Asia-Pac. J. Atmos. Sci., 52(4), 405-412, 2016
DOI:10.1007/s13143-016-0024-x pISSN 1976-7633 / eISSN 1976-7951

Analysis of Solar Radiation on the Surface Estimated from GWNU Solar Radiation Model with Temporal Resolution of Satellite Cloud Fraction

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(Manuscript received 9 September 2015; accepted 25 April 2016)
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Abstract: Preliminary analysis with a solar radiation model is generally performed for photovoltaic power generation projects. Therefore, model accuracy is extremely important. The temporal and spatial resolutions used in previous studies of the Korean Peninsula were 1 km × 1 km and 1-h, respectively. However, calculating surface solar radiation at 1-h intervals does not ensure the accuracy of the geographical effects, and this parameter changes owing to atmospheric elements (clouds, aerosol, ozone, etc.). Thus, a change in temporal resolution is required. In this study, one-year (2013) analysis was conducted using Chollian geostationary meteorological satellite data from observations recorded at 15-min intervals. Observation data from the intensive solar site at Gangneung-Wonju National University (GWNU) showed that the coefficient of determination (R^2), which was estimated for each month and season, increased, whereas the standard error (SE) decreased when estimated in 15-min intervals over those obtained in 1-h intervals in 2013. When compared with observational data from 22 solar sites of the Korean Meteorological Administration (KMA), R^2 was 0.9 or higher on average, and over- or under-simulated sites did not exceed 3 sites. The model and 22 solar sites showed similar values of annual accumulated solar irradiation, and their annual mean was similar at 4,998 MJ m^{-2} (3.87 kWh m^{-2}). These results show a difference of approximately ± 70 MJ m^{-2} (± 0.05 kWh m^{-2}) from the distribution of the Korean Peninsula estimated in 1-h intervals and a higher correlation at higher temporal resolution.

Key words: Chollian, geostationary meteorological satellite, surface solar radiation, GWNU solar radiation model, temporal resolution

1. Introduction

Renewable energy is attracting an increasing amount of attention owing to the Korean's government's low-carbon green development policy and the enforcement of the Certified Emissions Reduction plan developed by the Kyoto Protocol. In particular, interest in photovoltaic power is higher than that in other types of energy because it is a clean and limitless energy source and collects and utilizes energy emitted from the sun upon reaching the Earth's surface (Perez and Perez, 2008). In South Korea, installation and operation of photovoltaic power generators is increasing in locations such as building rooftops or reservoirs, where they can generate power without damaging forests. Such conditions are integral for obtaining Renewable Energy Certificates (RECs; Ministry of Trade, Industry, and Energy, 2014). Under this program, small-scale power generation in areas such as rooftops and parking lots are assigned high REC weights; that is, this type of power generation is beneficial for reducing emissions at sea level, which vary due to the effects of surface albedo and ambient temperature change.

Photovoltaic power has advantages of relative ease and low-cost operation compared with other types of power generation; however, it has the shortcoming of high initial costs. For this reason, optimal site surveys are conducted as a preliminary study of photovoltaic power, which uses a solar radiation model for estimation by parameterizing the processes of absorption and scattering of solar radiation, by atmospheric constituents direct and diffuse emissions due to gases in the atmosphere such as ozone, water vapour, aerosol, and clouds.

Geostationary satellite data are frequently utilized for radiation research because a wide area can be observed each hour. Perez et al. (2002) calculated the global and direct solar radiation at every hour, taking cloud effects into consideration using GOES data from a geostationary satellite, and the results showed increased accuracy based on comparative analyses using data from 10 observatories. Rigollier et al. (2004) calculated the hourly, daily, and monthly surface solar radiation using Heliosat-2 data and discussed the suitability of solar radiation research using satellite data. In Asia, Kawai and Kawamura (2005) and Qin et al. (2006) studied surface solar radiation using the solar radiation and satellite data (visible reflectance) observed over an ocean with low albedo changes. Such studies are performed using the solar radiation model, and studies regarding the cloud properties that affect solar radiation the most are being actively performed.

In Korea, in order to improve the accuracy of surface solar radiation estimated by the GWNU solar radiation model, Zo et al. (2014) increased the accuracy of the one-layer solar radiation model by using a Line-by-Line (LBL) multi-layer solar radiation model and vertical input data. In addition, Lee et al.

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(2011) estimated surface solar radiation with 1 km × 1 km resolution by improving the spatial resolution of the model to 4 km × 4 km for the Korean Peninsula. Moreover, Jee et al. (2013a, 2013b) produced a solar resource map at 500 m × 500 m resolution by using data on the visible light area obtained from the Geostationary Ocean Colour Imager (GOCI). They developed a solar resource map of the Seoul region with a resolution of 10 m × 10 m by using very high-resolution topographic data.

In terms of temporal resolution, surface solar radiation is estimated in 1-h intervals due to the observation time interval of geostationary meteorological satellite data used to calculate the transmittance of clouds. Clouds cover approximately 30% of the Earth and change significantly depending on time and space. A significant amount of solar energy is reduced by clouds (Rossow and Schiffer, 1999). That is, clouds have the greatest influence on surface solar radiation, which is influenced by the temporal resolution of the geostationary meteorological satellite that calculates cloud transmittance.

Because the Chollian satellite makes observations of the Korean Peninsula in 15-min intervals, the present study conducted analysis on the accuracy of surface solar radiation calculations as a function of the improvement of the temporal resolution of the model.

Table 1. Source and resolutions of input data for the Gangneung-Wonju National University (GWNU) solar radiation model.

Input Data	Source	Resolution	
		Spatial	Temporal
Surface Albedo	MODIS	0.05° × 0.05°	15 d
Aerosol	MODIS	1.0° × 1.0°	1 d
Ozone	OMI	1.0° × 1.0°	1 d
Total Precipitable Water, Temperature, Pressure	KLAPS	10 km × 10 km	1 h
Cloud mask and cloud fraction	Chollian MI	1 km × 1 km	15 min

2. Research materials and methods

a. Research materials

The input data for operation of the solar model used in this study included observation data from Moderate Resolution Imaging Spectroradiometer (MODIS), Ozone Monitoring Institute (OMI), and Chollian satellites and the results of numerical Korean Local Analysis and Prediction System (KLAPS) models. Their temporal and spatial resolutions are

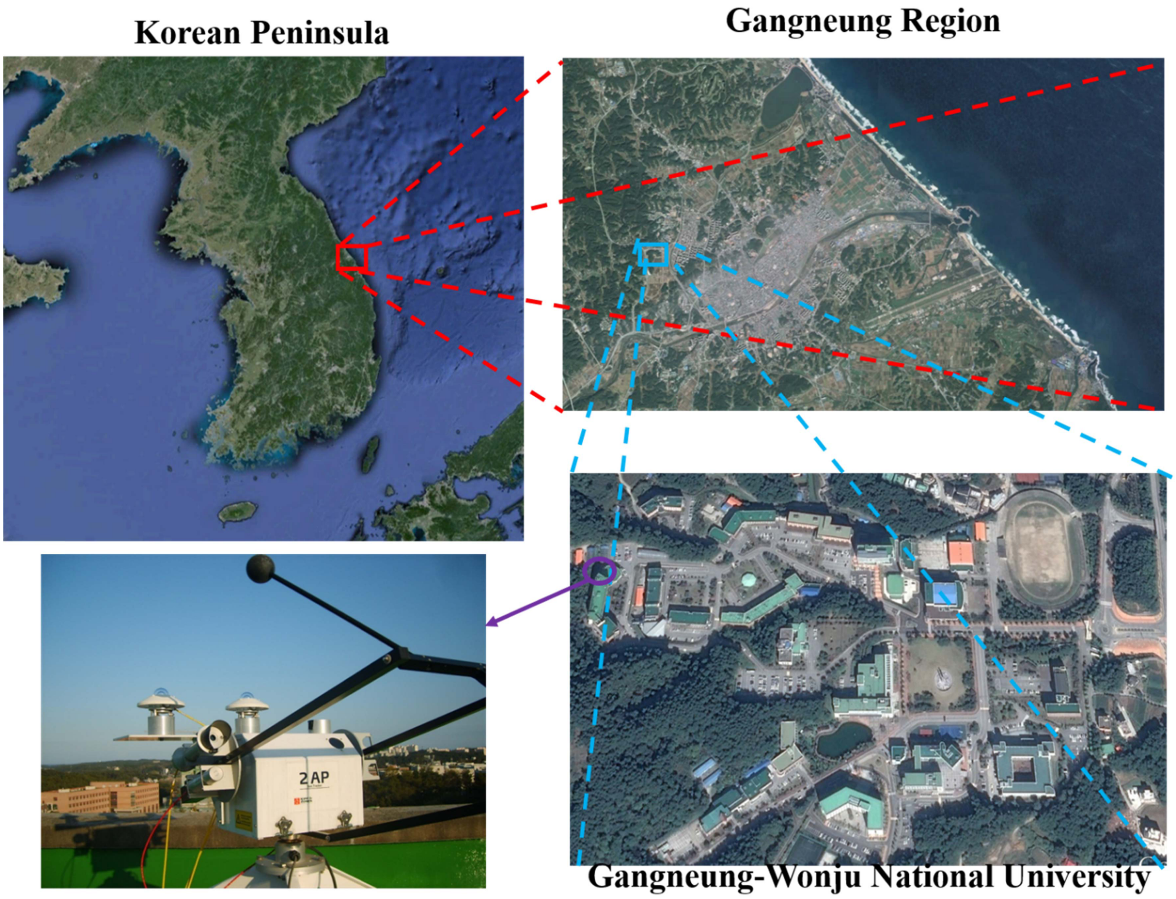

Fig. 1. Geolocation and radiation instrument of the Gangneung-Wonju National University (GWNU) solar site. (Source: Google Earth).

Table 2. Geographic locations of 22 the Korean Meteorological Administration (KMA) solar radiation sites.

Observatory	Lat. (°N)	Lon. (°E)	Observatory	Lat. (°N)	Lon. (°E)
Daegwallyeong	37.68	126.77	Andong	36.57	128.72
Chuncheon	37.90	127.73	Pohang	36.03	129.38
Gangneung	37.75	128.90	Daegu	35.88	128.62
Seoul	37.57	126.97	Jeonju	35.82	127.15
Incheon	37.47	126.63	Gwangju	35.17	126.90
Wonju	37.33	127.95	Busan	35.10	129.03
Suwon	37.27	126.98	Mokpo	34.82	126.38
Seosan	36.77	126.50	Heuksando	34.68	125.45
Cheongju	36.63	127.45	Jeju	33.52	126.53
Daejeon	36.37	127.37	Gosan	33.29	126.16
Chupungnyeong	36.22	128.00	Jinju	35.20	128.12

shown in Table 1. MODIS observation data were used for surface albedo and aerosol optical thickness (Ichoku et al., 2002; Zhang and Reid, 2006); OMI observation data were used for total ozone quantity (Bhartia and Wellemeyer, 2002); data produced by and KLAPS, the Korean Meteorological Administration's (KMA's) very short-term meteorological analysis and forecast system, were used for total precipitable water, temperature, and atmospheric pressure (Kim et al., 2002); and data of the Meteorological Imager (MI) of the Chollian geostationary meteorological satellite was used cloud mask and cloud fraction (Choi et al., 2007). Time and space of all input data were matched by using bilinear interpolation according to the temporal and spatial resolutions of cloud data, which have the greatest influence on surface solar radiation among input data.

For model calculations and comparative analysis, global solar radiation data from solar concentration sites (Lat: 37.8°, Lon: 128.9°, Alt: 63.5 m; Fig. 1) installed at the rooftop of Life Sciences Building II at Gangneung-Wonju National University (GWNU) were used. The GWNU pyranometer (CMP21, Kipp & Zonen; World Meteorological Organization, 2012, 2013) at the intensive solar site is examined annually by the Korea Meteorological Industry Promotion Agency by using a reference instrument comparative examination; the standard error (SE) was less than 1 W m^{-2} from comparison observations. The mean value of global solar radiation for 1-min was used for the observations; 2013 data were used for model calculation and analysis. The data from 22 KMA solar radiation sites listed in Table 2 were stored as cumulative data for 1-h (unit: MJ m^{-2}) and could not be used for analysis of 15-min intervals; therefore, the data were used for distribution analysis with accumulated data only.

b. Research methods

Figure 2 shows the flow chart for the solar radiation model. Input data were collected, temporal and spatial resolutions were matched, and interpolation and extrapolation were then performed. Here, the temporal and spatial resolutions for

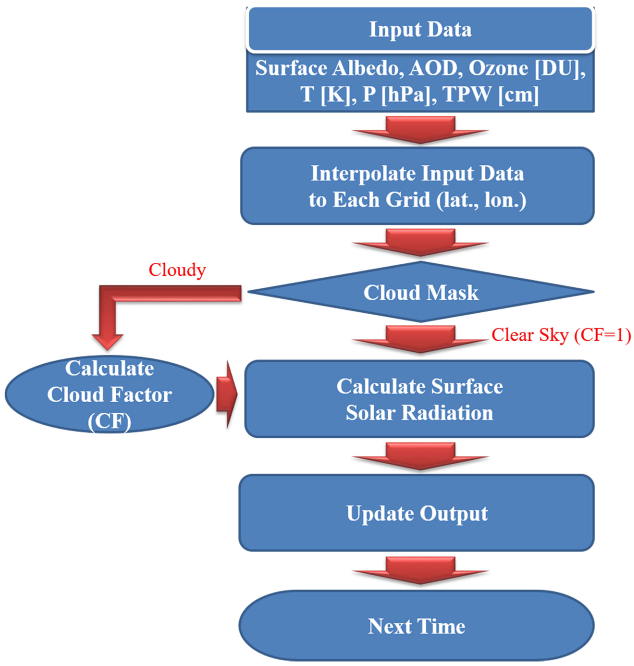

Fig. 2. Flow chart of GWNU solar radiation model. AOD, Ozone, T, P, and TPW represented aerosol optical depth, ozone amount, atmospheric temperature, surface pressure and total precipitable water, respectively.

reference were matched with the times of the satellite data, i.e., the cloud data having the greatest influence among input data. Once the input data were organized, surface solar radiation was estimated by determining the presence of clouds according to the amount of cloud mask. As shown in Eq. (1), after calculating the solar radiation for a clear sky ($S_{clr,Mod}$) the cloud factor (CF) was estimated by using visible albedo (α) and zenith angle (θ) as observed from the satellite (Kawamura et al., 1998; Lee et al., 2007; Zo et al., 2010).

$$S = S_{clr,Mod} \times CF(\alpha, \theta) \quad (1)$$

Here, S is solar radiation including cloud effect, and $S_{clr,Mod}$

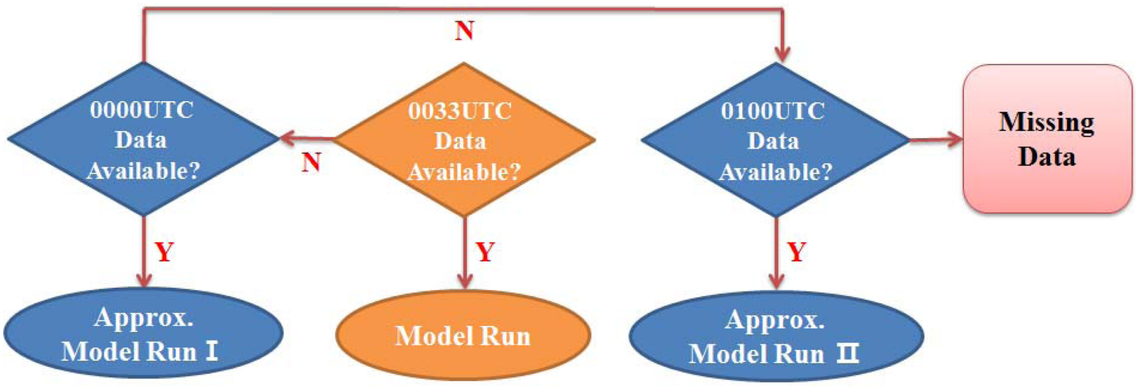

Fig. 3. Retrieval cloud information for the GWNU solar radiation model from data of the geostationary satellites.

represents solar ration in the absence of clouds. Cloud effect was calculated with Eq. (2) using results of solar radiation model in clear conditions ($S_{Clr,Mod}$) and solar radiation observed on the ground ($S_{Cld,Obs}$) (Kawai and Kawamura, 2005), using calculations by multiple regression equation with solar zenith angle and the function of visible reflectance obtained from satellite.

$$CF(\alpha,\theta) = \frac{S_{Cld,Obs}}{S_{Clr,Mod}} \quad (2)$$

CF represents the ratio of $S_{Cld,Obs}$ and $S_{Clr,Mod}$, determined based on the function of satellite data of visible reflectance (α) and zenith angle (θ).

Cloud data from previous studies (Jee et al., 2013a; Zo et al., 2014) used data of the meteorological Multi-functional Transport satellite (MTSAT; Oku et al., 2010) from the Japanese Meteorological Agency, which included observations of the Korean Peninsula at 00-min and 33-min each hour. However, considering data production cycles and errors, 33-min data were used in this study. If such data were unavailable, the data obtained at 00-min of the same hour were used; otherwise, 00-min observation data for the following hour were used. Therefore, as shown in Fig. 3, for 0900 LST (i.e., 0000 UTC) data calculation, satellite data from 0033 UTC were used; if 0033 UTC data were missing, 0000 UTC data were used. If 0000 UTC data were also missing, 0100 UTC data were used. If such data were also unavailable, calculations for 0900 LST were not performed and were treated as missing data.

The Chollian satellite makes four observations of the Korean Peninsula each hour in 15-min intervals at 00-min, 15-min, 30-min, and 45-min. However, when the satellite makes observations of East Asia and the entire Northern Hemisphere, it makes a minimum of two observations each hour. In addition, whereas MTSAT observations focus on Japan, those by the Chollian satellite focus on the Korean Peninsula, allowing more accurate observations. In this study, analysis of changes in accuracy due to the changes in temporal resolution was conducted by using the analysis of solar radiation when operating the model at 1-h intervals and 15-min intervals. Calculations performed with past MTSAT satellite data used 1-

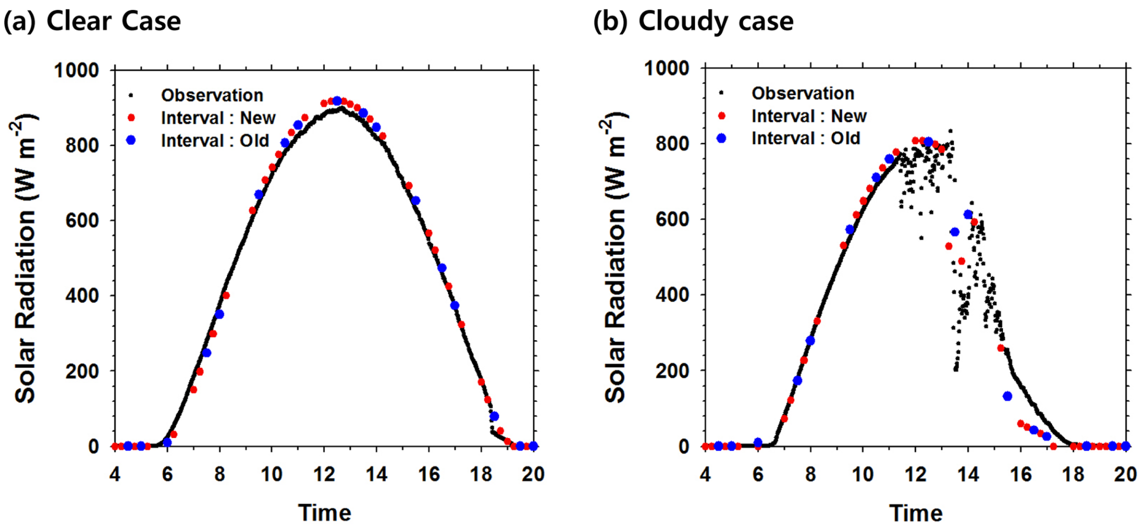

Fig. 4. Time series of solar radiation with observation (black point) and GWNU solar radiation model at the GWNU solar site: (a) 12 April 2013 and (b) 5 October 2013. Blue (red) points indicate old (new) calculation data of 1 h (15 min).

Table 3. Hourly mean solar radiation and differences between observation and the GWNU solar radiation model with old (1 h) and new (15 min) model calculations at the GWNU solar site measured on 12 April 2013.

Time (LST)	Observation ($W\ m^{-2}$)	Difference between model and observation ($W\ m^{-2}$)	
		Old	New
0700	98.18	9.94	42.39
0800	279.78	88.55	90.59
0900	473.97	73.86	84.51
1000	646.34	103.37	103.24
1100	778.62	103.46	101.29
1200	855.53	99.73	100.06
1300	889.99	103.13	100.04
1400	856.28	103.42	98.92
1500	770.78	109.89	103.55
1600	629.35	103.67	101.08
1700	459.86	102.94	101.40
1800	267.51	139.77	124.65
1900	69.15	113.93	92.16

h intervals.

3. Results

Figure 4 shows solar radiation observed by a pyranometer at the GWNU intensive solar site and the values estimated by the model. Black dots in the figure indicate surface solar radiation (interval: 1-min) observed by the pyranometer on a clear day; blue dots indicate values obtained by operating the model in 1-h intervals, which is the interval of the previous GWNU solar radiation model; red dots (include blue dots) indicate values

Table 4. Monthly and annual statistics of old and new calculation methods for solar radiation at the GWNU solar site during 2013.

Month	Old		New	
	R^2	Standard Error ($W\ m^{-2}$)	R^2	Standard Error ($W\ m^{-2}$)
January	0.80	66.36	0.84	60.14
February	0.86	78.46	0.88	71.83
March	0.88	88.00	0.89	83.38
April	0.81	127.57	0.85	110.91
May	0.86	115.87	0.89	104.16
June	0.81	131.50	0.83	122.22
July	0.84	107.50	0.86	99.78
August	0.85	115.32	0.87	104.11
September	0.85	86.94	0.87	79.60
October	0.81	91.64	0.86	77.33
November	0.83	77.38	0.86	67.84
December	0.84	60.06	0.87	54.66
Annual	0.84	92.54	0.86	85.53

obtained by operating the model in 15-min intervals. Operating the model in 1-h intervals yielded a total of 13 estimated values from sunrise to sunset, and that in 15-min intervals yielded a total of 40 estimated values in the case of 12 April (Fig. 4a) and 5 October (Fig. 4b) 2013.

For the quantitative analysis shown in Fig. 4a, observation data were averaged hourly, and error analysis was performed against the results based on respective calculation intervals. The results of the error analysis are shown in Table 3. At 0700, 0800, and 1900 LST, which were close to sunrise or sunset, significant errors were shown owing to large variations in the increase and decrease of solar radiation at sunrise and sunset.

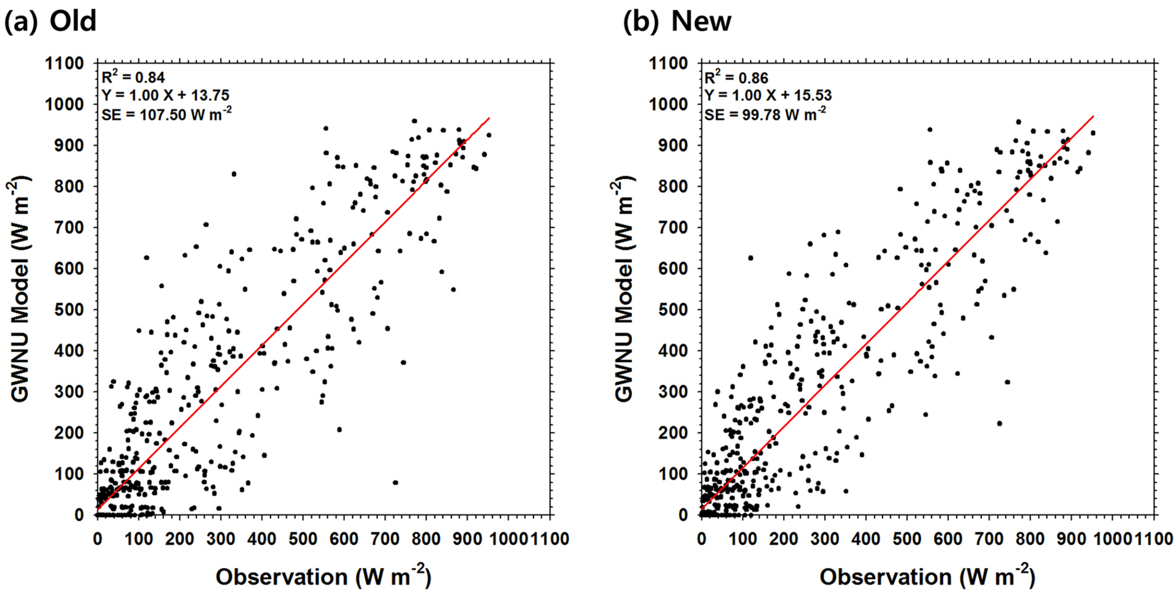

Fig. 5. Scatterplot between observation and the GWNU solar radiation model at the GWNU solar site during July 2013. (a) Old and (b) New methods are calculated the solar radiation every 1 h and 15 min intervals, respectively.

These variations were excessively large for representing one and four respective estimated values. Because solar radiation has a cosine form as a function of solar zenith angle, its accuracy is higher at 15-min intervals than at 1-h intervals. In Fig. 4b, the weather was clear in the morning, and the surface solar radiation decreased as a result of clouds in the afternoon. In the cloud mask dataset, clouds were observed in the afternoon, and the effect of the cloud factor was included in the model. When using 1-h interval data (blue dot), the number of data points available for comprehending the diminution effect of clouds is insufficient. Therefore, the surface solar radiation can be calculated with higher accuracy when using the 15-min interval data (blue and red dot) than when using the 1-h interval data.

The monthly results of model calculations and observation data are shown in Fig. 5 and in Table 4. Figure 5(a) shows a graph for July 2013, which shows the statistical analysis between solar radiations estimated at 1-h intervals and observation data, with R^2 of 0.84 and SE of 107.50 W m^{-2}. Figure 5(b) shows the results of analysis between solar radiations estimated at 15-min intervals and observation data, with higher R^2 (0.86) and lower SE (99.78 W m^{-2}) than those of Fig. 5(a). The results of this analysis are presented in Table 4, which shows a higher R^2 and lower SE for the values estimated at 15-min intervals than those at 1-h intervals for all months. In addition, the annual data analysis incorporating all data also showed a high correlation ($R^2 = 0.87$) and a small degree of error (SE = 85.53 W m^{-2}) when data of 15-min intervals were used. These results suggest an improvement in accuracy due to changes in temporal resolution.

The Korean Peninsula shows distinct meteorological changes by season; Fig. 6 graphs the results of seasonal analysis relative to these changes. The months were divided into the four seasons of spring (March, April, and May), summer (June, July, and August), fall (September, October, and November), and winter (January, February, and December), and R^2 (solid and dotted line) and SE (bar graph) were obtained. The results show that R^2 was higher and SE was lower for the calculations with higher temporal resolution at 15-min intervals, which is the same as that shown in the monthly and annual analysis. The season with the lowest R^2 was summer (0.86). Because summer is the season with the most clouds in the Korean Peninsula, this result is believed to be associated with problems of accuracy in relation to the presence and transmittance of clouds. In addition, spring showed the highest R^2 (0.88), which is believed to be due to the small amount of clouds in that season. SE was highest in summer, during which the highest solar radiation and is affected by clouds, whereas solar radiation was the lowest in winter, during which little solar radiation is experienced.

Table 5 shows the results of model calculations at 1-h intervals and at 15-min intervals by using data from 22 solar sites operated by the KMA. Because KMA data are expressed as 1-h accumulated data, the model results are presented in an accumulated unit (MJ m^{-2}) in the same manner. Only data

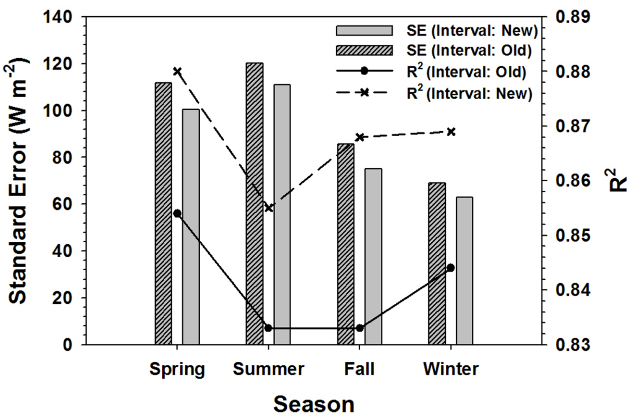

Fig. 6. Seasonal statistics (bar: standard error, line-point: correlation) of the old and new methods calculated by the GWNU solar radiation model at the GWNU solar site during 2013.

Table 5. Statistics of 22 KMA solar radiation sites for the old and new calculation methods of the GWNU solar radiation model.

Observatory	Old			New		
	R^2	Slope	Intercept	R^2	Slope	Intercept
Daegwallyeong	0.87	0.93	0.04	0.89	0.93	0.04
Chuncheon	0.88	0.93	0.07	0.89	0.93	0.08
Gangneung	0.87	0.87	0.15	0.88	0.87	0.15
Seoul	0.88	1.07	0.07	0.89	1.07	0.07
Incheon	0.89	1.02	0.06	0.90	1.02	0.06
Wonju	0.88	1.02	0.05	0.89	1.02	0.05
Suwon	0.89	0.95	0.06	0.89	0.95	0.07
Seosan	0.89	1.01	0.05	0.89	1.01	0.05
Cheongju	0.88	1.06	0.07	0.89	1.06	0.07
Daejeon	0.89	0.89	0.05	0.91	0.89	0.04
Chupungnyeong	0.89	1.12	0.03	0.89	1.11	0.03
Andong	0.89	1.04	0.05	0.90	1.04	0.05
Pohang	0.89	0.95	0.08	0.90	0.95	0.08
Daegu	0.89	0.90	0.04	0.90	0.90	0.04
Jeonju	0.89	1.03	0.06	0.90	1.03	0.06
Gwangju	0.89	0.98	0.05	0.90	0.98	0.05
Busan	0.91	0.99	0.04	0.91	0.99	0.04
Mokpo	0.90	1.04	0.06	0.91	1.03	0.06
Heuksando	0.89	0.91	0.06	0.90	0.91	0.06
Jeju	0.90	0.96	0.09	0.91	0.96	0.09
Gosan	0.89	0.85	0.08	0.89	0.85	0.09
Jinju	0.89	0.95	0.07	0.90	0.96	0.07

from 0900 to 1700 LST were used to eliminate the effects of light blocked by buildings at the observation sites. Similar to the results of previous analysis, the R^2 of the values estimated at 15-min intervals was higher at all 22 sites. Among the results estimated at 15-min intervals, the highest and lowest values were 0.91 (Busan) and 0.88 (Gangneung) and showed a high correlation of 0.90 on average. In addition, in slope analysis as a criterion for over- and under-simulation of the

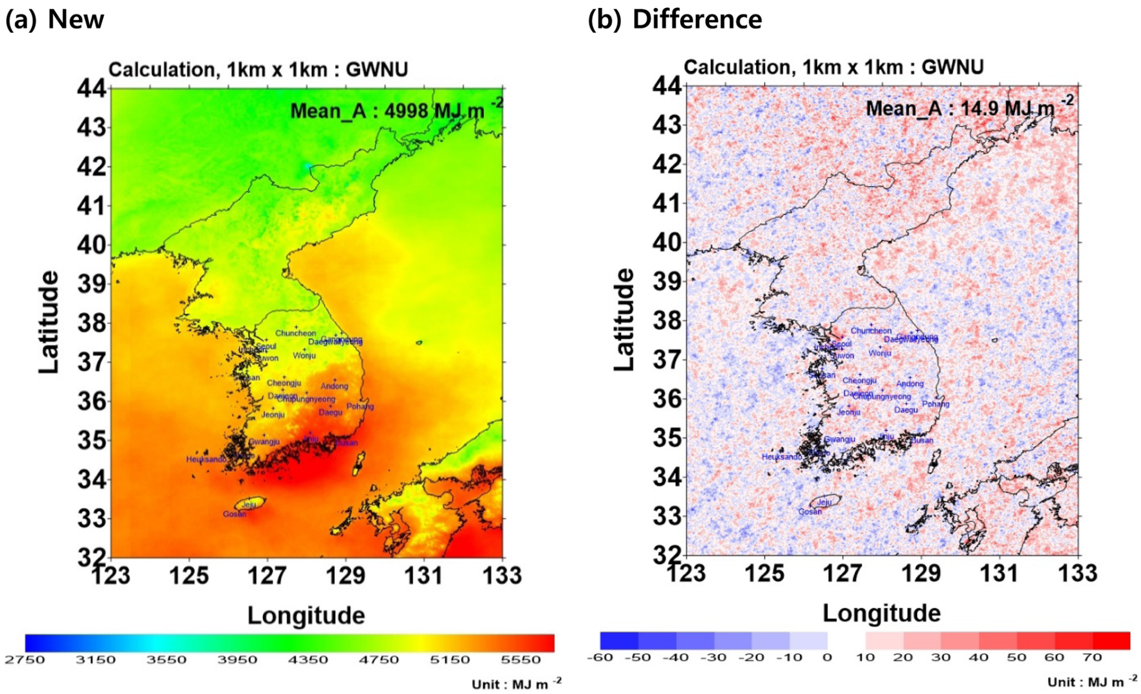

Fig. 7. (a) Annual accumulated solar radiation calculated by new GWNU solar radiation model (interval: 15 min) in 2013, and (b) difference of solar radiation between old and new GWNU solar radiation models. And area mean and difference solar radiations are 4998 MJ m^{-2} and 14.9 MJ m^{-2}, respectively.

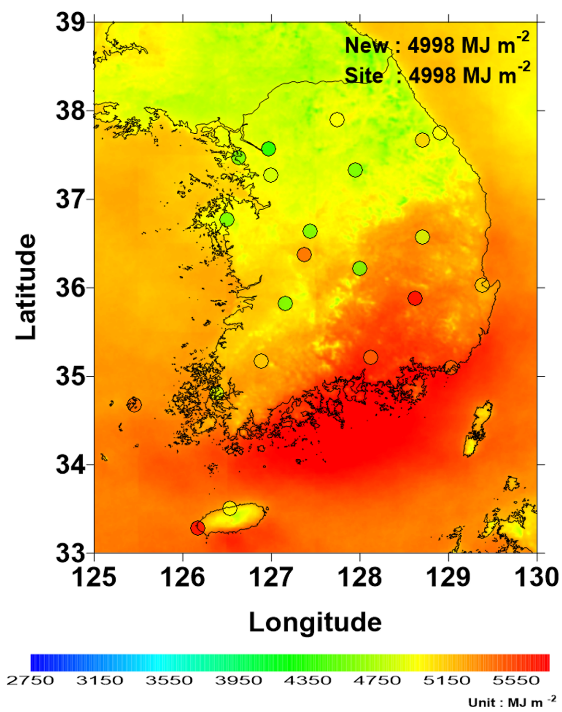

Fig. 8. Same as Fig. 7(a) except for added annual accumulated solar radiation from 22 KMA solar radiation sites. The new GWNU solar radiation model (New) and observation (Site) have the same mean solar radiation of 4998 MJ m^{-2}.

solar model, the difference between the two was found to be very small. Among the results estimated at 15-min intervals, one over-simulated site (1.10 or higher) was noted at Chupungnyeong (1.12), and two under-simulated sites (0.99 or lower) included Daejeon (0.89) and Gosan (0.85); other sites showed a similar pattern.

Distribution in the Korean Peninsula of annual accumulated surface solar radiation of model calculations and the observation data from the 22 KMA sites are shown in Fig. 7. Figure 7(a) shows the calculations with temporal and spatial resolutions of 15-min and 1 km × 1 km, respectively. Figure 7(b) shows differences owing to changes in temporal resolution. A positive value indicates that the calculation at 15-min intervals is larger than that at 1-h intervals, and a negative value indicates the reverse. The difference in temporal resolution was approximately ± 70 MJ m^{-2} at maximum and approximately 14.90 MJ m^{-2} on average. Figure 8 shows corresponding data as color of circle at the 22 KMA solar sites with New method (Fig. 7(a)). The average accumulated solar radiation of the New calculation and 22 observations have the same value as 4998 MJ m^{-2}, and the region with the highest value included Daegu and the surrounding Gyeongsang-do area. These results are believed to have occurred because Gyeongsang-do is located in the lower latitude zone of the Korean Peninsula and the downwind side of Sobaek mountains, resulting in smaller mean cloud quantities than those at other regions in the same latitude zone.

4. Conclusions

For the cloud data with the greatest influence on surface solar radiation, geostationary meteorological satellite data are generally used because visual ground measurements have problems related to accuracy and the spatial resolution of observational data. To analyse the distribution of high-resolution solar radiation for the Korean Peninsula, a GWNU solar radiation model was used in this study; for cloud data among input data, geostationary meteorological satellite data were used. Prior to operation of the Chollian geostationary meteorological satellite, a solar model was operated at 1-h intervals using MTSAT data. After the Chollian satellite began collecting data, cloud data at 15-min intervals were obtained for the Korean Peninsula. As a result, the spatial resolution of the solar model was 1 km × 1 km, and the temporal resolution of the model changed from 1-h to 15-min.

For analysis of temporal resolution changes, data obtained by a pyranometer in operation at concentration solar sites at GWNU were analysed in addition to model calculations. In both monthly and seasonal analyses, the results showed that R^2 was higher and SE was lower for calculations in 15-min intervals than those in 1-h intervals for 2013 data. In addition, analysis with data from 22 KMA solar sites showed that R^2 was greater than 0.90 on average, and only three over- or under-simulated sites were noted. The model and the 22 solar sites showed strongly similar patterns of annual cumulative solar radiation. In particular, the highest value was identical at Daegu and the surrounding Gyeongsang-do area. Moreover, the annual mean value was also similar at 4998 MJ m^{-2} and showed a difference of approximately ± 70 MJ m^{-2} from the distribution for the Korean Peninsula estimated at 1-h intervals.

These results can be used for various fields including the renewable energy sector in addition to meteorological research. However, in regions with significant topographic variation such as the Korean Peninsula, further research needs to be conducted using data similar to actual topography.

Acknowledgements. This work was funded by the Weather Information Service Engine Program of the Korea Meteorological Administration under Grant KMIPA-2012-0001-1.

Edited by: Jimy Dudhia

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