Absorption of Solar Radiation by Stratocumulus Clouds: Aircraft Measurements and Theoretical Calculations

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ABSTRACT

Aircraft observations of shortwave radiative properties of stratocumulus clouds were carried out over the western North Pacific Ocean during January 1991. Two aircraft were equipped with a pair of pyranometers and near-infrared pyranometers. Downward and upward shortwave fluxes above and below the cloud were synchronously measured by two aircraft. The cloud radiative properties, especially the absorptance obtained from measurements, were compared with those calculated. Aircraft measurements and Monte Carlo calculations showed that spatial inhomogeneities of clouds cause horizontal radiative convergence and divergence, and that vertical radiative convergence—that is, absorptance with a usual definition—apparently becomes extremely large or negative. The apparent absorptance could be corrected by a method that evaluates the true absorption from the difference between the apparent visible and near-infrared absorptions. The corrected absorptance agreed well with the theoretical absorptance calculated with plane-parallel cloud models. It is also inferred that the anomalous absorption pointed out by aircraft observations in previous studies does not exist.

1. Introduction

Aircraft measurements of radiative properties of clouds have been carried out for more than 40 years. In the 1970s, aircraft measurements were compared to cloud radiative properties calculated with radiative transfer theory. The comparison suggested that observed absorptance of solar radiation by clouds is larger than the theoretical calculations (Stephens et al. 1978). Insufficient performances in previous aircraft measurements, as well as other problems in the theoretical calculation such as handling of cloud inhomogeneity or water vapor continuum absorption, have been cited as reasons for this inconsistency (Stephens and Tsay 1990). Measurements of radiative flux above and below clouds were obtained by only one aircraft in most cases. Actual clouds are variable in time and space even though recognized apparently as stratus or stratocumulus, while most of cloud models are embedded in a plane-parallel atmosphere without temporal variations. In inhomogeneous clouds, solar radiation escapes from the cloud side wall, so that the measurements of cloud radiative properties cannot be compared simply to those calculated with plane-parallel cloud models. However, an assessment of plane-parallel approximation in the cloud radiative properties is required from climate models or other fields including radiative processes.

Ackerman and Cox (1981) proposed a method for correcting errors in aircraft observations of radiative properties of inhomogeneous clouds. In this method, the true absorptance is obtained by subtracting apparent absorptance in the visible region from that in the total or near-infrared region under two assumptions as follows. First, the absorption of solar radiation by cloud droplets and water vapor is negligible in the visible region, but effective in the near-infrared region. Second, the scattering properties in the near infrared are similar to those in the visible. The former is reasonable as far as cloud droplets consisting of pure water without contaminations, while the latter may need more careful consideration.

In the present study, synchronous measurements of shortwave radiative properties of stratocumulus clouds with two aircraft were obtained, as part of the Japanese WCRP Cloud-Radiation Experiment over the western North Pacific Ocean. The results are discussed with a Monte Carlo simulation. Moreover, the correction method of Ackerman and Cox (1981) was applied to the aircraft measurements, and the results are compared to theoretical calculations with plane-parallel cloud models, focusing especially on the absorption properties of clouds.

2. Summary of observations

Aircraft observations of radiative and microphysical properties of clouds were carried out over the western North Pacific Ocean during January 1991. In winter, clouds observed around this area are stratocumulus

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clouds that are formed at the top of the boundary layer by convection. Dry air masses from cold Asian continent flow over the warm East China Sea where convective energies of sensible and latent heat are supplied to the air mass. These clouds have different properties from the stratocumulus observed during FIRE [First ISCCP (International Satellite Cloud Climatology Project) Regional Experiment] off the coast of California where clouds are formed as marine fog, or from the stratus in the Arctic where warm air mass is cooled to condense on the cold current in summer. Aircraft observations and cloud conditions in this study are briefly summarized in Table 1.

The radiation measurements were obtained by two Cessna 404 aircraft flying synchronously above and below the cloud (hereafter referred as aircraft A and B). The instruments for measuring shortwave radiative fluxes were upward- and downward-looking pyranometers, mounted on the top and bottom of the fuselage, respectively. The pyranometers were calibrated with respect to a standard pyranometer of the Japan Meteorological Agency. Errors due to cosine properties of incident radiation and due to temperature dependence are 2% for 0° to ~80° incident zenith angle and 1% for −20° to ~+40°C, respectively. Since the response time of the pyranometer is 2.5 s, a measurement of relatively small or fast variation may not have sufficient accuracy. Downward and upward fluxes were measured in the 0.3–3.0-μm and 0.7–3.0-μm spectral regions. Visible fluxes (0.3–0.7 μm) were obtained by subtracting the near-infrared flux from the total flux. In addition to the measurements of cloud radiative properties, aircraft A was equipped with a 37-GHz microwave radiometer for measuring cloud liquid water path, that is, vertically integrated liquid water content. The 37-GHz microwave radiometer, which is nadir looking with a field of view of 4°, receives thermal emission from the sea surface, cloud droplets, and water vapor. The cloud liquid water path was estimated from a difference in the received brightness temperatures between cloud covered and cloudless regions. An algorithm for estimating liquid water path developed by Takeda and Liu (1987) was applied to the microwave radiometer measurements.

Aircraft B was equipped with a FSSP-100 cloud droplet spectrometer of the Particle Measuring Systems Inc. (PMS) for measuring cloud droplet size distributions. The PMS FSSP-100 probe measures the number of cloud droplet from 2 to 47 μm with an interval of 3.0 μm in diameter. The cloud droplets larger than 10 μm in diameter were also measured on a glass impactor with microscope video camera similar to the airborne video optical microscope (AVIOM, Tanaka et al. 1989). In the observation area, however, cloud droplets were rather small and rain was not observed, which may be ascribed to CCN abundant air mass originated from the Asian continent. Large particles out of the range of FSSP-100 were quite few and not effective to the radiative properties and total liquid water path. Accordingly, we used only the FSSP-100 data in the analysis. Figure 1 illustrates an example of typical cloud droplet size distribution in volume spectrum obtained with the FSSP-100 measurements. The obtained size distribution was well expressed by a lognormal distribution,

$$\frac{dV}{d\ln r} = \frac{V_0}{(2\pi)^{1/2}\ln\sigma}\exp\left[-\frac{1}{2}\left(\frac{\ln r - \ln r_m}{\ln\sigma}\right)^2\right], \quad (1)$$

where V_0 is the total volume of droplets, r_m the mode radius, and σ the standard deviation. The fitted line is also presented in Fig. 1. Therefore, the lognormal size distribution was used in the theoretical calculation in this study.

3. Synchronous radiation measurements

To avoid errors due to time difference in the radiation measurements between reflection and transmission, synchronous measurements above and below clouds were carried out with two aircraft. Aircraft A measured the downward and upward fluxes above clouds along a latitudinal or longitudinal line with a ground speed of 70 m s^{-1}, while aircraft B measured them below clouds along the same latitude or longitude.

TABLE 1. Summary of atmospheric conditions and aircraft observations.

Date 1991	Time (LT)	Cosine of solar zenith angle	Flight level aircraft A and B (m)	Cloud-layer base/top (m)	Column water vapor (g cm^{-2}): Sea surface–cloud base	Cloud layer	Cloud top–aircraft A	Aircraft A–air top
13 January	1024:00–1233:30	0.51–0.64	3000 300	1260/2100	0.466	0.233	0.089	0.199
18 January	1328:30–1446:00	0.63–0.51	2400 570	1050/1320	0.501	0.130	0.396	0.231
22 January	1306:00–1513:30	0.66–0.48	3000 300	1350/2250	0.741	0.626	0.627	0.198
27 January	1311:30–1458:00	0.66–0.54	2550 750	1200/1860	0.572	0.289	0.136	0.634

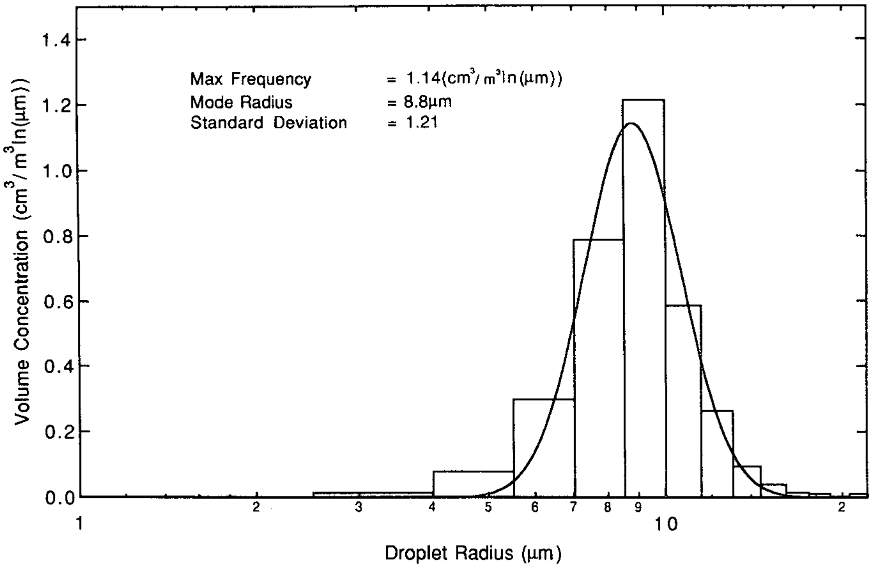

FIG. 1. An example of typical cloud droplet size distribution in volume spectrum obtained with the PMS FSSP-100 on 22 January in the western North Pacific. The solid line shows a lognormal distribution [Eq. (1)] fitted to the measurements.

Communication between the two aircraft assured the success of synchronous measurements.

Figure 2 illustrates downward and upward radiative fluxes in the solar spectral region obtained along the latitude of 28°15′N on 22 January. Fine and coarse dotted lines indicate the downward fluxes, and solid and dash–dotted lines indicate upward fluxes, above and below the cloud, respectively. The cloud top was visually observed as 2250 m and the cloud base as 1350 m. Aircraft A flew at 3000 m in altitude, while aircraft B flew at 300 m. Since the downward flux measured above the cloud top varies with aircraft attitude, the downward fluxes above the cloud top were corrected with the attitude data obtained by a vertical gyroscope. However, a small variation in downward flux still remained, so that the downward flux data were fitted with a function of cosine of solar zenith angle. After these corrections, the reflectance R, transmittance T, and absorptance A were obtained from the definitions

$$R = \frac{F_{u,t}}{F_{d,t}}, \qquad (2)$$

$$T = \frac{F_{d,b}}{F_{d,t}}, \qquad (3)$$

$$A = \frac{(F_{d,t} - F_{u,t}) - (F_{d,b} - F_{u,b})}{F_{d,t}}, \qquad (4)$$

where F is the radiative flux, suffixes d and u denote downward and upward, and suffixes t and b denote top and base of the cloud. The right half in Fig. 2 is inferred to be an open region without clouds, whereas the left half contains clouds partly broken. It should be noticed that the transmittance as defined with Eq. (3) sometimes shows unexpected large values; that is, $T \geqslant 1$. The reflection of solar radiation by a cloud sidewall is considered to be responsible for such an apparent large transmittance. Since the scattered radiation from clouds is brighter than that from the background clear sky, the total downward flux, including both direct and scattered radiation below the cloud base, may exceed that above the cloud top. Consequently, the absorptance estimated from these radiation data using Eq. (4) leads to unexpected values.

Figure 3 shows the absorptance of clouds in the visible and near-infrared spectral regions obtained from Eq. (4), applied to data in Fig. 2. The solid line indicates the near-infrared absorptance and the broken line indicates the visible absorptance. In the visible region where there is only negligible weak absorption by water vapor and cloud droplets, large positive and negative absorptance values are observed. The apparent positive absorptance seems to appear at shaded regions. In these regions, upward flux above the cloud is small because of small cloud liquid water path and downward flux below the cloud base is also small because of opacity of direct solar radiation. As a consequence, an apparent large absorptance is observed. On the other hand, the apparent negative absorptance seems to appear sharply at the cloud open area. In this case the reflection effect of direct solar radiation by the cloud sidewall, in addition to the direct radiation itself, is responsible for the large downward flux below the cloud. In the near-

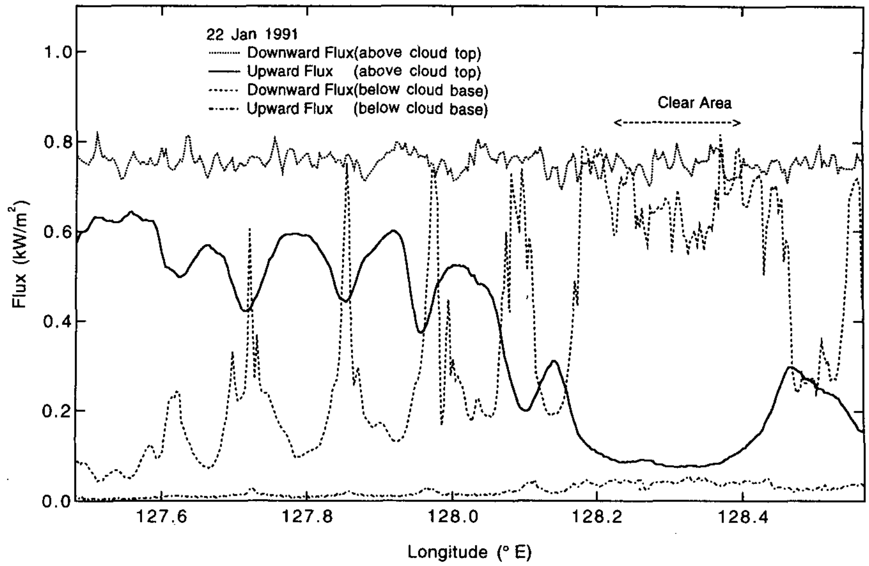

FIG. 2. Downward (fine and coarse dotted lines) and upward (solid and dash–dotted lines) shortwave radiative fluxes obtained by aircraft measurements above and below the cloud on 22 January.

infrared region, the variation of absorptance is almost the same as that of the visible region but with a positive bias of about 20%. It is inferred from Fig. 3 that the difference of apparent absorptance between visible and near infrared would be the true absorptance of cloud layer in the near-infrared region.

4. Calculation of broken cloud radiative properties with Monte Carlo method

In a context of investigating radiation fields of broken clouds such as observed, radiative properties were calculated by the Monte Carlo method including scattering by cloud droplets and absorption by water vapor and cloud droplets. The Monte Carlo method for radiative transfer calculates the trajectory of photon with probabilities of extinction and scattering direction (Mckee and Cox 1974). A photon coming into the cloud layer from the solar direction passes through the cloud until the next scattering point. The photon pathlength to the next scattering point is determined with a cumulative probability distribution related with the extinction coefficient. The scattering angle at the scat-

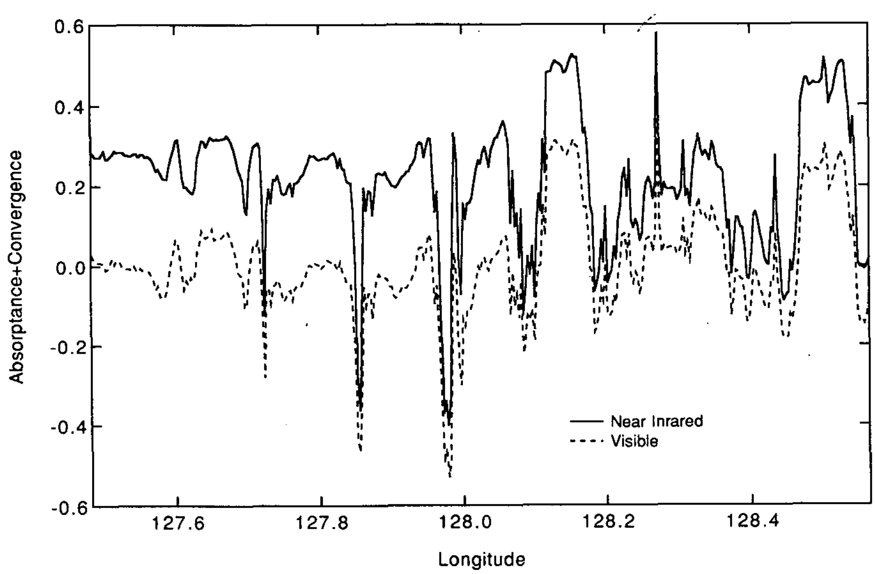

FIG. 3. Absorptances of clouds in the visible (broken line) and the near-infrared (solid line) spectral regions, as obtained from vertical flux convergence with Eq. (4).

tering point is determined with a cumulative probability distribution of phase function. The calculations of pathlength and scattering angle are repeated until the photon leaves the layer. A series of calculation was performed with 100 000 photons, which agreed better than 1% with discrete ordinate calculation for the plane-parallel cloud model.

The solar spectral region was divided into 15 subregions according to the water vapor absorption bands. The complex refractive indices compiled by Hale and Querry (1973) were used, but the imaginary part was assumed to be zero in the visible region. The single-scattering albedo and phase function were calculated with the Mie theory. Lognormal size distributions for the volume spectrum of cloud droplets were used as shown by Eq. (1). The absorption by cloud droplets was calculated with single-scattering albedo raised to a power of number of scattering. The absorption by water vapor was calculated from the photon pathlength distribution using a method of ESFT (exponential-sum fitting of transmittance). In the ESFT method, the transmission function is expressed as a sum of exponents,

$$T = \sum_j w_j \exp(-k_j u), \tag{5}$$

where u is the water vapor amount along the photon path. The absorption coefficients k_j and the weights w_j developed by Asano and Uchiyama (1987) were used.

Figure 4 illustrates a schematic cloud model used in the Monte Carlo simulation. The model consists of two-dimensional rectangular clouds in cyclic array, each 4000 m in width and 1000 m in thickness, separated by 4000 m. The cloud optical thickness at 0.5 μm is assumed to be 20 and cloud droplet size distribution is given by Eq. (1) with the mode radius r_m = 10 μm, and the standard deviation σ = 1.4. Cloud-top height is assumed to be 2 km. Water vapor of 0.626 g cm^{-2} is included in both cloudy and clear regions of the layer between 1 and 2 km. Water vapor above the clouds is assigned a value of 0.825 g cm^{-2}, as obtained from radiosonde measurements. In the simulation, one aircraft is assumed to fly 300 m above the cloud and the other just below the cloud. The layer between cloud top and the upper aircraft is assumed to contain 0.145 g cm^{-2} water vapor amount. Cloud area and clear area are divided horizontally into 10 regions, respectively, for which upward and downward fluxes are evaluated. Solar zenith angle is 53.1° perpendicular to extended cloud bar. This geometrical configuration allows the aircraft flying below the cloud base to be directly illuminated by the solar radiation between the two clouds.

Figure 5 shows the results of Monte Carlo simulation of the radiative fluxes in the visible and near-infrared spectral regions. In both spectral regions, the reflectance is large above the cloud area and to the side of the cloud wall illuminated by the sun, whereas the reflectance is small above the open area and the area shaded by the cloud. Conversely, the transmittance is large below the open area and the area influenced by the illuminated cloud sidewalls, whereas it is small below the cloud area and the area shaded by the cloud. Although the absorption of solar radiation in the visible spectral region by water vapor and cloud droplets is expected to be negligible, both positive and negative absorptances appear to exist, as seen in the measurements (Fig. 3). A positive absorptance appears in the area where cloud sidewalls are illuminated by the direct solar radiation, and the radiative flux converges horizontally. A negative absorptance appears in the shaded cloud sidewalls, and the radiative flux diverges horizontally. Therefore, the apparent positive or negative absorptance results from the horizontal convergence or divergence, respectively, of radiation in the cloud fields. In both spectral regions, properties of the reflectance and transmittance are almost the same. The apparent positive and negative absorptance are qualita-

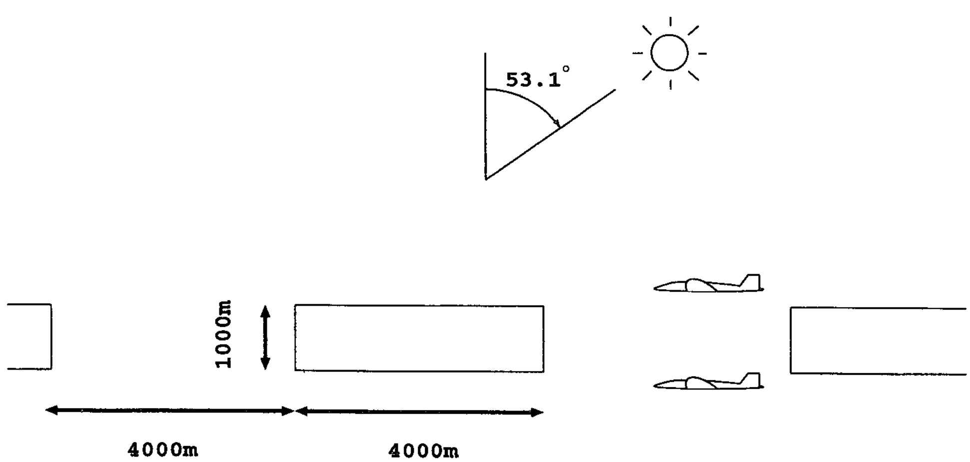

FIG. 4. A schematic of cloud model used in the Monte Carlo calculation of radiative properties.

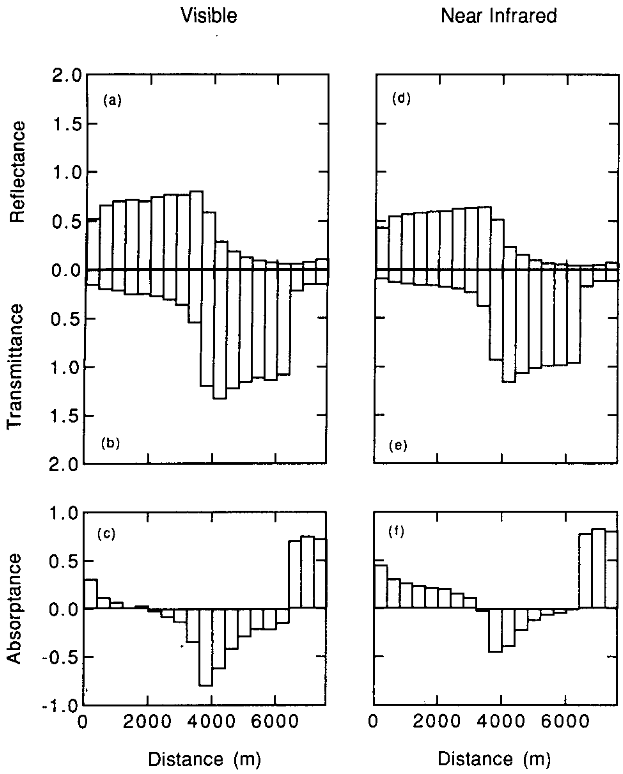

FIG. 5. Results of Monte Carlo calculation of shortwave cloud radiative properties. Reflectance, transmittance, and absorptance defined with Eqs. (2)–(4) are shown in the visible and the near-infrared regions.

tively consistent with those obtained by the synchronous aircraft observation as shown in Fig. 3. In the visible region, the absorptance averaged over one cycle of the cloud array is 0%, whereas in the near-infrared region it is 18.9%. The Monte Carlo simulation suggests that the shortwave absorptance of inhomogeneous clouds can be evaluated reasonably by means of appropriate spatial average.

5. Comparison between plane-parallel cloud model and measurements

a. Correction method of Ackerman and Cox

Monte Carlo simulation employs probability method so that high accuracy calculations consume time and cost. Calculations with plane-parallel cloud models are useful if the radiative field of broken cloud could be approximated by plane-parallel approximation. Thus, a comparison between the aircraft measurements and the calculations with plane-parallel clouds would be of interest. As shown in the previous sections, however, it is quite difficult to directly compare the measurements of inhomogeneous radiative properties to the calculations with plane-parallel clouds. Accordingly, a correction method is necessary and applied to the measurements for the comparison.

Ackerman and Cox (1981) introduced a method (hereafter referred as AC method) for correcting the absorptance of inhomogeneous clouds. The apparent cloud absorptance in the visible region frequently observed is caused by convergence or divergence of horizontal radiative flux. Therefore, the absorptance of vertical radiative flux could be corrected by using the convergence or divergence of horizontal radiative flux in the observed absorptance. The AC method requires two assumptions. One is that the absorption by water vapor and cloud droplets can be neglected in the visible region. The other is that a ratio of convergence or divergence of horizontal radiative flux in the near-infrared region is the same as in the visible region. It means that the scattering radiative properties in the near-infrared region are assumed to be the same as in the visible region. A Monte Carlo calculation by Welch et al. (1980) suggested that a difference in the percentage of the incident solar radiation exiting from the cloud side is small but not zero between visible and total wavelength. This difference is considered to give rise to an underestimation of the near-infrared absorption. However, since the difference between visible and near infrared depends on cloud geometry and microphysics, it cannot be evaluated quantitatively in advance. Therefore, the above two assumptions are used in the analysis.

The absorptance for inhomogeneous clouds is presented by

$$A = \frac{(F_{d,t} - F_{u,t}) - (F_{d,b} - F_{u,b}) - \sum E_i}{F_{d,t}}, \quad (6)$$

where $\sum E_i = dE_x/dx + dE_y/dy$ is the horizontal convergence or divergence of radiation. Since the visible absorptance is considered to be zero and the ratio of

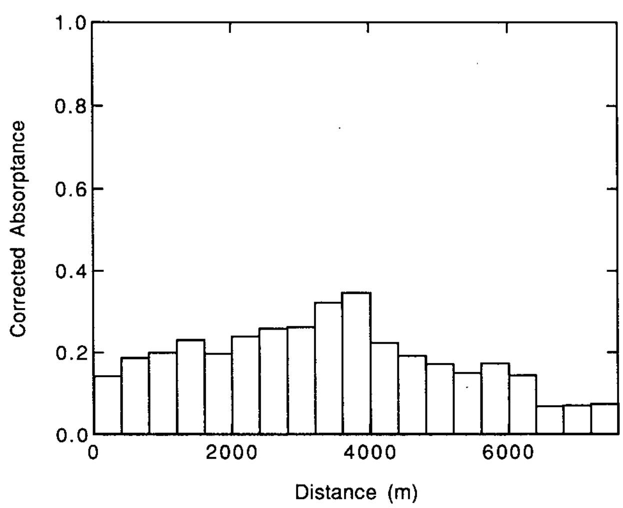

FIG. 6. The near-infrared absorptance of clouds calculated with the cloud model shown by Fig. 4, corrected with the method of Ackerman and Cox (1981).

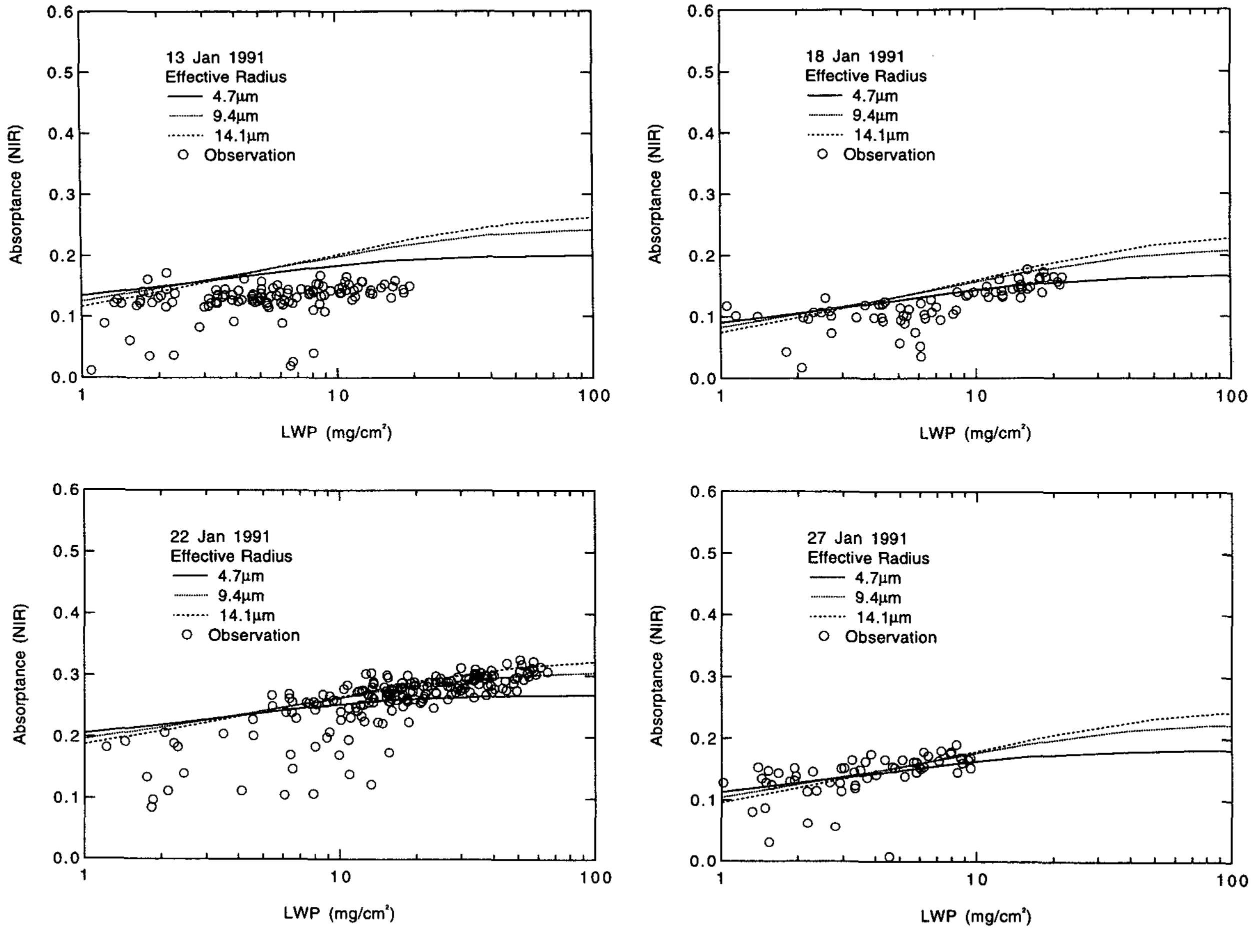

FIG. 7. The relationship between the cloud liquid water path and the near-infrared absorptance corrected by the method of Ackerman and Cox (1981). Circles shows the observed data. Three lines indicate the calculated values with size distributions of respective mode radii, under the assumption of plane-parallel atmosphere.

convergence or divergence of horizontal radiative flux in the near-infrared region is assumed to be the same as in the visible region, the following relation is obtained,

$$\left(\frac{\sum E_i}{F_{d,t}}\right)_{\mathrm{NIR}} = \left(\frac{\sum E_i}{F_{d,t}}\right)_{\mathrm{VIS}} = \left[\frac{(F_{d,t} - F_{u,t}) - (F_{d,b} - F_{u,b})}{F_{d,t}}\right]_{\mathrm{VIS}}. \quad (7)$$

Therefore, the corrected absorptance in the near-infrared region is obtained as

$$A_{\mathrm{NIR}} = \left[\frac{(F_{d,t} - F_{u,t}) - (F_{d,b} - F_{u,b})}{F_{d,t}}\right]_{\mathrm{NIR}} - \left[\frac{(F_{d,t} - F_{u,t}) - (F_{d,b} - F_{u,b})}{F_{d,t}}\right]_{\mathrm{VIS}}. \quad (8)$$

This method is applied to the result of the Monte Carlo simulation performed in the previous section (Fig. 5). The corrected absorptance in the near-infrared region is obtained by subtracting the absorptance in the visible region from that in the near-infrared region. The result is shown in Fig. 6. Relatively large absorptance appears in the cloudy region, whereas relatively small absorptance appears in the clear region. These absorptance values are reasonable; that is, unexpected large values or negative values such as seen in Figs. 3 and 5 are not obtained. This shows that the AC method is effective in correcting the shortwave absorptance of inhomogeneous clouds.

b. *Application of the correction method to the measurements*

The AC method was applied to the aircraft measurements obtained on 13, 18, 22, and 27 January by synchronous flights as mentioned in section 3. Figure 7 shows relationships between the cloud liquid water path and the near-infrared absorptance corrected by the AC method on these four days. The circles indicate the measurements where it should be noticed that a field of view of the microwave radiometer for measuring cloud liquid water path is different from that of pyranometer. On the other hand, three curves indicate calculated values for plane-parallel clouds with three different droplet effective radii. The atmospheric conditions and solar zenith angles corresponding to respective four days were used in the calculations.

In the calculation of radiation with plane-parallel atmosphere, the atmosphere has five layers over the sea surface. The uppermost layer includes absorption by ozone in the stratosphere. The second layer includes water vapor absorption and Rayleigh scattering between the altitude of aircraft A and the tropopause. The third layer is the same as the second layer but lying between the cloud top and the aircraft level. The fourth layer is the cloud layer. Vertical profiles of the cloud layer were not taken into account, so that the liquid water content, droplet size distribution, and water vapor content did not change throughout the layer. The last layer is the same as the second layer, but it lies between the cloud base and the sea surface. The temperature and water vapor content measured in and above the cloud by aircraft, supplemented by the 0900 LT radiosonde data at the Amami Observatory of the Japan Meteorological Agency, were used. The calculation of radiative properties were performed with a discrete ordinate method of Nakajima and Tanaka (1986). The intensity field in the vertical direction was divided into 10 streams and the phase function of cloud was truncated in the calculation. The solar spectrum was divided into 24 intervals and refractive indices of liquid water were referred to Hale and Querry (1973). The exponential sum fitting method of Asano and Uchiyama (1987) was employed to calculate water vapor absorption bands (0.94, 1.1, 1.38, 1.87, 2.7, 3.2 μm). Although their parameterization is based on Air Force Geophysics Laboratory 1982 absorption line parameters (Rothman et al. 1983), there still remain some uncertainties in the weak absorption line parameters in the near infrared. The scattering and absorption coefficients and phase function of the cloud droplet were calculated with the Mie theory. Lognormal expressions presented by Eq. (1) were used for the droplet size distributions with the mode radius $r_m = 5.0$, 10.0, and 15.0 μm and the standard deviation $\sigma = 1.4$.

As shown in Fig. 7, the measurements agreed well with the theoretical calculations, which implies that the AC method was successfully applied to the observed data. The overlap of three theoretical curves suggests insensitivity of the cloud absorptance to the cloud droplet radius in a range of mode radius from 5.0 to 15.0 μm. On the other hand, water vapor seems to play an important role in the absorption of solar radiation. Although the water vapor continuum absorption in the near infrared was not taken into account in the calculations, the observed values hardly exceed the calculated values. This may suggest that the water vapor continuum absorption is not so effective in the near-infrared region.

Davies et al. (1984) calculated the process of absorbing solar radiation by clouds, showing that the water vapor above the clouds affects the absorptance of cloud. A small amount of water vapor above the clouds during the period of study, therefore, did not absorb solar radiation so much. Because the absorption of radiation by clouds is dependent also on the amount of water vapor in the cloud, the cloud geometrical thickness becomes one of the important parameters, as well as the water vapor content per unit volume. On 22 January, the water vapor content in the cloud layer was the largest among four days of measurements, resulting in the contribution of water vapor to the absorption of solar radiation larger than on the other days. On 18 and 27 January, the water vapor content was smaller than 22 January, making the absorption by liquid water relatively large.

The observed reflectances on 13 January were almost constant and slightly smaller than those calculated, independent of the liquid water path. On this day the clouds were broken stratocumulus rather than stratus. Since the clouds were distributed systematically with small-scale variability, the reflectances measured by pyranometer with hemispherical field of view showed small variability. On the other hand, the cloud liquid water paths measured with the microwave radiometer of small field of view showed large variability.

6. Summary

The shortwave radiative properties of stratocumulus clouds were observed by two aircraft flying synchronously above and below the cloud. The effect of horizontal inhomogeneity of cloud structure to the radiative properties was interpreted with simple Monte Carlo calculations. The correction method by Ackerman and Cox (1981) for absorptance of inhomogeneous clouds was applied to the measurements and the results were compared to theoretical calculations with plane-parallel cloud models. The results obtained in this study are summarized as follows:

- Aircraft measurements and Monte Carlo simulations suggest that horizontal convergence or divergence of radiation in the inhomogeneous cloud causes large apparent vertical flux absorptance. However, the apparent absorptance could be corrected with the method proposed by Ackerman and Cox (1981).
- Using this correction method, the measured absorptance of inhomogeneous clouds, which was obtained by synchronized aircraft observation, becomes consistent with the theoretical absorptance obtained by plane-parallel cloud model approximation.
- Water vapor above and within the cloud seems to be important for the absorptance of clouds as well as cloud liquid water content.

• It is inferred that the anomalous absorption pointed out by aircraft observations in previous studies does not exist.

• It is expected that the cloud droplet size distribution is not so effective to the cloud absorptance in usual size range.

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