Significant Improvements in Pyranometer Nighttime Offsets Using High-Flow DC Ventilation

JOSEPH J. MICHALSKY

Cooperative Institute for Research in Environmental Sciences, University of Colorado Boulder, and NOAA/Earth System Research Laboratory, Boulder, Colorado

MARK KUTCHENREITER

National Renewable Energy Laboratory, Golden, Colorado

CHARLES N. LONG

Cooperative Institute for Research in Environmental Sciences, University of Colorado Boulder, and NOAA/Earth System Research Laboratory, Boulder, Colorado

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ABSTRACT

Ventilators are used to keep the domes of pyranometers clean and dry, but they affect the nighttime offset as well. This paper examines different ventilation strategies. For the several commercial single-black-detector pyranometers with ventilators examined here, high-flow-rate [50 cubic feet per minute (CFM) and higher] 12-VDC (where VDC refers to voltage direct current) fans lower the offsets, lower the scatter, and improve the predictability of the offsets during the night compared with lower-flow-rate (35 CFM) 120-VAC (where VAC refers to voltage alternating current) fans operated in the same ventilator housings. Black-and-white pyranometers sometimes show improvement with DC ventilation, but in some cases DC ventilation makes the offsets slightly worse. Since the offsets for these black-and-white pyranometers are always small, usually no more than 1 W m^{-2}, whether AC or DC ventilated, changing their ventilation to higher CFM DC ventilation is not imperative. Future work should include all major manufacturers of pyranometers and unventilated and ventilated pyranometers. An important outcome of future research will be to clarify under what circumstances nighttime data can be used to predict daytime offsets.

1. Introduction

Accurate solar radiation measurements using pyranometers are required to understand the radiative impacts on climate and solar energy production, and to validate radiative transfer models. Pyranometers with single black detectors often underestimate the downwelling global or diffuse solar irradiance measured unless offset corrections are applied. Offsets arise from the outer dome cooling by radiating to the atmosphere above the instrument, which allows the inner dome and thermopile hot junction to cool somewhat, leading to an underestimated solar irradiance signal. This paper examines changes in nighttime pyranometer offsets by converting from low-flow-rate AC fans to high-flow-rate DC fans in some pyranometers or by adding high-flow-rate ventilation to unventilated pyranometers—either change leads to lower and more predictable nighttime offsets. Ventilation is performed by placing the pyranometer in an enclosure, pulling ambient air using a fan through a port that is typically under the instrument, passing the air around the body of the pyranometer, and directing the exiting air onto the dome of the pyranometer.

Charlock and Alberta (1996) noted early on that global and diffuse irradiance measurements were lower than model predictions for clear skies. Diffuse solar irradiance measurements for cloudless skies were found by Kato et al. (1997) to be significantly lower than model predictions using carefully considered ancillary inputs into the radiative transfer models, especially aerosol optical depth, asymmetry parameter, and single-scattering albedo. Halthore et al. (1998) corroborated the clear-sky biases in an independent study, finding a smaller bias than Kato

Corresponding author: Joseph J. Michalsky, joseph.michalsky@noaa.gov

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et al. (1997) but only after correcting the diffuse measurements by subtracting the average measured nighttime offset. The latter two studies reasoned that the differences could not be explained by uncertainties in the physical inputs to the models or errors in the models themselves. Both studies suggested some additional, previously unassigned atmospheric absorption as a possible solution to the dilemma. Kato et al. (1997) and Halthore et al. (1998) used the U.S. Department of Energy's Atmospheric Radiation Measurement (ARM) (Stokes and Schwartz 1994) program's pyranometers for their studies. Cess et al. (2000) found that diffuse irradiance values for clear skies measured with ARM pyranometers were sometimes smaller than the Rayleigh–sky limit even when the averaged nighttime offset was subtracted from the daytime data, suggesting that using an averaged nighttime offset was inadequate to account for higher offsets present during clear daytime measurements.

Dutton et al. (2001) developed a method to estimate the offset correction for diffuse solar irradiance measurements made using a ventilated Eppley Precision Spectral Pyranometer (PSP); they used a linear relationship developed between the pyranometer offset ($W\,m^{-2}$) and a shaded and ventilated pyrgeometer thermopile signal ($W\,m^{-2}$; also called instrument net infrared) measured at night. Gulbrandsen (1978) had earlier suggested a relationship between the pyranometer offset and the instrument net infrared, but he did not suggest a practical methodology to correct the problem.

Younkin and Long (2003) made additional adjustments to the Dutton et al. (2001) corrections by identifying two modes of offset behavior. These are primarily associated with relative humidity as it relates to ambient liquid haze and fog development and are therefore dubbed the "wet" and "dry" modes, respectively. Further, the authors used the more complete Dutton et al. (2001) dependence of the offset on both the instrument net infrared and the dome–case temperature difference,

$$\text{offset} = a_0 + a_1 \times \text{IR}_{\text{net}} + a_2 \times \sigma(T^4_{\text{dome}} - T^4_{\text{case}}), \qquad (1)$$

where T_{dome} and T_{case} are the measured dome and case temperatures (K) of the pyrgeometer, respectively; offset is the pyranometer offset ($W\,m^{-2}$); and IR_{net} is the pyrgeometer instrument net infrared ($W\,m^{-2}$). In comparison to the offset-corrected single-black-detector data to black-and-white pyranometer data, which they assumed had no appreciable offset based on the Dutton et al. (2001) study, Younkin and Long (2003), whose algorithm was developed only for diffuse irradiance measurements made with the Eppley PSP and ventilated with the Eppley ventilator model VEN using a 35-cubic-feet-per-minute (CFM), 120-VAC (where VAC refers to voltage alternating current) fan, found that they needed to apply small multiplicative factors to the instrument net infrared term [measured with an Eppley Precision Infared Radiometer (PIR) that was shaded and ventilated with a 35-CFM, 120-VAC fan] during daylight hours to optimize the agreement with the black-and-white pyranometers.

All of the effort in correcting offsets in pyranometers by Dutton et al. (2001) and Younkin and Long (2003) were for diffuse irradiance measurements made using the Eppley PSP operating alongside an Eppley PIR, both of which were shaded and ventilated with 35-CFM, 120-VAC fans. Note that some infrared radiometers made by other manufacturers do not have a dome thermistor to measure its temperature (e.g., Kipp & Zonen CG4 and Hukseflux IR20); hence, the third term of Eq. (1) cannot be used. These manufacturers give as a reason that they have designed their infrared radiometers to eliminate the temperature difference between the dome and case through efficient thermal coupling of the dome to the radiometer case. Our tests on two CG4s find no significant differences in dome and case temperatures. Note that Dutton et al.'s (2001) corrections are based on Eq. (1) with the "a_2" term set to zero, allowing for the use of any pyrgeometer in developing these offset correction schemes.

Michalsky et al. (2003, 2005) looked at offsets of several different manufacturers' pyranometers, measuring diffuse irradiance as a function of the instrument net infrared as measured by an Eppley model PIR that was shaded and ventilated with a 35-CFM, 120-VAC fan. Many single-black detectors had nighttime-based predicted offsets during the day that were confirmed by capping experiments. Of the tested pyranometers, the Eppley PSP had the largest offset, followed by the Kipp & Zonen CM11, and then the CM 22, which had very little offset. Philipona (2002) was able to further minimize the small offset of the CM22 by designing a ventilator that slightly heated the airstream as it exited the ventilator and passed over the silicon dome of this instrument [see Fig. 10 in Michalsky et al. (2003)]. We note that black-and-white pyranometers have offsets that are typically no larger than about 1 $W\,m^{-2}$ (Michalsky et al. 2003, 2005; Fig. 4, this paper). A Yankee Environmental Systems prototype pyranometer in that study also had no offset even though it uses a single-black detector [see Fig. 10 in Michalsky et al. (2003)]. Table 1 from Michalsky et al. (2005) demonstrates that for all of the pyranometers studied in this paper, except for the SpectraSun SR-75, which was not part of the 2005 paper's study, nighttime offsets versus instrument net infrared can be used to predict the daytime offset if all instruments are ventilated. Linear fits of the nighttime pyranometer offsets versus the instrument net infrared, forced to zero offset at zero instrument net infrared, as prescribed in Dutton et al. (2001), produced an estimate of the daytime offset within $1\ \mathrm{W\,m^{-2}}$ of the offset determined by capping. The capping was performed during the daytime period that is expected to have the largest offset, that is, clear and dry midafternoon conditions.

Some pyranometer offsets were not predictable from the instrument net infrared, showing no dependence or inconsistent dependence on the measured instrument net infrared. Note that the pyranometers in Table 1 in Michalsky et al. (2005), for which nighttime data could not be used to accurately predict the daytime offset, were not ventilated.

Although not part of this study, other methods that require modification of the PSP pyranometer have been used to measure the offsets during the night and day. Bush et al. (2000) and Haeffelin et al. (2001) added thermistors to the dome and case of the pyranometer to directly measure their temperatures and then relate the temperature differences to an offset correction. More recently, Ji and Tsay (2010) used a novel approach for correcting pyranometer offsets that applies to daytime and nighttime measurements. They found that measuring the pressure between double-domed pyranometers, such as the Eppley PSP, permitted a nonintrusive way (the dome was not blocked by thermistors) to calculate the effective dome temperature. Using this calculated temperature and the measured case temperature allowed for a straightforward and accurate offset calculation.

In this paper, we investigate the role of ventilation on the nighttime offset. We show that most of the improvements are realized when we change from a low-flow-rate AC ventilator fan to a higher-flow-rate but lower-powered DC fan in the ventilation system, or when we change from no ventilation to DC ventilation. As a preview, consider Fig. 1, which contains data from the ARM program's site near Barrow, Alaska, during the 2006–09 North Slope of Alaska (NSA) Pyranometer IR Loss Study and the Evaluation of Heated Ventilators in the Arctic (www.arm.gov/campaigns/nsa2006PYIRloss; www.arm.gov/campaigns/nsa2007pyranometerext, respectively). The plot has the pyranometer offset on the *x* axis and the 35-CFM, 120-VAC ventilated Eppley PIR instrument net infrared on the *y* axis. Blue nighttime measurement points are for the PSP pyranometer with 35-CFM, 120-VAC ventilation, and the black points are for ventilation using a 50-CFM, 12-VDC (where VDC refers to voltage direct current) fan in the same ventilator housing. One can readily see that the DC fan produces a lower offset.

The setup and configurations for the measurements and the results of some experiments are presented in the next section. Recommendations from this study are summarized in the final section.

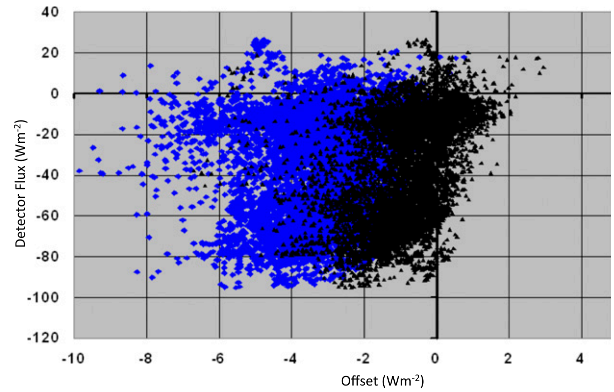

FIG. 1. Eppley PSP pyranometer offset when ventilated with a 35-CFM AC fan (blue) and when ventilated with a 50-CFM DC fan (black). Note the decreased offset at all instrument net infrared ("detector flux") values (*y* axis). Eppley PIR infrared measurements use a 35-CFM, 120-VAC fan for all measurements.

2. Experimental setup and results

In this study the focus was on the nighttime offsets associated with Eppley models PSPs and 8-48 pyranometers, with these offsets modeled using the Eppley PIR signals (instrument net infrared and dome–case temperature difference) as independent variables, as in Eq. (1); however, we present a sampling of offsets from other pyranometers with their dependence on signals measured by a PIR. Specifically, SpectraSun SR-75 and Kipp & Zonen CM11 and CM21 nighttime offsets were examined. The Eppley and SpectraSun pyranometers were ventilated using both low-speed AC (~35 CFM) fans and high-speed DC (~50 or ~80 CFM) fans. The flow rates indicated in this paper are the fan manufacturers' free-flow ratings; however, in pyranometer ventilator housings, the back pressure—primarily due to the small outlet around the dome—lowers these flow rates significantly. For example, ventilator output volumetric flow measurements performed at the National Renewable Energy Laboratory (NREL) using the Eppley model VEN ventilator with an installed PSP showed flow reductions to near 10% of the manufacturers' free-flow CFM ratings for the AC and DC fans that were tested. Kipp & Zonen pyranometer nighttime offsets with no ventilation and with 12-VDC ventilation were also examined. Table 1 contains the instruments used for this study and information about the instruments and their locations.

a. NREL offset measurements

The offsets' measurement work at NREL will be discussed first. This study used nighttime measurements when the sun was more than 10° below the horizon. The measurements were made on 32 consecutive days in

TABLE 1. Pyranometers tested and location

Pyranometer model	Manufacturer	Type	Ventilation	Location
PSP	Eppley	Single black detector	120 VAC, 35 CFM and 12 VDC, 50 CFM	Barrow, AK 71.3230°N, 156.6114°W
5 PSPs	Eppley	Single black detector	2–120 VAC, 35 CFM and 3–12 VDC, 50 CFM	Golden, CO 39.7424°N, 105.1786°W
SR-75 and 8-48	SpectraSun and Eppley	Single black detector, and black and white	120 VAC, 35 CFM and 12 VDC, 80 CFM	Goodwin Creek, MS 34.2550°N, 89.8736°W
PSP	Eppley	Single black detector	12 VDC, 50 CFM and 120 VAC, 35 CFM	Eugene, OR 44.0467°N, 123.0742°W
2 CM11s and 2 CM22s	Kipp & Zonen	Single black detector	None and 12 VDC, 100 CFM	Boulder, CO 39.9911°N, 105.2607°W

midwinter beginning 9 January 2014, at NREL in Golden, Colorado, with net infrared values covering the complete range one might experience in a year. Five Eppley PSPs, each with a different model or manufacturer's ventilating fan but the same Eppley VEN ventilator housing, were equipped with one of two different model AC fans (~35 CFM) or one of three different model DC fans (~50 CFM). Eppley PIR measurements were ventilated using an Eppley model VEN ventilator (~35 CFM, 120 VAC).

Figure 2 (left) shows nighttime offsets of two AC-ventilated PSPs (W m^{-2}) compared to the simultaneously measured instrument net infrared, that is, the thermopile signal of the PIR (W m^{-2}). The blue (Sanyo Denki 109-043UL, 35 CFM) and black (Comair Rotron SUZA1 "Sprite," 35 CFM) lines are robust linear least squares fits to the black and blue pyranometer offsets, respectively. The differences in the black and blue lines may be due to differences in the fan models; the black points use an older model AC fan that Eppley no longer offers, and the blue points use the current Eppley AC ventilation fan. Also, although PSPs are made to be very similar, some minor differences are inevitable. The general pattern (in an absolute sense) is for the offset to increase with

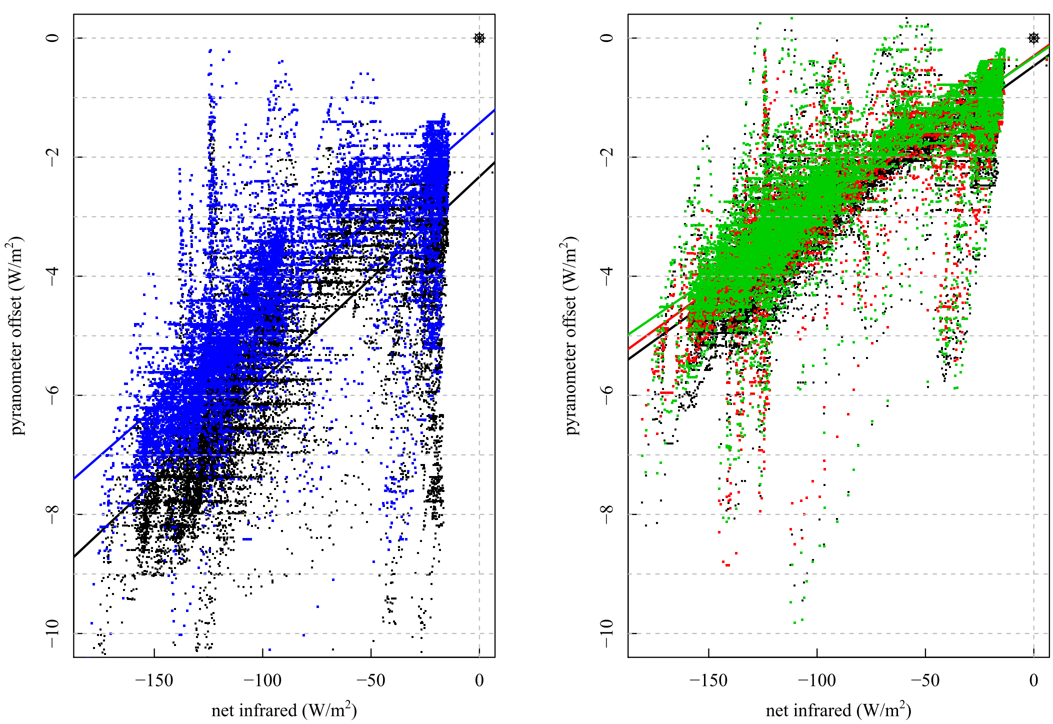

FIG. 2. (left) Offsets for two PSPs ventilated using 35-CFM, 120-VAC fans. (right) Offsets for three PSPs ventilated with 50-CFM, 12-VDC fans for the same period. Note that the right plot has lower offsets, less scatter, fewer extreme values, better linearity, and passes nearly through zero offset at zero instrument net infrared (indicated by the circled asterisk).

the instrument net infrared from approximately -2 to $-8\,\mathrm{W\,m^{-2}}$ for these nighttime winter data. The linear fits to the data do not pass through a zero offset at zero instrument net infrared. No attempt has been made to eliminate data that may have been affected by precipitation on the domes of the instruments, which is likely responsible for much of the scatter (Oswald et al. 2016). The highest instrument net infrared (least negative values) occurred when there were low overcast skies when precipitation was most likely but not necessarily occurring. The pyranometer offset range at near $-30\,\mathrm{W\,m^{-2}}$ instrument net infrared was from -1.5 to $-8\,\mathrm{W\,m^{-2}}$, which we assume is caused by conditions when there was no precipitation (low absolute offsets) to precipitation-covered pyranometers (high absolute offsets).

Three higher-flow DC-ventilated PSP offset plots are shown in Fig. 2 (right) at the same scale as Fig. 2 (left). The black, red, and green lines are again robust linear least squares fits to the data. Two points need to be made when comparing these three plots to the AC fans' data on the left are that the scatter on the right is less and that the offset is smaller overall. Further, note that the low (absolute) instrument net infrared points (near $-30\,\mathrm{W\,m^{-2}}$) show some spread, but it is within a smaller range than that in the left plot. The offset varies between -5 and $-0.5\,\mathrm{W\,m^{-2}}$. The DC-ventilated PSPs behaved very similarly to each other, and the offset is within $0.5\,\mathrm{W\,m^{-2}}$ of zero at zero instrument net infrared.

Figure 3 is a plot of the measured temperature of the case (or body) of the PSP compared to the temperature of the air before it enters the ventilator. These lines are lowess fits to the actual data to facilitate viewing of the differences. The largest temperature differences are for the AC fans with the older AC fan having the largest difference from the one-to-one line. The DC fans affect the ventilated air temperature much less than the AC fans. The offsets in Fig. 2 are positively correlated to these temperature differences, suggesting that a portion of the offset is caused by the amount of energy dissipated by the fan motor that heats the body of the pyranometer.

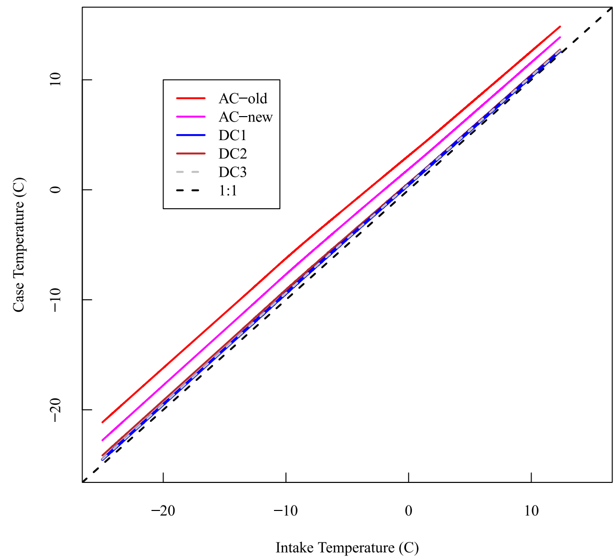

FIG. 3. Illustration of the difference between the temperature of the air before it enters the ventilator and the temperature of the pyranometer case, which is heated by the fan motor. Legend indicates the AC fans show more heating, which is a significant contributor to the offset.

b. SURFRAD offset measurements

SpectraSun pyranometers are used for global horizontal irradiance measurements in the Surface Radiation Budget Network (SURFRAD) (Augustine et al. 2005). Because they have nearly the same instrument profile as the Eppley PSP, SpectraSun SR-75s were originally ventilated using a slightly modified Eppley VEN with a 35-CFM AC fan with the modification allowing air to more directly flow toward the dome of the pyranometer. These were changed to 80-CFM DC fans in 2016 without further modifications to the Eppley VEN ventilator housing.

Figure 4 (top left) is a plot for an SR-75 pyranometer at the SURFRAD site near Goodwin Creek, Mississippi, with an AC fan ventilating an SR-75 before day 133 and then a DC fan ventilating a different SR-75 after day 133. Clearly, the offset improved after day 133. Each 1-min point at night is plotted, suggesting that there are many overlapping points. The offsets are not as large as those in Fig. 2 because this site has a humid climate; consequently, radiation cooling to space is limited. Further, without exception we find that the SR-75 has an inherently smaller offset than the PSP. As mentioned earlier, in order to use the Eppley ventilator for the SR-75, the instrument ventilation was slightly modified to allow the vented air to more directly impact the dome of the instrument. This could explain the smaller offset in the SR-75 compared to the PSP. If we perform a robust linear least squares fit to the pyranometer offset versus the instrument net infrared (thermopile signal from an Eppley PIR using an Eppley VEN ventilator with a 50-CFM, 12-VDC fan) forced through zero (for the days after day 133), we can subtract this offset as a function of the instrument net infrared from each point. The results are shown by the histograms in Fig. 4 (top right). The gray bars indicate the frequency distribution before the correction. After the correction the nighttime data (red bars with gray borders) are more "normally distributed" around zero, based on an examination of

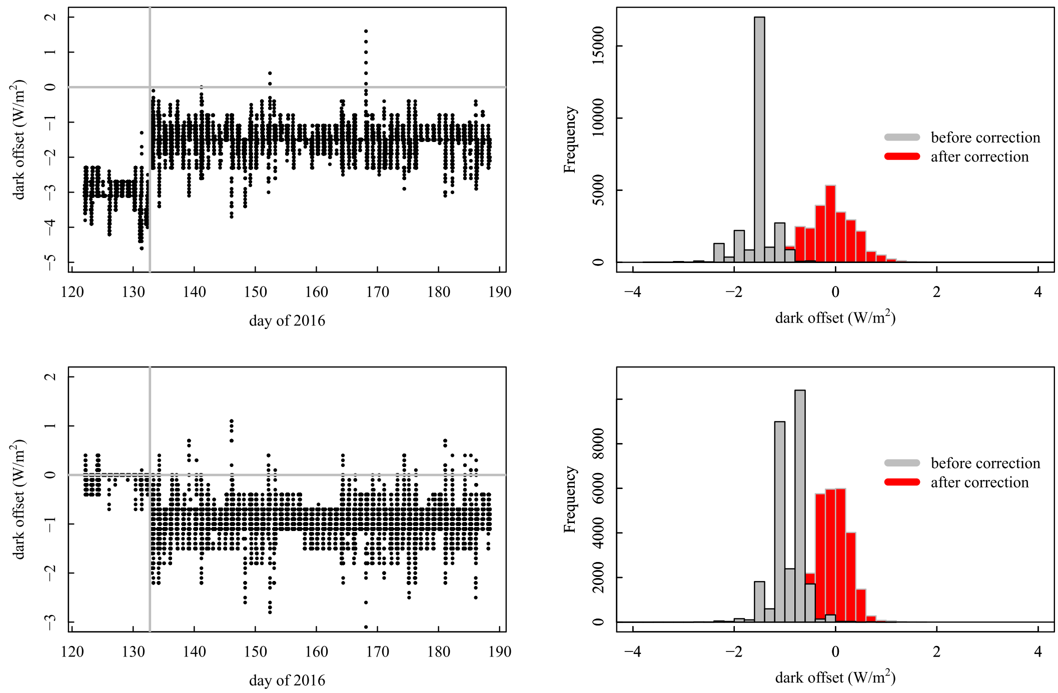

FIG. 4. (top left) SpectraSun pyranometer dark offsets before and after switching to DC ventilation on day 133. (top right) Gray histogram is for the offsets after day 133 but before the correction; red histogram is for the offsets after day 133 after a correction based on a linear fit of offset vs instrument net infrared forced through zero at zero net infrared irradiance; 95% of the red points are within $\pm 1.1\,\mathrm{W\,m^{-2}}$. (bottom left) Eppley model 8-48 (black and white) pyranometer dark offsets before and after switching to DC ventilation on day 133. Note that the offsets are larger than they were with AC ventilation, although offsets are always small for black-and-white pyranometers. (bottom right) As in (top right), but for the Eppley model 8-48 pyranometer data after day 133. In the post-correction histogram (red) 95% of the points are within $\pm 0.6\,\mathrm{W\,m^{-2}}$.

quantile–quantile (q–q) plots for both datasets, with 95% of the red points falling within $\pm\ 1.1\,\mathrm{W\,m^{-2}}$.

Figure 4 (bottom left) is a plot for an Eppley 8-48 (i.e., black and white) pyranometer at the SURFRAD site near Goodwin Creek, Mississippi, with a 35-CFM, 120-VAC fan ventilating an 8-48 pyranometer before day 133 and then a 50-CFM, 12-VDC fan ventilating a different 8-48 pyranometer after day 133. The offset is somewhat greater after day 133. The offsets for this instrument are inherently small. In this case, the offsets are slightly larger with DC ventilation, although this is not always the case; an examination of several sites with 8-48s suggests that DC ventilation sometimes improves the offsets, makes them worse, or causes no change at all, but the offsets are always modest, with generally less than $1\,\mathrm{W\,m^{-2}}$ of offset. We have no explanation for these differences for the 8-48. Figure 4 (bottom right) contains histograms of the offsets for this 8-48 before and after they are corrected using a robust linear fit of offset versus instrument net infrared forced though zero for days after day 133. Again, the frequency distribution after the correction (red bars) is more normally distributed around zero, based on an examination of q–q plots for both datasets, with 95% of the red points falling within $\pm\ 0.6\,\mathrm{W\,m^{-2}}$.

c. *University of Oregon offset measurements*

At the University of Oregon, the global irradiance measurements are made using an Eppley PSP ventilated with an Eppley VEN with a 35-CFM AC fan. A visiting Pacific Northwest National Laboratory (PNNL) system was set up next to it that also measures global irradiance with an Eppley PSP, but it uses a 50-CFM DC fan in the Eppley VEN ventilator. The PNNL system also has an Eppley PIR pyrgeometer ventilated with a 50-CFM DC fan in the VEN ventilator. These PSPs were operated side by side for 4 days and then ventilator systems were switched and run for 3 days in this alternate configuration.

Figure 5 is an offset plot of the PNNL PSP pyranometer data at night in the PNNL DC ventilator (blue) and then in the University of Oregon AC ventilator (red) during a 7-night span. In the prior discussion, we compared PSPs, but not the same PSP as we are showing here. For both periods, the offset behavior with instrument net infrared readings was linear. There was a

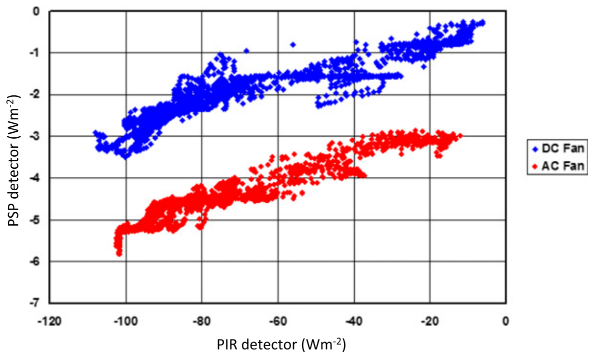

FIG. 5. Offsets for the *same* University of Oregon PSP plotted for 4 days in a DC ventilator (blue) and then switched to an AC ventilator (red) for 3 days.

significant increase in the magnitude of the offset when switched from DC to AC ventilation. The humidity and clouds on these nights limited the escape of infrared radiation and therefore limited the range of instrument net infrared readings (cf. to the range in Fig. 2). Not shown are data from the University of Oregon PSP that had the ventilation schemes swapped from that shown in Fig. 5 on the same days. The data are very similar but are not shown to avoid confusion because of overlapping points.

d. Offsets of Kipp & Zonen pyranometers

In Figs. 6 (top) and (middle), pyranometer offsets versus the instrument net infrared are plotted with neither CM11s nor CM21s ventilated; nor is the collocated Eppley PIR pyrgeometer measuring instrument net infrared ventilated. Unventilated CM11 offsets are plotted in Figs. 6 (top left) and (middle left) and offsets for two CM21s are plotted in Figs. 6 (top right) and (middle right). All of the patterns for these pyranometers are similar. The offsets of the CM11s are marginally smaller; however, the spread in the scatter is somewhat less for the CM21s. The red fit to the data is a lowess fit that indicates minor nonlinearity when compared to the green linear fit to the data. The linear fit is forced through zero at zero instrument net infrared (small red circle), but it appears that it has that tendency without the forcing. Note that the lowess fit passes very close to zero when the instrument net infrared is zero, confirming this tendency.

Figure 6 (bottom) illustrates the effect of ventilating with the standard CV 2 ventilator, which is no longer sold by Kipp & Zonen. This is a 100-CFM, 12-VDC ventilator that heats the pyranometer very little. By simple inspection (holding one's hand above the ventilator), we find that this ventilator pushes much more air over the CM pyranometers than the Eppley AC ventilator pushes over the PSP or 8-48. These two plots demonstrate that offsets are halved with DC ventilation compared to the unventilated results in the first two rows of plots. For the bottom plots, the Eppley PIR pyrgeometer is ventilated using a 50-CFM, 12-VDC fan. Note that the unventilated data were taken during July 2016 and that the ventilated data were measured in October 2016; this explains the larger range in instrument net infrared with the cooler and dryer fall atmospheric conditions. However, if we compare over the same ranges of instrument net infrared, we can see that the decrease in offset may be even more than one-half.

3. Summary and recommendations

Underestimating downwelling global or diffuse solar irradiance measurements in climate change research and in renewable energy applications because of radiometer thermal offset effects results in increased data uncertainty, if no attempt is made to correct this offset. Radiometric data with known uncertainties are essential for climate change studies to better understand Earth's radiation budget. Solar radiation resource measurements used in photovoltaic system performance evaluations are also impacted by the irradiance underestimation associated with thermal offset error.

We have shown several examples of improvements in the behavior and in the predictability of offsets by switching to a lower DC voltage and a higher-CFM fan when ventilating the PSP. Figure 2 suggests that there is less scatter [even for the extreme events around $-30\,\mathrm{W\,m^{-2}}$ on the instrument net infrared axis; compare Figs. 2 (left) and (right)], lower offsets, and more predictable linear behavior with DC ventilation. Figure 3 suggests that the decrease in magnitude of the offset may be in part due to the lower heating of the pyranometer due to the fan motor heat output. Figure 4 (top left) indicates that offsets are reduced by approximately one-half for the SpectraSun pyranometer and they indicate that the offsets, at least at night, are predictable and therefore removable to approximately $\pm 1.1\,\mathrm{W\,m^{-2}}$ [Fig. 4 (top right)]. Six SpectraSun pyranometers examined after higher-speed DC ventilation was added (although only one is shown here) indicated similar reductions in offsets. For the Eppley 8-48 black-and-white pyranometer, the small inherent offset may be slightly better or slightly worse with DC ventilation; nevertheless, it was predictable to $\pm 0.6\,\mathrm{W\,m^{-2}}$ (see Fig. 4, bottom). Some measurements of the effect of using high-speed ventilation on Eppley 8-48s have indicated decreases and stabilization of the offsets. In our study of eight 8-48 pyranometers (only the one in Fig. 4 is shown), we found two improved with DC ventilation, two were worse, and three showed little change. We emphasize that 8-48 offsets are very small, typically

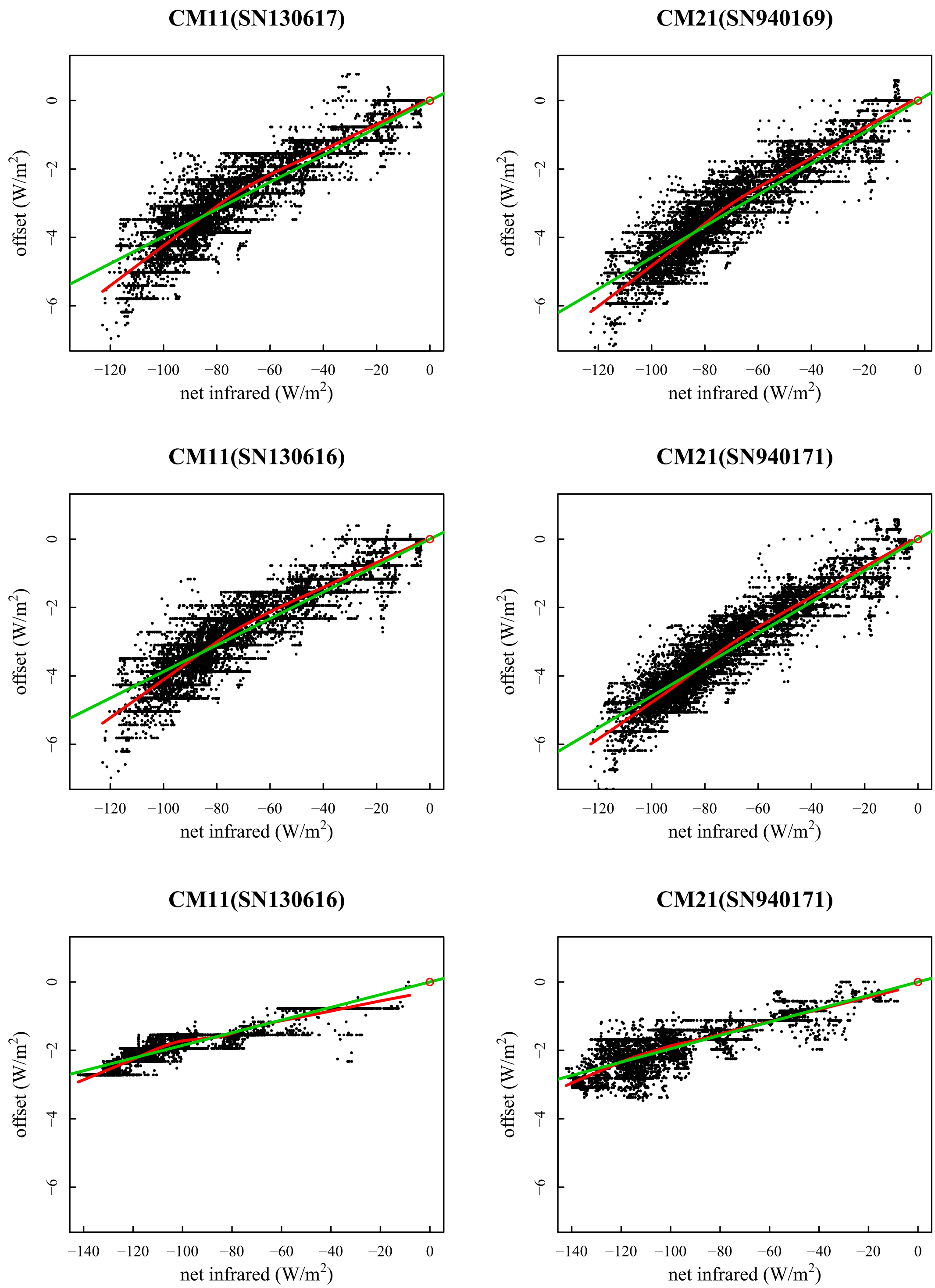

FIG. 6. (top left), (middle left) Offsets for unventilated Kipp & Zonen CM11s and (top right), (middle right) CM21s vs instrument net infrared from an unventilated Eppley PIR. Behavior in the two rows of plots is very similar. Green lines are linear fits forced through zero, and red lines are lowess fits, which pass very close to zero. (bottom) After ventilation was introduced for the CM11 [cf. (middle left) and (bottom left)] and the CM21 [cf. (middle right) and (bottom right)]. Note the decrease in absolute offset and in scatter. A few extreme outliers likely associated with precipitation events have been removed to focus on the general behavior.

about 1 W m^{-2}. Figure 5 is a direct example of the effect of ventilation because the same pyranometer is ventilated on seven consecutive days and only the ventilation fan type is changed from DC to AC. The nighttime conditions were very similar for this 7-night comparison. Not plotted are the data from another PSP at the same site whose ventilation was the complement of that shown and whose behavior was overlapping and opposite to that shown. As a side experiment, we found that the offset improvement was nearly the same for Eppley PSPs with 12-VDC ventilation using either 50- or 80-CFM fans (data not shown). The slight advantage of the 80-CFM fan would be to, perhaps, keep the domes cleaner or remove moisture more quickly. Figure 6 demonstrates that the offsets for the unventilated Kipp & Zonen CM11 and CM21 pyranometers were very similar and predictable when there were no precipitation events or abrupt changes in temperature or wind speed. The offsets improve significantly when the Kipp & Zonen CVF3 DC ventilators were added (Fig 6, bottom). It is important to note that Sanchez et al. (2015) and Serrano et al. (2015) found that *unventilated* CM11s [Figs. 6 (top left) and (middle left)] did not show the same offset behavior as a function of instrument net infrared during the day and during the night. There is likely to be similar behavior for the CM21s. Therefore, it is not known whether nighttime data can be used to predict daytime offsets when pyranometers are not ventilated.

If we consider Fig. 2 (right) and Fig. 6 (bottom), the offset behavior of the PSP and CM11 and CM21 become similarly predictable. To reach this conclusion, consider that all points are plotted in Fig. 2, including the exceptional outliers likely caused by precipitation events; these have been excluded from Fig. 6. Clearly, high-speed DC (~50 CFM, or higher), and perhaps more dome-directed ventilation, lowers the pyranometer offset and makes it more predictable.

The NREL PIR used an AC ventilator; in this regard, it may be that corrections developed for a pyranometer taking concurrent measurements with a DC fan would change somewhat if the ventilator for the PIR were switched to a DC ventilator as well. Further, if the ventilators were switched to different PSPs, there may be subtle changes in the dependence on instrument net infrared. But from Fig. 2 (right), there does not appear to be large differences among these three PSPs that are DC ventilated. Still, to optimize corrections, it seems prudent that offset corrections be developed using paired pyranometers and pyrgeometers.

More research remains regarding validations of the offset predictions during daytime conditions, such as those performed in the Michalsky et al. (2003, 2005) capping experiments and the Younkin and Long (2003) comparisons to infrared loss-resistant black-and-white pyranometers. We have good evidence from the Michalsky et al. (2005, their Table 1) capping experiment that the *ventilated* PSP, CM11, CM21, and CM22 nighttime offsets can be used to predict daytime offsets. Dutton et al. (2001) also found that daytime offsets could be predicted from nighttime data when all instruments were ventilated and shaded. Carlund (2013) further substantiated this predictable offset behavior for ventilated pyranometers, both shaded and unshaded. This predictability needs to be confirmed for the ventilated SR-75. We are fairly certain that the nighttime offsets of unventilated pyranometers cannot be used to predict daytime offsets for the reasons cited earlier (Serrano et al. 2015; Sanchez et al. 2015) and based on the Carlund (2013) results for unventilated pyranometers. Other commercial pyranometers should be tested; however, our focus was on those available to us. Most of the effort to date has focused on diffuse irradiance. Global irradiance offsets need to have more emphasis, but these often have more significant issues related to directional response effects that may complicate the offset issue discussed here.

Overall, the study provides insightful results toward obtaining accurate solar radiation measurements for solar energy applications and climate change studies. Manufacturers and researchers continue to improve designs of pyranometers and ventilation systems, which should assist in acquiring accurate solar radiation data with low uncertainty.

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