A COMPARISON OF METHODS TO ESTIMATE HOURLY TOTAL IRRADIATION ON TILTED SURFACES FROM HOURLY GLOBAL IRRADIATION ON A HORIZONTAL SURFACE

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ABSTRACT

The models for estimation of total irradiation on tilted surfaces are evaluated. Measurements at three of the Japanese International Daylight Measurement Programme (IDMP) sites; Sapporo, Tokyo and Fukuoka, are employed for the evaluation. At first, beam irradiation are estimated from horizontal global irradiation using three direct and six diffuse irradiance models. Root Mean Square Errors (RMSEs) of Perez, Erbs, Chandrasekaran and Reindl models are comparatively small among the nine models. Next, vertical surface irradiations are estimated from beam and diffuse irradiations using an isotropic and five anisotropic sky radiance models. RMSE of Perez anisotropic sky irradiance model is the smallest. Finally, vertical surface irradiations are estimated from horizontal global irradiation using each of the 54 combinations of the nine irradiance and six sky irradiance models. The combination of the Perez beam irradiance and the Perez anisotropic sky irradiance model gives the smallest RMSE.

INTRODUCTION

Solar irradiation received at tilted surfaces is called tilted surface irradiation in this report. The tilted surface irradiations are required for simulating building thermal environments, designing HVAC systems and solar energy utilization systems. However, the measurements of tilted surface irradiation[3,12,21] are very little. Therefore, tilted surface irradiation in most cases is calculated from measured global horizontal irradiation. The purpose of this report is to select the estimation method of tilted surface irradiation which can be applied to whole Japan. 54 estimation methods of tilted surface irradiation are compared and evaluated.

Two kinds of irradiace models are required in order to estimate tilted surface irradiation from global horizontal irradiation. One is a irradiace model which estimate beam and diffuse irradiation from global horizontal irradiation. The other is a tilted surface irradiance model.

In the previous report[27], irradiace models were compared. Three beam [4,10,20] and five diffuse irradiance models [7,8,9,15,24] were selected for the comparison. The comparison was performed, using hourly beam and global horizontal irradiation observed at fourteen Japan Meteorological Agency (JMA) sites. The estimations of beam irradiation were compared with the measurements (opening half angle is 2.5°). Among the eight models, RMSE of the Reindl diffuse irradiance model[15] was the smallest at seven sites out of fourteen sites. In the report[26],it was found that RMSE of the Perez beam irradiance model[20] was small, regardless of the amount of irradiation.

In this report, estimation methods of tilted surface irradiation from global horizontal irradiation are evaluated, combining the beam or diffuse irradiance models with tilted surface irradiance models. Three beam irradiance models; Udagawa[4], Maxwell[10] and Perez[20] models and six diffuse irradiance models; Nagata[5], Erbs[7], Watanabe[8], Skartveit [9], Reindl[15] and Chandrasekaran[24] models, are employed for the present comparison. An isotropic[1] and five anisotropic sky irradiance models; Hay[6], Skartveit[11], Perez[14], Reindl[16] and Akasaka [13,17] models are employed for the estimation of tilted surface irradiations.

METHODOLOGY

1. Tilted surface irradiace model. The calculation formula of tilted surface irradiation is shown by the following equation.

$$I_{T,G} = I_{T,b} + I_{T,d} + I_{T,r} \quad (1)$$

Beam, diffuse and ground reflection components of tilted surface irradiation are shown by the following equations.

$$I_{T,b} = I_b \cos i \quad (2)$$

$$I_{T,d} = I_d \; F \quad (3)$$

$$I_{T,r} = I_G \rho \left(\frac{1 - \cos\beta}{2} \right) \quad (4)$$

Equation(2) is used for angle conversion calculation. Equation(3) represents the sky irradiance model. *F* in

Table 1. Description of beam and diffuse irradiance models

Author	Model discription		Irradiation data used for the development	
	Output	Input	Irradiation	Instrument
Udagawa & Kimura (1978年)[4]	I_b	I_G	I_G	Gorczynski type pyranometer
			I_d	Gorczynski type, shadow ring,width4.2cm,radius50cm)
Nagata & Sawada (1978年)[5]	I_d	I_G	I_G	EKO MS4
			I_b	EKO MS51
Erbs, Klein & Duffie (1982年)[7]	I_d	I_G	I_G	pyranometer
			I_d	pyranometer, shade ring
Watanabe,Urano & Hayashi (1983年)[8]	I_d	I_G	I_G	EKO MS42
			I_d	EKO MS42 ,shadow band (width 7cm, radius 20cm)
Skartveit & Olseth (1987年)[11]	I_d	I_G	I_G	-
		h	I_d	-,(rotating disc)
Maxwell (1987年)[10]	I_b	I_G	I_G	-
			I_b	-
Reindl, Beckman & Duffie (1990年)[15]	I_d	I_G	I_G	U.S.sites : Eppley pyranometer European sites : Kipp solarimeter
		T_a		
		R_h	I_d	U.S.sites : Eppley pyranometer, European sites : Kipp solarimeter ,(shade ring)
		sin$h$		
			I_b	Eppley pyrheliometer
Perez, Ineichen, Maxwell, Seals, & Zelenka (1992年)[20]	I_b	I_G	I_G	-
		T_d	I_b	Eppley NIP,(OPH = 2.86 deg.)
Chandrasekaran & Kumar (1994年)[24]	I_d	I_G	I_G	-
			I_d	-

Note) —: It is not described in the literature. OPH : Opening Half Angle

Table 2. Symbols of beam and diffuse irradiance models

Symbol	Developer
C	Chandrasekaran
E	Erbs
M	Maxwell
N	Nagata
P	Perez
R	Reindl
S	Skartveit
U	Udagawa
W	Watanabe

Table 3. Symbols of sky irradiace models

Symbol	Developer
A'	Akasaka
H'	Hay
I'	Isotropic
P'	Perez
R'	Reindl
S'	Skartveit

Eq.(3) is the function representing the proportion of diffuse irradiation on tilted surfaces to horizontal diffuse irradiation, and it is different according to the treatment of sky radiation distribution.

2. Beam and diffuse irradiace model. Normal beam irradiation, I_b in Eq.(2), and horizontal diffuse irradiation, I_d in Eq.(3) are calculated using nine irradiace models shown in Table 1. Hereafter, these models are described according to the symbols in Table 2.

3. Sky irradiance model. F in Eq.(3) is calculated using six sky irradiance models shown as follows. Hereafter, these models are described according to the symbols in Table 3.

1) Isotropic model[1]

$$F = \frac{1+\cos\beta}{2} \tag{5}$$

2) Hay's model[6]

$$F = (1-A_I)\left(\frac{1+\cos\beta}{2}\right) + A_I R_b \tag{6}$$

where

$A_I = I_b / J_o$ and $R_b = \cos i / \sin h$

3) Skartveit's model[9]

$$F = A_I R_b + Z_f \cos\beta + (1-A_I-Z_f)\cos^2\frac{\beta}{2} - \sum_j \frac{(1-A_I-Z_f)}{\pi}\omega_j \cos i_j \tag{7}$$

Table 4. Perez sky irradiance model coefficients

ε	F11	F12	F13	F21	F22	F23
1.000-1.065	-0.008	0.588	-0.062	-0.060	0.072	-0.022
1.065-1.230	0.130	0.683	-0.151	-0.019	0.066	-0.029
1.230-1.500	0.330	0.487	-0.221	0.055	-0.064	-0.026
1.500-1.950	0.568	0.187	-0.295	0.109	-0.152	-0.014
1.950-2.800	0.873	-0.392	-0.362	0.226	-0.462	0.001
2.800-4.500	1.132	-1.237	-0.412	0.288	-0.823	0.056
4.500-6.200	1.060	-1.600	-0.359	0.264	-1.127	0.131
6.200- --	0.678	-0.327	-0.250	0.156	-1.377	0.251

4) Reindl's model[16]

$$F = (1-A_I)\left(\frac{1+\cos\beta}{2}\right)\left(1+f\sin^3\frac{\beta}{2}\right) + A_I R_b \tag{8}$$

where

$$f = \sqrt{I_b \sin h / I_G}$$

5) Perez's model[14]

$$F = (1-F_1)\left(\frac{1+\cos\beta}{2}\right) + F_1\frac{a}{b} + F_2\sin\beta \tag{9}$$

where

$a = \max(0, \cos i)$ and $b = \max(0.087, \cos Z)$

$$F_1 = F_{11}(\varepsilon) + F_{12}(\varepsilon)\Delta + F_{13}(\varepsilon)Z$$
$$F_2 = F_{21}(\varepsilon) + F_{22}(\varepsilon)\Delta + F_{23}(\varepsilon)Z$$

Perez's model coefficients are shown in Table 4.

Table 5. Description of experimental sites

Site	Sapporo	Tokyo	Fukuoka
Observer	Ochifuji	Igawa	Nakamura
Location	Faculty of Engineering, Hokkaido University Kyta 13 jo, Nishi 8 chome Sapporo 060, Japan	Research and Development Institute Takenaka corporation 2-5-14 Minamisuna, Koto, Tokyo 136, Japan	Kyushu University Chikushi Campus, 6-1 Kasuga-Koen, Kasuga-shi Fukuoka 816, Japan
Latitude	43°03'N	35°39'16''N	33°31'10''N
Longitude	141°20'E	139°44'41''E	130°28' 45''E
Altitude	38m	22m	69.25m
Data period(from)	1/1/94	3/1/92	1/1/94
Data period(to)	12/31/94	2/28/93	12/31/94

Table 6. Description of experimental data sets

Meteorological element		Unit*1	Measuring instrument and note
Irradiations	Global horizontal	MJ/m^2h	EKO MS-801
	Beam	MJ/m^2h	EKO MS-52, OHA*3=2.5°
	Diffuse horizontal*2	MJ/m^2h	EKO MS-801, shadow band (width 50mm, radius 250mm)
	North, east, south and west vertical	MJ/m^2h	EKO MS-801, shading metal*4
Temperature		℃	Measurements of JMA*5 Stations at Sapporo, Tokyo and Fukuoka
Dew-point temperature		℃	
Relative humidity		%	

*1 Though solar irradiation was measured in the 1 minute interval, it was converted into the 1 hour integrated value.
*2 Diffuse irradiation was used in quality check of solar irradiation data. *3 OHA: Opening half angle
*4 The vertical sensors are shaded from ground reflected irradiation using a black punched metal or black honeycomb material.
*5 JMA: Japan Meteorological Agency

6) Akasaka's model[13,17]

$$F = (1-A_c)\left(\frac{1+\cos\beta}{2}\right) + A_c R_b \qquad (10)$$

$$A_c = I_c(\theta_0,\theta)/I_d \qquad (11)$$

where

$$I_c(\theta_0,\theta) = J_0 \sin h(1-P^m)\left[0.3\sqrt{(\theta-\theta_0)} \times \sin hP^{(4/3)}(1-P)^{\{1/(1.13-0.75\sin h)\}}\right] \qquad (12)$$

$\theta_0 > 4$:

$$I_c(\theta_0,\theta) = I_c(4,\theta) - I_c(4,\theta_0) \qquad (13)$$

$2 < \theta_0 < 4$:

$$I_c(\theta_0,\theta) = I_c(4,\theta) + (4-\theta_0) I_c(4,5) \qquad (14)$$

θ_0 and θ were assumed 2.5° and 25° in this report, respectively.

4. Evaluation methodology - experimental data The evaluation is undertaken based on the comparison of estimations with measurements observed at three IDMP [21] stations; Sapporo[23], Tokyo[22] and Fukuoka [18], in Japan. Features of each sites are briefly summarized in Table 5. From the long-term measurements, global horizontal, beam, diffuse horizontal and total irradiation on vertical surfaces (N,E,S,W) for one year were used for the comparison. Beam irradiations are observed using the pyrheliometer (opening half angle is 2.5°) which satisfy the WMO standard. In the observation of vertical surface irradiation, the ground reflected irradiation is shielded by shading metals. Therefore, ground reflectance(ρ) of equation (4) was assumed 0%, when vertical surface irradiations were calculated. The quality of the data was examined by performing data checks as undertaken in the reference[19]. The description of data sets is shown in Table 6.

5. Evaluation methodology- evaluation index. Two statistical quantities, RMSE and Mean Bias Error (MBE) from the measurement of total vertical surface irradiation, are the evaluation indexes in this report. These indexes are shown by the following equations.

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}(I_{T,G,e,i} - I_{T,G,m,i})^2}{N}} \qquad (15)$$

$$MBE = \frac{\sum_{i=1}^{N}(I_{T,G,e,i} - I_{T,G,m,i})}{N} \qquad (16)$$

RESULT

6. Comparison of beam and diffuse irradiance models. At first, beam and diffuse irradiation were estimated from the measurement of global horizontal irradiation using three beam and six diffuse models listed in Table 1. RMSEs of P, E, C and R models are comparatively small among the nine irradiance models. MBEs of W, U, M and N models are comparatively large. This tendency almost agrees with the result in the previous report[27]. Mean

RMSE values over the sites become smaller in the order of N, W, U, S, P, E, C and R models.

Next, the ratios of the horizontal beam and diffuse irradiation to the global horizontal irradiation are compared. The beam and diffuse ratios are calculated by the following equations.

$$R_{bem} = \frac{I_b \sin h}{I_G} \times 100 \quad (17)$$

$$R_{dif} = \frac{I_d}{I_G} \times 100 = 100 - R_{bem} \quad (18)$$

Table 7 shows the annual mean values of hourly ratios obtained from the models. The balance of the ratios is influenced by the model's treatment of circumsolar irradiation. Beam ratios (R_{bem}) of C, E, M, P, R and S models are smaller than that of W, N and U models. This is due to the fact that the beam irradiations estimated by W, N and U models contain more circumsolar irradiation than the others.

7. Comparison of sky irradiance models. Vertical surface irradiations were estimated from the measurements of beam irradiation and calculated horizontal diffuse irradiation. This calculation was undertaken using measured beam and global horizontal irradiation. The comparison of the estimation of vertical surface irradiations and observed values in Tokyo is shown in Fig. 2. Generally, the estimation of P' model well represents the measurements. The estimates of the other models are smaller than the observed value, when irradiation is large. Especially, the estimations of I' model are smaller than the measurements, when irradiation is larger than 1MJ/m^{2}h. Figure3 shows the variation of RMSE and MBE as a function of the locations. RMSEs of H', S' and R' models are similar and those of A' model are smaller than these three models. Except for the north surface in Tokyo and the west surface in Sapporo, RMSE of P' model is the smallest among the six models. The MBE of P' model shows small fluctuation around zero. This indicates that P' model gives the better estimations than the other models.

8. Comparison of estimation methods of tilted surface irradiation. An isotropic and five anisotropic sky irradiance models are combined with three beam or six diffuse irradiance models. After beam and diffuse irradiations are estimated by the beam or diffuse models using the measurement of global horizontal irradiation as input, the total irradiation on vertical surfaces are estimated from the calculations of beam and diffuse irradiation, using the six sky irradiance models. Estimations of the 9x6 combinations are compared with measurements of vertical surface irradiations. The relationships between the mean

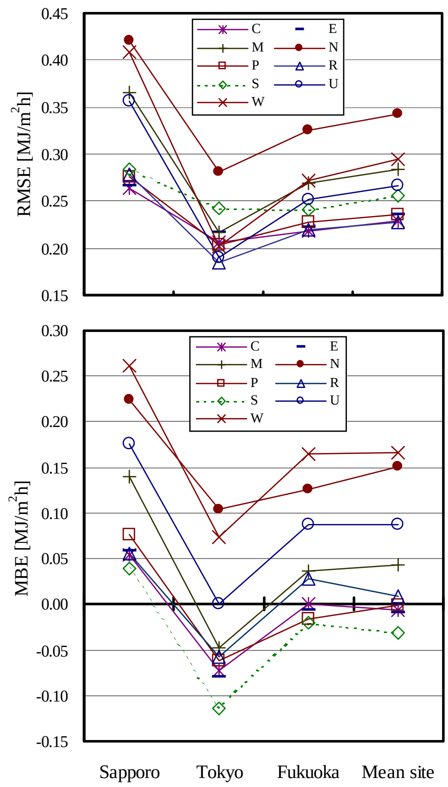

Fig. 1. Variations of RMSE and MBE of beam irradiation as a function of location

Table 7. Annual mean ratios of beam and diffuse irradiation

%	Sapporo		Tokyo		Fukuoka		Mean site	
	R_{dif}	R_{bem}	R_{dif}	R_{bem}	R_{dif}	R_{bem}	R_{dif}	R_{bem}
M_s *1	73.2	26.8	73.0	27.0	75.8	24.2	74.0	26.0
C	70.7	29.3	75.9	24.1	76.7	23.3	74.4	25.6
E	71.1	28.9	76.6	23.4	77.4	22.6	75.0	25.0
M	67.6	32.4	74.9	25.1	75.4	24.6	72.7	27.3
N	65.6	34.4	70.3	29.7	72.2	27.8	69.4	30.6
P	70.1	29.9	75.8	24.2	77.1	22.9	74.3	25.7
R	70.4	29.6	74.9	25.1	75.4	24.6	73.6	26.4
S	71.3	28.7	77.5	22.5	77.9	22.1	75.6	24.4
U	64.6	35.4	71.6	28.4	72.0	28.0	69.4	30.6
W	60.6	39.4	67.9	32.1	68.2	31.8	65.6	34.4

*1 The measurements ratios.

RMSE and mean absolute values of MBE over four azimuths are shown in Fig. 4. The four azimuths mean value of MBE was calculated from the absolute value of MBE. Generally, RMSEs of the methods for combining I' model (×) are large. Especially, the methods of combining C, E, M, P, R and S models with I' model remarkably show this tendency in Tokyo and Fukuoka. This indicates that it is impossible to assume that the sky irradiation distribution is uniform, since diffuse irradiations estimated using C, E, M, P, R and S models contain circumsolar irradiation. Therefore, the methods for combining C, E, M, P, R and S models with I' model are not suitable as the estimation methods of tilted surface irradiation. Among the methods of combining

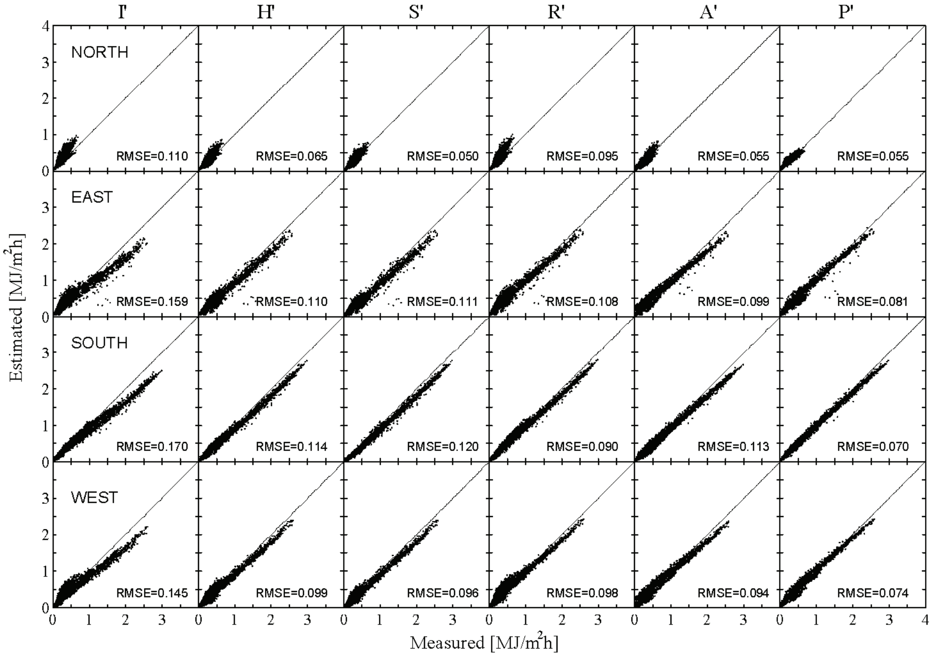

Fig. 2. Comparison between measured and estimated total irradiation on vertical surfaces in Tokyo

I' model, the methods of combining N and W models with I' model (N+ I', W+ I') are better than the other combinations. RMSEs by the methods of combining H', R', S' and A' models (■,△,∗,○) are similar. Among the 54 combinations (9x6), RMSEs of the methods of combining P' model (□) are generally small. Especially, four methods of combining C, E, P and R models with P' model ; C+P', E+P' , P+P' and R+P', are better than the others. Among the four methods, the RMSE fluctuations of the method of combining P model with P' model(P+P') according to the sites are comparatively small. In addition, mean RMSE value over three sites of P+P' is the smallest. The relationships between the estimations and the measurements of vertical surface irradiation facing four orientations are shown in Fig. 5.

In Table 9, the rankings of the 54 combinations are listed in the order of mean RMSE values over three sites (see Table 8). The estimation methods which have smaller absolute values of MBE are positioned in upper ranking, when the values of RMSEs are the same. Though RMSEs of four methods; P+P', C+P', E+P' and R+P', are very similar, the ranking of the method of combining P model with P' model (P+P') is the first.

CONCLUSIONS

In this report, 54 estimation methods of tilted surface irradiation are compared and evaluated.

1) At first, beam and diffuse irradiation are estimated from global horizontal irradiation using three beam and five diffuse irradiation models. Estimations of normal beam irradiation are compared with the measurements. RMSE obtained from the estimations

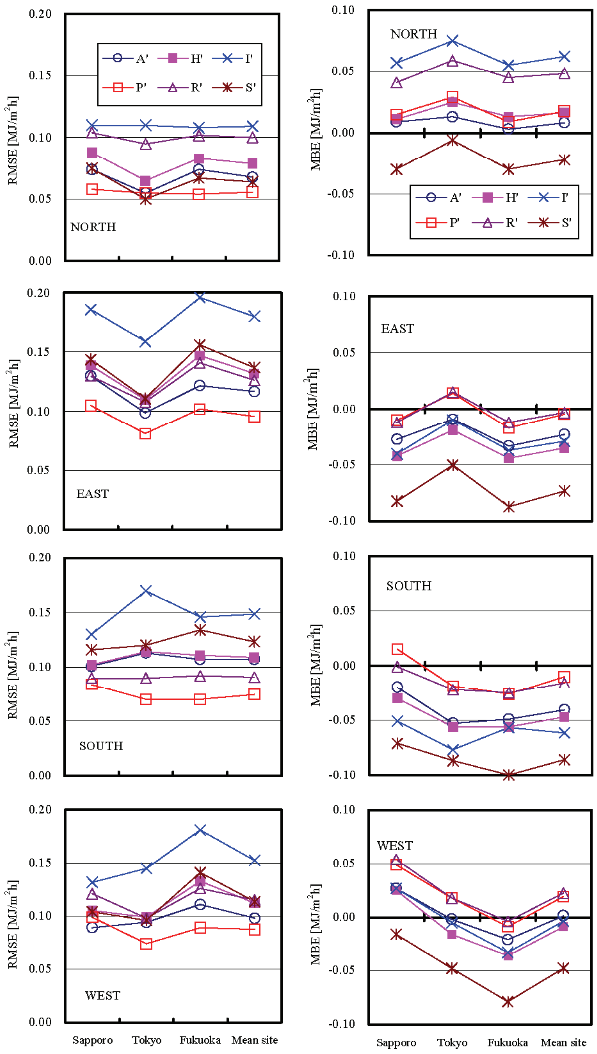

Fig. 3 Variations of RMSE and MBE of vertical irradiation as a function of location

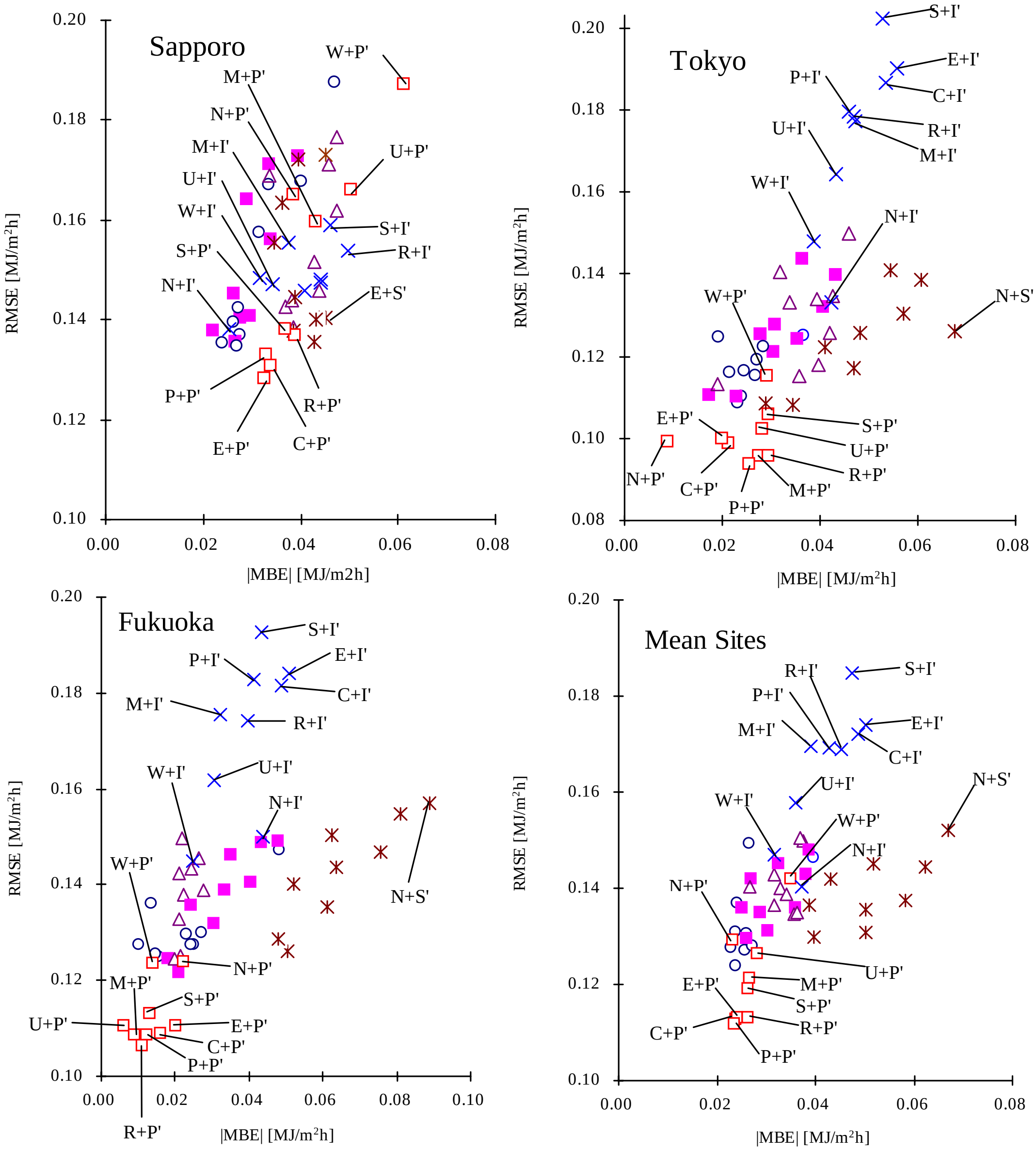

Fig. 4. Relationship between the mean RMSE and |MBE| values over four azimuths

of Perez, Erbs, Chandrasekaran and Reindl models are comparatively small among the nine irradiance models.

2) Next, total irradiation on vertical surfaces are estimated using six sky irradiance models. Among the six irradiance models, the Perez anisotropic sky irradiance model gives the best estimation.

3) Finally, an isotropic and five anisotropic sky irradiance models are combined with three beam or the six diffuse irradiance models. Among the 54 combinations(9x6), the combination of the Perez beam irradiance model with the Perez anisotropic sky irradiance model gives the smallest RMSE.

NORMENCLATURE

J_o solar constant 4.921[MJ/m^{2}h]（1367W/m^2）[25]

I_G horizontal global irradiation [MJ/m^{2}h]]

I_b normal beam irradiation [MJ/m^{2}h]

I_d horizontal diffuse irradiation [MJ/m^{2}h]

I_c horizontal circumsolar irradiation [MJ/m^{2}h]

$I_{T,G}$ total tilted surface irradiation [MJ/m^{2}h]

$I_{T,b}$ tilted beam irradiation [MJ/m^{2}h]

$I_{T,d}$ tilted diffuse irradiation [MJ/m^{2}h]

$I_{T,r}$ ground reflected irradiation [MJ/m^{2}h]

ρ ground reflectance [—]

β slope angle [°]

h altitude angle [°]

Z zenith angle [°]

i incidence angle [°]

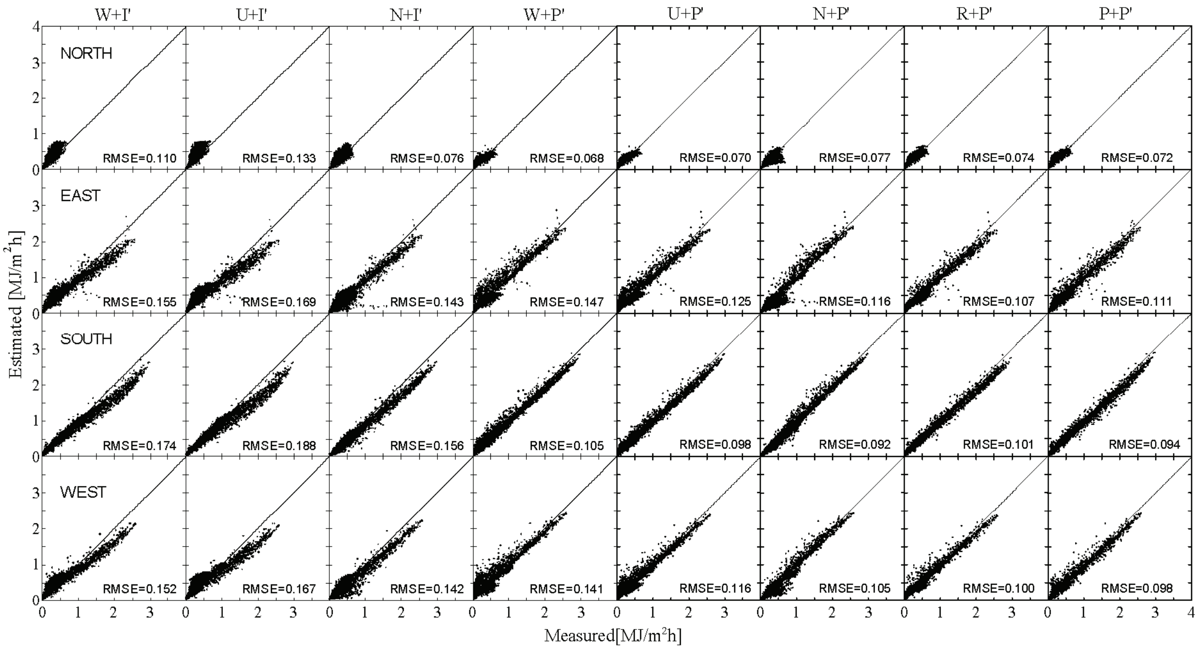

Fig. 5. Comparison between measured and estimated total irradiation on vertical surfaces in Tokyo

ω_j solid angle [°]

θ_0 opening half angle of pyrheliometer [°]

θ angle distance from center of the sun [°]

A_I anisotropy index [−]

H_t altitude [m]

m_r relative optical air mass [−]

$$m_r = (1-0.0001H_t)/[\ \sin h + 0.15(93.885-Z)^{-1.253}\ ]$$

m air mass [−]

$$m = \sqrt{(A_0 \sin h)^2 + 2A_0 + 1} - A_0 \sin h,\ A_0 = 797$$

P atmospheric transmittance

$$P = (I_b / J_o)^{1/m} \quad [\ -\ ]$$

Δ atmospheric brightness parameter

$$\Delta = I_d m_r / J_o \quad [\ -\ ]$$

ε atmospheric clearness parameter [−]

$$\varepsilon = [\ (I_d + I_b)/I_d + kZ^3\ ]/[\ 1 + kZ^3\ ],\ k = 1.041,\ Z\ (radian)$$

F_1 circumsolar brightening coefficient [−]

F_2 horizon brightening coefficient [−]

N number of measurements [−]

m: measurement, e: estimation

Table 8. Mean RMSE values over three sites [MJ/m²h]

Beam and diffuse irradiance model	Sky irradiance model					
	A'	H'	I'	P'	R'	S'
C	0.127	0.136	0.172	0.113	0.136	0.138
E	0.128	0.143	0.174	0.113	0.143	0.145
M	0.131	0.142	0.169	0.121	0.150	0.142
N	0.146	0.148	0.140	0.129	0.140	0.152
P	0.124	0.135	0.169	0.112	0.140	0.136
R	0.128	0.131	0.169	0.113	0.135	0.131
S	0.131	0.145	0.185	0.119	0.150	0.145
U	0.137	0.129	0.158	0.126	0.135	0.130
W	0.149	0.136	0.147	0.142	0.139	0.137

Table 9. Ranking according to the mean RMSE values over three sites

Beam and diffuse irradiance model	Sky irradiance model					
	A'	H'	I'	P'	R'	S'
C	9	24	52	2	25	28
E	11	37	53	3	36	38
M	16	33	51	6	45	34
N	41	43	32	12	31	47
P	7	20	50	1	30	22
R	10	18	49	4	19	17
S	15	39	54	5	46	40
U	27	13	48	8	21	14
W	44	23	42	35	29	26

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