Cirrus Microphysics and Radiative Transfer: Cloud Field Study on 28 October 1986

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ABSTRACT

Cloud data acquired during the cirrus intensive field operation of FIRE 86 are analyzed for a 75 x 50-km² cirrus cloud field that passed over Wausau, Wisconsin, during the morning of 28 October 1986. Remote-sensing measurements from the stratosphere and the ground detect an inhomogeneous cloud structure between 6 and 11 km in altitude. The measurements differentiate between an optically thicker (τ > 3) cirrus deck characterized by sheared precipitation trails and an optically thinner (τ < 2) cirrus cloud field in which individual cells of liquid water are imbedded. Simultaneous measurements of particle-size spectra and broadband radiative fluxes at multiple altitudes in the lower half of the cloud provide the basis for a comparison between measured and calculated fluxes. The calculated fluxes are derived from observations of cloud-particle-size distributions, cloud structure, and atmospheric conditions. Comparison of the modeled fluxes with the measurements shows that the model results underestimate the solar reflectivity and attenuation, as well as the downward infrared fluxes. Some of this discrepancy may be due to cloud inhomogeneities or to uncertainties in cloud microphysics, since there were no measurements of small ice crystals available, nor any micropysical measurements in the upper portion of the cirrus. Reconciling the model results with the measurements can be achieved either by adding large concentrations of small ice crystals or by altering the backscattering properties of the ice crystals. These results suggest that additional theoretical and experimental studies on small compact shapes, hollow ice crystals, and shapes with branches are needed. Also, new aircraft instrumentation is needed that can detect ice crystals with maximum dimensions between 5 and 50 µm.

1. Introduction

The radiative properties of cirrus clouds are one of the major unresolved problems in weather and climate research (Liou 1986). Uncertainties in ice-particle amount and size, as well as a general inability to model the single-scattering properties of complex particle shapes and cirrus inhomogeneity, prevent accurate model predictions. Thus, for improvements in our understanding of cirrus radiative effects and in current cirrus model parameterizations, field experiments that use aircraft to provide in situ measurements of cirrus properties are necessary. Until now, however, only a few cirrus field experiments have been conducted that attempt to relate microphysical and radiative measurements. Paltridge and Platt (1981) compared ice water paths to radiative properties, such as solar-flux

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absorption, solar albedo, and infrared emissivities. Foot (1988) related particle-size distributions to broadband absorptions and also compared solar with infrared optical depths.

The cirrus intensive field operation (IFO) of the First ISCCP Regional Experiment (FIRE) conducted in Wisconsin in 1986 provided a wealth of new cirrus cloud data. In this paper, we concentrate on combining aircraft in situ measurements of microphysics and radiation with remotely sensed data to develop a consistent model of a cirrus deck. The available instrumentation is described in the first section.

The second section summarizes the measurements and discusses the data intercomparison; the following section addresses the character of the cloud field using remotely sensed data. The modeling section explains how in situ particle measurements are converted into equivalent size distributions of spheres, which can be treated using Mie calculations. Single-scattering properties and radiative transfer calculations are then described. Finally, to pinpoint the importance of measurement and/or model deficiencies, comparisons of calculated and observed flux profiles are discussed.

2. Instrumentation

This paper is part of the 27–28 October case study of the cirrus IFO of FIRE over Wisconsin in 1986. A general overview of the meteorology is given by Starr and Wylie (1990). This paper focuses on remote sensing and in situ measurements of a cloud field as it passed over Wausau, Wisconsin, on the morning of 28 October. The cloud data used in this study were provided by the ground-based lidar at Wausau and two airborne platforms, the NASA ER-2 and the NCAR King Air. The aircraft trajectories are displayed in Fig. 1. The aircraft flight altitudes are shown in the upper graph of Fig. 2. The ER-2 supplied simultaneous lidar data and infrared radiances from the stratosphere. The King Air provided simultaneous in situ measurements of broadband radiative fluxes and cloud microphysics. The instrumentation used for this study is summarized in Table 1.

3. Measurements

This study is limited to ground-based lidar measurements obtained between 1630 and 1735 UTC,

![Fig. 1. Flight trajectories of the ER-2 (solid line) and King Air (dashed line) aircraft over Wisconsin between 1500 and 1800 UTC. Arrow heads are drawn at 12-min intervals along the flight paths. (Note that the airspeed of the ER-2 is about 200 m s⁻¹ and that of the King Air is about 100 m s⁻¹.) The rectangular frame around Wausau marks the position of the analyzed cloud field at 1700 UTC. Its average hourly displacement is portrayed by a wind vector in the lower left corner. Also marked are time limits (UTC) for cloud-field penetration by both aircraft.](image)

![Fig. 2. Flight altitudes of the ER-2 (solid line) and the King Air (dashed line) for the trajectories of Fig. 1. Symbols on the curves enclose time periods of cloud-field penetration. The horizontal separation of the aircraft is displayed in the lower graph.](image)

<table>
<thead>
<tr>
<th>Table 1. Instrumentation.</th>
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<tbody>
<tr>
<td>Wausau lidar</td>
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<tr>
<td>ER-2 lidar</td>
</tr>
<tr>
<td>ER-2 radiometer</td>
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<tr>
<td>King Air radiometer</td>
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<tr>
<td>King Air particle probes</td>
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ER-2 data collected between 1620 and 1710 UTC, and King Air data collected between 1630 and 1730 UTC. With a 6-h difference between UTC time and local time, all measurements fall in the time period of 1020–1135 LST. During this time period, the lidar and both aircraft penetrated the area of the selected 75 × 50-km² cloud field. The individual flight legs of the aircraft are summarized in Tables 2 and 3. Figure 1 marks the position of the cloud field at 1700 UTC. Its average hourly displacement of 80 km in an east-northeasterly direction (250°) is indicated by the wind vector in the lower left corner of Fig. 1. The cloud-field advection has been derived from matching ER-2 radiances and King Air wind measurements.

This choice of measurement period of approximately 75 min was dictated by the coincidence of the aircraft with the ground-based lidar at Wausau (Fig. 1). The flight altitudes and horizontal separation of the ER-2 and King Air are shown as a function of time in Fig. 2. Note that the two aircraft were never actually coincident in both space and time. If, however, the mean cloud advection is taken into account (Fig. 3), the two aircraft did occasionally sample the same portion of the cloud field (the ER-2 remotely and the King Air in situ), but at somewhat different times. These areas can be identified in Fig. 3 as locations where the advection-adjusted aircraft trajectories cross. Since this figure is constructed in the fixed frame of the cloud field (which is advecting from the southwest to northeast at a fixed speed of 80 m s⁻¹), Wausau follows an apparent trajectory from the northeast to southwest.

The King Air measurements of wind speed and direction within the cloud field are shown in Fig. 4. The wind speeds vary by as much as 20 km h⁻¹, and the wind directions by 20°. Consequently, the trajectories plotted in Fig. 3, which assume a constant average speed and direction, may be somewhat in error. It is estimated that after 30 min of elapsed time, the horizontal placement uncertainty in the trajectories is on the order of 10 km. Unfortunately, for this cloud field, the relative placement of trajectories is critical for the retrieval of vertical profiles. For example, the variations in the measured broadband fluxes along flight legs of constant altitude (compare panels 3 and 4 to panel 1 in Fig. 4) are evidence of horizontal (and vertical) inhomogeneities in the cloud field. With regard to constructing vertical profiles, this inhomogeneity limits the comparison between measurements from different altitudes in two ways. The trajectories have to be spatially nearly coincident (the crossing points in Fig. 3), but the measurements also must be close in time to avoid uncertainties relating to advected positioning and to changes in cloud structure. Since these conditions generally can not be met, the construction of vertical profiles was based on a statistical approach, using average quantities from measurements at constant altitudes.

However, there are two instances where measurements are nearly simultaneous in space and time. Both areas are highlighted in Fig. 3. The hatched area in the upper right marks the "double leg" where the trajectories of the ER-2 leg 3 and the King Air leg 1 almost match in time and cloud-field position along a 30-km path within the cloud field. This situation provides almost simultaneous data from above (ER-2) and below (King Air) the cloud. The location of the King Air at cloud base at an altitude of 6.1 km is confirmed by

| Table 2. ER-2 10-μm radiance and 0.532-μm lidar measurements. |
|---------------------------------|-----------------|-----------------|
| Altitude (km) | Direction | Time (UTC) |
| Leg 1 | 19.2 | east-west | 1619:52–1625:27 |
| Leg 2 | 19.2 | west-east | 1629:57–1636:07 |
| Leg 3 | 19.2 | east-west | 1640:07–1645:52 |
| Leg 4 | 19.2 | west-east | 1654:02–1658:12 |
| Leg 5 | 19.2 | northeast-southwest | 1706:47–1709:39 |

FIG. 3. ER-2 (solid line) and King Air (dashed line) trajectories in the reference frame of the advected 75 × 50-km² cloud-field area. (The cloud-field advection is at an average speed of 80 km h⁻¹ and direction of 250°.) Arrows or minute labels are drawn in 1-min intervals for the ER-2 and 2-min intervals for the King Air. The position of Wausau (dark diagonal line), moving west-southwest relative to the cloud field, is represented in 5-min steps by dark dots. Two sub-areas are highlighted: one is used for the optical depth comparison (upper right), the other marks the location of the spiral descent (lower left).
Fig. 4. King Air measurements in the selected cloud field. The first panel displays the flight altitude and time intervals of particle 2D imaging probe measurements (horizontal bars at top). The second panel shows ambient temperature (solid line) and dewpoint (dashed line). Broadband downward fluxes (solid lines) and upward fluxes (dashed lines) are shown in panel 3 for solar radiation and panel 4 for infrared radiation. Shaded areas mark inaccurate flux values due to occasions when the roll of the aircraft, shown in panel 5, exceeded 5°. The bottom two panels display wind direction and wind speed.
large differences between atmospheric and dewpoint temperatures in panel 2 of Fig. 4 and by video camera (VCR) images of surface features recorded from the cockpit during the flight. The hatched area in the lower left of Fig. 3 indicates the location of the King Air descent in a three-loop spiral from 8.2 to 6.1 km in altitude in only 7 min. The three loops in Fig. 3 appear almost on top of each other because the King Air was descending while drifting with the ambient wind (a so-called Lagrangian spiral). The weak wind shear within the cloud prevents an exact match of the loops. Both of these areas will receive special attention in the subsequent analysis.

4. Structure

Information on the cloud-field structure was obtained primarily by simultaneous remote-sensing measurements of infrared upwelling radiances and lidar backscattering from the ER-2 aircraft. Additional data was provided by ground-based lidar backscatter measurements at Wausau.

a. ER-2 10-µm radiance measurements

For ease of interpretation, the upwelling 10-µm radiances have been expressed as equivalent blackbody radiative temperatures. Since absorption by atmospheric gases (notably water vapor) at a wavelength of 10 µm is very small, radiative temperatures less than the surface temperature of approximately 290 K indicate the presence of clouds. Based on data taken along the five ER-2 trajectories that cross the cloud field (see Table 2 and Fig. 3), a contour plot of 10-µm radiative temperatures has been constructed for the cloud-field region of interest (Fig. 5). Due to the limited available data, this contour plot, as well as subsequent plots, assume a 2.5-km gridpoint separation along the x axis and a 10-km gridpoint separation along the y axis. Smaller-scale features are averaged out. In Fig. 5, the equivalent blackbody temperatures in the right half of the cloud are approximately 15 K colder than those in the left half. This variation may be interpreted either as a variation in cloud altitude and/or a variation in cloud optical thickness. Thus, the colder clouds in the right half of the cloud field are either higher, optically thicker, or some combination of both. Some insight is provided by analysis of the lidar data. Three lidar cross sections of the cloud field are shown, one by the ground-based Wausau lidar and two by the ER-2 lidar along ER-2 legs 3 and 5. The positions of these cross sections are marked in Fig. 5.

b. Wausau lidar measurements

The 0.694-µm lidar data from Wausau (Sassen 1990), shown in Fig. 6, were taken during the cloud-field overpass between 1630 and 1735 UTC along the trajectory in Fig. 5. The upper panel shows lidar backscattering signals, the lower panel inferred cloud extinction coefficients. There is considerable variation in the lidar attenuation, with many individual cells marked by large values of the extinction coefficient. This further indicates the strong horizontal and vertical inhomogeneity of the cloud field, already deduced from the measured broadband flux variations (Fig. 4). The division of the cloud field into two parts is supported not only by the difference in infrared temperature, but also by the difference in the cloud character.

Note that the left side of Fig. 6 corresponds to the right side of the cloud field in Fig. 5, and vice versa. On the right side of the cloud field (left side of Fig. 6), the large extinction coefficients near the cloud base, derived from lidar measurements before 1712 UTC, correspond to the bottom of sheared ice-crystal fallstreaks, which trail toward the cloud base. Warm cloud-base emissions and strongly reduced radiative temperatures suggest optical depths that are much larger than those derived from cumulative lidar extinctions, compared in the middle panel of Fig. 6 to radiative temperatures of Fig. 5. The attenuated lidar signal apparently becomes too weak to accurately reflect the structure and extinction of the upper cloud layers.

On the left side of the cloud field (right side of Fig. 6) the lidar signal is less attenuated. The cells of larger extinction have low depolarization ratios ($\delta < 0.15$) and, thus, represent predominantly liquid-phase altocumulus clouds. The presence of such clouds is supported by an infrequent detection of low depolarization ratios by the down-looking ER-2 lidar in the same cloud-field region and by occasional high particle counts ($10^5$–$10^7$ µm$^{-1}$ m$^{-3}$) in the 2–10-µm-size bins.
Fig. 6. Attenuated backscatter intensity from a ground-based upward-looking lidar [units of \(\log(\text{km sr}^{-1})\)] are presented in the upper panel for the Wausau lidar trajectory of Fig. 5. The middle panel compares ER-2 10-\(\mu\)m radiative temperatures (dashed line) to estimates of visible cloud optical depths from calculated cloud extinctions of the lower panel (solid line). The lower panel contours equivalent cloud extinctions (\(\text{km}^{-1}\)). These extinctions are based on pure molecular scattering below the cloud, a multiple-scattering correction (Platt et al. 1989) of 0.5, and a backscatter to extinction ratio of 0.04 \(\text{sr}^{-1}\), based on concurrent measurements with the high spectral resolution lidar at Madison, Wisconsin. Dotted lines in the lower panel indicate corresponding cloud-top heights from ER-2 downward looking lidar overpass measurements (see Figs. 7 and 8). The atmospheric temperature profile is given by the right-hand ordinate.

of the FSSP probe measurements taken by the King Air above 7 km.

The ground-based lidar data define the cloud base at or just above the 6-km altitude. This is consistent with King Air cockpit VCR observations at 6.1 km taken during leg I and after the spiral descent, when surface features were clearly visible. The uncertainty in cloud-top height deduced from ground-based lidar
data is resolved by the downward-looking ER-2 lidar data, especially for the right side of the cloud field. The ER-2 overpasses above Wausau at 1640:40 and 1707:20 UTC place cloud tops near 11 km, as indicated in the lower panel of Fig. 6.

c. ER-2 lidar measurements

The ER-2 0.532-μm lidar backscattering signals (Spinhirne et al. 1988) along the ER-2 legs 3 and 5 (Fig. 5) are presented in Figs. 7 and 8, respectively.

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Fig. 7. Attenuated backscatter intensity from the downward-looking ER-2 lidar between 1640 and 1646 UTC along the east-west trajectory in Fig. 5 (ER-2 leg 3). Surface returns (solid line at 45–65 km) indicate cloud optical depths less than about 2. In the absence of a surface return, the lower boundary in the ER-2 lidar image is a result of attenuation and does not represent the actual cloud base. The lidar signals are also compared to calculated cloud properties. The upper panel presents estimates of solar and infrared optical depths based on measured broadband fluxes near the cloud base. The middle panel compares 10-μm radiative temperatures to infrared optical depths deduced from these temperatures and the radiative equivalent cloud heights.
The data support the suggested twofold character of the cloud field. The transition in the cloud structure occurs near the 255-K contour line of Fig. 5 and is conveniently indicated in Figs. 7 and 8 by the presence of a surface return signal. This return is only observed if the total cloud-column optical depth is less than about two. Note again that the right side of the trajectories crossing the cloud field in Fig. 5 corresponds to the left side of the lidar images, and vice versa.

The right side of the cloud field in Fig. 5 ($T_{IR} < 255$ K) is characterized by ice-crystal fallstreaks and larger optical depth. The ER-2 lidar signal in that area is so strongly attenuated that returns are missing not only from the surface but also from the lower part of the cloud. Cloud-top altitudes are consistently located above 10 km, and high cirrus sheets at 11 km are frequently observed.

The left side of the cloud field in Fig. 5 ($T_{IR} > 255$ K) is characterized by an optically thin cirrus cloud field in which cells of liquid water are imbedded. Cloud-top altitudes vary between 8 and 11 km. The highest altitudes are associated with thin cirrus that appeared to be separated from a second cloud layer below 8 km. VCR cockpit observations from King Air flight legs near 8 km in that area frequently show good visibility with a cloud deck below, again suggesting two cloud decks in this area.

d. Combined data

Lidar backscattering signals were measured on all five ER-2 flight legs. From these data, contour plots similar to those in Fig. 5 have been constructed. Figure 9 shows contours of cloud-top heights, while Fig. 10
shows contours of the equivalent cloud heights. These equivalent heights have been derived by Spinhirne and Hart (1990) and represent the heights of blackbody clouds with equal emittance. Figure 11 displays contours of infrared optical depth, deduced from the combined information of Figs. 5 and 10. Statistics on all three properties are listed in Table 4 for the entire cloud field and for the two cloud-field sections with 10-μm radiative temperatures above and below 255 K. The standard deviation of the optical depths is only 28% of the mean value in the subsections, compared to 45% for the entire cloud field. This supports the subsequent independent analysis of both cloud-field sections. Since the differences in the infrared temperatures of Fig. 5 primarily represent differences in cloud-column optical depth, the cloud-field region with infrared temperatures below 255 K will be referred to as the optically thick section, and the remaining region with temperatures above 255 K as optically thin section.

The upper panel of Fig. 12 compares radiative temperatures and infrared optical depths. Optical depths in the optically thin section (open circles) are all less than 3.2, while values between 2.2 and 7.1 are found in the optically thick section (filled circles). The values larger than 6 are probably in error because strong lidar attenuation results in overestimates of equivalent heights and in corresponding overestimates of optical depths.

But are these optical depths correct? Along the double leg, marked by the upper right hatching in Fig. 3, the King Air measured broadband fluxes at the cloud base. Values of optical depths derived from the measurements of downward solar and infrared flux at the cloud base are presented in the top panel of Fig. 7. The middle panel shows the lidar-derived infrared optical depths, as well as 10-μm radiative temperatures from the ER-2. Statistics on radiative fluxes, radiative temperature, and optical depths are summarized in Table 5. The ER-2 infrared optical depths, based on the radiances and the lidar data, are slightly smaller than the

![Fig. 9. Contour plot of cloud top heights measured by the downward looking ER-2 lidar for the cloud-field area of Fig. 3.](image1)

![Fig. 10. Contour plot of radiative equivalent cloud heights for the cloud-field area of Fig. 3. These heights represent the altitudes of blackbody clouds with equal emittance.](image2)

![Fig. 11. Contour plot of calculated infrared optical depths for the cloud-field area of Fig. 3. The optical depths are calculated from the 10-μm radiances of Fig. 5 and the radiative effective cloud heights of Fig. 10.](image3)

**Table 4. ER-2 lidar cloud-field statistics.**

<table>
<thead>
<tr>
<th></th>
<th>Total area</th>
<th>T_{IR} &gt; 255 K</th>
<th>T_{IR} &lt; 255 K</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top height (km)</td>
<td>10.6 ± 0.7</td>
<td>10.3 ± 0.8</td>
<td>10.9 ± 0.4</td>
</tr>
<tr>
<td>Effective height (km)</td>
<td>8.7 ± 0.8</td>
<td>8.2 ± 0.8</td>
<td>9.1 ± 0.6</td>
</tr>
<tr>
<td>IR optical depth</td>
<td>2.7 ± 1.2</td>
<td>1.8 ± 0.5</td>
<td>3.6 ± 1.0</td>
</tr>
</tbody>
</table>
infrared optical depths derived from the King Air flux measurements near cloud base. If the unrealistically large values at the beginning of the ER-2 leg 3 are removed, the differences become even larger. The comparison to the King Air measurements suggests that the optical depths given in Figs. 11 and 12 are approximately 20% too small. Still, the overall similarity is encouraging, considering the different retrieval techniques and the fact that the ER-2 and King Air did not follow the same trajectory with respect to the cloud field.

The top panel of Fig. 7 compares solar and infrared optical depths derived from downward fluxes near the cloud base. On average, the solar optical depths are found to be larger by a factor of 1.1 (see Table 5). This difference may be due to the presence of undetected small particles with equivalent radii below 5 \( \mu \text{m} \) or to an overestimation of the ratio of forward to backward scattering by cloud particles in the solar spectral region of the model. This issue will be addressed later in more detail.

Finally, the lower panel of Fig. 12 presents differences between cloud-top height and radiative effective cloud height. The average difference is 1.8 km for the optically thick section and 2.1 km for the optically thin section. Given a lapse rate of 7.5 K km\(^{-1}\), the radiative effective temperature of the cloud is, on average, about 15 K higher than the cloud-top temperature.

**e. Summary**

Remote measurements from the ER-2 and the ground, coupled with flux measurements near cloud base, depict two distinct regimes in this inhomogeneous cloud field. The right, or eastern, half is characterized by a cirrus deck that extends from 6 to about 10 km in altitude. This deck structure is characterized by sheared ice-crystal fallstreaks, which have their largest extinction near cloud base. The cirrus deck is covered by thin cirrus sheets near 11 km. Cloud-column optical depths vary between 3 and 5. Based on flux measurements at the cloud base, the solar optical depths are larger than the infrared values by about 10%. The left, or western, half of the cloud field is characterized by a cloud deck in which cells of liquid water are embedded. The cirrus deck, which extends from 6.1 to about 8.0 km, is occasionally covered by a high cirrus deck whose cloud tops can exceed 10 km. Infrared cloud-column optical depths rarely exceed 2.

**5. Modeling**

To verify and understand the observed cloud properties, particularly the differences between solar and infrared optical depths, measured fluxes are compared to calculated fluxes. The calculations are based on in situ cloud-particle measurements. The presentation of these data and their formulation for radiative transfer calculations is addressed in this section.

**Table 5. Optical-depth comparison.**

<table>
<thead>
<tr>
<th></th>
<th>King Air broadband solar fluxes</th>
<th>King Air broadband IR fluxes</th>
<th>ER-2 10-(\mu)m IR radiance temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upward flux* (W m(^{-2}))</td>
<td>58.8 ± 4.4</td>
<td>310.8 ± 2.5</td>
<td>244.6 ± 3.3 K</td>
</tr>
<tr>
<td>Downward flux* (W m(^{-2}))</td>
<td>314.6 ± 29.7</td>
<td>213.2 ± 4.2</td>
<td></td>
</tr>
<tr>
<td>Deduced optical depth</td>
<td>4.80 ± 0.96</td>
<td>4.27 ± 0.56</td>
<td>4.00 ± 1.00</td>
</tr>
</tbody>
</table>

* At cloud-base altitude.
The size and concentration of cirrus cloud particles are inferred from measurements with the PMS 2-DC probe for the smaller ice crystals and the PMS 2-DP probe for the larger ice crystals. Time periods and altitudes of these measurements within the cloud field are presented in Table 6 for the two cloud areas: one with 10-μm radiative temperatures above 255 K and one with temperatures below 255 K (see Fig. 5). The particle measuring devices detect the cross sections of cloud particles as the airflow passes through the instruments. The sizes are binned according to their largest dimension. Each of the 29 size bins stores the measured surface areas as the fractional area of a circle whose diameter is the largest dimension. If the particles are nearly spherical, this fractional area approaches one; if the particles have large aspect ratios, the fractional area is much less than one. Thus, the smaller the area ratios are the more distinct a preferred dimension. Figure 13 represents a 7-min average of measurements acquired during the spiral descent from 8.2 km to the cloud base at 6.1 km in the optically thin cloud region (the location is marked by the lower patch in Fig. 3). Most particles with crystal lengths between 200 and 700 μm have large surface area ratios. This reflects results from a more thorough analysis on particle shapes by Heymsfield and Miller (1990). They conclude that the dominant ice-crystal habits are compact crystals with branches and bullet rosettes. Single columns are less frequent. They also find that, as the column size increases, hollowed-out regions appear at their ends.

To perform radiative transfer calculations for a cloud, the microphysical particle measurements in the cloud need to be expressed by their single-scattering properties. These properties not only depend on particle size and composition, but also on particle shape. Relatively simple techniques for computing single-scattering properties exist only for spheres. Ice particles, however, are nonspherical; they are usually characterized by a hexagonal structure. To avoid complex calculations for the various ice-crystal shapes and sizes, the information from the 2D imaging probes has been converted into size distributions of equivalent spheres.

The conversion to spheres is illustrated in Fig. 14 for two particles with the same largest dimension c but different cross sections. The conversion occurs in two steps. In the first step, the dimensions of a selected particle shape are constructed. Based on the detected dominant particle shapes, the “double hexagon with
branches” type has been selected. A double-hexagon column matching the measured largest dimension \( c \) is constructed. The particle width is automatically given by the requirement of an identical cross section. No width, however, may exceed the typical width-to-length ratio. An experimental relationship between length \( c \) and half-width \( a \) for hexagonal columns is given by Heymsfield (1975). Except for small particles with lengths less than 30 \( \mu \text{m} \), which have no preferred dimension \( (c = 2a) \), the length-to-width ratio \( (c/2a) \) is always greater than 1 and increases with increasing column length (e.g., \( c = 300 \mu \text{m}; c/2a = 3 \) or \( a = 50 \mu \text{m} \)). Any excess of a measured cross-sectional area that is not accounted for by the width limitation is expressed via 2–4 branches. These equally sized branches are attached to the center of the main double column [to represent frequently observed multiple column crystals (e.g., a bullet rosette)] typically having 4–5 branches (Kikuchi 1967; Uyeada and Kikuchi 1979; Heymsfield and Miller 1990).

In the second step, the modeled hexagonal columns or column rosettes are transformed into spheres. Assuming a random ice-crystal orientation, spheres of equal surface area provide almost identical extinction. Thus, surface equivalent spheres have been chosen. Branches of the multiple column shapes are assumed to be independent from the main column and are transformed separately.

The conversion from measurements of maximum length \( c \) and cross-sectional area on ice cloud particles into equivalent spheres is pictured in Fig. 14 for this “double hexagon with branches” shape and also for three other shapes. The “single hexagon and branches” shape is based around only one main column, while the “double hexagon” shape makes no limitation in regard to column width; thus, there is no need for branches. Also shown is the conversion assuming a “sphere.”

Conversion results based on the four different particle shapes of Fig. 14 are summarized in Fig. 15. The
An additional uncertainty in the extinction values is introduced by the measurements. The 2D image measurements have problems with detecting small ice crystals. The three smallest size bins in Fig. 13, but especially the smallest size bin, most likely represent an undercount by up to five (Dye, personal communication). The 2D images cannot detect small ice crystals whose largest dimension falls below 30 μm, even though these particles may be present. Little help can be expected from simultaneous PMS FSSP data. The particle-size detection of the FSSP probe is based on forward scattering by spheres. Unfortunately, the presence of large, nonspherical particles contaminates the forward scattering and leads to an overcounting. The four comparisons in Fig. 16 indicate an overcounting by up to two orders of magnitude. Actual particle concentrations are expected somewhere in between these curves. In reference to the possible presence of small particles, it should be noted that the FSSP probe did not detect any significant counts (>$10^4 \mu m^{-1} m^{-3}$) for particles with radii below 12 μm.

**Fig. 15.** Comparison of particle-size distributions of spheres based on the four different conversion shapes of Fig. 14 for the measurements of Fig. 13. The dashed shading displays the effective surface area per micron in units of square millimeters per cubic meter (mm² m⁻³). Also displayed are calculated extinction coefficients and ice water densities. The low densities for hexagons are a result of cavities in large particles.

Particle measurements of Fig. 13 have been used. Figure 15 also gives values for ice water content and extinctions of Mie calculations. Except for the sphere, all values for ice water contents take the lower density of ice and the hollowness of large crystals into account. Comparing extinction and ice water contents for the four different particle shapes, the most significant changes occur with the limitation in ice-column width and the assumption of branches. Compared to the assumption of a single or double particle (e.g., sphere), extinctions are cut about half, and ice water contents are lower by almost one order of magnitude. Maxima from the effective surface-area shading also indicate that the branch assumption reduces typical radii from approximately 200 to about 70 μm. Only minor changes are associated with the switch from a main double column to a single main column.

**Fig. 16.** Comparison between FSSP particle-size distributions (solid lines) and the lower end of size distributions (from 2-DC probe measurements) using a "sphere" conversion (dashed line). The simultaneous measurements were made in optically thick cirrus cloud sections near the cloud base in four 5-s time intervals. Also shown is the threshold for the FSSP data (dotted line).
In summary, the calculated cloud extinctions from 2D image particle measurements carry a significant uncertainty caused by importance of particle shape and the lack of quality measurements of small particles.

6. Calculations

The radiative transfer calculations are explained in this chapter. The calculations yield broadband solar and infrared radiative fluxes, which can be compared to values of in situ measurements. These calculations are also used inversely to retrieve cloud properties (e.g., optical depths) from flux measurements. The accuracy of these calculations depends critically on the quality of the model and its required input variables, the atmospheric and surface properties, and the cloud height and cloud microphysics.

a. Model

Calculations of broadband radiative fluxes for the selected cloud field are performed with a 1D radiative transfer model. The model follows the matrix operator method, which is based on the adding principle for radiative transfer (Plass et al. 1973). The application of the adding principle to a vertically inhomogeneous atmosphere is carried out by dividing the atmosphere, in this case, into 31 homogeneous layers. These layers have a thickness of 300 m at cloud height. In each layer, reflection and transmission are expressed in matrices, here of rank 5, to account for the zenith angle dependence. Broadband fluxes are based on calculations in 8 solar and 12 infrared spectral intervals. The absorption of atmospheric gases in these bands is expressed via exponential sum fitting of line-by-line data.

b. Atmospheric data

The atmospheric profile for all calculations is based on the 1800 UTC Green Bay (location marked in Fig. 1) radiosonde sounding (Starr and Wylie 1990). The sounding at cloud height has been modified to be consistent with in situ King Air measurements. The temperature profile is characterized by a constant lapse of about 7.5 K km⁻¹, and the atmospheric temperature at the cloud base height of 6.1 km is 251 K. The right abscissa in the lower panel of Fig. 6 indicates atmospheric temperatures. The water vapor concentration has been assumed to be saturated at cloud height. Humidity data above 11 km and the ozone profile (taken from the U.S. Standard Atmosphere) were not measured.

Solar calculations assume a solar constant of 1360 W m⁻² and a solar zenith angle of 60°. This angle is accurate to within 2° with respect to local time (1030–1130), latitude (45°), and time of year (28 October). Still, the sun angle change caused an increase in the downward solar flux at the top of the atmosphere from 645 W m⁻² at 1630 UTC to 705 W m⁻² at 1730 UTC.

A solar surface albedo of 15% was adopted, which is typical of midlatitude land surfaces. For infrared calculations, the surface temperature was assumed to be 290.1 K, the temperature of the atmosphere near the surface, and an infrared emissivity of 0.96 was prescribed.

c. Cloud data

The vertical thickness of the modeled cloud is based on the lidar data presented in Figs. 6–9. Several clouds have been modeled to accommodate the changing character of the cloud field. Although the cloud base remains fixed at 6.1 km, the cloud top has been assumed to be at 10.9 km for the optically thick section (T_R < 255 K, see Fig. 5) and to be at 10.3 km for the optically thin section (T_R > 255 K), according to averages from Table 4. Also, a case with a cloud top at 8.2 km in the optically thin section has been chosen.

Cloud microphysical information in radiative transfer models is described by the three single-scattering properties: volume extinction coefficient β_{EXT}, single-scattering albedo w₀, and asymmetry factor g. These properties have been derived from particle measurements, which for practical purposes have been converted into size distributions of equivalent spheres, as outlined in the previous chapter. Mie calculations provide the single-scattering properties for these spheres at all 20 model wavelengths using refractive indices for ice (Warren 1984). The assumption of surface area equivalent spheres, however, only guarantees similar extinction. Differences for the other two single-scattering parameters, which describe the scattering behavior, must still be accounted for.

Takano and Liou (1989) calculated accurate results for hexagonal columns using geometrical optics. A comparison to results for spheres (Kinne and Liou 1989) shows that surface equivalent spheres overestimate both the absorption-to-extinction ratio and, especially, the forward scattering. These differences, however, are relatively unimportant for infrared radiative transfer, where absorption effects dominate the scattering. Therefore, reductions to cosine-scattering albedo (1 − w₀) and asymmetry factor g are applied only to calculations at solar wavelengths. These adjustments depend strongly on the particle's aspect ratio. Assuming typical cloud-particle sizes with radii ranging from 50 to 100 μm, the solar cosine-scattering albedos (1 − w₀), calculated for spheres, are reduced to 0.7 of their original value, and the solar asymmetry factors g are reduced by 0.05 to about 0.85. The latter reduction is conservative for the most frequently detected ice-crystal shapes. Small branches are expected to act like small crystals, which, having low aspect ratios, require asymmetry-factor reductions of about 0.1. In addition,
the interaction between the branches and cavities in ice crystals is expected to decrease the forward scattering, suggesting even lower asymmetry factors.

Aside from the uncertainty in the derivation of the single-scattering properties, the particle measurements themselves vary with the inhomogeneity of the cloud field. Except for the period of the descent and a few isolated locations, particle measurements were taken generally at different locations with respect to the cloud field. Thus, the microphysical properties are based on average measurements for a given cloud altitude. Averages are calculated for the optically thin section and the optically thick section of the cloud field separately. Measurement times and altitudes, as well as calculated ice water contents and extinctions, are summarized in Table 6. Unfortunately, no microphysical measurements were available for the upper cloud layers between 8.5 and 11 km.

7. Comparison

Radiative flux profiles are calculated based on the model and its input data, which are explained above. Solar- and infrared-flux measurements from several cloud altitudes are compared to broadband flux calculations. Although the calculations were simplified by assuming spherical cloud particles, the special conversion to spheres and the use of nonspherical corrections, as described above, should allow for an accurate representation of the cloud's radiative properties.

General comparisons for broadband solar and infrared fluxes in both the upward (upper panel) and downward directions (lower panel) are given in Figs. 17 and 18, respectively. Small dots associated with a particular altitude mark all measured flux values taken under straight horizontal flying conditions between 1630 and 1730 UTC. The spread of flux values for a particular cloud altitude along distances of only 30 km proves the inhomogeneity of the cloud field. Curves in Figs. 17 and 18 represent calculated flux profiles for homogeneous clouds (uniform extinction) with the indicated optical depths. The clouds were placed between 6.1 and 10.3 km. The model calculations are based on the particle measurements of Fig. 13. Typical radii of equivalent spheres are about 70 μm, as indicated in Fig. 15. They are large enough to guarantee identical solar and IR optical depths.

Figures 17 and 18 present all flux measurements within the entire cloud field. However, these measurements at different altitudes do not represent an average flux profile. Measurements below 7.3 km occurred in an optically thicker section, while those above that al-
titude occurred in an optically thinner section of the cloud field. Regardless, general comparisons between measurements and calculations at particular altitudes are useful.

In the upper panel of Fig. 17, the measured upward solar fluxes are larger than the modeled values. This indicates that the model assumption of uniform extinction is wrong and that most of the optical depth is concentrated near the cloud base.

The lower panels of Figs. 17 and 18 present measurements of downward fluxes. Flux comparisons at the cloud base, at 6.1 km, suggest similar cloud optical depths for the solar and infrared spectral region. Values between 2 and 7 are indicated, although measurements at 6.4 and 7.0 km suggest even larger optical depths. The modeled downward solar fluxes are too large by as much as 5%, due to lower solar zenith angles during early measurements at the cloud base. The modeled downward infrared fluxes are too small because the largest cloud extinction is concentrated near the cloud base and not uniformly distributed over the entire cloud layer, as in the model. Thus, based on the flux comparison at the cloud base, solar optical depths of about 3–7 are found to be slightly larger than infrared optical depths of about 2–6. This is also reflected by the statistics along the double leg (Table 5).

In contrast, optical depths derived from comparisons along the three highest measurement altitudes are smaller. Infrared downward fluxes indicate the presence of higher clouds with optical depths of about 0.5–1. Adding to that the optical depth of the lower half of the cloud by comparing infrared upward fluxes at the same altitudes, total infrared cloud optical depths are found to vary between 1.5 and 3. Similar values are found from comparison of downward fluxes at the cloud base measured after the spiral descent. All measurements indicating optical depths smaller than 2.5 at the cloud base represent measurements after the descent. These low optical depths, however, are in contrast to large solar upward fluxes at the upper measurement altitudes, which suggest solar optical depths as large as 6.

To better compare the measured and calculated flux profiles, separate comparisons for the two cloud-field sections are performed. The cloud-field area with ER-2 radiative temperatures in excess of 255 K (see Fig. 5) defines the optically thin section; the area with temperatures below 255 K defines the optically thick section of the cloud field.

a. Optically thick section

Only measurements below 7.5 km may be used for the flux comparison in the optically thick section of the cloud field. From particle measurement averages at these altitudes, five size distributions of equivalent spheres have been modeled (see also Table 6). Four of the distributions are presented in Fig. 19. Measurement altitude, calculated extinction coefficient, and ice water content are indicated. The latter two cloud properties are largest at 7.0 km where the dominant particle size is also largest. There, particles with equivalent radii of 90 µm provide the largest surface area, as indicated by the maximum in the dashed shading.

Based on these average-particle-size distributions, flux profiles have been calculated and are indicated by solid lines in Fig. 20 for the solar spectral region and in Fig. 21 for the infrared spectral region. Based on the lidar observations, the cloud was inserted into the model between 6.1 and 10.9 km. In the absence of particle measurements for the upper cloud layers, a uniformly decreasing particle density and extinction from 7.5 km to the cloud top has been assumed. The total cloud optical depth is 3. The solid lines in Fig. 22 reflect the selected profiles for extinction coefficient and ice water content, and present calculated heating rates.

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**FIG. 19.** Average-particle-size distribution of equivalent spheres based on multiple measurements at constant altitude in the optically denser parts of the cloud field (see also Fig. 5). The dashed shading displays the effective surface area per micron in units of square millimeters per cubic meter (mm² m⁻³). Measurement altitude, calculated extinction coefficient, and ice water density are indicated.
a cloud with maximum optical depth. Along the lower altitudes, specific particle measurements are selected that produce the largest extinction. In addition, a large extinction has been assumed for the upper cloud layers. With the increase in total cloud optical depth to 5.3, heating at cloud base and cooling at cloud top approximately doubles.

Flux measurements in Figs. 20 and 21 are indicated by squares. The squares are 30-s averages, or averages over distances of 3 km, at constant cloud altitude. Their shading approximates local extinction, derived from measurements of infrared net fluxes.

The comparison of the solar fluxes in Fig. 20 shows a basic agreement. In general, however, the calculated profile from measurement averages (solid line) underestimates upward solar fluxes and overestimates downward solar fluxes. This may suggest much larger extinctions near the cloud base than the model is able

The dotted lines in Figs. 20–22, in contrast, are based on identical assumptions, except for the addition of small crystals. An artificial 10–25-µm-size bin (for comparison see Fig. 13) has been added with five times the number of ice crystals detected in the 25–50-µm range. These small particles of no preferred dimension have been added to account for the presence of small particles that the instrumentation could not detect. In the presence of many large crystals, the effect on the cloud ice water content is negligible. The difference between the solid and the dotted lines in Figs. 20–22 also indicates that differences in the extinction and flux profiles, and in the heating rates remain small. Differences in the ice-density profile indicate that ice water values nearly double if water density is assumed and the ice cavities in large ice crystals are neglected. In summary, unless a notably larger number of small particles exists, their effects on the overall radiative cloud properties are minor.

The dashed lines in Figs. 20–22 present profiles for

**Fig. 20.** Comparison between measured and calculated hemispheric solar fluxes for the optically denser parts of the cloud field. Squares represent 30-s averages of flux measurements. The square shading indicates infrared extinction (km⁻¹) derived from infrared net flux measurements. Lines represent calculated flux profiles (their ice water and extinction profiles are given in Fig. 22). The solid-line profile is based on the size distributions of Fig. 19 at the lower altitudes and at the assumption of decreasing ice density toward the cloud top. Also shown are calculated flux profiles with small particles added (dotted line), results of a calculation (dashed line) that assumes the largest derived optical depths near the cloud base, and a large, almost constant, ice-particle density toward cloud top.

**Fig. 21.** Same as Fig. 20, but for infrared radiation. For better clarity, enlargements are also given.
the cloud base should be attributed to the modeling procedure (e.g., a "no-branch" assumption for the conversion into equivalent spheres) or to the undetected particles (the instrumentation was unable to detect small ice crystals with lengths below 30 \textmu m, and crystals with lengths below 100 \textmu m are probably undercounted). It is also uncertain if the larger solar differences are caused by the presence of small particles or by an underrepresentation of ice-crystal backscattering properties. Below, some sensitivity studies are presented.

Figure 23 displays the effects on radiative fluxes as different types of particles add an identical solar optical
to reproduce. The use of maximum extinctions (dashed line) substantially improves the agreement; still, maximum solar attenuations near the cloud base are not matched.

The comparison of the infrared fluxes in Fig. 21 shows a less dramatic but similar result. A few measurements agree with the calculated profile from measurement averages, but most of the measurements indicate larger extinctions near the cloud base. However, in contrast to the solar comparison, calculations with the maximum extinction produce a close match with the maximum downward infrared fluxes.

In summary, the calculations based on the measured particle profiles underestimate the cloud extinction near the cloud base. Differences seem to be larger for the solar spectral region than for the infrared spectral region. This is also supported by flux measurements at the cloud-field location where, at 1637 and 1647 UTC, King Air trajectories cross at different cloud altitudes. The attenuation of the downward solar flux from 390 W m\(^{-2}\) at 7.0 km to a value of 270 W m\(^{-2}\) at 6.4 km suggests an average solar extinction coefficient in excess of 2.0 km\(^{-1}\). The 2D imaging probe data, in contrast, suggest values of 0.8 km\(^{-1}\) at 6.4 km and 1.7 km\(^{-1}\) at 7.0 km. Infrared-flux measurements give estimated extinctions of only about 1.0 km\(^{-1}\) at this cloud location.

It is uncertain whether the lack of extinction near

fig. 22. Extinction, ice density, and heating-rate profiles associated with the flux profiles in Figs. 20 and 21. The dotted ice-density profile, in contrast to the solid line, assumes no ice-crystal cavities.

fig. 23. Comparison between measured and calculated hemispheric fluxes near the cloud base in the optically denser parts of the cloud field. Squares represent 10-s averages of flux measurements at constant cloud altitude. The shading of the square indicates the corresponding infrared extinction (km\(^{-1}\)). The solid-line profile, which at the lower cloud altitudes is based on the size distributions of Fig. 19, underestimates measured solar and infrared optical depths. The broken-line profiles result from adding water drops (dashed), ice spheres of the same size as the water drops (dotted), small ice crystals (dash-dot), or large ice crystals (variable dash). In each case, the same total optical depth was added; the vertical profile of extinction is shown in the upper panel. Also indicated are the mean particle radius for each case and the reflected solar radiation at cloud top.
depth of 2.2 near the cloud base in the model. The standard profile without the added optical depth is based on particle measurement averages and is indicated by the solid line. The added optical depth dominates the change in the flux profiles. However, for the solar-flux profile, scattering properties related to particle size and shape are important as well. Both the reduced forward scattering by smaller sizes and the increased backscattering by nonspheres enhance the effect of larger optical depths. Small ice crystals, whose quantity (not to mention presence) is still subject to speculation, produce a particularly large increase in solar reflection and a corresponding decrease in solar transmission. In the infrared, particle-scattering effects are less important. Particle-size effects are only important if maximum particle dimensions drop below 10 μm, in which case infrared optical depths become much smaller than solar optical depths. The presence of ice crystals that small (based on FSSP data) seems unlikely.

Measured fluxes along the lowest two flight altitudes are represented in Fig. 23 by squares. The squares give 10-s averages or averages over horizontal distances of 1 km. Their shading, as before, approximates local extinction. Under the assumption that the downward infrared-flux measurements at cloud base provide an accurate estimate of the cloud optical depth (3–6 for this optically thick section of the cloud field), then effective forward-to-backscattering ratios, or asymmetry factors, may be estimated from the comparison of the solar downward fluxes near the cloud base. Such a comparison suggests asymmetry factors as low as 0.7. In contrast, a value of 0.85 has been used in the model calculations. Also, theoretical values for hexagonal columnar shapes exceed 0.77, based on geometrical optics calculations (Takano and Liou 1989). Such calculations, however, do not consider air cavities and interactions between different branches of the frequently detected shape of a bullet rosette. More single-scattering studies on complex-shaped particles are necessary.

b. Optically thin section

For the flux comparison in the optically thin section of the cloud field, only measurements above 6.8 km may be used. From particle-measurement averages at these altitudes, four size distributions of equivalent spheres have been modeled and are presented in Fig. 24 (see also Table 6). Measurement altitude, calculated extinction coefficient, and ice water content are indicated. Significant extinction occurs only at 7.0 km where cloud properties are almost identical to those observed in the optically thick cloud-field section at the same cloud height.

Using these average-particle-size distributions at their altitudes in a cloud model, flux profiles have been calculated and are indicated by solid lines in Fig. 25 for the solar spectral region, and in Fig. 26 for the infrared spectral region. Based on the lidar observations, the cloud was inserted into the model between 6.1 and 10.3 km. Based on good visibilities of VCR cockpit observations near 8 km, a two-layer cloud has been selected: an optically thicker layer centered near 7.0 km and an optically thinner layer centered near 9.5 km. The total cloud optical depth is 1.8. The solid lines in Fig. 27 reflect the selected profiles for extinction coefficient and ice water content, and also present calculated heating rates.

The dotted lines in Figs. 25–27 present results from a sensitivity study that is identical to that for the dotted lines in Figs. 20–22. Small ice crystals are artificially added to those size distributions defined by the solid line profiles. Although fewer large particles are observed in this optically thin section of the cloud field, their number is sufficiently large to suppress small-particle
Fig. 25. Comparison between measured and calculated hemispheric solar fluxes for optically thinner parts of the cloud field. Squares represent 30-s averages of flux measurements. The shading of the square indicates the corresponding infrared extinction (km⁻¹) derived from infrared net flux measurements. Lines represent calculated flux profiles (corresponding ice water and extinction profiles are given in Fig. 27). The solid-line profile is based on the size distributions of Fig. 24 at the middle and lower cloud altitudes, and the upper cloud is assumed to be a thin cirrus layer. Also shown are calculated flux profiles with small particles added (dotted line) and a profile calculated assuming the smallest derived optical depths (dashed line).

Effects. Deviations of the dotted lines from the solid lines in Figs. 25–27 are small. The large differences for the ice density relate to the effect of neglected ice-crystal cavities, as in Fig. 22.

The dashed lines in Figs. 25–27 present profiles for a cloud with a cloud optical depth. Measurements that yield the smallest extinction at a given altitude have been selected. Lower extinctions in both cloud layers, which are now separated by a cloud-free area, reduce the total cloud optical depth to 1.2.

Flux measurements in Figs. 25 and 26 are indicated by squares. The squares are 30-s averages, or averages over distances of 3 km, at constant cloud altitude. All measurements are taken above 6.8 km, except for a single square at 6.1 km, representing a measurement after the spiral descent. The shading of the squares approximates local extinction, which is derived from measurements of infrared net flux.

The comparison of the solar fluxes in Fig. 25 shows, similar to the comparison in Fig. 20, that the calculated profile (solid line), on average, overestimates downward solar fluxes and more significantly underestimates upward solar fluxes. The large values for the downward solar flux at the higher cloud altitudes probably include

Fig. 26. Same as Fig. 25, but for infrared radiation.

Fig. 27. Extinction, ice density, and heating-rate profiles associated with the flux profiles in Figs. 25 and 26.
contributions from reflections from higher clouds. These high clouds are probably also responsible for the observed variability in the downward infrared fluxes in Fig. 26.

The comparison of the infrared fluxes in Fig. 26 shows a good agreement for the upward fluxes, while the calculated profile (solid line) underestimates downward fluxes. This indicates a small underrepresentation of cloud optical depth in the upper cloud layers by the model.

In summary, the calculations based on the measured particle profiles underestimate the cloud extinction near the cloud top. Differences in the measurements in the solar spectral region indicate an underrepresentation of the backscattering properties in the model and raise the question of whether typical particle sizes are much smaller than 70-μm radius for equivalent spheres indicated by the 2D image measurements.

Due to the cloud-field inhomogeneity, profiles for cloud properties are only accurate if measurements in clouds are taken at different altitudes for the same cloud-field position. Such a situation exists for the spiral descent. This cloud-field area within the optically thin section is highlighted in Fig. 3. The descent from 8.2 to the cloud base at 6.1 km occurred within a 7-min time span in a three-loop spiral. Since the aircraft was drifting with the ambient wind, each loop followed an identical circle with respect to the cloud field. Thus, the comparison of measurements from different loops will provide profiles of cloud properties.

Figure 28 presents size distributions of equivalent spheres from 2D image probe measurements. The conversion follows the procedure outlined in the modeling section. The 2D image data represent 5-s averages of measurements at different altitudes in the southwest, southeast, northeast, and northwest quadrants of the spiral. The calculated ice water contents in Fig. 28 demonstrate an increase from the cloud top to an altitude of 6.5 km, just above the cloud base. Significant in the size distributions is the shift to larger particle sizes with the development of multimodal peaks in the size distribution with decreasing altitude. This effect is particularly well illustrated for the northeast quadrant and is consistent with an in-depth analysis of the particle habits by Heymsfield and Miller (1990). Small columnar ice crystals and compact crystals without ap-

![Figure 28](image-url)

**Fig. 28.** Calculated particle-size distribution for spheres based on the King Air 2D imaging probe data taken at different altitudes in the southwest, southeast, northeast, and northwest sections of the downward spiral. Units for altitude z and ice water density (IWC) are in kilometers (km) and grams per cubic meter (g m⁻³), respectively.
papadage are observed near the cloud top, while compact crystals with branches are detected near the cloud base.

Model calculation for 2-km-thick clouds with the size distributions of Fig. 28 are presented for all four quadrants separately in Figs. 29 and 30. Figure 29 presents flux profiles, and Fig. 30 presents extinction and ice water profiles, and also heating rates. Cloud-column optical depths vary between 1.0 and 1.8. A comparison with measured fluxes is difficult because, due to the continuous aircraft roll, flux measurements during the spiral descent cannot be used without correction. A few data, however, are available for the loop entry at the cloud top and the loop exit at the cloud base in the southwest quadrant of the spiral. The flux comparison in Fig. 29 is limited to upward fluxes, because the measurements of downward fluxes are affected by optical depths above 8.5 km, which are not considered in the model. Since no measurements were made at these altitudes, model assumption would be speculative.

The comparison of the upward infrared fluxes in the lower panel of Fig. 29 indicates good agreement. However, since most of the measurements are taken near the southwest quadrant (dotted line), the comparison again suggests a slight underestimation of infrared cloud optical depth by the model. Measurements for the upward solar fluxes in the upper panel of Fig. 29 are mostly larger than the modeled fluxes and support the misrepresentation of scattering properties at solar wavelengths.

c. Summary

The comparison to measured fluxes indicates that calculated fluxes based on cloud-particle measurements in cirrus underestimate solar reflection, solar attenuation, and the infrared downward flux. From the comparison of infrared fluxes, it is concluded that the model slightly underestimates infrared optical depths. Infrared optical depths are found to be 2–6 for the optically thick section and 1–3 for the optically thin section of the cloud field. In contrast, solar optical depths derived from the comparison of solar downward fluxes are up to 30% larger.

It is not very likely that the larger solar optical depths are due to the size effect of undetected small ice crystals less than 10 μm in size. Large concentrations (>10^6 μm^-1 m^-3) would be necessary. Also, FSSP counts of small particles with maximum dimensions of less than 25 μm are low. The larger solar optical depths probably reflect an incorrect particle scattering behavior in the model. The use of smaller (solar) asymmetry factors,
0.7 instead of 0.85 for the optical-depth retrieval method, can explain the detected optical-depth differences. This theory is supported by the unmatched high solar reflection measurements. Since smaller asymmetry factors are associated with smaller sizes, the importance of small particles remains. Lower asymmetry factors, however, may also originate in the complex shapes of ice crystals. The interaction between ice-crystal branches and the hollowness of ice crystals is believed to reduce forward scattering and, consequently, asymmetry factors.

8. Conclusions

The FIRE cirrus IFO was conducted to increase our understanding of cirrus clouds and to improve cirrus cloud simulations, especially in radiative transfer models. By simultaneously measuring cloud-particle properties and radiative fluxes, it was hoped that the dataset could provide a test of calculated fluxes. In keeping with this objective, data in a single cloud field are analyzed. This dataset included flux and microphysical measurements at seven cloud altitudes, ground-based lidar measurements, and high-altitude lidar and infrared radiometric measurements.

Despite this wealth of data, several problems were encountered that made it difficult to test model calculations against observations:

1) Broadband solar- and infrared-flux measurements, made at different cloud altitudes, suffer from the considerable horizontal inhomogeneity of the cloud field. Since measured flux values at a particular cloud altitude exhibited considerable variability, fine tuning model calculations proved impossible.

2) Because the in-cloud aircraft measurements were made in a fixed pattern relative to the ground while the cloud field advected by, flux measurements could not be combined to construct a meaningful profile.

3) The instrumentation for measuring cloud-particle size was unable to detect small ice crystals.

4) The cloud modeling suffered from the lack of microphysical and flux measurements at high cloud altitudes.

5) A general lack of simultaneous broadband flux measurements above cloud top or below cloud base limits the usefulness of the in-cloud measurements.

6) For cloud-column optical depth larger than two, lidar systems are unable to penetrate the entire cloud layer. In these cases, lidar (cloud structural) information is limited to the nearer cloud boundary.

Since most of these problems are linked to the inhomogeneity of the cloud field, only studies on more homogeneous cirrus cloud cases are likely to improve radiation calculations in current cirrus models. However, such studies will still be hampered by the lack of quality measurements on small ice particles.

To study the interaction between radiation and microphysics, future experiments should ideally accompany in-cloud measurements of fluxes and microphysics to be accompanied by continuous flux (and lidar) measurements above cloud top and below cloud base. These measurements are absolutely crucial for inhomogeneous cloud fields. Simultaneous in-cloud measurements of microphysics and radiation is highly desirable but unlikely to be obtained. Consequently, there will be a time lag between measurements made at different cloud altitudes. Drifting the aircraft with the ambient wind would make these in-cloud measurements much more useful. It also would be desirable to develop radiometers that are less sensitive to atmospheric temperature changes and could compensate for aircraft pitch and roll, and thereby maintain their horizontal alignment. Given such radiometers, spiral ascents and descents through a cloud would provide an excellent tool to determine flux profiles despite cloud inhomogeneities.

The comparison between measured and calculated fluxes in this study has indicated that, based on the measured downward fluxes near the cloud base, the model retrieves larger optical depths for the solar spectral region than for the infrared spectral region. The larger solar optical depths probably reflect an overestimation of forward scattering (or the use of asymmetry factors that are too large) in the model. Since smaller asymmetry factors are associated with smaller sizes, information on small ice crystals is important. In future experiments, an instrument is needed that can detect the concentration of ice crystals with maximum dimensions between 5 and 50 \( \mu \text{m} \).

Lower asymmetry factors may also originate in the complex ice-crystal shapes. Interaction between ice-crystal branches and hollowness of ice crystals is believed to reduce forward scattering and, consequently, asymmetry factors. Quantitative information for these effects is speculative at this point, and more and new experimental (e.g., microwave experiments) and theoretical studies (e.g., geometrical optics) on the scattering properties of ice crystals with branches (e.g., bullet rosettes) and ice crystals with cavities are needed.

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