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A NEW MODEL FOR SOLAR RADIATION ESTIMATION

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SYNOPSIS

In this paper, a new formulation (referred to as the hybrid model hereafter) for calculating solar radiation is proposed. The main idea is to use a term derived from the spectral theory of radiation to account for geographic influence such as latitude and so forth, while handle the cloud effect by correlation method. The model is validated at several locations across Japan. The comparison is also made between the results from the hybrid model and that from other model.

INTRODUCTION

In environmental studies, the surface temperature and evaporation are of great concern, which are determined by heat balance at the ground surface. When solar radiation reaches the surface, this energy flux is redistributed into the sensible heat flux, latent heat flux, ground heat flux, and long wave radiative heat flux by which the energy balance is maintained. Factors influencing the relative magnitude of these energy balance components, such as surface albedo, surface moisture, surface thermal conductivity have been discussed extensively in previous studies (ref. (4), (9), (11)). Nevertheless, there still remains some fundamental issues concerning the heat budget, which deserve further considerations. The issue we address in this paper is the estimation of solar radiation.

Solar radiation refers to electromagnetic radiation originating in thermonuclear reaction on the sun.. In the past several decades, several methods were presented to calculate the solar radiation. One of them is the Spectral Model (ref. (1), (2)) which considers the physical behavior of the atmosphere such as absorption and scattering. Another approach is to make use of empirical relations between solar radiation and meteorological parameters. Angstrom model (ref. (1), (2)), was the pioneering work in this line, its general form is

$$\frac{R_s}{R_0} = a + b(S/S_0) \tag{1}$$

where

R_s = solar radiation on a horizontal surface

R_0 = extraterrestrial solar radiation on a horizontal surface

S = sunshine duration

S_0 = maximum possible sunshine duration

a and b are regression coefficients.

The difficulty in using eq.(1) is that one often encounters substantially temporal as well as spatial scatter in the values of the regression coefficients, even for nearby and climatologically similar locations. Jain (6) modified the Angstrom model by introducing a quadratic term, Gopinathan (5) suggested equations for computing the regressing coefficients in terms of the latitude, altitude and percent of possible sunshine. Although those efforts improved Angstrom model, they still suffer from the lack of generality as the original Angstrom model.

In the present study, we attempt to develop a hybrid model by combining the correlation method with the spectral approach. The objective is to establish a more universal, but not too complicated model for accurately estimating solar radiation. The proposed model is validated at several locations with quite different latitude and surface elevations across Japan.

HYBRID MODEL

In daytime, solar radiation is the main driving force to account for variation of surface temperature and hence it must be estimated accurately. Latitude, altitude, water vapor and cloud effect are main factors affecting solar radiation, but they are so complex that their effect on solar radiation varies from one place to another, which causes the coefficients a and b in eq.(1) lack generality as mentioned above.

Spectral model takes account for Rayleigh scattering, ozone absorption, absorption by CO_2, O_3 etc, water vapor absorption and aerosol attenuation, respectively. It considers variation of latitude and altitude and precipitable water, hence, in some sense, it is a universal method. With this method, the direct solar radiation reaching ground level can be computed as:

$$I=\sum I_0(\lambda)\tau_r(\lambda)\tau_a(\lambda)\tau_w(\lambda)\tau_{oz}(\lambda)\tau_g(\lambda) \qquad (2)$$

where $I_0(\lambda)$ is extraterrestrial solar radiation at a wavelength $\lambda, \tau_r(\lambda), \tau_a(\lambda), \tau_w(\lambda), \tau_{oz}(\lambda), \tau_g(\lambda)$ are transmittance functions for Rayleigh scattering, aerosol attenuation, water vapor absorption, ozone absorption and mixed gas absorption, respectively. The drawback of spectral method lies in its complexity and the uncertainty in the description of the transmittance functions for cloudy or partly cloudy skies. In the present study, an attempt is made to develop a hybrid model for solar radiation, which is more universal than Angstrom type of regression models, and relatively simple as compared to the original spectral model. The basic idea is to calculate the transmittance functions by introducing representative parameters $\bar{\lambda}_r$, $\bar{\lambda}_a$, $\bar{k}_{oz}$, $\bar{c}_g$, $\bar{\tau}_w$, while account for the diffuse radiation by correlation method, so that the total radiation is calculated as

$$R_s = K(S)F(\bar{\lambda}_a, \bar{\lambda}_a, \bar{k}_{oz}, \bar{c}_g, \bar{\tau}_w) \qquad (3)$$

where $K(S)$ is assumed to be a quadratic function of sunshine hours, its coefficient will be determined through regression analysis.

According to the spectral theory described by Leckner (8), the transmittance functions of Rayleigh scattering, aerosol attenuation, ozone absorption, water vapor absorption, and mixed gas absorption can be approximated as:

$$\begin{aligned}
&\tau_r(\lambda)=\exp(-0.008735m\lambda^{-4.08}P/P_0)\\
&\tau_a(\lambda)=\exp(-\beta m\lambda^{-1.3}) \qquad (4)\\
&\tau_{oz}(\lambda)=\exp[-lmk_{oz}(\lambda)]\\
&\tau_w(\lambda)=\exp[-0.238k_w(\lambda)mw/(1+20.07k_w(\lambda)mw)^{0.45}]\ \tau_g(\lambda)=\exp[-1.41k_g(\lambda)m/(1+118.3k_g(\lambda)m)^{0.45}]
\end{aligned}$$

where the relative mass of atmosphere

$$m=\frac{1-0.0001z_s}{\sin h+0.15(57.296h+3.885)^{-1.253}} \qquad (5)$$

β is Angstrom turbidity, which can be calculated for latitude 0^0N ~60^0N [6)] by:

$$\beta=\bar{\beta}+\Delta\beta \qquad (6)$$

$\overline{\beta} = (0.025 + 0.1\cos\phi)\exp(-0.7z_s/1000)$ $\Delta\beta = \pm(0.02 \sim 0.06)$, plus for summer season and minus for winter season. Thickness of ozone layer l is approximated as below (see (1)):

$$l = l_{\max} - (l_{\max} - 0.15)(1 - \frac{\phi}{60})^2 \tag{7}$$
$$l_{\max} = 0.25 + 0.05\sin(2\pi J_d/365)$$

The precipitable water is computed according to Kondo (7):

$$w = 10^{0.03127T_{\text{dew}} - 0.0963} \text{ (cm)} \tag{8}$$

J_d is Julian day, ϕ the latitude, z_s the surface elevation, h is solar angle. k_{oz}, k_w, k_g are respective absorptance of ozone, water vapor and mixed gases. $P_0 = 1.013 \times 10^5\text{Pa}$, P is local air pressure, and T_{dew} the dew-point temperature (^{0}C).

Integration of (4) over the whole solar spectrum is obviously tedious. To simplify the calculation while retaining the accuracy achievable by rigorous spectral integration, we define representative parameters $\overline{\lambda}_r$, $\overline{\lambda}_a$, $\overline{k}_{oz}$, $\overline{c}_g$, $\overline{\tau}_w$, in the following way:

$$\exp(-0.008735\frac{P}{P_0}m\overline{\lambda}_r^{-4.08}) = \frac{1}{I_0}\int\exp(-0.008735\frac{P}{P_0}m\lambda_r^{-4.08})I(\lambda)d\lambda$$
$$\exp(-\beta m\overline{\lambda}_a^{-1.3}) = \frac{1}{I_0}\int\exp(\beta m\lambda^{-1.3})I(\lambda)d\lambda$$
$$\exp(-\overline{k}_{oz}ml) = \frac{1}{I_0}\int\exp[-k_{oz}(\lambda)ml]I(\lambda)d\lambda \tag{9}$$
$$\exp(-\overline{c}_g) = \frac{1}{I_0}\int\exp[-\frac{1.41k_g(\lambda)m}{(1+118.3k_g(\lambda)m)^{0.45}}]I(\lambda)d\lambda$$
$$\overline{\tau}_w(mw) = \frac{1}{I_0}\int\exp[-\frac{0.2385k_w(\lambda)mw}{(1+20.07k_w(\lambda)mw)^{0.45}}]I(\lambda)d\lambda$$

where I_o is the solar constant.
By numerically integrating (9) and keeping the quadratic terms to take non-linearity into consideration:

$$\overline{\lambda}_r = 0.5595 + 0.01044(m\frac{P}{P_0}) - 0.000129(m\frac{P}{P_0})^2$$
$$\overline{\lambda}_a = 0.6777 + 0.1464(m\beta) - 0.00626(m\beta)^2$$
$$\overline{k}_{oz} = 0.0404 - 0.0045(ml) + 0.000225(ml)^2$$
$$\overline{c}_g = 0.013147 + 0.001188m - 0.000064m^2 \tag{10}$$
$$\overline{\tau}_w(mw) = \begin{cases} 0.883 - 0.0053mw + 0.000064mw^2 \\ \quad\quad \text{for } mw \le 50 \\ 0.7684 - 0.000347(mw - 50) \\ \quad\quad \text{for } mw > 50 \end{cases}$$

Combining the above formulations, and representing *K(S)* by a quadratic function of sunshine hours, the hybrid model for solar radiation takes a form as below:

$$R = R_0(a + bn + cn^2)\overline{\tau}_w e^{-(\frac{P}{P_0}\overline{\lambda}_r^{-4.08} + \beta\overline{\lambda}_a^{-1.3} + \overline{k}_{oz}l)m - \overline{c}_g} \tag{11}$$

Since the term related to the spectral composition in eq.(11) can take account for the effect of latitude, altitude and water vapor; and the quadratic function of solar hours can take care of diffuse radiation and cloud effect, the model may have more universality than Angstrom type of simple regression models.

Based on hourly radiation data at Tokyo observation station of the Japan Meteorological agency for 1995, coefficients a, b, c are determined as:

$$a = 0.28013,\quad b = 1.3167,\quad c = -0.4915$$

To validate the model, we apply it to three different locations. They are Minamitorishima which is situated in the southernmost part of Japan, Wakkanai, northernmost in Japan, and Kofu, in the central part of Japan. To compare the error of estimation, we define the root mean square error:

$$\mathrm{RSME} = \left\{\left[\sum (H_{i,cal} - H_{i,meas})^2\right] / n\right\}^{1/2} \tag{12}$$

The comparisons of observation and estimation with different models at the three stations are shown in Fig.1-a,b, Fig.2-a,b, and Fig.3-a,b, respectively. And the estimation error is summarized in Table.1

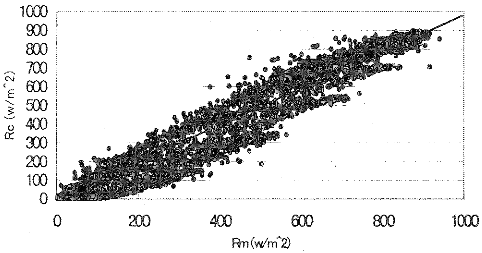

Fig. 1-a Comparison of global solar radiation of measurement and calculation by hybrid model at Minamitorishima In 1995

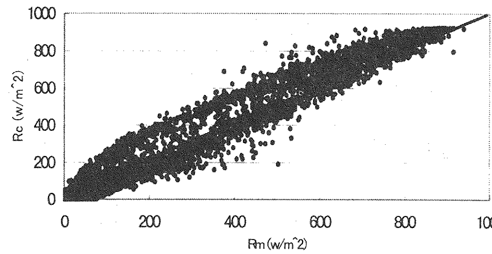

Fig.1-b Comparison of global solar radiation of measurement and calculation by Gopinathan model at Minamitorishima In 1995

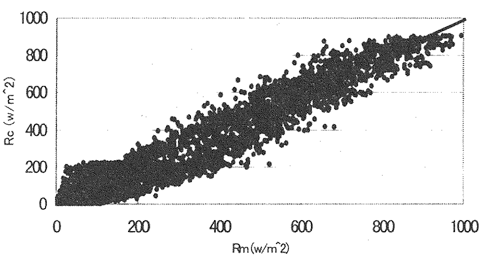

Fig.2-a Comparison of global solar radiation of measurement and calculation by hybrid model at Kofu In 1995

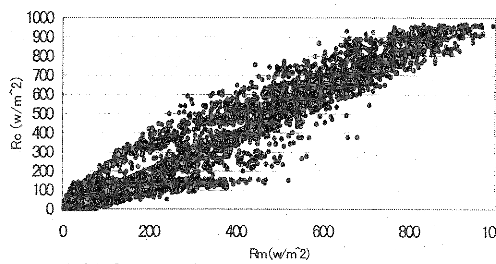

Fig.2-b Comparison of global solar radiation of measurement and calculation by Gopinathan model at Kofu In 1995

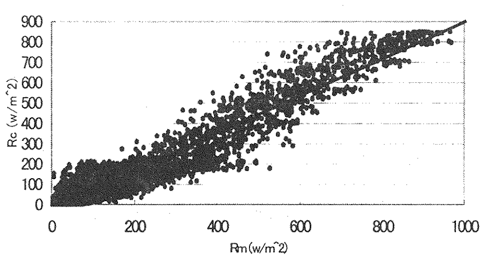

Fig.3-a Comparison of global solar radiation of measurement and calculation by Hybrid model at Wakkanai In 1995

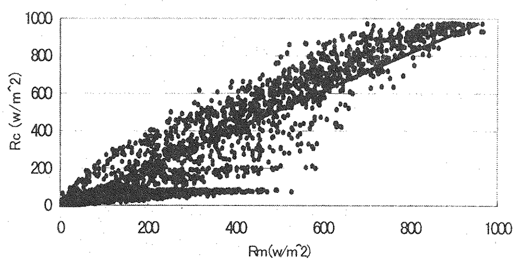

Fig.3-b Comparison of global solar radiation of measurement and calculation by Gopinathan model at Wakkanai In 1995

As can be seen from the figures, the hybrid model performs well at three different locations, and gives better estimations of solar radiation than the Gopinathan model, particularly, at the northernmost location, Wakkanai, where the output of Gopinathan model deviates greatly from measured data. It can also be seen from

Table 1 that the RSME generated by the hybrid model is quite close to each other at the three stations. The better performance of the present model may be attributed to the fact that the dependence of solar radiation on latitude in the present model was derived by approximating the spectral integration, while in the Gopinathan model the relationship between solar radiation and latitude was developed with field data at locations outside of Japan. Since the hybrid model is developed and validated with measured data at locations with quite different latitude and altitude across the territory of Japan, the better performance and universality of the model across Japan might be expected as compared with models established with different data sources.

Station	Longtitude(E), Latitude(N) Elevation(m)	RSME (w/m^2)	
		Hybrid	Gopinathan
Minamitori-shima	$153^0 58'$, $24^0 18'$ 8.3	86.99	91.36
Kofu	$138^0 33'$, $35^0 40'$ 272.8	82.38	93.43
Wakkanai	$141^0 41'$, $45^0 25'$ 2.8	88.14	124.2

Table 1 Comparison of estimation error with different model for 1995

CONCLUSION

In this study, a new hybrid model for computing the solar radiation is developed. It can account for geographic influence, and its accuracy is comparable to that achievable by rigorous spectral integration while being much simpler to use. The model is verified, and shown to give better agreement with observational data as compared to the formula proposed by Gopinathan. It should be mentioned that we are now applying the hybrid model to some other locations such as Naha, Akita, Sapporo and so on. The performance of the hybrid model is being evaluated by comparison with measured data and the output from three different models. Those results will be published in a separate paper.

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