Asia-Pac. J. Atmos. Sci., 50(S), 23-32, 2014
DOI:10.1007/s13143-014-0047-0

pISSN 1976-7633 / eISSN 1976-7951

Development of GWNU (Gangneung-Wonju National University) One-Layer Transfer Model for Calculation of Solar Radiation Distribution of the Korean Peninsula

Il-Sung Zo[1], Joon-Bum Jee[2], and Kyu-Tae Lee[1]

[1]*Department of Atmospheric and Environmental Sciences, Gangneung-Wonju National University, Gangneung, Korea*
[2]*Weather Information Service Engine, Center for Atmospheric sciences and Earthquake Research, Seoul, Korea*

(Manuscript received 24 October 2013; accepted 28 July 2014)

Abstract: Gangneung-Wonju National University (GWNU) one-layer solar radiation model is developed in order to resolve the lack of the vertical structure of atmospheric components and fast calculation with high horizontal spatial resolution. GWNU model is based on IQBAL and NREL methods and corrected by precise multi-layer Line-By-Line (LBL) model. Further, the amount of solar radiation reaching the surface by using 42 types of vertical atmospheric data as input data was compared with detailed models and one-layer models. One-layer solar radiation models were corrected depending on sensitivity of each input data (i.e., total precipitable water, ozone, mixed gas, and solar zenith angle). Global solar radiation was calculated by corrected GWNU solar model with satellites (MODIS, OMI and MTSAT-2), KLAPS model prediction data in Korea peninsula in 2010, and the results were compared to surface solar radiation observed by 22 KMA solar radiation sites. Calculated solar radiation annually accumulated showed highest solar radiation distribution in Andong, Daegu, and Jinju regions, meanwhile the observation data showed lower solar radiation in Daegu region compared to model result values.

Key words: One-layer solar radiation model, line-by-line model, correction, global solar radiation, vertical atmospheric data

1. Introduction

Solar radiation reaching the surface of the earth not only serves as a crucial role in climate change of global atmosphere but also is extensively used for industrial activity of human beings. In particular, as solar energy, one of clean energy resources, is attenuated by 65% when radiant energy (65,700 $\mathrm{TW\,yr^{-1}}$) released from the sun passes atmosphere, the amount reaching the surface of the earth is about 23,000 $\mathrm{TW\,yr^{-1}}$, a more amount compared to other types of energy sources (Perez and Perez, 2008). Thus, many countries in the world show their great interest and have heavily invested in energy power projects using solar energy. Germany Trade & Invest (GTAI), a leader in photovoltaic generation, reported that a growing trend of Germany's annual solar radiation capacity reached 7.6 GW in 2012, and approximately 180,000 photovoltaic systems were newly operated for a year, which proves photovoltaic generation sharply increases.

The U. S. Department of Energy's National Renewable Energy Laboratory (NREL) developed the Climatological Solar Radiation (CSR) model in 1995 to calculate daily accumulated solar radiation (George and Maxwell, 1999). A solar energy map was produced at 10 km × 10 km spatial resolution by using the State University of New York (SUNY)'s Satellite Radiation Model (Perez *et al*., 2002) developed by NREL and Perez, and was analyzed by using the US Climate Reference Network (USCRN) data and the Typical Meteorological Year (TMY) Ver.3 model. The German Weather Service (Deutscher Wetterdienst, DWD) completed a solar energy map for the first time in 1999 by using observation data on monthly and annual average solar radiation daily accumulated from 1981 to 1998, and a solar energy map using a solar radiation model was developed by using relevant meteorological and meteorological satellite observation data based on Kerschgens *et al*. (1978)'s two-stream method. Further, a solar energy map was produced by using the European Center for Midrange Weather Forecasts (ECMWF) data and the Model Output Statics (MOS) method, and additional studies that calculate photovoltaic power generation are being conducted. Recently, new technic, research actively conducted using the neural network method (Takenaka *et al*., 2011).

Solar energy that is released from the sun and reaches the surface of the earth changes with astronomical conditions (i.e., location change of the sun and the earth), distribution of the earth's atmospheric components (e.g., water vapor, mixed gas, aerosol, cloud, etc., Yeom *et al*., 2012; Lee *et al*., 2013), and the earth's surface conditions (i.e., geography and topography). It is important to consider multiple scattering between substrates by dividing atmosphere into multiple layers and inputting observation data by altitude. However, as stations observing the atmosphere's vertical structure are limited, and observation for calculating radiation characteristics does not exist except for specific observation, calculation for high-resolution solar radiation requires a one-layer solar radiation model that assumes atmosphere as a one-layer to calculate.

Therefore, this study herein corrects the existing Gangneung-Wonju National University (GWNU; hereafter GWNU) one-

Corresponding Author: Joon-Bum Jee, Weather Information Service Engine, SAIT Tower 12 Fl., 434 Worldcupbukro, Mapo-gu, Seoul 121-835, Korea
E-mail: rokmcjjb717@gmail.com

layer solar radiation model's calculation process on transmittance and solar radiation by comparing results derived from a multiple-layer solar radiation model. The input data for solar radiation model operation calculated a correction equation by using the atmosphere's 42 types of vertical data. The correction equation calculated solar energy distribution of the Korean peninsula by applying the GWNU one-layer solar radiation model, and was analyzed by comparing observation data. The research results will resolve deficiency of input data to calculate solar radiation models and will be used for super resolution and accurate solar energy calculation in an efficient manner.

2. Solar radiation model

Solar radiation released from the sun and reaching the surface are classified as direct and diffuse solar radiation by physical process, and these elements can be observed in a separate manner (i.e., direct, diffuse and global solar radiation) on the surface. In other words, the solar radiations reaching the surface are observed and attenuated by clouds, aerosol, and gas components in the atmosphere, which are varied by wavelength (see Fig. 1). The ozone layer in the stratosphere absorbs some parts of visible and ultraviolet ray areas at 0.4 μm or less, while water vapor and carbon dioxide absorb infrared wavelength regions at 0.75 μm or more.

a. Multi-layer line-by-line solar radiation model

Solar radiation energy entering at top of atmosphere is absorbed, diffused, and reflected by gas components, clouds, and aerosol in the atmosphere, and the surface. Under the assumption of a plane-parallel atmosphere, provided that the definition of solar zenith angle (θ), azimuth (ϕ), and μ ≡ cosθ on radiation process directions is used, a general solar radiation transfer equation is as follows (Dave, 1974).

$$\mu\frac{dI_\lambda(\tau_\lambda,\mu,\phi)}{d\tau} = I_\lambda(\tau_\lambda,\mu,\phi) - J_\lambda(\tau_\lambda,\mu,\phi)\ . \quad (1)$$

In this equation, τ_λ stands for optical thickness by wavelength and J_λ stands for a source function.

In atmosphere, although solar radiation transfer equation can be simplified by neglecting the Planck function, it is not easy to find accurate values with the equation if multiple scattering is included, resulting from many layers and the surface of the earth. However, provided that a phase function (P_v) does not change depending on azimuth (ϕ), downward flux of radiation in a τ layer can be specified as follows.

$$F^{\downarrow}(\tau) = \int dv\left[2\pi\int_0^{1} I_\lambda(\tau_v,\mu)\mu d\mu + \mu_0\pi F_0 e^{-\tau/\mu_0}\right]. \quad (2)$$

Herein, F_0 stands for solar radiation flux entered in atmosphere, and as solar radiation calculated in this equation drastically changes by wavelength, the Line-by-Line (LBL) method that calculates by densely dividing wavelength spacing was used to accurately calculate transfer equation values for solar radiation, meanwhile Stamnes *et al*. (1988)'s discrete ordinate approximation was used for transmission and diffusion calculation by atmospheric components.

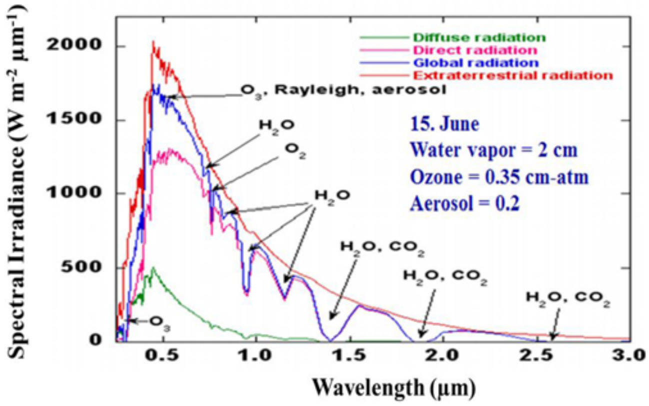

Fig. 1. A comparison of the extraterrestrial spectrum with the diffuse, direct, and global radiation (W m^{-2} μm^{-1}) on June 15.

This method is based on Chandrasekhar (1960), and with it, a multiple scattering process of layer was included to calculation by Stamnes *et al*. (1988) For absorption line data, as intervals by wavelength are not constant and are arranged in a random manner, band models for the equation (2)'s transmission function calculation produce errors in some parts. For a range of solar radiation wavelength, coefficient by wavelength was calculated at 0.002 cm^{-1} intervals from HITRAN2k absorption line data (Rothman *et al*., 2003).

b. One-layer solar radiation model

The intensity (I_λ) of solar energy reaching the surface of the earth can be written as follows based on Beer's law (Siegel and Howell, 1981).

$$I_{g\lambda} = I_{d\lambda}\cos\theta + I_{s\lambda}. \quad (3)$$

Herein, λ stands for wavelength, global solar radiation ($I_{g\lambda}$) can be divided into direct components ($I_{d\lambda}$) and diffuse components ($I_{S\lambda}$), and provided that atmosphere is a one layer, direct solar energy reaching the surface is calculated as the following equation (4).

$$I_{d\lambda} = I_{0\lambda}\exp(-\tau_\lambda). \quad (4)$$

Herein, $I_{0\lambda}$ and τ_λ, respectively, stand for extraterrestrial radiation and optical thickness resulting from absorption gas, and atmospheric transmittance can be specified as $t_\lambda = \exp(-\tau_\lambda)$. For absorption gas and particles, the following empirical equations were used to obtain each transmittance ratio of optical thickness on air molecule, aerosol, ozone, water vapor, and mixed gas.

$$t_{o\lambda} = \exp(-k_{o\lambda}\, lm_o), \quad (5)$$

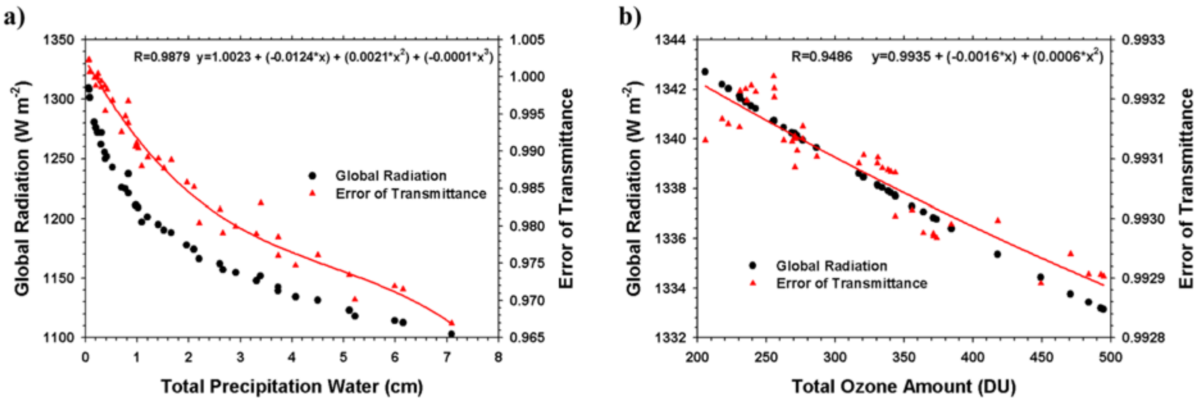

Fig. 2. Global solar radiation of LBL solar radiation model (black point) and error between GWNU and LBL solar radiation model for transmittance (red triangle) with total precipitable water (a) and total ozone amount (b).

$$t_{wa\lambda} = \exp[-0.2385 k_{wa\lambda} \omega m_r / (1 + 20.07 k_{wa\lambda} \omega m_r)^{0.45}], \quad (6)$$

$$t_{r\lambda} = \exp(-0.008735 m_a \lambda^{-4.08}), \quad (7)$$

$$t_{a\lambda} = \exp[-\beta(\lambda / 0.55)^{-\alpha} m_r], \quad (8)$$

$$t_{g\lambda} = \exp[-1.41 k_{g\lambda} m_a / (1 + 118.93 k_{g\lambda} m_a)^{0.45}]. \quad (9)$$

Herein, $k_{o\lambda}$, $k_{g\lambda}$ and $k_{wa\lambda}$ stand for classified wavelength absorption coefficient on ozone, mixed gas, and water vapor. Provided that aerosol is less than 0.5 μm, α is 1.027, meanwhile 1.206 is used for others, and l and ω, respectively, stand for vertical concentration and total precipitable water. Further, m_r, m_a, and m_o, respectively, stand for relative optical mass, pressure-corrected value, and relative optical mass on ozone.

Diffuse solar radiation ($I_{s\lambda}$) on the surface is changed by air molecule, aerosol, and multiple scattering at the surface, which can be calculated as follows.

$$I_{s\lambda} = I_{r\lambda} + I_{a\lambda} + I_{g\lambda}. \quad (10)$$

From the above equation, solar radiation diffused by Rayleigh ($I_{r\lambda}$), aerosol ($I_{a\lambda}$), and atmosphere ($I_{g\lambda}$) is calculated by empirical equations as follows.

$$I_{r\lambda} = I_{0\lambda} E_0 \cos\theta\, \tau_{o\lambda} \tau_{g\lambda} \tau_{wa\lambda} [0.5(1 - \tau_{r\lambda}) \tau_{a\lambda}], \quad (11)$$

$$I_{a\lambda} = I_{0\lambda} E_0 \cos\theta\, \tau_{o\lambda} \tau_{g\lambda} \tau_{wa\lambda} [F_c \omega_0 (1 - \tau_{a\lambda}) \tau_{r\lambda}], \quad (12)$$

$$I_{g\lambda} = Q_\lambda [(\rho_{g\lambda} \rho'_{a\lambda}) / (1 - \rho_{g\lambda} \rho'_{a\lambda})], \quad (13)$$

$$Q_\lambda = (I_{r\lambda} + I_{a\lambda}) + I_{d\lambda}, \quad (14)$$

$$\rho'_{a\lambda} = \tau_{o\lambda} \tau_{g\lambda} \tau_{wa\lambda} [0.5(1 - \tau_{r\lambda}) \tau_{a\lambda} + (1 - F_c) \omega_0 (1 - \tau_{a\lambda}) \tau_{r\lambda}]. \quad (15)$$

Herein, E_0 stands for eccentricity, and F_c stands for a ratio of forward scattering on the total energy scattering, meanwhile $1 - F_c$ stands for backward scattering. ω_0 stands for a single scattering albedo. $\rho'_{a\lambda}$ and $\rho_{g\lambda}$, respectively, stand for multiple scattering by all the absorption gases in atmosphere and surface albedo.

The GWNU model used for this study was based on the IQBAL model, which is a solar radiation model corrected by using a multiple solar radiation model after adapting and applying the NREL's aerosol process method. The IQBAL model was produced on a basis of Iqbal's theory (Iqbal, 1983) and the NREL model is a one-layer model Bird and Riordan (1986) produced by the National Renewable Energy Laboratory (NREL) for development and to compare observed values, and the two above-stated models are a spectrum model calculating solar radiation by wavelength. Further, BIRD (Bird and Hulstrom, 1981) stands for a one-layer solar radiation model to develop wavelength ranges of solar radiation as a one band.

3. Correction of one-layer solar radiation model

The τ_λ of the equation (4) in section *2.b* stands for optical thickness, which is a function of absorption coefficients (e.g., $k_{o\lambda}$, $k_{g\lambda}$, $k_{wa\lambda}$, etc.) of pressure components, and basically, a function of altitude or pressure, but the GWNU one-layer solar radiation model does not include change in altitude or pressure of absorption coefficient because atmosphere was assumed as a single layer to save calculation time and calculation resolution. Therefore, for this study, methods correcting one-layer solar radiation models of the equations from (3) to (15), were used by comparing detailed solar radiation models including altitude or pressure effects by dividing atmosphere into multiple layer.

To operate accurate solar radiation models, vertical atmospheric distribution data require input data, and reference atmosphere data (i.e., standard atmosphere data by latitude) are mostly used. To compare calculation results of radiation models, Garand *et al.* (2001)'s 42 types of vertical atmospheric data were used for this study. The 42 types of vertical atmospheric data include not only 6 standard atmospheres (i.e., standard, tropical, middle latitude summer, middle latitude winter, sub-arctic summer, and sub-arctic winter) but also distribution by altitude observed at many stations of the earth.

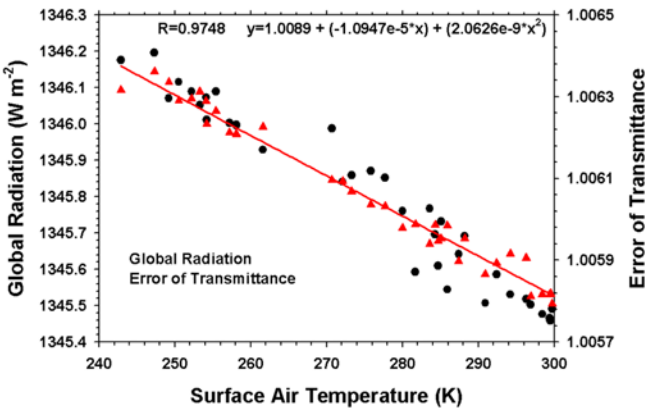

Fig. 3. Same as Fig. 2 except for surface air temperature (K).

For total precipitable water, total ozone amount and mixed gas, the results and the error of transmittance derived from the LBL model were shown by using 42 types of vertical atmospheric data. Total precipitation water (a) and total ozone amount (b) of Fig. 2 showed that solar radiation and the error of transmittance decreased depending on change in the amount of input data, indicating that the one-layer model calculates transmittance more depending on the amount of absorber compared to detailed models. In other words, for the amount of gas absorbed in the same atmosphere, the one-layer model calculates less transmittance compared to detailed models. Therefore, transmittance calculated in the one-layer model should be corrected by the amount of gas absorption so that transmittance derived from total precipitable water and total ozone amount can be decreased to the same amount of detailed models. Transmittance was corrected by using a third-degree polynomial to obtain the amount of total precipitable water as the fluctuation of its error is large compared to total ozone amount, meanwhile a second-degree polynomial was used to obtain the amount of total ozone amount.

Further, the mixed gas of Fig. 3 was calculated on the assumption that the mixture ratio in atmosphere is constant.

Table 1. The error correction equation between GWNU and LBL solar radiation model for global solar radiation with cosine of solar zenith angle.

Solar zenith angle	Equation (quadratic polynomial)
0.0	$y = 1.0083 + (-0.0062/x) + (-2.8119e^{-5}/x^2)$
0.1	$y = 1.0080 + (-0.0063/x) + (-2.6584e^{-5}/x^2)$
0.2	$y = 1.0077 + (-0.0063/x) + (-2.4944e^{-5}/x^2)$
0.3	$y = 1.0074 + (-0.0064/x) + (-2.3077e^{-5}/x^2)$
0.4	$y = 1.0071 + (-0.0065/x) + (-2.1002e^{-5}/x^2)$
0.5	$y = 1.0067 + (-0.0066/x) + (-1.8675e^{-5}/x^2)$
0.6	$y = 1.0063 + (-0.0067/x) + (-1.6053e^{-5}/x^2)$
0.7	$y = 1.0059 + (-0.0068/x) + (-1.3253e^{-5}/x^2)$
0.8	$y = 1.0054 + (-0.0069/x) + (-9.8984e^{-6}/x^2)$
0.9	$y = 1.0049 + (-0.0070/x) + (-6.1025e^{-6}/x^2)$

And as the amount of solar radiation change resulting from the amount of mixed gas is not large, the relationship of global solar radiation and temperature of the surface was examined. As a result, correlation coefficient showed a relatively high correlation as 0.97. Therefore, for correction derived from the amount of mixed gas, transmittance was corrected by surface temperature by applying a second-degree polynomial, which is the same method applied to total precipitable water and total ozone amount. When it comes to correction of global solar radiation depending on solar zenith angle, as shown in Table 1 below, surface albedo was each corrected at 0.1 interval of cosine the solar zenith angle by using the rate of global solar radiation. The interaction between atmosphere and the ground surface is sensitive to change in solar zenith angle, and the LBL model and the error increase as solar zenith angle increases. This is caused by while the LBL model considers a mixture ratio by altitude and accumulates calculated values to calculate, the one-layer solar radiation model considers multiple scattering and path length of absorption gas by considering a one-layer to calculate the amount of solar radiation. At a part with small solar zenith angle, although solar radiation corrected

Table 2. Surface solar radiation (W m^{-2}) by solar radiation models with surface albedo and mid-latitude summer atmosphere. And differences (%) between LBL and solar radiation models.

Surface albedo	Multi-layer LBL model (W m^{-2})	Difference (%)				
		Multi-layer	One-layer			
		Band model	Spectral model			Band model
		NASA	IQBAL	NREL	GWNU	BIRD
0.0	**1060.1**	−0.121	−2.274	−1.654	−1.654	−0.812
0.1	**1067.7**	−0.078	−2.308	−1.613	−0.211	0.512
0.2	**1075.5**	−0.031	−2.344	−1.547	−0.217	1.031
0.3	**1083.7**	0.019	−2.383	−1.453	−0.215	1.822
0.4	**1091.4**	0.074	−2.425	−1.329	−0.216	2.585
0.5	**1101.0**	0.133	−2.470	−1.174	−0.210	3.412
0.6	**1110.3**	0.196	−2.519	−0.986	−0.208	4.051
0.7	**1119.9**	0.265	−2.573	−0.761	−0.211	4.717
0.8	**1130.1**	0.339	−2.632	−0.498	−0.209	5.581
0.9	**1140.8**	0.419	−2.697	−0.132	−0.213	6.833

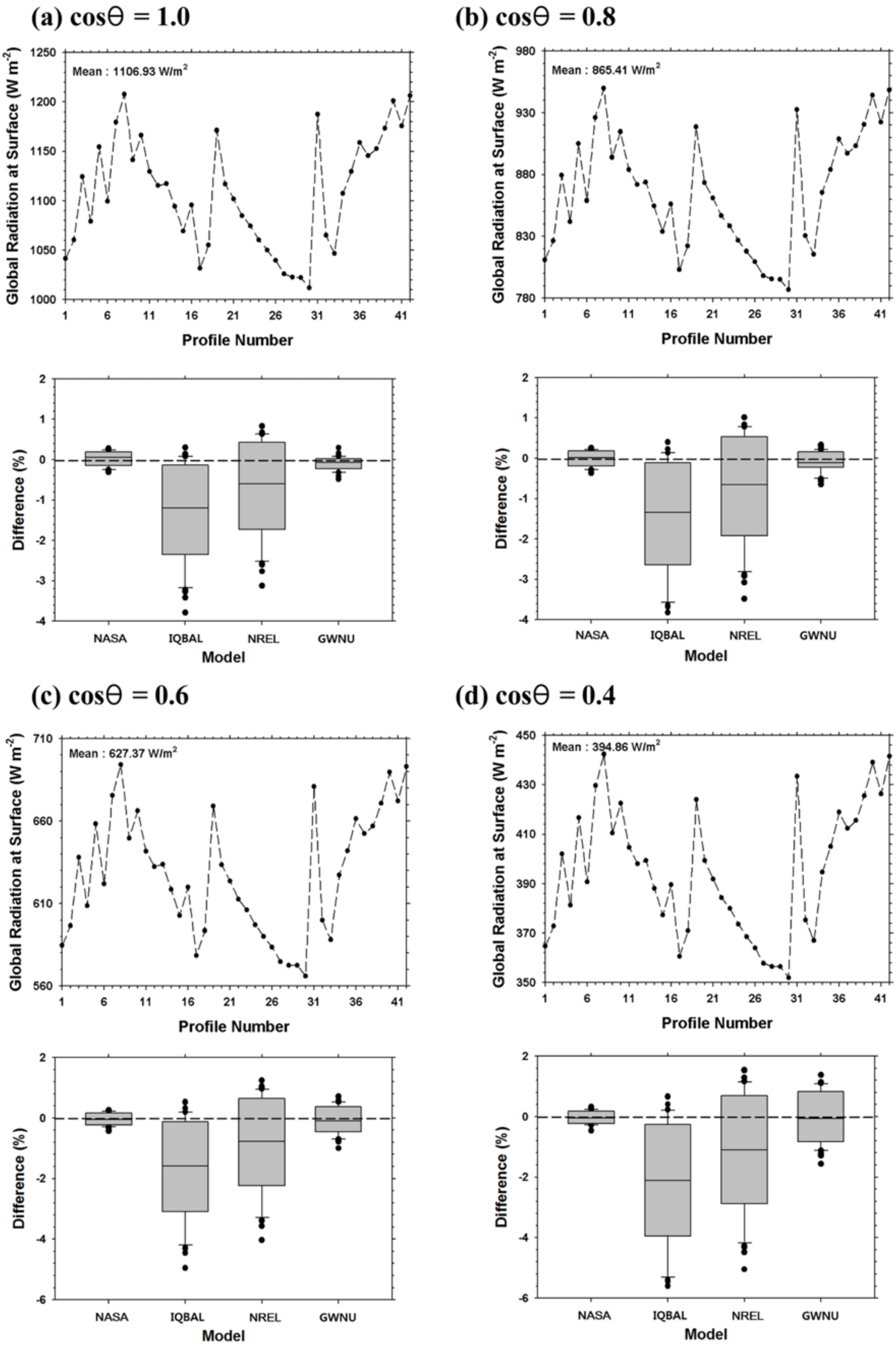

Fig. 4. Global solar radiation (W m^{-2}) by LBL model and box-plots of differences (%) between solar radiation models and LBL model with atmospheres from Garand *et al*. (2001).

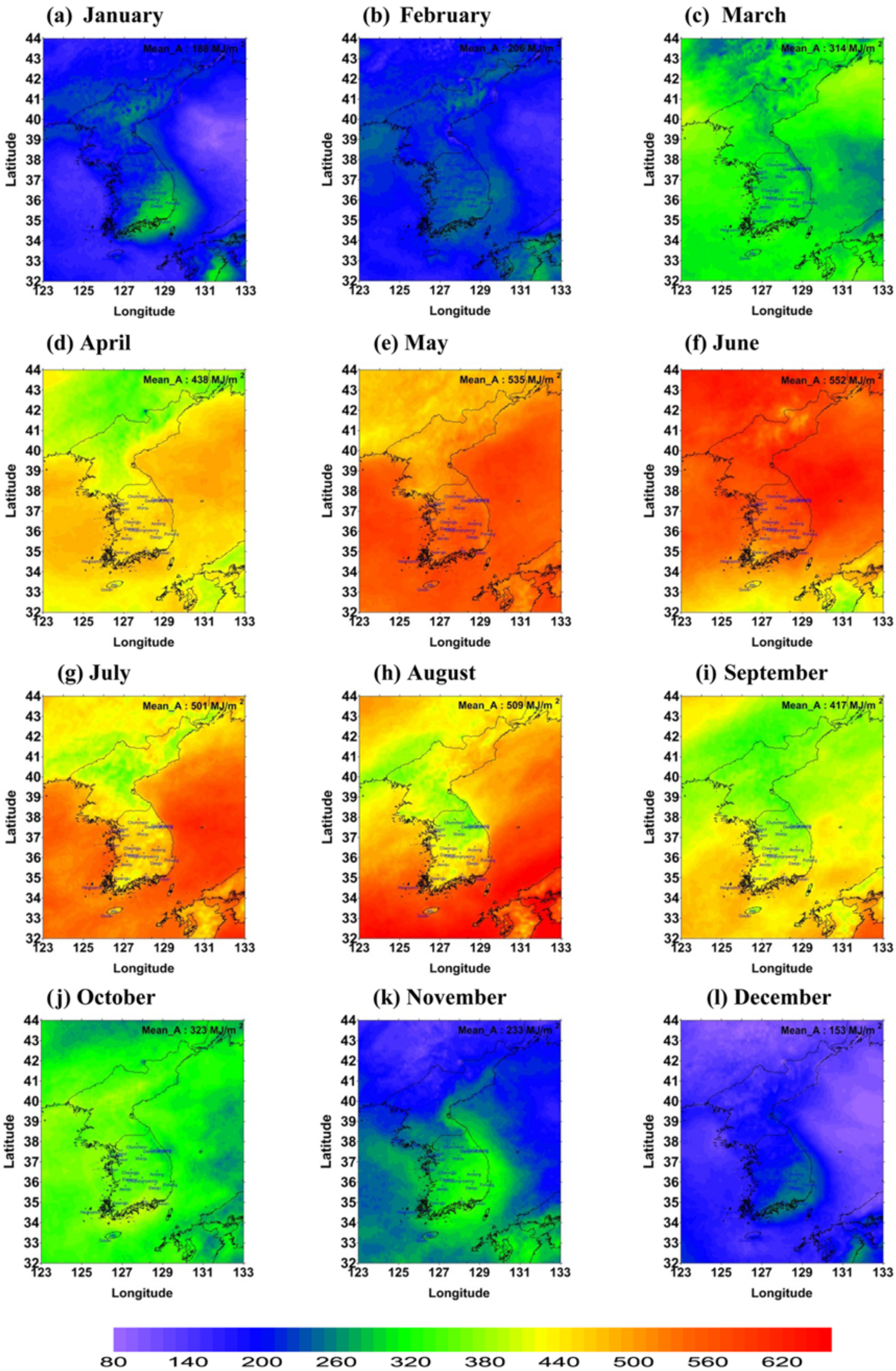

Fig. 5. Monthly accumulated surface solar radiations (unit: MJ m^{-2}) calculated by GWNU model with 1 km × 1 km resolution (Jan. to Dec., 2010).

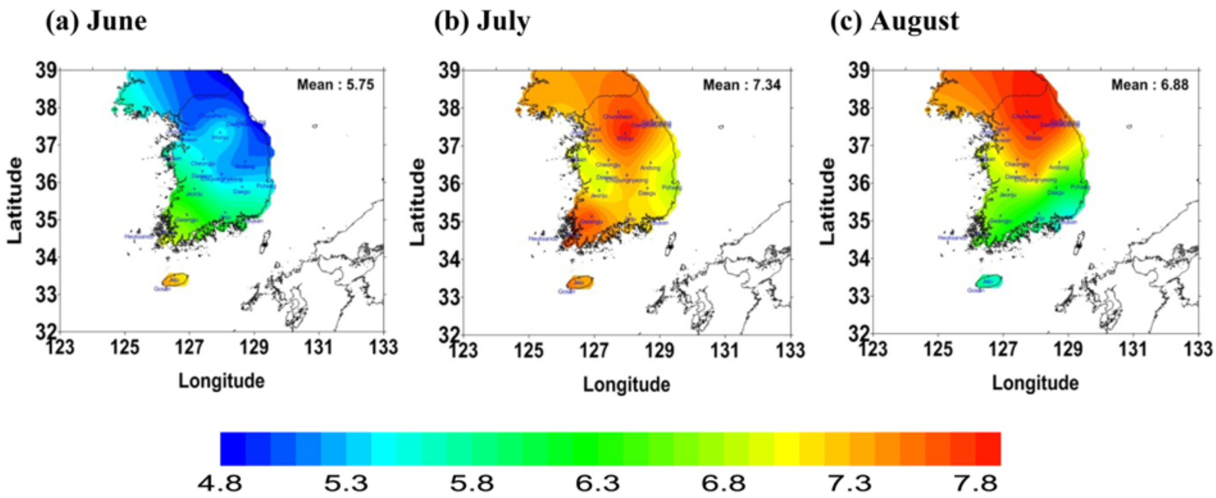

Fig. 6. Monthly accumulated cloud amounts (unit: okta) observation by 22 KMA solar sites (Jun. to Aug. 2010).

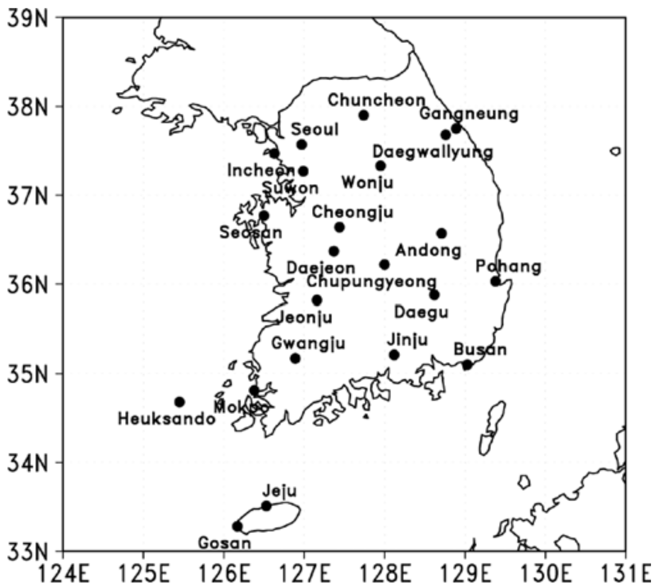

Fig. 7. KMA 22 solar radiation sites on Korea peninsula.

is small, a second-degree polynomial regression equation was applied as errors radically occur when the solar zenith angle is big. As shown in Figs. 2 and 3, and Table 1, the GWNU model was established for this study as a conclusive solar radiation model, by including corrected regression equation to solar radiation models of the equations (3)-(9) depending on absorption gas and surface albedo.

Out of calculation results derived from the multi-layer LBL radiation model, the multi-layer band model (Chou and Suarez, 1999; hereafter NASA), and 4 types of one-layer solar radiation model (e.g., IQBAL, NREL, and BIRD) including the GWNU model, results of mid-latitude summer atmosphere were shown in Table 2. Surface temperature of mid-latitude summer atmosphere is 294.2 K, total precipitable water is 2.91 cm, total ozone amount is 330.5 DU, and solar zenith angle is 0^o, and the flux of extraterrestrial solar radiation used 1366.05 W m^{-2}. Results showed that the amount of solar radiation on the surface increased by surface albedo, and the GWNU was the most similar model out of one-layer models, and the Bird model, one-layer band model, showed the biggest difference.

When surface albedo is 0.0, the value of solar radiation calculated on the surface and the difference between NASA, IQBAL, NREL, and GWNU were shown in Fig. 4 as box-plot after changing the cosine value of solar zenith angle into 1.0, 0.8, 0.6, and 0.4. It is analyzed that the values calculated in the LBL model were calculated dependently on amounts of ozone and total precipitable water that are input data, and the smallest difference showed in NASA, followed by GWNU, NREL and IQBAL. Comparing with calculation results derived from the LBL model showed that while the error increased in the GWNU as albedo increased, and the error was below 0.50% on average. The error of IQBAL and NREL model, similar kinds, was 2% or more. Further, the error of one-layer solar radiation model increased as solar zenith angle increased (cosine values decreased). This occurs when the increasing ratio on length of optical path is bigger in the one-layer model, and the amount of absorber in layer equally increases.

4. Results

The GWNU model, a corrected one-layer solar radiation model, calculated surface solar radiation by inputting real atmospheric conditions obtained from model forecasting and satellite observations data of the Korean peninsula. To calculate the amount of solar radiation reaching the surface of the earth, required are amounts of gas absorbing solar radiation such as water vapor (or total precipitable water), ozone, etc., aerosol, and cloud cover data, and also surface pressure and altitude at calculation spots and surface albedo data. Out of these data, for data on pressure and the amount of water vapor, etc., the Korea Local Analysis and Prediction System (KLAPS), a regional forecast model of the Korea Meteorological Administration (KMA; hereafter KMA), was used, for the amount of ozone,

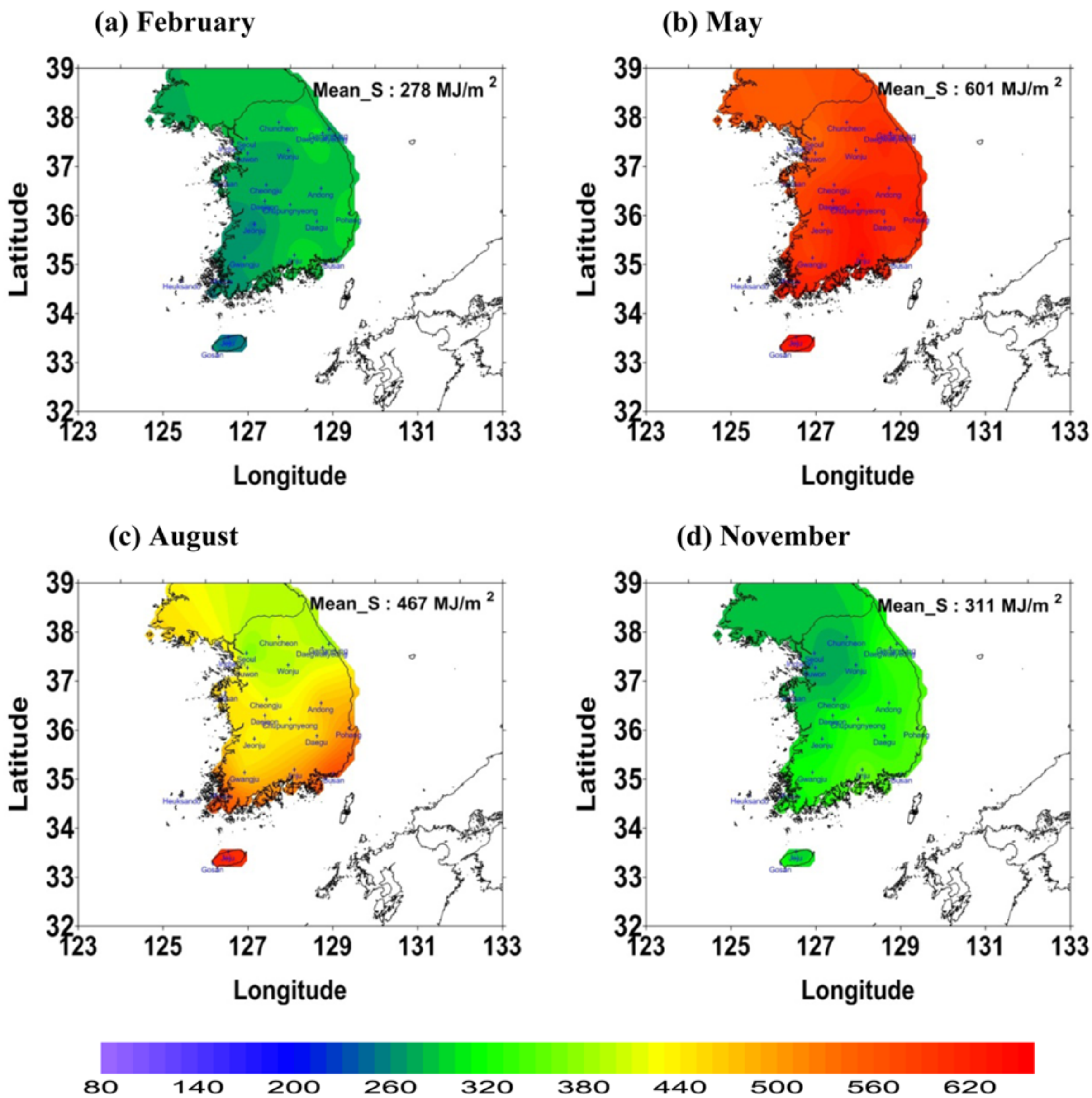

Fig. 8. Monthly accumulated surface solar radiations (unit: MJ m^{-2}) observation by 22 KMA solar radiation sites in 2010.

the Ozone Monitoring Instrument (OMI) sensor data (daily average; when missing use to month average data) at $1^o \times 1^o$ resolution was used, and for aerosol, showing very strong characteristics in size, shape, and region, MODIS satellite data (daily average; when missing use to month average data) at $1^o \times 1^o$ resolution were used. Further, for surface albedo data, used were MODIS's high resolution ($0.05^o \times 0.05^o$ resolution) data, and for the digital elevation model, used were 3-second data (about 90 m resolution) of NASA's Shuttle Radar Topography Mission (SRTM) from United State Geological Survey (USGS). For cloud data, one of the most important factors attenuating solar radiation energy reaching the surface, MTSAT-2 satellite data were processed by a method used in Kawamura *et al*. (1998) and Communication, Ocean and Meteorological Satellite Data Processing System (Korea Meteorological Administration, 2009). Cloud data (hereafter cloud factor) using visible and infrared spin scan radiometer data supplied by the MTSAT-2 satellite and solar zenith angle. Cloud factor is the observation and calculation (in clear sky) on cloudy pixel. And look up table of cloud factor is calculated by Gauss-Jordan elimination (Gilbert, 2003) and multiple regression (Cohen *et al*., 2003) methods with 1^o of solar zenith angle and visible albedo, respectively. The above-stated data were used in a way of interpolation scheme in accordance with 1 km × 1 km resolution regarding the Korean peninsula, research area.

Analysis was conducted from January 2010 to December 2010, and spatial distribution of monthly accumulated solar radiation calculated by the GWNU model, which was cor-

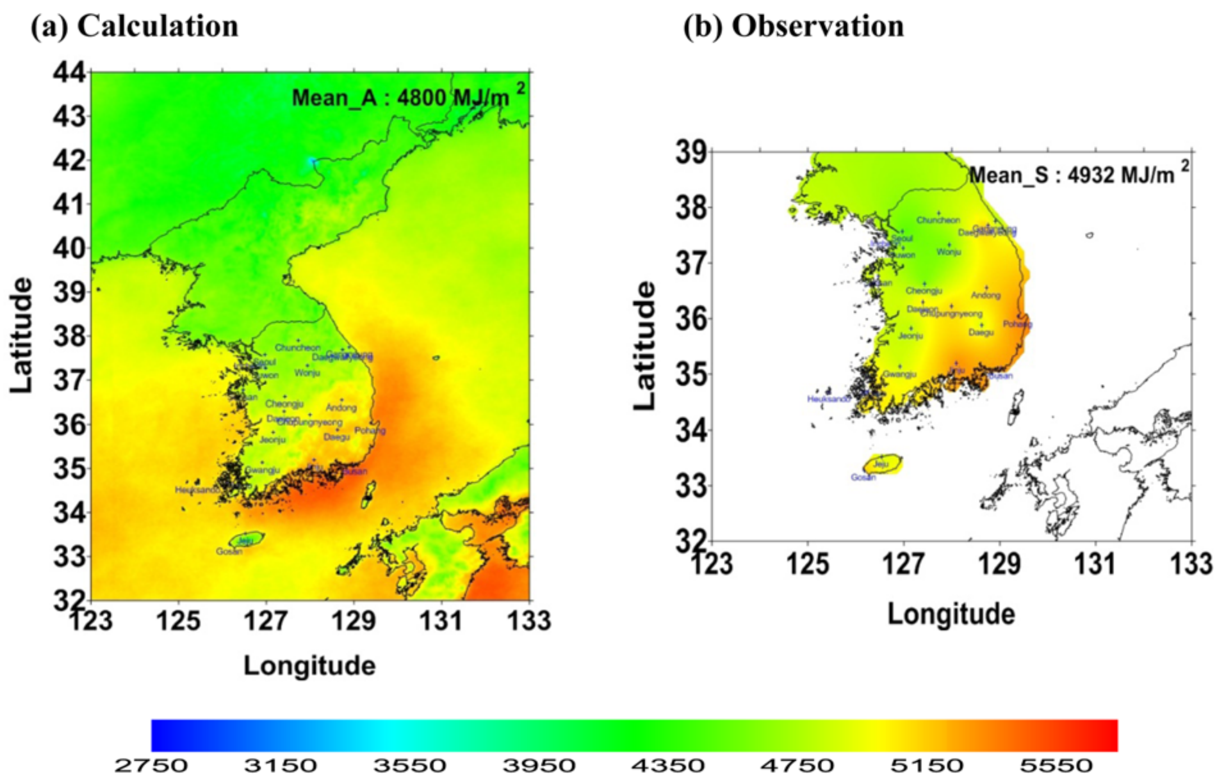

Fig. 9. Annual accumulated global solar radiations (unit: MJ m^{-2}) of calculation by GWNU model (a) and observation by 22 KMA solar radiation sites (b) in 2010.

rected, was shown in Fig. 5. For monthly solar radiation distribution of the Korean peninsula, seasonal and regional distribution characteristics were distinctively shown by the effect of cloud, solar zenith angle, aerosol, and the amount of water vapor. In particular, as the solar zenith angle is small during summer season, the solar radiation of surface is expected to be strong. However, due to frequent clouds, monthly maximum accumulated solar radiation was shown in June, early summer. That is, the reason that surface solar radiation is strong compared to mid-summer (July to August) is that although the sun's altitude was lower in June compared to mid-summer season, the amount of clouds, the most important factor in the attenuation effect, was less in June compared to July and August, mid-summer season (5.75 okta in June, 7.34 okta in July, 6.88 okta in August, See Fig. 6). Further, the lowest month of the year was December in the amount of average monthly solar radiation, about 27% compared to June, the highest month, analyzed that it is due to the solar zenith angle is large and much cloud amount in Dec.. Fig. 7 indicates that 22 solar radiation sites operated by the KMA, and out of monthly accumulated data observed in the sites, main months of season was shown in Fig. 8. Although the distribution of solar radiation was similar with model calculation values in Fig. 5, it partially shows a difference, which is resulting from that as model calculation results are calculated at one-hour intervals while observation data are hourly accumulated. However, this will be resolved, provided that collection intervals are shortened on input data of solar radiation models including cloud.

Further, Fig. 9 stands for calculation of the GWNU model on the amount of solar radiation annually accumulated and solar radiation observation data provided by the KMA's 22 sites. The amount of average solar radiation on the Korean peninsula's calculated solar radiation was 4,800 MJ m^{-2}, and the average value of 22 observatories' data was 4,932 MJ m^{-2}. Results of model calculation showed that solar radiation annually accumulated was relatively less in the Korean peninsula's western coast area as the area has more amount of cloud compared to other regions, while the intensity of solar energy was strong as Andong, Daegu, and Jinju show little amount of cloud related to downwind location of Sobaek mountainous areas. During the same period, although the KMA's solar radiation shows a similar tendency, Daegu showed relatively lower solar radiation compared to the model. This difference can be analyzed and described through environment investigation of solar radiation observatories and comparative observation of pyranometer.

5. Summary

The one-layer solar radiation model was developed to resolve deficiency of vertical atmospheric data and improve high-resolution computing speed. The GWNU solar radiation model was developed on a basis of the IQBAL and NREL theories, a one-layer solar radiation model, and the LBL was selected as a reference model to improve accuracy. Further, the amount of solar radiation reaching the surface of the earth by using 42 types of vertical atmospheric data as input data was compared with detailed models and one-layer models. One-layer solar radiation models were corrected depending on sensitivity of each input data (i.e., total precipitable water, ozone, mixed gas, and solar zenith angle). Analysis results derived from the GWNU solar radiation model showed that a difference showed 0.5% or less compared to the LBL model, which is a similar value with the NASA model, a multi-layer model, and the error increased by solar zenith angle, which was lower compared to other one-layer solar radiation models.

By using satellite and numerical model data as input data, calculated was solar radiation reaching the surface in the Korean peninsula for one year in 2010, which were compared with surface observation data. The results showed a similar distribution with observation data, partially showing a difference, which was caused by a time difference between model and observation data. This is analyzed as an error occurring, resulting from that the observation data are accumulated by time meanwhile the model is calculated at hourly intervals. As a factor affecting the most is cloud, June least affected by cloud during summer showed high solar radiation compared to July and August of mid-summer, due to change in cloud. Calculated solar radiation annually accumulated showed highest solar radiation distribution in Andong, Daegu, and Jinju regions, meanwhile the observation data showed lower solar radiation in Daegu region compared to model result values. This difference can be analyzed and described through comparative observation conducted by solar radiation observation stations on environment investigation and pyranometer.

In conclusion, the one-layer solar radiation model developed herein in this study can partially resolve problems occurring in input data of solar radiation models, and can be applied to high-resolution calculation requiring much computation. Further, it is considered that the one-layer solar radiation model can be basic research for further renewable energy and photovoltaic generation studies.

Acknowledgments. This work is funded by the Korea Meteorological Administration Research and Development Program under the Weather Information Service Engine (WISE) project (Grant No. 153-3100-3133-302-350).

Edited by: Tadahiro Hayasaka

REFERENCES

Bird, R. E., and R. L. Hulstrom, 1981: Simplified clear sky model for direct and diffuse insolation on horizontal surfaces, Technical Report No. SERI/TR-642-761, Golden, CO: Solar Energy Research Institute, 46 pp.

______, and C. Riordan, 1986: Simple solar spectral model for direct and diffuse irradiance on horizontal and tilted planes at the earth's surface for cloudless atmospheres. *J. Climate Appl. Meteor.*, **25**, 87-97.

Chandrasekhar, S., 1960: *Radiative Transfer*. Dover Publications Inc., New York, 393 pp.

Chou, M. D., and M. J. Suarez, 1999: A solar radiation parameterization for atmospheric studies. NASA/TM-19990104606, **15**.

Cohen, J., P. Cohen, S. G. West, and L. S. Aiken, 2003: *Applied multiple regression/correlation analysis for the behavioral sciences (3rd ed.).* Lawrence Erlbaum Associates, Inc. Mahwah, New Jersey, 702 pp.

Dave, J. V., 1974: A direct solution of the spherical harmonics approximation to the radiative transfer equation for an arbitrary solar elevation. Part I: Theory. *J. Atmos. Sci*., **32**, 790-798.

Garand, L., and Coauthors, 2001: Radiance and jacobian intercomparison of radiative transfer model applied to HIRS and AMSU channels. *J. Geophys. Res.,* **24**, 17-31.

George, R., and E. Maxwell, 1999: High-resolution maps of solar collector performance using a climatological solar radiation model. *Proceedings of the 1999 Annual Conference*, American Solar Energy Society, Portland, Maine, 243-248.

Gilbert, S., 2003: *Introduction to Linear Algebra* (3rd ed.). Wellesley-Cambridge Press, Wellesley, Massachusetts, 571 pp.

Iqbal, M, 1983: *An introduction to solar radiation*. Academic Press, New York, 390 pp.

Kamamura, H., S. Tanahashi, and T. Takahashi, 1998, Estimation of insolation over the Pacific Ocean off the Sanriku coast. *J. Oceanogr.*, **54**, 457-464.

Kerschgens, M., U. Pilz, and E. Raschke, 1978: A modified two-stream approximation for computations of the solar radiation budget in a cloudy atmosphere. *Tellus*, **30**, 429-435.

Korea Meteorological Administration, 2009: Development of Meteorological Data Processing System of Communication, Ocean and Meteorological Satellite (V). Final Report, 513-538.

Lee, J.-S, W.-J. Choi, D.-R. Kim, S.-Y. Kim, C.-K. Song, J.-S. Hong, Y.-D. Hong, and S.-J. Lee, 2013: The effect of ozone and aerosols on the surface erythemal UV radiation estimated from OMI measurements. *Asia-Pac. J. Atmos. Sci*., **49**, 271-278.

Perez, R., and M. Perez, 2008: Making the case for solar energy. Daylight & architecture magazine by velux. Autum 2008, **9**, 8-17.

______, P. Ineichen, K. Moore, M. Kmiecik, C. Chain, R. George, and F. Vignola 2002: A new operational model for satellite-derived irradiances: Description and validation. *Solar Energy*, **73**, 307-317.

Rothman, L. S., and Coauthors, 2003: The HITRAN molecular spectroscopic database: edition of 2000 including updates through 2001. *J. Quant Spectrosc RA*, **82**, 5-44.

Siegel R., and J. R. Hewell, 1981: *Thermal radiation heat transfer*. Hemisphere Pub. Corp., Washington, 524 pp.

Stamnes, K., S. C. Tsay, W. Wiscombe, and K. Jayaweera, 1998: Numerically stable algorithm for discrete-ordinate-method radiative transfer in multiple scattering and emitting layered media. *Appl. Opt.*, **27**, 2502-2509.

Takenaka, H., T. Y. Nakajima, A. Higurashi, A. Higuchi, T. Takamura, R. T. Pinker, and T. Nakajima, 2011: Estimation of solar radiation using a neural network based on radiative transfer. *J. Geophys. Res.,* **116**, doi: 10.1029/2009JD013337.

Yeom, J.-M., K.-S. Han, and J.-J. Kim, 2012: Evaluation on penetration rate of cloud for incoming solar radiation using geostationary satellite data. *Asia-Pac. J. Atmos. Sci.*, **48**, 115-123.