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A HYBRID MODEL FOR ESTIMATING GLOBAL SOLAR RADIATION

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Abstract—In view of the site-dependence of Ångström correlation, this study developed a hybrid model to estimate global radiation H. Unlike Ångström correlation $H=(\alpha+\beta S/S_0)H_0$, this model suggested that $H=(a+b\ S/S_0)H_b+(c+d\ S/S_0)H_d$, H_b and H_d are effective beam radiation and effective diffuse radiation, which imply latitude, elevation and seasonal effect on radiation. H_b and H_d are calculated by an arithmetic model derived from spectral model. The hybrid model was designed for estimating monthly mean daily global radiation with hourly-recorded bright sunshine time, and its applicability was verified at observatories in Japan.

1. INTRODUCTION

Solar radiation received at the surface is of primary importance for the purpose of building solar energy devices, estimating crop productivity, etc. However, direct measuring is not available in many cases, so numerical technique becomes an effective alternative to estimate global radiation through observed meteorological data.

The Ångström (1924) correlation has served as a basic approach to estimate global radiation for a long time. Prescott (1940) has put the correlation in a convenient form as

$$H=(\alpha+\beta S/S_0)H_0 \tag{1}$$

where H (Jm^{-2}) and H_0(Jm^{-2}) are solar radiation on a horizontal surface at ground level and at extraterrestrial level, respectively. S/S_0 is the time fraction of bright sunshine, α and β are constants.

The Ångström formula only involves S/S_0 and thus is quite convenient for application. Unfortunately, it does not consider the effect of latitude and elevation, so α and β are site-based coefficients. For instance, $\alpha=0.1\sim0.3$, $\beta=0.4\sim0.7$ in China (Xu, 1993). Up to now, there are some attempts to explore more accurately α and β or consider other factors such as elevation and latitude. Iqbal (1979) appended a quadratic term of S/S_0 in Eq. (1). Gopinathan (1988) proposed a formula which relates latitude, elevation and S/S_0 to α and β. Yeboah-Amankwah and Agyeman (1990) believed that α and β are time-dependent and so developed a differential Ångström model with a set of coefficients which vary with time. Ninomiya (1994) considered the effect of snow and rainfall of rainy days. Sahin and Sen (1998) proposed a method to dynamically estimate the coefficients α and β. However, their work doesn't consider the radiation damping processes when solar rays pass through the atmosphere. Some researchers (Leckner, 1978; Bird, 1984) employed a damping spectrum to calculate global solar radiation in clear sky. Their models consider physical processes in detail, so the effects of latitude, elevation and other factors are taken into account automatically. However, damping spectrums are very irregular and hence a numerical integration is indispensable, which is an onerous task. Furthermore, the uncertainties associated with cloudiness limit the application of spectral models.

Therefore, this study attempts to develop a model that can consider the physical processes but still maintain the simplicity of the Ångström correlation. In Section 2, a model form is proposed to incorporate effective beam radiation and diffuse radiation with global radiation. Then the Leckner spectral model is simplified to calculate effective beam radiation and diffuse radiation in Section 3. The model is calibrated in Section 4 and its verification is carried out in Section 5.

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2. NEW FORM OF SOLAR RADIATION MODEL

When solar rays pass through the atmosphere, there are five types of radiation-damping processes, viz. Rayleigh scattering, aerosol extinction, ozone absorption, water vapor absorption and permanent gas absorption, which are represented by transmittance functions $\tau_{oz}(\lambda)$, $\tau_w(\lambda)$, $\tau_g(\lambda)$, $\tau_r(\lambda)$, $\tau_a(\lambda)$, respectively. λ(m) represents wave-length. In order to consider the effect of all transmittance functions, we define the beam transmittances $\overline{\tau_b}$ and diffuse transmittance $\overline{\tau_d}$ as

$$\overline{\tau_b} \equiv I_0^{-1} \int_{\lambda_{min}}^{\lambda_{max}} I_{0i}(\lambda)\tau_{oz}(\lambda)\tau_w(\lambda)\tau_g(\lambda)\tau_r(\lambda)\tau_a(\lambda)\,d\lambda, \tag{2a}$$

$$\overline{\tau_d} \equiv I_0^{-1} \int_{\lambda_{min}}^{\lambda_{max}} I_{0i}(\lambda)\tau_{oz}(\lambda)\tau_w(\lambda)\tau_g(\lambda) \times [1 - \tau_r(\lambda)\tau_a(\lambda)]\,d\lambda. \tag{2b}$$

And define effective beam radiation H_b (J m^{-2}) and diffuse radiation H_d (J m^{-2}) at ground level as

$$H_b \equiv I_0 \int \overline{\tau_b} \sin h\,dt, \tag{3a}$$

$$H_d \equiv I_0 \int \overline{\tau_d} \sin h\,dt, \tag{3b}$$

where $I_0 = \int_{\lambda_{min}}^{\lambda_{max}} I_{0i}(\lambda)\,d\lambda$. I_{0i} (wm^{-2} μm^{-1}) is the solar irradiance spectrum at extraterrestrial level, λ_{min} and λ_{max} are the lower and higher wavelength limits of solar spectrum, respectively (Thekaekara, 1973). h(rad) is the altitude angle of the sun, t(s) is the time.

Effective beam radiation H_b and diffuse radiation H_d mainly vary with the position of the sun. Fig. 1 is an example to show its temporal variation. The site is Tokyo and the date is Jul. 1, 1996. The calculation follows the Leckner (1978) model (see Section 3). The horizontal axis represents the daytime and the vertical H_b, H_d and their ratio H_d/H_b. During sunrise and sunset, the diffuse radiation is higher than the beam radiation due to intense Rayleigh scattering and aerosol extinction. However, the former is much lower than the latter at noon. Therefore, the ratio H_d/H_b is not a constant. Actually, it depends on location, date and time, etc.

In a cloudy sky, a part of H_b may directly pass through the cloud layer and arrive on the ground as beam radiation, which is assumed as $(a_1 + b_1 S/S_0)H_b$, analogous to Eq. (1); also, a part of H_b may be diffused by the cloud layer but finally arrive on the ground as diffuse radiation, which is assumed as the $(a_2 + b_2 S/S_0)H_b$. Similarly, we assume the diffuse radiation from H_d is $(c + dS/S_0)H_d$ after the reflection and scattering at the cloud layer. Therefore, the global radiation H is the sum of the three parts, which has the form as below,

$$H = (a + b\, S/S_0)H_b + (c + d\, S/S_0)H_d \tag{4}$$

where a, b, c and d are coefficients. a_1 and a_2 are merged as a, b_1 and b_2 are merged as b, so the

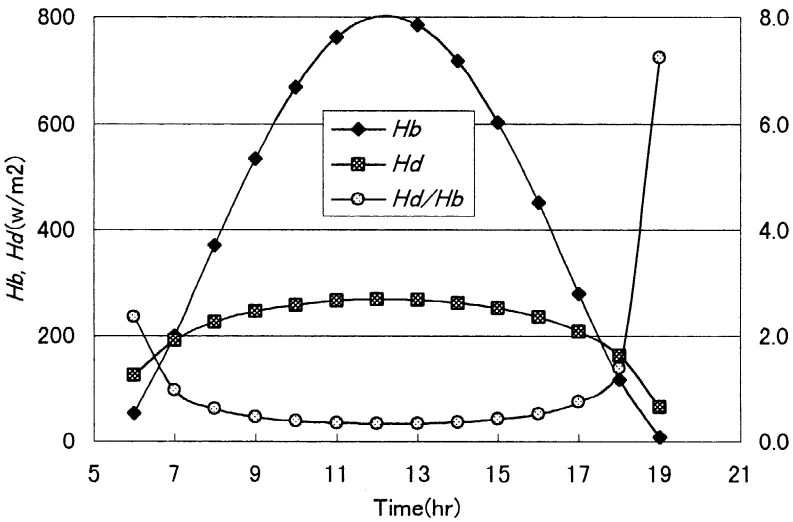

Fig. 1. Temporal variation of effective beam radiation H_b, diffuse radiation H_d, and the ratio H_d/H_b. Date: Jul. 1, 1996. Place: Tokyo (139°46′E, 35°41′N).

term $(a + b\ S/S_0)H_b$ includes both beam and diffuse radiation. Eq. (4) is an analogue to Ångström correlation Eq. (1), but H_b and H_d are calculated from spectral model as follows, so it is a hybrid model.

3. SIMPLIFIED MODEL FOR $\overline{\tau_B}$ AND $\overline{\tau_D}$

To estimate global radiation, H_b and H_d have to be calculated at first. Since, altitude angle h in the Eqs. (3) can be easily calculated, the main difficulty lies in the integration of beam transmittances $\overline{\tau_b}$ and diffuse transmittance $\overline{\tau_d}$ through Eqs. (2). As mentioned above, this costly integration is one weakness of the spectral model. The purpose of this section is to explore a simple method to replace numerical integration for calculating $\overline{\tau_b}$ and $\overline{\tau_d}$.

As shown in Leckner (1978) spectral model, the five transmittance functions in Eqs. (2) can be expressed as:

$$\tau_{oz}(\lambda) = \exp\{-lmk_{oz}(\lambda)\}, \tag{5a}$$

$$\tau_w(\lambda) = \exp\{[-0.2385k_w(\lambda)mw] / [1 + 20.07k_w(\lambda)mw]^{0.45}\}, \tag{5b}$$

$$\tau_g(\lambda) = \exp\{-1.41k_g(\lambda)m/[1 + 118.3k_g(\lambda)m]^{0.45}\}, \tag{5c}$$

$$\tau_r(\lambda) = \exp\{-0.008735m\lambda^{-4.08}P/P_0\}, \tag{5d}$$

$$\tau_a(\lambda) = \exp\{-\beta_t m\lambda^{-1.3}\}, \tag{5e}$$

where Air mass $m = (1 - 0.0001z_s)/[\sin h + 0.15(57.296h + 3.885)^{-1.253}]$; z_s(m) is ground level. β_t is Ångström turbidity. If β_t is unavailable, the following formula is adopted to estimate its value:

$$\beta_t = \overline{\beta_t} + \Delta\beta_t,$$

$$\overline{\beta_t} = (0.025 + 0.1\cos\phi)\exp(-0.7z_s/1000),$$

$$\Delta\beta_t = \pm(0.02 \sim 0.06).$$

$\overline{\beta_t}$ is the annual mean values of turbidity, following Fig. 3 of Ångström (1961). $\Delta\beta_t$ is the seasonal deviation from the mean values, i.e. low values in winter, high values in summer.

l (cm) is the thickness of ozone layer. If l is unavailable, its value is estimated through

$$l = 0.44 - 0.16 \times \{[(\phi - 80)/60]^2 + [(d - 120)/(263 - \phi)]^2\}^{1/2},$$

with

$$d = \begin{cases} J_d & \text{if } J_d < 300 \\ J_d - 366 & \text{if } J_d > 300 \end{cases}$$

which is a roughly fitting formula based on Fig. 9.12 of Xu (1993), J_d is the Julian day. T_{dew} (°C) is dew point, and w (g/cm^2) is precipitable water $w = 0.493(T_{dew} + 273.15)^{-1}\ \exp[26.23 - 5416(T_{dew} + 273.15)^{-1}]$. k_{oz}, k_w, k_g (cm^{-1}) are absorption coefficients of ozone, water vapor and permanent gases, respectively. P (mb) is local pressure, and $P_0 = 1.013 \times 10^3$ mb.

Since Ångström turbidity, thickness of ozone layer and precipitable water vary with season, latitude and/or elevation, the transmittance functions have considered their effect on solar radiation. In order to simplify the calculation of Eqs. (2), we derive each energy-weighted average transmittance function as follows.

For the transmittance function due to ozone absorption, it is defined as

$$\overline{\tau_{oz}} \equiv I_0^{-1}\int_{\lambda_{min}}^{\lambda_{max}} I_{0i}(\lambda)\tau_{oz}(\lambda)\,d\lambda = I_0^{-1}\int_{\lambda_{min}}^{\lambda_{max}} I_{0i}(\lambda)\exp(-lmk_{oz}(\lambda))\,d\lambda \tag{6}$$

Evidently, $\overline{\tau_{oz}}$ is a function of ml rather than wavelength λ. With the absorption coefficients $k_{oz}(\lambda)$ provided by Leckner (1978), we can obtain the transmittance due to ozone absorption through numerically integrating Eq. (6). As shown in Fig. 2, the dots are integrated values. Fitting the discrete data by least square method, we can obtain the following approximate relation.

$$\overline{\tau_{oz}} = \exp(-lm\bar{k}_{oz}), \tag{7a}$$

Similar processing is applied to other transmittance functions. The final result is

$$\overline{\tau_w} = \exp(-\overline{c_w}) \tag{7b}$$

$$\overline{\tau_g} = \exp(-\overline{c_g}) \tag{7c}$$

$$\overline{\tau_r} = \exp(-0.008735m\bar{\lambda}_r^{-4.08}P/P_0) \tag{7d}$$

$$\overline{\tau_a} = \exp(-\beta_t m\bar{\lambda}_a^{-1.3}) \tag{7e}$$

where

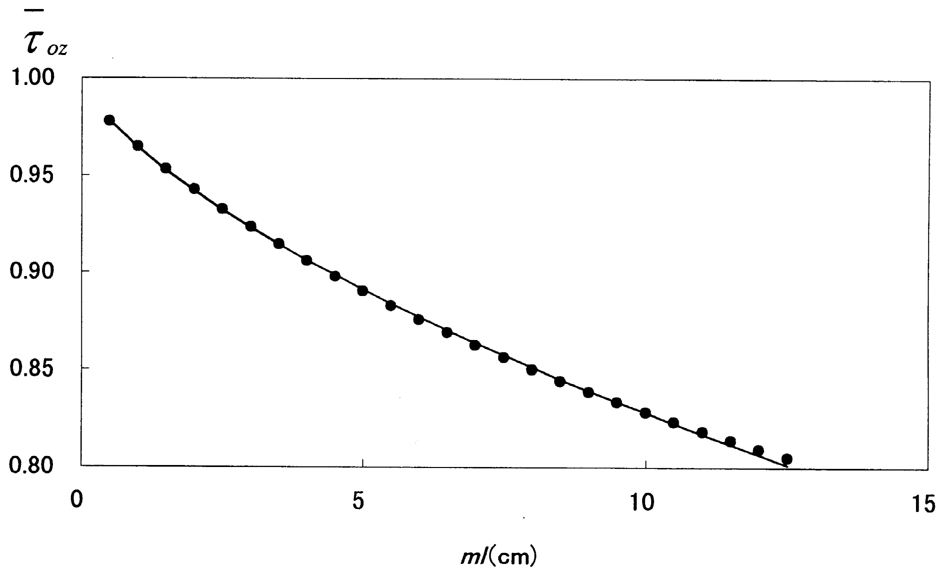

Fig. 2. The comparison of transmittance values $\overline{\tau_{oz}}$ between integration and fitting. Dot represents integrated values from Eq. (6). Line represents the fitting values from Eq. (7a).

$$\overline{k_{oz}} = 0.0365(ml)^{-0.2864} \tag{8a}$$

$$\overline{c_w} = -\ln[0.909 - 0.036\ln(mw)] \tag{8b}$$

$$\overline{c_g} = 0.0117m^{0.3139} \tag{8c}$$

$$\overline{\lambda_r} = 0.547 + 0.014(mP/P_0) - 0.00038(mP/P_0)^2 + 4.6 \times 10^{-6}(mP/P_0)^3 \tag{8d}$$

$$\overline{\lambda_a} = 0.6777 + 0.1464(m\beta_t) - 0.00626(m\beta_t)^2 \tag{8e}$$

As an approximation, we replace Eqs. (2) with

$$\overline{\tau_b} \approx \overline{\tau}_{oz}\overline{\tau}_w\overline{\tau}_g\overline{\tau}_r\overline{\tau}_a - 0.013, \tag{9a}$$

$$\overline{\tau_d} \approx \overline{\tau}_{oz}\overline{\tau}_g\overline{\tau}_w(1 - \overline{\tau}_a\ \overline{\tau}_r) + 0.013 \tag{9b}$$

to calculate beam transmittance and diffuse transmittance. The second terms at the right hand side (RHS) of Eqs. (9) are average biases of the first terms from the RHS of Eqs. (2). To fully show the performance of Eqs. (9), we calculated the values of both Eqs. (9) and Eqs. (2) for a number of cases, which set the range of required parameters as: pressure ratio $P/P_0 \sim 0.5 - 1$, air mass $m \sim 1 - 7$, turbidity $\beta_t \sim 0.05 - 0.4$, ozone thickness $l \sim 0.2 \sim 0.4$ cm, precipitable water $w = 1 \sim 10$ g cm^{-2}. The comparison between the approximate values from Eq. (9a) and exact values from Eq. (2a) is shown in Fig. 3a, and the bias of Eq. (9a) from Eq. (2a) is shown in Fig. 3b. The horizontal axis of Fig. 3b only represents the number of dots. It is clear that the approximate values of beam transmittance are close to the exact values. The maximum positive bias is 0.016 and maximum negative bias is 0.024. Similarly, the maximum positive bias of diffuse transmittance is 0.027 and maximum negative bias is 0.020. Considering the errors of the sunshine duration measurement and the determination of some parameters (e.g. turbidity and precipitable water), it is reasonable to use Eqs. (9) to replace Eqs. (2) for calculating $\overline{\tau_b}$ and $\overline{\tau_d}$.

4. DETERMINATION OF COEFFICIENTS

Until now, only coefficients *a*, *b*, *c*, *d* in Eq. (4) are unknowns, which will be calibrated with observed data. In Japan, there are 155 JMA (Japan Meteorological Agency) stations covering this country for observing regular meteorological data. Each station collects hourly data of air temperature, relative humidity, pressure, sunshine time etc.; and 70 stations measure hourly global radiation. In these stations, the measurement of sunshine duration follows its definition by the World Meteorological Organization in 1982, i.e., beam radiance is greater than 120 W/m^2 in sunshine duration.

In order to remove measurement errors, data at 16 stations in 1995 have been used to determine the coefficients. At first, we calculate Eqs. (7)–(9) for beam transmittance $\overline{\tau_b}$ and diffuse transmittance $\overline{\tau_d}$; then calculate effective beam radiation H_b and diffuse radiation H_d by Eqs. (3). With

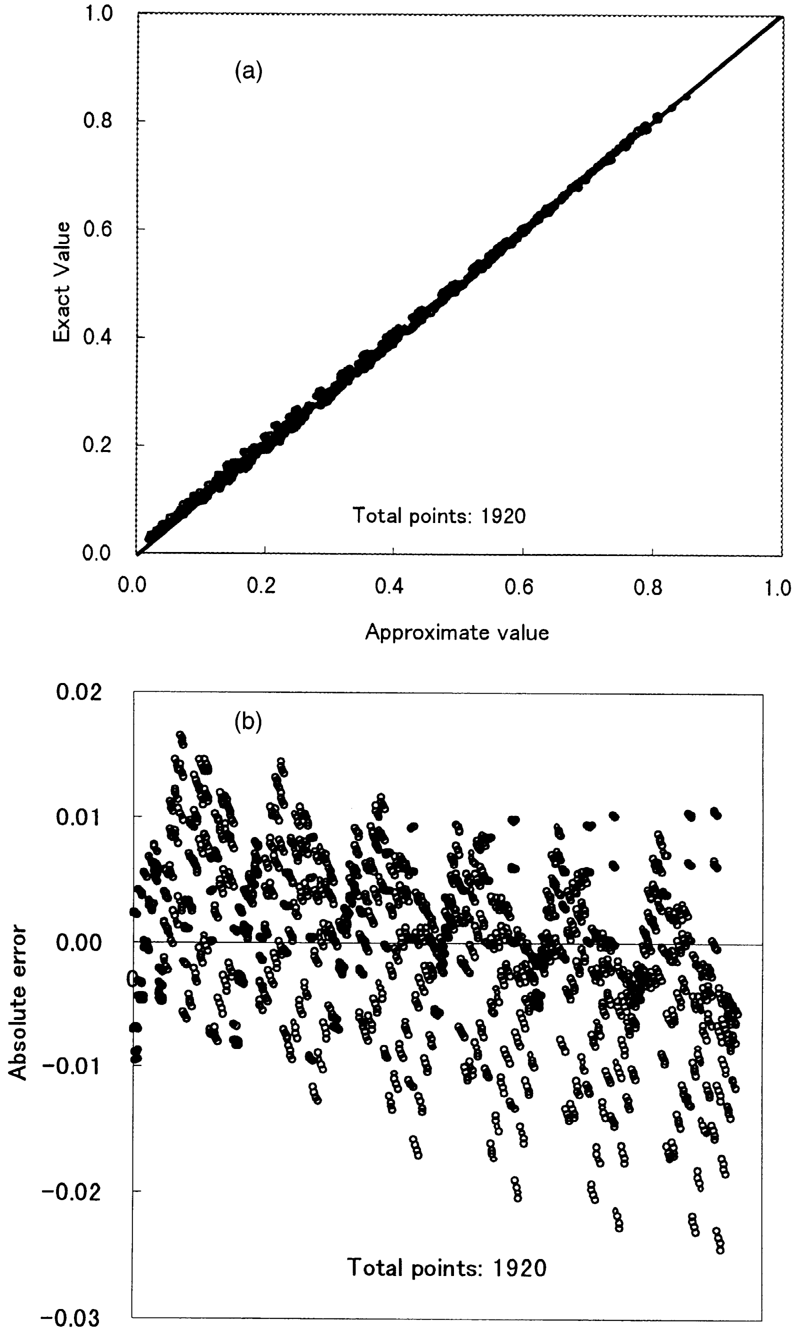

Fig. 3. (a) Comparison of beam transmittance $\overline{\tau_b}$ between exact value from Eq. (2a) and approximate value from Eq. (9a). (b) Absolute errors of beam transmittance $\overline{\tau_b}$ from Eq. (9a). The horizontal axis represents the number of dots.

measured global solar radiation and sunshine duration, we obtained the coefficients in Eq. (4) by least square fitting.

In the case $S/S_0 > 0$,

$a = 0.391, b = 0.518, c = 0.308, d = 0.320.$

In the case $S/S_0 = 0$

$a = 0.222, c = 0.199.$

5. VERIFICATION OF HYBRID RADIATION MODEL

Through the presented model, we can calculate hourly global radiation (HGR), which is accumulated to obtain daily global radiation and monthly mean daily global radiation (MMDGR). In order to investigate the elevation and latitude effect on radiation, 14 JMA stations are intentionally selected so that they include: the southernmost, the northernmost, the highest, the biggest city and other stations distributing from south to north. The geometrical parameters at these stations are shown in Table 1. So these stations with geometrical features are believed to represent all stations in Japan.

Firstly, the applicability of Ångström correlation in Japan is investigated. The coefficients α and β of Eq. (1) for four typical locations are regressed and shown in Table 2 for 1995. It is obvious that: (1) α and β at southern station (No. 1) are less than at northern station (No. 13) since turbidity decreases with respect of increase of latitude; (2) α and β at urbanized area (No. 7) are less than at mountain (No. 8) due to lower turbidity and less air mass at mountain areas. If coefficients α and β from mountainous station (No. 8) are applied to urbanized area (No. 7), the Ångström correlation will overestimate global radiation more than 10%. Therefore, α and β are site-dependent in Japan.

Secondly, the estimation to MMDGR by the hybrid model is compared with observations at all 14 stations. Figs. 4a and b show the estimated and observed MMDGR for 1995 and 1996, respectively. The horizontal axis represents the observed values and the vertical axis represents the estimated values. Apparently, the estimation of MMDGR at most stations is quite close to the observation for both 1995 and 1996, which indicates that the performance of the presented model doesn't have obvious dependence on elevation, latitude or seasons. In other word, this model can account for the effect of elevation, latitude or seasons. However, some obvious errors are still found at station No. 7 and No. 13 for 1995, and No. 1, No. 7, and No. 13–14 for 1996. It was found that the errors at these stations are also greater than that at other stations even though site-dependent Ångström-type model is applied (not shown). The analysis shows the causes of the greater errors are different at the stations.

Table 2. Coefficients of Ångström correlation at 14 JMA stations for 1995 (in case $S/S_0 > 0$)

Station No.	α	β	$\alpha+\beta$
1	0.283	0.367	0.650
7	0.272	0.374	0.646
8	0.315	0.410	0.725
13	0.348	0.386	0.734

(1) At No. 1, the radiation may be undermeasured due to system error in 1996. Fig. 5 shows the measurement difference at this station during July 1995 and 1996. Each point in this figure satisfies (a) measurement under very clear sky ($S/S_0 = 1$), and (b) same date and time except that the horizontal axis represents the measured values in 1995 and the vertical one represents the measured values in 1996. This figure clearly shows that the radiation in 1996 may be undermeasured if the measurement in 1995 is correct, which leads to the greater deviation of estimation from measurement.

(2) The greater error at station No. 7 (Tokyo) may be caused by the larger turbidity in urban areas due to air pollution. The radiation seems to be overestimated since the turbidity given in this model is an average value on longitude, which is lower than that in urban areas.

(3) At No. 13–14, the error is mainly caused owing to estimation difficulties under completely cloudy sky ($S/S_0 = 0$). Radiation in cloudy conditions is very variable, so estimations error is usually larger than under clear conditions. Since stations No. 13–14 locate in northernmost Japan, the duration of completely cloudy sky ($S/S_0 = 0$) is longer than that of sunshine and partial cloud-covered sky ($S/S_0 > 0$). Computation shows that the overall cloud duration contributes to about 1/4 of the total radiation, but to about half of the

Table 1. Geometrical parameters at 14 JMA stations

No.	Station	Longtitude (E)	Latitude (N)	Elevation (m)
1	Minamitorishima	153°58′	24°18′	8.3
2	Naha	127°41′	26°12′	28.0
3	Naze	129°30′	28°23′	2.8
4	Kakoshima	130°33′	31°34′	4.2
5	Fukuoka	130°23′	33°34′	2.5
6	Kofu	138°33′	35°40′	272.8
7	Tokyo	139°46′	35°41′	5.3
8	Matsumoto	137°58′	36°15′	610.0
9	Niigata	139°03′	37°55′	1.9
10	Akita	140°06′	39°43′	6.3
11	Hakodate	140°45′	41°49′	35.0
12	Sapporo	141°20′	43°03′	17.2
13	Kitamiesashi	142°35′	44°56′	6.7
14	Wakkanai	141°41′	45°25′	2.8

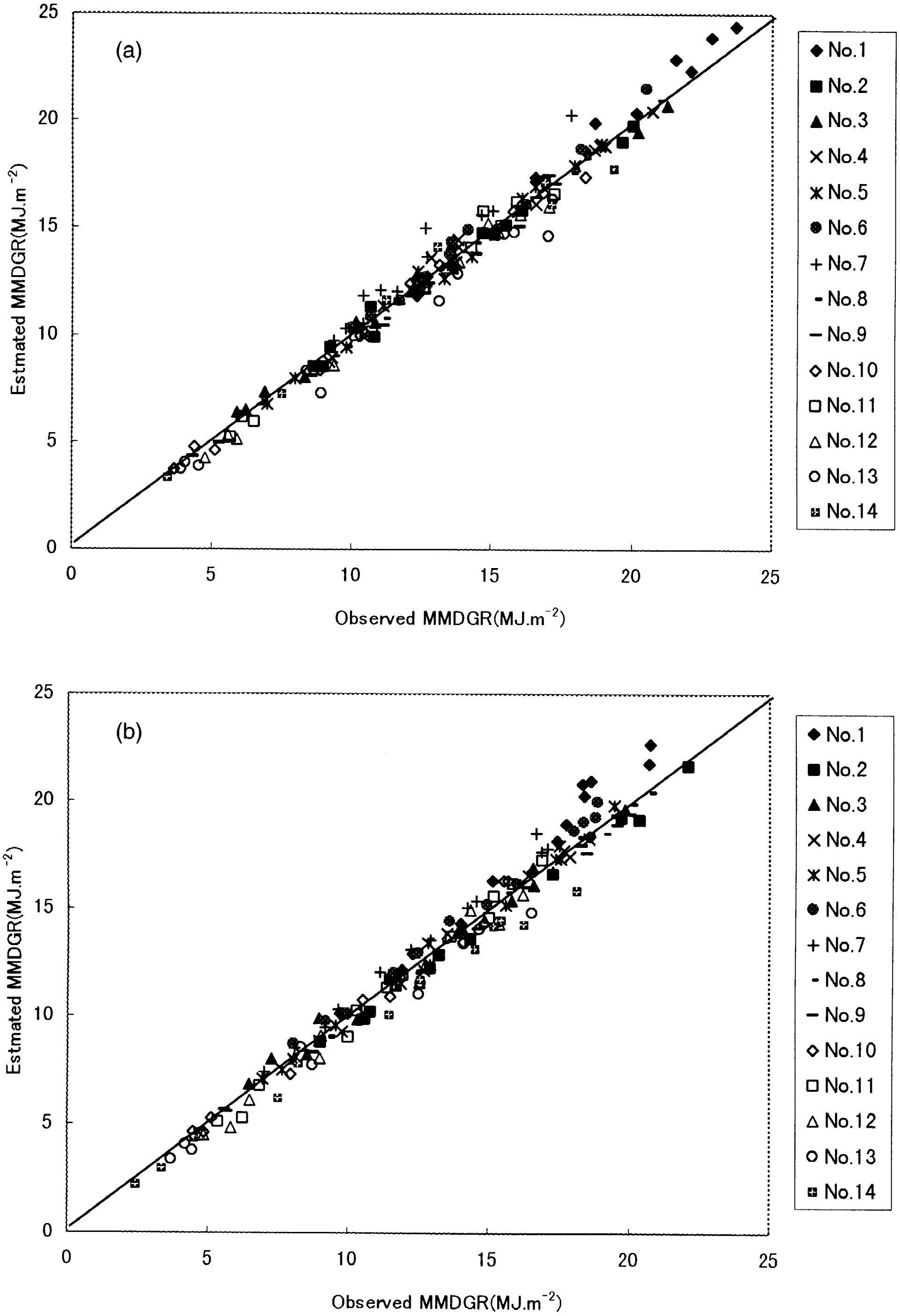

Fig. 4. (a) Comparison of MMDGR between observation and estimation with hybrid model at 14 stations in Japan for 1995. (b) Comparison of MMDGR between observation and estimation with hybrid model at 14 stations in Japan for 1996.

errors. Therefore, the cloudy weather condition is one main contributor to the greater errors.

Finally, the errors of MMDGR estimation are compared between the hybrid model and the Gopinathan (1988) model. The latter was developed to estimate MMDGR with consideration of latitude and elevation, and has been verified at 14 stations on both southern and northern hemisphere by Gopinathan. The mean bias error (MBE) and root mean square error (RMSE) are chosen to show the errors, which are defined as

$$\mathrm{MBE} = \frac{\left[\sum_{i=1}^{n} (H_{i,\mathrm{cal}} - H_{i,\mathrm{meas}})\right]}{n} \tag{10a}$$

Table 3. Mean daily global radiation (MDGR) and errors of monthly mean daily global radiation predicted by hybrid model (HM) and Gopinathan model (GM)

	Station No.		1	2	3	4	5	6	7	8	9	10	11	12	13	14
1995	MDGR (MJ/m^2)		17.89	13.64	12.08	14.22	13.73	14.30	12.16	14.80	11.70	11.21	11.81	11.51	11.26	12.80
	MBE (MJ/m^2)	HM	0.424	−0.262	0.004	−0.096	−0.052	0.332	0.952	−0.229	−0.209	−0.203	−0.111	−0.435	−0.894	−0.243
		GM	2.286	1.162	0.606	1.395	1.287	1.282	1.971	0.090	0.277	−0.171	0.516	−0.193	−1.119	−0.144
	RSME (MJ/m^2)	HM	0.684	0.463	0.411	0.416	0.374	0.475	1.209	0.323	0.426	0.430	0.474	0.549	0.920	0.773
		GM	2.371	1.277	0.737	1.494	1.413	1.433	2.153	0.660	0.874	0.589	0.818	0.535	1.136	0.852
1996	MDGR (MJ/m^2)		16.33	14.41	12.27	14.19	13.18	14.25	12.55	15.12	12.90	11.70	11.62	11.62	10.63	10.82
	MBE (MJ/m^2)	HM	1.180	−0.495	0.007	−0.220	−0.027	−0.495	0.732	−0.266	−0.326	−0.080	−0.158	−0.512	−0.731	−1.023
		GM	3.172	1.155	0.977	1.198	1.241	1.255	1.914	−0.042	0.430	0.279	0.363	−0.314	−1.030	−1.541
	RSME (MJ/m^2)	HM	1.406	0.631	0.446	0.358	0.315	0.565	0.823	0.348	0.542	0.467	0.460	0.689	0.920	1.217
		GM	3.297	1.237	1.057	1.249	1.384	1.325	2.002	0.575	0.808	1.144	1.064	0.774	1.625	1.840

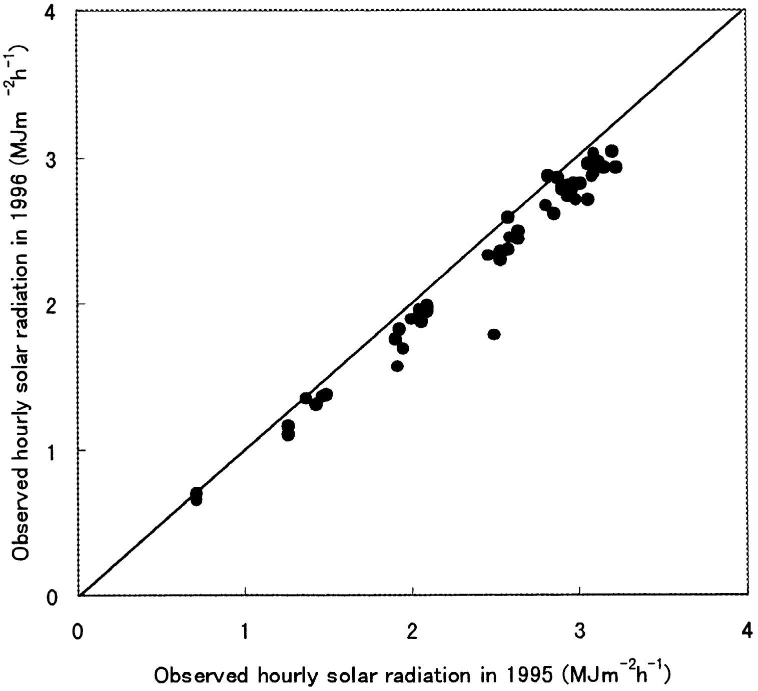

Fig. 5. Comparison of hourly radiation between 1995 and 1996 at station No.1. Including all data in July satisfying (1) $S/S_0 = 1$, (2) same date and time at each point in both years.

$$\mathrm{RSME} = \left\{ \frac{\left[\sum_{i=1}^{n} (H_{i,\mathrm{cal}} - H_{i,\mathrm{meas}})^2 \right]}{n} \right\}^{1/2} \tag{10b}$$

where $n = 12$, $H_{i,\mathrm{meas}}$ and $H_{i,\mathrm{cal}}$ are measured and estimated MMDGR, respectively.

The comparison in MBE and RSME of MMDGR for 1995 and 1996 are shown in Table 3. Also, the values of mean daily global radiation (MDGR) are shown in the table. The presented model shows small MBE and RMSE values at most stations. Particularly, the MDGR indicates that the radiation at mountain station (No. 8) is obviously stronger than near stations (e.g. No. 9). The small estimation errors at mountain stations show the presented model successfully reproduces the difference caused by elevation. In addition, the hybrid model shows a smaller error than does the Gopinathan model at most stations. It seems that the former has a higher accuracy than the latter when estimating MMDGR.

6. CONCLUSIONS

By analysis of spectral model and Ångström correlation, a new form of model was proposed to estimate monthly mean daily global solar radiation. Previous Ångström correlation considered global solar radiation linear with fractional sunshine time and radiation at extraterrestrial level. This model, however, assumed global solar radiation has linear relationship with effective beam radiation and diffuse radiation as well as fractional sunshine time. The two types of effective radiation are calculated by a simple method derived from spectral model so it takes physical processes into account automatically. The behavior of the presented model was investigated at many stations with quite different latitude and elevation. The study shows that the model is applicable to most stations across Japan. However, it needs a greater turbidity when applied to urban area due to air pollution, otherwise, global radiation may be overestimated. Also, the estimation under completely cloudy sky is still difficult so efforts should be devoted to it in the future.

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