Ground-based Spectral Measurements of Solar Radiation (II) —Global and Diffuse Sky Radiation—

by

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(Received December 2, 1978)

Abstract

A newly designed spectro-pyranometer was used for the measurement of the global (direct+diffuse) and the diffuse sky radiation reaching the ground. By the subtraction of the diffuse component from the global radiation, we got the direct radiation component which leads to the spectral distribution of the optical thickness (extinction coefficient) of the turbid atmosphere. The measurement of the diffuse sky radiation reveals the scattering effect of aerosols and that of the global radiation allows the estimation of total attenuation caused by scattering and absorption of aerosols. The effects of the aerosols are represented by the deviation of the real atmosphere measured from the Rayleigh atmosphere. By the combination of the measured values with those obtained by theoretical calculation for the model atmosphere, we estimated the amount of absorption by the aerosols. Very strong absorption in the ultraviolet region was recognized.

1. Introduction

In recent studies on the solar radiation, many authors have investigated the absorption by the aerosol particles in the atmosphere (e. g. Drummond and Robinson, 1974; Robinson, 1962 and 1966; Liou and Sasamori, 1975). In them, the optical property of the aerosol, especially the imaginary part of the refractive index of the particle, is the essential parameter to determine the amount of absorption by the aerosols.

In a previous paper (Murai et al., 1977), we described the analysis of the measurements of the direct solar radiation and the year-to-year variation of the extinction coefficient of aerosols in Tokyo. The extinction coefficient thus obtained represents the total attenuation due to the scattering and the absorption of the aerosols, but does not give us any information on the scattering or the

absorption alone. To clarify the characteristics of absorption by the aerosols, it is necessary to make some additional measurements of the solar radiation. And theoretical calculations are needed for comparison with the measurements, assuming various values of the parameters contained in the transfer equation in the turbid atmosphere.

For the purpose of studying the aerosol absorption under various atmospheric conditions, we made the spectral measurements of the global and the diffuse sky radiation at the ground surface, as well as of the direct solar radiation. We further analysed the data of the diffuse sky radiation with the aid of the theoretical calculation for the model atmosphere. In this report, we describe the effects of the aerosols on the global and the diffuse sky radiation and estimate the absorption of solar radiation in the atmosphere.

2. Instruments and Measurement

The spectro-pyranometer was used to measure the spectral distributions of global and sky radiation reaching the ground. As the details of the instruments were explained in the previous paper (*loc. cit.*), our description of them will be necessarily brief. The instrument is composed of a double monochromator, an integrating sphere, a disk for shielding the direct beam, an amplifier and a data recording system. A diffraction grating and a quartz prism are combined for building up the double monochromator, so that the dispersion of wavelengths is nearly constant throughout the wavelength region for the measurement. The integrating sphere providing the receiving surface of incident fluxes is attached to the entrance slit of the monochromator. The scanning of wavelengths from 0.35 to 2.00 μm is performed by a pulse motor with which we can fix the wavelength interval for the data sampling. The time needed for the scanning with wavelength interval 250 Å is about 10 min. and during the scanning the light quantity entering the monochromator is reduced by the neutral density filters to get a suitable value of photocurrent for the data recording. The shade disk is for interrupting the direct beam radiation, and the global and the diffuse sky radiation were alternately measured with and without the disk respectively.

The measurement was carried out in a cloudless sky to clarify the effects of the aerosol particles on the solar radiation. The data used for analysis were obtained from measurements on six days during the period from January to March in 1978 in Tokyo. In these measurements, the sky was clear throughout the day and the time sequences of the global and the diffuse sky radiation were obtained by the continuous automatic operation of the spectro-pyranometer. Thus we easily got the values for each component at the time corresponding to the optical air mass desired for the analysis. By the subtraction of the diffuse component from the global radiation we got the direct solar radi-

ation component. The direct component thus obtained for various optical air masses was applied to the long method to derive the spectral conversion factor corresponding to the extraterrestrial value of solar radiation. According to these conversion factors, all measured values are represented by the fractions relative to the solar radiation incident on the unit horizontal surface at the top of the atmosphere.

3. Results of Measurement

The spectral distributions of the extinction coefficient were calculated from the direct components which were derived by the subtraction described above. An example of the relative values of the global, $G(\lambda)$, and the diffuse sky radiation, $D(\lambda)$, measured is shown in Fig. 1. In the figure, $G_R(\lambda)$ and $D_R(\lambda)$ represent the values of the global and the diffuse sky radiation in the Rayleigh atmosphere, respectively. An example of the spectral extinction coefficient determined from the direct components is shown in Fig. 2. In the figure, the upper curve represents the total extinction of the vertical column of the atmosphere and the lower one the extinction due to the aerosols. The hatched area represents the ozone absorption in the Chappuis band. To get the spectral values of ozone absorption we used Vigroux's absorption coefficients and the total amount of ozone obtained by routine observation at Tateno (36°03'N; 140°08'E). To remove the effect of water vapor absorption in the near infrared region, we used the smooth curves which pass through four measured values at 0.8, 1.05, 1.25 and 1.55 μm instead of the original measured curves. The absorption at the above four wavelengths is negligibly small.

According to the procedures described above, we got the spectral distributions of the aerosol extinction coefficient for all cases as shown in Fig. 3. For the sake of comparison, the distribution curve proportional to λ^{-1} is written in the figure. On average, the distributions in the shorter wavelength

Fig. 1. Spectral distributions of global and diffuse sky radiation. $G(\lambda)$ and $D(\lambda)$ are measured distributions represented by the unit relative to the energy incident on the unit horizontal surface at the top of the atmosphere. $G_R(\lambda)$ and $D_R(\lambda)$ represent distributions for the Rayleigh atmosphere.

Fig. 2. Spectral distribution of the extinction coefficient calculated from the direct radiation component. $\tau(\lambda)$ represents the total extinction coefficient, $\tau_M(\lambda)$ the aerosol extinction coefficient. Hatched area shows the ozone absorption component.

Fig. 3. Spectral distributions of the aerosol extinction coefficient obtained in the period of the measurement.

region are steeper and in the longer, flatter than λ^{-1} -distribution. The size distributions corresponding to these extinction curves are calculated by using the inversion technique (Yamamoto and Tanaka, 1969) and are shown in Fig. 4. The absolute energy distributions of the global and the diffuse radiation measured are represented in Fig. 5. The absolute values were obtained from the relative values represented in Fig. 1 as an example, multiplied by the absolute values of solar radiation incident on the unit horizontal surface at the top of the atmosphere. We used the Table of the absolute energy of the extra-terrestrial solar radiation published by NASA (Thekaekara, 1971).

In the figure, we can see that the spectral distribution of the global radiation on Feb. 20, the most turbid case in our measurements, is quite different from that on Jan. 25, the clearest case. For comparison, the distribution for the Rayleigh atmosphere is shown in the figure. The deficit of the measured values to those of the Rayleigh

Fig. 4. Size distributions of aerosol particles corresponding to the spectral distributions of extinction coefficient represented in Fig. 3.

Fig. 5. Spectral distributions of the absolute energy of global and diffuse sky radiation. I_0 represents the extra-terrestrial irradiance, G_R and D_R the Rayleigh atmosphere, and G and D the measured.

atmosphere generally increases with the increase of the extinction coefficient, and a part of it appears as the excess of the measured diffuse radiation reaching the ground over the Rayleigh case. The rest of the deficit is partly scattered out to the space and partly absorbed by the aerosols.

The excess of diffuse radiation in the visible and the near infrared regions generally increases with the increase of aerosol extinction, but in the region shorter than about $0.4 \mu\text{m}$ the excess becomes zero or negative, the negative amount increasing with the increase of the extinction (See the following section). To compare the measurements with the theoretical calculations, the spectral distributions of diffuse radiation for the model atmosphere are shown in Fig. 6 (Yamamoto, Tanaka and Ohta, 1974), in which the extinction coefficient of aerosols, $\tau_M(\lambda)$, is represented by

$$\tau_M(\lambda) = \beta \lambda^{-1}, \quad \beta = 0.15,$$

the refractive index $\tilde{n} = 1.50 - 0.10i$ and $= 1.50 - 0.03i$, and the surface albedo $A_s = 0.15$. The comparison shows that the discrepan-

Fig. 6. Comparisons of the measured diffuse sky radiation with the theoretical calculation for the model atmosphere.

cies between measurement and calculation are pronounced in the ultraviolet and near-infrared region. The agreement of the measurement is better to the curve of $\tilde{n}=1.50-0.10i$ than to that of $\tilde{n}=1.50-0.03i$.

It should be noticed in this comparison that the aerosol extinction in the calculation is assumed to be proportional to λ^{-1} , while the measurement is not simply proportional to λ^{-1} as shown in Fig. 3. And the absorption by aerosols possibly depends on the wavelength, i.e., the imaginary part of the refractive index will be a function of the wavelength.

4. Effects of Aerosols on the Solar Radiation

From the results of measurement described in the previous section, we can extract the effects of aerosols on the solar radiation. The loading of the aerosols in the molecular atmosphere causes a deficit of global radiation at the ground, because of the increase of diffuse radiation emergent to the space and the absorption by particles. On the other hand, this leads to the excess of the diffuse radiation reaching the ground by the amount of the downward flux due to the scattering by the aerosols. The amount of aerosol effect obtained by measurement are shown in Figs. 7 and 8, as a function of the extinction coefficient. Both the deficit and the excess are represented by the fraction of energy to the flux incident on the horizontal unit surface at the top of the atmosphere. The deficit of the global radiation increases in proportion to the extinction coefficient in the whole wavelength region. The excess of the diffuse radiation increases with the increase of the extinction coefficient in the visible and near-infrared region. In the ultraviolet region, however, we have the noticeable feature that the excess is nearly zero or negative and that the

Fig. 7. Deficit of the global radiation due to the scattering and the absorption of aerosols as a function of $\tau_M(\lambda)$.

Fig. 8. Excess of the diffuse sky radiation due to the scattering of aerosols as a function of $\tau_M(\lambda)$.

negative amount increases with the increase of the extinction coefficient. This suggests that the aerosol loading increases not only the upward scattering but also the absorption by particles themselves.

In order to estimate the amount of absorption by the aerosols, we calculated the net flux divergence in the atmosphere between the top and the ground level for each wavelength. The net fluxes at the ground were calculated by using the measured global radiation and the surface albedo which was determined from the aircraft measurements previously performed by the authors. The surface albedo, $A_s(\lambda)$, measured for three wavelengths are shown in Fig. 9. Although the measured values are rather scattered, the simple mean curve was applied to the calculation of the net flux at the ground level, $F_s = (1 - A_s)G(\lambda)$. The spectral values of the diffuse radiation emergent from the top of the atmosphere were calculated from the measured diffuse sky radiation multiplied by the ratio of the upward to the downward fluxes for the model atmosphere. The spectral values of the ratio, $r(\lambda) = U(\tau_0, \lambda)/D(\tau_s, \lambda)$, for the model atmosphere are shown in Fig. 10. The net flux at the top of the atmosphere was calculated by

Fig. 9. Spectral values of surface albedo obtained by the aircraft measurements previously performed by the authors. Dotted curve was used to the present analysis.

$$F_0(\lambda) = \mu_0 I_0(\lambda) - r(\lambda) D(\lambda),$$

where I_0 is the extraterrestrial solar radiation and $\mu_0 = \cos Z_0$, and Z_0 the solar zenith angle. Then we can estimate the net flux divergence for the vertical column of the atmosphere by

$$\Delta F_\lambda = F_0(\lambda) - F_s(\lambda).$$

This reveals the absorption of solar radiation by the aerosols suspended in the atmosphere.

Fig. 10. Ratio of the emergent to the downward flux for the model atmosphere. The curve of interpolation was used to the present analysis.

In Fig. 11, the relative absorptions are represented for two extreme cases in the measurements and in Fig. 12, the absolute energy absorbed is shown. In Fig. 11, the measurement shows a larger amount of absorption and a rather steeper distribution than the model. The clearest case shows that the distribution is approximately proportional to λ^{-3} in the region shorter than

Fig. 11. Spectral distributions of the aerosol absorption derived from measurement. Two extreme cases are shown in relative unit.

Fig. 12. Absolute energy of the absorption by the aerosols and the water vapor obtained by measurement.

about $0.45 \mu\text{m}$, to λ^{-1} from 0.45 to $0.70 \mu\text{m}$ and slightly increases in the near infrared region. In a turbid case, a large amount of absorption is noticed and the distribution curve is approximately proportional to $\lambda^{-1.7}$ in the ultraviolet and visible region.

The above-described values of the emergent radiation which were obtained with the aid of the model calculation are not enough for discussing the precise estimation of the absorption by aerosols, because of the assumption of the wavelength independent values of the optical parameter in the model calculation. We will have to take into account in the model calculation the measured values of the optical thickness and the wavelength dependent refractive index of particles and the surface albedo as a function of the wavelength. On the other hand, accurate measurement in the ultraviolet region and the precise estimation of the absorption of water vapor in the near-infrared region are important future problems.

5. Summary

We made the spectral measurements of the global and the diffuse sky radiation at the ground level in an urban area. By the subtraction of the diffuse component from the global radiation, we got the direct component and the spectral extinction coefficients

were deduced from that component (See Fig. 3).

From the data obtained we see a remarkable difference in the spectral distribution of the global radiation between the clear and the turbid sky. The effects of aerosols on the global and the diffuse sky radiation, that is, the deficit of the global radiation and the excess of the diffuse radiation to the Rayleigh atmosphere are generally proportional to the extinction coefficient (See Figs. 7 and 8). It is noticeable that the excess of the diffuse radiation becomes negative in the wavelength region shorter than about $0.40 \mu\text{m}$.

The absorption of solar radiation by the aerosols in the entire atmosphere was estimated from the net flux divergence between the top and the bottom of the atmosphere. The diffuse radiation emerging to the space was deduced from the diffuse radiation measured at the ground multiplied by the ratio of the upward to the downward radiation calculated for the model atmosphere.

The absorption of the aerosols is predominant in the ultraviolet region compared with the visible and the near-infrared region (See Figs. 11 and 12). In the visible and the near-infrared region, the absorption does not show violent variation; its values are about 20 per cent or so for a rather wide variation of turbidity of the atmosphere.

Acknowledgements:—The authors are indebted to Prof. G. Yamamoto, Prof. M. Tanaka and Dr. S. Ohta, Tohoku Univ., Sendai, for offering us a lot of data on the calculation of the model atmosphere and to the

staff concerned with radiation measurement at the Aerological Observatory, Tateno, who gave us the ozone data at Tateno. They are also grateful to Dr. M. Kano of the Meteorological Research Institute for his kind suggestions and critical reading of the manuscript.

References

- Drummond, A.J. and G. Robinson, 1974: Some measurements of the attenuation of solar radiation during BOMEX. *Appl. Opt.*, **13**, 487-492.
- Liou, K.-N. and T. Sasamori, 1975: On the transfer of solar radiation in aerosol atmosphere. *J. Atm. Sci.*, **32**, 2166-2177.
- Murai, K., M. Kobayashi, R. Goto and T. Yamauchi, 1977: Ground-based spectral measurements of solar radiation (I)—extinction and size distribution of aerosol particles in the atmosphere—. *Pap. Met. Geophys.*, **28**, 169-184.
- Robinson, G.D., 1962: Absorption of solar radiation by atmospheric aerosols, as revealed by measurements at the ground. *Arch. Met. Geoph. Bioclim.*, **12**, 19-40.
- , 1966: Some determination of atmospheric absorption by measurement of solar radiation from aircraft and at the surface. *Quart. J. Roy. Met. Soc.*, **92**, 263-269.
- Thekaekara, M.P., 1971: Solar electromagnetic radiation. NASA Rep. SP-8005, 33pp.
- Yamamoto, G. and M. Tanaka, 1969: Determination of aerosol size distribution from spectral attenuation measurements. *Appl. Opt.*, **8**, 447-453.
- , ——— and S. Ohta, 1974: Heating of the lower troposphere due to absorption of the visible solar radiation by aerosols. *J. Met. Soc. Jap.*, **52**, 61-68.

地上における日射の分光測定 (II)

—全天および天空散乱日射—

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グレーティングを用いた複式分光計と積分球を組合せて全天分光日射計を試作し、全天日射と天空散乱日射の分光測定を行った。散乱光の測定の場合には遮光用円板を用いて直射成分をさえぎる。全天日射量から散乱日射量を差し引いて直達日射成分を求め、消散係数の波長分布を得る。レーリー大気についての計算値と比較しエアロゾルの効果を求めた。エアロゾルによる全天日射の減少量は消散係数の増加とともに増加することが認められる。散乱日

射は、可視および近赤外域ではエアロゾルによる消散係数の増加とともに増加するが、紫外域付近の波長領域ではエアロゾルの増加によって散乱光は減少し、レーリー大気の値よりも小さくなることが認められる。エアロゾルを含む大気による日射の吸収量を求めるために、大気の上端と地表面における net flux の計算を行った。大気上端に入射する日射量はNASAの測定値を用い、上端から散逸する散乱日射は地上における散乱日射の測定値と混濁大気についての計算値を組合せて推定した。地表面におけるアルベードの値は、先に著者等が行った飛行機による測定によって得た値を用い、これと全天日射の測定値を組合せて地表面における net flux を求めた。大気上端と地表面における net flux の差引きによって吸収量を波長別に計算した。吸収量は可視および近赤外域では、大気上端への入射量の約 20% であるが、大気の混濁度によってかなり変動する。波長約 $0.45\ \mu\text{m}$ 以下の短波長領域では著しく大きい吸収量が測定され、50% を超える値が得られている。