Pyranometer Thermal Offset: Measurement and Analysis

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ABSTRACT

The reliable estimation of the radiative forcing and trends in radiation requires very accurate measurements of global and diffuse solar irradiance at the earth’s surface. To improve measurement accuracy, error sources such as the pyranometer thermal offset should be thoroughly evaluated. This study focuses on the measurement and analysis of this effect in a widely used type of pyranometer. For this aim, a methodology based on capping the pyranometer has been used and different criteria for determining the thermal offset have been applied and compared. The thermal offset of unventilated pyranometers for global and diffuse irradiance has been measured under a wide range of cloud, ambient temperature, wind speed, and radiation conditions. Significant differences in absolute values and variability have been observed between daytime and nighttime, advising against correcting the thermal offset effect based only on nighttime values. Notable differences in the thermal offset between cloudy and cloud-free conditions have been also observed. The main results show that the ambient temperature, the radiation, and its direct/diffuse partitioning are the variables more related to the daytime thermal offset.

1. Introduction

Numerous studies published over the past decades have revealed important differences in the irradiance values estimated by climate or radiative transfer models and those measured with pyranometers at the earth’s surface (Garratt 1994; Kato et al. 1997; Halthore et al. 1998; Wild et al. 1998; Valero and bush 1999; Wild 2005). These differences could result in important variations in the subsequent calculation of the radiative forcing and climate trends. Recent studies have estimated a global annual mean solar irradiance at the earth’s surface of $184 \pm 10 \text{W m}^{-2}$ (Wild et al. 2013). A widely used pyranometer, such as the Kipp and Zonen CM11 with a manufacturer error of 3% (Kipp and Zonen 2000), would record the above-mentioned global mean irradiance with an absolute error of $\pm 5.5 \text{W m}^{-2}$. This means a very high uncertainty compared to the typical magnitude of the other forcing agents, which has been estimated by the Intergovernmental Panel on Climate Change in the order of $2 \text{W m}^{-2}$ (Pachauri and Reisinger 2007). The mentioned uncertainty is also very large in comparison with the magnitude of the decreasing and increasing trends observed in solar radiation between 1960 and 1990 (dimming period) and after 1990 (brightening period) (Wild et al. 2005). During the dimming and brightening periods, the observed variations ranged in the intervals between $-5.1$ and $-1.6 \text{W m}^{-2} \text{decade}^{-1}$, and between $2.2$ and $5.1 \text{W m}^{-2} \text{decade}^{-1}$, respectively (Wild 2009).

Besides climate studies, accurate irradiance measurements are indispensable for the development of solar energy systems. Thus, the efficiency and lifespan of solar systems highly depend on the actual radiation field for each specific location. For instance, a high variability in the solar radiation, occurring mainly under broken cloud conditions, increases the fatigue of materials (Patsalides et al. 2007; Patsalides et al. 2012).

This demand of high-quality radiation values leads to the identification and correction of the main errors in pyranometer measurements. One of the sources of error first detected in solid black pyranometers is the thermal offset error. The thermal offset is a spurious signal due to the difference in temperature between the inner dome and the detector of a pyranometer. In the most common Moll–Gorzynski-type pyranometer, the solar radiation passes through the two glass domes and is absorbed by a black-painted ceramic disk that is intimately bonded to the thermopile detector. However,
the black ceramic disk absorbs not only the solar radiation transmitted through the domes but also the wavelength infrared radiation emitted by the instrument optics. Thus, the temperature of the inner dome and the detector differ, since they are made of different materials and in contact with different parts of the radiometer: the inner dome with the outer dome, and the detector with the thermopile and the pyranometer case. This different temperature leads to a potentially significant imbalance in the net infrared radiation budget of the detector, subsequently producing a spurious signal that is superimposed on the output signal. This temperature imbalance remains continuously due to the differences in the thermal capacity of the dome and the detector and in the radiation budget of each part of the pyranometer.

True irradiance is underestimated in most occasions, as the detector is at a higher temperature than the dome. It is worth noting that a thermal offset error between $-5$ and $-30 \text{ W m}^{-2}$ in diffuse irradiance results in underestimating the irradiance values in $0.7\%-4.3\%$ (Reda et al. 2003). It is worth noting that an offset error of $15 \text{ W m}^{-2}$, which is a typical value under cloud-free conditions, is about $30\%$ of the high-sun Rayleigh diffuse signal (Dutton et al. 2001). Some studies have reported that thermal offset error decreases under cloudy-sky conditions and at nighttime due to the decrease in the dome-detector temperature difference (Bush et al. 2000; Philipona 2002). Additionally, several authors have pointed out the important role played by local and specific factors such as the environment conditions (Long et al. 2003; Vignola et al. 2007, 2008, 2009), the pyranometer model (Cess et al. 2000; Haeffelin et al. 2001; Dutton et al. 2001), the ventilated/unventilated conditions (Philipona 2002), and the radiometric variable measured (global or diffuse) (Bush et al. 2000).

Although being acknowledged as a source of error in solar radiation measurements, there are still numerous uncertainties about the thermal offset and its impact on measurements. For example, there is no general agreement about whether the thermal offset for a pyranometer differs depending on the measurement of global or diffuse irradiance. Thus, while Philipona (2002) found similar thermal offsets for diffuse and global irradiance measurements, Bush et al. (2000) stated that a shaded radiometer operates in a different thermal state than the same instrument in unshaded conditions.

Other unresolved issue is the absence of a standard methodology for measuring the daytime thermal offset of pyranometers. Thus, several methodologies have been applied with that aim (Bush et al. 2000; Dutton et al. 2001; Philipona 2002; Ji and Tsay 2010). In this framework, this study aims to contribute to a better knowledge of the thermal offset error. It focuses on the measurement and analysis of the daytime thermal offset of unventilated Kipp and Zonen CM11 pyranometers. Although this pyranometer model is extensively used worldwide by international (such as the Baseline Surface Radiation Network) and national radiation networks (deployed by most European national weather services), its thermal offset has not been sufficiently investigated. To measure the daytime thermal offset, the capping methodology has been followed. This technique allows for estimating the thermal offset of a pyranometer by monitoring the response of the output signal when the detector is suddenly covered by a cap. According to this technique, numerous capping events have been conducted under a wide range of air temperature and cloud conditions, and different estimates of the thermal offset have been compared. Additionally, other environmental variables have been simultaneously recorded during the capping events in order to determine the main factors affecting the thermal offset. The analysis has been applied to two similar instruments, so as to account for the variability between instruments of the same type.

### 2. Instrumentation

This study relies on measurements performed at the radiometric station installed in Badajoz, southwestern Spain (38.9$^\circ$N, 7.01$^\circ$W; 199 m MSL), on the roof of the Department of Physics building on the campus of the University of Extremadura, guaranteeing an open horizon. This radiometric station is managed by the research group Atmosphere, Climate and Radiation in Extremadura (AIRE) of the University of Extremadura. This location in western Spain is characterized by a mild Mediterranean climate with very dry and hot summers. During this season measured solar irradiance values are among the highest recorded in Europe.

In this station, global and diffuse irradiance have been measured by two Kipp and Zonen CM11 pyranometers with serial numbers 068948 and 027784 and denoted as pyranometer A and pyranometer B, respectively. The CM11 pyranometer manufactured by Kipp and Zonen is based on the Moll–Gorczynski thermopile and it is formed by 100 thermocouples. The sensing element is a black-painted ceramic ($\text{Al}_2\text{O}_3$) disk. Only the border of this disk is in good thermal contact with the pyranometer body. The 100 cold junctions are located along this border, while the 100 hot junctions are near the center in a rotational symmetric arrangement (Kipp and Zonen 2000). These hot junctions are heated by solar radiation,
resulting in a different temperature than the reference temperature of the isolated shielded cold junctions and therefore producing a voltage. The pyranometer is provided with two hemispherical glass domes that are essentially transparent to solar radiation within the interval 0.28–2.8 μm and opaque to longer wavelengths. On the other hand, the thermopile detector is sensitive to both shortwave and longwave radiation (approximately from 0.28 to 100 μm).

The CMP 11 Kipp and Zonen instrument complies with International Organization for Standardization (ISO) 9060 criteria for an ISO secondary standard pyranometer. It is classified as “high quality” according to the WMO nomenclature (WMO 2008), with a directional error lower than 10 W m⁻² for zenith angles up to 80° with a 1000 W m⁻² beam (Kipp and Zonen 2000). In addition to the manufacturer calibration, both pyranometers participated in two intercomparison campaigns carried out in 2013. The first one took place in April 2013 at the Spanish State Meteorological Agency [Agencia Estatal de Meteorología (AEMET)] station in Badajoz and the second in June 2013 at the Atmospheric Sounding Station [Estación de Sondeos Atmosféricos (ESA)] of the National Institute for Aerospace Technology [Instituto Nacional de Tecnica Aeroespacial (INTA)] in “El Arenosillo” (Huelva, Spain). In these campaigns our two pyranometers were compared to the ventilated Kipp and Zonen CM21 pyranometers 070122 and 041219, respectively, which had been recently calibrated. The calibration factors obtained in the different campaigns and the one provided by the manufacturer notably agree, with relative differences lower than 0.5%, proving the high stability of the response of both pyranometers.

The diffuse solar irradiance was measured by installing the pyranometer (A or B) on a Kipp and Zonen SOLYS2 sun tracker with a shading ball that moves automatically, following the sun’s motion and continuously blocking the radiation coming in the sun’s direction.

To measure the direct solar radiation, a CHP1 pyrheliometer manufactured by Kipp and Zonen was used. Its first calibration was performed by the manufacturer in 2008 by exact interchange of the test pyrheliometer and the reference pyrheliometer PMO2 of the World Radiation Center (WRC) using the sun as source, resulting in an error sensitivity of ±0.5%. Our pyrheliometer was subsequently calibrated in 2013 at the AEMET Radiometric Laboratory in Madrid, Spain, using the calibrated Kipp and Zonen CH1 pyrheliometer 050408 as reference, which is directly traced to WRC Davos, Switzerland, reference. Both calibrations show a notable agreement, with calibration factors differing in less than 0.1%. The CHP1 pyrheliometer was also installed on the Kipp and Zonen SOLYS2 sun tracker.

Simultaneously, a Kipp and Zonen CG1 pyrgeometer recorded its body temperature \( T_p \) and the Net IR irradiance on its detector, allowing for the calculating of the downward infrared irradiance (IR) as follows:

\[
\text{IR} = \text{Net IR} + \sigma T_p^4,
\]

where \( \sigma \) is the Stefan–Boltzmann constant. The pyrgeometer CG1 is provided with a 64-thermocouple thermopile detector and has been designed for meteorological measurements of downward atmospheric longwave radiation with good reliability and accuracy. It guarantees an inaccuracy of measurement lower than 20 W m⁻² and a zero offset lower than 2 W m⁻² due to a change in temperature of 5 K h⁻¹ (Kipp and Zonen 2003). It is very stable, with a sensitivity change per year lower than 1%. It has been calibrated by intercomparison with Kipp and Zonen reference CG1 FT002, resulting in a sensitivity error of ±5% at 20°C and 140 W m⁻² (Kipp and Zonen 2003).

In addition to the radiative measurements, the ambient temperature during the capping events was monitored by a shadowed and ventilated fast response temperature probe PS-2135 with a precision of 0.1°C and a PASCO GLX datalogger. The temperature probe was located next to the radiometers, being representative of the ambient air temperature at the radiometric station. At the same time, the wind speed was monitored by anemometer model compact 4.3159.00.150 manufactured by THIES. This instrument is installed at the AEMET station in Badajoz, which is located 400 m from our radiometric station.

In its usual configuration, the station records radiation every minute. However, for this particular study, a specific campaign at a temporal frequency of 1 s was performed. Thus, the dataset consists of simultaneous measurements of global, diffuse, direct, and infrared irradiance on a 1-s basis recorded by a Campbell CR1000 acquisition system. The capping events were conducted on seven specific days between March and July 2013, selected according to their atmospheric situations in an attempt to account for a large variety of environment and sky conditions. During these days more than 200 measurements of thermal offset were recorded under different cloud conditions, ambient temperatures, wind speed and solar positions, and operational configurations (measuring global or diffuse). Additionally, the same number of cases was randomly selected at nighttime for each day of study among those measurements registered at solar elevation under −10°. This elevation was selected as the threshold for
nighttime data not affected by solar radiation refracted or scattered by atmospheric components and clouds.

3. Methods

a. Technique for measuring the thermal offset

Although different methodologies have been applied up to date for measuring the thermal offset (Bush et al. 2000; Dutton et al. 2001; Philipona 2002; Ji and Tsay 2010), none of them can be universally recommended, since each method has its specific limitations.

One methodology consists of installing thermistors in the pyranometer for measuring the temperatures of the detector and of the outer/inner dome (Bush et al. 2000; Haeffelin et al. 2001). This method provides a reliable description of the thermal offset behavior, since it directly measures the difference of temperature between the detector and the dome. However, under inhomogeneous radiative fields, temperatures within the dome can vary significantly (Smith 1999) and therefore the temperature measured may not be representative. Moreover, attaching thermistors to the dome can affect the measurements, since they interfere with the incoming radiation.

To avoid the need for attaching a thermistor to the dome, Ji and Tsay (2010) proposed a new technique consisting of installing a barometer inside the pyranometer. This new methodology is based on the relationship between the effective temperature of the dome and the pressure of the air trapped between the outer and inner domes. Then, assuming that the air between the domes behaves as an ideal gas, the thermal offset can be determined. The main drawback of these two methodologies is the need to modify the pyranometer by installing thermometers and barometers inside and/or outside the instrument.

The third method estimates the thermal offset as the difference between the signal of the analyzed pyranometer and a reference pyranometer with a negligible thermal offset (Dutton et al. 2001; Philipona 2002). This method has the advantage of being nonintrusive. However, this procedure generally underestimates the thermal offset, since even the reference pyranometers present a nonzero thermal offset (Ji and Tsay 2010; Dutton et al. 2001). Moreover, this methodology ignores other differences between the reference pyranometer and the pyranometer of study, such as their specific cosine error, spectral response, time response, and temperature dependence.

The fourth methodology for estimating daytime thermal offset relies on conducting capping events. These experiments consist of instantaneously blocking the shortwave (SW) radiation to the detector (a thermopile) of the pyranometer while continuously recording its signal output. The monitoring of the signal evolution once the detector has been blocked allows for determination of the thermal offset. This monitoring is performed until the detector has responded to the SW blocking but before the dome temperature changes significantly. This is a reliable procedure, since the dome temperature has a time constant that is distinguishably longer than the detector (several minutes vs a few seconds) (Bush et al. 2000; Dutton et al. 2001; Haeffelin et al. 2001; Michalsky et al. 2005; Carlund 2013). Its main drawback is the possible effect of the capping on the thermal balance due to the cap emission and the alteration of the circulation of the air (Ji and Tsay 2010).

In the present study this fourth method consisting of capping events was preferred despite being highly demanding. It has the advantage of providing realistic values of the thermal offset independently of other reference instruments and not requiring installation of thermometers in the pyranometers. In this study, the capping events and the cap itself were designed in order to minimize the limitations of the method.

To minimize the effect of IR exchange between the capping device and the domes, a cap with a low-emissivity inner surface was manufactured. The cover was fabricated of polystyrene coated with a reflective material on both inside and outside surfaces (Fig. 1). The emission of the cap was measured covering the pyrgeometer for 5 min (more than 3 times the capping events’ duration) during several days under overcast and under cloud-free conditions, and with the temperature ranging between 13.5° and 30°C. The mean net infrared irradiance measured during these experiments was 0.36 W m\(^{-2}\). These values are negligible compared to the thermal offset magnitude, as it will be shown in next sections. Additionally, the cap was placed in a refrigerated room before and after each capping event in order to avoid overheating the cap. The cap was built to cover the dome and the screen but not the entire pyranometer body in order to block only the irradiance arriving at the detector. In this way, the temperature of the pyranometer body and the air circulation around it are less affected.

To observe the evolution of the signal of our two pyranometers once capped, a long capping event was essayed. Figure 2 shows a 1-h capping event for pyranometers A and B. It is observed that once the detector was capped, the signal rapidly decreased to negative values and then smoothly increased to approach a stable value. Pyranometer A takes 20 min to reach a stable value around 1.20 W m\(^{-2}\), while pyranometer B takes 15 min to stabilize around 2.98 W m\(^{-2}\).

b. Criteria for estimating the thermal offset

Although the capping technique has been used by several authors, there is no general agreement about the
exact time when the output signal reaches the thermal offset value, and different criteria are usually applied. For instance, Bush et al. (2000) and Michalsky et al. (2005) estimated the thermal offset as the minimum signal value reached once the pyranometer is covered. Haeffelin et al. (2001) used the average value within 10 and 20 s after the capping starts. Dutton et al. (2001) used the signal value at 10 times the pyranometer time constant after the capping starts. Recently, Carlund (2013) proposed to calculate the thermal offset as the y intercept of the lineal fit of the output signal versus time within 42 and 84 s after the capping starts.

It must be noted that these criteria were developed for specific instruments and conditions and therefore they need to be adapted to our particular case. Thus, while the criteria proposed by Bush et al. (2000), Michalsky et al. (2005), Dutton et al. (2001), and Carlund (2013) can be appropriately applied in their original version, the criterion used by Haeffelin et al. (2001) is specific for a Precision Spectral Pyranometer (PSP) pyranometer and is unsuitable for Kipp and Zonen CM11 pyranometers. The reason is the longer time constant of the CM11 pyranometers with respect to PSP pyranometers. In the case of the CM11 pyranometers, the output signal is high between 10 and 20 s after the capping event starts. Applying the original version of this criterion overestimates the thermal offset. Therefore, this methodology was adapted to CM11 pyranometers and a time interval between 20 and 40 s was considered.

![Cap used for the capping events](image1)

**FIG. 1.** Cap used for the capping events.

![Long capping events for (a) pyranometer A and (b) pyranometer B](image2)

**FIG. 2.** Long capping events for (a) pyranometer A and (b) pyranometer B.
The selection of a proper lasting time for the capping events had to comply with different requirements. On the one hand, it must be long enough to allow the application of the described methodologies. The methodology that was more demanding was that from Carlund (2013), which requires at least 84 s of capping. On the other hand, the capping must be short enough not to significantly modify the thermal balance between the dome and the detector. To comply with both requirements, we decided to perform capping events lasting 1.5 min. This is the minimum time needed to calculate the thermal offset according to the different criteria described above without significantly affecting the pyranometer temperature imbalance.

Subsequently, numerous 1.5-min-lasting capping events were conducted. The thermal offset of our two pyranometers were measured one after another. The interval between the two consecutive capping events was, at least, 2 min in order to avoid memory effects. The irradiance (global, diffuse, direct, and IR), wind speed, and ambient temperature values ascribed to each capping event were considered as those registered 2 s before capping the pyranometer.

The thermal offset will be calculated by applying these four different criteria under different environment conditions and the results will be analyzed. Finally, a suitable criterion will be chosen.

c. Analysis

Once the most suitable criterion for estimating the thermal offset was selected, the values obtained for the two pyranometers under different conditions were studied in detail. Differences in the thermal offset between daytime and nighttime, under different cloud conditions, and between pyranometers working in the same conditions were analyzed and compared. Differences in thermal offset error between global and diffuse measurements were also investigated.

The relationship between thermal offset and various radiation and environmental variables have been addressed in numerous studies (Bush et al. 2000; Haeffelin et al. 2001; Dutton et al. 2001; Vignola et al. 2007; Ji and Tsay 2010). In particular, the ambient temperature has been reported by many authors as a main factor for the thermal offset (Bush et al. 2000; Dutton et al. 2001; Haeffelin et al. 2001; Philipona 2002; Ji and Tsay 2010). Additionally, the temperature $T_p$ of a collocated pyrgeometer is of special interest, since some authors have indicated its high correlation with the pyranometer temperature due to the similar design of both instruments (Dutton et al. 2001; Ji and Tsay 2010). Moreover, several authors have pointed out the relationship between the thermal offset of a pyranometer and the Net IR measured by a collocated pyrgeometer (Dutton et al. 2001; Haeffelin et al. 2001). These magnitudes are key factors in the local energy balance, which affects the temperature of the pyranometer dome.

In addition, thermal offset dependences on the clearness index $k_t$ and the diffuse fraction $K_d$ were analyzed. These ratios provide information about the relative attenuation suffered by the radiation when crossing the atmosphere. These ratios are defined by the following expressions:

$$k_t = \frac{I_g}{I_{TOA}},$$

$$K_d = \frac{I_d}{I_g},$$

respectively, where $I_g$ and $I_d$ are the global and diffuse irradiance on a horizontal surface on the earth’s surface, respectively, and $I_{TOA}$ represents the actual irradiance on a horizontal surface at the top of the atmosphere, which is calculated as follows:

$$I_{TOA} = 1370 \text{ W m}^{-2} E_0 \cos(\theta),$$

where $E_0$ stands for the eccentricity correction due to the earth–sun actual distance and $\theta$ stands for the solar zenith angle.

d. Schedule of measurements

To investigate the thermal offset of the two pyranometers under different cloud and ambient temperature conditions, measurements with different configurations were performed. Table 1 summarizes the main characteristics of the capping events conducted. It provides information about the date, the cloud condition, the variable measured by each pyranometer (global or diffuse), the number of capping events for each day of measurement, and the ranges of different variables (ambient temperature, wind speed, net infrared irradiance, global solar, and diffuse solar irradiance). The range refers to the interval of variation of each variable corresponding to the capping events conducted each day.

The variety of episodes allowed for studying several aspects of the thermal offset effect. Thus, with the aim to analyze the possible differences in the thermal offset between the two pyranometers, both instruments measured the same variable (global or diffuse) during days 171, 172, 177, and 178. On the other hand, in order to evaluate the main factors affecting the thermal offset, each pyranometer measured the same variable (global or diffuse irradiance) during days with different temperature,
wind speed, and cloud conditions. For example, pyranometer A measured global irradiance during days 73, 87, 136, 171, 178, and 199 (Table 1). Additionally, in order to study the possible differences in the thermal offset values when the pyranometer measures global or diffuse irradiance, pairs of consecutive days have been used; one day the pyranometer measured global irradiance, while the next day it measured diffuse irradiance. For this comparison, consecutive days with similar temperature, wind speed, and cloud conditions, such as days 199 and 200, were selected. Finally, during some days one pyranometer measured global irradiance, while the other measured diffuse irradiance, with the aim to have enough measurements of all the variables used in the study.

4. Results and discussion

a. Comparison of criteria

The thermal offsets of the two pyranometers were estimated following the original criteria proposed by Bush et al. (2000), Dutton et al. (2001), and Carlund (2013), and the Haefelin et al. (2001) criterion was adapted as described in section 3.

Figure 3 shows the thermal offset values obtained by applying the four criteria to pyranometer A on an overcast day and a clear day (days 136 and 199, respectively). During both days pyranometer A measured global irradiance. In general, the absolute differences between different criteria are mostly under 1.5 W m$^{-2}$ on clear days, and nearly zero on cloudy days. In particular, the results obtained by applying Bush and Dutton’s criteria agree overall. In contrast, on clear days, the adapted Haefelin et al.’s criterion seems to give slightly higher values. These results agree with the paired t tests at a 95% confidence level performed between the two criteria. The tests indicate no statistically significant differences between Bush et al.’s and Dutton et al.’s criteria. On the other hand, Carlund’s and Haefelin et al.’s criteria show significant differences with respect to any other criterion.

In this framework it is worth noting that no best criterion can be established and that the decision must be based on practical considerations. In this study, the Bush et al. (2000) methodology was preferred, since it requires no estimation of any characteristic of the pyranometer, such as its time constant, which can be inaccurate or difficult to determine.

b. Experimental values of the thermal offset

Figure 4, top panels, shows the thermal offset obtained by capping pyranometers A and B under different cloud
conditions along with the corresponding nighttime measurements. In spite of corresponding to the same pyranometer model, significant differences between pyranometers A and B are observed when they were measured under the same environmental conditions (days 171, 172, 177, and 178). The absolute thermal offset of pyranometer A is usually higher than the thermal offset of pyranometer B. This fact can be also observed in Fig. 2. The larger differences, up to 3.48 W m\(^{-2}\), occur when both pyranometers measure global irradiance, while the differences decrease to a mean value of 0.37 W m\(^{-2}\) when they measure diffuse irradiance. To statistically assess the significance of these differences, two sample t tests were performed. The test resulted in significant differences at a 95% confidence level. This result indicates that the thermal offset must be determined for each instrument individually, even if they correspond to the same manufacturer and model.

The thermal offset of pyranometer A (B) ranges from \(-19\) W m\(^{-2}\) \((-16\) W m\(^{-2}\)) on a cloud-free hot day to \(-0.5\) W m\(^{-2}\) \((+0.6\) W m\(^{-2}\)) on an overcast day with a mild temperature. This decrease in the absolute value of the thermal offset under cloudy conditions agrees with results obtained by other authors (Bush et al. 2000; Dutton et al. 2001) who suggest it is due to the enhancement of downward IR by clouds, heating the pyranometer dome and reducing the dome-detector temperature difference. Under certain atmospheric conditions, the temperature of the dome can be higher than the temperature of the detector, resulting in a positive offset (Bush et al. 2000; Dutton et al. 2001). The thermal offset on clear days (73, 171, 177–200) is notably lower at sunrise/sunset than at noon. At sunrise and sunset, the diffuse fraction \(K_d\) is higher because of the longer path traveled by the radiation within the atmosphere. These results point out the important effect on the thermal offset of both the quantity and distribution of the radiation. Figure 4, bottom panels, shows the normalized thermal offset (divided by the irradiance) for daytime measurements. These relative values range from 1% for irradiance during cloudy days to over 15% for diffuse irradiance during cloud-free days.

Figure 4, top panels, shows notable differences in the thermal offset between daytime and nighttime (see, for instance, days 199 and 200). This fact agrees with results reported by several authors for other pyranometer models and locations (Cess et al. 2000; Haefelin et al. 2001; Philipona 2002; Ji and Tsay 2010). The nighttime offset on different days ranges from 0 to \(-5\) W m\(^{-2}\). In contrast, the daytime thermal offset can reach values under \(-15\) W m\(^{-2}\). There are also notorious differences in the variability. Thus, while the daytime thermal offset under cloud-free conditions can vary up to \(8\) W m\(^{-2}\), during the corresponding nighttime the variability rarely exceeds \(2\) W m\(^{-2}\). These significant differences between day and night advise against the common procedure of using the averaged nighttime measurements as daytime thermal offset.

It is worth noting the differences in thermal offset between days with similar cloud cover, Net IR, and wind speed but different temperature ranges, such as days 73 and 199 (see Table 1). Figure 4, top panels, shows that lower ambient temperatures in day 73 result in lower thermal offset for both pyranometers.

Days 199 and 200 show differences regarding measuring global or diffuse radiation. These differences have been evaluated, and values in the range from 0.61 to \(5.86\) W m\(^{-2}\) for pyranometer A and from 0.56 to \(3.74\) W m\(^{-2}\) for pyranometer B have been obtained. Although these differences are lower than the values obtained by Bush et al. (2000) for a PSP pyranometer (about \(8.5\) W m\(^{-2}\)), these differences are significant, as confirmed by a two-sample t test at a 95% confidence level. This finding is counter to results obtained by Philipona (2002) but agrees with Bush et al. (2000) and Cess et al. (2000), who reported differences depending on whether global or diffuse irradiance is measured. This open issue emphasizes the need for studying different pyranometers’ families and models.

c. Relationship with some radiative variables

The relationship of the experimental thermal offset with some radiative and environment variables was
studied. It must be noted that, since the essayed variables are not independent, they are considered individually in the search of a good fit. Figures 5a–f show the daytime thermal offset (gray points) versus the ambient temperature, the clearness index, the diffuse and direct fractions, the Net IR irradiance, the temperature in a collocated pyrgeometer, and the wind speed for pyranometer A. Figures 5e,f show also the nighttime measurements (black points). A clear relationship with ambient and pyrgeometer temperatures and with radiation is found, in agreement with results reported for other pyranometer models (Gulbrandsen 1978; Wardle et al. 1996; Ji and Tsay 2010). Thermal offset decreases when ambient temperature (Fig. 5a), pyranometer temperature (Fig. 5f), and clearness index (Figs. 5c) increase. The diffuse fraction of the radiation plays an important role. Hence, the thermal offset increases when \( K_d \) increases (Fig. 5d). The analysis of the Net IR dependence shows similar thermal offset values for cloudy conditions (black points with higher Net IR) and nighttime (gray points) but large differences with daytime values (black points with lower Net IR) (Fig. 5e). A similar result can be observed in the thermal offset versus pyrgeometer temperature relationship (Fig. 5f).

To assess these relationships, least squares regressions between the thermal offset of pyranometer A and each independent variable have been constructed. For this aim the dataset has been split into two subsets: 75% (84 data) for the fitting and the remaining independent 25% (28 data) for the validation. The fittings are moderately good with the coefficient of correlations ranging from 0.64 for the wind to 0.84 for \( K_d \). When these fittings are applied to the independent set, root-mean-square errors (RMSE) under 3.8 W m\(^{-2}\) are obtained, showing a moderate predictive skill.
Figures 5a–f show a complex relationship of the thermal offset with the ambient temperature, the radiation magnitude, and its distribution. Higher thermal offset takes place on clear days around noon, when irradiance, but not the ambient temperature, reaches its maximum value. The simultaneous dependence on temperature and irradiance can be clearly seen in Figs. 6a, where the thermal offset of each pyranometer
has been plotted versus the diffuse fraction $K_d$, using colored symbols to indicate the ambient temperature. It can be seen that the thermal offset is low for high diffuse fraction and low ambient temperature. At the same time, the thermal offset is higher for ambient temperatures above 25°C and diffuse fraction below 0.3, that is, when the direct component is the main irradiance component. A similar behavior can be observed for Net IR, as is shown in Fig. 6b.

5. Discussion and conclusions

In this study, more than 200 experimental measurements have been performed, aimed to investigate the thermal offset of unventilated pyranometers. Thus, capping events under different cloud, wind speed, temperature, and radiation conditions were conducted. The capping methodology was preferred to other methods, since it requires no physical modification of the pyranometers and avoids the nonzero offset and other sources of error that could appear when other instruments are used as reference.

Different criteria to estimate the thermal offset from capping events’ measurements (Bush et al. 2000; Dutton et al. 2001; Carlund 2013; Haefelin et al. 2001) have been applied and compared. Some criteria were adapted to our specific pyranometer model: the Kipp & Zonen CM11. Although all criteria resulted in similar thermal offset values on cloudy days, significant differences for Carlund’s and Haefelin et al.’s criteria with respect to any others have been detected. It was concluded that the convenience of coming to an agreement for establishing a standard procedure would make comparisons easier.

In this study, the criterion proposed by Bush et al. (2000) and Michalsky et al. (2005), which consists of selecting the lower signal value after the pyranometer is capped, was chosen because it allows to directly estimate the thermal offset without the need to specify any additional characteristic of the pyranometer.

The significance of differences between the thermal offset of pyranometers A and B has been assessed by means of a two-sample $t$ test. The test indicates statistically significant differences between the means at a 95% confidence level, concluding the need to characterize each radiometer individually.

Significant differences in the thermal offset between daytime and nighttime were also found. This important result agrees well with results reported by Cess et al. (2000), Philipona (2002), and Ji and Tsay (2010) for other pyranometer models and locations. This finding advises against the common procedure of assuming that the nighttime offset constitutes an appropriate estimation for the daytime thermal offset.

Regarding measuring global or diffuse radiation, differences in the range from 0.61 to 5.86 W m$^{-2}$ for pyranometer A and from 0.56 to 3.74 W m$^{-2}$ for pyranometer B have been obtained. These differences were confirmed by a two-sample $t$ test at a 95% confidence level. This finding agrees with Bush et al. (2000) and Cess et al. (2000) but dissents with results obtained by Philipona (2002). This diversity in results is probably related to the different methodology, instrumentation, and location used in these studies. These results argue for the need to develop studies focusing on different pyranometer types.

The relationship between the thermal offset and various characteristics of the environment and radiation conditions have been also examined. There are strong relationships with the ambient temperature, radiation, and the direct/diffuse partitioning. Thus, the highest thermal offset occurs in situations with low diffuse fraction and high ambient temperatures. Conversely, the lower thermal offset is found in situations with high
diffuse fraction and low ambient temperatures. The corresponding least squares regression between the thermal offset and each independent variable has been constructed, showing moderate predictive skill and the relationship with $K_d$, the one with the best performance, with a correlation coefficient of about 0.84.

This work aims to contribute to better knowledge of the pyranometer thermal offset error, in particular for the widely used Kipp & Zonen CM11. It is worth noting that, due to the difference in atmospheric conditions, the thermal offset of a particular pyranometer at one location may be different from the offset measured at another location. This fact emphasizes the importance of performing on-site measurements of the thermal offset. However, although our results apply solely to our specific instruments at our particular location, the methodology and comparisons described in this paper can be used to develop similar analysis at other locations, with other instruments and environmental conditions. In fact, the complete knowledge of the thermal offset issue will be achieved by a collection of studies that analyze specific instruments at particular locations. This study also suggests directions for future research concerning the development of correction models for the thermal offset.

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REFERENCES


