NOTES AND CORRESPONDENCE

A Method to Measure the Daytime Long Wave Radiation

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1. Introduction

In order to determine the long wave atmospheric radiation flux in the daytime, the spectral dependence of the sensitivity of the pyrriadiometer must be considered. Yasuda (1975), Kano *et al.* (1975), and Akita (1977) studied this problem by the shading disk method (SDM) and concluded that the pyrriadiometer covered with a polyethylene dome was more sensitive to the short wave radiation than to the long wave radiation.

In the present study, differences in the sensitivity of the pyrriadiometer among direct solar radiation, diffuse sky radiation, and long wave radiation are examined by applying a regression method to the radiation data under clear sky conditions. For practical use in the field observations, an empirical formula to estimate the daytime long wave radiation flux is proposed.

2. Method of analysis

Under clear sky conditions, the output voltage from the pyrriadiometer is caused by the direct solar radiation, the diffuse sky radiation, and the long wave atmospheric radiation. The direct solar radiation generally displaces towards the longer wavelength region of the solar spectrum as compared with the diffuse sky radiation (Robinson, 1966). The direct solar radiation comes only from the direction of the sun, while the diffuse sky radiation from the entire hemisphere.

On the basis of these backgrounds, the short wave radiation is divided into two components in the analysis. In the similar way of Yasuda (1975), the energy balance equation at the sensor surface is expressed by

$$\frac{a_{s1}\tau_{p1}}{1-r_{s1}r_{p1}}S_1 + \frac{a_{s2}\tau_{p2}}{1-r_{s2}r_{p2}}S_2 + \frac{a_{sL}\tau_{pL}}{1-r_{sL}r_{pL}}L$$

$$+ \frac{a_{sL}a_{pL}}{1-r_{sL}r_{pL}}\sigma T_p^4 + \frac{a_{sL}^2r_{pL}}{1-r_{sL}r_{pL}}\sigma T_s^4 = a_{sL}\sigma T_s^4 + Kv, \quad (1)$$

where the multiple reflections between the sensor surface and the polyethylene dome are considered. The notations are as follows:

S_1, S_2, L : direct solar radiation flux, diffuse sky radiation flux, and long wave atmospheric radiation flux on a horizontal plane

a, r, τ : absorptivity, reflectivity, and transmissivity

T : temperature

v : output voltage from the pyrriadiometer

K : numerical constant which determines the heat flux between the sensor surface and the base of the sensor

σ : Stefan-Boltzmann's constant

first suffixes p and s indicate polyethylene dome and sensor surface, respectively, second suffixes 1, 2, and L correspond to S_1, S_2 and L , respectively.

$$L = \sigma T_s^4 + K_L v - \frac{K_L}{K_1} S_1 - \frac{K_L}{K_2} S_2, \quad (2)$$

where only the principal terms are considered (Yasuda, 1975). The calibration constants K_1, K_2 , and K_L are defined as

$$K_1 = \frac{1-r_{s1}r_{p1}}{a_{s1}\tau_{p1}}K, \quad K_2 = \frac{1-r_{s2}r_{p2}}{a_{s2}\tau_{p2}}K, \\ K_L = \frac{1-r_{sL}r_{pL}}{a_{sL}\tau_{pL}}K. \quad (3)$$

The $1/K_1, 1/K_2$, and $1/K_L$ are the sensitivities of the pyrriadiometer to the direct solar radiation, to the diffuse sky radiation, and to the long wave radiation, respectively. The K_L can be determined comparing with a standard instrument in the nighttime. The K_1 and K_2 can be determined by the present regression method

(RM) if the values of S_1 , S_2 , and L are known. Note that the SDM gives the value of K_1 .

3. Data

Two sets of the pyrradiometer (EKO Ltd., Japan) are examined in this study. Both pyrradiometers (Pyrr A and Pyrr B) are covered with the hemispherical polyethylene domes and the detailed structure is described in Yasuda (1975).

The observation of radiation was carried out from August 1979 to October 1980 at the Institute (Aramaki, Sendai, Japan). The total solar radiation flux was measured with a hemispherical pyranometer and the direct solar radiation flux with a pyrhelimeter. So, the diffuse sky radiation flux was obtained by subtracting the direct solar radiation flux from the total solar radiation flux. Regardless of the atmospheric turbidity or the elevation of the sun, the data that satisfy the clear sky conditions (cloud amount $\leq 1/10$) are analysed.

The daytime long wave radiation flux, which is necessary to the RM, was calculated by the use of the modified Yamamoto's radiation chart (Uchiyama, 1981, private communication) from the rawinsonde data (at 9:00) at the Sendai District Meteorological Observatory. The low altitude radiosonde data at the Institute together with the rawinsonde data were used in the calculations on November 2nd, 1979. The value of the long wave radiation flux between sunrise and 9:00 was obtained by interpolating the measured value just before sunrise and the calculated one.

The K_L was determined in the clear night with a standard instrument (Yamamoto and Sasamori, 1954). This calibration constant K_L gave reasonable long wave radiation fluxes in comparison with those calculated from the rawinsonde data at 21:00.

4. Results and discussion

4-1) Sensitivities of the pyrradiometer

Transforming Eq. (2), one can obtain

$$\frac{\sigma T_s^4 + K_L v - L}{S_1} = \frac{K_L}{K_1} + \frac{K_L}{K_2} \frac{S_2}{S_1}. \quad (4)$$

The values of $(\sigma T_s^4 + K_L v - L)/S_1$ are plotted against S_2/S_1 in Fig. 1a for Pyrr A and in Fig. 1b for Pyrr B. The open circles correspond to the data at 9:00 and the solid circles to those at other time. The S_2/S_1 varies both with the atmospheric turbidity and with the elevation of the sun. The linear relations shown in the

Fig. 1 The relation between $(\sigma T_s^4 + K_L v - L)/S_1$ and S_2/S_1 under clear sky conditions for Pyrr A (a) and for Pyrr B (b). ○: at 9:00, ●: at other time.

figures support the present treatment of dividing the solar radiation into two components.

The regression lines give the values of K_L/K_1 and K_L/K_2 as summarized in Table 1. These sensitivity ratios do not show any trend with respect to the elevation of the sun. The values of K_L/K_1 for the two pyrradiometers are determined to be less than 1.0 by both SDM and RM, which do not agree with the results (being

Table 1 Summary of the results by SDM and RM.

		Pyrr A	Pyrr B
SDM	K_L/K_1	0.89	0.96
RM	K_L/K_1	0.92	0.93
	K_L/K_2	1.07	1.15
	$f(S)$	1.00-0.06S	1.04-0.08S
	Number of clear days	24	3

more than 1.0) of previous workers. This discrepancy has not been solved. The difference in the magnitude between K_L/K_1 and K_L/K_2 may be arised from the spectral characteristics of the hemispherical polyethylene dome and of the sensor surface. The published transmissivity curve of the polyethylene dome (Yasuda, 1975), however, cannot explain this difference satisfactorily. It may be considered to be one of other causes that the direct solar radiation comes from one direction and the diffuse sky radiation from the entire hemisphere. Detailed experiments should be conducted to discuss these problems quantitatively.

4-2) Empirical formula for practical use

In order to estimate the long wave radiation flux in the daytime by the use of Eq. (2), it is necessary to measure the direct solar and the diffuse sky radiation fluxes separately. When only the total solar radiation flux $S(=S_1+S_2)$ is measured, which is usually the case in field observations, the following empirical formula is practical:

$$L=\sigma T_s^4+K_Lv-f(S)S,$$

(5)

where $f(S)$ is a function of S and must be determined experimentally. The $f(S)$ corresponds to the ratio of the sensitivity in the short wave region to that in the long wave region. Fig. 2 shows the relation between $(\sigma T_s^4+K_Lv-L)/S=f(S)$ and S for the two pyrradiometers under clear sky conditions. These plots reveal that $f(S)$ is a decreasing function with respect to S , which is explained by the difference between K_1 and K_2 as follows: From Eq. (2) and Eq. (5), $f(S)$ can be related to K_L/K_1 and K_L/K_2 as

$$f(S)=\left(\frac{K_L}{K_1}+\frac{K_L}{K_2}\frac{S_2}{S_1}\right)\bigg/\left(1+\frac{S_2}{S_1}\right).$$

(6)

When S increases, S_1 generally occupies the greater part of S , that is, S_2/S_1 decreases; consequently $f(S)$ is shown to decrease by Eq. (6). The $f(S)$ is approximated by a linear equation from the plotted data and is shown in Table 1.

In the strict sense, the $f(S)$ under overcast or rainy conditions differs from the present $f(S)$ determined under clear sky conditions. This is because the spectral composition of the short wave radiation scattered by the clouds does not coincide with that of combined solar and sky radiations. Since S is smaller under such conditions, however, a little difference in $f(S)$ does not lead to serious error in the estimate of L . Therefore, the present $f(S)$ may be applicable under all weather conditions.

The function $f(S)$ seems to be slightly different between pyrradiometers, so that, it is desirable to determine $f(S)$ of the individual instrument by examining the relation shown in Fig. 2.

Fig. 2 The relation between $(\sigma T_s^4+K_Lv-L)/S=f(S)$ and S under clear sky conditions. The plots include the data at 9:00 and those at other time. $\square$: Pyrr A, $\circ$: Pyrr B.

Fig. 3 An example of the time variations of the long wave and the total solar radiation fluxes. ●: measured nighttime long wave radiation flux, ○: estimated daytime long wave radiation flux from Eq. (5), △: same as the above except that $f(S) = K_L/K_1$ (SDM) is assumed, crosses: calculated long wave radiation fluxes by the modified Yamamoto's radiation chart from the rawinsonde data (+) and from the low altitude radiosonde data together with the rawinsonde data (x), solid line: total solar radiation flux.

Moreover, it is hoped to determine $f(S)$ in each observation area by the following reason: the relation between S and S_2/S_1 is implicitly involved in $f(S)$, which depends on mean atmospheric conditions (such as turbidity) peculiar to the area.

Finally, an example of the time variation of the long wave radiation flux is shown in Fig. 3 together with that of the total solar radiation flux (solid line). The solid circle denotes the

measured value in the nighttime and the open circle the daytime value estimated by the use of practical formula Eq. (5). Eq. (2) gives almost the same value as Eq. (5). The crosses are the calculated long wave radiation fluxes from temperature and humidity profiles. The estimated daytime long wave radiation flux agrees well with the calculated one.

The open triangle denotes the estimated value with a constant $f(S)$ -value (equal to K_L/K_1 determined by the SDM) in Eq. (5). On the assumption that $f(S)$ is constant, which has been accepted so far, the long wave radiation flux is somewhat overestimated.

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日中の長波長放射の測定法

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ポリエチレン膜のドーム付風防型全天放射計の、短波長放射（直達光，散乱光）と長波長放射に対する感度の違いを，快晴時のデータから，従来の Shading Disk Method とは別の方法（Regression Method）により調べた。

その結果，直達光，長波長放射，散乱光の順に感度が高いことがわかった。感度の違いは，ポリエチレン・ド

ームの透過率と反射率, それに受光面の吸収率の波長依存性, および, 直達光は太陽の方向のみから入射するのに対し, 散乱光は全天から入射することによるものと思われるが, 定量的な議論はなされていない。

日中の長波長放射は, 全天日射量 S の経験的な関数 $f(S)$ を用いて, 次式で求めるのが実用的である。

$$L = \sigma T_s^4 + K_{Lv} - f(S)S$$

$f(S)$ は S の減少関数であるが, これは本研究で明らかにされた直達光と散乱光に対する感度の違いに起因する。

$f(S)$ は快晴時のデータから決定されたが, 他の気象条件 (曇天, 雨天) の時でも使用可能である。