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EFFECTIVE EMISSIVITY OF CLOUDS FROM RADIOMETERSONDE MEASUREMENTS AT SYOWA STATION, ANTARCTICA

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Abstract: The effective emissivity of Antarctic clouds is calculated from radiation measurements using the radiometersonde in 1987 at Syowa Station, Antarctica. The accuracy of the radiometersonde near the surface is evaluated by comparison with a pyrgeometer on the ground surface. The effective emissivity is referred to vertical integrated liquid water content (LWC) from microwave radiation measurements.

Though disagreement of measured volume might occur between the microwave radiometer and the sonde, the effective emissivity for downward flux correlates well to the LWC, but that for upward flux does not. A large discrepancy is found between the effective emissivity for upward flux and that for downward flux, and especially, for upward flux, the effective emissivity is very small in some cases. It is assumed that the scattering of longwave radiation by water and ice particles produces this discrepancy. The value of the LWC suggests that water particles may exist much closer to the cloud top than the cloud base. Difference among features of the effective emissivity due to type of cloud systems resolved from NOAA/AVHRR imagery is not found in this study.

1. Introduction

Longwave broadband radiative properties of clouds are usually represented by the effective emissivity (LIOU, 1992). Not many observational studies have been done on the emissivity of polar clouds. CURRY and HERMAN (1985) presented aircraft measurements of longwave radiation and cloud microphysics during the July 1980 Arctic Stratus Experiment and derived the effective emissivity and some parameters of radiative properties of Arctic stratus clouds. KAWAGUCHI (1983) examined the radiative properties of clouds from radiometersonde at Syowa Station, Antarctica in the 1967–1969 winter and presented the effective emissivity of low or middle clouds. A correlation between the emissivity and the cloud thickness was pointed out. The cloud microphysics, however, was not measured.

The Antarctic Climate Research (ACR) program was carried out by Japanese Antarctic Research Expeditions (JAREs) from 1987 to 1991 (YAMANOUCHI, 1992). During the ACR observation period, many kinds of observations were made. They were 1) satellite observation (NOAA and MOS-1), 2) radiation measurement (longwave, shortwave and microwave), 3) sonde observation (radiometersonde and hydrometeor video sonde) and 4) airborne observation (longwave, shortwave and microwave radiation).

In this study, radiation measurements using the radiometersonde and the microwave radiometer in 1987 at Syowa Station, Antarctica are analyzed. The effective emissivity is calculated and evaluated in terms of the vertical integrated liquid water content (LWC) from microwave measurements and the forms of cloud system resolved from NOAA/AVHRR imagery.

2. Methodology

2.1. Radiometersonde

In 1987, at Syowa Station, 21 radiometersonde measurements were carried out, 11 under low or middle overcast cloud. These data were reported by JAPAN METEOROLOGICAL AGENCY (1989). However, it is found that these flux data have some error due to inappropriate calculation of the time change rate of the detector temperature. Hence, the flux is recalculated from the original detector temperature. The type of radiometersonde used in these measurements is R78-D; it is somewhat different in sensor structure from the R66A that KAWAGUCHI (1983) used. However, there is not a great difference in measured fluxes between the two types of instrument (MIYAUCHI and OHKAWARA, 1992).

The longwave fluxes of these measurements agree well with the fluxes from the

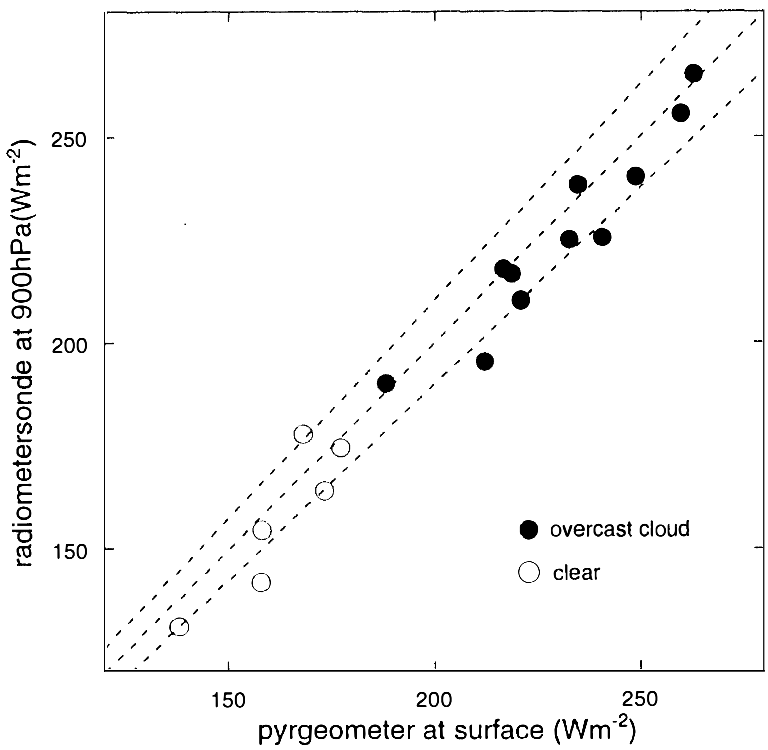

Fig. 1. A comparison of downward longwave fluxes obtained from measurements using a pyrgeometer at the surface by YAMANOUCHI (1989) and using a radiometersonde at 900 hPa height in this study. The points for the cloudy case (cloud amount more than 7/8) are distinguished from those for the clear case (less than 1/8). The dashed lines show 5%, 0% and −5% deviation from the pyrgeometer value.

pyrgeometer at the ground surface by YAMANOUCHI (1989) as shown in Fig. 1. There is no systematic difference between measurements taken under overcast cloud and clear sky. The figure shows that the values of the radiometersonde are slightly less because of the difference of measurement height. The standard error in fluxes measured by radiometersonde is equivalent to 7 Wm^{-2} (3.5%). KANETO *et al.* (1990) compared measurements made with a radiometersonde tethered near the surface and a pyrgeometer. The result showed good agreement, the difference was within about $\pm 5\%$. However, while ascending the sonde is ventilated by about 5 ms^{-1} wind, and the heat balance of the sonde sensor is quite different depending on whether it is ascending or tethered. In this study, the fluxes measured by the radiometersonde at 900 hPa (about two minutes after launching) were compared to those measured by the pyrgeometer at the ground surface.

The lapse rate of the longwave flux, especially downward for low or middle level cloud, changes at the cloud top and bottom so that the heating rate indicates distinct cooling at the cloud top and slight warming at the cloud base. Thus, we can detect the cloud top and the base from the profile of longwave radiation and heating rate of the atmosphere for horizontal homogeneous overcast cloud.

The (broadband) effective emissivity for downward longwave radiation can be written as (*e.g.* LIOU, 1992)

$$\varepsilon\downarrow = \frac{F_b\downarrow - F_t\downarrow}{\sigma T_b^4 - F_t\downarrow}, \tag{1}$$

and for upward longwave radiation,

$$\varepsilon\uparrow = \frac{F_t\uparrow - F_b\uparrow}{\sigma T_t^4 - F_b\uparrow}, \tag{2}$$

where $F\downarrow$ and $F\uparrow$ are upward and downward longwave fluxes measured by the radiometersonde respectively, T is temperature and the subscripts t and b refer to the top and base of the cloud layer. σ is the Stefan-Boltzmann constant.

2.2. *Microwave radiation*

In 1987 and 1988 at Syowa Station, 37 GHz microwave radiation at the surface was measured (WADA *et al.*, 1991). The microwave brightness temperature was calculated from the output voltage of the microwave radiometer considering the antenna loss and the antenna physical temperature (WADA, 1991).

LWC can be obtained from the microwave brightness temperature, where the following assumptions are made:

(1) In the Antarctic, clouds do not include such large ice particles as hailstones, hence in the 37 GHz band, the absorption of ice particles can be neglected compared to that of water particles.

(2) Clouds are accompanied with no or very weak precipitation, so that the water particles are smaller than a critical size, hence the scattering coefficient of the water particles is negligible (TAKEDA *et al.*, 1985).

Thus, the microwave brightness temperature T_{MB} below a cloud layer is represented as

$$T_{MB} = T_{MU} \exp(-\tau) + \int_0^{\tau} T(\tau') \exp(-\tau') \, d\tau', \tag{3}$$

where τ is the optical thickness, T is the cloud temperature and T_{MU} is the brightness temperature at the top of the cloud. For a cloud in which the temperature is constant with height, the microwave brightness temperature below the cloud layer is thus

$$T_{MB} = T_{MU} \exp(-\tau) + T\{1 - \exp(-\tau)\}. \tag{4}$$

If the water particles are sufficiently small, the optical thickness of the cloud is proportional to the vertical integrated liquid water content W.

$$\tau = kW. \tag{5}$$

According to STAELIN (1966) the coefficient k is approximately as follows:

$$\begin{aligned} k &= \frac{10^{0.0122(291-T)}}{\lambda^2} \\ &= 1.11 \times 10^{0.0122(291-T)-3} \nu^2, \qquad (\mathrm{g}^{-1}\,\mathrm{cm}^2) \end{aligned} \tag{6}$$

where λ is the wavelength (cm) and ν is the frequency (GHz). This expression is valid for the wavelength in the range 0.8 to 3cm (10 to 38 GHz frequency) and is a good approximation for sufficiently small water particles compared with $\lambda/2\pi$. We may assume that $kW \ll 1$. Thus,

$$1 - \exp(-kW) \approx kW. \tag{7}$$

From eqs. (4), (5) and (7)

$$W \approx \frac{1}{k} \cdot \frac{T_{MB} - T_{MU}}{T - T_{MU}}. \tag{8}$$

The brightness temperature T_{MU} at the top of the cloud is not measured, therefore we regard T_{MU} as equal to the brightness temperature measured at the surface on a clear day. The value of k is derived from eq. (6); it is appropriate for the mean of the temperature of the cloud base and top obtained from the radiometersonde measurements to be substituted for T.

2.3. NOAA-9/AVHRR imagery

The forms of cloud system resolved from the imagery of NOAA-9/AVHRR received at Syowa Station (TAKABE and YAMANOUCHI, 1989) were observed. Two types of cloud system were recognized: low level flat clouds in the coastal region of Antarctica (WADA, 1987; YAMANOUCHI and SEKO, 1992) and cyclonic clouds with extratropical cyclones (SEKO *et al.*, 1992).

3. Results

3.1. Example

Figures 2 and 3 illustrate the case of September 19, 1987. The cloud type is stratocumulus (Sc) and the cloud amount is 8/8 according to surface observation. From the longwave flux profile, we conclude that the heights of the cloud top and bottom are 2300 m and 1450 m respectively. The cooling at the cloud top is very noticeable, beyond 30 Kday^{-1}. From the radiometersonde data we obtain $T_b = 248.2$ K, $T_t = 244.7$ K, $F_b \downarrow = 211$ Wm^{-2}, $F_t \downarrow = 94$ Wm^{-2}, $F_b \uparrow = 222$ Wm^{-2}, $F_t \uparrow = 203$ Wm^{-2}. Substituting these values into eqs. (1) and (2), we obtain $\varepsilon \downarrow = 0.97$, $\varepsilon \uparrow = 1.03$.

The microwave brightness temperature before and after the radiometersonde measurement is shown in Fig. 4. The weather on each day is also shown. At the time of the sonde measurement, the microwave brightness temperature shows a large value in comparison with the time before and after. In this case the effect of diurnal variation of the antenna temperature is not eliminated completely. However, at night the brightness temperature takes a minimum value under clear sky, about 10 K. Hence, we regard this as T_{MU}. T_{MB} is the brightness temperature under the cloud at the time of the radiometersonde measurements, 21.5 K. From radiometersonde measurements we obtain $T = 246.5$ K. Substituting these values into eqs. (6) and (8), we obtain $W = 92$ gm^{-2}.

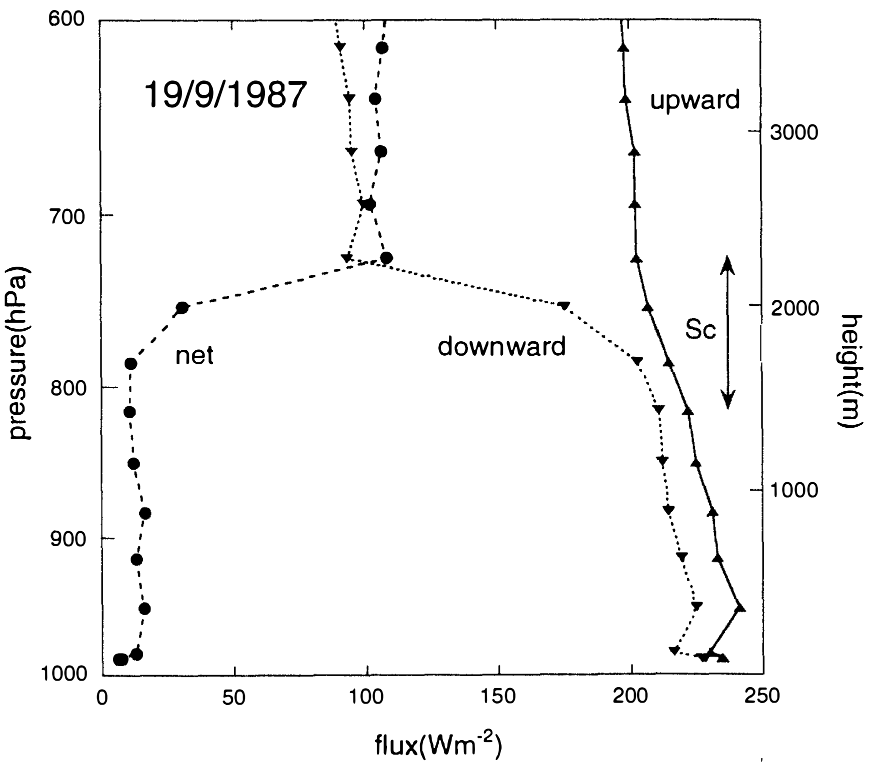

Fig. 2. Profiles of downward, upward and net longwave radiation fluxes by a radiometersonde for the case of Stratocumulus (Sc) on September 19, 1987.

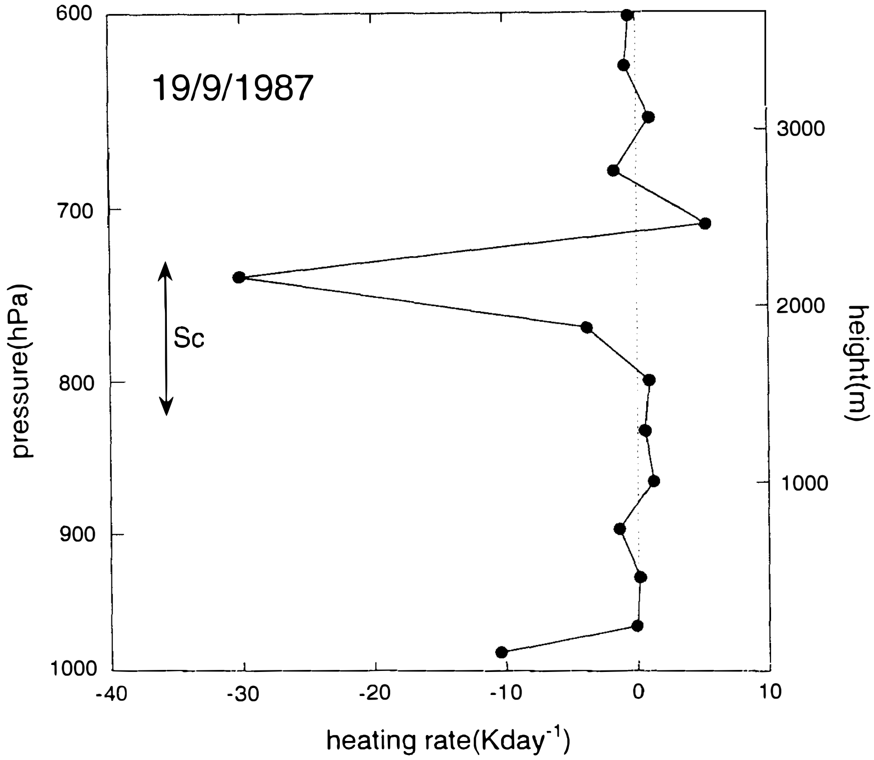

Fig. 3. Profiles of heating rate of the air with longwave radiation by a radiometersonde for the same case as in Fig. 2.

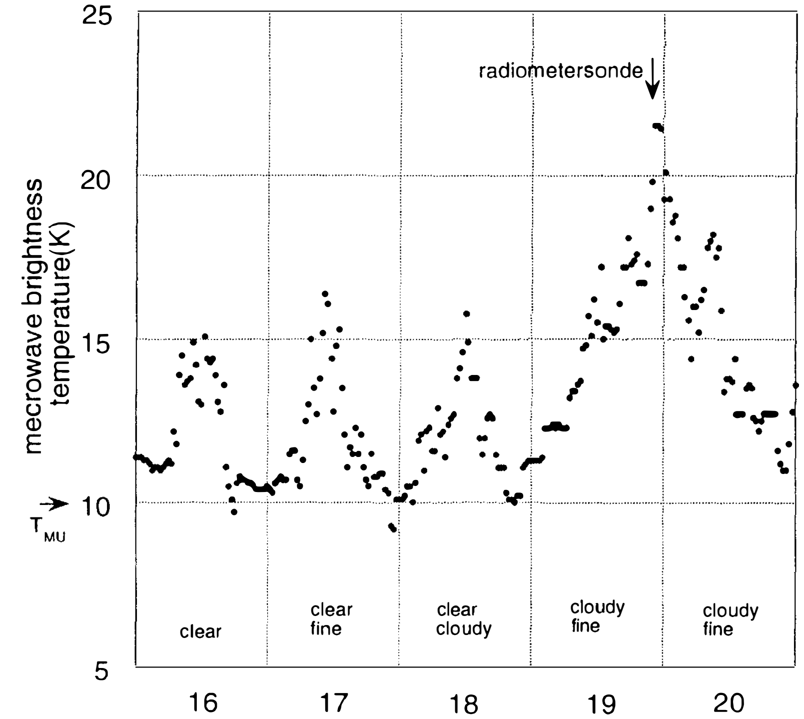

Fig. 4. 37 GHz microwave brightness temperature before and after the radiometersonde measurement of September 19, 1987. The weather on each day is also shown. The arrows show T_{MU} (see text) and the time of the radiometersonde measurement.

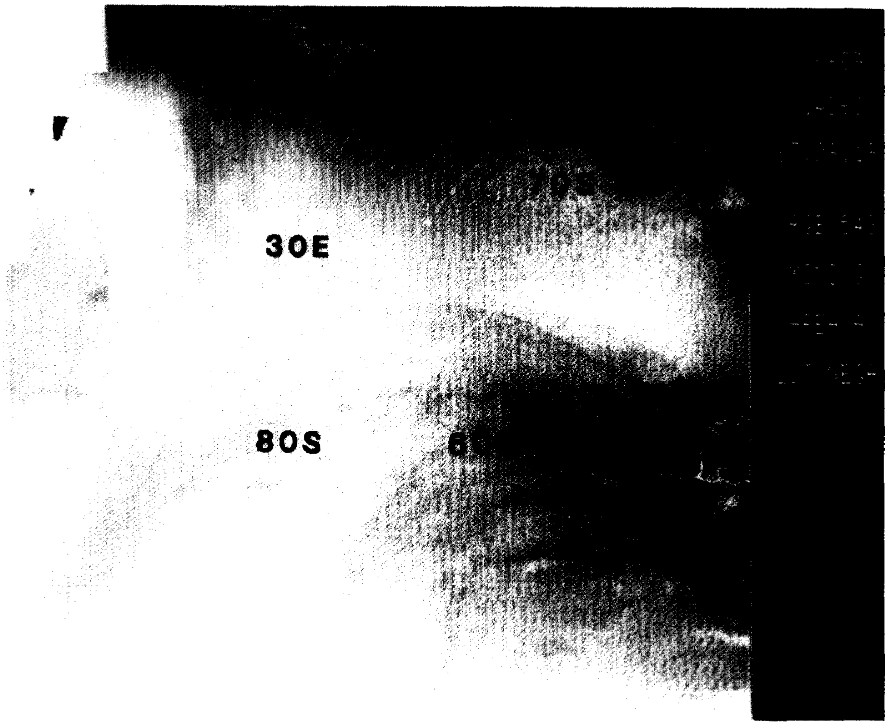

Fig. 5. NOAA-9/AVHRR imagery four hours before the radiometersonde measurement. The measured point is under a gray colored (relatively high temperature) cloud system in the coastal region of Antarctica.

Figure 5 is NOAA-9/AVHRR imagery 4 hours before the measurement. From the imagery, this cloud is recognized as a low level flat cloud in the coastal region of Antarctica.

3.2. Effective emissivity of clouds

It is recognized that two cloud layers existed in two case out of 11. They are omitted from the analysis for simplification of the discussion. Table 1 summarizes the measured data obtained in this study. The values of the effective emissivity are similar to those obtained by KAWAGUCHI (1983) who showed that the effective emissivity for downward flux $\varepsilon\downarrow$ was greater than that for upward flux $\varepsilon\uparrow$ in almost all cases (25 cases out of 26). The same result is obtained in this study: $\varepsilon\downarrow$ is greater than $\varepsilon\uparrow$ in 7 cases out of 9 and the averages of $\varepsilon\downarrow$ and $\varepsilon\uparrow$ for all cases are 0.90 and 0.75 respectively. We will discuss this difference between $\varepsilon\uparrow$ and $\varepsilon\downarrow$.

Figure 6 shows the effective emissivity as a function of the LWC. $\varepsilon\downarrow$ correlates well to the LWC but $\varepsilon\uparrow$ does not. There are large variations in $\varepsilon\downarrow$ and $\varepsilon\uparrow$ between the cases. Furthermore, $\varepsilon\uparrow$ presents very low value under 0.4 in two cases. Such low values are also presented in KAWAGUCHI (1983). In Fig. 6 the clouds accompanying with the extratropical cyclones are marked by arrows. No typical difference in the emissivity is found between the extratropical cyclones and a low level flat cloud in the coastal region.

For small cloud particles, the scattering contribution may be neglected, moreover,

Table 1. Summary of radiometersonde measurements of clouds in 1987.

Date	Start–end time(TSL)	Height (m) base	Height (m) top	T_b (K)	T_t (K)	Flux(Wm $^{-2}$) $F_b\uparrow$	$F_t\uparrow$	$F_b\downarrow$	$F_t\downarrow$	$\varepsilon\uparrow$	$\varepsilon\downarrow$	W (gm $^{-2}$)	HR*[1] (Kday $^{-1}$)	N*[2]	Cloud*[3]	Weather	Type
April 9	2206–2338	1305	2232	260.4	254.9	263	257	257	200	0.24	0.93	111	−7.5	8	Ac	snow	cyclone
May 22	2318–2345	2056	2535	252.8	249.8	237	223	230	125	0.84	0.98	75	−30.7	7	Ac	snow	cyclone
June 10	2253–0001	1405	5210	258.4	230.2	272	168	246	86	0.92	0.96	21	−9.9	8	As	cloudy	cyclone
June 25	1730–1855	3945	7604	241.8	215.2	204	133	173	45	0.84	0.86	59	−5.3	7	As	cloudy	coast?
July 5	1740–1901	953	3153	256.2	246.6	242	230	238	145	0.35	0.94	147	−14.5	8	As	snow	coast
July 14	2103–2231	2142	3073	249.8	243.5	236	201	200	94	0.96	0.84	30	−21.3	7	Ac	cloudy	coast
Aug. 6	2104–2229	887	3212	248.8	238.1	225	197	181	87	0.66	0.72	20	−3.9	8	As	snow	coast
Sep. 11	2139–2322	1367	3001	243.9	240.2	214	191	192	99	0.95	0.89	43	−12.0	7	As	snow	coast
Sep. 19	2157–2324	1450	2307	248.2	244.7	222	203	211	94	1.03	0.97	92	−30.1	8	Sc	cloudy	coast

*[1] Radiational heating rate of cloud top.
*[2] Cloud amount in eighths of the sky.
*[3] Ac; Altocumulus, As; Altostratus, Sc; Stratocumulus.

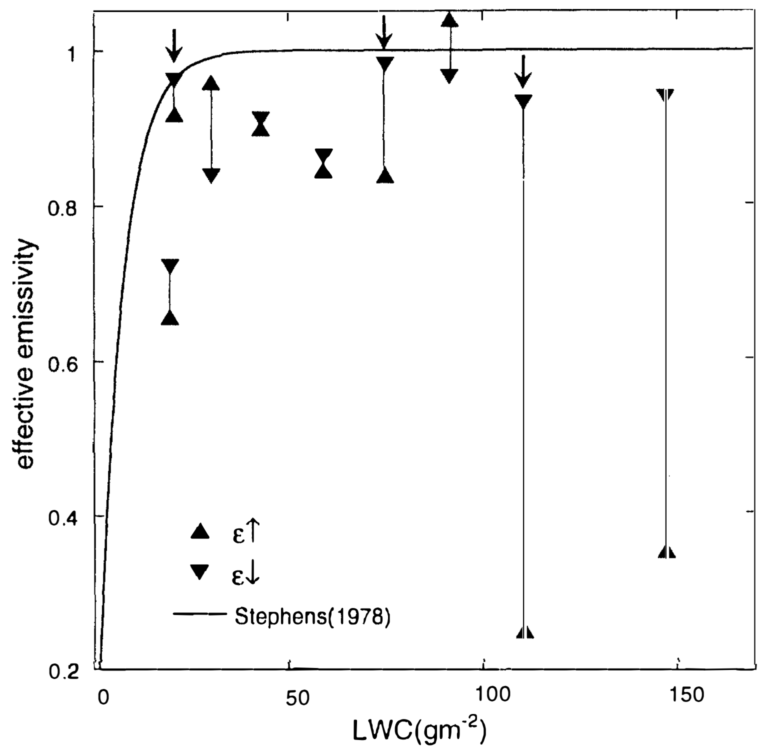

Fig. 6. The effective emissivity as a function of the LWC. The solid curve is a parameterization of Stephens *(1978) for ε ↓. The thin solid lines connect ε ↑ and ε ↓ in the same measurement. Arrow-pointed data are of the clouds with extratropical cyclones.*

because of the relatively small variation in the mass absorption coefficient with wave number, the gray approximation may be applied, that is, (*e.g.* Liou, 1992)

$$\varepsilon \cong 1-\exp(-k^c W), \tag{9}$$

where k^c is the wavenumber-averaged mass absorption coefficient. The value of k^c was obtained by some workers from measured fluxes and from fluxes determined by rigorous radiative transfer calculation. The value ranged from 0.08 to 0.15 for boundary layer cloud and 0.056 to 0.096 for cirrus cloud (Stephens, 1984). Stephens (1978) suggested the parameterization of the effective emissivity for water clouds based on the exact radiation calculation:

$$\varepsilon\downarrow = 1-\exp(-0.158\,W), \tag{10}$$

$$\varepsilon\uparrow = 1-\exp(-0.13\,W). \tag{11}$$

Equation (10) is plotted in Fig. 6. There is poor agreement with the LWC parameterization. It is notable that even at very large values of LWC most values of the emissivity are less than unity. The scatter of measured points and the discrepancy between parameterization and observations were also presented in earlier studies (Platt, 1976; Stephens *et al.*, 1978; Paltridge and Platt, 1981; Curry and Herman, 1985).

4. Discussion and Conclusion

It has been assumed that inhomogeneity of a cloud and uncertainties of measurement by radiometersonde account for the measured data (PLATT, 1976; STEPHENS *et al.*, 1978).

As shown earlier, the accuracy of the radiometersonde is evaluated by comparison with the pyrgeometer at the ground surface. This comparison confirms the radiometersonde observation, however, only near the surface. Radiometersonde performance has also been estimated by comparison to theoretical calculations (KANO and MIYAUCHI, 1977; YAMANOUCHI *et al.*, 1981; MIYAUCHI and OHKAWARA, 1992); however, this only applies under clear sky. We have no strict estimation of radiative fluxes through clouds to compare with the radiometersonde observations.

Inhomogeneity of clouds will partly account for the scattering of data. The radiometersonde will measure the longwave flux near clouds, thus in the sonde data the influence of inhomogeneity of cloud properties is minimized in comparison with airborne observation. However, the microwave radiometer will obtain the volume average overhead, and the sonde will not ascend straight above the launched station in general. This disagreement of measured volume accounts partly for the discrepancy.

As KAWAGUCHI (1983) pointed out, the discrepancy of $\varepsilon\uparrow$ and $\varepsilon\downarrow$ can be due to

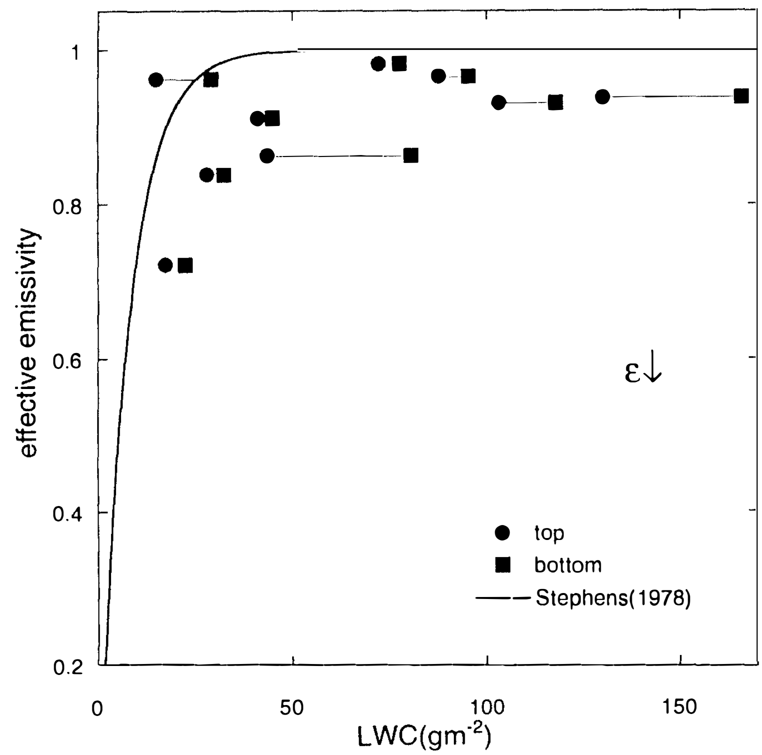

Fig. 7. Same as Fig. 6 but the effective emissivity is for downward flux only and LWC is calculated assuming that the cloud temperature T is that of the top of the cloud T_b and the bottom T_t in eqs. (7) and (8). The thin solid lines connect LWC using T_b and T_t in the same measurement.

the difference of the spectra between $F_t\downarrow$ and $F_b\uparrow$. Equations (10) and (11) imply that $\varepsilon\downarrow$ is only 5% greater than $\varepsilon\uparrow$ for $W=15$ gm^{-2}, and the deviation is less for greater W. That is, the difference of the spectra may account for this discrepancy only partly. It is likely that the scattering of longwave flux by water and ice particles produces this discrepancy. In eqs. (1) and (2), the scattering causes greater $F_t\uparrow$ and $F_b\downarrow$, then less $\varepsilon\uparrow$ and greater $\varepsilon\downarrow$ (in general, $\sigma T^4 > F_t\downarrow$ in eq. (1) and $\sigma T^4 < F_b\uparrow$ in eq. (2)), and then this discrepancy can be explained. CURRY and HERMAN (1985) showed that the reflectance of Arctic stratus (water clouds) is not negligible, about 6 to 9% in the window region. In this study the cloud top temperatures range from 258 K to 215 K, so that in most cases the clouds include ice particles, and the reflectance will take a greater value.

The effective emissivity may be greater than eq. (10) or eq. (11) since emission from ice particles will be added, but this happens in few cases. SUN and SHINE (1994) investigated the radiative properties of mixed phase clouds. It was shown that emissivity decreased when ice particles were neglected. This result, however, depend on some assumptions, the validity of which should be assessed by further observation, of the size spectra and distribution of ice particles.

When using eqs. (6) and (8) in Section 2.2, the vertical homogeneous distribution of water particles is assumed; consequently, T is the mean of temperature of the cloud base and top. The distribution of water particles, however, would have vertical inhomogeneity, and T should be between T_b and T_t assuming that the cloud layer has no inversion. Figure 7 shows the same as Fig. 6 but only the effective emissivity for downward flux; the LWC is calculated assuming that T equals T_b and T_t in eqs. (6) and (8). Difference of T causes about two times difference in W for the case of thick cloud. Applying T_t brings better agreement with the parameterization of STEPHENS (1978) than applying T_b. This result suggests that water particles exist closer to the cloud top than the cloud base.

The radiative property of Antarctic cloud, under conditions of poor shortwave radiation and very low temperature, might differ from that of a middle latitude or tropical region. It is expected that Antarctic cloud will be examined more by direct measurement. Moreover, synchronized observations of cloud using satellites, ground based remote sensing and sonde, for example, radiometersonde and hydrometeor video sonde (MURAKAMI and MATSUO, 1990), should be made.

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