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Abstract

In this paper, using two databases of observed weather data for the major cities in China, we developed models with three variables to estimate hourly solar radiation on the horizontal surfaces for these cities. The errors in estimating solar radiation in different locations were discussed. Two methods to estimate monthly solar radiation were developed and compared. Models to estimate yearly solar radiation were also developed using latitude, elevation and average cloud cover.

Keywords: China, solar radiation, observation, models, estimation

Introduction

Weather is one of the primary determinants of indoor thermal conditions and space conditioning energy use. In building simulations, solar radiation is one of the most important meteorological elements, because solar radiation influences both heating and cooling loads significantly.

There are two major barriers in finding observed solar data in China: (1) although the Chinese weather service has recorded weather data for all major cities for several decades, most of the data are not in a digital format, making their transcription and purchase prohibitively expensive, (2) solar data, when available, usually consist of daily total horizontal and diffuse solar radiation, which is especially true before 1992. Therefore it is necessary to develop some models to estimate solar radiation in the major cities in China in order to produce solar data and add them to the observation databases. Cui et al.[1)] tried to estimate solar data for Beijing and Shanghai using measured dry-bulb temperature, humidity, cloud cover and wind speed, but encountered problems in interpolating between the six-hour intervals. The authors developed models to estimate solar radiation using measured dry-bulb temperature etc. at three-hour intervals[2)]. The estimated values of solar radiation agree with measured values in Beijing and Guangzhou in 1993, but the accuracy of estimation could not be verified for other cities due to insufficient observed data.

In this paper, using two databases of observed weather data for the major cities in China, we developed models with three variables to estimate hourly solar radiation on the horizontal surfaces for these cities. The errors in estimating solar radiation in different locations were discussed. Two methods to estimate monthly solar radiation were developed and compared. Models to estimate yearly solar radiation were also developed using latitude, elevation and average cover cloud.

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Source Data for Solar Models

Two databases of weather data were used in establishing the solar models: one is the database of International Surface Weather Observations[3)] which is called the ISWO database; another one is the observed solar data in 1993 for 24 major cities of China[4)], which is called OSR database in this study. The ISWO database consists of dry-bulb temperature, dew point temperature, the amounts of cloud cover, wind speed etc. from observation in the period of 1982-1998 at three-hour intervals, but there are not any solar radiation data included in the database. The ISWO database covers more than 70 major cities in China. On the other hand, only data of observed solar radiation in 1993 are included in the OSW database with one-hour intervals. Therefore, it is necessary to combine these two databases to develop models to estimate solar radiation for the ISWO database in order to develop the Typical Meteorological Years and other uses.

Models to Estimate Hourly Solar Radiation

In order to estimate the hourly solar radiation for the cities included in the ISWO database, it is necessary to find relations between solar radiation and other variables. Cui et al.[1)] showed the correlation between solar radiation and temperature change from previous hours, the amount of cloud cover, relative humidity and wind speed at six-hour intervals, but the accuracy was not sufficient due to the large time intervals. It is possible to improve the accuracy using the data from ISWO database because the observation intervals are smaller (three hours) than that of Cui's. Also it is possible for us to develop models which are applicable to more locations because there are solar data included in the OSR database for 24 locations.

In order to select parameters in the models to estimate solar radiation, the relations between solar radiation and other variables like the amount of cloud cover, temperature changes, relative humidity are examined.

It is obvious that increase in ambient temperature is mainly the results of solar radiation. Therefore there should be some relations between solar radiation and temperature changes. Figure 1 shows the relations between hourly global radiation on the horizontal surface and temperature change from previous three hours in Beijing. It is clear that a strong correlation exists between them.

The amount of cloud cover can be another parameter to estimate solar radiation because solar radiation reaching the ground surface is filtered by cloud all the time. It is reported that the percentage of sunshine has a strong correlation with the global solar radiation on the horizontal surface[5)], but it is difficult to estimate solar radiation with the percentage of sunshine due to lack of observed data of this percentage in the ISWO and OSW databases.

Figure 2 shows the relationship between the global solar radiation on the horizontal surface and the total cloud cover. The relationship between the two variables is approximated by a quadratic equation instead of a linear equation. The maximum value of solar radiation does not appear at the point when the cloud cover is zero but at the amount of three to four. This is because that the strongest solar radiation appears when the radiation comes from both the sun and cloud but not from the sun only.

The relationship between the global solar radiation on the horizontal surface and relative humidity is also examined. As shown in Fig.3, relative humidity has a negative correlation to solar radiation. Therefore relative humidity can also be considered as one of the variables to estimate solar radiation.

The relationship between solar radiation and wind speed is also examined, but little relation can be found between them, therefore wind speed is not included as a variable in estimating solar radiation.

Multiple regressions were carried out to establish models to estimate hourly solar radiation. Based on the discussion above, dry-bulb temperature changes, total amount of cloud cover and relative humidity were adopted as variables as shown in Equation 1.

$$I_h = [I_0 \cdot \mathbf{sinh} \cdot \{C_0 + C_1 \cdot \frac{CC}{10} + C_2 \cdot (\frac{CC}{10})^2 + C_3 \cdot (\theta_n - \theta_{n-3}) + C_4 \phi\} - C_5] / k \quad (1)$$

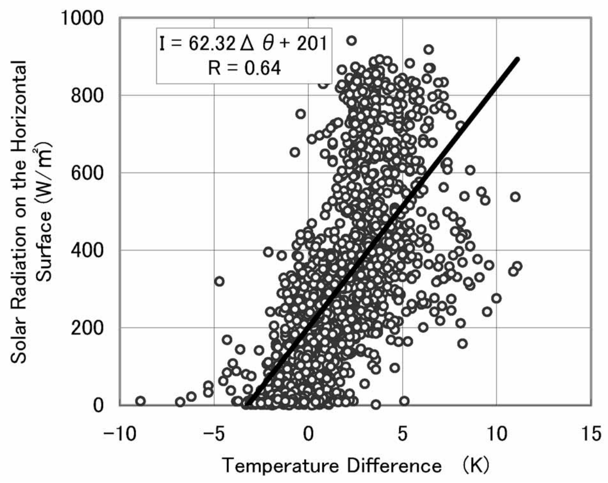

Fig.1. Correlation between Solar Radiation and Temperature Difference

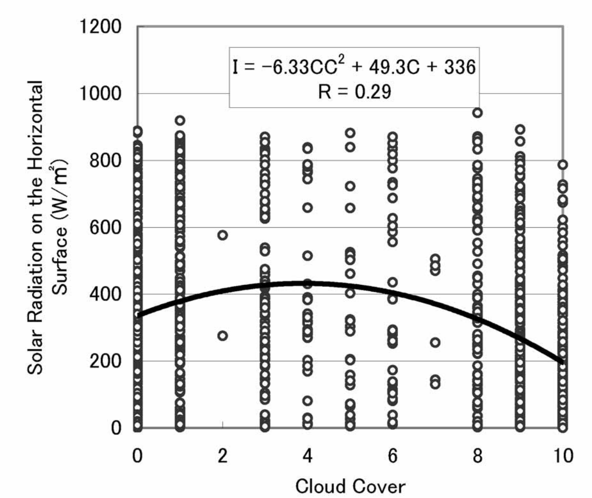

Fig.2. Correlation between Solar Radiation and Cloud Cover

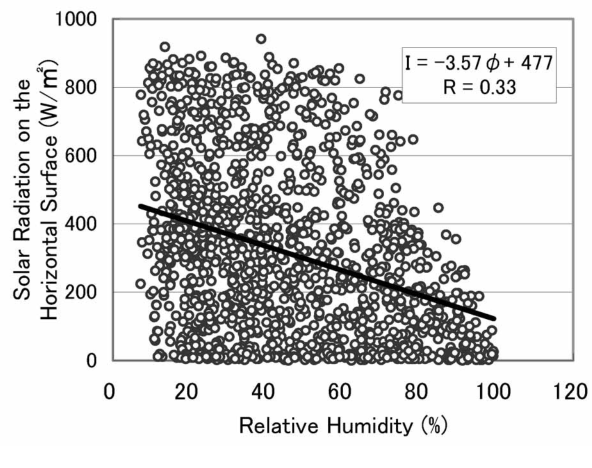

Fig.3. Correlation between Solar Radiation and Relative Humidity

Table 1. Variables in Equation 1 for Different Cities

Cities	C_0	C_1	C_2	C_3	C_4	C_5	k	R	RMSE
BEIJING	0.6584	0.4864	−0.6647	0.0203	−0.0039	36.6114	0.9300	0.97	80
CHANGCHUN	0.8412	0.4406	−0.6853	0.0021	−0.0047	40.2260	0.8868	0.94	116
CHANGSHA	0.7085	0.7065	−0.9413	0.0230	−0.0038	42.2020	0.8747	0.94	84
CHENGDU	0.3645	0.4800	−0.6335	0.0495	−0.0011	40.5660	0.8250	0.92	103
FUZHOU	0.7960	0.7279	−0.9365	0.0200	−0.0052	35.7491	0.9112	0.94	96
GUANGZHOU	0.6050	0.5755	−0.7893	0.0278	−0.0030	36.8362	0.8998	0.95	87
GUIYANG	0.4688	0.4750	−0.7223	0.0321	−0.0008	38.3084	0.8743	0.93	96
HANGZHOU	0.4378	0.8395	−1.1174	0.0408	−0.0001	41.3412	0.8702	0.91	115
HARBIN	1.0235	0.5162	−0.6877	−0.0056	−0.0063	35.0285	0.8924	0.93	136
HEFEI	0.8084	0.6724	−0.8846	0.0189	−0.0051	35.6732	0.9197	0.96	88
JINAN	0.6497	0.4679	−0.6317	0.0242	−0.0038	27.2746	0.9178	0.96	88
KUNMING	0.4817	0.2936	−0.5768	0.0403	0.0003	43.9962	0.8745	0.93	137
LHASA	0.6996	−0.0929	−0.2399	0.0162	0.0026	56.6359	0.8811	0.94	165
LANZHOU	0.3545	0.6723	−0.8564	0.0430	0.0007	40.8254	0.8954	0.95	110
NANCHANG	0.7638	0.8086	−1.0198	0.0348	−0.0048	35.5071	0.9192	0.96	90
NANNING	0.4989	0.7322	−0.9156	0.0402	−0.0020	42.7619	0.8687	0.93	114
NANJING	0.7586	0.5914	−0.7919	0.0181	−0.0050	31.8024	0.9350	0.97	76
SHENYANG	0.8199	0.6304	−0.8533	0.0035	−0.0051	39.2128	0.9047	0.96	98
TIANJIN	0.7297	0.5113	−0.7432	0.0118	−0.0036	38.6689	0.9110	0.97	106
WUHAN	0.7395	0.7426	−0.9817	0.0276	−0.0043	37.0186	0.9123	0.96	90
XIAN	0.5283	0.6062	−0.7861	0.0353	−0.0024	36.6207	0.9070	0.96	91
XINING	0.3856	0.6237	−0.8658	0.0376	0.0015	41.7887	0.8910	0.94	122
YINCHUAN	0.5831	0.4261	−0.7089	0.0282	−0.0006	37.4911	0.9237	0.96	105
ZHENGZHOU	0.7085	0.5092	−0.7069	0.0165	−0.0037	37.0826	0.9250	0.97	86

where Ih is the estimated hourly global solar radiation on the horizontal surface in W/m^2; I_0 is the solar constant, 1354 W/m^2; CC is the amount of cloud cover in tenths; θ_n and θ_{n-3} are dry-bulb temperature at hours n and n-3, respectively; h is the sun's altitude and the term ($I_0 \sin h$) means solar radiation on the horizontal surface in the outer space; ϕ is relative humidity in %; $C_1 \ldots C_5$ and k are regression coefficients, the values of which differ from place to place as shown in Table 1. The coefficients of correlation R for all the 24 locations are between 0.91 and 0.97 with maximum error of 137 W/m^2 except for Lhasa. The error for Lhasa is larger than that for other locations because the total amount of solar radiation in Lhasa is also much stronger than other locations.

The relationship between the observed solar radiation and the values from Equation 1 for Beijing is shown in Figure 4. The correlation coefficient R is 0.97, and the root mean square errors of the estimation is 80 W/m^2, which implies that Equation 1 can be used to estimate the hourly horizontal solar radiation with good accuracy in Beijing. Similarly, the relationship between the estimated and observed solar radiation in Guangzhou in the south and Harbin in the north are shown in Fig.5 and Fig.6. Based on these figures and Table 1, it is reasonable to conclude that Equation 1 can be used to estimate hourly global solar radiation on the horizontal surface for the 24 Chinese locations.

Models to Estimate Monthly Solar Radiation

Monthly solar radiation is required in some energy calculations of buildings. One of the methods to calculate monthly solar radiation is to sum up hourly solar radiation estimated with Equation 1 throughout the month. Figure 7 shows a comparison of monthly solar radiations from observation and estimation from Equation 1 for Beijing in 1993. The values from observation and estimation agree with each other well in most months throughout the year.

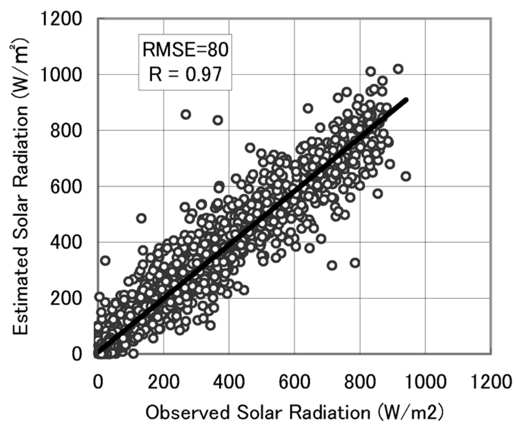

Fig.4. Correlation between Obseved and Estimated Solar Radiation by Equation1 (Bejing. 1993)

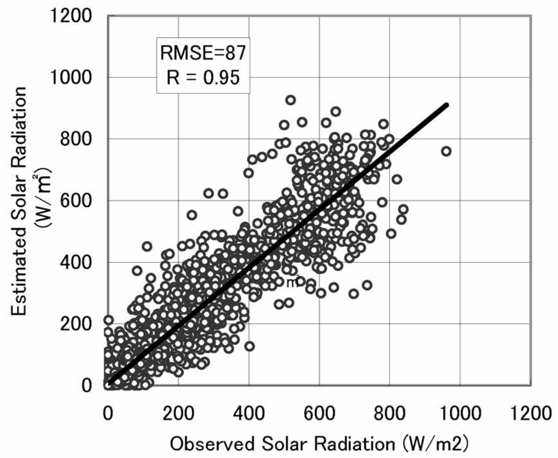

Fig.5. Correlation between Observed and Estimated Solar Radiation by Equation1 (Guangzhou 1993)

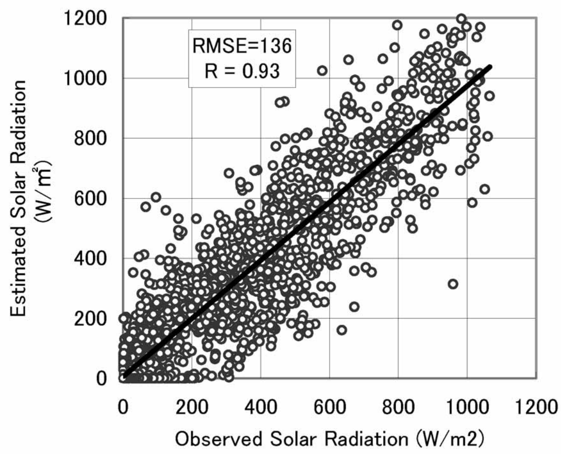

Fig.6. Correlation between Observed and Estimated Solar Rediation by Equation1 (Harbin, 1993)

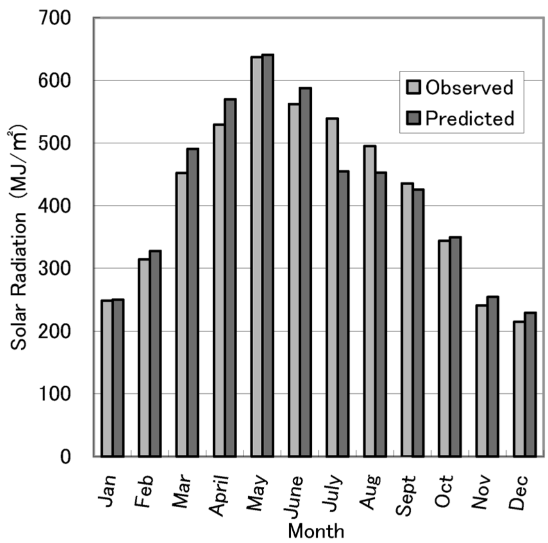

Fig.7. Comparison of Observed and Predicted Solar Radiation on the Horizontal Surface in Bejing

Table 2 shows the comparison of monthly solar radiation from observation and estimation with Equation 1 for the 24 Chinese cities in 1993. The data of monthly solar radiation listed here can also serve as the material of building energy calculations because very few data on solar radiation about Chinese locations have been published up to now. The monthly solar radiation estimated with Equation 1 and coefficients in Table 1 for each location agrees with observation with minor errors.

The main problem to estimate monthly solar radiation using Equation 1 is that one has to calculate solar radiation hourly, and sum them up throughout the month. Without hourly observed data of dry-bulb temperature, relative humidity and cloud cover, it is impossible to estimate monthly solar radiation with this method. To simplify the procedure of estimating the monthly solar radiation, a new equation is developed in the form of Equation 2, using elevation, latitude and monthly average cloud cover as variables by multivariate analysis.

$$I_m = d_0 + d_1 \cdot H + d_2 \cdot \psi + d_3 \cdot \overline{CC}_m \qquad (2)$$

where $\overline{CC}m$ is monthly average cloud cover; $d_0 \cdots d_3$ are regression coefficients shown in Table 3; H is the elevation of a location in m; Ψ is the latitude; *Im* is the monthly accumulated solar radiation on the horizontal surface in MJ/m^2. As shown in Table 3, the values of $d_0 \cdots d_3$ are different for different months. Coefficients of correlation R and errors of estimation (RMSE) for each month are also shown in the table. Figure 8 shows an example of the relationship between monthly solar radiations from observation and estimation with Equation 2 for January, 1993. Generally speaking, the errors of estimation are slightly larger in summer than that in other seasons.

Models to Estimate Yearly Solar Radiation

The yearly solar radiation can be obtained by summing up the hourly radiation values from Equation 1, as well as by summing up the monthly solar radiation from Equation 2. However, it is impossible to calculate the yearly solar radiation using Equations 1 or 2 without knowing the daily or monthly weather data like cloud cover etc. Therefore an equation was developed to estimate the yearly solar radiation *Iy* with the elevation *H*, latitude Ψ and yearly average cloud cover $\overline{cc}_y$ as shown in Equation 3:

$$I_y = 9377.57 + 0.5124 \cdot H - 55.54 \cdot \psi - 587.84 \cdot \overline{CC}_y \qquad (3)$$

The correlation between observation and estimation of solar radiation by Equation 3 is shown in Fig.9. The root mean square error of estimation with Equation 3 is 231 MJ/m^2, which is about 5% of the average yearly solar radiation over the 24 locations.

The comparisons of yearly solar radiation from observation and Equations 1, 2 and 3 are shown in Fig.10. The results from the equations are close to the observation; therefore Equation 3 is the simplest way when only yearly solar radiation is concerned.

Table 2. Comparison of Observed and Estimated Solar Radiation in the Chinese Locations (MJ/m^2)

Cities	Month->	Jan	Feb	Mar	April	May	June	July	Aug	Sept	Oct	Nov	Dec	SUM
BEIJING	Observed	249	314	452	529	637	562	539	495	435	344	241	215	5013
	Estimated	250	327	490	570	640	588	455	453	426	350	255	230	5034
CHANGCHUN	Observed	228	305	458	537	621	642	560	508	454	333	233	190	5068
	Estimated	191	270	480	619	714	637	494	501	437	342	221	155	5064
CHANGSHA	Observed	201	199	246	310	447	435	566	512	426	322	242	225	4132
	Estimated	216	239	257	320	419	409	493	470	457	357	242	247	4127
CHENGDU	Observed	146	169	263	343	416	398	408	399	275	203	156	137	3313
	Estimated	181	212	298	342	443	357	419	363	294	202	168	159	3440
FUZHOU	Observed	245	254	297	370	440	466	557	546	449	365	277	250	4517
	Estimated	261	269	331	385	405	413	526	515	486	382	286	268	4527
GUANGZHOU	Observed	258	239	258	278	372	387	442	410	410	407	336	299	4097
	Estimated	283	273	291	278	336	337	403	411	424	399	326	294	4056
GUIYANG	Observed	156	179	280	333	396	377	476	485	397	274	232	181	3766
	Estimated	170	207	262	357	437	437	469	434	393	259	227	194	3848
HANGZHOU	Observed	245	271	342	399	494	455	580	513	415	354	261	229	4558
	Estimated	269	296	348	414	512	464	589	509	488	397	283	249	4819
HARBIN	Observed	183	269	452	540	639	665	612	525	458	309	202	148	5002
	Estimated	143	216	423	576	694	571	576	549	450	401	247	156	5003
HEFEI	Observed	245	277	374	454	533	483	552	485	438	336	271	227	4675
	Estimated	229	311	419	477	512	452	492	422	441	355	261	242	4614
JINAN	Observed	234	290	422	511	612	566	509	493	439	347	244	205	4871
	Estimated	232	319	475	575	612	573	480	433	447	362	257	259	5023
KUNMING	Observed	437	459	588	647	579	474	448	455	435	384	391	390	5684
	Estimated	479	471	613	689	584	439	450	439	453	443	395	402	5856
LANZHOU	Observed	233	302	440	510	609	618	611	560	424	339	243	209	5096
	Estimated	292	309	458	484	585	591	616	554	438	356	284	250	5217
LHASA	Observed	486	504	632	702	819	789	766	682	638	633	521	483	7655
	Estimated	530	511	610	751	823	795	753	774	752	668	526	475	7968
NANCHANG	Observed	226	254	306	364	481	468	581	529	482	391	288	247	4617
	Estimated	245	318	335	401	474	451	524	475	495	400	286	258	4660
NANJING	Observed	242	277	357	426	514	459	526	477	430	332	257	227	4524
	Estimated	240	315	383	453	517	450	468	413	425	337	232	241	4474
NANNING	Observed	215	217	266	337	445	454	500	508	476	423	338	275	4455
	Estimated	253	249	314	378	444	413	455	475	507	443	357	283	4571
SHENYANG	Observed	215	300	443	518	590	558	525	506	462	344	230	189	4880
	Estimated	222	308	488	606	651	548	495	462	427	342	262	192	5003
TIANJIN	Observed	224	285	428	511	623	541	528	495	438	330	228	203	4836
	Estimated	229	312	455	574	673	527	458	441	415	345	225	200	4855
WUHAN	Observed	231	253	320	409	503	476	544	508	438	336	260	227	4505
	Estimated	248	340	359	425	519	448	510	450	473	343	252	240	4607
XIAN	Observed	218	259	367	441	536	529	573	529	379	278	211	189	4508
	Estimated	217	282	374	438	512	562	540	491	396	295	229	201	4537
XINING	Observed	294	358	495	576	648	620	639	583	453	397	310	261	5634
	Estimated	323	352	478	537	655	642	672	630	487	393	336	296	5799
YINCHUAN	Observed	293	347	503	591	736	698	691	624	496	417	302	264	5961
	Estimated	282	350	511	594	718	688	708	645	496	442	307	266	6007
ZHENGZHOU	Observed	242	300	407	489	585	559	547	512	420	339	253	226	4879
	Estimated	217	310	426	522	572	543	491	467	419	344	247	225	4784

Table 3. Values of Constants in Equation 2

Month	d1	d2	d3	d4	R	RMSE
Jan	832.0	0.0244	−12.590	−43.28	0.97	16
Feb	724.9	0.0370	−7.980	−42.23	0.97	18
Mar	659.7	0.0576	−1.487	−46.91	0.97	23
Aprl	638.6	0.0612	1.768	−47.87	0.97	23
May	645.7	0.0663	5.008	−51.85	0.96	29
June	821.2	0.0616	2.327	−64.78	0.93	36
July	987.5	0.0501	−1.441	−68.20	0.80	38
Aug	894.1	0.0548	−3.101	−53.70	0.75	32
Sept	912.9	0.0550	−6.588	−58.06	0.85	27
Oct	914.9	0.0334	−10.202	−51.31	0.98	16
Nov	806.7	0.0180	−11.240	−42.69	0.97	18
Dec	743.6	0.0211	−11.576	−36.84	0.95	21

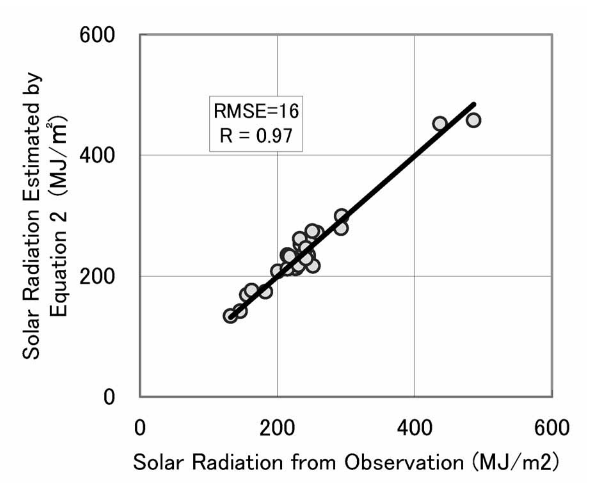

Fig.8. Correlation between Monthly Solar Radiation Values from Observation and Equation 2 (January)

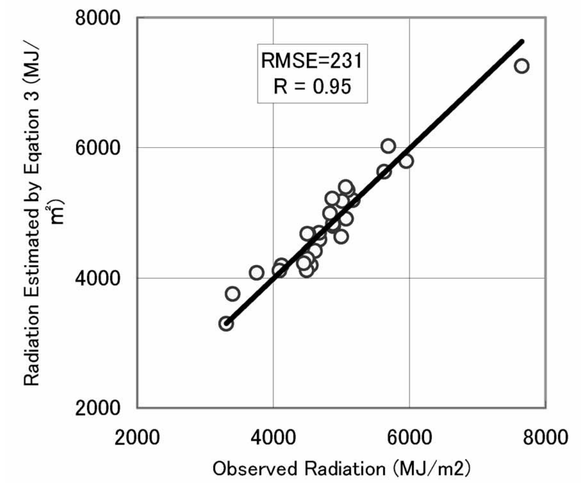

Fig.9. Correlation between Yearly Solar Radiation from Observesion and Equation 3

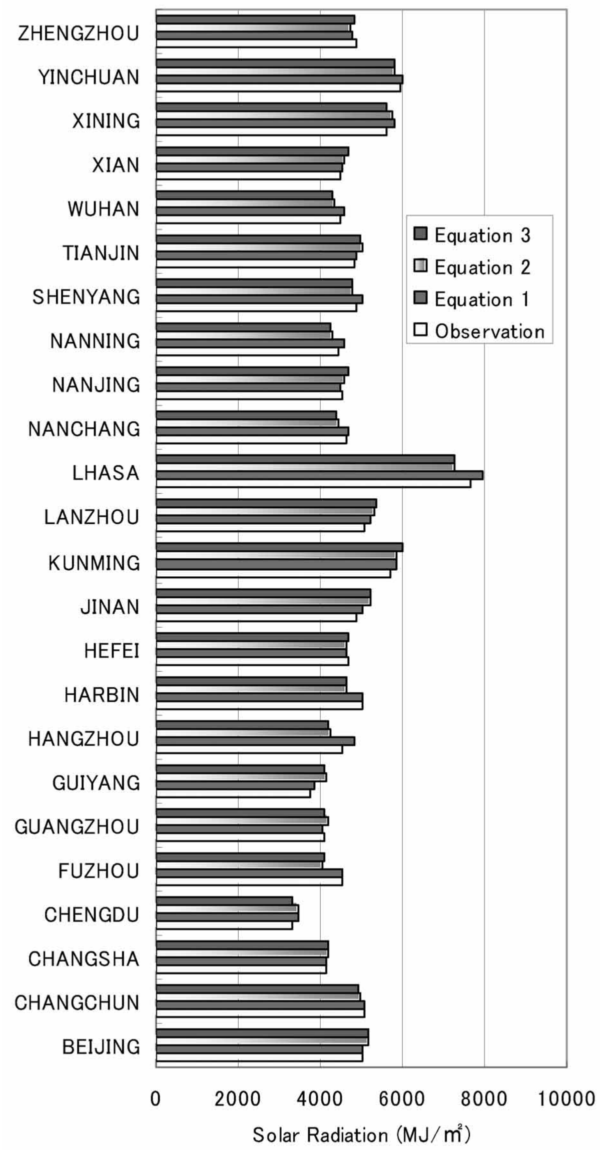

Fig.10. Comparison of Yearly Solar Radiation from Observation and Eqations 1,2 and 3

Conclusions

In order to estimate solar radiation in Chinese locations, hourly, monthly and yearly models were developed in this paper. The main conclusions of this study are as follows:

1. Hourly models were developed for the 24 cities with variables of cloud cover, temperature changes and relative humidity.
2. Monthly solar radiation can be obtained by summing up the hourly radiation, or by Equation 2 and a set of constants.
3. Three methods of estimating yearly solar radiation were suggested; the results from all the three methods are close to observation. Equation 3 is the simplest way to estimate yearly solar radiation.

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