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Baseline Surface Radiation Network (BSRN) Quality Control of Solar Radiation Data on the Gangneung-Wonju National University Radiation Station

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Abstract: Gangneung-Wonju National University (GWNU) radiation station has been collecting data on global, direct, and diffuse solar radiation since 2011. We conducted a quality control (QC) assessment of GWNU data collected between 2012 and 2014, using procedures outlined by the Baseline Surface Radiation Network (BSRN). The QC process involved the comparison of observations, the correction of observational equipment, the examination of physically possible limits, and the comparative testing of observations and model calculations. Furthermore, we performed a shading check of the observational environment around the GWNU solar station. For each solar radiation element (observed every minute), we performed a QC check and investigated any flagged problems. 98.31% of the data were classified as good quality, while the remaining 1.69% were flagged as bad quality based on the shading check and comparison tests. We then compared the good-quality data to the global solar radiation data observed at the Gangwon Regional Office of Meteorology (GROM). After performing this comparison, the determination coefficient (R^2; 0.98) and standard deviation (SD; 0.92 MJ m^{-2}) increased compared to those computed before the QC check (0.97 and 1.09 MJ m^{-2}). Even considering the geographical differences and weather effects between the two stations, these results are statistically significant. However, we also confirmed that the quality of the GROM data deteriorated in relation to weather conditions because of poor maintenance. Hence, we conclude that good-quality observational data rely on the maintenance of both observational equipment and the surrounding environment under optimal conditions.

Key words: Solar radiation, observation, Quality Control (QC), Baseline Surface Radiation Network (BSRN), Gangneung-Wonju National University (GWNU)

1. Introduction

Currently, many studies on climate change are focusing on global energy balance (Ramanathan et al., 2001; Mercado et al., 2009). For example, Wild et al. (1995) analyzed global mean Absorption Solar Radiation (ASR) at the surface using the Global Circulation Model (GCM) and the Baseline Surface Radiation Network (BSRN), where the GCM estimated ASR of about 9-18 W m^{-2}. Furthermore, Philipona (2002) found that analyses by absolute cavity radiometers and the MODTRAN (MODerate resolution atmospheric TRANsmission) program had underestimated solar radiation. Solar radiation data are very important in the analysis of the Earth's energy budget (Pinker et al., 1996; Tarpley et al., 1996) and so the World Radiation Center (WRC; Fröhlich, 1997) is making efforts to normalize various data series (Augustine et al., 2005).

In October 1988, the World Meteorological Organization/International Council of Scientific Unions (WMO/ICSU) formed the BSRN to observe long-term changes in Earth's radiation (Hegner et al., 1998; Ohmura et al., 1998; World Meteorological Organization, 2008). The BSRN's archives include long-term radiation and meteorological data, which scientists use for studies of climate and radiation budgets as well as satellite repositioning (Heimo et al., 1993; Charlock et al., 2000, 2003; Augustine and Dutton, 2013; Gueymard and Ruiz-Arias, 2016). Observational stations measure the shortwave and longwave radiation elements (downward, upward, and net flux), climatological elements (e.g., temperature, pressure, cloud, and aerosol), and conduct real-time quality evaluations (Gilgen et al., 1995). Currently, 70 operational stations offer regular seminars on radiation measuring tools and the collected data. In Asia, stations have been established in Japan (Fukuoka, Ishigakijima, Minamitorishima, Sapporo, Tateno, and Syowa in Antarctica) and in China (Xianghe) (König-Langlo et al., 2013). The Korea Meteorological Administration (KMA) has been observing global solar radiation since 1980, operating twenty-three stations and six regional meteorological offices (Seoul, Busan, Gangneung, Gwangju, Daejeon, and Jeju). These stations, along with the Chupungnyeong observatory, have collected direct solar radiation data since 2010. However, the KMA does not observe diffuse solar radiation (Jee et al., 2013; Zo et al., 2014).

Unlike other meteorological instruments, a radiometer produces electric current when it reacts with radiation, which is converted into a measurement of solar radiation. Solar radiation instruments should be handled and maintained with special care because they are susceptible to changes in sensitivity, thermal offset, other spectral effects, geometry, and

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environment (Christian and Daryl, 2007). In most cases, the WMO and ISO9060 guidelines for a particular piece of equipment define the factors influencing solar radiation measurements. However, the equipment requires hourly checkups when environmental factors that can influence solar radiation measurements are present, including shade (trees, buildings etc.), cleaning, and maintenance (Morrison, 1998). Therefore, quality control (QC) methods defined by the BSRN are required for a precise analysis of the effects of such environmental factors.

2. Data and methods

a. Station information and data

The Gangneung-Wonju National University (GWNU) radiation station is located at 37.8°N, 128.9°E, at an elevation of 63.5 m. Figure 1 shows four different views of the pyrheliometer (Kipp & Zonen, CHP1) and pyranometer (Kipp & Zonen, CMP21) of the solar tracking device (Kipp & Zonen, 2AP) installed at GWNU. This station also measures diffuse radiation using a pyranometer with a shading ball. The Automatic Weather System (AWS) records meteorological elements such as temperature, pressure, humidity, and wind speed and direction; other ground-based instruments detect sunshine, aerosol concentration (Sky-radiometer, POM-02), and cloud amount (Sky-view, PSV-100H). A data logger records all measured data every minute on average (Campbell Sci., CR1000). Radiation data are plotted on charts daily; Figure 2 shows an example plot of a clear day (11 October 2012). Figure 2a shows the elements of radiation and Fig. 2b shows sky images at 0900 LST, 1200 LST, and 1500 LST. Figure 2a shows the data distortion that occurred for 20 minutes at 1630 LST due to shade from a forested hill toward the west, shown in the sky-view image (Fig. 2b) at 180° field of view. In such cases, the contaminated data are flagged as poor quality and excluded.

We conducted a QC check using solar radiation data collected at GWNU to establish the quality management of the solar radiation data. In 2011, GWNU installed a variety of instruments (e.g., a pyrheliometer and a pyranometer) to observe global, direct, and diffuse solar radiation. Periodic sensitivity tests are conducted on the pyranometer and pyrheliometer using KMA standard equipment and calibration inspections. In this study, we applied the QC methods of the BSRN (Long and Dutton, 2002) to solar radiation data obtained at GWNU between 2012 and 2014. We analyzed the QC-checked solar radiation data and compared them with global solar radiation data obtained at the Gangwon Regional Office of Meteorology (GROM), which is the nearest station to GWNU.

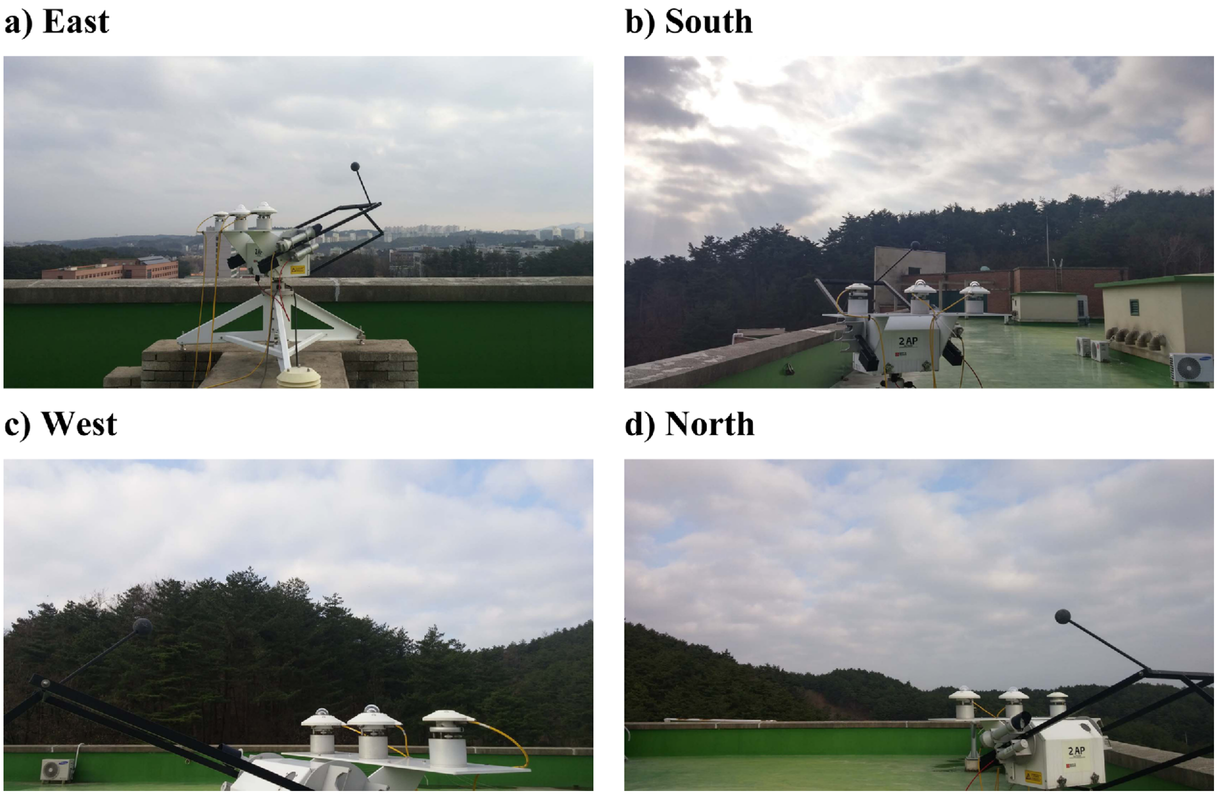

Fig. 1. Views of GWNU radiation station: (a) east, (b) south, (c) west, and (d) north. Solar radiation is blocked when it is observed during the sunset (Fig. 1c) due to the shading effect on the mountains.

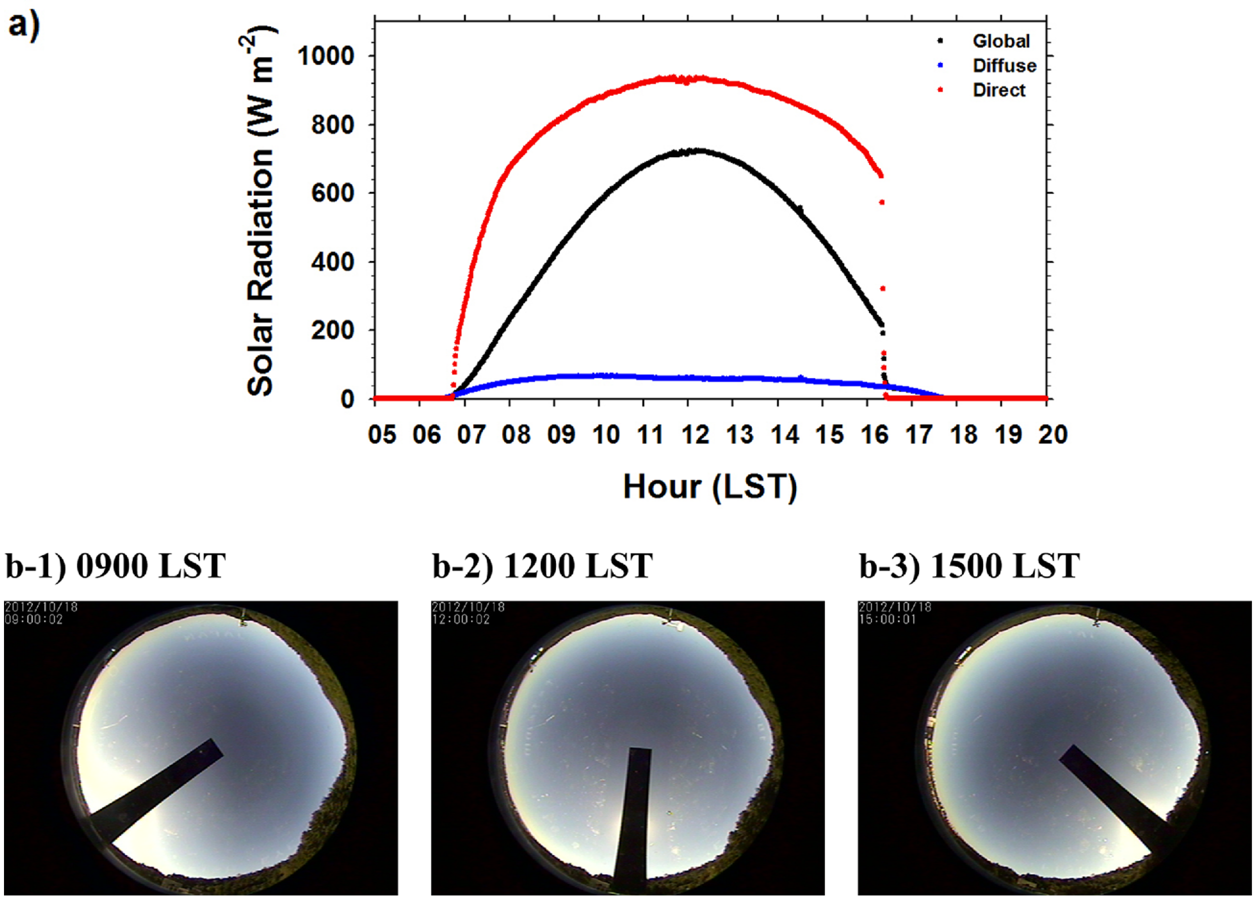

Fig. 2. Measurement data: (a) solar radiation and (b) sky images of the GWNU radiation station on 18 October 2012. In Fig. 2a), solar radiation is blocked and significantly reduced from 16:30 onward due to the effect of mountains, as shown in Fig. 1c).

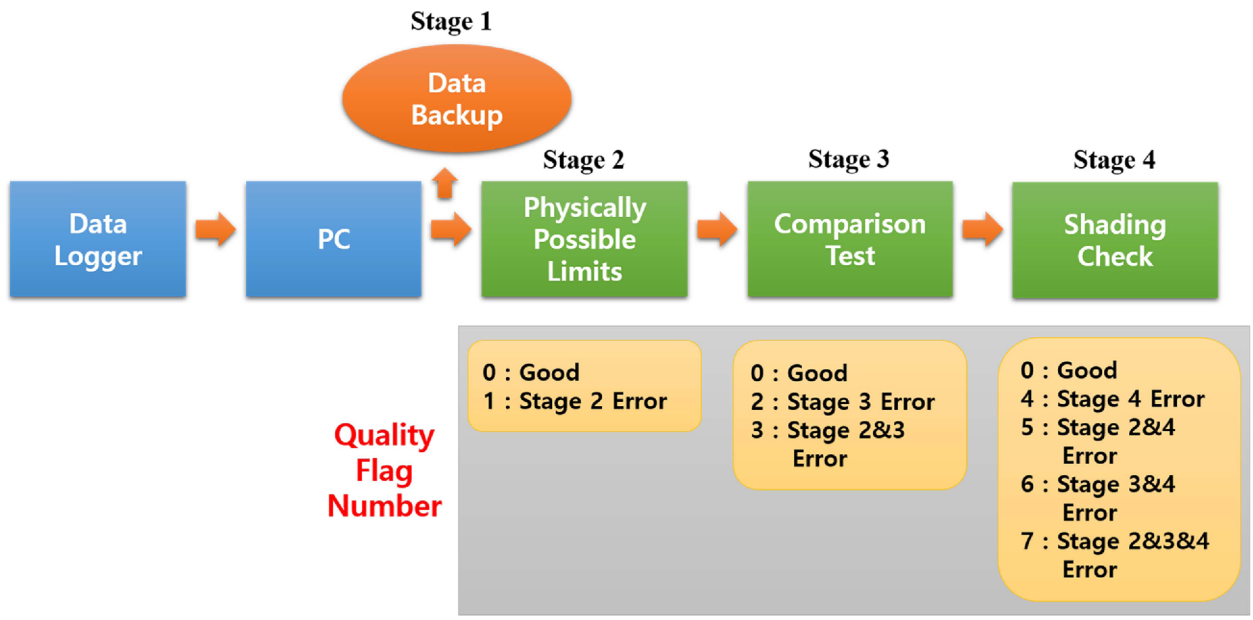

Fig. 3. Diagram of quality control (QC) procedure at GWNU radiation station. QC flag checks are performed at each procedure in the green boxes. The gray box indicates the quality flag numbers from Table 1.

Table 1. Descriptions of the QC flags for solar radiation data. The flag numbers indicate the stage of the QC test where bad data were determined.

Flag number	Description
0	Good quality
1	Physically Possible Limit check
2	Comparison Test check
3	Physically Possible Limit & Comparison Test check
4	Shading check
5	Physically Possible Limit & Shading check
6	Comparison Test & Shading check
7	Physically Possible Limit & Comparison Test & Shading check

b. QC check of solar radiation data

Figure 3 shows a schematic plot of the QC procedure and QC flags for solar radiation data at the GWNU radiation station; Table 1 shows the numbered QC flags used to define various problems in the data. In stage 1, the information collected by the data logger is stored in a computer and backed-up to avoid possible data loss. In stage 2, data beyond the physically possible limits (Gilgen et al., 1995) receive the label Flag 1. In stage 3, data that fail a comparison test receive the label Flag 2. For stages 2 and 3, we labeled the research data in accordance with the BSRN regulations manual (Long and Shi, 2006). In stage 4, we performed a shading check (to find data perturbed by geographic features), labeling any data contaminated by shading as Flag 4. We labeled any remaining data that passed all QC checks as Flag 0. Thus, we confirmed the presence or absence of data based on the summation of flags assigned at each stage. We only considered data labeled as Flag 0 suitable for further utilization. We explain these QC stages further in Section 3. Finally, we analyzed and compared the QC-checked data with the GROM data.

In the context of this study, it is important to note that the GWNU stations and the GROM observatory use the same type of pyranometer (CMP 21). GROM collects solar radiation data as accumulated hourly data. Therefore, in this study, we used the GWNU global solar radiation data collected during the same period. For the analysis of these two data sets, we applied accumulated time to the GWNU data that had successfully completed the QC checks. After performing the time match, we then assessed the correlation between the two data sets and their standard errors.

3. QC procedures

a. Radiometer comparison and calibration

A radiometer is a tool that measures solar energy directly. Because the radiometer sensitivity reduces with time, instrumental calibration is periodically required. The KMA holds the reference radiometer in South Korea, assessing and re-calibrating it with reference to the Regional Radiation Center radiometer every five years (World Meteorological Organization, 2012). For the Korean Peninsula, this procedure occurs in January because it is generally less cloudy around that time (Takeuchi, 2010). Figure 4 shows the percent error over time between the KMA reference radiometer and the equipment at the GWNU radiation station in January 2013. The pyrheliometer (Fig. 4a) and the pyranometer (Fig. 4b) show an error of ± 1 W m^{-2} and ± 2 W m^{-2}, respectively.

b. Physically possible limits of measured solar radiation

A solar radiometer uses a thermopile, which absorbs solar energy, for carrying out observations. As shown in Eq. (1), solar radiation (I) is determined from the measured voltage (V, Units: mV) multiplied by the sensitivity constant (c, Units: W m^{-2} mV^{-1}):

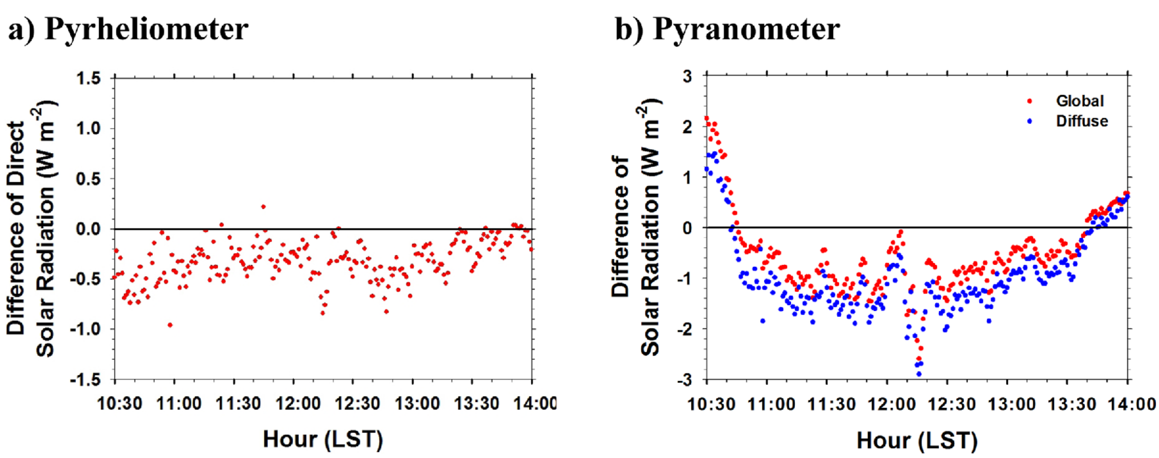

Fig. 4. Difference in direct and diffuse solar radiation between Korea's Reference and the GWNU instrumentation during the comparison observation in January 2013. The direct and global solar radiation observed from pyrheliometer and pyranometer, respectively, and diffuse solar radiation observed from pyranometer blocked direct sun light with shading ball.

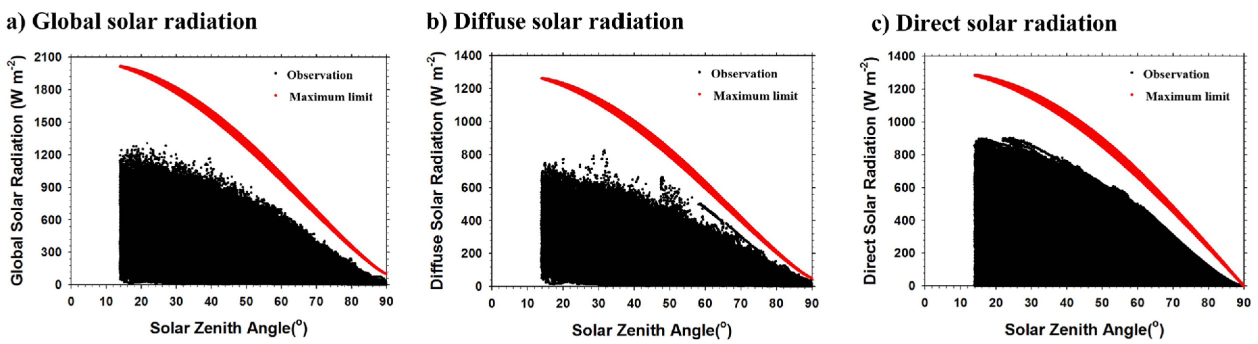

Fig. 5. Observed solar radiation (black) and Baseline Surface Radiation Network physically possible maximum limits (red) at GWNU radiation station: (a) global solar radiation, (b) diffuse solar radiation, and (c) direct solar radiation.

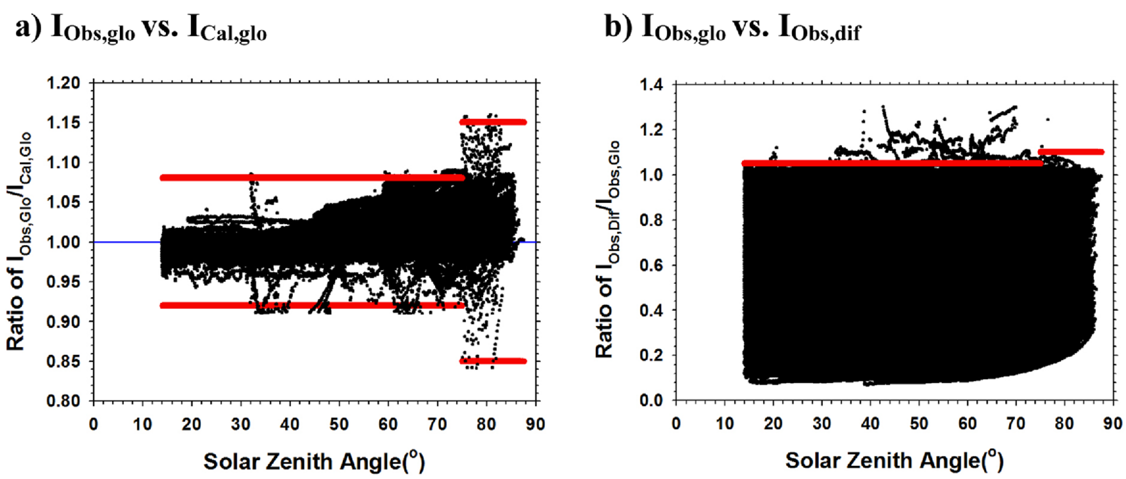

Fig. 6. Comparison test: (a) $I_{Obs,glo}$ vs. $I_{Cal,glo}$ and (b) $I_{Obs,glo}$ vs. $I_{Obs,dif}$ with solar zenith angle at the GWNU radiation station.

$$I = V \cdot c \quad (1)$$

During the night, the sensor cools below the temperature of the equipment, which generates a negative (-) voltage; hence, negative solar radiation is measured (Carnicero, 2001). As a negative value is not theoretically reasonable, the equipment considers it an error, and so the minimum possible limit is set at -4 W m^{-2} (Roesch et al., 2011). In our study, the results from the GWNU pyranometer and pyrheliometer radiation station were all within the specified possible limits. Radiometers currently in use are designed based on standards issued by the World Meteorological Organization (2008) and International Organization of Standardization (1990), so finding results beyond the QC limits is very rare. The maximum possible limit depends on the solar constant (S_0) and the solar zenith angle (θ) (Major, 1994). Eqs. (2) through (4) show the calculations of the maximum possible limit for downward ($I_{Obs,glo}$), diffuse ($I_{Obs,dif}$), and direct ($I_{Obs,dir}$) global solar radiation (Lanconelli et al., 2011).

$$I_{Obs,glo} < S_0 \cdot 1.5 \cdot \cos\theta^{1.2} + 100 \ [\mathrm{W\ m^{-2}}] \quad (2)$$

$$I_{Obs,dif} < S_0 \cdot 0.95 \cdot \cos\theta^{1.2} + 50 \ [\mathrm{W\ m^{-2}}] \quad (3)$$

$$I_{Obs,dir} < S_0 \ [\mathrm{W\ m^{-2}}] \quad (4)$$

Figure 5 shows that all GWNU data (global, diffuse, and direct solar radiation) were within the maximum limits.

c. Comparison test

The global solar radiation ($I_{Cal,glo}$) reaching the Earth's surface can be calculated as shown in Eq. (5), using the direct ($I_{Obs,dir}$) and diffuse ($I_{Obs,dif}$) solar radiation and the solar zenith angle (θ). The global solar radiation ($I_{Cal,glo}$) is calculated using $I_{Obs,dir}$ and $I_{Obs,dif}$, which are obtained from the observatory equipment, as shown below:

$$I_{Cal,glo} = I_{Obs,dir} \cdot \cos\theta + I_{Obs,dif} \quad (5)$$

The three components of the observed data (global, diffuse, and direct solar radiations) can also be compared in the same way as the comparison between $I_{Obs,glo}$ and $I_{Cal,glo}$, if the observed radiation is > 50 W m^{-2}. For values of $\theta \le 75°$, the ratio

Table 2. Ratio of QC flags for the GWNU solar radiation data for the period 2012-2014. During the entire QC processes, the greatest amount of bad data were found at the stage of shading check (4), followed by the ones obtained during the comparison test, the shading test, and the comparison test.

Flag number	Ratio (%)	Flag number	Ratio (%)
0	98.31	4	1.36
1	0.00	5	0.00
2	0.12	6	0.21
3	0.00	7	0.00

between $I_{Cal,glo}$ - $I_{Obs,glo}$ and $I_{Cal,glo}$ must be less than ± 8%, as shown in Eq. (6), whereas for $75^o < \theta < 93^o$, the ratio must be less than ± 15% (Eq. (7); McArthur, 2004):

$$(I_{Obs,glo} - I_{Obs,glo}) / I_{Cal,glo} \times 100\% < \pm 8\% \ (\theta \leq 75^o) \tag{6}$$

$$(I_{Obs,glo} - I_{Obs,glo}) / I_{Cal,glo} \times 100\% < \pm 15\% \ (75^o < \theta < 93^o) \tag{7}$$

The amounts of global ($I_{Obs,glo}$) and diffuse solar radiation ($I_{Obs,dif}$) can be measured using a pyranometer. Diffuse solar radiation passes through a filter to eliminate the direct component; hence, it must be equal to or less than the global solar radiation. Consequently, the ratio of the two must be < 5% when $\theta \leq 75^o$ (Eq. (8)), whereas it must be < 10% when $75^o < \theta < 93^o$ (Eq. (9); McArthur, 2004):

$$(I_{Obs,glo} - I_{Obs,dif}) / I_{Obs,glo} \times 100\% < 5\% \ (\theta \leq 75^o) \tag{8}$$

$$(I_{Obs,glo} - I_{Obs,dif}) / I_{Obs,glo} \times 100\% < 10\% \ (75^o < \theta < 93^o) \tag{9}$$

Figure 6 depicts the analysis of the observed data using the above Eqs. Figure 6a compares $I_{Cal,glo}$ and $I_{Obs,glo}$ during sunrise and sunset; both show values beyond the specified limits. Figure 6b compares $I_{Obs,glo}$ and $I_{Obs,dif}$; most radiation values are less than the limits. These errors were caused by problems with the sun tracker (such as powering off and miss-tracking) and other environmental factors during the observations.

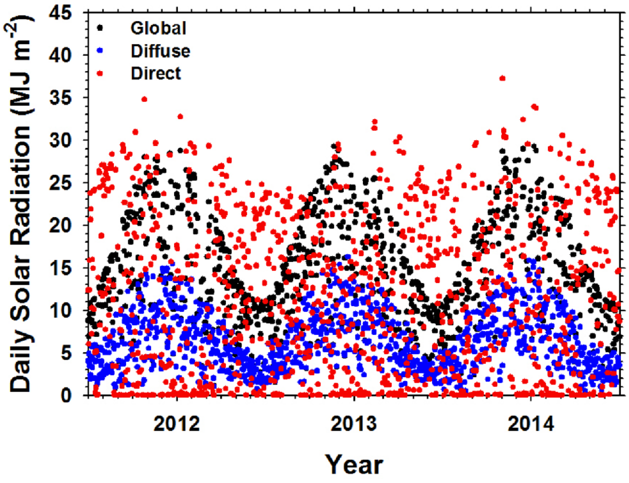

Fig. 7. Accumulated daily solar radiation (Units: MJ m^{-2}) observed at GWNU radiation station (2012-2014). These data have passed the quality control. Colored dots mean global (black point), diffuse (blue point), and direct (red point) solar radiation, respectively.

4. Results

Of the total number of data points (1,576,800) we assessed in this study through the QC flagging process (section 3a-3c), 98.31% were flagged as good quality (Table 2). Furthermore, 0.12% of the data failed the stage 2 comparison test, 1.36% of the data failed the stage 3 shading check, and 0.21% of the data failed the comparison test and shading check. Over 1.5% of the data were unusable because of the effects of shading.

Figure 7 shows the accumulated daily data that passed all QC checks (assigned Flag 0), with global solar radiation in black, diffuse solar radiation in blue, and direct solar radiation in red. The GWNU radiation-observation station is located in the middle of the Northern Hemisphere in an area that has four distinct seasons, where the amount of radiation is low in winter, but increases as summer approaches (Zo et al., 2014). Direct radiation is prominent on clear days, but lower on rainy or overcast days. When direct radiation is low (because of the

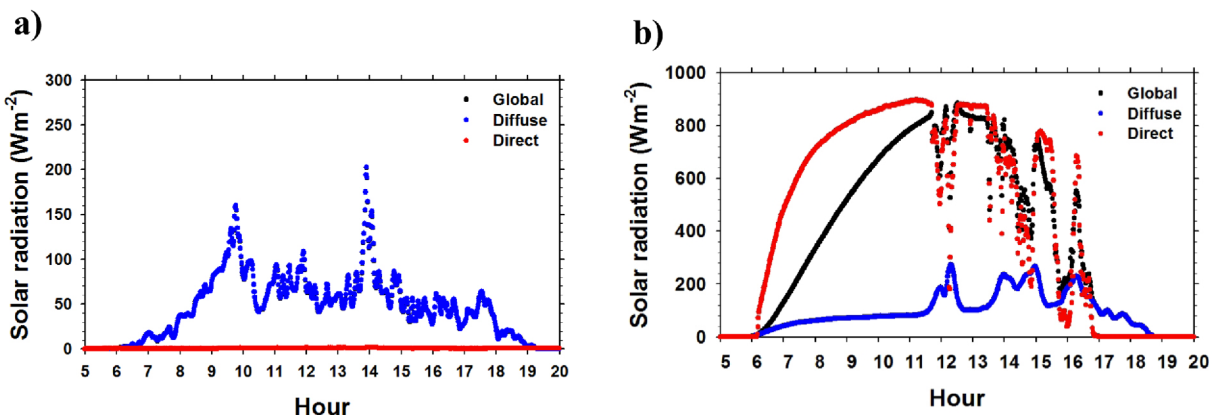

Fig. 8. Time series of solar radiation (black: global, blue: diffuse, and red: direct): (a) overcast conditions on 23 August 2012 and (b) partly cloudy conditions on 11 September 2012.

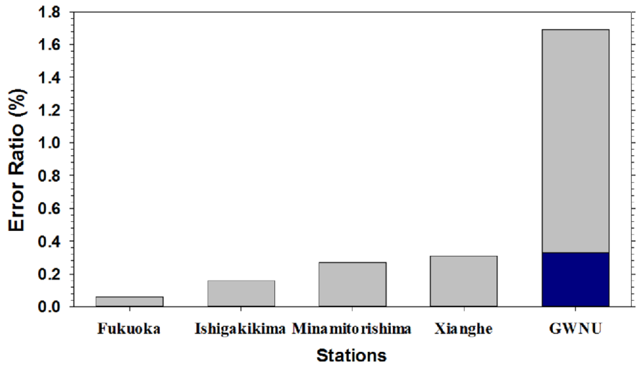

Fig. 9. Error ratios of GWNU and Asia (Japan and China)'s BSRN stations during the same period as in Table 2. The blue bar on GWNU represents the error ratio for the case when QC flag procedure 4 is not performed. The Xianghe station in China is excluded with missing (non-observation) data from 6 July 2012 to 1 March 2013.

effects of clouds or aerosol concentrations), the amount of global solar radiation is very similar to the amount of diffuse solar radiation.

Figure 8 shows two cases of daily observational data showing how variations in weather conditions can influence the diurnal pattern of solar radiation. Figure 8a shows a case of all-day precipitation (23 August 2012) when direct solar radiation is close to 0 W m^{-2} and the amounts of global and diffuse solar radiation are very similar. Figure 8b shows a case of an intermittently cloudy day (11 September 2012); during cloud-free periods, direct solar radiation peaks, whereas when the clouds obscure the sun, the direct and global solar radiation levels are low and the level of diffuse solar radiation is elevated (Jung et al., 2011). The three components of the observed radiation (global, diffuse, and direct) vary according to changes in weather conditions and so are used often in meteorological analyses.

Figure 9 shows the error ratios from four BSRN stations in Asia (Fukuoka, Ishigakijima, Minamitorishima and Xianghe). We retrieved these records from the same period as those from the GWNU station. Minamitorishima had the largest error ratio at 0.27% (69.7 hr), followed by Ishigakijima at 0.16% (42.0 hr) and Fukuoka at 0.06% (16.5 hr). Data from the Xianghe station had a gap from 6 July 2012 to 1 March 2013; the rest of the data had an error ratio of 0.31% (64.5 hr). Moreover, missing data were most likely to occur before sunrise, after sunset, and before 1100 LST; this occurred all day long for one to two days. The BSRN error ratios are relatively small compared to values from the GWNU station and are similar to the ratio found when excluding Flag 4 (the shading check). In other words, the data quality from the GWNU station is similar to that from the existing BSRN stations in Asia if the analysis omits the effects of shading by trees. This implies that accurate QC checks should be performed at stations such as GWNU where the effects of shading are experienced.

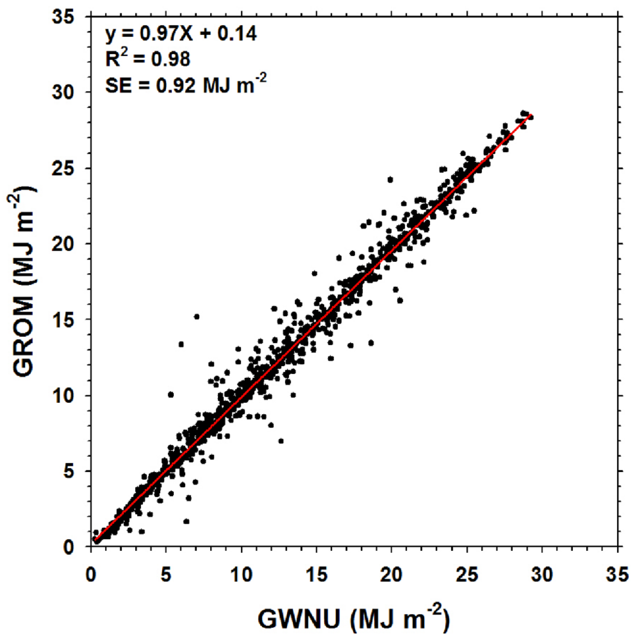

Fig. 10. Scatter plot of daily global solar radiation (Units: MJ m^{-2}) between Gangwon Region Office of Meteorology (GROM) and GWNU radiation station (2012-2014).

In order to validate measured solar radiation at the GWNU station, we compared GWNU global solar radiation data with data collected at the GROM station, located 4 km away. GROM provided accumulated hourly data and therefore we collated the GWNU data on an hourly basis. To avoid the effects of shade generated after 1600 LST, we only used data collected between 0700 LST and 1600 LST in this analysis, focusing on the period from 2012 to 2014. Figure 10 compares the two data sets after QC. The coefficient of determination (R^2) is 0.98, representing a very high correlation, and the value of standard deviation (SD) is 0.92 MJ m^{-2}. These statistic values increased compared to those ($R^2 = 0.97$ and SD = 1.09 MJ m^{-2}) computed before the QC checks. However, this difference became insignificant after 1600 LST, because the shading effect from nearby trees interfered with the proper collection of solar radiation.

These results were also affected by the small amount of bad data. Among the observational data shown in Fig. 10, the greatest error occurred on 27 February 2012. Although the weather on that day was clear, values of 16.49 and 5.7 MJ m^{-2} were observed at GWNU and GROM, respectively. This significant difference appears to have been caused by snowfall in the Gangneung region during the previous day, which had been cleared at GWNU but not at GROM. In addition to the condition of the equipment, the effects of weather and the surrounding environment on solar radiation can be significant; thus, caution is required when conducting observations and using the collected data.

5. Concluding remarks

Solar radiation surveillance data are useful for studies in various areas such as radiation modeling, climate and satellite data analysis, and renewable energy. The BSRN is dedicated to providing standardized and accurate data. Currently, there are about 70 registered branches of the BSRN. These branches cannot have any obstruction shielding the sun in any direction, and in addition to collecting solar radiation data, they must measure weather parameters such as temperature, humidity, and pressure. Currently, South Korea has a limited number of stations that can measure and collect global, diffuse, and direct solar radiation data. Therefore, it is difficult to perform cross-comparison the data for further analysis.

To measure solar radiation, the GWNU radiation station has installed observational equipment such as a pyrheliometer, pyranometer, and sun tracker, which have been in operation since 2010. In order to test the quality of data from the GWNU station, we performed a series of QC checks. First, we conducted a comparison test after filtering data based on the BSRN's physically possible limits using solar radiation data collected between 2012 and 2014. Next, we performed a shading check to eliminate the data distorted by trees on the western side of the station. After these QC processes and validation with the GROM measurement, we determined the quality of solar radiation measurements at the GWNU station with seven kinds of flags. Overall, 98.31% of data appeared to be good quality, 1.36% failed the shading check, 0.12% failed the comparison test, and 0.21% failed both the comparison test and shading check.

Furthermore, we concluded that there was no data loss due to technical issues such as equipment errors. We analyzed and compared the produced data with global solar radiation data (2012-2014) observed at GROM (4 km from the GWNU radiation station). The coefficient of correlation between the two data sets was 0.98 and the SD was 0.92 MJ m^{-2}. Considering the effects of clouds, and given the distance between the two stations, the statistically high results confirm the appropriate observation procedures and the good quality of the solar radiation data at the GWNU radiation station.

The observation of direct solar radiation using a pyrheliometer requires tracking of the sun, and the observation of global and diffuse solar radiation using a pyranometer requires horizontal alignment of the equipment. Furthermore, artificial shielding should be eliminated by removing objects such as dust or raindrops near the observing sensors. Thus, the management of solar radiation observations requires more involvement than weather observations, requiring further research into appropriate QC methods. For example, setting the maximum and minimum observable values for the equipment (as defined by the BSRN) helps verify data accuracy through comparison of each solar radiation element.

Furthermore, necessary quality management of the observational data can be performed by applying various test procedures to the observed data. The BSRN QC method is very useful because it can detect the effects around the equipment throughout the day. For example, it can detect the extreme values caused by equipment malfunctions and can identify the shielding effect from moving objects such as birds. However, periodic inspections and management of observational equipment are not prioritized, the quality management of observational data can be nothing more than a follow-up plan for the data. The quality of data may vary greatly, especially for accumulated and averaged data. Solar radiation constitutes a very important observational element: researchers use accurate solar radiation data for analyses of weather and climate, in other fields such as agriculture, construction, and energy, and for the verification of numerous satellites. Therefore, QC checks such as those conducted in this research, are essential for radiation observations. Furthermore, the high quality data obtained from meticulous observation processes can become a benchmark and index for further studies in other research areas.

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