0 \, \mu \text{m} \).

and \( N \) profiles above land have a comparable shape to profiles of marine stratocumulus clouds.

Figure 5 shows the profiles for \( r_{\text{eff}} \) (defined in Eq. (5)) for flights RF06 and RF07. An increase in the effective radius with height inside the cloud layer is seen for small droplets only, i.e. for \( r_{\text{eff}} \) derived from the FSSP spectrum. It should be noted, however, that \( r_{\text{eff}} \) is an optical parameter for the determination of \( \beta_{\text{a}} \) according to Eq. (4).

The increase in \( r_{\text{eff}} \) with height for small cloud droplets (measured with the FSSP) corroborates the dominant effect of the small droplets in the observed relation between the profiles for \( q_{\text{l}} \) and \( N \). Therefore, small cloud droplets measured by the FSSP probe make the dominant contribution to the cloud liquid-water content.

A summary of the cloud parameters described above is given in Tables 2 and 3 for flights RF06 and RF07, respectively. Each table gives detailed information on
### Table 2. Summary of Parameters for the In-Cloud Runs during Flight RF06 (See Text for Explanation of Symbols)

<table>
<thead>
<tr>
<th>Run</th>
<th>(\mu_0)</th>
<th>C</th>
<th>(z')</th>
<th>(\rho_{c}^{\text{fsp}}) (m(^{-1}))</th>
<th>(\rho_{c}^{\text{total}}) (m(^{-1}))</th>
<th>(r_{\text{eff}}^{\text{fsp}}) ((\mu)m)</th>
<th>(r_{\text{eff}}^{\text{total}}) ((\mu)m)</th>
<th>(q_{l}^{\text{fsp}}) (g kg(^{-1}))</th>
<th>(q_{l}^{\text{total}}) (g kg(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>R21</td>
<td>&lt;0</td>
<td>0.71</td>
<td>0.06</td>
<td>0.010</td>
<td>0.011</td>
<td>5.63</td>
<td>8.40</td>
<td>0.033</td>
<td>0.058</td>
</tr>
<tr>
<td>R22</td>
<td>&lt;0</td>
<td>0.46</td>
<td>0.06</td>
<td>0.005</td>
<td>0.006</td>
<td>7.24</td>
<td>18.2</td>
<td>0.018</td>
<td>0.060</td>
</tr>
<tr>
<td>R23</td>
<td>&lt;0</td>
<td>0.95</td>
<td>0.36</td>
<td>0.022</td>
<td>0.024</td>
<td>8.32</td>
<td>13.6</td>
<td>0.103</td>
<td>0.180</td>
</tr>
<tr>
<td>R24</td>
<td>&lt;0</td>
<td>1.0</td>
<td>0.36</td>
<td>0.042</td>
<td>0.043</td>
<td>7.69</td>
<td>8.93</td>
<td>0.182</td>
<td>0.214</td>
</tr>
<tr>
<td>R51</td>
<td>0.17</td>
<td>0.33</td>
<td>0.07</td>
<td>0.002</td>
<td>0.002</td>
<td>5.87</td>
<td>21.8</td>
<td>0.005</td>
<td>0.024</td>
</tr>
<tr>
<td>R52</td>
<td>0.20</td>
<td>0.51</td>
<td>0.08</td>
<td>0.006</td>
<td>0.006</td>
<td>5.18</td>
<td>9.46</td>
<td>0.018</td>
<td>0.055</td>
</tr>
<tr>
<td>R53</td>
<td>0.24</td>
<td>1.0</td>
<td>0.64</td>
<td>0.051</td>
<td>0.052</td>
<td>7.78</td>
<td>8.42</td>
<td>0.225</td>
<td>0.245</td>
</tr>
<tr>
<td>R54</td>
<td>0.27</td>
<td>1.0</td>
<td>0.64</td>
<td>0.046</td>
<td>0.048</td>
<td>8.23</td>
<td>11.0</td>
<td>0.214</td>
<td>0.298</td>
</tr>
<tr>
<td>R73</td>
<td>0.59</td>
<td>1.0</td>
<td>0.82</td>
<td>0.060</td>
<td>0.061</td>
<td>11.1</td>
<td>13.0</td>
<td>0.374</td>
<td>0.448</td>
</tr>
<tr>
<td>R74</td>
<td>0.61</td>
<td>0.92</td>
<td>0.82</td>
<td>0.030</td>
<td>0.033</td>
<td>12.5</td>
<td>17.6</td>
<td>0.215</td>
<td>0.330</td>
</tr>
</tbody>
</table>

### Table 3. Summary of Parameters for the In-Cloud Runs during Flight RF07 (See Text for Explanation of Symbols)

<table>
<thead>
<tr>
<th>Run</th>
<th>(\mu_0)</th>
<th>C</th>
<th>(z')</th>
<th>(\rho_{c}^{\text{fsp}}) (m(^{-1}))</th>
<th>(\rho_{c}^{\text{total}}) (m(^{-1}))</th>
<th>(r_{\text{eff}}^{\text{fsp}}) ((\mu)m)</th>
<th>(r_{\text{eff}}^{\text{total}}) ((\mu)m)</th>
<th>(q_{l}^{\text{fsp}}) (g kg(^{-1}))</th>
<th>(q_{l}^{\text{total}}) (g kg(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>R35</td>
<td>0.55</td>
<td>0.98</td>
<td>0.44</td>
<td>0.018</td>
<td>0.020</td>
<td>8.68</td>
<td>13.6</td>
<td>0.085</td>
<td>0.158</td>
</tr>
<tr>
<td>R36</td>
<td>0.53</td>
<td>1.0</td>
<td>0.45</td>
<td>0.022</td>
<td>0.024</td>
<td>8.32</td>
<td>13.6</td>
<td>0.107</td>
<td>0.190</td>
</tr>
<tr>
<td>R51</td>
<td>0.35</td>
<td>1.0</td>
<td>0.78</td>
<td>0.036</td>
<td>0.038</td>
<td>9.51</td>
<td>13.5</td>
<td>0.203</td>
<td>0.303</td>
</tr>
<tr>
<td>R52</td>
<td>0.31</td>
<td>1.0</td>
<td>0.77</td>
<td>0.036</td>
<td>0.037</td>
<td>9.29</td>
<td>10.9</td>
<td>0.200</td>
<td>0.240</td>
</tr>
<tr>
<td>R64</td>
<td>0.13</td>
<td>0.11</td>
<td>0.03</td>
<td>0.001</td>
<td>0.001</td>
<td>7.23</td>
<td>18.4</td>
<td>0.004</td>
<td>0.012</td>
</tr>
<tr>
<td>R65</td>
<td>0.10</td>
<td>0.31</td>
<td>0.04</td>
<td>0.005</td>
<td>0.005</td>
<td>6.69</td>
<td>17.3</td>
<td>0.019</td>
<td>0.052</td>
</tr>
<tr>
<td>R66</td>
<td>0.06</td>
<td>0.99</td>
<td>0.79</td>
<td>0.023</td>
<td>0.028</td>
<td>9.00</td>
<td>13.6</td>
<td>0.140</td>
<td>0.224</td>
</tr>
<tr>
<td>R67</td>
<td>0.02</td>
<td>0.99</td>
<td>0.77</td>
<td>0.023</td>
<td>0.023</td>
<td>7.80</td>
<td>8.71</td>
<td>0.104</td>
<td>0.118</td>
</tr>
<tr>
<td>R68</td>
<td>&lt;0</td>
<td>1.0</td>
<td>0.98</td>
<td>0.040</td>
<td>0.040</td>
<td>8.88</td>
<td>9.49</td>
<td>0.207</td>
<td>0.223</td>
</tr>
<tr>
<td>R69</td>
<td>&lt;0</td>
<td>1.0</td>
<td>0.99</td>
<td>0.036</td>
<td>0.037</td>
<td>9.83</td>
<td>13.3</td>
<td>0.207</td>
<td>0.294</td>
</tr>
</tbody>
</table>

Every in-cloud run performed during the flights. The solar zenith angle, \(\theta_0\), is given as \(\mu_0 = \cos(\theta_0)\). Cloud fraction, \(C\), is defined as the ratio between the number of measurements for which \(\beta_c > 5 \times 10^{-4} \text{m}^{-1}\) and the total number of measurements during a run. The values of \(q_l\), \(r_{\text{eff}}\), and \(\beta_c\) are shown separately for the FSSP-only observations (labelled with superscript fssp) and the FSSP+260X probe observations (labelled with superscript total).

If one compares \(\beta_c^{\text{fsp}}\) with \(\beta_c^{\text{total}}\) only small differences (about 10%) are found between the two parameters. By contrast, both \(r_{\text{eff}}\) and \(q_l\) show considerable differences between the values deduced from the FSSP spectrum and the FSSP+260X spectrum (up to 40%). These two parameters are obtained by means of the third moment of the droplet spectrum. Because the third moment strongly weights large droplets, \(r_{\text{eff}}\) and \(q_l\) are more sensitive to the shape of the droplet spectrum than \(\beta_c\) which is deduced from the second moment of the droplet spectrum only. Hence, large droplets have little effect on \(\beta_c\) if it is calculated by Eq. (1). As long as the parameters \(r_{\text{eff}}\) and \(q_l\) are consistent, in that they are both calculated from the spectra measured by a particular instrument, \(\beta_c\) can also be calculated from \(r_{\text{eff}}\) and \(q_l\) according to Eq. (4) which yields the same results as by Eq. (1). However, problems may occur in the determination of \(\beta_c\) if \(r_{\text{eff}}\) and \(q_l\) are measured independently and if each parameter is obtained with a different measurement device. It is likely that different measurement devices with their own characteristics have a different sensitivity to droplet sizes. In that case, \(\beta_c\) deduced from \(r_{\text{eff}}\) and \(q_l\) through Eq. (4) may lead to erroneous estimations of \(\beta_c\) due to the high sensitivity of \(r_{\text{eff}}\) and \(q_l\) to large cloud droplets because of the third moment of the droplet spectrum. Consider,
for example, $r_{eff}$ and $q_1$ in Tables 2 and 3. By calculating one parameter from the FSSP-only observations and the other from data from both probes (FSSP+260X) one obtains two different values for $r_{eff}$ and two different values for $q_1$, which yield four $\beta_e$s. Using the smallest as well as the largest values for $r_{eff}$ and $q_1$, $\beta_e$ can differ by up to 40% due to the observation of cloud parameters from different measurement devices.

3. **Monte Carlo model**

A Monte Carlo model is used to simulate radiative transfer through a cloud layer. The method is based on the random walk of a large number of photons which is tracked through the cloud. Variability of cloud optical parameters is restricted to the $x$- and $z$-directions whereas, for the random walk of the photons, full three-dimensional motion is allowed. However, models which include the variability of cloud optical parameters in all three dimensions can produce small differences in the variability of the cloud albedo because of photon diffusion around optically thick regions (Cahalan et al. 1994). The interaction of the photons with cloud particles (scattering) is calculated by means of the Henyey–Greenstein scattering function (see, for example, Liou (1980)). The free photon path-length between two successive scattering events depends on the local extinction properties inside the cloud. We determined the free photon path-length following the method presented by Barker (1992). The resulting radiative fluxes are obtained by adding together the number of photons passing through the grid surfaces inside the cloud. For example, the cloud albedo is given by the ratio of the number of photons escaping from the cloud top to the number of photons entering the cloud layer from above. Photons leaving the cloud layer at the vertical borders, i.e. photons reaching the limits of the measured time-series in the horizontal direction, experience cyclical boundary conditions.

To define the cloud field in as detailed a way as possible we used observations and thermodynamical properties of stratocumulus. We searched for a method that describes the cloud optical depth field such that the modelled variability of cloud optical properties is comparable with the variability obtained from observations. To enable the reproduction of realistic cloud fields, both horizontal and vertical cloud optical properties can vary. The vertical dependency of cloud optical parameters is obtained by correlating the mean vertical gradient of the cloud liquid-water content with the (horizontal) measurements of cloud liquid-water content inside the cloud field. This two-dimensional cloud field is referred to as VCB (variable cloud base). In the Monte Carlo model each measurement point of cloud microphysics in the $x$-direction represents a 100 m wide cloud fragment. To emphasize the importance of taking the vertical variability into account to produce realistic cloud inhomogeneities, a simplified method is introduced, which assumes a vertically homogeneous cloud layer and variable optical properties in the $x$-direction, i.e. the cloud inhomogeneity is based on the time-series of measured cloud microphysical properties. This vertically homogeneous cloud field is referred to as constant cloud base (CCB). The derivations of the cloud optical properties are presented in subsections (a) and (b), first for the CCB method and thereafter for the VCB method.

(a) **Constant cloud base (CCB) with vertical homogeneous cloud structure**

In the determination of optical properties for the Monte Carlo model with vertical homogeneous cloud structure no vertical variation of microphysical properties is taken into account. We assume that cloud-top height and cloud-base height are fixed and that the specific liquid-water content, $q_1$, is constant with height. The integration of the local
Figure 6. (a) Sketch of the cloud optical property calculations starting with the observed extinction parameter \( \beta_e \) time series of run R73 during flight RF06. (b) A 14-second close-up view extracted from (a) between the vertical dashed lines; this is used in (c) to calculate the corresponding cloud optical depth \( \tau \) (left axis) with the CCB structure (see section 3(a)). The shaded areas (bars) inside the columns of the cloud field denote the cloud optical depth. The legend on the right indicates the cloud-base height, which scales with \( \tau^{3/5} \). The same close-up as in (b) is used to deduce \( \tau \) in the lowest figure (d) where \( \tau \) is obtained with a \( \beta_e \) according to the VCB structure presented in sections 3(b) and (c).

\( \beta_e \) over \( H \) yields the local cloud optical depth, \( \tau = \tau(x) \). In order to conserve the mean cloud optical properties the ensemble averaged \( \bar{\tau}_{\text{ccb}} = \frac{1}{L} \int_0^L \int_0^H \beta_e(x) \, dx \, dz \) must be equal to the volume-integrated mean cloud optical depth, \( \langle \tau \rangle \), deduced from Eq. (3) and given in Tables 2 and 3.

The curve in Fig. 6(a) shows a typical time series for \( \beta_e \) (deduced from run R73 during flight RF06). The small section in Fig. 6(b) represents 1.4 km of the \( \beta_e \) time series which is equivalent to 14 measurement points with the present resolution of 100 m. The variability of the cloud optical depth, \( \tau(x) \), in such a cloud field is illustrated in
Fig. 6(c). Note that the cloud-top height and cloud-bottom height do not change because the vertical optical properties are kept constant with height. This vertically homogeneous cloud field is referred to as CCB.

(b) Variable cloud base (VCB) with adiabatic liquid-water content profile

In a well-mixed cloud layer it can be assumed that, to good approximation, conserved quantities are constant with height. This means that, in the equation \( q_t = q_v + q_l \), the gradient of \( q_l \) is the negative of the change with height in \( q_{\text{sat}} \), the saturated specific water-vapour content \( q_v \). The decrease in \( q_{\text{sat}} \) with height can be calculated with the Clausius-Clapeyron equation, provided that the process follows the moist adiabatic lapse-rate. The gradient of the adiabatic specific liquid-water content, \( \Gamma_1 \), has been derived by Albrecht et al. (1990). Here we use a slightly modified formulation for \( \Gamma_1 \):

\[
\Gamma_1 = \frac{d q_l}{dz} = -\frac{d q_{\text{sat}}}{dz} = q_{\text{sat}} \left( \frac{l_v}{R_v T^2} \Gamma_w - \frac{g}{RT} \right),
\]

where \( l_v \) is the latent heat of vaporization, \( R_v \) is the specific gas constant for water vapour, and \( \Gamma_w \) is the moist adiabatic lapse-rate.

The derivation of the ‘adiabatic’ \( \beta_{e,a} \) with a VCB structure is based on Eq. (4). However, Eq. (4) uses the effective radius \( r_{\text{eff}} \) for which a real physical description has yet to be found. It is, therefore, difficult to give an accurate description for \( r_{\text{eff}} \) that is generally true for all stratocumulus cases. In Eq. (4) \( r_{\text{eff}} \) is, therefore, replaced by \( r_v \), where \( r_v \) is the volume radius obtained with the formula

\[
q_l = \frac{4}{3} \frac{\rho_l}{\rho_{\text{air}}} \pi r_v^3,
\]

where \( N \) represents the ensemble-averaged cloud droplet-number concentration (see section 2). Martin et al. (1994) found \( r_{\text{eff}}^3 \) to be a linear function of \( r_v^3 \) for relatively homogeneous marine stratocumulus where penetration by cumulus clouds is negligible. However, the uncertainty introduced by replacing \( r_{\text{eff}} \) with \( r_v \) is about 10%. With \( r_v \) replacing \( r_{\text{eff}} \), the resulting \( \beta_{e,a} \) becomes

\[
\beta_{e,a}(x, z) = \frac{9}{2} \pi \left( \frac{9}{2 \pi} \right)^{1/3} \frac{\rho_{\text{air}}^{2/3} N^{1/3}}{\rho_l^{2/3}} q_l(x, z)^{2/3}.
\]

With the equation \( q_l(x, z) = \Gamma_1 (z - h_b(x)) \), \( \beta_{e,a} \) is obtained in its final form as

\[
\beta_{e,a}(x, z) = \kappa \Gamma_1^{2/3} (z - h_b(x))^{2/3},
\]

where \( \{9 \pi N \rho_{\text{air}}^2 (2 \rho_l^2)\}^{1/3} \) is replaced by \( \kappa \). Note, that \( \kappa \Gamma_1^{2/3} \) represents a mean value for the entire cloud and, as a consequence, the vertical structure of the cloud field is the same in each cloud cell, i.e. \( \Gamma_1^{2/3} \) is a constant for the entire cloud layer.

The stratocumulus observations of cloud-base and cloud-top height suggest that the cloud-base height is much more variable than cloud-top height. The cloud-base height variability is presented in section 3(c). The analysis of the porpoising run R56 during flight RF06 presented by de Roode and Duykerke (1997) is used to show that cloud-top structure is rather homogeneous. Figure 10 in the paper by de Roode and Duykerke (1997) shows the time series of height, potential temperature, \( \theta \), specific water vapour, \( q_v \), specific liquid-water content, \( q_l \), and ozone. De Roode and Duykerke (1997) pointed out that sharp, as well as fluctuating, transitions of all variables coexist,
indicating the presence of both an entrainment interface layer only a few metres thick (Caughey et al. 1982) and a corrugated cloud top with a standard deviation of cloud-top height of about 20 m. The cloud-top height was measured with a downward-facing Lidar during runs R32 and R61 of flight RF06. Two factors play a dominant role in the formation of the observed corrugated cloud top: the strength of the potential-temperature gradient at the inversion (generated by radiative cooling), and the intensity of convection in the boundary layer. Convection moves air upwards and downwards which induces entrainment of warm and dry air into the boundary layer. Entrainment generates filaments of optically thin cloud regions through which radiation 'leakage' occurs.

As a consequence of the observed small variability in cloud-top height, we assumed in our analysis that cloud-top height was constant. To deduce the local cloud geometrical thickness, \( H \), Eq. (9) is reformulated in order to obtain \( H \) from the observed \( \beta_e \) time series. Hence, with \( H = H(x) = h_t - h_b(x) \), the geometrical thickness determines the local cloud-base height, i.e. \( h_b = h_b(x) \). This cloud field is, therefore, referred to as VCB.

For the cloud optical depth, defined as \( \tau = \int_{h_b}^{h_t} \beta_e \, dz \), the variable cloud thickness implies that \( \tau \) is proportional to \( H^{5/3} \). In contrast to the CCB structure, the variability of \( \tau \) in the VCB structure increases with the 5/3 power of \( H(x) \). Figure 6(d) illustrates the effect of the VCB structure on \( \tau \). Obviously the minima are smaller and the maxima are larger in Fig. 6(d) than in (c).

The cloud description with the VCB structure given by Eq. (9) is based on thermodynamic properties of stratocumulus only, i.e. the extinction parameter \( \beta_e(x, z) \) is defined without using empirical relations. However, the derivation of Eq. (9) uses simple assumptions that were validated using observed microphysical properties, such as that constant values for \( N \) and \( \Gamma_1 \) can be used for the entire cloud layer. More complex relations that are difficult to generalize, such as the relation between \( r_{\text{eff}} \) and cloud height, are replaced by other functions. Nevertheless, this approach is preferable to the method where the cloud field is obtained directly from observations; because we analyse the observed microphysical properties separately, we can assess the quality of the statistical properties derived from observations before using them to initialize the model. For example, the cloud geometrical height can be obtained from the in-cloud observed liquid-water content time series, the vertical liquid-water gradient, and the droplet-number concentration, which are all obtained from cloud-droplet measurement probes only. Consequently, the derivation of cloud optical properties based on Eq. (9) avoids the problem which can be expected when using different water-content measurement devices (discussed in section (c)).

(c) Observed liquid-water content profile (based on VCB structure)

Two parameters, \( \Gamma_1^{ob} \) and \( \langle \tau \rangle \), derived from observations are used to scale \( \beta_e \) with VCB structure to obtain a cloud field with the same mean cloud optical properties as for the homogeneous (plane-parallel) cloud field. The corresponding procedures are as follows. First, the gradient of the adiabatic specific liquid-water content, \( \Gamma_1 \), is replaced by the observed diabatic value, \( \Gamma_1^{ob} \), which reduces the local cloud geometrical thickness because \( \Gamma_1^{ob} < \Gamma_1 \) (Eq. (9)). Second, the ensemble-averaged cloud optical depth, \( \bar{\tau}_{\text{vcb}} \), given by

\[
\bar{\tau}_{\text{vcb}} = \frac{1}{L} \int_0^L \tau(x) \, dx = \frac{1}{L} \int_0^L \int_{h_b}^{h_t} \beta_e(x, z) \, dz \, dx, \tag{10}
\]
Figure 7. Distribution function of the calculated cloud-base height (marked MC (R73)) and the observed cloud-base height (marked IR (R72)). The upper panel gives the calculated distribution function of \( h_b \) and the lower panel gives the observed distribution function of \( h_b \). The mean cloud-base heights are given by the dotted vertical lines.

Figure 8. Vertical profiles of the VCB structure \( \beta_e \) for (a) flight RF06 and (b) flight RF07 compared with the observed values. The same symbols are used as in Fig. 2. The mean profiles are given by the solid lines and dashed lines show standard deviations. The filled symbols denote the mean values of \( \beta_e \) time series deduced from observed microphysics and horizontal error bars indicate the standard deviations.

has to be scaled with the mean cloud optical depth, \( \langle \tau \rangle \), deduced from observations (Eq. (3)). The scaling factor, defined as \( \langle \tau \rangle / \bar{\tau} \), either reduces or enhances the local cloud geometrical thickness depending on whether \( \langle \tau \rangle / \bar{\tau} < 1 \) or \( \langle \tau \rangle / \bar{\tau} > 1 \). In Eq. (10) \( \beta_e(x, z) \) is the same as \( \beta_{\text{e,un}} \) given in Eq. (9), but with \( \Gamma_1^\text{ob} \). From the fitted function in Fig. 3 we obtained \( \Gamma_1^\text{ob} = 0.97 \text{ g kg}^{-1}\text{km}^{-1} \) for RF06 and \( \Gamma_1^\text{ob} = 0.68 \text{ g kg}^{-1}\text{km}^{-1} \) for RF07. The typical length of a flight leg (about 60 km) is denoted by \( L \).
TABLE 4. THE RELATIVE STANDARD ERROR $\sigma(\tau)$ AND THE VOLUME-INTEGRATED MEAN OPTICAL DEPTH $\langle \tau \rangle$ FOR RUNS R73 AND R74 OF FLIGHT RF06

<table>
<thead>
<tr>
<th>Run</th>
<th>CCB</th>
<th>VCB</th>
<th>$\langle \tau \rangle$</th>
</tr>
</thead>
<tbody>
<tr>
<td>R73</td>
<td>0.20</td>
<td>0.40</td>
<td></td>
</tr>
<tr>
<td>R74</td>
<td>0.62</td>
<td>0.77</td>
<td>18</td>
</tr>
</tbody>
</table>

Figure 9. Distribution function of the extinction parameter, $\beta_e$, deduced from observed microphysics. Runs R73 and R74 of flight RF06 and runs R51 and R52 of flight RF07 were used for initialization of the Monte Carlo model. The vertical (dashed) lines indicate the mean value of $\beta_e$ (see also Tables 2 and 3).

As the cloud-top height is assumed to be constant in the present investigation, cloud geometrical thickness varies only with cloud-base height. The comparison between the calculated and the observed cloud-base height, $h_b$, measured with an upward-facing Barnes PRT-5 sensor, is shown in Fig. 7. Although the width of the distribution is larger for the calculated cloud-base height the mean values are in close agreement.
Vertical profiles are shown in Figs. 8(a) and (b) of the two-dimensional retrieved \( \beta_e(x, z) \) based on R73 and R51, respectively. Very good agreement is found between the calculated and the observed variability of the extinction parameter for both flights. In Fig. 8(a) it is only run R74, with marked cloud inhomogeneities, which yields a mean \( \beta_e \) outside the standard deviation. However, the diabatic \( \beta_e(x, z) \) vertical profile shown in Fig. 8(a) is based on the initialization run R73 which is more homogeneous than R74 and, therefore, explains the relatively small variability of the profile.

The relative standard error \( \sigma(\tau) \) in Table 4 illustrates the effect of the VCB structure on the variability of the local cloud optical depth. The increase in \( \sigma(\tau) \) from the CCB structure to the VCB structure is larger for run R73 than for run R74. The relatively large inhomogeneity observed during run R74 reduces the effect of the VCB structure on the cloud optical depth variability.

\( (d) \) Monte Carlo simulations

To account for cloud inhomogeneities in the radiative-transfer simulations the optical properties are calculated from the VCB structure. For the Monte Carlo model initialization, we chose the runs R73 and R74 of flight RF06, and the runs R51 and R52 of flight RF07 (see Fig. 1). The distribution functions of \( \beta_e \) of the initialization runs are presented in Fig. 9. Broken-cloud conditions are only present during run R74 of flight RF06, with a cloud fraction \( C = 92\% \). However, the widths and shapes of the \( \beta_e \)-distribution functions (Fig. 9, see also Fig. 2) show the variability of cloud optical properties in the initialization runs.

Results of the simulated broad-band albedo, transmission, and absorption and the observations of albedo and transmission are shown in Fig. 10 for flights RF06 and RF07 as functions of the solar zenith angle, \( \theta_0 \).

The Monte Carlo simulations for runs R73 (RF06), R51, and R52 (RF07) yield a cloud albedo which is about 3% to 10% lower than the plane-parallel cloud albedo. For run R74 (RF06), which contains larger inhomogeneities than runs R73, R51, and
R52, the differences between the Monte Carlo simulations and the plane-parallel model results are 12% to 19%.

Uncertainties in cloud observations, and uncertainties originating from the assumptions made for the Monte Carlo model initialization, limit the accuracy of the modelled cloud albedo. From the uncertainties in the cloud observations, the error introduced by the assumption that \( r_{\text{eff}} \) can be replaced by \( r_v \), and the statistical uncertainties of the fit functions, it follows that there is an uncertainty in the mean cloud optical depth of about 10%. The resulting albedo varies by less than 0.05 for \( \tau \approx 18 \). Note, that the exact albedo variation depends on \( \tau \) because the albedo is a convex function of \( \tau \).

The observed cloud inhomogeneity was largest during run R74. Therefore, special attention is given to run R74 and the corresponding runs R75 and R71 which were all performed along the mean wind direction. The observed cloud albedo (run R75) and transmission (run R71) show large standard deviations which reflect large inhomogeneities. The model initialization cloud field (run R74), described by the VCB structure, has a variability in \( \tau \) of 77%. This yields a variability in the modelled cloud albedo which is comparable (about 10% larger) to the uncertainty in the observed cloud albedo of run R75. The good agreement between observations and model results shows that the VCB structure describes a useful method of investigating radiative fluxes in inhomogeneous cloud fields.

4. Summary and Conclusions

Detailed observations of microphysical quantities in stratocumulus during ASTEX are investigated for their optical properties. To assess the radiative effects of stratocumu-
lus, such as inhomogeneous boundary-layer clouds, radiative fluxes are simulated with a Monte Carlo radiative-transfer model. The model is initialized with optical properties calculated from the observed microphysics.

Special attention is given to microphysical properties in relation to the optical properties. The important optical quantity, the extinction parameter, \( \beta_e \), can be derived from the ratio \( q_l / r_{\text{eff}} \). The critical factor is how to calculate the specific liquid-water content, \( q_l \), and the effective radius, \( r_{\text{eff}} \). Both terms are obtained with the third moment of the droplet spectrum. Because the third moment strongly weights large droplets, \( r_{\text{eff}} \) and \( q_l \) are more sensitive to the shape of the droplet spectrum than \( \beta_e \) which can be calculated directly from the second moment of the droplet spectrum. Consequently, the derivation of \( q_l \) and \( r_{\text{eff}} \) from observations based on different measurement techniques (with their own sensitivity to droplets) is likely to cause erroneous estimates of \( \beta_e \). However, with consistent determination of \( q_l \) and \( r_{\text{eff}} \) from the same observed droplet spectrum, the difference in \( \beta_e \) derived from the FSSP spectra only and \( \beta_e \) derived from the sum of the FSSP and the 260X probe spectra shows very small differences (10%) although the contribution of large droplets measured with the 260X probe increases \( q_l \) and \( r_{\text{eff}} \) by up to 40%.

The Monte Carlo model is initialized with horizontal and vertical cloud optical properties obtained from observed microphysics. The convolution of horizontal time series with vertical profiles for \( \beta_e \) yields a cloud optical depth, \( \tau \), proportional to \( H^{5/3} \), where \( H \) is the local cloud geometrical thickness. This cloud inhomogeneity (as used in the Monte Carlo model) compares very well with the observed variability of cloud optical properties. Simulated and observed cloud albedo are in good agreement for flight RF06, especially for the results obtained with run R74 where the cloud inhomogeneity was largest. However, the model simulations based on other runs overestimate the cloud albedo and underestimate cloud transmission. In contrast to the well-mixed
stratocumulus with occasional small cumulus developing beneath the boundary layer during flight RF06, the cloud field during flight RF07 was decoupled, which means that limited vertical mixing between the cloud layer and the subcloud layer exists. During flight RF07, shallow cumulus penetrated the stratocumulus cloud layer; this is typical of decoupled stratocumulus in the boundary layer. Appendix B shows the difference in the boundary-layer status with the profiles of the maximum observed cloud liquid-water content of all in-cloud runs. While the maximum profile of flight RF06 is similar to the adiabatic liquid-water gradient (typical for well-mixed cloud layers), the maximum profile of flight RF07 is nearly constant with height.

In these cloud albedo simulations we used the VCB structure only. For a cloud field described by the VCB structure we assumed that the boundary layer is well-mixed and that the gradient of the specific liquid-water content is constant for the entire cloud field. Appendix B indicates that, on this assumption, the Monte Carlo model initialization is more appropriate for flight RF06 than for flight RF07. Therefore, the model performance should be better for flight RF06 than for flight RF07.

In the study we assumed that the calculation of cloud optical properties from observed cloud microphysical properties and from the theory of cloud dynamics is suitable for well-mixed boundary-layer cloud fields only, i.e. in cloud fields where the conserved thermodynamic properties are nearly constant with height throughout the boundary layer. In contrast to the observations in the well-mixed boundary layer during flight RF06, the situation during flight RF07 was not so clear: Therefore, the results are better understood for flight RF06 than for flight RF07. This is also evident from the model results presented in Fig. 10 which performed better for flight RF06 than for flight RF07.

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APPENDIX A

Four-band scheme

In the Monte Carlo model the solar radiative transfer is simulated with a four-band scheme defined between 0.25 and 4.0 μm. The albedo, transmission, and absorption, are obtained by adding the weighted results of the simulations performed separately for the four different bands.

To assess the accuracy of the four-band scheme it was compared with a reference model output calculated with 62 bands for plane-parallel clouds. The 62 bands have been chosen according to the tabulated refractive indices of pure water (Hale and Querry 1973). The cloud optical parameters $\tilde{a}_0$ and $g$ are obtained with the Mie code of Wiscombe (1979). The Mie calculations are based on the mean droplet spectrum of all in-cloud runs with $0.1 < \zeta' < 0.9$. Figure A.1 shows the distribution function of the cloud droplet radius, $r$, as used in the Mie calculations for flights RF06 and RF07. Two extra distribution functions of runs R74 and R51 are included in the figure. Run R74 represents an inhomogeneous cloud with cloud fraction $C = 92\%$ and run R51 represents an overcast situation (no cloud gaps).
TABLE A.1. VALUES OF THE OPTICAL PARAMETERS $\bar{\omega}_0$ AND $g$ (SEE TEXT) FOR THE FOUR-BAND SCHEME

<table>
<thead>
<tr>
<th>Band</th>
<th>Wavelength interval ($\mu$m)</th>
<th>Bands of the 62-band scheme</th>
<th>Weight</th>
<th>Flight RF06 $\bar{\omega}_0$</th>
<th>Flight RF06 $g$</th>
<th>Flight RF07 $\bar{\omega}_0$</th>
<th>Flight RF07 $g$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.25–1.4</td>
<td>1–32</td>
<td>0.82</td>
<td>0.999</td>
<td>0.863</td>
<td>0.999</td>
<td>0.864</td>
</tr>
<tr>
<td>2</td>
<td>1.4–2.4</td>
<td>33–37</td>
<td>0.13</td>
<td>0.983</td>
<td>0.848</td>
<td>0.983</td>
<td>0.848</td>
</tr>
<tr>
<td>3</td>
<td>2.4–2.8</td>
<td>38–42</td>
<td>0.02</td>
<td>0.866</td>
<td>0.859</td>
<td>0.867</td>
<td>0.860</td>
</tr>
<tr>
<td>4</td>
<td>2.8–4.0</td>
<td>43–62</td>
<td>0.03</td>
<td>0.669</td>
<td>0.864</td>
<td>0.670</td>
<td>0.865</td>
</tr>
</tbody>
</table>

For the four-band scheme $\bar{\omega}_0$ and $g$ were interpolated and weighted with the extraterrestrial solar spectrum due to Thekaekara and Drummond (1971) to obtain the average values in each spectral band according to Eq. (11) in the paper by Slingo and Schrecker (1982).

Because the radiometers are sensitive between $\lambda = 0.285$ and 2.8 $\mu$m, three of the four bands are forced to be within this sensitivity range. The fourth band is fixed between 2.8 and 4.0 $\mu$m. The three remaining bands are chosen in order to minimize the difference between the 62-band and the four-band scheme. A doubling-and-adding radiative transfer model (de Haan et al. 1987) was used to calculate the difference in the modelled albedo for the 62- and the four-band scheme. For the chosen wavelength intervals the difference is less than 1% for both flights. For details on wavelength intervals and optical parameters of the four-band scheme see Table A.1.

APPENDIX B

Measurement of specific liquid-water content, $q_1$

Specific liquid-water content, $q_1$, is calculated with the droplet spectra obtained from the FSSP and 260X probe observations. Various methods to obtain liquid-water content from cloud microphysical observations have been reported in the literature (e.g. Korolev et al. 1999). However, no accurate method has yet been devised. For $q_1$ derived from the FSSP spectra an uncertainty of 55% is given in the ASTEX operational
CLOUD OPTICAL PROPERTIES

Figure B.1. Vertical profiles of \( q_l \)-maxima obtained during in-cloud runs of (a) flight RF06 and (b) flight RF07. The filled symbols represent \( q_l \) values derived from both the one-second mean values of the FSSP (10 Hz) and the 260X probe (1 Hz), whereas the open symbols are for FSSP (10 Hz) only. The dashed profile is the (theoretical) gradient of the adiabatic liquid-water content, \( \Gamma_1 \approx 2 \text{ g kg}^{-1}\text{km}^{-1} \). According to the definition of \( q_l \) large droplets are strongly weighted which explains the distribution of the filled symbols.

plan (ASTEX 1992a). Although there are high uncertainties in the FSSP-derived liquid-water content, the latter corresponds well with the value obtained from the PMS King probe for droplets with a diameter smaller than 30 \( \mu \text{m} \). The correlation between the specific liquid-water content, \( q_l \), derived from the FSSP and the \( q_l \) derived from the PMS King probe was better than 3% for droplets smaller than 30 \( \mu \text{m} \). Larger droplets are not correctly measured by the PMS King probe. However, large droplets can be detected by optical probes (mainly the 260X probe).

To assess the quality of the \( q_l \) determination based on the two optical probes (FSSP and 260X), vertical profiles with the maxima in the observed liquid-water content are compared with theoretical adiabatic liquid-water content profiles. Figures B.1(a) and (b) show vertical profiles of \( q_l \)-maxima obtained during flights RF06 and RF07, respectively.

The \( q_l \)-maxima taken from the observed time series on all in-cloud runs, shown in Fig. B.1, give an upper limit for the observations, and should be lower than the adiabatic curve for \( \Gamma_1 \). With an estimated uncertainty of about 10% in the determination of \( \Gamma_1 \) (due to local cloud-base variations of about 50 m) good agreement is obtained between the observed \( q_l \) maxima and the adiabatic liquid-water content profile during flight RF06, whereas during flight RF07 the \( q_l \) maxima are nearly constant with height. However, Fig. B.1(a) indicates that the boundary layer, as observed during flight RF06, was well-mixed because the \( q_l \) maxima follow the quasi-conserved quantity \( \Gamma_1 \) throughout the cloud layer (in a well-mixed boundary layer quasi-conserved quantities are nearly constant with height).

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