I. INTRODUCTION

To evaluate the performance of radiometric devices, both in a laboratory setting and in the field, it is necessary to have accurate knowledge of the luminous radiation that stimulates the equipment [1]. Pyrheliometers, pyranometers, and pyrgeometers are used to obtain solar and infrared radiation data from observatories worldwide [2]. Typical solar radiometers measure the entire optical range of the electromagnetic spectrum emitted by the sun, including certain parts of the ultraviolet (UV - A, B; 0.285-0.4 μm), visible (VIS; 0.4-0.7 μm), and near-infrared regions (NIR; 0.7-2.8 μm). The pyrheliometer was invented by Pouillet in 1837, and he observed a TSI (Total Solar Irradiance) of 1,227 W m^{-2}, which is within 10% of the current standard TSI of 1,366 W m^{-2} [3]. In addition, the Smithsonian Institution began surface solar radiation observation in 1890, while the US National Weather Service contributed to the improvement of meteorological observation capability and the development of agrometeorology by beginning observations in 1901 [4]. The Kimball-Hobbs pyranometer, developed in 1923, became the prototype of the Eppley pyranometer. Meanwhile, the Moll-Gorczynski radiometer, which was based on the first model developed by Kipp...
and Zonen, was developed in 1924 [5]. In 1930, the Eppley Laboratory began production of commercialized pyranometers, leading to their worldwide installation and operation. Nowadays the significant growth of the photovoltaic industry has led to an increase in the use of pyranometers, which are often used to select a development site, and help to develop models for predicting solar radiation [6, 7]. The amount of generated solar power increases as the solar radiation reaching the surface of the earth becomes stronger, and thus accurate solar radiation observations are considered to be a very important tool for solar power generation [8].

Solar radiation is observed according to WMO (World Meteorological Organization) and WRC (World Radiation Center) regulations [9, 10]. The pyranometers used are classified based on performance, using the WMO and ISO 9060 pyranometer classification standards. The WMO standard classifies pyranometers as High Quality, Good Quality, and Moderate Quality, while the ISO classifies them as Secondary Standard, First Class, and Second Class. Such an instrument must be carefully managed and handled because pyranometers are affected by uncertainties resulting from their sensitivity function, thermal offset, other spectral effects, and geometrical, environmental, and instrumental factors [11]. Although most of the uncertainty factors have already been studied, the problem related to thermal offset has not been solved [12-14].

Thermal offset refers to errors generated because the thermopile in the pyranometer is affected not only by solar energy, but also by the ambient temperature [15]. This effect generates a larger error when the sky is clear during the night, compared to cloudy conditions [16]. One study attempted to decrease the error by reducing the increase of case temperature using a fan [17]. Analysis has also been performed of the correlation of thermal effect with the difference between long-term observation data (BSRN observations) and model results from the GCM (Global Circulation Model), and the MODTRAN (Moderate resolution atmospheric Transmission) radiative transfer model [18, 19].

Ji and Tsay [20] calculated the temperature difference between outer and inner domes of a pyranometer using pressure observations and the ideal gas equation. The thermal offset was calculated using the TDE (Thermal Dome Effect), and the change in solar radiance was determined using the calculated temperature and the temperature observed at the inner pyranometer case. In this study the thermal offset difference was calculated and the change in solar radiation due to the TDE was analyzed, using solar radiation data classified into clear, cloudy, and rainy days, from intensive observations at Gangneung-Wonju National University.

II. RESEARCH METHODS AND MATERIALS

2.1. Research Methods
For a general pyranometer, the global solar radiation (I, in units of W m⁻²) is determined by multiplying the calibration constant (c, in units of W m⁻² mV⁻¹) of each pyranometer by the voltage measurement from the pyranometer (V, in units of mV), as shown in Eq. (1). In the night case without solar radiation, the observation is 0 W m⁻². However, most pyranometers actually show a negative (-) value, such as the result of Carnicero [21]. This is because the temperature of the case (Tc) was higher than the temperature of the dome (Td), opposite the daytime situation. Thus the TDE can be found using Eq. (2) as the energy difference generated by the temperature difference between dome and case.

\[ I = cV \] (1)

\[ \text{Thermal offset} \propto \sigma(T_c - T_d) \] (2)

where \( \sigma \) denotes the Stefan-Boltzmann constant (5.6697 \times 10⁻⁸ W m⁻² K⁻⁴).

Similarly, Ji and Tsay [20] built a modified pyranometer to study the thermal offset, as illustrated in Fig. 1. Unlike for a general pyranometer, the Tc and Pd (dome pressure) between outer and inner dome were also observed. Smith [11] directly attached a temperature sensor to the dome to observe Td, but because this can cause an error in the pyranometer’s measurements, the Ji and Tsay method was used in this study.

Using Eqs. (1) and (2), the equation for global solar radiation of Ji et al. [22] can be deduced as:

\[ I = cV + I\sigma(T_c^0 - T_d^0) \] (3)

Here the dome factor f accounts for the optical and radiative properties of the domes and detector surface [23], and Tc is the thermopile temperature calculated from Tc using Hickey’s method [24], while Td is calculated using Pd and the ideal gas equation. Thus, to observe an accurate value from the pyranometer, the energy generated by the first general term and the temperature difference between the pyranometer case and dome must be considered.

Table 1 shows the TDE calculation procedure of Ji and Tsay, consisting of 4 steps. In step 1, Tdlight is estimated

![FIG. 1. Schematic diagram of a modified pyranometer.](image-url)
Table 1. Procedure for obtaining the solar radiation corrected thermal dome effect

<table>
<thead>
<tr>
<th>Step</th>
<th>Action</th>
<th>Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Calculation of $T_d^{\text{night}}$ during night time</td>
<td>$T_d^{\text{night}} = (T_s^4 + cV/\sigma T_d^{\text{night}})^{1/4}$</td>
</tr>
<tr>
<td>2</td>
<td>Calculation of $r_0$ and $k$ using $T_d^{\text{night}}$</td>
<td>$P_d/T_d^{\text{night}} = r_0 + k(P_d - P_a)/T_d^{\text{night}}$</td>
</tr>
<tr>
<td>3</td>
<td>Calculation of $T_d^{\text{daytime}}$</td>
<td>$T_d^{\text{daytime}} = [(1-k)P_d + kP_a]/r_0$</td>
</tr>
<tr>
<td>4</td>
<td>Calculation of solar radiation corrected thermal effect</td>
<td>$I = cV + f\sigma(T_s^4 - T_d^4)$</td>
</tr>
</tbody>
</table>

During the night (2000 LST to 0400 LST) when the solar radiation becomes 0 W m$^{-2}$, by setting the left side of Eq. (3) to zero. To compensate for the small pressure loss generated around the pressure observation hose, $P_d$ is defined by 2 terms, as in Eq. (4), and each term can be expressed as in Eqs. (5) and (6).

$$P_d = P_0 + \delta P_d$$

$$P_0 = r_0 T_d$$

$$\delta P_d = k(P_d - P_a)$$

Here $P_0$ is the dome pressure without pressure loss using the state equation in Eq. (5), $\delta P_d$ is the pressure difference between inner and outer domes with pressure loss, and $k$ is the dome factor. Combining these gives

$$P_d = r_0 T_d + k(P_d - P_a),$$

where $P_d$ and $P_a$ are the measurements. $r_0$ (y-intercept) and $k$ (slope) are calculated with the first equation form in Step 2, by dividing both sides of Eq. (7) by the $T_d$ calculated in Step 1. In Step 2, the dome temperature during daytime can be calculated by substituting the calculated $r_0$ and $k$ into Eq. (7) and arranging the $P_d$-related equation into the $T_d$-related equation, as given in Step 3. The daytime $T_d^{\text{daytime}}$ is calculated with the obtained $r_0$ and $k$, using the daytime dome pressure ($P_d$), atmospheric pressure ($P_a$), and night data. The $T_d (T_d^{\text{night}} + T_d^{\text{daytime}})$ calculated in Steps 1 and 3 is substituted into Eq. (3), and the irradiance including the TDE can be calculated.

### 2.2. Research Materials

This study used a modified Eppley PSP (Precision Spectral Pyranometer) device, as illustrated in Fig. 1. The $c$ and $f$ values of the modified pyranometer required for Eq. (3) were determined by experiment [25]. In addition to the usual observation data, $T_0$ and $P_d$ were observed. In addition, measurements were made of the solar radiation (direct, global, and diffuse), temperature, relative humidity, and pressure during the night (2000 LST to 0400 LST) when the solar radiation becomes 0 W m$^{-2}$, by setting the left side of Eq. (3) to zero. To compensate for the small pressure loss generated around the pressure observation hose, $P_d$ is defined by 2 terms, as in Eq. (4), and each term can be expressed as in Eqs. (5) and (6).

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</tr>
</tbody>
</table>

### Table 2. The cases were classified as clear, cloudy, and rainy according to sky and weather conditions during an intensive observation period in 2011 (from 9 October to 7 November, 2011)

<table>
<thead>
<tr>
<th>Case</th>
<th>Date (Month/Day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clear</td>
<td>10/13, 10/17, 10/18, 10/19, 10/31</td>
</tr>
<tr>
<td>Cloudy</td>
<td>10/09, 10/10, 10/11, 10/12, 10/16, 10/20, 10/23, 10/24, 10/25, 10/26, 10/27, 10/28, 11/01, 11/02, 11/03, 11/04</td>
</tr>
<tr>
<td>Rainy</td>
<td>10/14(4.0), 10/15(4.5), 10/21(4.5), 10/22(37.5), 10/29(9.0), 10/30(0.5), 11/05(6.0), 11/06(28.0), 11/07(2.0)</td>
</tr>
</tbody>
</table>

### Figure 2. Time series of hourly solar radiation and daily mean total cloud amount at Gangneung-Wonju National University during an intensive observation period in 2011 (from 9 October to 7 November, 2011).
III. RESULTS

3.1. Clear Case

The global solar radiation data from 18 October 2011, which is among the selected clear days, is shown in Fig. 3. The global solar radiation was observed using the modified pyranometer (PSP, EPPLEY), while the direct and diffuse solar radiation were observed at 1 minute intervals using the Kipp & Zonen instrument (direct: CHP1, diffuse: CMP 21, sun-tracker: 2AP). The direct (red dots) and diffuse (blue dots) solar radiation observations could be considered accurate because the effect of atmospheric components such as aerosols, including clouds in the optical path, was insignificant [28, 29]. From about 1620 LST, the majority of direct solar radiation was shaded by a mountain, and a value close to 0 W m$^{-2}$ was observed. Accordingly the total solar radiation and diffuse solar radiation were observed to have a very similar. Figure 3(b) shows the magnification of the solar radiation change at night. As stated before, the observation during the night should be 0 W m$^{-2}$; however, a negative (-) energy was observed, due to the TDE error.

The TDE in the clear case was determined according to the procedure in Table 2. Figure 4 presents the graphs of $T_{d, \text{night}}$ during the night as a function of time from the observed $T_{c}$ and Step 1 in Table 2. As shown in Fig. 4(b), $T_{d}$ was lower than $T_{c}$ during the night. The difference between these two values resulted in a small current being generated, and an error in the observation data.

The calculated dome factor ($k = 0.064$) and $r_0$ ($3.457$ g m$^{-2}$ K$^{-1}$) were obtained using the equation and the night observation data from Fig. 5(a) for the calculation in Step 2 of Table 1. The $R^2$ and standard error were 0.889 and 0.0008.
0.0008 MJ m\(^{-2}\) respectively. The dome factor and \(r_0\) calculated in Step 2 were implemented in Step 3 and are presented in Fig. 5(b), which shows both \(T_c\) and \(T_d\)\(^{\text{daytime}}\). It can be seen that the case temperature was higher than the dome temperature, in a similar situation to that at night. Hence, because of the difference between the two temperatures, the actual daytime irradiance was lower than the observation from the pyranometer. It can be concluded that the reduction of global solar radiation during daytime was larger than the reduction that occurred at night, because the temperature difference was higher in the daytime than the nighttime.

After the daytime temperature of the inner dome was calculated per Step 3, the global solar radiation in one day could be calculated using Eq. (3) to compensate for the pyranometer temperature. Figure 6 shows the change of pyranometer thermal offset for 18 October 2011, while Fig. 6(a) shows the global solar radiation before (red dots) and after (blue dots) correction with the pyranometer thermal offset. Additionally, Fig. 6(b) presents the global solar radiation change at nighttime after sunset, without global solar radiation. The global solar radiation at night without sunlight must be 0 W m\(^{-2}\), but in Fig. 6(b), the pyranometer showed a negative (-) global solar radiation at night. Thus, as has been mentioned previously, the compensation for pyranometer temperature is needed since a negative (-) global solar radiation was found during the night due to the difference between the dome temperature and case temperature. The corrected irradiances by pyranometer (blue dots) give a value much closer to 0 W m\(^{-2}\).

### 3.2. Cloudy Case

The cloudy cases in this study were the case with upper and middle clouds (15 October 2011; Fig. 7(a)), and the case with the rainfall until morning and clouds in the afternoon (30 October 2011; Fig. 7(b)). The case on October 2011, which same season as the clear case, was selected. The temperature difference between \(T_d\)\(^{\text{night}}\) and \(T_c\) before sunrise is shown in Fig. 8 using the analysis method in Table 1, in a similar manner as for the clear case. The red color indicates data from the clear case on 18 October 2011, while blue and black indicate data from the cloudy and rainy cases on 15 and 30 October 2011 respectively. The clear case data exhibited the highest temperature difference of 0.3 K, while the temperature difference for the rainy day was less than 0.05 K. Hence, the temperature of the inner pyranometer during the night was higher than...
the dome’s temperature, whereas the largest difference was found for a day with a higher temperature difference.

The calculated $T_{d\text{night}}$ from Fig. 8 was used to calculate $T_{d\text{daytime}}$, and then inserted into Eq. (3) to produce the results in Fig. 9. First, the maximum value of the cloudy case on 15 October 2011 was consistent with the clear day (18 October 2011). However, the global solar radiation change was significant, due to the effect of clouds. Especially at 1400 LST and 1500 LST, the global solar radiation that reached the surface of the earth was significantly reduced, owing to the clouds. The global solar radiation for the rainy day (30 October 2011) was also significantly reduced. In addition, negative (-) global solar radiation was found for the cloudy case before sunrise and after sunset, as shown by the black line. Correction of the offset reduced the negative (-) global solar radiation, producing a measured global solar radiation close to 0 W m$^{-2}$, as shown in blue.

As the negative (-) global solar radiation before sunrise was very small owing to the rain, the difference between $T_c$ and $T_{d\text{night}}$ was also very small (Fig. 8, black points; 30 October 2011). Moreover, because the difference between $T_c$ and $T_{d\text{night}}$ becomes larger after sunset for the rainy case, the negative (-) error was decreased by the offset correction.

The daily accumulated TDE during the observation period is quantitatively presented in Fig. 10. The gray bar represents the daily accumulated global solar radiation, the red bar shows the daily accumulated TDE, and the line indicates the total cloud amount. The TDE was proportionally larger for days with high daily accumulated global solar radiation. The maximum daily accumulated TDE of 1.16 MJ m$^{-2}$ was calculated for 31 October 2011. Moreover, the lowest TDE of 0.02 MJ m$^{-2}$ was found on 6 November 2011, when clouds and rain occurred all day. When the

<table>
<thead>
<tr>
<th>Case</th>
<th>DSR (MJ m$^{-2}$)</th>
<th>TDE (MJ m$^{-2}$)</th>
<th>Ratio of TDE (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clear</td>
<td>16.29</td>
<td>0.88</td>
<td>5.41</td>
</tr>
<tr>
<td>Cloudy</td>
<td>10.56</td>
<td>0.69</td>
<td>6.53</td>
</tr>
<tr>
<td>Rainy</td>
<td>3.35</td>
<td>0.21</td>
<td>6.38</td>
</tr>
</tbody>
</table>
surface-reaching global solar radiation became stronger, the temperature increased. Thus, the temperature difference of the inner and outer pyranometer cases became larger, resulting in the TDE. Table 3 shows the average TDE for the clear, cloudy, and rain cases, with the highest value found for the clear case. These maximum differences can also be stated for the cloudy, rainy, and clear cases as percentages: 6.53%, 6.38%, and 5.41%.

IV. CONCLUSION

Pyranometers for the observation of global solar radiation have been developing, into their present form since the 19th century. However, studies are still being conducted to solve the problems related to thermal offset, owing to the temperature difference between case and dome. In this study, intensive observations were performed and the TDE was analyzed using the Ji and Tsay (2010) method [20] and a modified pyranometer at Gangneung-Wonju National University, in collaboration with NASA. The analysis involved classifying the observation period into clear, cloudy, and rainy cases using observations of the total cloud amount. The difference between $T_a$ and $T_d$ was large for clear days, leading to an increase of the TDE, and a value of 0.88 MJ m$^{-2}$ day$^{-1}$ was found. For the cloudy case, the temperature difference between case and dome was reduced and the TDE increased to a value of 0.69 MJ m$^{-2}$ day$^{-1}$, while the rainy case showed only 0.21 MJ m$^{-2}$ day$^{-1}$. However, when these were expressed as a daily accumulated global solar radiation percentage ratio, the cloudy case day exhibited the highest percentage difference (6.53%), followed by the rainy case (6.38%), and clear case (5.41%).

As a result, even though the TDE strongly affected the measured global solar radiation on a clear day, the TDE had a relatively higher effect on cloudy or rainy day. Thus, the TDE must be considered in all weather conditions. Correcting for the TDE in a solar observation instrument should be considered necessary for global solar radiation observations and the study of its application. In particular, the observation of the TDE in the field of atmospheric optics could provide an error range for the utilization of global solar radiation data. However, the data used in this study resulted from the analysis of intensive observation data over only one month, and thus a generalization for all global solar radiation instruments is problematic. Hence the quantification of TDE should be considered as a prerequisite for long-term observations and analysis.

ACKNOWLEDGMENT

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