Aircraft Observations of the Radiative and Microphysical Properties of Stratocumulus and Cumulus Cloud Fields

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ABSTRACT

This paper reports on a series of flights that were conducted off the east coast of Australia through and over stratocumulus and fair-weather cumulus cloud fields. The CSIRO Fokker F-27 research aircraft was used to obtain radiation and in situ cloud microphysical and thermodynamical measurements. Central to the analyses presented in this paper were the measurements obtained by a spectrally scanning visible near-infrared radiometer (SPERAD) which was designed specifically for the experiments reported herein.

Analyses of the data obtained during the flights that are reported in this paper showed that the clouds sampled were warm and mainly maritime in character, with both low droplet concentrations and liquid water contents. The stratiform clouds were shallow, with optical depths of about 10. Despite the lack of cloud vertical development, significant concentrations of large droplets were recorded by the Knollenberg 2D probe. Variance analyses of the cloud optical properties indicated that the sampled cloud layers possessed highly variable volume extinction coefficients with fractional deviations exceeding 0.5 at most levels, whereas the single-scattering albedo and the asymmetry parameter were more uniform along any given level. Variance analyses of the bidirectional reflected radiation from Sc clouds indicated a variability of cloud reflectance on two distinct horizontal scales, which could in turn be related to the scale of the relevant mixing processes. It was also found that the reflected radiances from cumulus clouds were far more anisotropic in character than those reflected from stratocumulus clouds. The spectral variation of cloud reflectance with wavelength also exhibited features that, on the basis of the comparisons reported, could not be fully explained by existing theory.

1. Introduction

It has long been recognized that clouds are one of the most crucial, but least understood, components of the climate system. This basic lack of understanding stems from our inability both to realistically describe the various life cycle processes of clouds and to predict their radiative properties. Incorporation of these processes is crucial in any attempt to model the realistic feedbacks between clouds, radiation and dynamics. Perhaps the greatest difficulty associated with the modeling of these feedbacks is that the fundamental processes that govern cloud production and dissipation occur on a scale smaller than that resolved by large-scale atmospheric climate models.

A process that is likely to play a central role in the evolution of clouds and cloud systems is the interaction of radiation with the atmospheric environment both in and around clouds. This interaction depends on the geometric structure of the cloud in a highly nonlinear manner, and just how important the interaction is in deriving the bulk radiative budget of the cloudy environment is not yet fully understood. As a first step, it seems important to establish the extent to which ensemble average-cloud variables (such as a bulk-averaged liquid water and perhaps some bulk descriptor of cloud shape, for example) are sufficient predictors of the radiative budget of clouds. Because of the complexity of this issue, and the lack of adequate multidimensional radiative transfer theories, observational studies will play an increasingly important role in providing an understanding of the radiative transfer through a randomly fluctuating cloudy medium.

This paper reports on aircraft measurements made during two field experiments and their subsequent interpretation. The experiments attempted to provide some basic information on the structural, microphysical and radiative properties of cumulus and stratocumulus clouds with the intention of obtaining some insight into the complex transfer problems mentioned earlier. The outline of this paper is as follows. Section 2 presents the specific objectives of the experiment and much of the scientific background that provided the original motivation for the study. Section 3 contains a summary of the various parameters observed and the instruments used. Section 4 contains a description of
the aircraft configuration and a summary of the various flights conducted over the period of the experiment. Section 5 presents an analysis of the cloud microphysical and thermodynamic data, followed in section 6 by a discussion of the optical properties of the clouds which are derived from the measured cloud microphysics. In section 7, the resulting analysis of the radiation measurements are discussed, while section 8 includes a study of the spatial variability of reflectance. Section 9 brings together the results obtained from the microphysics and radiation measurements with those derived from a theoretical model. The results and implications of this study are then summarized in section 10.

2. Objectives and background discussion

The overall objective of the experiments discussed in this paper was to provide high-quality radiation and supporting cloud microphysics data which, on analysis, might provide some insight into the following factors:

(i) The spatial variability of cloud reflectivity. The scattering of radiation by clouds is a highly complex and ill-defined function of the geometry of the cloud. The structure and variability of clouds occur on horizontal scales that are much smaller than the resolution of atmospheric circulation models, for example, and, for that matter, occur on a scale smaller than that resolved by modern day or planned meteorological satellite radiometers. The extent to which these smaller-scale radiative transfer processes influence satellite measurements and the specification of domain-averaged radiation budgets in models are issues of paramount importance in atmospheric radiation. Since our current knowledge of the spatial and temporal variations of cloud physical and radiative properties is poor, it seems appropriate to design an experiment which attempts to define spatial variabilities typical of different cloud types.

(ii) The spectral variation of cloud reflectivity. There are a number of reasons why multiwavelength measurements of cloud reflectivity are desirable. For example, it seems possible in principle, but yet to be demonstrated in practice, to utilize the reflection spectra to extract certain microphysical properties of clouds (e.g., Twomey and Seton, 1980; DeVault and Katsaros, 1983). Another reason for making spectral measurements is to study more specifically the amount of solar radiation absorbed in the near-infrared region by clouds. This absorption is important to the energetics of certain clouds (e.g., Nicholls, 1984; Herman and Goody, 1976; Webster and Stephens, 1980; among others), and reported measurements show that solar heating is often as large as the longwave cooling at certain levels in the cloud. The possibility of a systematic difference between the observed and calculated shortwave absorption was mentioned by Stephens et al. (1978), and has been discussed at length since then (Ackerman and Cox, 1981; Wiscombe et al., 1984; Welch et al., 1980; among others). However, the major problem in reconciling this difference is the lack of credibility of the measurements upon which the estimates are based. Measurements of shortwave absorption are difficult to make and hitherto have been obtained by differencing spatially and temporally varying data. Certainly the conclusion that more sophisticated radiometric techniques are required to resolve the absorption issue (e.g., Herman, 1977; King, 1980) is well justified.

(iii) Validation of theory. Quality radiation measurements together with the supporting cloud microphysical data are and will continue to be required to test theories which attempt to solve the radiative transfer equation in spatially inhomogeneous media. While the theory is not as advanced as we would like, definition of the variabilities of the key cloud optical properties (such as volume extinction, single-scatter albedo and the asymmetry factor) will be an important consideration in developing these theories. For example, the theoretical developments of Stephens (1986) employ the spatial variations of these optical properties explicitly, and it is possible to simplify this theory with certain assumptions about the nature of these variations.

(iv) The interpretation of satellite radiances. It is the object of the International Satellite Cloud Climatology Program (ISCCP) to obtain some global index of cloud over a continuous 5-yr period (e.g., Schiffer and Rossow, 1984). The data that are being stored for this task are primarily visible (0.5–0.7 μm) and infrared window radiances (10–12 μm) from which it is hoped to glean relevant cloud information. To this end, it is crucial to test the appropriateness of the various analysis techniques (referred to as algorithms) with independent data. Indeed, this recognition is one of the central motivations for the proposed First ISCCP Regional Experiment (FIRE). Examples of algorithms presently in the literature are the spatial coherence approaches of Coakley and Bretherton (1982), the bispectral techniques described by Platt (1983) and Reynolds and Vonder Haar (1977), and the thresholding method of Rossow et al. (1985), to mention a few. Observations such as those reported in this paper can be employed to validate and clarify certain issues upon which these techniques are based, and therefore are likely to play an important role in the further development of these algorithms.

3. Summary of observations

An observational program was designed with the previously mentioned objectives in mind. The experimental design centered on the use of an airborne platform equipped with radiation and cloud microphysical instrumentation for simultaneous in situ measurements.
of the cloud microphysics, radiative fluxes and spectral radiances. This platform was the CSIRO Fokker F-27 research aircraft which operated at speeds typically between 80–100 m s⁻¹. The aircraft was equipped with new radiation instrumentation as well as a number of other instruments that have been employed previously in similar experiments (e.g., Stephens et al., 1978; Platt, 1976; King et al., 1978). The instruments used are listed in Table 1 and are subsequently discussed in more detail.

The main experiment was conducted in the vicinity of the east coast of Australia during May–June 1984 (hereafter referred to as Phase II). A total of 13 flights were carried out during this phase, mostly over the ocean. Four flights were conducted off Cairns (17°S, 146°E), another eight out of Coffs Harbour (30°S, 153°E) and a single flight was conducted overland east of Sale (38°S, 148°E). With the exception of the latter flight and the few occasions on which measurements were obtained in clouds west of Coffs Harbour overland, the majority of flights were over the Pacific Ocean east of the cited locations. Thus, the data obtained provide a relatively unique opportunity to compare the radiative properties of clouds at three different latitudes and with three different solar elevation angles.

In the year preceding Phase II, a trial experiment was carried out in September 1983 and some data obtained from these flights (we hereafter refer to these measurements as Phase I) are subsequently discussed. Some results have already been described by Stephens and Scott (1985). Changes in the instrumentation were made for Phase II in order to meet the more specific objectives of the experiment. The major change concerned the modification of the spectral radiometer that will be described. Details of these changes have been described elsewhere in Scott and Stephens (1984).

Table 1 also serves as a summary of the observational capabilities of the instrumented aircraft, as well as an outline of the principal data to be used in the following analyses. By way of summarizing the observations, we divide the instrumentation into the following four categories.

a. Radiation

The radiation instrumentation for Phase II consisted of a coupled narrow-field-of-view radiometer and hemispheric field radiometer specially designed for the experiment that spectrally scanned across the visible and near-infrared spectral regions (SPERAD), a narrow-field-of-view infrared radiometer which could be used to measure either upward or downward radiances in the 10–12 µm or 8–13 µm spectral regions, and upward- and downward-viewing Eppley pyranometers and pyrgeometers. The spectral response characteristics of the instruments, the data sampling rates and relevant references describing the technical aspects of the equipment can be found in Table 1.

Because SPERAD was specially designed for the experiments reported in this paper, and because most of the following analyses are based on the data obtained by this instrument, further discussion of the instrument is warranted here although more specific technical information can be found elsewhere (e.g., Scott and Stephens, 1984). The instrument is essentially two radiometers combined in one housing. The optics of each is identical, except for the different circular variable filters used to spectrally filter the radiation entering this instrument. One circular variable filter scans from approximately 0.4 to 1.2 µm and the other from approximately 1.2 to 2.5 µm. The instrument is designed to simultaneously measure the (more or less) unobstructed hemispheric downwelling spectral irradiance $H^d(\lambda)$ observed through diffuse quartz windows, while the vertical upwelling radiation is observed through clear quartz windows and confined to a narrow field of view (approximately 7 mrad). With suitable calibration, the measured reflected radiation represents the vertical upwelling radiance $N^u(\lambda)$. Therefore, the ratio of these two measured quantities in the form

$$R(\mu = 1, \mu_0) = \pi N^u(\lambda)/H^d(\lambda)$$  (1)

defines the bidirectional reflectance quantity where $\mu_0$ is the cosine of the solar zenith angle and $\mu$ the cosine of the zenith angle of measured radiation. This quantity defines an equivalent isotropic albedo of the underlying surface.

Only those measurements of $H^d(\lambda)$ obtained in the clear sky above cloud top are used to define $R$. As a check on the quality of these irradiance measurements, the spectrally integrated and calibrated quantity $\int H^d(\lambda) d\lambda$ was directly compared to the measurements obtained from the upward-looking Eppley pyranometers. Taking into account the slightly different spectral ranges of these two measurements, we found agreement within 0.5% on all occasions.

The radiometers were mounted on the aircraft in such a way that their fields of view were maintained to within a tolerance of 1–2 deg from zenith and nadir when the aircraft was level in flight. The natural pitch and roll of the aircraft, which was also recorded in flight, added an additional uncertainty of the order of 2–4 deg. Thus, the orientation of the fields-of-view of the instruments was generally maintained within 5 deg from the vertical and represents an approximate 6% uncertainty in downwelling solar flux for the solar zenith angles of 40°.

Specification of the response time of the instrument was also critical to the instrument design. One of the principal objectives of the experiment was to provide measurements of cloud and surface reflectances from an airborne platform moving at speeds of about 100 m s⁻¹ at a rate capable of resolving the dominant (horizontal) spatial scales of reflectances. Since there were no a priori estimates of these scales and since they were
TABLE 1. A summary of the observational capabilities of the CSIRO research aircraft as employed for Phase II.

1. Radiation equipment

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Time constant</th>
<th>Sampling rate</th>
<th>Wavelength response</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spectrally scanning radiometer NADIR (SPERAD)</td>
<td>&lt;100 Hz</td>
<td>Ten spectra of 72 data points each second</td>
<td>0.4 μm &lt; λ &lt; 2.5 μm</td>
<td>Continuously scanning fast response radiometer with a narrow (approximately 20 nm) bandwidth and narrow field of view (~7 mrad) in the nadir and hemispheric field of view in the zenith. An early version of this radiometer (with a response 0.4 μm &lt; λ &lt; 1.2 μm) is described in Stephens and Scott (1984).</td>
</tr>
<tr>
<td>Infrared radiometer*</td>
<td>~5 sec</td>
<td>~3½ s</td>
<td>10 μm &lt; λ &lt; 12 μm</td>
<td>Narrow field of view (~10 mrad) fixed in the nadir direction (refer Platt, 1971).</td>
</tr>
<tr>
<td>Eppley pyranometer (model PSP)</td>
<td>~1</td>
<td>~10 s⁻¹</td>
<td>0.285 μm &lt; λ &lt; 2.8 μm</td>
<td>Upward and downward-looking with hemispheric fields of views. Both sets of instruments were precision radiometers.</td>
</tr>
<tr>
<td>Pyrogeometer (PIR)</td>
<td>~2</td>
<td>10 s⁻¹</td>
<td>4 μm &lt; λ &lt; 50 μm</td>
<td>200-line resolution over ~60 degree field of view. Data recorded on standard VHS format.</td>
</tr>
<tr>
<td>Video camera</td>
<td></td>
<td></td>
<td>Visible</td>
<td></td>
</tr>
</tbody>
</table>

2. Cloud microphysics

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Particle size range (r)</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>FSSP</td>
<td>2 &lt; r &lt; 47 μm</td>
<td>Knollenberg (1981)</td>
</tr>
<tr>
<td>OAP 300Y</td>
<td>300 &lt; r &lt; 4500 μm</td>
<td></td>
</tr>
<tr>
<td>2D probe</td>
<td>25 &lt; r &lt; 800 μm</td>
<td></td>
</tr>
</tbody>
</table>

3. Thermodynamics†

<table>
<thead>
<tr>
<th>Variable</th>
<th>Instrument</th>
<th>Response</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cloud liquid water</td>
<td>CSIRO King hot wire</td>
<td>~100 Hz</td>
<td>King et al (1978)</td>
</tr>
<tr>
<td>Dry bulb temperature</td>
<td></td>
<td></td>
<td>Reverse flow thermometer</td>
</tr>
<tr>
<td>Dewpoint temperature</td>
<td>Rosemount</td>
<td>~1 s</td>
<td></td>
</tr>
<tr>
<td>Atmospheric pressure</td>
<td>Rosemount</td>
<td>~1 s</td>
<td></td>
</tr>
<tr>
<td>Aircraft air speed</td>
<td>Pitostatic tube</td>
<td>~10 s⁻¹</td>
<td></td>
</tr>
</tbody>
</table>

4. Other variables*          

<table>
<thead>
<tr>
<th>Variable</th>
<th>Sampling rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ground speed</td>
<td>10 s⁻¹</td>
</tr>
<tr>
<td>Pitch angle</td>
<td>10 s⁻¹</td>
</tr>
<tr>
<td>Roll angle</td>
<td>10 s⁻¹</td>
</tr>
<tr>
<td>Drift angle</td>
<td>10 s⁻¹</td>
</tr>
<tr>
<td>Magnetic reading</td>
<td>10 s⁻¹</td>
</tr>
<tr>
<td>Position latitude</td>
<td>10 s⁻¹</td>
</tr>
<tr>
<td>Position longitude</td>
<td>10 s⁻¹</td>
</tr>
<tr>
<td>True heading</td>
<td>10 s⁻¹</td>
</tr>
<tr>
<td>Inertial altitude</td>
<td>10 s⁻¹</td>
</tr>
<tr>
<td>Vertical acceleration</td>
<td>10 s⁻¹</td>
</tr>
<tr>
<td>Wind angle</td>
<td>10 s⁻¹</td>
</tr>
<tr>
<td>Wind speed</td>
<td>10 s⁻¹</td>
</tr>
</tbody>
</table>

*(Recorded from Inertial Navigation System)
† These measurements are also supplemented by the operational radiosonde data obtained from the nearest Australian Bureau of Meteorology site.

likely to vary from one cloud type to another, data were recorded at the fastest possible rate given the compromise between a fast instrument response and the practical aspects of data management. The level of compromise reached is summarized in Table 1. A sampling rate of 10 s⁻¹ was chosen for Phase II, which represents the rate at which a single spectrum (i.e., 72 individual measurements from 0.4 to 2.5 μm) was re-
corded and translates into approximately one reflectance spectrum every 8 m along the flight track.

The remaining instrumentation has been described at length in a number of different publications. The narrow-beam 10–12 μm wavelength infrared radiometer is a compact version of the instrument originally described by Platt (1971) and used previously in an aircraft by Paltridge and Platt (1981). Solar irradiances were measured by Eppler Precision Spectral Pyranometers, which had a response time of about 1 s and were compensated internally for temperature fluctuations during flight, leading to an uncertainty in calibration of only about 1% over the temperature range of operation. Longwave irradiances were measured by Eppler precision pyrgeometers which were similarly internally compensated for temperature.

b. Cloud microphysics measurements

Included in the standard suite of cloud physics probes were the FSSP cloud droplet spectrometer, an OAP-2D-C particle imager (2D probe) and an OAP-300-Y precipitation spectrometer. While the sampling rate of these instruments was of the order of 10 Hz, the data to be described are 1-s averages. The particle size ranges relevant to each instrument are summarized in Table 1.

c. Thermodynamic variables

Wet- and dry-bulb free air temperatures were measured by reverse flow Rosemount thermometers. A CSIRO liquid water hot wire probe (King et al., 1978) was also mounted on the aircraft. The calibration of this instrument was somewhat involved (e.g., see King et al., 1978) and its absolute accuracy was around 0.5 g m⁻³. Aircraft speed and atmospheric pressure were obtained using standard Prandtl design pitot-static tubes (Goldstein, 1965), and when calibrated against a laboratory standard, the aircraft speed was found to be within 0.5%.

d. Ancillary data

In addition to the previously described measured quantities, parameters obtained from the inertial navigation system were also recorded. These data are not presented below and were indirectly used by way of support of the analyses.

4. Aircraft configuration and flight procedures

All instruments were mounted on the CSIRO F-27 research aircraft. The aircraft had been modified to take strut-mounted instruments at 10 hard point locations around the fuselage 0.8 m ahead of the propeller line (Fig. 1). For Phase II, the three Knollenberg probes (FSSP, OAP-2D-C and the OAP-300-Y) were mounted in locations D, C and G, respectively and all were mounted 45 cm from the fuselage, as shown schematically in Fig. 1. The hot wire instrument was also mounted at the end of a small strut and was located at position E. While the distance of this probe from the fuselage could vary, the probe was fixed at 45 cm during Phase II, thus minimizing fuselage-related flow distortions (King, 1984).

The upward-viewing Eppler radiometers and SPERAD were similarly mounted at the end of a strut and fixed at the anchor points X and Y, respectively. During Phase I, a vertically downward-viewing narrow beam infrared radiometer was mounted in the bombay located in the belly of the aircraft some 2.2 m behind the propeller line. For Phase II, a different version of this instrument was relocated in the aircraft and replaced by the downward-viewing Eppler radiometers and a video camera. The new IR radiometer was constructed for Phase II and mounted inside the aircraft 0.5 m in front of the propeller line with a mirror protruding through a window pressure seal so that the radiometer could look either vertically upwards or downwards. In the former case, the downward-measured radiance (10–12-μm wavelength) was effectively zero at altitudes of approximately 15,000 ft, thus providing a calibration for the detected signal, which was chopped against a 40°C blackbody.

Power supplies and the data acquisition systems were located in racks inside the aircraft. All data were written directly to magnetic tape in a format fully compatible with ANSI specifications. The duration of each flight was typically 3 h and all data for such a period could be stored on two magnetic tapes.

The flight patterns used in the field experiments varied according to the type of experiment being conducted at the time. Schematics of the two main flight patterns used for the fair weather cumulus experiments are depicted in Figs. 2a and b. Pattern A involved sampling within and around individual and reasonably
isolated clouds. Typically, three or four in-cloud passes were possible within the most stable of these clouds. A total sampling time from base to top was about 10 min. Data were only obtained for a relatively small number of individual cases, since the majority of clouds were far too unstable and often broke up during sampling.

Figure 2b shows a plan view of flight pattern B. This flight pattern was adopted for cloud field studies and involved a series of straight and level traverses at a
fixed altitude. The flight plan was designed to sample in an approximate 8 km × 8 km grid, which was repeated at selected and random levels in order to provide vertical profiles of the radiative, microphysical and thermodynamic properties of that particular volume of the atmosphere.

The flight patterns employed over and within stratocumulus clouds were more conventional, and were similar to those described by Stephens et al. (1978) and others (e.g., Slingo et al., 1982; Noonkester, 1984). The measurements recorded in these clouds apply to horizontal flight paths approximately 16 km long, typically at five selected collocated depths.

Table 2 identifies the different experiments conducted during each flight of Phase II and the cloud conditions encountered during the flights. In the following discussion, the different experiments are referred to by the flight number listed in this table. In addition to these flights, data from a few flights of Phase I are also presented.

5. Characteristics of the cloud microphysics and thermodynamic properties

The following analyses are presented to illustrate the typical microphysical and thermodynamic properties of the clouds sampled during the experiments. The majority of the experiments were conducted in maritime fair weather cumulus and stratocumulus clouds east of Coffs Harbour and in trade wind cumulus east of Cairns, with an occasional experiment conducted in clouds that formed in more continental air mass conditions west of Coffs Harbour. Because of the similarity in the measurements within like cloud types, and because the measurements in cumulus clouds were sporadic by nature owing to the difficulty in obtaining profiles through these clouds, we have separately composited all the in-cloud measurements obtained from the flights out of Cairns and refer to them as trade wind Cu. Similarly, all the measurements in cumulus clouds over the ocean east of Coffs Harbour have been grouped and are referred to as fair weather Cu. The measurements obtained in the Sc clouds are described individually for each flight.

Figures 3 and 4 show vertical profiles of various cloud properties for the two composited data sets identified above. Shown are the profiles of cloud liquid water content (LWC) measured directly by the King hot wire probe (open histogram) and determined separately by integrating the particle spectrometer data (shaded), the FSSP-derived total droplet concentrations \( N_0 = N_0 \) cm\(^{-2}\) and the effective radius of the distribution \( r_e \) defined as

\[
r_e = \frac{\int_0^{\infty} n(r)r^2 dr}{\int_0^{\infty} n(r)r^2 dr}
\]

where \( n(r) \) is the size distribution measured by the FSSP spectrometer. Also included in these diagrams are the profiles of total concentration \( N_{2D} \) no. \( L^{-1} \) obtained from the 2D probe (which is a measure of the concentration of large droplets) and the environmental temperature profile.

From these analyses, we categorize the trade-wind Cu clouds as typically warm, maritime small Cu with low concentrations of droplets (around 40–50 cm\(^{-2}\)), effective radii varying from around 4 \( \mu \)m at cloud base to in excess of 10 \( \mu \)m at cloud top, and liquid water contents that, on average, are less than 0.3 g m\(^{-3}\). We also note that the concentration of droplets decreases with increasing altitude while the droplet size shows the reverse trend. The decrease in the concentration of the smaller droplets in the upper levels of the cloud is consistent with the occurrence of droplet growth by coalescence and with the measured profiles of droplet concentration obtained by the 2D spectrometer. This, in turn, is consistent with the observation that these clouds sometimes precipitated despite their relative shallowness.

Figure 4 shows the composite of the profiles of LWC, \( N_0 \) (FSSP), \( r_e \), \( N_{2D} \) and environmental temperature measured in the fair weather Cu over the Pacific east of Coffs Harbour. These cloud properties are not as well characterized as those for trade-wind Cu. In general, the measurements obtained were in warm clouds containing less liquid water than for the clouds of Fig.
Fig. 3. Vertical profiles of liquid water content (LWC), FSSP-determined droplet concentration \( N_0 \) (FSSP), the effective radius \( r_e \), droplet concentration from the 2D probe and temperature for clouds sampled east of Cairns. Cloud measurements and composites of all in-cloud samples. The two profiles of LWC apply to the measurements of the hot wire probe (shaded) and the LWC obtained by integrating the FSSP data.

Fig. 4. As in Fig. 3, but for fair weather cumulus sampled east of Coffs Harbour.
3. The clouds sampled near Coffs Harbour were also shallower, but contained greater concentrations of droplets (as measured by the FSSP spectrometer) of generally smaller droplets ($r_e$'s varied typically from 6 to 8 $\mu$m). The greater variability in these measurements is a direct result of the airmass influence on the clouds sampled on different days, despite the fact that the clouds formed over the Pacific. Study of the droplet concentrations for individual flights showed that these concentrations varied from typical maritime values of around 40 cm$^{-3}$ on certain days to in excess of 200 cm$^{-3}$ on others.

In order to accentuate the variability in the measurements of cloud LWC, a scatter diagram of spot measurements of the hot wire liquid water content is presented in Fig. 5. This diagram presents LWC as a function of altitude and highlights some of the potential difficulties in using the hot wire probe. Although the instrument was carefully calibrated in flight according to the procedure discussed by King et al. (1978), a zero offset occurred in the data that varied with altitude (a result of a temperature effect in the calibration). This offset, accentuated by the dashed line in Fig. 5, was removed in the subsequent analyses.

If we compare the FSSP-derived LWCs to those obtained by the hotwire device, we notice apparent systematic differences between the two. Such differences have been reported before (e.g., Slingo et al., 1982; Stephens et al., 1978) and are often used to correct or renormalize the FSSP measurements. For this study, we have chosen not to do this type of adjustment to the FSSP data as we could not discount the possibility of contributions by droplets larger than those sampled by the probe to the total LWC. Indeed the measurements shown in Fig. 3 and in the diagrams to follow strongly support the contention that the FSSP probe did not sample all droplets.

Figures 6a, b and c show similar data obtained in three individual Sc cloud decks sampled during the Phase II experiment. The open points (and cross points for the FSSP-derived LWC) represent an average over the level flight path at the altitudes specified. The extent of the bars attached to each point represents the magnitude of the standard deviation $\sigma_x$ of the associated parameter $x$. The mean microphysical characteristics of the Sc clouds are much the same as those reported from earlier experiments (Platt, 1976; Paltridge, 1974; Stephens et al., 1978) and similar to those sampled over the North Sea and reported by Slingo et al. (1982).

The cloud layers sampled during flights 3 and 4 were warm-based maritime clouds with low liquid water contents, low concentrations of small droplets, effective radii that increased systematically from cloud base, and detectable concentrations of droplets of radii in excess of 50 $\mu$m. The cloud sampled during flight 1 was more continental in character, with larger droplet concentrations and smaller drop size.

A notable feature of these clouds is the large variability of the microphysical properties measured at all in-cloud flight levels. In order to accentuate this feature, we introduce the fractional deviation ratio $\sigma_{nx}$ as a measure of the horizontal variability of the given parameter $x$. This ratio is portrayed in Fig. 7 as a function of altitude for FSSP droplet concentration $N_0$ (FSSP), the FSSP-derived LWC and $r_e$. The results indicate that the sampled cloud layers possess highly variable LWCs and droplet concentrations with fractional deviations exceeding 0.5 at most levels, whereas the effective size of the droplets is more uniform along any given level. Such results are consistent with those obtained by Platt (1976) and agree with the homogeneous mixing theory of Corbin et al. (1977). Vertical turbulent mixing is probably the reason for this variability and, as we shall see later, this mixing seems to occur on preferred horizontal scales. It is somewhat surprising, however, that the variance of droplet concentration and LWC is large throughout the entire cloud layer and not confined to the upper and lower cloud boundaries.

6. Cloud optical properties

The volume extinction coefficient $\alpha$, single-scatter albedo $\omega_0$, and asymmetry parameter $\langle \cos \theta \rangle$ were calculated from Mie theory using the FSSP size distributions and are shown here for a wavelength of 1.29 $\mu$m. The value of refractive index used in the calculations reported here is listed in the caption of Fig. 8. The wavelength chosen for analysis occurs in the wings of overlapping H$_2$O vapor band and liquid water bands. The contribution by vapor absorption is not included in the results discussed in this section, but is included.
Fig. 6a. Average vertical profile of LWC, $N_0$ (FSSP) and $r_e$ from measurements in a Sc cloud deck. The extent of the horizontal bars represent the standard deviation of the associated parameter at the given flight level.

Fig. 6b. As in Fig. 6a for the Sc deck of flight 03 with the FSSP derived liquid water (cross points and skewed deviations) and the 2D probe measured concentrations also shown.
in the theoretical simulations described in section 9. Volume extinction (excluding vapor absorption) and asymmetry parameter for cloud droplets do not vary appreciably within the wavelength range of SPERAD (e.g., Stephens, 1984), whereas the single-scatter albedo varies significantly over these wavelengths. We choose 1.29 μm in this analysis, as this corresponds to a weak-to-moderate absorption region of the water droplet absorption spectrum, and the value of single-scatter albedo at this wavelength is roughly typical of the spectrally averaged value which would be obtained by integrating over the wavelength range of SPERAD.

The results of the analysis of the cloud optical properties are presented in a manner analogous to the presentation of the cloud microphysics data discussed previously. Figures 8 and 9 show vertical profiles of
Fig. 8. The vertical profiles of the 1.29 μm volume extinction coefficient, single-scatter albedo and asymmetry parameter as derived from Mie theory using the PSSP size distributions and a refractive index of $1.291 - i 1.266 \times 10^{-4}$. These profiles are composite averages of all measurements made in trade wind cumulus.

Fig. 9. As in Fig. 8, but for measurements in fair weather cumulus.
the three optical properties as derived from the FSSP data, and were composited from in-cloud measurements made in trade-wind cumulus and fair-weather cumulus. From these figures we derive, for example, an estimate of the average optical thickness of the clouds represented by the composite dataset. This value is $\tau \approx 25$ for both trade wind cumulus and fair weather cumulus.

The same analysis was performed using the FSSP data obtained for the three Sc cases reported in Figs. 6a, b and c. The results for volume extinction, and $\langle \cos \theta \rangle$ are shown in Figs. 10a, b, and c as averaged vertical profiles of these properties. We also include the standard deviation associated with each of these parameters. The volume extinction coefficient generally increases from cloud base to some point in the upper part of the cloud and then decreases to cloud top. (This overall trend is also apparent in the composite analysis shown in Figs. 8 and 9.) The cloud droplet absorption, defined by $1 - \omega_0$, tends to show a systematic increase from cloud base and can be directly related to the similar increase of $r_e$ from cloud base. The asymmetry parameter, in contrast to the other optical properties illustrated in Figs. 8–10, is fairly invariant both with horizontal and vertical position.

Comparison of the volume extinction and droplet absorption fraction $(1 - \omega_0)$ between the stratocumulus cloud of flight 01 and the later flights show interesting differences. The Sc cloud of flight 01 could be characterized as forming in continental air mass conditions with droplet concentrations around 100 cm$^{-3}$ and effective radii varying from 7–11 $\mu$m. The average optical thickness deduced for this cloud according to Fig. 10a is $\tau \approx 10$. The results of the cloud layers shown in Figs. 6b and c indicate lower droplet concentrations with some evidence of slightly larger droplet sizes. The optical thicknesses of these clouds were deduced to be $\tau \approx 6$ and $\tau \approx 5$, respectively. Comparison of $1 - \omega_0$ also reveals the cloud layer sampled during flight 01 to be less absorbing due to the generally smaller droplets, despite their higher concentrations.

Figure 11 presents the fractional deviations of the volume extinction coefficient, single-scattering albedo and asymmetry parameter. The fractional deviations were determined from the means and standard deviations of the optical properties derived for Sc clouds which were illustrated in Figs. 10a, b and c. In general, volume extinction shows the greatest variability within the clouds and is related to the variability of $N_0$. The variability of the single-scatter albedo is somewhat less and similar to that of $r_e$ (refer to Fig. 7). As expected, the scattering asymmetry parameter showed little variability within the cloud.

7. Analyses of the radiation measurements
   a. Directional reflectance spectra

Figure 12 is a graphic example of the raw (uncalibrated) voltage output from SPERAD. The diagram shows the voltage trace for radiation reflected by cumulus and stratocumulus clouds. This signal is depicted as the voltage ($V_\lambda$) on the diagram. The downwelling irradiance is represented by the voltage ($V_\phi$) and was recorded approximately every 3.5 sec and thus appears as spikes on the diagram.

If we take the measurements of $V_\lambda$ for flight levels in the clear sky above the cloud and average these measurements along the flight level, we can derive the downward solar irradiance spectrum at that level. An example of such a spectrum, averaged over several minutes of data (about 300 scans) is shown in Fig. 13 (lower panel) with the extraterrestrial solar flux data (taken from Thekackara and Drummond, 1971) graphed in the upper panel for reference. We also highlight the principal molecular absorption features on the measured spectra.

Figures 14a, b, and c present examples of the bidirectional reflectance spectra as defined by (1). The spectra are averages along the flight levels at the specified altitudes through the Sc decks whose other properties were discussed in relation to Figs. 6a, b and c. Thus, each of the spectra shown in these diagrams are an average of approximately 5 min of data (and thus about 3000 individual spectra) obtained along the appropriate flight level. Also included on Fig. 14a are the positions of the various molecular absorption bands.

The shapes of these reflectance spectra are qualitatively similar to the theoretical spectra calculated by Wiscombe et al. (1984) and Davies et al. (1984), although there are notable differences, which will be highlighted. It is also relevant to consider the magnitude and variability of these measured reflectances in comparison to the hemispheric flux measurements obtained from the Eppley pyranometers. The reflectances of Fig. 14 can be interpreted as equivalent isotropic cloud albedos. These albedos vary from around 60% at the shorter wavelengths for the thicker cloud of flight 01 (Fig. 14a) to less than 25% for the very thin cloud of flight 04 (Fig. 14c). Comparison with the theoretical calculations indicated that these isotropic reflectances at any given wavelength were similar in magnitude to the hemispheric albedos at the same wavelength for stratiform clouds (refer Fig. 22). However, this is not the case for Cu clouds for which the equivalent isotropic albedo was often found to exceed unity by a substantial amount, especially at the shorter wavelengths. This aspect can be appreciated by comparing the reflectance spectra for Cu shown in Fig. 15 to those of Fig. 14. The measurements shown in Fig. 15 represent an average for three different cumulus clouds at three dif-

1 One of the reviewers of this paper pointed out that there may be some ambiguity in the Thekackara and Drummond data for the near-IR spectral region. These data are used here only as a reference to the measurements. Perhaps a better source of data in the near-infrared wavelengths is that of Labs and Neckel (1968, 1981).
Fig. 10a, b, c. Averaged vertical profiles of the 1.29 \(\mu\)m cloud optical properties reported in Fig. 8 through the three Sc cloud layers identified by the flight numbers. The extent of the horizontal bars represent the standard deviation of the associated parameter.

different locations indicated on the diagram, and thus three different solar zenith angles. In contrast, the hemispheric albedo measured over the Sc are larger than those measured over Cu (refer Figs. 17a and b). This observation is expected and has been discussed in the theoretical context by a number of authors (e.g., McKee and Cox, 1974; Davies, 1978; Stephens and Preisendorfer, 1984, among others). Therefore, the measurements suggest that the radiance fields around cumulus clouds are much more anisotropic in character.
Fig. 10. (Continued)

Fig. 11. Vertical profiles of the fractional deviation of the three optical properties illustrated in Figs. 8, 9 and 10 for the three identified Sc cloud layers.
than the radiance fields reflected from stratiform clouds.

b. Comparison of hemispheric and narrow beam reflectances

Figure 16 shows a time series of the 0.59-μm reflectance measured by SPERAD, and the hemispheric albedo measured by the Eppley pyranometer for the flight level just above the Sc cloud layer of flight 04. The first feature apparent from this comparison is the trace of the hemispheric albedo is smoother and less structured than the comparative trace of the directional reflectance. This is partly a result of the slower response time of the pyranometers, but is mainly due to the hemispheric field of view of the instrument which acts to integrate over and thus smooth out the variations that would be otherwise detected by a narrow-field-of-view radiometer. The second significant feature is the large variability in both the hemispheric albedo and directional reflectance along the given flight level. Clearly, the notion of radiometric homogeneity in the horizontal is not valid.

Figures 17a and b present similar comparisons for cumulus clouds, which were sampled during flight 10. These comparisons show that it is not possible to determine the associated structure of these clouds in detail using pyranometer data alone. For example, it is not possible to detect the presence of two of the clouds which are quite apparent in the narrow-field-of-view radiometer data, nor is it possible to conclude that the measurements of Fig. 17a apply to an ensemble of multicelled clouds. From a closer examination of Fig. 17b, we also detect the effects of the anisotropic nature of the reflection by these clouds from the Eppley measurements. The flight path relevant to the measurements shown in Fig. 17b was such that the aircraft flew across and just above the clouds from its solar to antisolr side. The illuminated side of the cloud contributed significantly to the hemispheric albedo even prior to the aircraft overflying the cloud.

In order to emphasize the variability of the reflectance measured across the tops of these clouds, the reflection spectra corresponding to those points along the path which are numbered 1, 2, and 3 on Fig. 17b are shown in Fig. 18. This figure adequately illustrates
the large variability in the reflectance across the tops of clouds and also highlights the large values of reflectance detected above the center of the cloud which exceed any values measured over the stratiform clouds.

We have also used the reflection data, such as those shown in the bottom half of Figs. 17a and b, as a means of estimating a cloud-cover factor for the straight and level flight path above the cumulus clouds over the sea.

Fig. 13. Example of the calibrated downwelling solar radiance spectrum measured in the clear sky above cloud (bottom curve) at an altitude of approximately 2 km and averaged over some 300 scans. Also shown on this curve are identifiable molecular absorption features. The upper curve for reference is the data of Thakaekara and Drummond (1971) representing the solar irradiance at the top of the atmosphere.
This factor was derived from a reflected-radiance threshold criteria. This criteria simply amounted to defining cloud whenever the detected signal exceeded the background clear-sky signal. It was a simple task to unambiguously define this background signal. The lower panel of Fig. 17a shows a typical example for which a background reflectance of 0.05 was assumed. The hemispheric albedo deduced from the Eppley pyradiator measurements and averaged along the given flight path is shown in Fig. 19 as a function of the onedimensional cloud-cover factor. The measured albedos group as an approximate linear function of the cloud-
cover factor, perhaps with some indication of a solar zenith angle effect. Harshvardhan (1982) and Schmetz (1984) predicted a parabolic relationship between albedo and areal cloud cover from modeling studies. Although the scatter in the data precludes any accurate comparison, the results shown in Fig. 19 are not inconsistent with these modeling studies.

c. Correlation of visible and infrared radiances: bispectral relationships

In this section we present two-dimensional histograms which relate the measured reflectances at 0.59 μm to the measured 10–12 μm radiances. Such diagrams have been previously described in relation to
satellite data (e.g., Platt, 1983) where the resolution is quite different and of the order of several kilometers. Three examples of these diagrams obtained from the aircraft measurements are shown in Figs. 20a, b, and c for a Sc cloud layer (Fig. 20a) and ensembles of fair weather Cu over land (Fig. 20b) and sea (Fig. 20c). The points clustered on each diagram represent individual instantaneous measurements at some point along the given flight track.

There are two principal effects that influence the overall relationship between visible and infrared radiances. First, for a field of view completely filled by cloud any change in cloud optical properties (ostensibly cloud optical depth) systematically alters the radiances in a more or less predictable way (at least for stratiform clouds where cloud top temperature is reasonable uniform). Second, a change in the area covered by cloud within the field of view of the instrument also changes the relationship between the radiances but in a different and hopefully predictable way provided the optical depth stays constant. Platt (1983) used a simple physical model to demonstrate that these two effects were separable in radiances diagrams such as those presented in Fig. 20, and suggested that any combination of the two effects could also be identified.

Because of the narrow field of view of both radiometers, the relationships shown in Figs. 20a, b and c are primarily a result of optical thickness or temperature variations. For the Sc cloud, the relationship between visible reflectance and infrared radiances (represented on the diagram as a brightness temperature) is one that Platt (1983) predicted from theory for a range of optical thicknesses. What is perhaps unexpected is the extent to which the cloud optical thickness varies. The fact that the points stretch out along an inverted J-shape clearly indicates that the cloud is far from horizontally uniform, as the points for a uniform cloud would cluster around a single region on such a diagram. It is interesting, but not surprising, that the J-shape is evident on the present horizontal scale of measurements as well as on the scales of satellite data (Platt, 1983).

The results for the Cu fields do not agree with the simple theory of Platt (1983) for a stratiform cloud. The radiances in Fig. 20b are clearly affected by the variability in surface temperatures and albedos, although the radiances through the Sc over land would be similarly affected. The Cu case over sea in Fig. 20c is more directly comparable with the Sc case shown in Fig. 20a. However, the shape of the histogram is still different to that of Fig. 20a, with the J-shape being completely absent. There are several possible reasons for the above differences. First, the emitting temperature from the top of a cumulus cloud varies significantly as an aircraft transits over the cloud. The reflected solar radiance will also vary somewhat differently, although it can also be expected to decrease as the cloud thickness decreases and the emitting temperature increases toward the cloud edges. The reflecting properties of a geometrically finite cloud will also ensure an inhomogeneous situation across the cumulus cloud with different levels of reflection on the solar and antisolar sides. Another reason for the confused 2D histogram is, in part, due to instrumental factors. The IR radiometer time constant is 5 s, which is considerably greater than that of SPERAD (see Table 1), with a consequent lag in the IR radiance. Despite this, it is clear that a more complex model is required to account for the 2D patterns over cumulus, taking the cloud inhomogeneity into full account.

8. Spatial variability of reflectance and scale analysis

The dominant spatial scales of reflectance measured over the Sc cloud layers during the flights listed in Table 2 were analyzed from the time series of directional reflectance, of which a typical example was shown in Fig.
16 (lower trace). Figures 21a and b show two examples of the analyses for two flights during Phase I over Sc clouds. In the left panels of each of these diagrams are the time series of the 0.59 μm spectral reflectance R. The power spectrum p(f) of R' (with R' being the deviation of the reflectance from the mean, i.e., R = R + R') associated with these time series is presented in the form of p(f)/R versus frequency f. The results illustrated in Fig. 21 were typical for all measurements over Sc clouds. For example, two predominant peaks occurred in all cases with horizontal scales of approximately 0.5 to 1 km and 3 km, respectively. The former scale is readily identifiable with the approximate vertical extent of the cloud layers in question, while the larger horizontal scale is commensurate with the depth of the entire mixed layer itself. From the plot of the quantity p(f)/R versus frequency, we can assess the contribution of those scales that contribute most to the total explained variance in the cloud reflectance. From Figs. 21a and b it is evident that the majority of the measured variability in the reflectances measured over these Sc clouds typically resides in the two preferred scales previously identified.

9. Comparison with theory

In this section we compare the spectral reflectance measurements obtained for Sc clouds with the reflectance spectra calculated from theory. The theoretical calculations use the measured size distributions, averaged along a given straight and level path. These distributions were incorporated into Mie calculations to provide a necessary single-scatter input to the theoretical multiple-scatter model. No attempt was made to correct the FSSP measurements (as discussed previously in relation to Figs. 3 and 4), nor was any attempt made to incorporate any large drop tail to the distribution, even though on some occasions significant concentrations of large droplets were detected. Inclusion of the large droplets would tend to decrease the cloud reflectivity by more or less the same amount at all wavelengths (Wiscombe et al., 1984).

Before we present the comparisons, a number of features relevant to the model require brief mention.
a. The multiple scattering model

The basic multiple scattering model employed for the comparisons is similar to that described elsewhere (e.g., Stephens, 1978) but with the following notable changes:

(i) Twenty-two (22) spectral bands were chosen to span the interval from 0.7 to 2.5 μm. These intervals were chosen, more or less, to match the specific wavelengths of SPERAD and are summarized in Table 3. The emphasis on the comparisons between theory and observation is thus placed on the near-infrared spectral region.

(ii) Water vapor absorption was incorporated in the model by the exponential fitting algorithm developed by Wiscombe and Evans (1977). The absorption data fitted by this approach for the given intervals were taken from LOTRAN 5. The number of terms used to fit these data are also included in Table 3 for each interval. No other molecular-absorbing species were included although there are some weak CO₂ bands in the spectral region of interest. The water vapor path in the cloud was determined assuming water saturation at the measured temperature. The path was then linearly scaled by pressure to account (crudely) for pressure effects on the molecular absorption.

(iii) The flux incident on the cloud top was assumed to be collimated and confined to the appropriate solar zenith angle determined for each flight. The incident fluxes employed in the calculations were taken from

![Figure 20](image-url)
the calibration measurements, an example of which was shown in Fig. 13. We specifically chose not to extend the calculations into the shorter wavelengths, partly because of the uncertainty in apportioning the amount of diffuse to direct radiation correctly and partly in view of our stated interests in comparing the reflectance spectra in the near-IR.

(iv) The incident upwelling radiation at cloud base was determined using the measured directional reflectance at cloud base with the assumption that the lower surface was a Lambertian reflector.

b. Comparisons of the Sc case studies

The comparison of the calculated (heavy solid curves) and measured (light curves) spectral reflectances are shown in Figs. 22a, b and c for the three Sc case studies. We show the reflectances appropriate to cloud top and some level approximately in the middle of the cloud. For two of the three cases (flights 01 and 03), the reflectances at the shorter wavelengths agree well with theory but the theoretical reflectances in the near-infrared, particularly in the windows centered on 1.6 and 2.2 μm, are systematically larger at cloud top. These differences are not as dramatic in the midcloud levels. A similar systematic difference is also implied in Fig. 22c if we adjust the theoretical curve upward to bring the visible reflectances to agreement.

Not only are the magnitudes of the reflectance systematically different, but the shape of the windows is also different with some suggestion of more extended absorption wings. The coldest cloud temperatures measured were generally near or above freezing and we can therefore discount any possibility of ice absorption.

Included in Fig. 22b are the Eppley-measured cloud albedo and absorptances and the theoretical estimates after the model was extended to include spectral regions not accounted for in Table 3. These results perhaps suggest that the discrepancies apparent in the comparisons of the reflection spectra also appear in the broadband albedo and absorption estimates. These comparisons are consistent with and support the notion that there is perhaps more absorption in the near-IR than predicted by theory. This notion is similar to that stated by Twomey and Cocks (1982) and proposed by several
other investigators. The spatial heterogeneity of cloud optical properties can also introduce a systematic bias in the reflectances compared to those calculated, based on the usual plane-parallel horizontally homogeneous assumptions (Stephens, 1986). It has not yet been established, however, whether this bias varies with changes in the strength of droplet absorption from wavelength to wavelength, and therefore whether the effects of heterogeneity are more pronounced in the near-infrared region than in the visible spectral region.

10. Summary and conclusions

This study reports on a series of aircraft flights, during which radiation and supporting in situ cloud microphysics measurements were made. On analysis of these measurements and subsequent comparisons with theory we conclude that

(i) The cumulus clouds sampled during the course of the experiments were fair weather, warm-based clouds mainly maritime in character (low droplet con-
centrations) with low liquid water contents. The effective radii of the droplet distributions, a parameter relevant to the specifications of the cloud optical properties, increased systematically from cloud base to cloud top. The stratiform clouds were of similar character but much shallower (from 200 to 400 m in depth). Despite the confined vertical extent of these clouds, significant concentrations of large droplets were recorded.

(ii) From the optical properties of volume extinction, single-scatter albedo, and asymmetry parameter derived from the FSSP droplet distributions, we conclude that the optical depths of the clouds sampled in the experiments described in this paper were relatively small. The composite optical depth of the cumulus clouds was around \( \tau = 25 \) at a wavelength of 1.29 \( \mu m \), while the optical depths of the Sc clouds varied from 5 to 10 at the same wavelength. The volume extinction coefficient was the most variable optical property in the clouds sampled. The variance of the scattering albedo was smaller than that of volume extinction and similar in magnitude to the variance of effective radius. The asymmetry parameter, by contrast, was approximately uniform throughout the clouds sampled. These results can assist in developing theoretical transfer models, as they imply that it is important to accommodate variations in volume extinction but perhaps not so important to allow for variations in scattering phase functions.

(iii) The directional reflectance measured over cumulus clouds was shown to possess large horizontal variability with the brightest portion of the (vertical) reflectances located over the center of the clouds. Based on comparison with Eppley-derived cloud albedo, we could infer that angular distribution of this reflected energy appeared to be more anisotropic for cumulus clouds than for stratiform clouds.

(iv) Significant variability of the reflectance of the

![Fig. 22. (Continued)](image)

**TABLE 3. Spectral regions used in a model to stimulate the SPERAD measurements.**

<table>
<thead>
<tr>
<th>Interval no.</th>
<th>Spectral region (( \mu m ))</th>
<th>Vapor absorption</th>
<th>No. of terms*</th>
</tr>
</thead>
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<tr>
<td>1</td>
<td>0.700–0.75</td>
<td>Yes</td>
<td>6</td>
</tr>
<tr>
<td>2</td>
<td>0.75–0.78</td>
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<td>3</td>
<td>0.78–0.85</td>
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<td>5</td>
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<tr>
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<td>4</td>
</tr>
<tr>
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<td>1</td>
</tr>
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<td>6</td>
<td>1.09–1.21</td>
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</tr>
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<td>1.24–1.26</td>
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<tr>
<td>22</td>
<td>2.42–2.51</td>
<td>Yes</td>
<td>4</td>
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</table>

* No. of terms in sum of exponential fit to LOTRAN 5 water vapor transmission averaged over given spectral interval.
Sc clouds sampled occurred on two scales which are perhaps indicative of cellular overturning through the entire depth of the cloud, and of an organization of this process on a scale which might be associated with the overturning of the entire mixed layer.

(v) Two-dimensional histograms relating the 0.59 μm to the 10–12 μm window radiances measured over Sc and cumulus cloud fields were examined. A clear relationship such as would be anticipated from theory existed for the case of Sc over sea. The relationship of the visible to IR radiances was more confused for cumulus clouds and was influenced by a number of factors. Variabilities of the underlying land albedo, for example, demonstrated by the measurements over cumulus clouds, caused a smearing-out of the relationship between the visible and infrared radiances. It is evident that the effects of the variations of optical depth and of cloud amount on the measured radiances cannot be separated in the case of cumulus clouds without some appropriate account of cloud inhomogeneities.

(vi) The measured reflectance spectra, while consistent and reproducible within themselves, could not be reconciled with the reflectance spectra computed by currently acceptable theoretical methods using averaged optical properties derived from the measured FSSP data. In particular, the computed reflectances in the near-infrared were distinctly larger than the measured values. There are a number of possible explanations for such a discrepancy. Inclusion of the effects of large droplets in the computations reduces the computed reflectances of optically thick clouds (Ackerman and Stephens, 1987). This decrease occurs at all wavelengths, including those in the visible where agreement with the model is good. The Sc clouds of this study were not optically thick and the work of Ackerman and Stephens (1987) suggests that the effect of large droplets in thin cloud is opposite to that in thick cloud, resulting in a reduction in the droplet absorption (and an increase in reflection) in the near-IR. This is contrary to observations. Another possible explanation relies on the effects of cloud inhomogeneities somehow invalidating the assumption of plane-parallel geometry and the use of spatially averaged optical properties. Stephens (1986) demonstrated that the albedo of a horizontally nonuniform cloud is less than that calculated for a plane-parallel cloud with equivalent averaged optical properties. The effect of heterogeneity has to vary with wavelength and be more pronounced at those wavelengths where absorption is strong in order to explain the results reported in this paper. This aspect needs further research with a suitable theory. The other plausible possibilities are that some additional near-IR absorber is present, or the absorption incorporated into the model is not correct or that the measurements themselves are in error. To this end, comparisons with other models seem warranted and further measurements of the type reported here are needed.

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REFERENCES


Labs, D., and H. Neckel, 1968: The radiation of the solar photosphere from 200 Å to 100 μ. Z. Astrophys., 69, 1–73.


