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ON THE VERTICAL PROFILES OF LONG WAVE RADIATION AT SYOWA STATION IN ANTARCTICA

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Abstract: Vertical profiles of long wave radiation have been measured with radiometersonde since 1966 at Syowa Station in Antarctica. The measurements have been carried out mainly from March to October of each year. Much data have been stored but most have not been analyzed or evaluated. Here the data from 1966 to 1988 were analyzed for respective sky conditions: cloudless, overcast and all conditions. The upward fluxes at the 100 mb and 850 mb levels, and the downward fluxes at those levels in each month, are discussed, and also the budgets of radiative flux in the atmosphere and at the ground surface for all three conditions are discussed.

All downward and upward measured fluxes and those calculated are compared for cloudless conditions. The downward fluxes show good agreement with each other on average. But there are discrepancies in the case of upward flux. It can be inferred that the discrepancies might be caused by setting the ground surface temperature equal to the surface air temperature in calculation, and by the temperature change of the ground surface over location that the radiometersonde observed.

There are 6 types of radiometersonde used which are basically almost the same as each other. Discrepancies among vertical profiles of the flux measured with each type are discussed by comparing with those obtained by theoretical calculations concerning only the downward flux for cloudless conditions. Generally the vertical profiles of flux measured with each type of radiometersonde agree well with those calculated except for one type.

1. Introduction

In the past, some countries including Japan had carried out measurements of vertical profiles of long wave radiation. In 1970 international intercomparison of measurements was carried out in the Caribean Sea. GILLE and KUHN (1973) reported that there was a certain discrepancy among the fluxes measured by respective countries which participated (*e.g.* Japan, USA, USSR and West Germany). They noted that the measured flux might have some errors. They also reported that there is a certain difference between the measured and calculated flux.

In Japan routine measurements of long wave radiative fluxes in the atmosphere have been made at four observatories Sapporo, Tateno, Hachijojima and Kagoshima. KANO and MIYAUCHI (1977) compared measured and calculated fluxes at the three observatories (excluding Hachijojima).

Several researchers have reported discrepancies between measured and calculated fluxes (*e.g.* Kuhn and Suomi, 1965; Gille and Kuhn, 1973; Kano and Miyauchi, 1977; WMO, 1984). Generally speaking the downward flux calculated was smaller than that measured and the upward flux calculated was larger than that measured. Reasons given for the differences include 1) the calculation scheme had no contribution from aerosol, because of uncertain absorption characteristics; 2) the contribution of H_2O vapor in continuum absorption bands, which is said to have very strong absorption at higher temperature and concentration of water vapor, are not clear; 3) the measured flux usually has error.

Measurements with radiometersonde at Syowa Station have been made since 1966. They give us vertical profiles of long wave radiation in the atmosphere over Syowa Station in Antarctica. They are fundamental data for understanding the characteristics of the heat budget of long wave radiation in the polar region.

There are several studies about radiative energy in Antarctica because it has the own unique characteristics concerning radiation; most are restricted to ground-based measurements. Data obtained by Japanese Antarctic Research Expeditions in Antarctica from 1967 to 1969 were analyzed by Kawaguchi (1979), who discussed the properties of long wave radiation in the atmosphere. Yamanouchi *et al.* (1981a) reported on the comparison between measured and calculated fluxes in four cases of clear days in 1979.

Here we are going to analyze and evaluate all data measured with radiometersondes at Syowa Station from 1966 to 1988. First, measured flux in the atmosphere will be analyzed, mainly for monthly variations, and the results will be discussed. Second, the difference between measured and calculated fluxes in the case of cloudless conditions for respective downward and upward profiles will be discussed. Furthermore the greater difference of upward flux than downward flux will be discussed. Since several types of radiometersonde were used, the discrepancy among them will be discussed by comparing measured and calculated fluxes.

2. Measurements

There are 356 data during the years 1966–1988, of which 149 were in cloudless, 125 in overcast and 82 in other conditions. The number of the data

Table 1. Number of data measured each year from 1966 to 1988. The type of radiometersonde used is shown on the lowest line. N denotes the fractional cloud amount for 0 – 8.

Year	66	67	68	69	70	71	72	73	74	75	79	80	81	82	83	86	87	88	Total
Cloudless ($N \leqq 1$)	3	17	12	20	9	10	8	8	1	3	4	18	4	5	5	10	6	6	149
Overcast ($N \geqq 7$)	4	25	22	18	9	9	8	4	3	0	0	10	0	0	0	0	11	2	125
All data	14	53	44	45	23	25	21	17	6	3	8	31	9	7	9	10	21	10	356
Type	R62	R66		R68		R69					R78			R78-D					

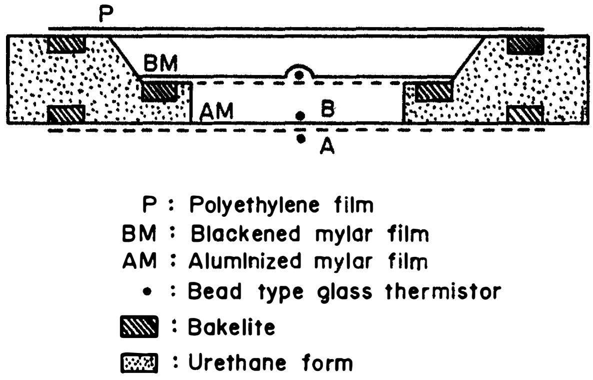


Fig. 1. Scheme of the radiometersonde sensor. Point A is where the film temperature was measured for types before 1975, B after 1979.

measured varies much from year to year; measurements were not carried out in the years 1976–1978, 1984 and 1985 (Table 1). The 6 types of radiometersonde used and the numbers of measurement carried out in cloudless, overcast and all conditions are shown in Table 1. The type of radiometersonde was changed often. Construction remained basically unchanged (Fig. 1); however, the materials and manufacturing procedure were somewhat different for each type. The most important change is that the point measuring the radiometersonde film temperature was moved from outside to inside the film (from A to B in Fig. 1). This point relates to heat transfer from the sensor surface to the film which covers the optically blackened sensor. These improved radiometersonde have been used since 1979. Radiative flux can be obtained from the next equation, of which the second term on the right hand side is related to the point moved from A to B described above.

$$F = \sigma T_r^4 + K\,(T_r^2 - T_s^2) + C\,\frac{dT_r}{dt},$$

here T_r : Temperature of sensor surface,
T_s : temperature of film,
K, C : constants,
σ : Stefan Boltzmann's constant.

Details of the construction and equation are shown in Antarctic Meteorological Data published by the JAPAN METEOROLOGICAL AGENCY (1991).

Releases of radiometersonde must be carried out during the night, so they were restricted from March to October. Measurement time was not fixed but

Table 2. Total number of data each month from 1966 to 1988.

	Mar.	Apr.	May	June	July	Aug.	Sep.	Oct.
Cloudless	7	10	24	18	30	29	21	9
Overcast	6	13	18	24	22	20	14	8
All data	19	29	54	55	70	65	45	17

most measurements were carried out from 17 to 24 hours local standard time at Syowa Station (GMT+3 hours). Table 2 shows the total numbers of measurement in each month of all years; the largest number were in July and August.

3. Analysis of the Data

The measurements were not done everyday, but several were done in a month. The mean fluxes at 100 and 850 mb for upward and downward in all years were made each month. The level 100 mb is considered the uppermost level measured because the fluxes above that level are suspected to be erroneous as described later. Although there is an ozone layer above 100 mb, the upward flux at that level is almost the same as that of out-going long wave radiation to space, so sometimes in the present paper the flux at the 100 mb level is regarded as out-going long wave radiation. There are some data at the 900 mb level; however, the 850 mb level is the lowest one at which most of the radiometersondes made measurements.

3.1. Monthly variations of the fluxes at the 100 and 850 mb levels

Figure 2a shows the monthly variation from March to October for upward fluxes at 100 mb, Fig. 2b downward fluxes at 100 mb, Fig. 2c upward fluxes at

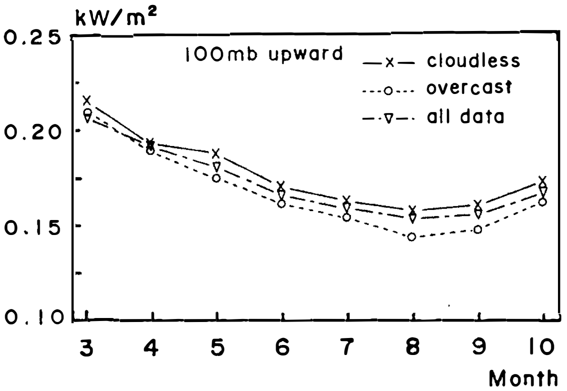


Fig. 2a. Monthly variations of upward fluxes from March to October at 100 mb for cloudless, overcast and all conditions.

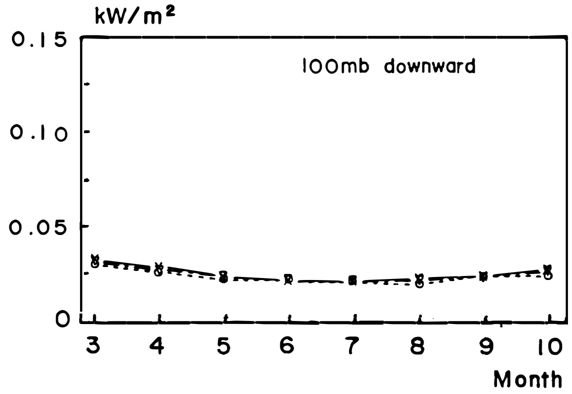


Fig. 2b. The same as Fig. 2a but downward fluxes at 100 mb.

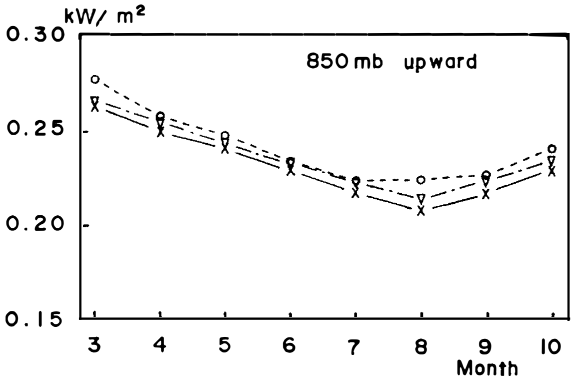


Fig. 2c. The same as Fig. 2a but upward fluxes at 850 mb.

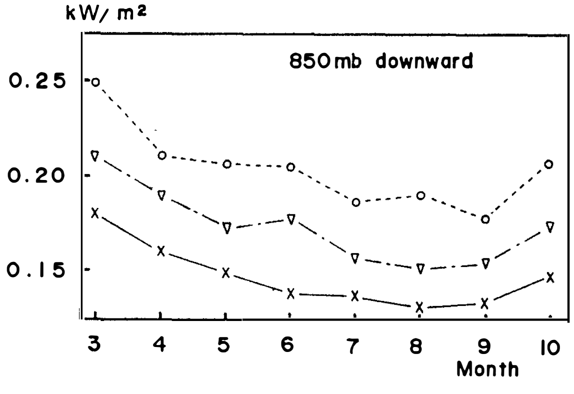


Fig. 2d. The same as Fig. 2a but downward fluxes at 850 mb.

Table 3a. Upward flux at 100 mb and the standard deviation.

	Cloudless		Overcast		All	
Month	Flux	St. dev.	Flux	St. dev.	Flux	St. dev.
3	0.211	0.011	0.205	0.015	0.202	0.020
4	0.188	0.027	0.185	0.027	0.187	0.026
5	0.184	0.010	0.170	0.034	0.176	0.025
6	0.166	0.020	0.156	0.029	0.160	0.025
7	0.158	0.016	0.150	0.017	0.155	0.021
8	0.153	0.013	0.140	0.018	0.149	0.016
9	0.157	0.012	0.143	0.024	0.152	0.017
10	0.168	0.025	0.157	0.009	0.163	0.020

Table 3b. Downward flux at 100 mb and the standard deviation.

	Cloudless		Overcast		All	
Month	Flux	St. dev.	Flux	St. dev.	Flux	St. dev.
3	0.032	0.007	0.030	0.011	0.033	0.010
4	0.029	0.012	0.026	0.009	0.027	0.010
5	0.024	0.007	0.022	0.009	0.023	0.008
6	0.022	0.009	0.023	0.014	0.023	0.012
7	0.021	0.006	0.021	0.008	0.021	0.007
8	0.022	0.009	0.019	0.009	0.021	0.009
9	0.023	0.009	0.023	0.007	0.024	0.008
10	0.025	0.012	0.027	0.007	0.026	0.010

Table 3c. Upward flux at 850 mb and the standard deviation.

	Cloudless		Overcast		All	
Month	Flux	St. dev.	Flux	St. dev.	Flux	St. dev.
3	0.263	0.010	0.277	0.009	0.263	0.024
4	0.250	0.030	0.257	0.025	0.254	0.026
5	0.240	0.012	0.246	0.034	0.241	0.025
6	0.230	0.024	0.231	0.029	0.233	0.025
7	0.218	0.019	0.223	0.027	0.222	0.024
8	0.206	0.019	0.223	0.025	0.212	0.024
9	0.215	0.017	0.224	0.036	0.224	0.027
10	0.228	0.029	0.239	0.017	0.233	0.025

Table 3d. Downward flux at 850 mb and the standard deviation.

	Cloudless		Overcast		All	
Month	Flux	St. dev.	Flux	St. dev.	Flux	St. dev.
3	0.180	0.019	0.250	0.017	0.210	0.040
4	0.159	0.015	0.212	0.030	0.188	0.034
5	0.150	0.017	0.207	0.033	0.171	0.036
6	0.138	0.029	0.206	0.026	0.177	0.039
7	0.137	0.021	0.183	0.030	0.158	0.032
8	0.129	0.022	0.191	0.031	0.152	0.038
9	0.133	0.017	0.178	0.037	0.155	0.034
10	0.149	0.020	0.208	0.020	0.174	0.035

850 mb and Fig. 2d downward fluxes at 850 mb, respectively, for cloudless, overcast and all conditions. These fluxes are averaged and have comparatively large standard deviations because the atmospheric conditions were varied when measurements were made. They are shown in Tables 3a to 3d where standard deviation for cloudless condition is a little smaller than the others generally, except for the downward flux at 100 mb, and that of downward flux at 850 mb for all conditions is the largest one. It is reasonable that each downward flux at 100 mb is the smallest for the respective conditions. These figures and tables show that the presence of cloud affects the radiative fluxes, especially for the downward flux at 850 mb. So the following discussions are valid only on average.

In Fig. 2a, the upward fluxes at 100 mb for the three conditions change monotonously with each month; all of them have minimum values in August. This means that the loss of energy from the earth-atmosphere system is minimum in August. In other words, the temperature of the earth-atmosphere system in August is the lowest on average, although strictly speaking the amounts of absorption gases are related. The flux for cloudless condition slightly exceeds that for the condition overcast in all months. It appears that the difference between cloudless and overcast conditions is the effect of cloud on out-going long wave radiation. The difference is much smaller than that at lower level. This is a remarkable feature, which reflects the difficulty of detecting the existence of cloud over Antarctica from the measurement of out-going long wave radiation by satellite. A curve for the case of all data lies between the two other curves except for March.

Downward fluxes at 100 mb are the smallest among all of the fluxes measured. These fluxes are not influenced by the atmosphere below 100 mb; moreover, there is no cloud and the amounts of absorbers such as water vapor do not vary so much above 100 mb. So it is natural that the downward fluxes for the three conditions are almost the same and do not vary much through the year. But they have slight variation, with minima around June and July, and become larger toward March and October. This means that atmospheric conditions above 100 mb, as far as radiative properties are concerned vary gradually. The cause of the slight variation is interesting, but not discussed here. It is a further problem.

In Fig. 2c, upward fluxes at 850 mb have minima around August for all conditions. Upward fluxes at 850 mb for overcast conditions are always greater than those for cloudless conditions in every month. Assuming that the cloud lies above the 850 mb level, this figure means that the ground surface temperature for overcast condition is higher than that for cloudless condition. From this it is speculated that the decrease of ground surface temperature is obstructed by cloud because there is much more downward flux on the ground surface for overcast condition than cloudless.

In Fig. 2d there is much difference in downward flux at 850 mb between cloudless and overcast conditions. The difference is nearly constant, about 0.07 kW/m^2, from March to October. This means that clouds produce much downward flux. This causes temperature decrease of the cloud layer, and also reduces the net flux divergence of the whole atmosphere, as discussed in the next section.

In the figure for cloudless condition, flux changes smoothly, but it does not for the overcast condition. As is well known, cloud affects the downward flux considerably, and varies with month, probably due to the height and thickness of the clouds. In the figure the minimum fluxes for the three conditions can be seen around August. This shows that the atmospheric temperature is minimum around August if the other factors are constant.

3.2. *Cooling of the ground surface, the earth-atmosphere system and the atmosphere itself*

The budget of radiative energy on the ground surface is approximated by the net flux at 850 mb although the contribution of the layer from the ground surface to 850 mb to the net flux at ground level is not necessarily negligible. In this case, net flux denotes downward flux–upward flux. The direction of the ordinate in Fig. 3 is opposite to conventional one. In the figure the effect of cloud on radiative budget at the ground surface can be seen. This effect is caused by the much larger downward flux for overcast condition than cloudless, whereas the difference of the upward fluxes between overcast and cloudless conditions is slight. Net fluxes at 850 mb in April are less than those in March for all conditions. This is due to the fact that the downward flux decreases much more rapidly from March to April than the upward flux as time changes (Figs. 2c and 2d). In cloudless condition, the decrease of net flux in the figure from March to April corresponds to the rapid decrease of downward flux; from April to June the net flux is almost constant. Then the net flux increases toward mid-winter. Yamanouchi *et al.* (1981b) made ground based measurements of net flux of long wave radiation on the ground surface in 1979 at Mizuho Station, East Antarctica, and reported the annual variations for all conditions. In that report, the net flux for cloudless condition seems to increase slowly from March to August. This tendency does not necessarily agree with the present result. But for April to August (mid-winter) tendency in present study is almost the same as the result obtained by Yamanouchi *et al.* (1981b) on the whole, although the net flux in

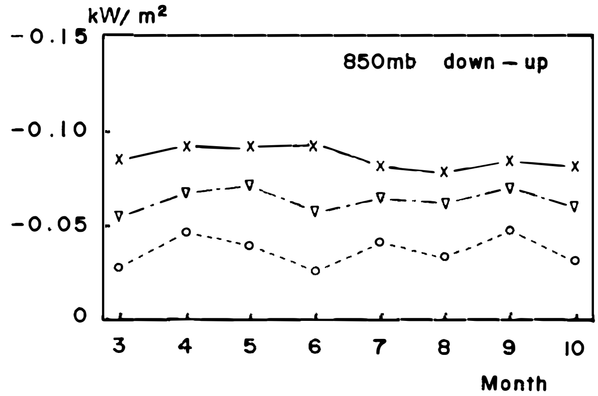


Fig. 3. Net fluxes at 850 mb (downward-upward flux in this case) for cloudless, overcast and all conditions. They mean approximately the energies that the ground surface gains. Symbols are the same as Fig. 2a.

Table 4. Standard deviation of net flux at the 850 mb level.

	Cloudless		Overcast		All	
Month	Net flux	St. dev.	Net flux	St. dev.	Net flux	St. dev.
3	−0.082	0.028	−0.027	0.016	−0.054	0.034
4	−0.091	0.017	−0.044	0.028	−0.066	0.030
5	−0.091	0.016	−0.039	0.035	−0.069	0.034
6	−0.092	0.028	−0.025	0.032	−0.055	0.042
7	−0.081	0.021	−0.040	0.031	−0.064	0.030
8	−0.077	0.020	−0.032	0.022	−0.060	0.030
9	−0.082	0.009	−0.046	0.035	−0.068	0.028
10	−0.079	0.019	−0.031	0.015	−0.058	0.030

June in the present study is slightly larger than that in May. The long wave net radiation on the ground surface in 1980 at Mizuho Station was also measured so that the tendency of variation is similar to that of Yamanouchi (1988). Mizuho Station is located on the slope of a glacier (always covered by snow), 2230 m above sea level, inland, but Syowa Station is on a small island near the coast of the continent. The discrepancy might be caused by the different location of the measurement site and also the different altitude above sea level and also measurement level. The net flux increase for overcast condition in June cannot be explained.

Standard deviations of the net flux at 850 mb are shown in Table 4 with the values of net fluxes. As shown in the table, standard deviations are much larger. This shows that the tendency of net flux at 850 mb is very changeable.

Figure 4 shows the net flux divergence of the layer from 850 to 100 mb for three conditions. In this case, net flux is defined as upward–downward flux. So the upward direction of the ordinate of Fig. 4 means loss of energy from the atmosphere. Obviously, the atmosphere with cloud has temperature much lower than the atmosphere without. Net flux divergence of whole atmosphere in

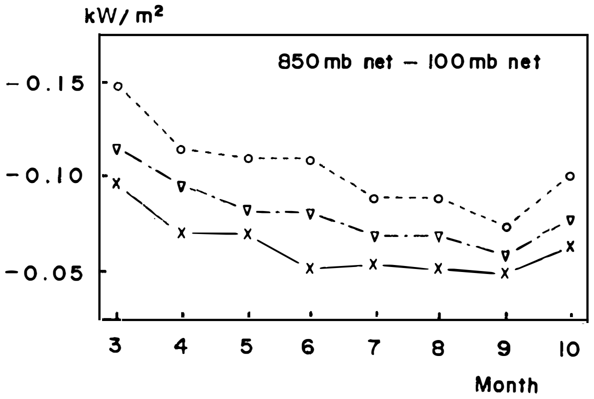


Fig. 4. The net flux divergences of the layer from 850 to 100 mb for cloudless, overcast and all conditions. The absolute value of the ordinate is the loss of energy from the layer. Symbols are the same as Fig. 2a.

mid-winter especially in cloudless condition, is larger than in other seasons. That is, there occurs less cooling of the atmosphere in mid-winter. This is consistent with the small upward flux at 100 mb and downward flux at 850 mb. In the figure, much more cooling of the atmosphere occurs in autumn than in mid-winter due to higher temperature and water vapor concentration in the atmosphere. Net flux divergences have large dispersion. This discussion applies to the average over months as described before.

It is very interesting to discuss the yearly variation of the long wave radiative flux in the atmosphere. To do so requires continuous and frequent measurements over a long term; the present data are not sufficient. Since cloud easily changes the long wave radiative flux, the yearly variation of all fluxes has no special meaning.

3.3. *Monthly variation of vertical profile*

Mean vertical profiles of each month are shown in Fig. 5 for upward and downward fluxes for cloudless condition. In the case of upward flux their profiles are more varied than for downward flux. Ground surface temperature change makes the upward flux vary considerably. Downward fluxes in the higher layer, especially near 100 mb, are almost the same as each other (note Fig. 2b). The fluxes above the 250 mb level in March are obviously not correct. The same increase as in height appears in upward flux in May. It was possibly affected by solar radiation because of the position of the sun in May. The errors are also found in upward and downward fluxes at about 800 to 700 mb in October that

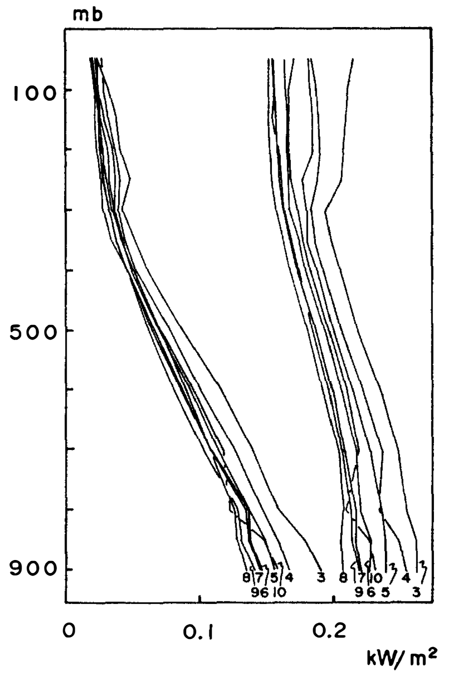


Fig. 5. Monthly variations of vertical profiles.

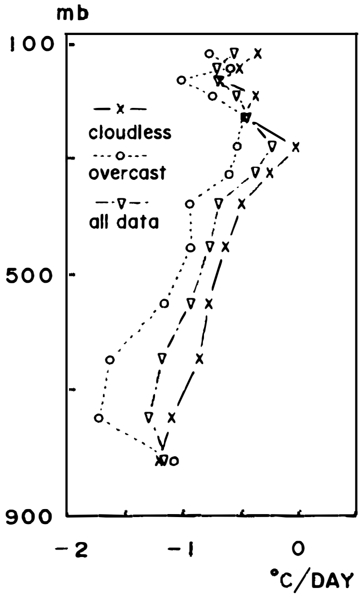


Fig. 6. Vertical profiles of cooling rate in the atmosphere averaged from March to October for cloudless, overcast and all conditions.

cannot be explained. These profiles were measured during the night; therefore, the profiles in the daytime might be slightly different, especially for upward flux, because of the diurnal change of ground surface temperature.

3.4. Vertical profiles of cooling rate

Vertical profiles of cooling rate for each condition, cloudless, overcast and all, are shown in Fig. 6. In the figure it is obvious that the distribution of cooling rate in the atmosphere depends on the cloud; much more cooling occurs for cloudy than for cloudless condition in most of the atmosphere. This is consistent with the net flux divergence shown in Fig. 4. It is also shown that the cooling rates for three conditions become close to each other as the level becomes higher.

Yamanouchi *et al.* (1981a) showed four vertical profiles of cooling rate measured for cloudless condition in May, April, June and July 1979 in which the mean profile of the cooling rate of the four is similar to our result for cloudless condition in shape. Vertical distribution of cooling rate changes day by day, especially in a cloudy sky, so the standard deviations of the cooling rate become larger (Table 5). In the table the largest standard deviation of cooling rate appears at the 750 mb level for overcast condition. This shows that the cooling rate changes depending on the height of the cloud layer.

Table 5. Standard deviation of cooling rate.

	Cloudless		Overcast		All	
mb	C. rate	St. dev.	C. rate	St. dev.	C. rate	St. dev.
875	-1.17	2.27	-1.36	3.75	-1.23	2.46
825	-1.20	2.40	-1.08	3.66	-1.14	1.92
750	-1.09	2.05	-1.73	5.24	-1.29	1.98
650	-0.86	1.26	-1.63	2.96	-1.17	1.42
550	-0.77	1.08	-1.15	2.12	-0.92	1.08
450	-0.63	0.97	-0.92	1.53	-0.76	0.85
375	-0.49	1.42	-0.94	2.02	-0.68	1.37
325	-0.25	0.88	-0.59	1.50	-0.38	1.38
275	-0.03	2.18	-0.54	1.22	-0.24	2.11
225	-0.47	2.34	-0.47	1.45	-0.44	1.75
187	-0.37	1.39	-0.74	1.60	-0.53	1.43
162	-0.67	1.66	-1.00	2.10	-0.70	2.95
137	-0.52	1.70	-0.58	1.95	-0.71	3.04
112	-0.35	1.79	-0.76	2.09	-0.54	1.72

4. Comparison of Vertical Profiles Between the Measured and Calculated Fluxes

By comparing the measured flux with that calculated, the characteristics of the radiometersonde used at Syowa Station and the properties of long wave radiation in the atmosphere in Antarctica can be discussed.

4.1. Scheme and data used in calculations

The calculations are done by using a transfer equation in which the transmission function of Goody's random model (Goody, 1964) is employed. There has been some discussion about the accuracy of the calculation scheme (*e.g.*, Chou and Arking, 1980; WMO, 1984; Aoki and Shibata, 1990; Tjemkes and Nieuwstadt, 1990); however, here the scheme given by Rodgers and Walshaw (1966) is used. This scheme has no contribution from aerosol and it has been said that there is uncertainty as to absorption in the water vapor continuum, but it has been used widely in the world. Since Kano and Miyauchi (1977) and Yamanouchi *et al.* (1981a) also used this scheme, we can compare with their results. The accuracy of this scheme itself is a separate problem.

Meteorological data, *e.g.* temperature and water vapor in the atmosphere over Syowa Station, were obtained by meteorological radiosondes, usually twice a day (Japan Meteorological Agency). They are interpolated linearly to the hour when radiometersondes were released between the hours of two meteorological measurements with radiosondes. The ground surface temperature is set to be equal to the surface air temperature although this assumption does not hold generally and will be discussed later. The vertical distributions of the ozone amount are taken from the statistical monthly values which were measured at Syowa Station from 1967 to 1987 (Japan Meteorological Agency). The amount of carbon dioxide is fixed at 340 ppm. These concentrations, as well as the water vapor amount used for calculation, are not always correct. The calculated flux has an error from the uncertainties of these concentrations. But it cannot be specified how much the error is.

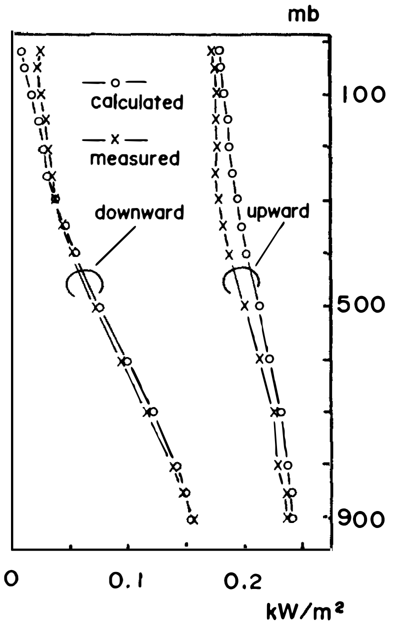


Fig. 7. Comparisons between mean vertical profiles of the fluxes measured and calculated for cloudless condition.

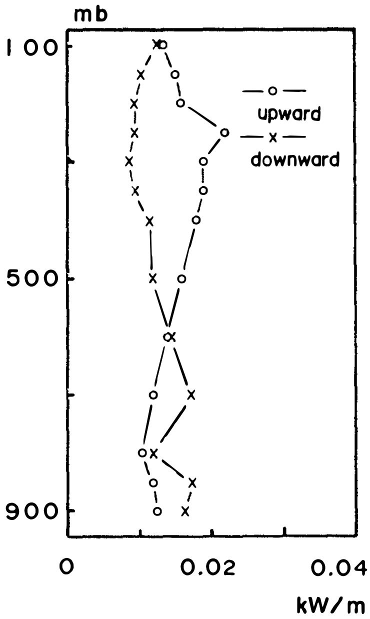


Fig. 8. Root mean square of the difference between measured and calculated fluxes for cloudless condition.

Figure 7 compares the mean of all data for cloudless conditions, 149, between the measured and calculated fluxes. The root mean square of the difference between them (hereafter written merely R.M.S.) is shown in Fig. 8. In Figs. 7 and 8, the number of data measured at the 900 mb level is much less than at other levels.

The following discussions are restricted to the average for cloudless condition.

4.2. Downward flux

Ozone amount and the other constituents have some uncertainties in the vertical profile and calculation scheme, however, the measured and calculated downward fluxes agree well with each other on average as shown in Fig. 7 except for the upper layer above 100 mb. The R.M.S. of the difference between them is always less than about 0.02 kW/m^2 at all levels up to 100 mb (Fig. 8). In the lower atmosphere near the ground surface the fluxes agree well with each other but in the layer from 800 to 300 mb the calculated flux is slightly larger than that measured. The relation between the measured and calculated fluxes is opposite to that reported by KANO and MIYAUCHI (1977), although the difference in the present study is very small. And in the upper layer above about 300 mb the calculated flux changes smaller than that measured. These tendencies in the present study are similar to the result reported by YAMANOUCHI *et al.* (1981a) although the difference reported by them is larger than the present value.

It is assumed that the measurement accuracy of the radiometersonde used at Syowa Station is not necessarily the same as that used in Japan in the past. Unfortunately we cannot know how much the accuracy has changed. But the calculation scheme is the same as that used by KANO and MIYAUCHI. If the accuracies of the radiometersondes used by them and in the present study are the same, the discrepancy of the result for downward flux between the report by KANO and MIYAUCHI (1977) and the present result would be caused by only the difference of atmospheric conditions used in the respective calculation.

KANO and MIYAUCHI (1977) reported that the measured flux is always larger than that calculated for downward profiles obtained in Japan at levels up to 200 mb, and the difference decreases slightly with altitude. They inferred that the difference might be due to the effect of H_2O dimmer molecules and aerosols in the lower layer, and also measurement error, especially above 200 mb. Absorption of the water vapor continuum is less active for less water vapor and lower temperature (BIGNELL, 1970) in the atmosphere in Antarctica. There are some data reported that the concentration of aerosols in Antarctica are much less than in Japan. Their effect on the downward flux in the calculation scheme can be lessened much in the winter atmosphere in Antarctica. From this viewpoint the present result at Syowa Station is consistent with their results for downward flux if both measurement data are correct. It is noted that the water vapor amounts used for calculation in this study was obtained from meteorological radiosondes but that used in KANO and MIYAUCHI were obtained from dewpoint sondes. At the time when the measurements with radiometersondes were carried out at four observatories in Japan, the water vapor amounts measured with meteorological sondes were erroneous, but after that the sensor for measuring water vapor as used in Antarctica has been much improved. The vertical profile of long wave radiation depends much on the water vapor amount in the atmosphere. In this study it is considered that the measured water vapor amounts used in both studies are correct.

As for the upper layer above 100 mb, the measured downward flux becomes much larger than that observed. There are many cases in which the flux increases as the radiometersonde ascends. In this case the data are evidently erroneous. It is possible that the measured downward flux tends to be larger than that calculated above 300 mb. KANO and MIYAUCHI (1977) did not compare the measured and calculated fluxes in the layer above 200 mb because of this evident measurement error. This problem still awaits settlement and must be investigated.

We find that for downward flux below the 100 mb level, the measured profile agrees well with that calculated using Rodgers and Walshaw's scheme on average, although the calculated flux is slightly larger than that measured in the layer from 800 to 300 mb and becomes smaller than that measured above 300 mb.

4.3. Upward flux

Figure 7 also shows the mean upward fluxes, both measured and calculated for cloudless condition. At all levels the calculated flux is a little larger than that measured. The difference around the 850 mb level is the smallest of all levels, and increases gradually as height increases to about the 300 mb level and then decreases above 300 mb.

In the present calculation the ground surface temperature is set equal to the surface air temperature because of lack of ground surface temperature data. But generally during the night the ground surface temperature becomes lower than the surface air temperature (KANETO *et al.*, 1990). If the ground surface temperature is set several degrees lower, the measured and calculated fluxes near the ground surface (at 900 or 850 mb) will agree with each other and the difference in the whole atmosphere will decrease.

The ground surface temperature which the radiometersonde sees changes during the wind-driven flight. The same process is described by KANO and MIYAUCHI. The effect of the ground surface temperature is discussed below.

A radiometersonde can also see the clouds as the sonde moves horizontally even if the condition is cloudless at Syowa Station. Generally the cloud temperature is lower than the surface air temperature (note Fig. 2a). As a sonde is going up and moving, the colder area probably including cloud that it sees spreads. Traces of twelve radiometersondes released in 1983 and 1987 in cloudless condition are shown in Fig. 9. Most of the radiometersondes flew toward the continent and the rest also saw a part of the continent as the sondes ascended.

In the calculation scheme, if the altitude of the continent above the sea level and the atmospheric conditions (water vapor, etc.) are constant horizontally, the

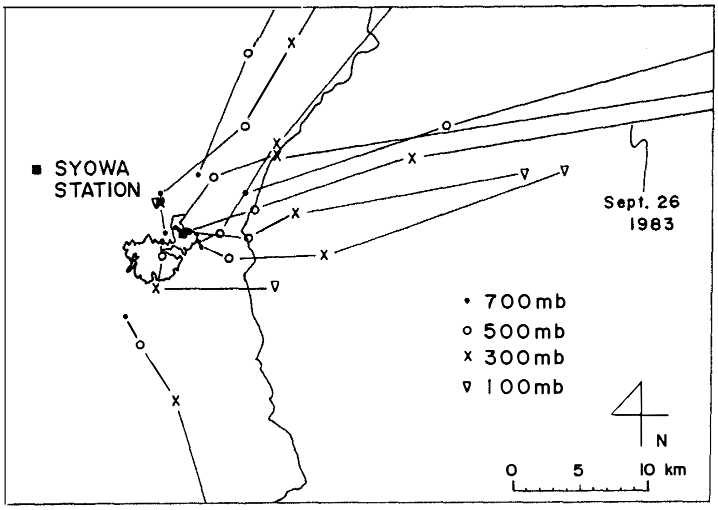


Fig. 9. Traces of radiometersonde released in 1983 and 1987 for cloudless condition.

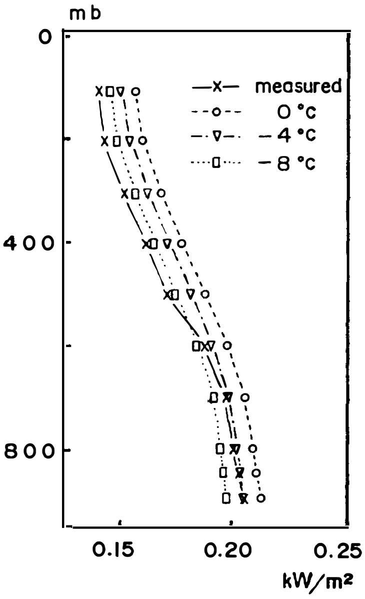


Fig. 10. Vertical profiles of the measured and calculated fluxes. Ground surface temperature is set to 0, 4, 8°C lower than surface air temperature.

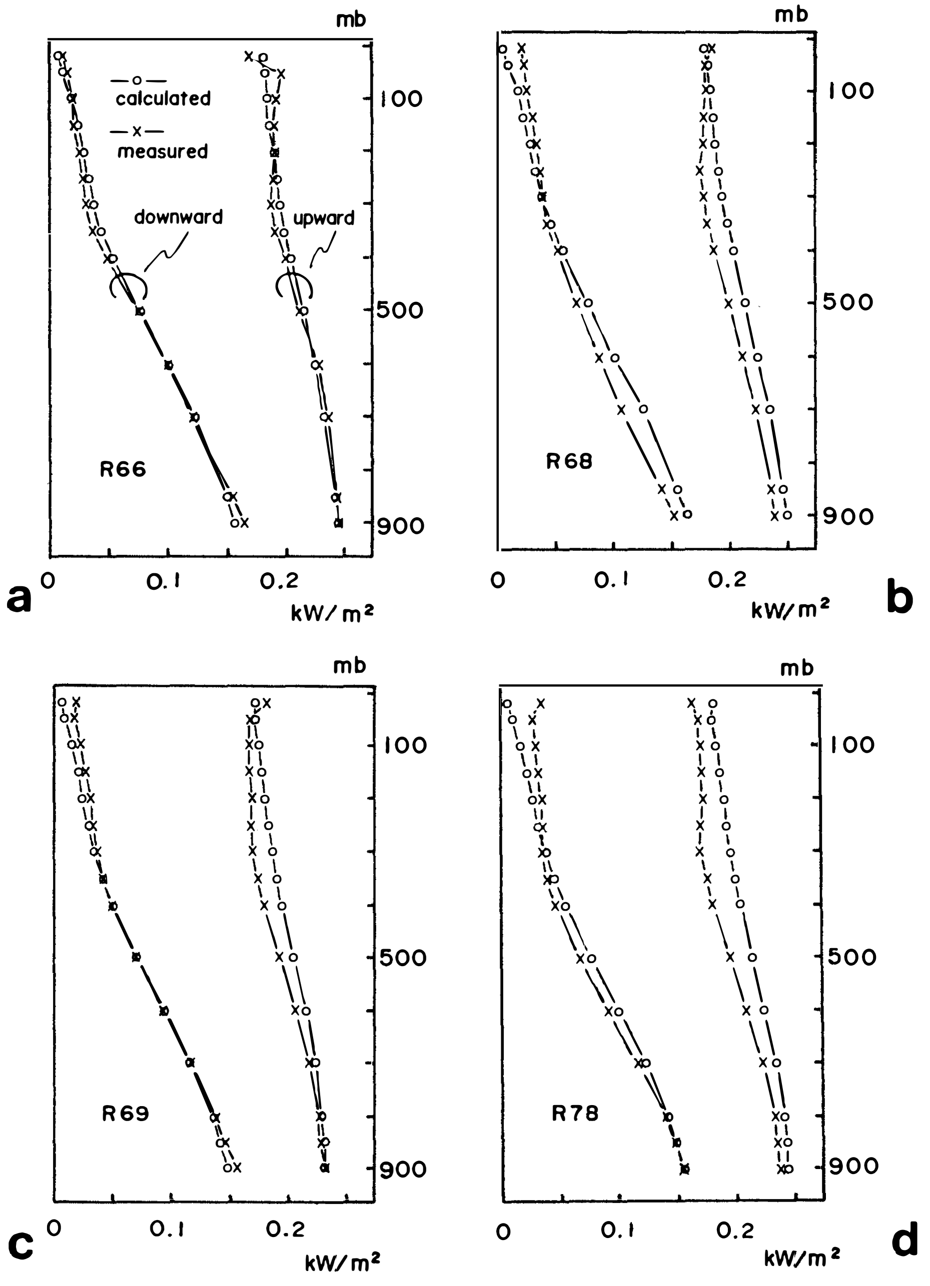
upward flux depends on the ground surface temperature (including cloud patch, if it exists) only in the view angle that the sonde sees. Assuming that the ground surface temperature is 4 and 8°C lower than the surface air temperature, profiles of the upward flux in one case released on September 26, 1983 in Fig. 9 are calculated; the results are shown in Fig. 10. In the figure it can be seen that the upward profile depends greatly on the ground surface temperature.

The surface temperature of the sea seems to be higher than that of the continent, and that of the interior continent is much lower than that around the coast. Syowa Station is located on a small island. The difference between the measured and calculated fluxes can be explained qualitatively in these situations. A quantitative comparison could not be made because the temperature of the ground surface and the atmospheric conditions below the flying sonde were not known. The ground surface temperature around Syowa Station needs to be investigated.

The measured flux becomes close to that calculated in the layer above 300 mb in Fig. 7. This tendency is not consistent with the above description. Because, in the case of downward flux the measured flux has the tendency to increase, compared with that calculated; it is speculated also in the case of upward flux that the measured flux has the same tendency as downward flux to increase in comparison with that calculated.

5. Comparisons of the Fluxes Obtained from Each Type of Radiometersonde

Measurements with the radiometersonde have been made for a long period at Syowa Station where several types of radiometersonde were used, as described in Section 2. It must be made clear whether there is any discrepancy among the fluxes obtained from each type, or not. Since there is no downward flux at the top of the atmosphere, only downward flux is used for analysis, compared with the reference flux calculated for cloudless condition.



Figs. 11a–e. Mean upward and downward profiles measured with each type R66, R68, R69, R78 and R78–d and those calculated for cloudless condition.

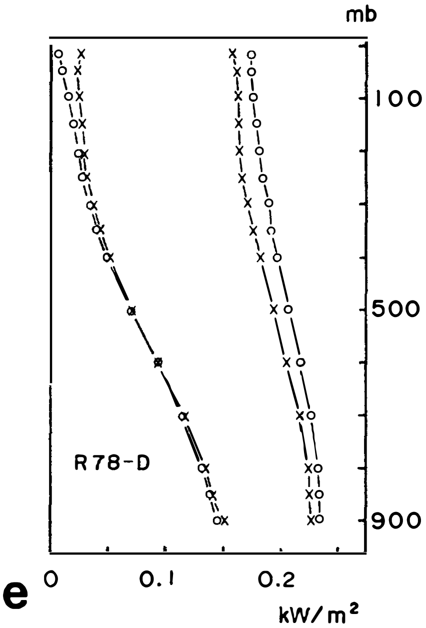


Fig. 11 (Continued).

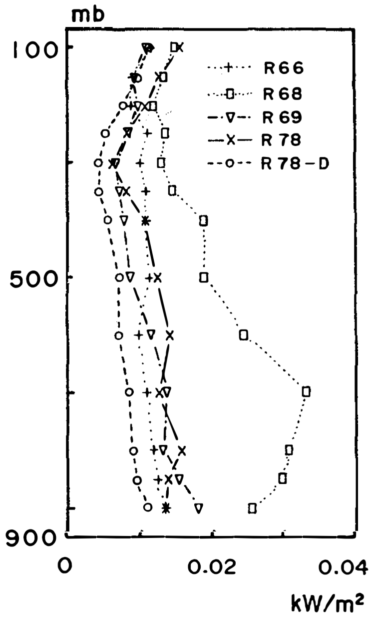


Fig. 12. Root mean square of the difference of the flux along vertical profile between the measured and calculated fluxes for each type of radiometersonde.

In Figs. 11a to 11e the mean measured and calculated fluxes are shown for each type, except for type R62, which cannot be analyzed and is omitted because of its small number of data (only three). With regard to downward measured and calculated fluxes, they agree well with each other generally for types R66, R69 and R78-D. There is slight difference for type R78 and more difference for R68 than for the others.

The differences in R.M.S. between the measured and calculated fluxes along the vertical profiles for each type are shown in Fig. 12. There are two kinds of groups, one includes R66 and R68 before the minor change described in Section 2, and the other types R69, R78 and R78-D. Although the R.M.S. of R68 is the largest and that of R78 is somewhat larger than the others, it seems that there is no relationship among the types and that there is no clear discrepancy between the two kinds of group, because the R.M.S. of R66 is not so large compared with the other group.

Generally, above the 300 mb level, R.M.S. increases with height. The only downward flux measured with R66 has almost constant R.M.S. at all levels. The R.M.S. of R66, R69, R78 and R78-D are less than about 0.015 kW/m^2. The downward flux measured with R68 has the largest R.M.S. among them, as shown in the figure. But the reason is not clear. Assuming that the calculated flux is correct, the flux measured with type R78-D is the most reliable; it is the newest type used and its R.M.S. is always less than 0.01 kW/m^2.

6. Conclusions

The Antarctic region loses more energy through long wave radiation emitted to space than that received from solar radiation. It is interesting to know long wave radiative energy flow by measurement in the polar region. Here the monthly energy budget of the long wave radiation is discussed on the basis of measurement data and compared with that calculated. And also the contribution of cloud to the energy budget at Syowa Station is analyzed. Unfortunately measurements with radiometersonde could not be carried out in summer; also measurements were not done every day but relatively infrequently. So annual variations could not be analyzed; only monthly variations from March to October of an average over 18 years were obtained. The present results must be closely related to the meteorological and climatic conditions at Syowa Station, but the relations were not analyzed. This will be taken up in the future.

Measured and calculated fluxes were compared for cloudless condition. For downward flux they agree with each other below the 100 mb level. Above the 100 mb level, measurement error seems to become large as the sonde height increases. For the upward flux, the large difference is explained qualitatively by the effect of the ground surface temperature and the underlying cloud. Measurements and calculations have some errors. But considering that the ground surface temperature is lower than the surface air temperature, and that radiometersonde sees a colder ground surface as it ascends, it can be said from the present analysis that the measured fluxes are close to those calculated. Therefore it might be said also that the measured fluxes for cloudy condition are also close to true values if the calculated fluxes are correct. The radiometersonde is an absolute radiometer, but it is very difficult to specify the measurement error, especially in the upper atmosphere. KANETO *et al.* (1990) compared a ground based radiometer with the radiometersonde used in 1987 at Syowa Station for upward and downward fluxes. They agree with each other within about ±5 % for both upward and downward fluxes.

It seems that there is no remarkable discrepancy among the fluxes obtained with each type of radiometersonde except the type R68. The downward flux measured with the type R68 is smaller than that calculated below 300 mb, and the R.M.S. is the largest of all types.

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References

Aoki, T. and Shibata, K. (1990): Some developments of the method to apply band models to an inhomogeneous atmosphere. J. Meteorol. Soc. Jpn., **68**, 385–394.

Bignell, K. J. (1970): The water vapor infra-red continuum. Q. J. R. Meteorol. Soc., **95**, 390–403.

Chou, M. D. and Arking, A. (1980): Computation of infrared cooling rates in the water vapor bands. J. Atmos. Sci., **37**, 855–867.

Gille, J. G. and Kuhn, P. M. (1973): The International Radiometersonde Intercomparison Programme (1970–1971). Geneva. WMO, 127 p. (WMO Tech. Note, 128).

Goody, R. M. (1964): Atmospheric Radiation I Theoretical Basis. Oxford, Clarendon Press, 436 p.

Japan Meteorological Agency (1991): Meteorological data at the Syowa Station in 1989. Antarct. Meteorol. Data, **30**, 274 p.

Kaneto, S., Sugiwara, H., Ogiwara, H. and Yamamoto, A. (1990): Dai-28-ji Nankyoku chiiki kansokutai kishô bumon hôkoku 1987 (Meteorological observations at Syowa Station in 1987 by the 28th Japanese Antarctic Research Expedition). Nankyoku Shiryô (Antarct. Rec.), **34**, 15–45.

Kano, M. and Miyauchi, M. (1977): On the comparison between the observed vertical profiles of longwave radiative fluxes and the computed ones in Japan. Pap. Meteorol. Geophys., **28**, 1–8.

Kawaguchi, S. (1979): Nankyoku Taiki no Hôsha Tokusei (Radiation Properties of Antarctic Atmosphere). Doctoral Thesis, Tohoku Univeristy, 179 p.

Kuhn, P. M. and Suomi, V. F. (1965): Airborne radiometer measurements of effects of particulates on terrestrial flux. J. Appl. Meteorol., **4**, 246–252.

Rodgers, C. D. and Walshaw, C. D. (1966): The computation of infrared cooling rate in planetary atmospheres. Q. J. R. Meteorol. Soc., **92**, 67–92.

Tjemkes, S. A. and Nieuwstadt, F. T. M. (1990): A long wave radiation model for the nocturnal boundary layer. J. Geophys. Res., **95**, 867–872.

WMO (1984): The Intercomparison of Radiation Codes in Climate Models. WCP-93, Geneva, WMO, 37 p.

Yamanouchi, T. (1988): Hôsha (Radiation). Nankyoku no Kagaku 3. Kishô (Science in Antarctica 3. Meteorology), ed. by Natl Inst. Polar Res. Tokyo, Kokon Shoin, 10–56.

Yamanouchi, T., Yamamoto, Y., Meshida, S. and Uchiyama, A. (1981a): On the measurements by radiometersonde at Syowa Station, Antarctica. Mem. Natl Inst. Polar Res., Spec. Issue, **19**, 62–74.

Yamanouchi, T., Wada, M., Mae, S., Kawaguchi, S. and Tsukamura, K. (1981b): Measurements of radiation components at Mizuho Station, East Antarctica in 1979. Mem. Natl Inst. Polar Res., Spec. Issue, **19**, 27–39.

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