MEASUREMENTS OF RADIATION COMPONENTS AT MIZUHO STATION, EAST ANTARCTICA IN 1979

Takashi YAMANOUCHI, Makoto WADA, Shinji MAE, Sadao KAWAGUCHI

National Institute of Polar Research, 9–10, Kaga 1-chome, Itabashi-ku, Tokyo 173

and

Koji TSUKAMURA

Japan Meteorological Agency, 3–4, Otemachi 1-chome, Chiyoda-ku, Tokyo 100

Abstract: Radiation budget measurements were made at Mizuho Station under the program of POLEX-South. Global and reflected shortwave downward and upward longwave radiations were measured at the snow surface and at the top of a 30 m tower. Direct solar radiation was also measured at the snow surface. The spectral measurements of shortwave radiation divided into four wavelength regions were made.

Sensitivity constants of the pyranometers used for the measurement of global and reflected radiations showed large deviation from the cosine law response at a low solar elevation. Field calibration of the pyranometers was made extensively and some realistic equation to derive the global radiation under a broken sky from several calibration factors was proposed. As for the longwave radiation measurements, the pyrgeometer was equipped with a simple shading ring in order to eliminate the heating effect of the hemispherical dome due to solar radiation.

Diurnal and seasonal variations of radiation components are shown and those of the net radiation are also given. Daily totals of the net radiation remain negative even in the summer for the clear sky, on account of high albedo of the snow surface and large upward longwave radiation compared with the downward. Downward longwave radiation was much more sensitive than the global radiation to the cloud amount and controlled the daily variations of the net balance.

1. Introduction

Extensive measurements of radiation components were made at Mizuho Station under the program of POLEX-South (Polar Experiment-South). The three-year project of POLEX-South, as one of the subprograms of GARP (Global Atmospheric Research Program), has been carried out by the Japanese Antarctic Research Expedition (JARE) from 1979 to 1982. Details of the program were described elsewhere by KUSUNOKI (1981). Mizuho Station (70°42′S, 44°20′E) is located at the height of

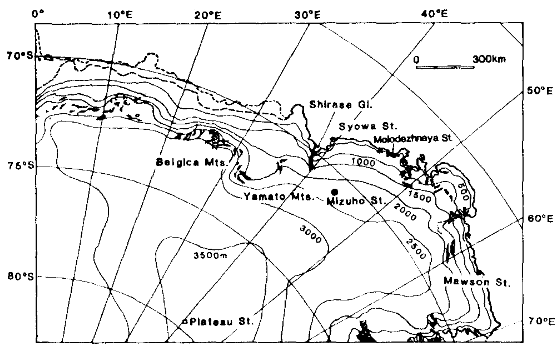

Fig. 1. Location of Mizuho Station.

2230 m above sea level on the slope of the Antarctic glacier as shown in Fig. 1. The climate of Mizuho Station is characterized mainly by the katabatic wind which blows continuously and by low temperatures yearly average being below −30°C.

Several observations of radiation components were executed in the past at Mizuho Station by JARE. Net radiation at the snow surface was measured by a net radiometer in the austral summer of 1971–1972 and the data were reported by YAMADA (1975). The results of the solar radiation balance measured from July to December 1972 were discussed by KAWAGUCHI and SASAKI (1975). To make a more accurate measurement with precise calibration of the sensor, the spectral measurement of solar and reflected radiations was recommended by them. The global radiation measured in 1977 was reported by FUJII and KAWAGUCHI (1978).

The present observation of radiation was made in order to describe the annual variation of radiation budget and to make clear the heat balance of the snow surface at Mizuho Station. In order to clarify the effect of drifting snow, measurement was made at two sites, one at the height of 1.5 m above snow surface and another at the top of a 30 m tower. Effects of clouds, aerosol particles and snow surface on the radiation field were also the subjects of the observation. Spectral measurements of direct, global and reflected solar radiations, and measurements of atmospheric and terrestrial radiations were made. Radiation measurement especially in the polar region is accompanied with difficulty in maintaining accuracy, on account of high albedo of snow surface which results in a small amount of net radiation, and on account of low solar elevation which results in large uncertainties of pyranometer measurements. Emphasis was placed particularly on the calibration of the sensor throughout the measurements.

This paper presents the methods of measurement and calibration in detail. Preliminary results of radiation budget measurements at the ground are also given.

2. Measurements and Calibrations

Global, reflected downward longwave and upward longwave radiations were measured by means of pyranometers and pyrgeometers at the height of 1.5 m above the snow surface and at the top of a 30 m tower. Direct solar radiation was also measured by a pyrheliometer at the height of 1.5 m. Shortwave radiation was measured spectrally by cutoff filters of four different wavelength regions; 305–2800 nm with the filter of WG305 (no filter but only with a quartz window for the direct radiation), 530–2800 nm with OG530, 630–2800 nm with RG630 and 695–2800 nm with RG695, respectively. Installation and performance of the system of measurements were previously reported by MAE *et al.* (1981a). Calibration of the pyrheliometer had also been mentioned and the temperature coefficient of the sensitivity constant was obtained as $-0.13\%/°C$. In this section, methods of measurements and successive calibrations are presented.

2.1. Pyranometer

As for the pyranometers, sensitivity constant of the present model MS-800 made by Eko Instruments Co., was said to be less sensitive to the variation of incident angle. However, in the observation it was found that the sensitivity of some of the sensors showed large deviation from a cosine law response on the incident angle and the incident angle dependence of sensitivity differed from sensor to sensor. In this observational program, one of the sensors was treated as the field standard. This pyranometer was carefully calibrated in the field by the sun occulting method in comparison with the pyrheliometer which was occasionally calibrated against the Ångström compensation absolute pyrheliometer of International Pyrheliometric Scale IPS-1956. Calibration factor $D(h)$ defined as a ratio of the measured global radiation S' to the true global radiation S was derived as follows,

$$D(h) \equiv \frac{S'}{S} = \frac{\Delta S'}{I \sin h}, \tag{1}$$

where $\Delta S'$ is a reduction of pyranometer output (in radiation unit) by shading the sensor from direct radiation. $\Delta S'$ corresponded to the horizontal component of the direct solar radiation $I \sin h$, where direct radiation I was derived from the pyrheliometer and h was solar elevation. With this method, $D(h)$ can only express the calibration factor for direct component. At Mizuho Station the maximum solar elevation is limited to about 40°, and it was impossible to make a field calibration at a higher solar elevation. Then the sensor which was used as the field standard was brought back to Japan and laboratory calibration was made by the aid of a testing instrument of the Japan Meteorological Agency in the next year of the observation. Because the laboratory calibration could not present an absolute value but only a relative value of $D(h)$, two sets of calibration curves from field and laboratory were joined at about 40° of solar elevation. Then the calibration curve for larger solar elevation derived from laboratory calibration also gained an absolute value. In Fig. 2, $D(h)$ is shown with thick solid line.

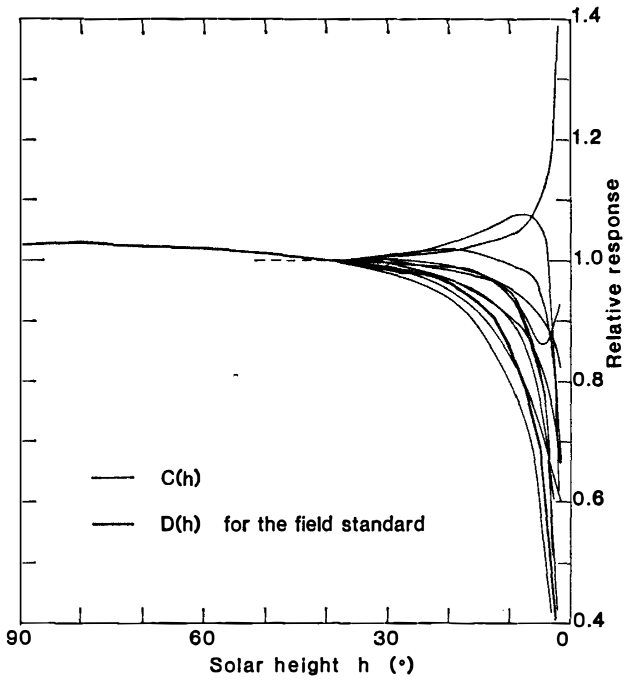

Fig. 2. Incident angle dependence of pyranometers. Ordinate indicates a relative response and all curves are normalized at 40°.

Though a resistance-thermistor circuit was equipped in order to compensate for the temperature dependence of the sensitivity constant, the pyranometer still had some dependence on the temperature. It was difficult to obtain the temperature dependence independently of the incident angle dependence. In the laboratory, measurement of the temperature dependence was not made below −10°C, but the temperature dependence was assumed to be within 0.1%/°C from the measurement at high temperatures. The present value of calibration curve was assumed to be an absolute value, that is to say, the calibration factor also contains the temperature dependence implicitly, for the temperature around −20°C±10°C, which was a typical temperature at Mizuho Station in the summer.

Actual global radiation contains direct component and diffuse component, but the calibration factor $D(h)$ is applicable only to direct radiation. Another calibration factor applicable to diffuse radiation had to be determined. The sensitivity for isotropic radiation F_I was obtained by integration over the hemisphere, taking into account Lambert's law as

$$F_I=\int_0^{\pi/2} D(h)\sin 2h\,dh\,. \tag{2}$$

Reflected radiation from the snow surface and radiation from cloud were assumed to be isotropic and F_I was applied. For the anisotropy of sky radiation, the intensity was simply assumed to increase toward the horizon proportionally to the number of diffusing particles present, *i.e.*, proportional to the air mass $m=1/\sin h$ as mentioned by WELLER (1967) and KUHN *et al.* (1977). The sensitivity for clear sky radiation F_A was as follows:

$$F_A=\int_0^{\pi/2} D(h)\sin 2h\frac{1}{\sin h}\mathrm{d}h\Big/\int_0^{\pi/2}\sin 2h\frac{1}{\sin h}\mathrm{d}h\,,$$

$$=\int_0^{\pi/2} D(h)\cos h\,\mathrm{d}h\,. \tag{3}$$

These assumptions for F_I and F_A were very simple, but used as an only realistic method of a first order approximation. Radiation field of an actual atmosphere is very complicated, and its characteristics are different in wavelength, in aerosol amount, in cloud type and in surface albedo, as shown by COULSON (1975). However, investigation of the characteristics of radiation field is an object of the present study.

Twelve pyranometers used in the measurement were all the same type except for the cutoff filters for the wavelength selection. Calibration of the other eleven sensors was made mainly by comparing with the field standard pyranometers on clear days in November and December, 1979. The incident angle dependence of the sensitivity (deviation from the cosine law) $C_i(h)$ of each pyranometer was obtained as

$$C_i(h)=\frac{S_i'}{S}\,, \tag{4}$$

where S_i' is measured global radiation of pyranometer i and S is the true value derived from the standard sensor using $D(h)$ and F_A. $C(h)$ of each pyranometer is shown in Fig. 2 with a thin solid line. $C(h)$, opposed to $D(h)$, is applicable to the global radiation, provided that the ratio of diffuse to direct radiation does not vary so much from that of calibration measurements. Experimental accuracy of pyranometer measurements was estimated to be $\pm 3\%$ from the scattering of points in the determination of calibration curve shown in the figures by YAMANOUCHI *et al.* (1981).

A difficulty occurred in the case of broken cloud cover. Cloud amount was observed only 3 or 6 hourly by eye and not recorded continuously. In the present study, derivation of data was restricted to the mean value of 30 minutes or one hour, and approximate clear index C_c was introduced.

$$C_c=\frac{\bar{I}(h)}{\bar{I}_0(h)}\,, \tag{5}$$

where $\bar{I}_0\ (h)$ is a typical direct solar radiation at the surface of Mizuho on clear days with the solar height h, and $\bar{I}(h)$ is an average of actual direct solar radiation. As $I(h)$ was assumed to be 0 when direct radiation was obscured by cloud and the effect of thin cloud to decrease $I(h)$ was not accounted, C_c was regarded also as the duration of sunshine. Though C_c was derived from the time average value, it was treated as a space average attributed to the long averaging time interval compared with the speed of cloud variation. Then in the clear sky condition C_c was reduced to 1, in the completely overcast sky C_c was 0, and in the rest cases C_c was calculated only to the order of one-tenth between 0 and 1. Using these calibration factors, global radiation S was derived by the following equation from measured global radiation S' and direct solar radiation I with solar height h,

$$S = I\sin h + \frac{S' - D(h)\cdot I\sin h}{C_c F_A + (1-C_c)F_I}\,. \tag{6}$$

In the right hand side of the equation, the first term expresses direct component and the second term expresses diffuse component. Using the calibration factor $C(h)$, the same kind of equation

$$S = \frac{S'}{C_c C(h) + (1-C_c)F_I}\,, \tag{7}$$

was used.

2.2. *Pyrgeometer*

A new type of Eppley PIR with a hemispherical dome made of silicon was used as a pyrgeometer (MAE *et al.*, 1981a). Radiation flux L was calculated from two terms as

$$L = \frac{V}{K} + \sigma T^4\,, \tag{8}$$

where V is the thermopile emf output, K is the sensitivity constant, σ is Stefan-Boltzmann constant and T is the temperature of the body of the sensor. In order to verify the sensitivity constant K of the sensor, a simple black body source with a heater wire and thermistors was prepared. By measuring radiation from the black body source, accuracy of the sensitivity constant was verified to be within $\pm 5\%$. In the actual condition, uncertainty of longwave radiation flux was about 0.005 ly/min.

Heating of the hemispherical dome by solar radiation brought on the temperature difference between the dome and the sensor surface. In this case, radiation flux should be expressed in another equation

$$L = \frac{V}{K} + \sigma T^4 - k\sigma(T_d^4 - T^4)\,, \tag{9}$$

as by ALBRECHT and COX (1977), where T_d is the temperature of the dome and k is a constant, and the third term in the right hand side would result in an error if eq. (8) was used. In the present type of Eppley PIR, heating effect of the dome was less than that by an older type of KRS-5 dome, but there still exists some heating of the dome. Several techniques had been tried to eliminate this error. One method by

ENZ *et al.* (1975) was to cool the dome surface by ventilation so as to reduce the temperature difference between T and T_d. However, an apparatus for the ventilation would be complicated and not suitable for the routine observation in Antarctica. Another method by ALBRECHT and COX (1977) was to obtain the coefficient k of eq. (9) and to measure the temperature of the dome T_d. With this technique, however, it is very difficult to obtain constant value k for various conditions and to obtain an effective temperature of the dome, since the temperature measured at one point might not give a representative value of the average dome temperature.

In the present measurement, a simple shading method was used to eliminate the heating effect of the hemispherical dome. Upfacing pyrgeometer set at the surface was equipped with a chrome plate shading ring of 4 cm in width and 40 cm in diameter as shown in Fig. 3. The effect of the shading ring, which was only effective to the

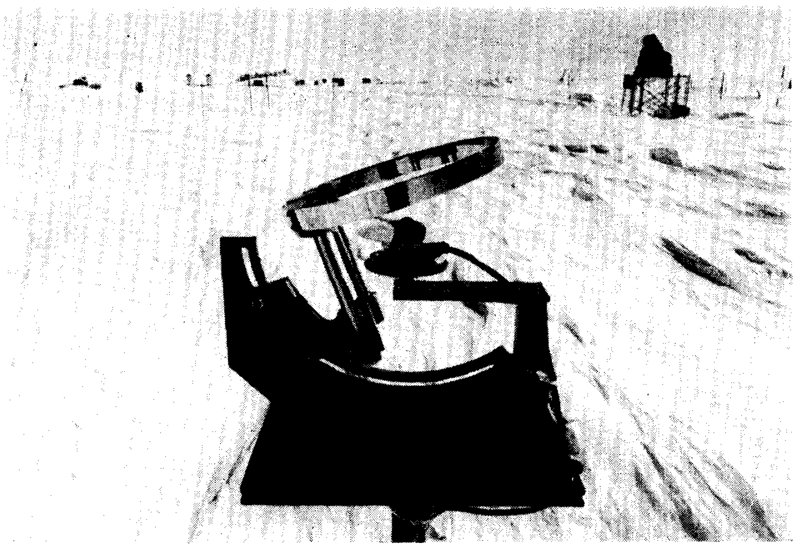

Fig. 3. Pyrgeometer with the shading ring for atmospheric radiation measurements.

direct solar radiation, is shown in Fig. 4 with white circle. In the figure, ordinate indicates a difference of longwave flux measured with (L) and without (L') the shading ring, and abscissa indicates horizontal component of shortwave flux (S_s) shaded by the ring, which may be identical to the direct flux. From Fig. 4, an approximate relation

$$L = L' - 0.02S_s \,, \tag{10}$$

was obtained (solid line in Fig. 4). Improper effect of the shading ring to obscure the real atmospheric radiation or to emit unrequired emission was ascertained to be negligible by a field examination.

Another heating effect of diffuse solar radiation was assumed to be analogous

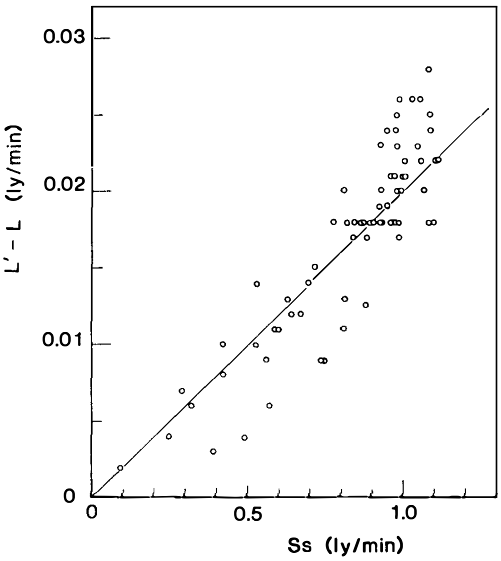

Fig. 4. Effect of the shading ring on the pyrgeometer measurements. Ordinate indicates a difference of longwave flux measured with and without the shading ring, and abscissa indicates shortwave flux shaded by the ring.

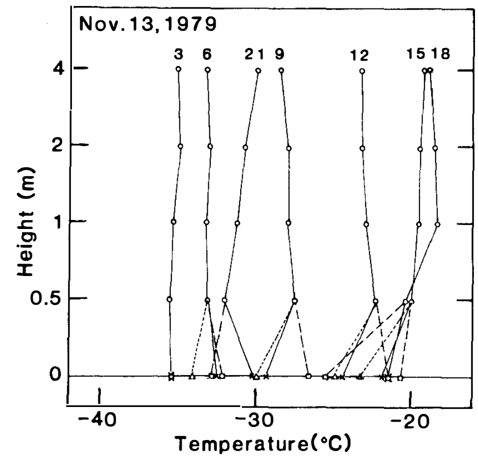

Fig. 5. Temperature profile of a 4 m layer. Surface temperature by platinum resistance thermometer; (cross), by pyrgeometer; (square) and by pyrgeometer with the correction of eq. (10); (triangle).

to that of direct radiation, and in order to eliminate the heating effect of diffuse solar radiation or of global radiation in the case of pyrgeometer without the shading ring, eq. (10) was applied to the measured longwave radiation L', where S_s denotes diffuse component or global radiation.

As for the downfacing radiometer for upward radiation, no correction as in eq. (10) was made. Since the direct measurement of heating of the dome—temperature difference between T and T_d—due to shortwave radiation, was not made, calibration by the snow surface emission was indispensable. However, because measurement of snow surface temperature was difficult in itself as reported by MAE *et al.* (1981b), direct *in situ* calibration of upward radiation could not be made. In the present measurement, though it is only a circumstantial evidence, downfacing radiometer was verified by the temperature profile measured with 30 m tower (WADA *et al.*, 1981). One example of the verification is shown in Fig. 5, where upward radiation was converted to the brightness temperature with surface emissivity assumed to be unity. Surface temperature from upward longwave radiation with no correction (indicated by square) seems to be most plausible within experimental accuracy of $\pm 1°C$ which corresponds to ± 0.005 ly/min at around $-20°C$. If the same correction as eq. (10) was made, the surface temperature would become too low (triangle). Surface temperature by a platinum resistance thermometer (cross) shows very slow response, which suggests that the thermometer was buried in the drifting snow. Consequently, upward longwave flux obtained by the present method seems to be reasonable.

Measured data of each radiation component were compiled and reported in JARE Data Reports No. 61 by YAMANOUCHI *et al.* (1981).

3. Results and Discussion

3.1. Diurnal variation

A typical example of diurnal variation of four components of radiation flux measured at Mizuho Station at the ground on a clear day is shown in Fig. 6. Net radiation R_n was calculated by the following equation;

$$R_n = S_n + L_n$$
$$= S_d - S_u + L_d - L_u \,, \qquad (11)$$

where S_n and L_n are the net radiation of shortwave and longwave respectively, S_d, S_u, L_d and L_u are global, reflected shortwave, downward and upward longwave radiations. The global radiation increased monotonously to the maximum value about 0.75 kW/m^2 (1.1 ly/min) at solar noon, and the reflected radiation increased to the maximum value about 0.60 kW/m^2 (0.85 ly/min) which means that the surface albedo lied around 0.8. Downward longwave radiation showed no large diurnal variation which would exceed experimental accuracy. In the former observation as by KUHN

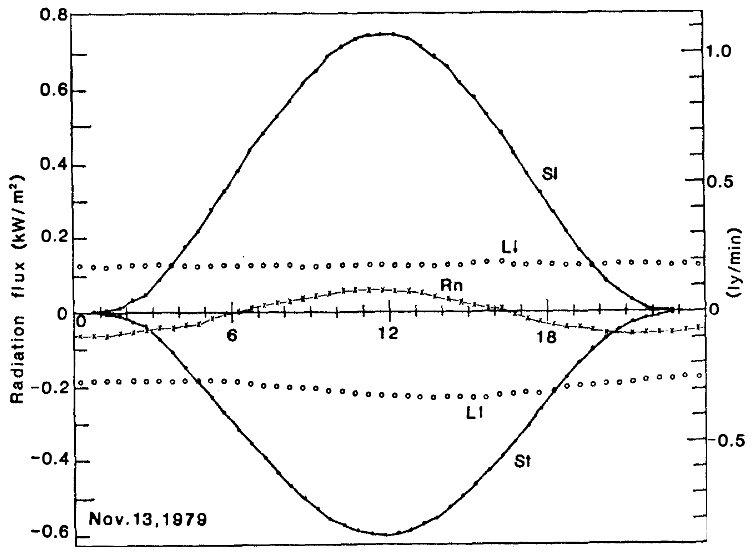

Fig. 6. Diurnal variation of radiation components at the surface of Mizuho Station for clear sky.

et al. (1977), direct measurement of downward longwave radiation was not made satisfactorily on account of the contamination by solar radiation, and diurnal variation was disordered. Efficiency of the present simple shading ring method for the pyrgeometer measurement described in the preceding section was confirmed. Upward longwave radiation showed variation from 0.18 kW/m^2 (0.26 ly/min) to 0.23 kW/m^2 (0.33 ly/min), corresponding to the variation of surface snow temperature of more than 15°C and had a peak value in the afternoon. The reliability of these values is discussed in the previous section. As for the net radiation, the peak of maximum appeared before noon, the value was negative for about 5 hours after the sunrise and became positive for about 6 hours until the sunset. The total value of the net radiation for 24 hours was −1.0 MJ/m^2 (−24 ly) as shown afterwards for this example.

In Fig. 7, an example of variable sky is illustrated. In the afternoon cloud appeared from about 16 LT and the amount of cloud increased to 10/10 at 21 LT when the genus of cloud observed was altostratus (As). Downward longwave flux greatly increased from about 0.13 kW/m^2 (0.18 ly/min) to about 0.21 kW/m^2 (0.30 ly/min) between 1530 and 2000 LT. This means the increase of effective brightness temperature from −56°C to about −27°C, and the temperature of cloud might be close to the surface air temperature of about −26°C. Upward longwave flux remains almost constant about 0.21 kW/m^2, same as downward flux, throughout the evening, because the surface temperature stopped to decrease from about 16 LT on account of the increased downward flux. In the same period, decrease of the global radiation on account of cloud was not so large and then decrease of the net shortwave flux was so small as comparable to the increase of the downward longwave flux. Large

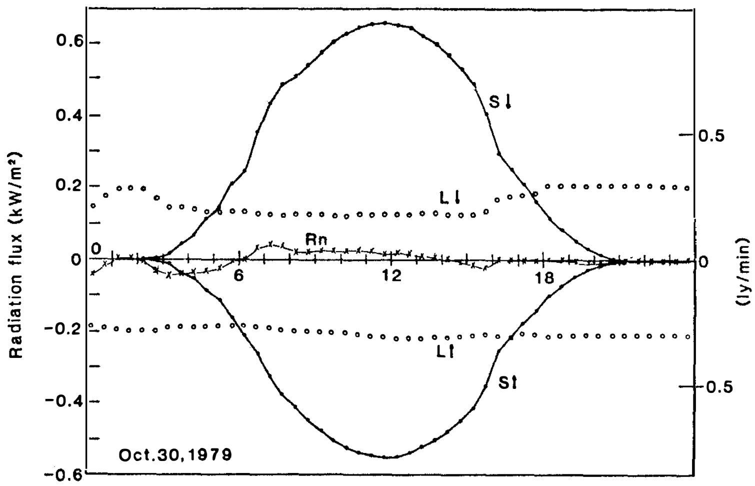

Fig. 7. Diurnal variation of radiation components at the surface of Mizuho Station for variable sky.

global radiation under the overcast sky is due to high albedo of the snow surface. Consequently, the net flux did not decrease to a large negative value as on a clear day and remained around 0 throughout the evening. The total net radiation for this day was $-0.05\ \mathrm{MJ/m^2}$. In the morning side there also existed some clouds till about 08 LT. However, the amount of cloud or the genus of cloud might not be uniform as the cloud in the evening, and showed some variations. Large peak in downward longwave flux and net flux around 02 LT suggested the appearance of thick and low cloud as in the evening, and in the other time, cloud seemed to be thin or cloudiness might be small. From 0830 to 15 LT, the global radiation showed the value for the clear sky, but from 07 to 08 LT or from 15 to 16 LT the value became larger than for the clear sky. This excess of the global radiation might be a result of reflection from broken clouds when direct radiation was not obscured.

3.2. Annual variation

Daily totals of net shortwave, net longwave and net total radiation are plotted on Fig. 8 for all the observational periods in 1979. Cloud amounts obtained from

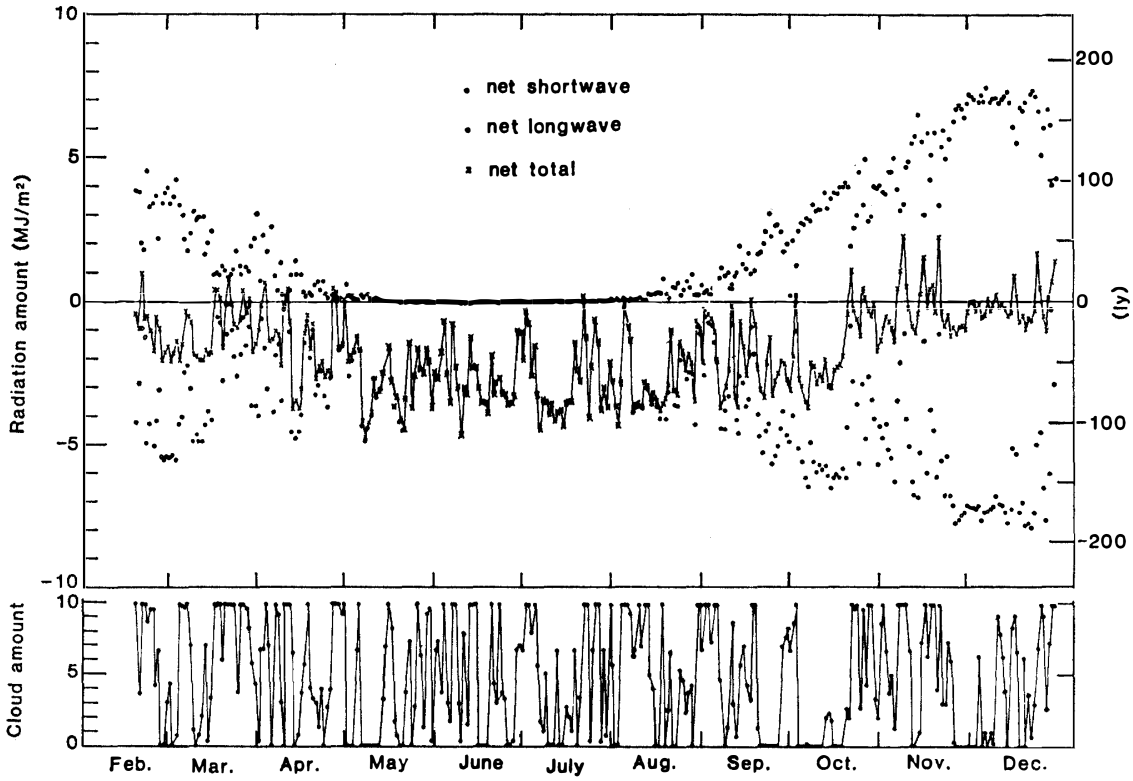

Fig. 8. Annual variation of daily totals of net radiation at the surface of Mizuho Station, from February 18 to December 31, 1979.

the synoptic measurement (WADA *et al.,* 1980) are also illustrated in the lower part of the figure. Though it is not always the case for the upper cloud, an effect of clouds on the radiation balance is evident. The net radiation would shift to a positive direction, often to a positive value, on account of cloud as explained in Subsection 3.1. Daily variation of the net radiation amounted to a few MJ/m^2 at most, due mainly to the variation of cloud cover.

Besides frequent variations from day to day, there is a large slow-varying trend as the seasonal variation in each component. A lower envelope of the net radiation shows the seasonal variation for the clear sky, and it remained negative all through the year of 1979 even in the summer. On the other hand, an upper envelope of the net radiation shows the seasonal variation for the overcast sky, and it shows small negative values in the winter (May to August) and increases to large positive values in the summer. The net radiation for the overcast day is larger than that for the clear day in any seasons at Mizuho Station. In general, however, in the place of low albedo the net radiation for clear days must be larger than that for overcast days. The net shortwave radiation increases from 0 to about 7 MJ/m^2/day (170 ly/day) in the summer. As for the net longwave radiation, its seasonal variation is smaller than that of the net shortwave, and varies from about 3 to 7 MJ/m^2/day (70 to 170 ly/day).

As for the results of the measurements, the present paper is restricted only to the description of general features of radiation budget, and the analytical treatment will be mentioned in another coming paper.

Acknowledgments

The authors wish to express their sincere thanks to the members of the wintering party of JARE-20 led by Mr. M. YAMAZAKI, Japan Meteorological Agency, for their support to the observation. Special thanks are due to Prof. M. TANAKA, Tohoku University, and Prof. K. KUSUNOKI, National Institute of Polar Research, for planning the investigation. Thanks are also due to Solar Radiation Calibration Office, Japan Meteorological Agency, for the use of the testing instrument of pyranometer.

Data analysis was made with the aid of HITAC M 160-II computer of the National Institute of Polar Research.

References

ALBRECHT, B. and COX, S. K. (1977): Procedures for improving pyrgeometer performance. J. Appl. Meteorol., **16**, 188–197.

COULSON, K. L. (1975): Solar and Terrestrial Radiation. New York, Academic Press, 322 p.

ENZ, J. W., KLINK, J. C. and BAKER, D. G. (1975): Solar radiation effects on pyrgeometer performance. J. Appl. Meteorol., **14**, 1297–1302.

FUJII, Y. and KAWAGUCHI, S. (1978): Meteorological data at Mizuho Station, Antarctica in 1977–1978. JARE Data Rep., **47** (Meteorology 5), 107 p.

KAWAGUCHI, S. and SASAKI, H. (1975): Mizuho Kansokukyoten no nissha shûshi (Solar radiation balance at Mizuho Camp, East Antarctica). Nankyoku Shiryô (Antarct. Rec.), **54**, 34–41.

KUHN, M., KUNDLA, L. S. and STROSCHEIN, L. A. (1977): The radiation budget at Plateau Station, Antarctica, 1966–1967. Meteorological Studies at Plateau Station, Antarctica, ed. by J. A. BUSINGER. Washington, D. C., Am. Geophys. Union, 41–73 (Antarct. Res. Ser., **25**).

KUSUNOKI, K. (1981): Japanese Polar Experiment (POLEX) in the Antarctic in 1978–1982. Mem. Natl Inst. Polar Res., Spec. Issue, **19**, 1–7.

MAE, S., WADA, M. and YAMANOUCHI, T. (1981a): The system of measurements of radiation and micrometeorological elements at Mizuho Station, East Antarctica: Installation and performance. Nankyoku Shiryô (Antarct. Rec.), **71**, 44–57.

MAE, S., YAMANOUCHI, T. and WADA, M. (1981b): The measurement of the surface temperature at Mizuho Station. Mem. Natl Inst. Polar Res., Spec. Issue., **19**, 40–48.

WADA, M., YAMANOUCHI, T., MAE, S. and KAWAGUCHI, S. (1980): Meteorological data at Mizuho Station, Antarctica in 1979. JARE Data Rep., **57** (Meteorology 7), 92 p.

WADA, M., YAMANOUCHI, T., MAE, S., KAWAGUCHI, S. and KUSUNOKI, K. (1981): POLEX-South data, Part 2. Micrometeorological data at Mizuho Station, Antarctica in 1979. JARE Data Rep., **62** (Meteorology 9), 321 p.

WELLER, G. E. (1967): Radiation fluxes over an Antarctic ice surface, Mawson, 1961–1962. ANARE Sci. Rep., Ser. A (IV) Glaciology, **96**, 106 p.

YAMADA, T. (1975): Net radiation at the snow surface at Mizuho Camp in 1971–1972. JARE Data Rep., **27** (Glaciology 2), 114.

YAMANOUCHI, T., WADA, M., MAE, S. and KAWAGUCHI, S. (1981): POLEX-South data, Part 1. Radiation data at Mizuho Station, Antarctica in 1979. JARE Data Rep., **61** (Meteorology 8), 350 p.

(Received April 20, 1981; Revised manuscript received May 26, 1981)