気象研究所研究報告 第26巻 第3号 111—119頁 昭和50年9月
Papers in Meteorology and Geophysics Vol. 26, No. 3, pp. 111—119. September 1975

On the Measurement of Hemispherical Longwave Radiation Flux in the Daytime

by

Muneyasu Kano, Masashi Suzuki and Masaatsu Miyauchi
Meteorological Research Institute, Tokyo

(Received May 31, 1975)

Abstract

There are two methods, the "direct" and the "indirect (or subtraction)", in obtaining the hemispherical (downward or upward) longwave radiation flux in the daytime. Both of them have some defects. The defect of the direct method is that the method is not practicable in the field where weather conditions vary, whlile that of the indirect method is troubles coming from difference in the sensitivity of the total radiometer as between the shortwave and the longwave spectral region.

Here is presented a methed by which the troubles in the indirect method can be eliminated and consequently the hemispherical longwave radiation flux in the daytime can be adequately obtained. An example of downward longwave radiation flux obtained by the method is presented.

1. Introduction

There has been increased the need to measure the longwave radiation flux in connection with the radiation budget in the atmosphere and on the ground surface and with the climatic variation of the earth.

For the measurement of net longwave radiation flux in the daytime, there are two kinds of method. One is a direct method in which the net flux of longwave radiation is measured by a net total radiometer (e.g. FUNK radiometer) covered with a spherical black polythene, which cuts off the shortwave radiation, rotating around the net total radiometer (PALTRIDGE, 1969). The other is an indirect (or subtraction) method in which the net total (shortwave+longwave) radiation flux is measured with a net total radiometer and simultaneously the net shortwave radiation flux is measured with a net pyranometer and then the net shortwave radiation flux is subtracted from the total radiation to get the net longwave radiation flux (JENSEN and ASLYNG, 1967).

For the measurement of hemispherical longwave radiation flux in the daytime, too, the above two methods can be used. In applying the direct method, however, it is necessary to set a hemispherical black body with a known temperature at the side of the net radiometer opposite to the direction of radiation being measured (PALTRIDGE, 1969). This may not be practicable in the field where weather conditions vary. When the indirect method is applied, the deduction of hemispherical longwave radiation flux from the measurements of total and shortwave radiation fluxes is not so simple as in the case of getting net longwave radiation in the daytime.

The defect of the indirect method is that the sensitivity of the total radiometer in the shortwave spectral region differs from that in the longwave spectral region. As far as this point is concerned, the "ventilation-type" radiometer (e.g. GIER and DUNKLE radiometer) is superior to the "wind-shield-type" radiometer (e.g. FUNK Radiometer) because of the less spectral dependency of its sensitivity. The ventilation-type radiometer, however, has its sensitivity influenced by the wind more seriously than the wind-shield-type radiometer (KANO et al., 1976). On the other hand, troubles due to the spectral dependency of the sensitivity of the radiometer mentioned above can be eliminated by the method proposed in the present paper. On the whole the wind-shield-type radiometer is, therefore, preferable for the measurement of radiation flux in the field.

The authors presented a method to obtain the hemispherical longwave radiation flux in the daytime using the indirect method (1974). The present paper is based on that report.

2. Estimation of hemispherical longwave radiation flux in the daytime

The hemispherical shortwave radiation flux, S, is given by Equation (1)

$$S=kV \tag{1}$$

where V is an electric potential caused by the temperature difference between the black and the white sensor surface (e.g. EPPLY pyranometer) or between the sensor surface and the sensor base (e.g. GORCZINSKY pyranometer). K is an instrumental constant of the pyranometer which can be easily determined by the ordinary calibration procedure.

The hemispherical total radiation flux obtained directly from the total radiometer calibrated in the usual way is erroneous, because the sensitivity of the radiometer in the shortwave spectral region differs from that of the longwave spectral region. Consequently the hemispherical longwave radiation flux deduced from such a hemispherical total radiation flux is also erroneous. A procedure eliminating the error is, therefore, necessary in order to obtain the hemispherical longwave radiation flux in the daytime. The procedure is as follows.

The heat balance of a sensor surface of a wind-shield-type radiometer is given by the following equation:

$$\frac{\alpha_S\tau_S S}{1-r_S(1-\alpha_S)}+\frac{\alpha_L\tau_L L}{1-r_L(1-\alpha_L)}+\frac{\alpha_L(1-\tau_L-r_L)\sigma T^{*4}}{1-r_L(1-\alpha_L)}+\frac{\alpha_L{}^2 r_L\sigma T_{S+L}^4}{1-r_L(1-\alpha_L)}$$
$$=\alpha_L\sigma T_{S+L}^4+KV_{S+L} \tag{2}$$

where

$S(L)$: hemispherical shortwave (longwave) radiation flux incident on the radiometer,
$\alpha_S(\alpha_L)$: mean absorptivity of the sensor surface in the shortwave (longwave) spectral region,
$\tau_S(\tau_L)$: mean transmissivity of the polythene dome in the shortwave (longwave) spectral region,
$r_S(r_L)$: mean reflectivity of the polythene dome in the shortwave (longwave) spectral region,
T_{S+L}: temperature of the sensor surface exposed in the shortwave and longwave radiation field,
V_{S+L}: electric potential between the sensor surface and the sensor base of the radiometer exposed in the shortwave and longwave radiation field,

T^*: temperature of the polythene dome
σ: Stefan-Boltzmann Constant
K: Constant depending upon the materials of which the sensor surface and sensor base consist, and the thermal conductivity of air.

The first term of the left-hand side of (2) is the absorption by the sensor surface of shortwave radiation incident on the radiometer and multi-reflected between the sensor surface and the polythene dome. The second term is the absorption of longwave radiation which is incident on the radiometer and multi-reflected in a similar way. The third term is the absorption of longwave radiation emitted by the polythene dome and multi-reflected in a similar way. The fourth term is the absorption of longwave radiation emitted by the sensor surface and multi-reflected in a similar way. The first term of the right-hand side of (2) is the longwave radiation emitted by the sensor surface, and the second is the one which corresponds to the heat flow from the sensor surface to the sensor base and to the air.

For a conventional wind-shield-type total radiometer, α_S, α_L, r_S, r_L and τ_L have the following values: α_S, $\alpha_L \simeq 0.97$, r_S, $r_L \simeq 0.15$ and $\tau_L \simeq 0.80$. Taking these figures into account, Equation (2) becomes

$$\alpha_S\tau_S S+\alpha_L\tau_L L+\alpha_L(1-\tau_L-r_L)\sigma T^{*4}+\alpha_L^2 r_L\sigma T_{S+L}^4=\alpha_L\sigma T_{S+L}^4+KV_{S+L} \qquad (3)$$

The first and second terms on the left-hand side of Equation (3) can be rewritten by

$$\alpha_S\tau_S S+\alpha_L\tau_L L=\alpha_{S+L}\tau_{S+L}(S+L) \qquad (4)$$

where τ_{S+L} and α_{S+L} are a mean transmissivity of the polythene dome and a mean absorptivity of the sensor surface in the spectral region including both the shortwave and longwave radiations. From Eqs. (3) and (4), we have

$$S+L=\frac{K_{S+L}}{K_L}\left[\sigma T_{S+L}^4+K_L V_{S+L}-\left(1-\frac{1-\alpha_L r_L}{\tau_L}\right)\sigma T_{S+L}^4+\left(1-\frac{1-r_L}{\tau_L}\right)\sigma T^{*4}\right] \qquad (5a)$$

Taking $T_{S+L}-T^*\lesssim 10°\mathrm{C}$ and taking the above figures of α_L and r_L into account, Equation (5a) can be transformed into the following simple expression (5), in which the error of the order of one percent of σT_{S+L}^4 is neglected,

$$S+L=\frac{K_{S+L}}{K_L}\left[\sigma T_{S+L}^4+K_L V_{S+L}\right] \qquad (5)$$

where

$$\left.\begin{aligned} K_L&=\frac{K}{\tau_L\alpha_L}\\ K_S&=\frac{K}{\tau_S\alpha_S}\end{aligned}\right\} \qquad (6)$$

From Eqs. (4) and (6), K_{S+L} becomes

$$K_{S+L}=\frac{K}{\tau_{S+L}\alpha_{S+L}}=\frac{K}{(S/(S+L))\tau_S\alpha_S+(L/(S+L))\tau_L\alpha_L}$$

or

$$1/K_{S+L}=1/K_L+(S/S+L)(1/K_S-1/K_L) \qquad (7)$$

The hemispherical longwave radiation flux can be obtained by the subtraction of S given by (1) from the hemispherical total radiation flux given by (5). The total radiation flux given by (5), however, contains K_{S+L} which is not a constant but a function of K_L, K_S, S and L. K_L and K_S are instrumental constants and S is measured independently by a pyranometer. L is an unknown quantity which is to be obtained. Therefore the longwave radiation flux in the daytime can not be obtained by the direct subtraction of (1) from (5) but can be obtained from Eqs. (1), (5) and (7) by the following iteration method:

$$\left.\begin{aligned} &K_{S+L}^{(1)}=K_L \\ &R^{(1)}=S+L^{(1)}=\sigma T_{S+L}^4+K_L V_{S+L} \\ &L^{(1)}=R^{(1)}-S \end{aligned}\right\} \tag{8}$$

$$\left.\begin{aligned} &1/K_{S+L}^{(n+1)}=1/K_L+(S/(S+L^{(n)}))\,(1/K_S-1/K_L) \\ &R^{(n+1)}=(K_{S+L}^{(n+1)}/K_L)\,(\sigma T_{S+L}^4+K_L V_{S+L}) \\ &L^{(n+1)}=R^{(n+1)}-S \end{aligned}\right\} \tag{9}$$

where R is the hemispherical total radiation flux. The superscription (n) denotes the order of iteration. $L^{(n+1)}$ is the longwave radiation flux L in the daytime is to be obtained when the iteration is continued until the following condition is satisfied:

$$|(L^{(n+1)}-L^{(n)})/L^{(n)}|<\epsilon \tag{10}$$

3. Determination of the sensitivity of the total radiometer in the shortwave spectral region K_S

In the previous section, K_L and K_S are assumed to have known values. Although the determination of K_L is not so easy, it can be carried out with a calibration device (e.g. KANO et al., 1976). The determination of K_S is more troublesome compared with that of K_L, because of the difficulty of obtaining a uniform light source and the disturbances from surrounding longwave radiation sources. In the following, a method by which K_S is determined is shown.

On a clear day, the hemispherical total radiometer and the pyranometer are alternately exposed to and shield with sunsades from the direct solar radiation in the field. When the total radiometer and pyranometer are shielded from the direct solar radiation, the downward longwave radiation flux is given from Equation (5) as follows:

$$L=\frac{K_{S'+L}}{K_L}[\sigma T_{S'+L}^4+K_L V_{S'+L}]-S' \tag{11}$$

where S' is the downward diffuse solar radiation flux measured with the pyranometer. When the total radiometer and the pyranometer are exposed to direct solar radiation, the hemispherical shortwave radiation flux and the total radiation flux are given by Eqs. (1) and (5). In Eqs. (5), (7) and (11), S, S'; T_{S+L}, $T_{S'+L}$; V_{S+L}, $V_{S'+L}$ are directly measured and the physical parameters are all known except K_S.

K_S can be obtained from (1), (5), (7) and (11) by an iteration method similar to that in the previous section. That is,

$$\left.\begin{aligned}
&K_{S'+L}^{(1)}=K_L\\
&L^{(1)}=\sigma T_{S'+L}^4+K_L V_{S'+L}-S'\\
&K_{S+L}^{(1)}=K_L(S+L^{(1)})/(\sigma T_{S+L}^4+K_L V_{S+L})\\
&1/K_S^{(1)}=(1+L^{(1)}/S)/K_{S+L}^{(1)}-(L^{(1)}/S)/K_L
\end{aligned}\right\}\tag{12}$$

$$\left.\begin{aligned}
&1/K_{S'+L}^{(n+1)}=1/K_L+(S'/(S'+L^{(n)}))(1/(K_S^{(n)}-1/K_L)\\
&L^{(n+1)}=(\,K_{S'+L}^{(n+1)}/K_L)(\sigma T_{S'+L}+K_L V_{S'+L})-S'\\
&K_{S+L}^{(n+1)}=K_L(S+L^{(n+1)})/(\sigma T_{S+L}^4+K_L V_{S+L})\\
&1/K_S^{(n+1)}=(1+L^{(n+1)}/S)/K_{S+L}^{(n+1)}-(L^{(n+1)}/S)/K_L
\end{aligned}\right\}\tag{13}$$

$K_S^{(n+1)}$ is the instrumental constant K_S we shall get when the iteration is continned until the following condition is satisfied:

$$|(K_S^{(n+1)}-K_S^{(n)})/K_S^{(n)}|<\epsilon \tag{14}$$

4. Downward longwave radiation flux in the daytime

The downward longwave radiation flux in the daytime is obtained with the method

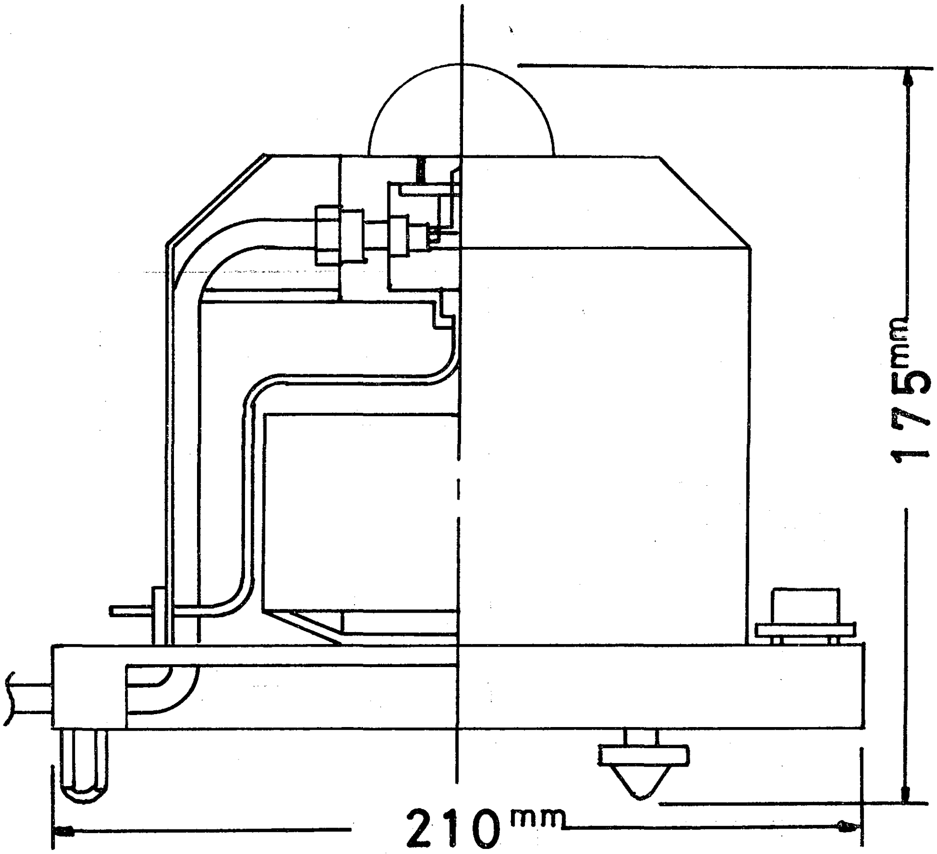

Fig. 1. A schematic diagram of the total radiometer used.

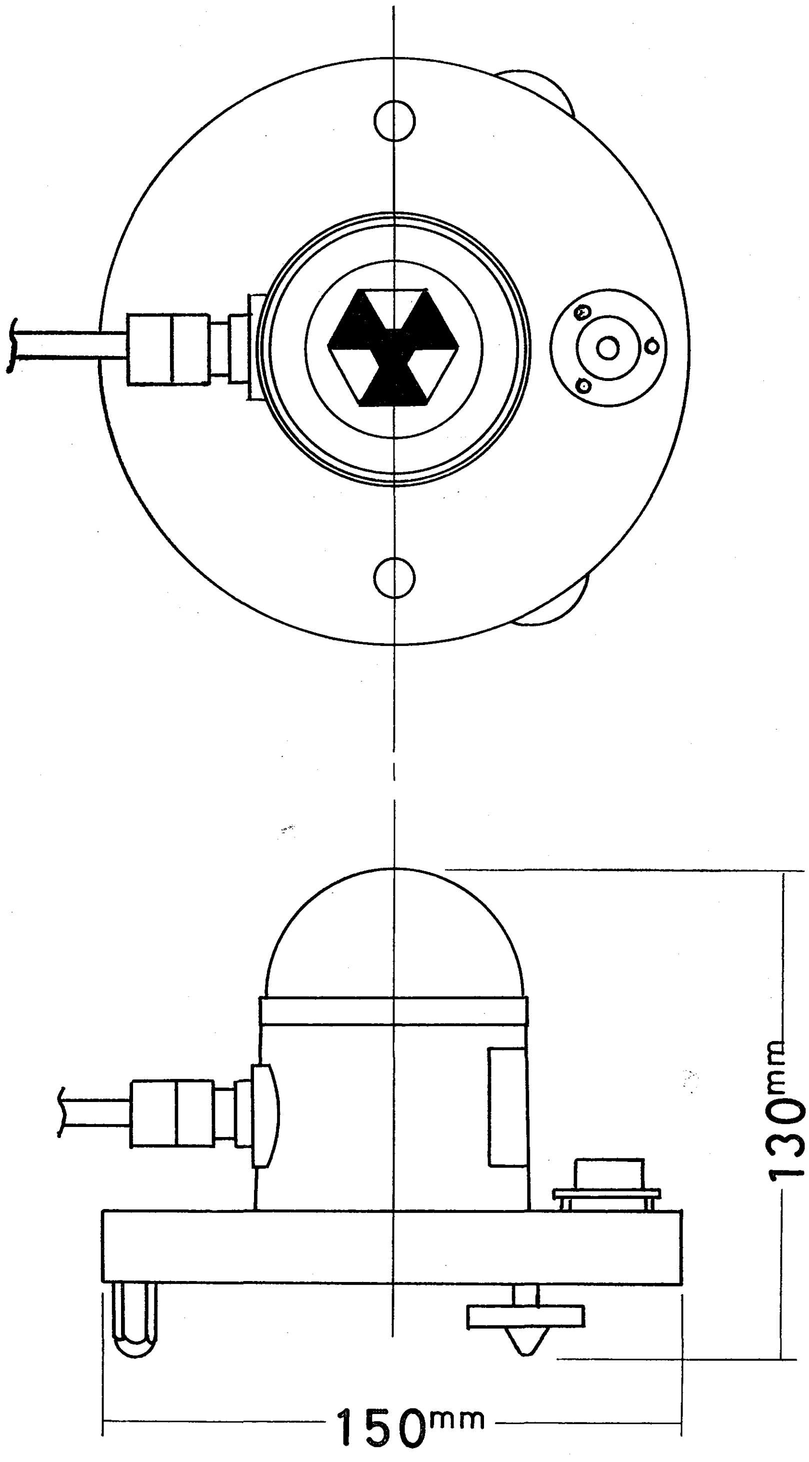

Fig. 2. A schematic diagram of the pyranometer used.

described in the previous sections from observations.

A schematic diagram of the structure of the total radiometer used is shown in Fig. 1. The sensor surface of the radiometer is painted with black lacquer and covered by a polythene dome. The inside of the dome is slowly ventilated to expand the dome and the outside of it is also ventilated to prevent it from frosting. The ventilation outside the dome has the additional effect of eliminating the difference in sensitivity asserted by BERTRAND ROGER to exist between the sensor surface which faces a cold object and that which faces a warm one.

The pyranometer used is shown in Fig. 2. The sensor surface consists of three black and three white flakes alternately arranged around a center of the sensor plate.

In Fig. 3 is shown a downward longwave radiation flux observed on the 24th of February, 1975 at Naha Aerological Station. The sky was mostly clear with less than 0.1 of fractional cloudiness except 7^h to 9^h and 16^h to 18^h. Obtaining L, the iteration was carried out by $n=2$. This is enough if the value of ϵ in (10) is 0.001.

The figure shows large errors in the values which were obtained from the total radiation and solar (shortwave) radiation fluxes without consideration of difference of sensitivity described in the previous sections. On the other hand, the values obtained

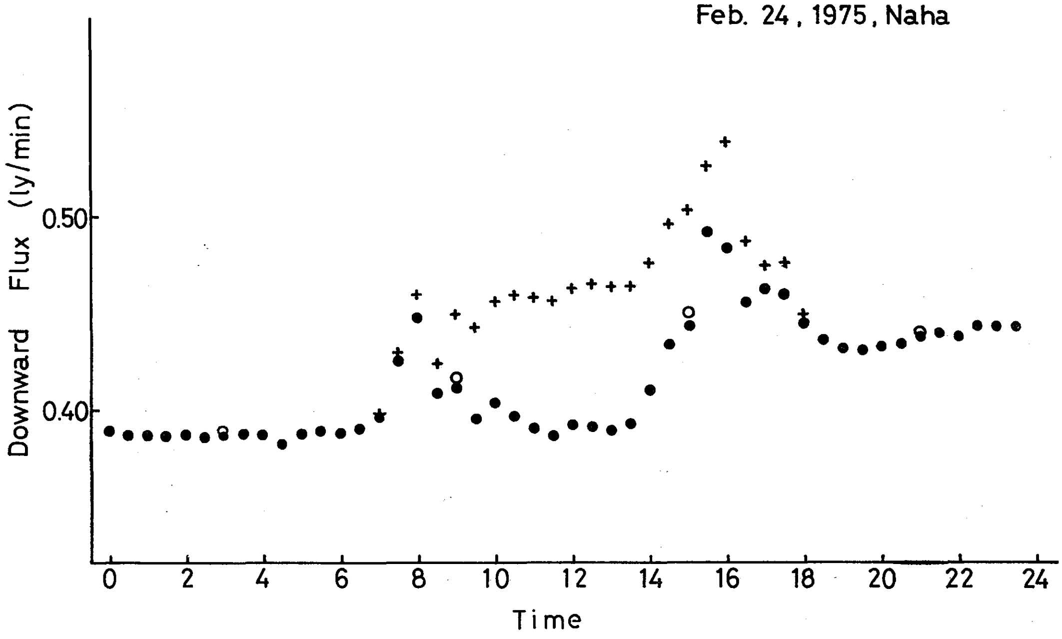

Fig. 3. An example of measured downward longwave radiation flux. +: the downward flux obtained from the total radiation and solar (shortwave) radiation fluxes without consideration of difference of sensitivity of the total radiometer in the shortwave and longwave spectral regions. ●: the downward longwave radiation flux obtained using the method described in the present paper. ○: the downward longwave radiation flux computed from the temperature and humidity profiles observed at Naha Aerological Station using the method developed by two of the authors (1974).

using the method described above agree well with the theoretical values. The theoretical values are obtained from the temperature and humidity profiles observed at Naha Aerological Station using the method doveloped by two of the present authors (1974).

5. Discussion

The difference of sensitivity of the wind-shield-type total radiometer in the shortwave and longwave spectral regions is mainly due to the differnce of transmissivity of the polythene dome in the shortwave and longwave spectral regions (JENSEN et al., 1967; BERTRAND). Thus the ventilation-type total radiometer is superior to the wind-shield-type radiometer, as far as this point is concerned. As described in the previous sections the ventilation-type radiometer has a larger wind effect than that of the wind-shield-type radiometer (KANO et al., 1976) and troubles due to the sensitivity difference in measurements of the hemispherical longwave radiation flux in the daytime can be eliminated as described in the previous sections. Thus the wind-shield-type radiometer is, on the whole, preferable for use in the field.

In the above was presented a method by which the hemispherical longwave radiation flux in the daytime can be obtained from those measured by a wind-shield-type radiometer and a pyranometer. The method can be also applied to cases where use is made of any type of total radiometer with different sensitivities as between the shortwave and the longwave spectral region.

Acknowledgement:—The authors would like to express their thanks to Mr. S. SEKINE for his help in calibrating the total radiometer and the pyranometer, to the members of Naha Aerological Station for their help in measuring the radiation fluxes, and to Miss M. UNO for her assistance in drawing the figures.

References

BERTRAND, R.,: Contribution a L'Etude Experimentale des Pyrradiometers. Notes Preliminaires N° 1, Institute Royal Meteorological de Belgique.

JENSEN, Sv. E. and H. C. ASLYNG, 1967: Net radiation and net longwave radiation at Copenhagen 1962–1964. Arkiv. Met. Geophys., **15**, 127–140.

KANO, M., M. SUZUKI and M. MIYAUCHI, 1974: On the measurement of the longwave radiation flux in the daytime. Annual Meeting of Japan Met. Soc., May

KANO, M. and M. MIYAUCHI, 1974: Computation of infrared radiative fluxes in the cloudy atmosphere. Pap. Met. Geophys., **25**, 125–137.

KANO, M. and M. SUZUKI, 1976: On the calibration of the radiometer for longwave radiation (II) The case of hemispherical radiometer (to be published in Pap. Met. Geophys., **27**)

PALTRIDGE, G. W., 1969: A net longwave radiometer. Quart. Jour. Roy. Met. Soc., **95**, 635–638.

昼間の長波長放射量の測定について

嘉納宗靖，鈴木　正，宮内正厚

昼間の天空長波長放射量の測定には，２通りの方法が考えられる。第１の方法は，全波長放射計を日射を通さない「黒い」ポリエチレンの球で覆い，その覆いを放射計の周りで回転させ，日射の影響を除去して測定する方法である。この場合，放射計の受感面と反対側で覆いのすぐ外に温度既知の標準黒体を置く

必要がある。種々の天候を考えると，この方法は実際的でない。第2の方法は全波長放射計と日射計で同時に全波長（短波長＋長波長）放射量と日射（短波長放射）量を測定し，前者から後者を差引いて求める方法である。この場合全波長放射計の感度が短波長域と長波長域とで異なるために，単純な差引操作は大きな誤差を伴う。当論文では全波長放射計の受感面の熱エネルギーの釣合いの式を基にして，短波長域と長波長域とで放射計の感度が異なることを考慮に入れ，全波長放射計と日射計による測定値より昼間の天空長波長放射量を正確に求める方法を提出する。実際の測定例より，この方法で求めた結果が妥当であることを示す。