Measurement of Broadband Diffuse Solar Irradiance Using Current Commercial Instrumentation with a Correction for Thermal Offset Errors

ELLSWORTH G. DUTTON,* JOSEPH J. MICHALSKY,+ THOMAS STOFFEL,# BRUCE W. FORGAN,@
JOHN HICKEY,&,++ DONALD W. NELSON,* TIMOTHY L. ALBERTA,**,## AND IBRAHIM REDA#

* *NOAA/Climate Monitoring and Diagnostics Laboratory, Boulder, Colorado*
+ *Atmospheric Sciences Research Center, University at Albany, State University of New York, Albany, New York*
# *National Renewable Energy Laboratory, Golden, Colorado*
@ *Bureau of Meteorology, Melbourne, Victoria, Australia*
& *Eppley Laboratory, Newport, Rhode Island*
** *Analytical Services and Materials, Inc., Hampton, Virginia*

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ABSTRACT

Diffuse-sky solar irradiance is an important quantity for radiation budget research, particularly as it relates to climate. Diffuse irradiance is one component of the total downwelling solar irradiance and contains information on the amount of downward-scattered, as opposed to directly transmitted, solar radiation. Additionally, the diffuse component is often required when calibrating total irradiance radiometers. A variety of pyranometers are commonly used to measure solar diffuse irradiance. An examination of some instruments for measuring diffuse irradiance using solar tracking shade disks is presented, along with an evaluation of the achieved accuracy. A data correction procedure that is intended to account for the offset caused by thermal IR exchange between the detector and filter domes in certain common diffuse pyranometers is developed and validated. The correction factor is derived from outputs of a collocated pyrgeometer that measures atmospheric infrared irradiance.

1. Introduction

Total broadband incident solar irradiance is a quantity of major interest in climate research studies (e.g., Budyko 1969; Ramanathan 1987; Gilgen and Ohmura 1998). Recent studies (Michalsky et al. 1999; Ohmura et al. 1998; Bush et al. 2000) suggest that significant improvements in total surface solar irradiance observations can be obtained by combining separate measurements of the direct and diffuse, which minimizes the effects of cosine response errors. This is the recommended procedure for obtaining surface solar irradiance by the World Climate Research Program's (WCRP's) Baseline Surface Radiation Network (McArthur 1998). Similarly, accurate physical models of radiative transfer within the atmosphere and at the surface compute direct and diffuse solar irradiance as separate quantities (e.g., Stamnes et al. 1988; Liou 1992, p. 103). The separate component measurements and calculations allow the quantities to be individually compared with any sources of disagreement partially isolated. It can be ascertained that the measurement and computation of the direct beam at the surface are simpler and more accurate than for either the total or diffuse irradiance (Fröhlich 1991; Fouquart et al. 1991; Halthore et al. 1997). The diffuse quantity is problematic to measure because of the need to integrate hemispherically and difficult to compute because of the difficulty of properly specifying the optical properties of the atmosphere in the presence of clouds and aerosols. Several recent studies (Charlock and Alberta 1996; Kato et al. 1997; Halthore et al. 1998) made comparisons between measured and modeled diffuse irradiance and showed disagreement, with measurements being less than calculations, consistent with earlier studies (Joseph and Wolfson 1975; Forgan 1984a).

The purpose of this paper is to further evaluate and validate diffuse observations that are commonly made with current commercial thermopile pyranometers that were used in the above most recent studies. Measurement errors that can bias diffuse measurements to the low side are identified as resulting from thermal infrared effects within these radiometers (Robinson 1966; Gulbrandsen 1978; Wardle and Barton 1988; McArthur 1998; Halthore et al. 1998). Thermal infrared cooling of the instrument's protective glass dome to the sky is

++ Retired.
Current affiliation: University Corporation for Atmospheric Research, Boulder, Colorado.

Corresponding author address: Ellsworth Dutton, NOAA/Climate Monitoring and Diagnostics Laboratory, R/CMDL1, 325 Broadway, Boulder, CO 80303.
E-mail: edutton@cmdl.noaa.gov

typically the largest source of this offset error. Although the cause of thermal offset error has been known for some time, corrections are often not made in routinely produced data because manufacturers strive to minimize the error and forced ventilation is often added to the instrument in an attempt to further reduce the error. In addition, the means for properly correcting for remaining errors have not always been available. Thermal offset errors in some common, currently used, shaded pyranometers were recognized as a significant source of uncertainty in diffuse irradiance measurements and efforts were initiated to understand and correct for them (WCRP 1997). Recent papers by Bush et al. (2000) and Cess et al. (2000, hereafter CQS) highlighted this error source. CQS demonstrate an analysis procedure to detect the error in certain operational data, and Bush et al. presented an unvalidated correction procedure that requires instrument modification such that previously existing and current routine measurements could not be corrected. The present work discusses a validated correction procedure applicable to existing broadband diffuse data acquired with certain common broadband commercial pyranometers.

Several commercial solar radiometers are available for diffuse measurements from which a diverse subset was used in the current study. Because of their various designs and principles of operation, these instruments inherently have different sources and magnitudes of errors. Of particular concern are the thermal infrared (IR) induced offset errors that are introduced when the instrument detector responds to differences in internal surface temperatures. Commercial pyranometers are typically engineered and calibrated for optimal total solar irradiance signal levels, for example, making a single observation of the sum of direct and diffuse irradiance in a 2π sr field of view, or calibrating in an integrating sphere at high irradiance levels. Using these instruments in a shaded configuration to measure only the diffuse component results in measured irradiance levels well below the typical calibration irradiance levels; therefore, small percentage bias errors in total irradiance measurements can become larger percentage errors in diffuse measurements.

Previously suggested and newly developed empirical correction procedures accounting for the thermal offset errors are derived and applied to measurements obtained under normal field conditions. The corrections and corrected diffuse values are validated by three independent methods: 1) comparison to clear-sky Rayleigh diffuse calculations, 2) comparison to an inherent minimal-offset diffuse radiometer, and 3) an approximate direct measurement of the daytime offset error. The results show that in the mean the corrected diffuse observations agree to within about 4 W m^{-2} (5%) of the validation values under clear clean skies. Validation under cloudy conditions is less rigorous because an absolute reference, like the Rayleigh case for clearest skies, does not exist. Under cloudy conditions the error sources tend to decrease and there is excellent agreement ($<$3% or $<$7 W m^{-2}, whichever is larger) between independent measurement techniques.

2. Theoretical operation of the differential thermal sensing pyranometer

A common type of instrument for routinely measuring total and diffuse solar irradiance is the differential-heating thermopile pyranometer described by Drummond (1970), Coulson (1975), Wardle and McKay (1984), Wardle et al. (1996), and others. The fundamental basis of operation of a typical pyranometer is the measurement of the differential heating produced as sunlight is absorbed in a highly absorptive portion of the instrument relative to a less- or nonsolar absorptive portion. The instruments are designed so that the absorption of incident solar energy is intended to be the only significant source of the differential heating within the elements of the pyranometer. If this assumption holds true over the timescale of interest, then the response of the instrument, usually an electrical signal generated by a heat sensitive element, can be characterized relative to the amount of solar energy absorbed as determined by a calibration reference such as an absolute cavity radiometer (Fröhlich 1991). Typically, a thermopile is used to determine the heating difference, but other methods are also utilized. The instruments are typically engineered to produce a voltage output that is linear with incident irradiance and with minimal sensitivity to ambient temperature in the expected operating temperature range of the instrument.

It is useful to examine the heat budget of a typical pyranometer detector to identify the inherent and potential sources, in addition to the sun, that could heat (or cool) the sensor detector. In the following sections we will examine the main features of the design and heat budget of two different types of pyranometers, the solid black detector (SBD) and the black and white detector (B&W).

a. Solid black detectors

In SBD pyranometers the solar heating of a blackened surface is compared to an isolated shielded reference point utilizing comparative electrical measurements of relative heating change. The flat spectral response of an optically blackened surface is preferred over other possible detector spectral responses for the measurement of total solar irradiance across the solar spectral range. The spectral range of the instrument is typically limited to 0.28–2.8 μm by a glass dome covering the detector and protecting it from the environment. Other sources of differential heating of the detector or the reference point include ambient temperature changes, conductive and convective heat transfer in the immediate vicinity of the detector, and infrared exchange between exposed component surfaces of different temperatures.

TABLE 1. NOAA/CMDL and NREL diffuse pyranometer identification and features.

Manufacturer	Type and owner	Model and serial number	Ventilation	Special features
Kipp & Zonen	SBD–NOAA	CM21-940171	No	Hidden compensation detector
Eppley	SBD–NOAA	PSP-12268	Yes	—
EKO	SBD–NOAA	801-96068	No	Exposed compensation detector
Eppley	SBD–NOAA	PSP-14886	Yes	—
Eppley	B&W–NOAA	8-48-9095	No	Black and white
Eppley	SBD–NOAA	PSP-19918	Yes	—
Kipp & Zonen	SBD–NOAA	CM21-940169	No	Hidden compensation detector
Eppley	B&W–NOAA	8-48-32347	No	Black and white
EKO	SBD–NOAA	801-94019	No	Exposed compensation detector
Schenk	B&W–NOAA	1295	No	Black and white
Eppley	B&W–NOAA	Bulb-5437	No	Black and white
Eppley	SBD–NREL	PSP-17878	Yes	—
Eppley	B&W–NREL	8-48-32645	Yes	Black and white

The heat budget of a generic SBD is given in Eq. (1). A formulation of the heat budget of a similar black thermopile radiometer used for IR measurements was also given by Philipona et al. (1995) and Fairall et al. (1998):

$$\mathrm{SW}\tau(1 - \rho) + \mathrm{LW}\!\downarrow - \mathrm{LW}\!\uparrow - \Delta Tk + C = 0. \qquad (1)$$

The first term represents the shortwave irradiance, where SW is the incident shortwave irradiance, τ is the total transmittance of the glass dome, and ρ is the reflectance of the detector. The second term, LW$\downarrow$, is irradiance emitted from the glass dome and absorbed at the detector surface. Note that the absorption of the dome in solar wavelengths is $<0.1\%$ and does not significantly contribute to heating the glass. The third term, LW$\uparrow$, is the energy emitted from the detector surface. The fourth term, ΔTk, is the energy conducted away from the detector to the thermal sink, where ΔT is the temperature difference between the detector and sink, and k is the thermal diffusion coefficient. The last term, C, is the combination of the convective and other conductive processes that may be affecting the detector but cannot readily be determined. Ideal operation of the instrument would have SW $\tau(1 - \rho) = \Delta Tk$, LW$\downarrow$ = LW$\uparrow$, and $C = 0$. The condition LW$\downarrow$ = LW$\uparrow$ can be met for a given fixed geometry and temperature difference between the dome and detector. However, fluctuating sensor temperatures caused by ambient variations and differences in exposure of the dome and detector to the atmosphere lead to a potentially significant imbalance between the LW$\downarrow$ and LW$\uparrow$. Also, term C can be nonzero because of the different physical locations of the detector surface and the temperature reference point, and because the instruments are typically filled with air that can differentially affect both the turbulent and conductive heat transfer away from or toward the components. Pyranometer manufacturers have included an electrical temperature compensation component that accounts for the temperature effects on the sensitivity of the detector. While it is difficult to determine the magnitude of C, such errors should be random, at least over periods of many days. However, it is possible to estimate extraneous heating and cooling effects on the domes of the instruments that can cause a bias in the observations, that is, LW$\downarrow \neq$ LW$\uparrow$. Any mechanism that would consistently result in a dome temperature different from a reference condition under which the instrument was calibrated will bias the instrument output and result in measurement error. This error can become a high percentage of the measured diffuse component.

There are two different methods used to maintain the reference junction temperature in SBD pyranometers. One method is to attach the reference temperature junction to the instrument case that has relatively high thermal mass, whereas the other method is to maintain a low thermal mass reference point that is in radiative equilibrium with the dark interior of the instrument. Both methods achieve the same goal of providing a reference temperature to which the exposed detector is compared but the design does affect the performance characteristics and time constants of each instrument. Of the instruments investigated here (see Table 1 for partial list), the Eppley Precision Spectrum Pyranometers (PSPs) use the high thermal mass connection while the Kipp and Zonen and EKO units use the internal radiative equilibrium method. As will be seen, the method and success of the thermal offset correction procedures suggested here varies between these instrument types. The recent studies of Charlock and Alberta (1996), Kato et al. (1997), and Halthore et al. (1998) all used Eppley PSPs.

b. Black and white detectors

In a black and white pyranometer (B&W) the differential heating of a blackened element is also measured, but the detector reference component is a collocated white surface that is exposed to the same conditions, including solar and IR exposure, as the adjoining equal area blackened elements. The energy balance equation for these instruments effectively has no terms LW$\downarrow$, LW$\uparrow$, or C, as long as the emissivities of the black and white surfaces are the same. Several commercial designs for B&Ws exist, but they do not fulfill World Meteorological Organization (WMO) criteria for highest quality operational irradiance measurement instrumentation because of slower time response, uneven angular responses, and problematic spectral responses. Fortunately for diffuse-sky measurements, these requirements are not as relevant, and the merit of B&Ws having a low sensitivity to dome and convective temperature variations becomes a major advantage (Wardle and Barton 1988; Gulbrandsen 1978). It is more difficult to determine the exact spectral response of a given B&W since it depends on the characteristics of both the white and black coatings as well as the glass cover, and that information is not typically supplied by the manufacturer. Since the white coating used on these instruments tends to spectrally darken before (at a shorter wavelength) the glass window spectral cutoff, the assigned calibration value will result in an overestimate of clear-sky diffuse radiation. This is because the energy beyond the effective cutoff is compensated for in the typical direct-beam calibration but is not present in a clear-sky diffuse spectrum. However, for the strongly blue-shifted diffuse spectrum for clear skies this effect amounts to 2 W m^{-2} if the cutoff is abrupt and as low as 1.4 μm, or is less than 0.3 W m^{-2} if the cutoff is at 2.3 μm. In the samples of white detector sections that we tested the reflectivity was still near 80% at 2.3 μm and could not be determined beyond that on the equipment we had available.

3. Erroneous signals

The sources for erroneous detector heating resulting in thermal offsets in SBDs are included in Eq. (1). The dome and detector temperature imbalance can be maintained indefinitely due to the relatively low thermal capacity of the dome relative to the SBD body (reference) and the tendency of the dome to continually radiatively cool to the sky more efficiently than the body of the instrument. Additional random transient dome temperature fluctuations result from the dome's faster temperature response to changing ambient conditions. SBD instruments typically have two domes to reduce the response of the inner dome to ambient conditions.

Other sources of potential pyranometer error for both SBDs and B&Ws include calibration, linearity, ambient temperature response, angular (cosine and azimuth) response, spectral definition, and time response. A brief description of these additional error sources is given in the appendix. All of these other sources of error are usually specified by the manufacturer and combine to $<$3%–5% of the instantaneous instrument signal (Dutton et al. 1985; Myers 1988). However, erroneous detector heating in SBDs during times of low-level signals encountered during clear-sky diffuse irradiance measurements can be as high as 40% of the signal in some instruments under extreme conditions and are often in the 10%–30% range. Manufacturer specifications for thermal offsets often refer only to the magnitude of nighttime offsets that are observed and do not account for potential daytime enhancements or the high percentage error relative to clear-sky diffuse only signals.

4. Corrections to the SBD diffuse: Development of a procedure

Because of the SBD's advantages over the B&W, SBDs have been more widely used and it is, therefore, desirable to develop and test thermal offset corrections for diffuse measurements. Determining the relationship between the source and magnitude of thermal offsets would permit the development of such a correction function (Wardle and Barton 1988; Bush et al. 2000; Bush and Valero 1999). The relationship between the magnitude of thermal offsets and their causes can be investigated in the absence of a light source and are often called dark- or zero-offsets or signals. A correction for the thermal offsets based on the relationship between readily available information relating to the factors that help control the differential temperature of the SBD dome is desired. Observationally realistic thermal offset relationships can be obtained in outdoor nighttime conditions using the same instrumentation and installation configuration used for daytime observations. Our experience has shown that the nighttime offsets on a variety of SBD pyranometers will vary from about $+2$ to -12 W m^{-2} depending on specific instrument and ambient conditions, particularly surface infrared cooling and to a lesser extent wind speed. As expected, the B&W instruments show little to no ($<$1.5 W m^{-2}) nighttime offsets.

A measure of the cause of dome temperature differences is captured in the output signals of certain pyrgeometers (Wardle and Barton 1988). Pyrgeometers are used to measure atmospheric infrared radiation and are often collocated with diffuse pyranometers. Pyrgeometers used in this study were shaded, factory ventilated, Eppley Precision Infrared Radiometers, unless otherwise stated. The thermopile voltage of the pyrgeometer is highly correlated with the ambient net IR, which is a significant factor in the local surface energy budget affecting the temperature of the pyranometer glass domes. At many sites, pyrgeometer dome and case temperatures are routinely measured and are indicative of the balance of all components of thermal transfer in and around the instrument similar in design to a pyranometer. A relationship between the SBD night-offsets and the IR instrument's signals can be developed and applied to pyranometer data during daylight hours with the assumption that the shaded diffuse SBD does not respond significantly different to net radiation than at night. For this reason, it is recommended that the corrections derived here be applied only to shaded pyranometers.

Figure 1 is an example comparison between SBD night offsets and the pyrgeometer signals. Figure 1a is the offset versus the net IR signal, and Fig. 1b is the offset versus a measure of the dome heating/cooling in the pyrgeometer [the dome minus case temperatures converted to irradiance, DC, as defined below in Eq. (2)]. Much of the noise around the indicated linear relationships is due to ambient fluctuations of internal and external temperatures. Empirical relationships between these quantities can be developed with multiple linear regression analysis. Various forms of Eq. (2) were used for least-squares fits to the observed nighttime offsets:

$$\mathrm{os} = b_0 + b_1\mathrm{NetIR} + b_2\mathrm{DC}, \tag{2}$$

where

os = offset in W m^{-2},
NetIR = the net IR irradiance measured by the thermopile of a shaded and ventilated pyrgeometer,
DC = $\sigma^*[T^4_{\mathrm{dome}} - T^4_{\mathrm{case}}]$,
T = measured pyrgeometer temperatures,
σ = Stefan–Boltzmann constant,
b_x = regression coefficients.

The corrected SBD diffuse irradiance (Dif$_{\mathrm{corr}}$) is then given by Eq. (3), where Dif$_0$ is the uncorrected diffuse irradiance, and corr is the correction equal to −os:

$$\mathrm{Dif}_{\mathrm{corr}} = \mathrm{Dif}_0 + \mathrm{corr}. \tag{3}$$

The relationship between pyrgeometer signals and pyranometer offsets can vary considerably between different instruments, particularly instruments of different design and manufacture. Therefore, Eq. (2) should be fit to each instrument pair separately. For example, Table 2 shows that the range of sensitivity of a pyranometer group (see Table 1 for instrument identification) varies from negligible up to 0.065 W m^{-2} (W m^{-2})$^{-1}$ for the fit to Eq. (2) with b_0 and b_2 set to 0.0. Physically, the NetIR term is related to the net radiant heating of the outer pyranometer domes, while DC relates to all the net energy budget variations affecting the pyrgeometer dome. While these terms are not independent, statistical fits to Eq. (2) using nighttime data are improved when using both terms, although daytime offset corrections were not improved.

5. Diffuse correction validation techniques

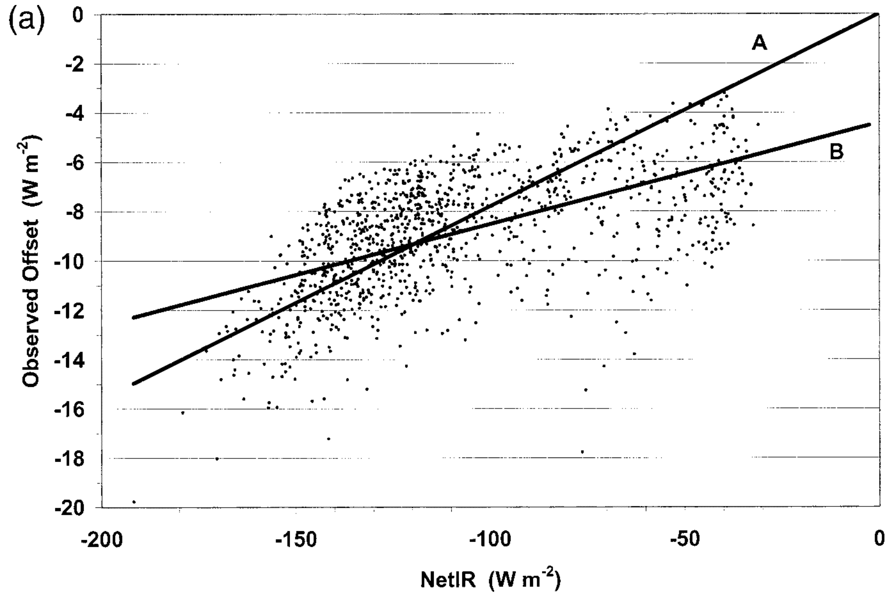
Since there are several assumptions in the proposed correction procedure, it is desirable to validate the corrections against those from alternate but less practical operational methods. One method for confirming daytime thermal offset corrections to SBDs is a comparison of the corrected diffuse with simultaneous diffuse measurements using B&W pyranometers that do not have the potential for significant thermal offsets. However, because of the potential spectral mismatch of these two instruments, the B&W diffuse irradiance could have a small positive bias resulting in the B&W being an upper limit for corrected SBD diffuse irradiance under clear skies.

A second independent method of estimating the daytime SBD thermal offset is to obtain instrument ''zero'' readings. This can be done during daytime conditions by instantaneously completely blocking shortwave (SW) radiation from the instrument and recording its signal output before the dome temperature changes significantly but after the thermopile has responded to the SW blocking. The dome temperature has a distinguishing longer time constant than the detector (several minutes vs a few seconds, as can easily be seen in a high time-resolution record of the blocking, or ''capping'' event) making this a viable procedure. To minimize the effect of IR exchange between the capping device and the domes, a cap with a low emissivity inner surface was used. (When placed over a pyrgeometer dome and detector, this cap results in a zero signal from the pyrgeometer that confirms the IR neutral inner surface of the capping device.)

A third technique for checking the validity of corrected diffuse irradiance is to compare with near-Rayleigh (no-aerosol, but including absorbing gases) diffuse calculations (Kato et al. 1999; CQS). Under certain near-Rayleigh conditions, this comparison allows a check on the absolute accuracy of the measurement. Rayleigh scattering of the atmosphere is well characterized due to its analytical solution in radiative transfer theory and due to the reasonably well-characterized state of the atmosphere relative to Rayleigh scatters (e.g., Bodhaine et al. 1999). Calculated Rayleigh diffuse irradiance for the appropriate surface albedo is a lower limit for clearest-sky diffuse measurements with the observed diffuse expected to exceed the Rayleigh limit because of ubiquitous background aerosol. The Rayleigh irradiance calculations used here are from a spherical version of multiple-scattering computer code commonly called DISORT (Stamnes et al. 1988 and Robert Portmann 1998, personal communication). The DISORT results were compared to several other simpler plane-parallel models at smaller zenith angles with an agreement to within 1–2 W m^{-2} for solar zenith angles $<75°$. For the Rayleigh calculations an albedo of 0.04 was used to give a lower limit and is representative of many natural surfaces in the shorter wavelength region where Rayleigh scattering dominates (Forgan 1983). Representative water vapor and ozone amounts were used with the Rayleigh calculations being insensitive to reasonable variations in both (CQS).

To get agreement using any of the above validation techniques, internal conductive and convective effects [C from Eq. (1)] would need to be small. The intent of this work is to use a sufficiently large number of cases so that random errors in C are eliminated.

An additional method of validating the offset corrections would be to observe all of the components of Eq. (1) and compute IR contributions to the measured detector response directly. It is a difficult task to accurately determine the necessary effective radiating temperatures and this is beyond the scope of this work. Work is being done on this approach by some of the authors and other



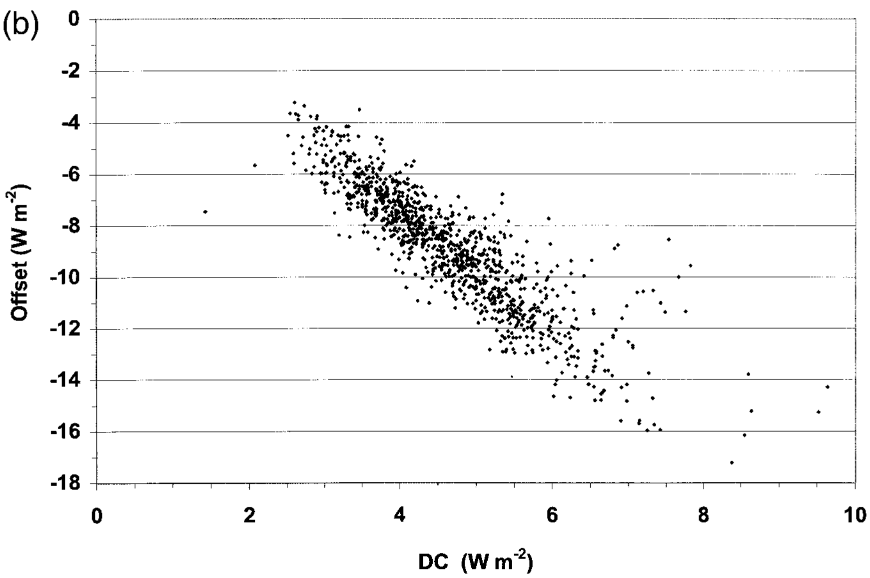


FIG. 1. Scatterplot of nighttime offsets vs (a) NetIR as measured by the thermopile output of a pyrgeometer, and (b) the dome–case temperature difference converted to an IR imbalance [Eq. (1)]. Data are for an entire year (1998) at the Boulder Atmospheric Observatory tower. Each point is a 1-min average sampled once every 14.5 nighttime hours, thereby reducing autocorrelation to less than 0.3. The two straight lines are linear fits to the data: line A being forced through the origin and line B's intercept being determined from the fit.

groups. Further work in this area should contribute to a more thorough understanding of the performance of individual instruments.

6. Experimental observations

Several pyranometers of the SBD and B&W designs (see Table 2 for details) were operated side by side (within 10 m) in the shaded diffuse mode in Boulder, Colorado, from June 1998 into January 1999. To further confirm and generalize the results, other SBD and B&W instrument pairs were operated at additional times at the National Renewable Energy Laboratory (NREL); the State University of New York at Albany (SUNY/Albany); Melbourne, Australia; Boulder; and Mauna Loa, Hawaii. To obtain diffuse irradiance, the instruments were blocked from the direct sun by a small solar tracking shade-disk subtending a linear angle of 5°–6°, appropriate to the opening angle of the direct beam measurement that usually accompanies these measurements.

TABLE 2. Sensitivity of nighttime offsets of diffuse pyranometers to changes in NetIR taken from the least squares fit to Eq. (2) with b_0 and b_2 set equal to 0.0.

Instrument ID	b_1
940171	0.027
12268	0.0587
96068	0.0161
14886	0.0615
9095 B&W	0.0053
19918	0.0648
940169	0.0302
32347 B&W	0.003
94019	0.0123
5437 B&W	0.015
1295 B&W	0.007

The usual calibration of the instrument determines the slope of the linear relationship between voltage and irradiance by comparisons between pyranometer output voltage and irradiance measured by a cavity radiometer. All diffuse pyranometers used in this study were calibrated by routine WMO procedures such as implemented at the National Oceanic and Atmospheric Administration (NOAA) Climate Monitoring and Diagnostics Laboratory Solar Radiation Facility (Nelson 2000), NREL, SUNY/Albany, the Australian Bureau of Meteorology, and by the manufacturers. Further discussion of pyranometer calibration is given in the appendix. Direct beam measurements were also simultaneously made during the experiments to help document sky conditions. The pyrgeometers operated along side the diffuse pyranometers and were shaded and ventilated, except in Australia where the instruments were both unventilated. Nearly simultaneous 1-Hz measurements were made on all instruments and 1-min averages were recorded 24 h per day.

The basic measurement configuration employed at all experimental sites was suitable for obtaining offset error estimates from the nighttime net IR relationships and validating them using both the B&W difference and the Rayleigh comparison methods. However, special procedures had to be used to directly observe daytime offsets. This was accomplished by capping (complete shortwave blocking) of the instruments during the daytime and recording the instrument response at 1–10-s intervals until the thermopile output stabilized but before significant dome temperature change occurred, usually 0.5–2 min. The data system's zero offsets were routinely checked and confirmed or set to 0.00.

7. Results

a. Deriving the offset corrections

Data were acquired from the different sites for several days to several months. Nighttime data were used to derive the thermal offset corrections to the SBD diffuse pyranometers by developing least squares fits to various forms of Eq. (2). The exact form of Eq. (2) used depended on what pyrgeometer signals were available with the merit of a particular correction expression evaluated based on the agreement with the different daytime validation procedures. An example of comparison between observed nighttime offsets and values derived from a least-squares fit to all the terms in Eq. (2) is shown in Fig. 2 and is contrasted to Fig. 1 where the dependence of the individual terms is illustrated. It was not possible to test all forms of Eq. (2) on all possible instrument

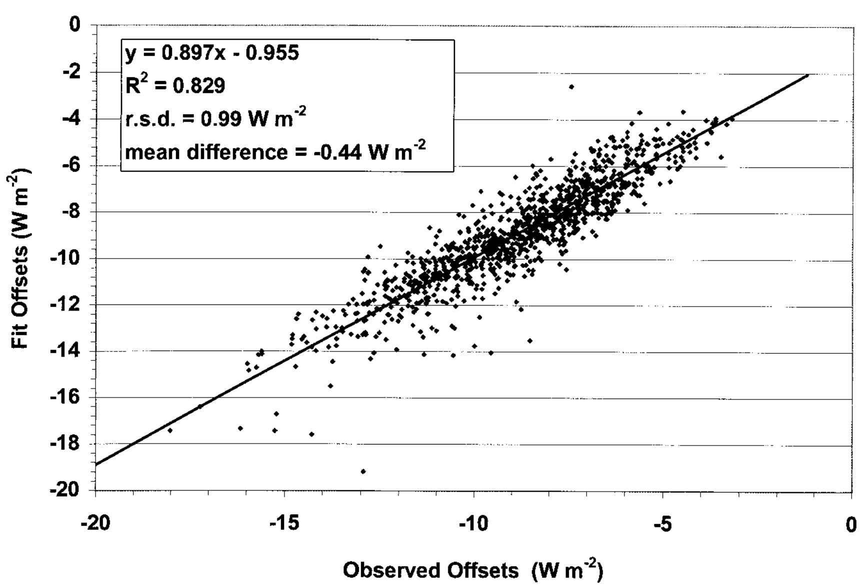


FIG. 2. Comparison of the observed and computed [from full Eq. (2)] nighttime offsets also plotted in Fig. 1. The straight line is a regression fit to the comparison. (In the legend, ''r.s.d.'' refers to the residual standard deviation of the fit.)

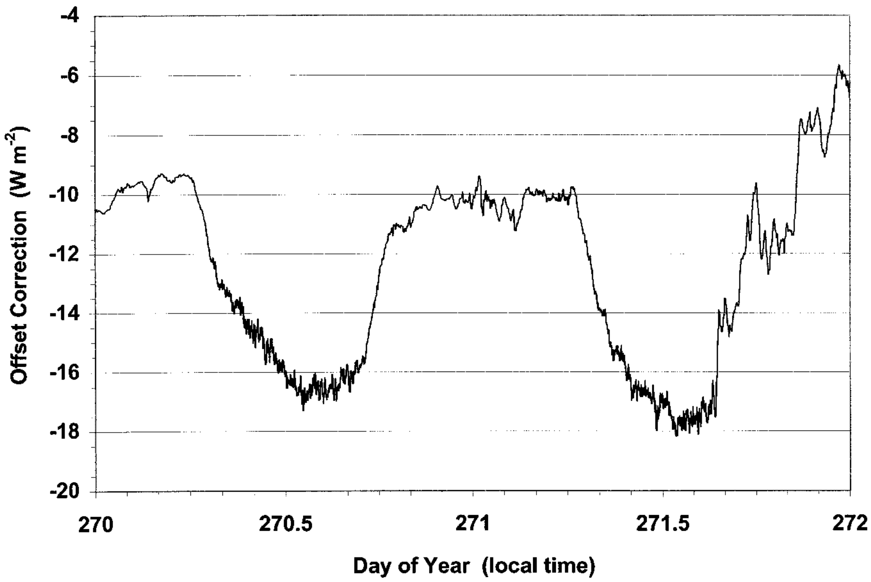


FIG. 3. Example of offset corrections over two complete diurnal cycles showing the relative magnitude of the clear-sky daytime values to the nighttime values. Clouds encroached toward the last half of the second day (day of year 271).

configurations, in part, because ventilation systems were not available for all instruments and because the pyrgeometer temperature signals necessary to compute the DC term were not always available.

The correction expressions used were verified to account for all, or nearly all, the thermal offset error in the cases tested. In some cases, minor improvements to the regression fit to nighttime data were achieved by adding other linear terms (e.g., air temperature) to Eq. (2). However, the quality of the least-squares fit of Eq. (2) to nighttime offset data is not a good indicator of how well the corrections perform under daytime conditions.

In the cases examined and validated in the current work using ventilated pyranometers and pyrgeometers, correction expressions using only the NetIR dependence with b_0 and b_2 set equal to zero often completely accounted for mean daytime offsets. This implies that this fitting procedure will work best when the net IR dominates the energy budget of the pyranometer dome. By setting b_0 to zero the fit is forced through the origin, which is physically expected, because the IR error forcing goes to zero. Other sources of dome heating and cooling tend to dominate when the IR forcing is small and, therefore, prevent the best fit from passing through the origin. Setting b_0 to zero also provides a better fit though the portion of the data in the region where the fit will be extrapolated into the more negative net IR irradiance conditions encountered in the daytime clear skies, as illustrated by contrasting fit lines (A) and (B) in Fig. 1a. Much of the subsequent analysis is based on the NetIR-only dependence because it yielded encouraging results in preliminary tests and because DC is not completely orthogonal to NetIR. Also, the DC term is subject to slight daytime SW heating of the dome thermistor. Results from Australia, where unventilated SBDs (Kipp and Zonen CM-11s) were used along with unventilated pyrgeometers, indicate that a DC-only dependence expression ($b_1 = 0$, and b_0 computed to be generally <0.5) provides consistent offset daytime corrections. The DC-only dependence of thermal offsets for the unventilated Kipp and Zonen instruments was not investigated in the Boulder or other datasets where the pyrgeometers are ventilated. A separate study (Reda and Stoffel 2000) was done on the potential influence of several other variables such as dewpoint and wind speed on the offsets but no dominant relationships other than those included in Eq. (2) were suggested. Some minor improvement to the nighttime fits is obtained by including many environmental variables but does not assure better results when applied in daytime conditions.

Figure 3 shows the correction values determined for a particular instrument for 2 days in Boulder, the first day and a half being clear. Daytime values are larger than nighttime values as might be predicted and as reported by CQS. It is also noted that the daytime afternoon values are larger than morning values relating to diurnal surface heating continuing to increase into the p.m. hours. The high level of noise is typical, reflecting the turbulent heat exchange.

The computed corrections are negative more than 99% of the time, becoming positive only when the downward IR might be unusually enhanced by a low warmer-than-the-surface cloud. All SBD diffuse data collected were then corrected using Eq. (3) and the os value specifically determined for each instrument. An example of clear-sky diffuse irradiance data from Boulder before and after the applied correction is given in

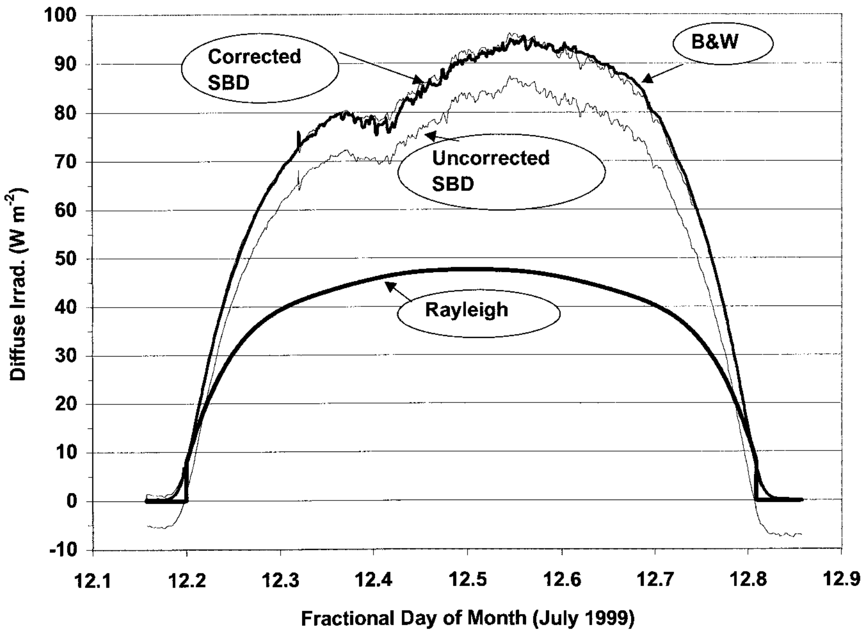


FIG. 4. Corrected and uncorrected diffuse irradiance from an SBD pyranometer (#19918) for 12 Jul 1999 for Boulder. Also shown for comparison are the unadjusted diffuse irradiance for a B&W pyranometer and the modeled near-Rayleigh diffuse irradiance. Note that the Rayleigh calculations are for a spherical atmosphere but end (are set to 0.0) at a zenith angle of 90°.

Fig. 4. The corrected data close the gap between the SBD and B&W as well as remain at or above the Rayleigh limit, even at large zenith angles in this example. Both the derived values of the offset corrections and the corrected diffuse data were compared to validation criteria to assess the merit of not only the correction but the overall accuracy of the resulting diffuse irradiance value.

b. Validation of offset corrections

Since the offset correction is determined from data obtained during dark conditions and the correction is to be applied during the day, it is of particular interest to examine the values of the corrections used in the daytime. The evaluation of a specific correction procedure must be based on its daytime performance. Three methods were used to validate the offset corrections applied here 1) comparison with B&W instruments, 2) comparison between the corrected observations from clearest and cleanest skies with the Rayleigh limit, and 3) comparison of computed daytime offset corrections with instrument zero values. The evaluation of the validation results shows that specific correction procedures were not always as effective for certain types of pyranometers as others.

1) COMPARISON WITH B&W PYRANOMETERS

Data were available for three pairs of B&W and SBD instruments for 4.5 months at two Colorado locations, Boulder and Golden. The data were collected as previously described, with all instruments being ventilated. For the analysis, one 1-min average was subsampled every 15 min to reduce autocorrelation. The offset corrections were obtained by regression fits to Eq. (2) with b_0 and b_2 set to 0.0. Histograms (plotted as probability density curves, PDCs) of the clear-sky (direct beam greater than 500 W m^{-2} and diffuse less than two times Rayleigh) daytime diffuse differences (SBD minus B&W) for the three pairs of instruments are shown in Fig. 5 both before and after the SBDs were corrected (see Table 1 for additional information on the instruments used.) While 7% of the uncorrected differences for one of the instrument pairs excecded -25 W m^{-2} in Fig. 5, the well-defined peaks of all three corrected distributions were within 3 W m^{-2} of the 0.0 difference line. Less than 3% of the points for one of the corrected pairs exceeded -10 W m^{-2} with the other two corrected distributions lying entirely within ± 6 W m^{-2}. After the data reported here were acquired, some of the authors continued to make extended similar comparisons at other locales (not shown) and continue to get results consistent with those reported here. There is a tendency for the corrected SBD diffuse to be less than that obtained from the B&W. This could be due to differences in the calibration of the instruments, incomplete offset corrections, spectral response, differences in shade geometry, or some combination of all four. Further evaluation of these sources of comparison differences is a subject for future work.

Comparisons for overcast conditions (direct beam less

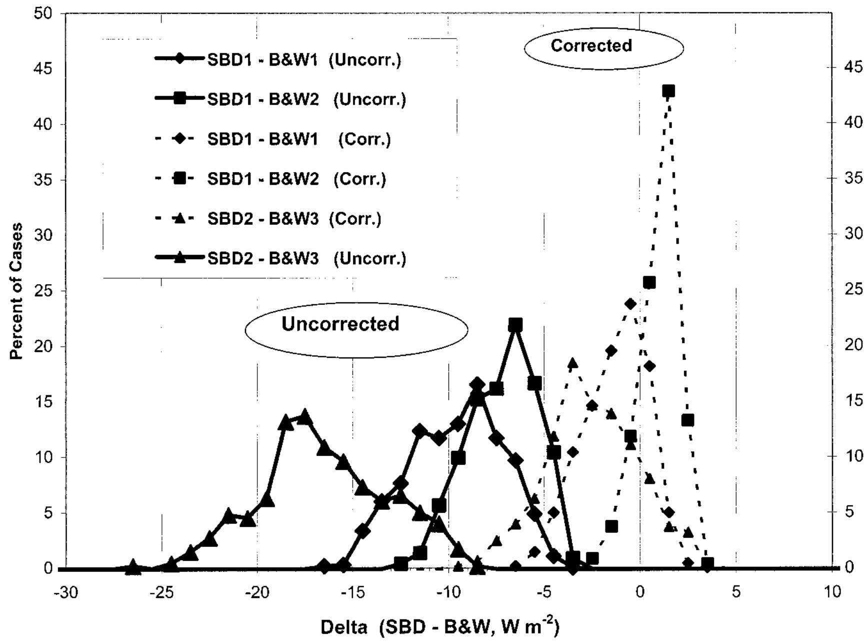


FIG. 5. Histograms (probability distribution curves) for the difference between the diffuse irradiance measured by B&W and SBD pyranometer, SBD–B&W. All cases were for clear-sky or near-clear-sky conditions. The solid curves are for cases when the SBD was not offset corrected; the dashed lines are for offset-corrected SBD. Serial numbers of the instruments identified in the legend correspond to: SBD1 = #19918, SBD2 = #17878, B&W1 = #32347, B&W2 = #32637, B&W3 = #32645 (see Table 1 for additional information on the instruments by serial number).

than 2 W m^{-2} and diffuse less than three times Rayleigh) are given in Fig. 6 and show smaller offset corrections, and again there is close agreement between the two types of instruments when the SBD diffuse is corrected. Diffuse measurements under cloud conditions are discussed further in section 8.

2) Rayleigh comparisons

To further facilitate validation of the offset corrections and to check on the absolute accuracy of the corrected SBD diffuse under clear-sky conditions, both corrected and uncorrected measured diffuse irradiances were subtracted from corresponding computed Rayleigh values. Data used here were from a 2.5-month period in Boulder with the instruments and correction functions given in Table 2. The PDCs were computed for these differences to summarize a large number of the clearest-sky cases. The low sides, or shoulders, of these PDCs give indications of the overall agreement with the Rayleigh limit for the clearest cases and a view of the statistical distributions of the results. Figure 7 shows the PDCs for the differences for two groups of diffuse pyranometers before any corrections were applied. The data represented in Fig. 7 are 1-min averages filtered to include only cases were the direct solar beam exceeded 500 W m^{-2}. This filtering eliminates virtually all measurements during thick overcast conditions where the cloud diffuse irradiances could be sub-Rayleigh. Low diffuse values possibly near or below the Rayleigh limit value, but not eliminated by this method, could arise from rare cases of a thick near-overcast sky with a cloud break near the sun's position. The lower limit of each PDC (left-hand side) in Fig. 7 shows that for all the SBD instruments the clear-sky boundary is well below the Rayleigh limit, while the B&Ws, not subject to thermal dome correction, are above the limit. This is consistent with the SBD domes in clear-sky conditions being cooler than the detector giving a negative bias due to an imbalance between the LW$\downarrow$ and LW$\uparrow$ terms in Eq. (1).

The results of the corrected SBD diffuse minus Rayleigh is shown in Fig. 8, where it is seen that there is better agreement with both the Rayleigh limit and the B&Ws as compared to the uncorrected case in Fig. 7. Although the true value of the diffuse irradiance is not known, truth must be consistently above the Rayleigh limit by an amount that equals the downward Mie scattering in the atmosphere unless there is absorption unaccounted for in the Rayleigh limit calculation, which given the results of Kato et al. (1999) is unlikely. It is seen that the lower shoulders of the PDCs agree within $\pm$3–4 W m^{-2} of each other and the major portion of the shoulders lie 3–5 W m^{-2} above the 0.0 line representing the Rayleigh limit. The agreement between the corrected SBD, the B&W, and the proximity to the Rayleigh limit suggests overall absolute agreement because of their mutual independence. However, it is noted that

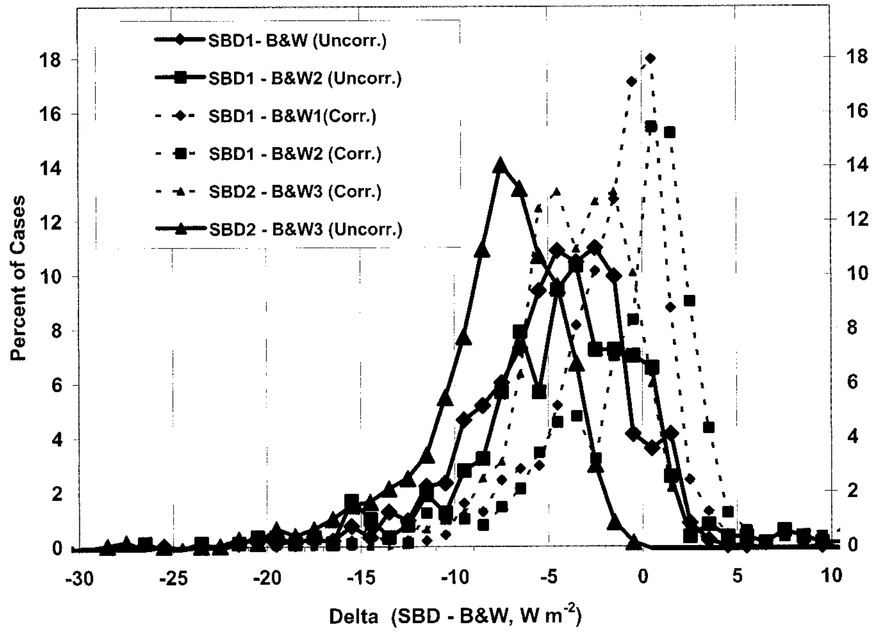


FIG. 6. Same as Fig. 5 except for overcast sky conditions.

certain corrected instruments still have a significant number of values below the Rayleigh limit. These instruments were unventilated and the offset correction is not confirmed to better than indicated by the extent of the sub-Rayleigh values.

A similar comparison for data obtained at the Mauna Loa, Hawaii, observatory, 3.4 km above sea level, indicates the lower limit of the corrected diffuse within 2–4 W m^{-2} of the Rayleigh limit over the entire range of solar zenith angles (Fig. 9). These data were acquired simultaneously from two ventilated Eppley PSPs. The measured background aerosol optical depth at Mauna Loa is near 0.007 (Dutton et al. 1994) in the visible wavelength. This amount of aerosol accounts for a small diffuse enhancement (about 2–3 W m^{-2} at a solar zenith angle of 60° assuming a forward scatter of 80%), giving nearly complete and absolute agreement between Rayleigh-plus-aerosol calculation and the observation. This

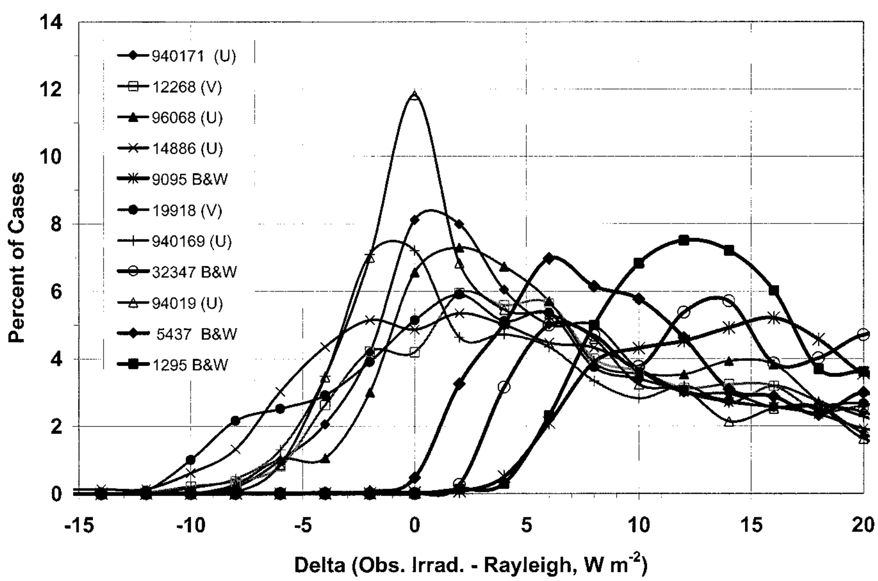


FIG. 7. Histograms of the difference between diffuse irradiance observed with a number of instruments (uncorrected) and the corresponding theoretical Rayleigh diffuse. Note the grouping of the B&W and SBD instruments. Numbers in the legend refer to instrument serial numbers, (U) indicates an unventilated SBD, and (V) indicates a ventilated SBD.

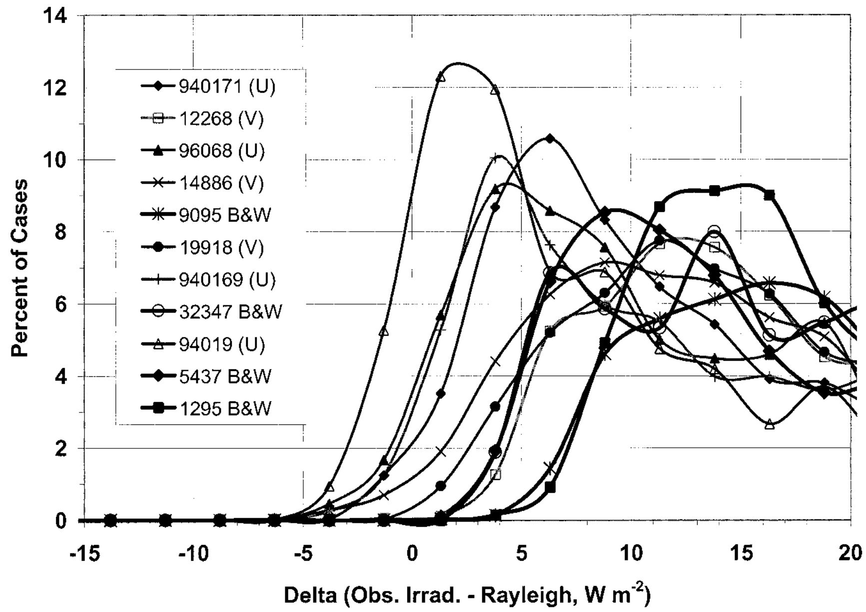


FIG. 8. Same as Fig. 5 except the SBD instruments were offset corrected.

not only suggests that the diffuse correction procedure is correct in this case but that the absolute calibration of the diffuse pyranometer is likewise accurate to within 1–2 W m^{-2} at this irradiance level for clear-sky diffuse irradiance.

3) INSTRUMENT ZEROS FROM CAPPING

Another check on the consistency of the diffuse corrections is to compare them directly to observed daytime offsets. On occasion, several of the diffuse pyranometers used in this study were capped during the daylight hours to provide an independent estimate of the dome temperature induced offset. Figure 10 shows typical instrument responses during one of these capping episodes. The capping events lasted only long enough to get a stable signal from the detector consistent with the published time response. The slower time response of the B&W instruments is evident in Fig. 10. Two distinct time constants, the thermopile response with a 1/*e*-folding time of 1–5 s for the SBDs and the response to the changing dome temperatures with a 1/*e*-folding time of about 45 s affect the trace in Fig. 10. The zero offsets after 10 detector time constants following capping are taken as resulting from the dome-detector temperature difference, although actual offset values would be higher to account for the dome temperature change during the delay while waiting for the detector to stabilize.

Table 3 shows the average offset errors determined by three different methods spanning multiple capping episodes. The B&W reference used in Table 3 is serial number 9095, as identified in Table 1. In Table 3 it is readily noted that the B&W instrument shows a small offset consistent with the heat budget expression that does not include the dome temperature term. The small differences between the B&Ws could be due to different construction and geometrical arrangements, as well as spectral response of the detector paints. Some SBD instruments—serial numbers 12268, 14886, and 19918—show a consistent offset error determination across the three methods, while three others (940171, 96068, and 940169) show a low sensitivity from Eq. (2) fits but display large offsets when covered and when compared to the B&W reference. It should be noted that the instruments that show the least agreement between the three methods were not ventilated and also use an internal radiative-equilibrium reference temperature as described at the end of section 2a. These same instruments also showed the poorest agreement with the Rayleigh limit after offset correction (Fig. 8). The reader should recall that these results are for offset determinations using only the NetIR term in Eq. (2). Inclusion of the other terms in Eq. (2) did not improve the results for the ventilated pyranometers but that investigation was not extended to the unventilated pyranometers used in this study. Unpublished investigations have suggested that using an unventilated pyrgeometer with unventilated pyranometers might yield better results and is a subject for further work.

c. Ventilation

The relationship between thermal offsets and parameters in Eq. (2) is better defined and more stable over a larger range of ambient conditions if the pyranometer domes are subject to continued forced ventilation (Wardle and Barton 1988; Ohmura et al. 1998). Different designs for ventilation were developed with the primary

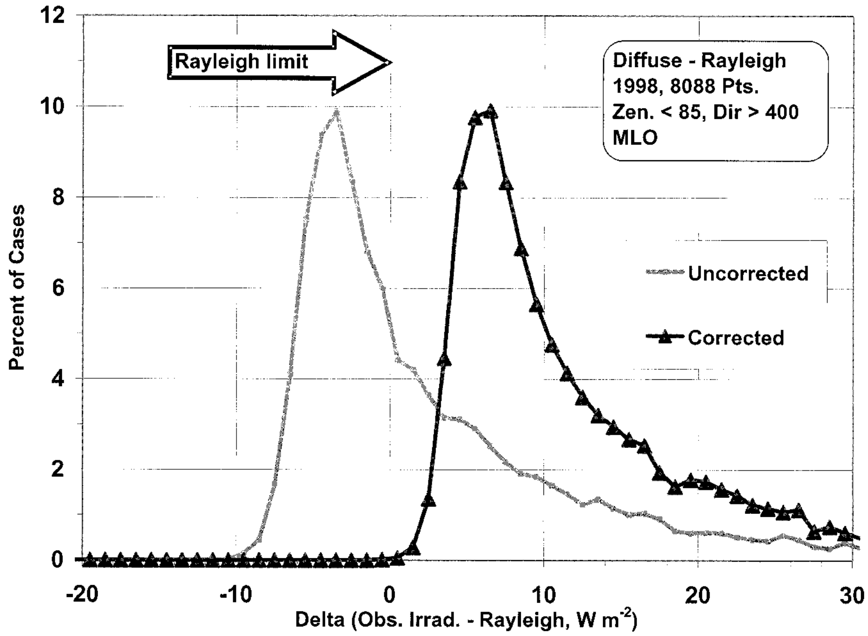


FIG. 9. Probability density for the difference between the observed diffuse (corrected and uncorrected) and modeled Rayleigh irradiance at Mauna Loa. Data were selected for clear times over the entire year of 1998. Only every 15th clear-sky data point (1-min average) was included to reduce autocorrelation. (Delta = observed diffuse minus Rayleigh diffuse.)

goal to force ambient airflow around the body of the instrument and then over the exterior surface of the domes. Such ventilation is commonly offered by the manufacturers and is suggested for maximum accuracy. Our preliminary investigation of new manufacture-supplied ventilation systems for some instruments listed in Table 1 shows reduced day and night offsets to an extent that offset corrections may not be required. Our experience is that there can be substantial differences between the effects of different ventilation systems on a given instrument. It is highly recommended that individual ventilation systems be tested and evaluated before being deployed for critical diffuse irradiance measurements. No ventilation system was available for in-

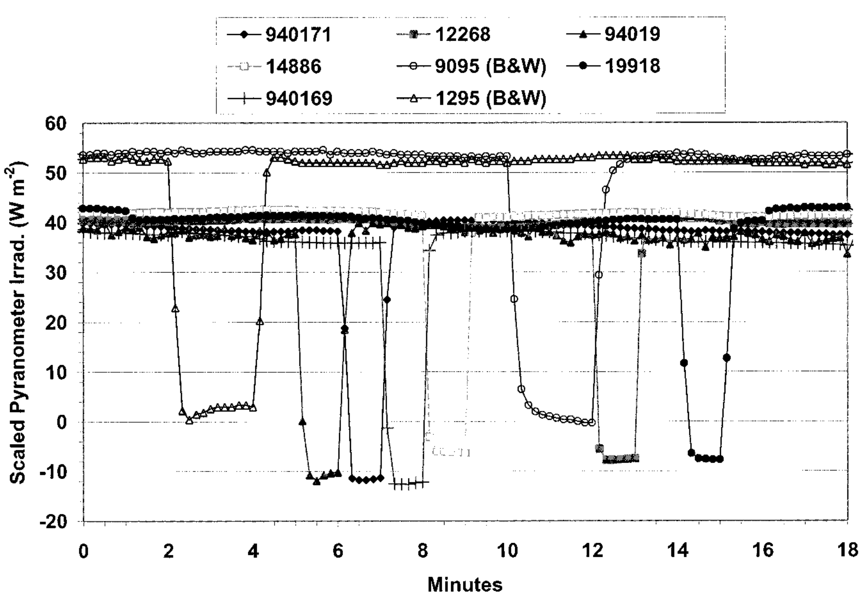


FIG. 10. Ten-second resolution pyranometer data before, during, and after a ''capping'' episode for several pyranometers.

TABLE 3. Comparison of daytime diffuse pyranometer zero offsets determined by three different methods. ''Day cap''—capping as described in text, ''OS from Eq. (2)''—from fits to nighttime offsets extended into the daytime, and ''Del B&W''—difference between the instrument #9095 and the uncorrected diffuse measurement.

Instrument	Day cap OS ($W\ m^{-2}$)	OS from Eq. (2) ($W\ m^{-2}$)	Del B&W ($W\ m^{-2}$)
940171	−10.8	−5.7	−14.9
12268	−9.3	−8.9	−10.2
96068	−10.5	−3.4	−12.9
14886	−8.4	−9.7	−10.9
9095 B&W	−0.4	—	—
19918	−10.4	−10.8	−10.5
940169	−11.3	−5.6	−14.2

strument numbers 96068 and 94019 and further investigation of the offset errors for this type of instrumentation is needed.

8. Diffuse irradiance under clouds

Under cloudy conditions the diffuse irradiance can be several times greater than Rayleigh but still less than the clear-sky total irradiance values at which the pyranometer is typically calibrated. It is, therefore, desirable to substantiate the pyranometer's measurement of diffuse irradiance under cloudy conditions not only because the signal levels are different from either the calibration or Rayleigh comparison levels, but also because the spectral and directional radiation fields are different. Unfortunately, there is no reliable cloudy diffuse reference to which the measurements can be compared, such as the Rayleigh atmosphere or absolute cavity for clear skies. Given this lack of a reference it is of value to compare the instruments with two dissimilar detector types, SBD and B&W, under cloudy conditions.

To compare the cloudy diffuse from the two types of instruments, the SBD thermal offset corrections are computed and applied as described previously. The magnitudes of the thermal offset corrections are diminished under clouds because of smaller net IR losses, depending on cloud-base height and optical thickness. Diffuse irradiance from clouds or thick haze conditions can be identified in the data acquired for this investigation by selecting those times well away from the Rayleigh limit case, that is, when the diffuse is several times greater than the Rayleigh value or when the direct beam is less than 100–200 $W\ m^{-2}$ with solar zenith angle less than 85°. Figure 6 shows the comparison between irradiance measured with B&W and SBD sensor types for mean cloud conditions. The comparison under various cloud conditions for two and a half months in Boulder are shown in Fig. 11 as a function of the Rayleigh ratio. The Rayleigh ratio is the measured diffuse divided by the corresponding computed Rayleigh value. Also plotted in Fig. 11 are plus or minus one standard deviation curves. Since each plotted point represents a population of more than one hundred points, and since only every fifteenth 1-min average was used to reduce autocorrelation, the standard error of the mean is less than 0.5 $W\ m^{-2}$ in each case. The relatively large standard deviations represent instrumental variability related

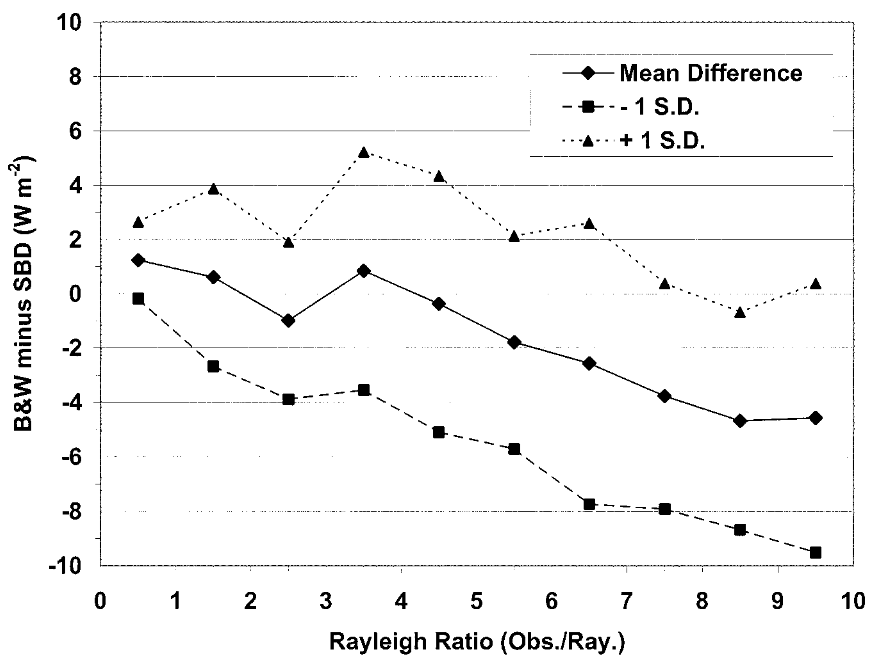


FIG. 11. Difference between the average of the B&W and the average of the corrected SBD ventilated diffuse pyranometer groups under cloudy conditions for mean differences plotted as a function of the Rayleigh ratio (observed/Rayleigh). The data consist of nearly 3 months of data collected between the middle of Nov 1998 to the middle of Feb 1999.

to sample-timing differences of 1–3 s, different time responses of the instruments, and instrumental and data system noise. The results shown in Fig. 11 are consistent with those shown in Fig. 6 for cloudy conditions.

Given the small standard errors in Fig. 11, the downward trend is significant. This pattern could relate to slightly different spectral responses between the B&W and SBD instruments and the varying spectral nature of the diffuse irradiance under different cloud conditions. Therefore, this feature would be expected to vary with different instruments, especially as different materials are used in the manufacture of the B&W detector. Note that points corresponding to a Rayleigh ratio near 1.0 (Fig 11) are not for clear skies but rather for thick overcast skies since a condition of minimal direct beam was imposed when the Rayleigh ratio was less than 3.0.

The data shown in Fig. 11 cover a full range of cloud conditions except for the few cases where the Rayleigh ratio is greater than 10. There were not enough independent cases of these conditions to get meaningful statistics. Although the 2.5 months covered by this dataset were in the Colorado wintertime, similar comparisons from summer months show no significantly larger differences than those presented in Fig. 11. For the extreme cases of thick clouds and sudden temperature changes with diffuse approaching minimum daytime values, B&W or other low thermal mass pyranometers should provide the best results.

9. Conclusions

Uncertainties in the measurement of diffuse solar irradiance with certain thermopile pyranometers were quantified. Dome-temperature-induced errors under diffuse-sky measurement conditions can be a significant source of correctable error in diffuse measurements with solid-black-detector pyranometers. The simple energy budget analysis of a typical pyranometer detector identifies the source and origin of this error. Several pyranometers of different design and manufacture were examined and an apparent offset error due to the dome temperature difference was determined for some of the susceptible instruments. An algorithm for determining the offset error based on the sky net IR forcing was determined and substantiated, on the average, within ± 4 W m^{-2} for ventilated SBD pyranometers. The correction procedure based on nighttime offsets and the NetIR-only dependence was problematic for accurately determining the offset errors in some unventilated pyranometers. In another test case, the addition of newly available ventilation systems significantly reduced the magnitude of the verifiable offset errors compared to being unventilated. It is, therefore, important to develop corrections for each instrument in the specific observing configuration in which it will be used, preferably as a postprocessing activity where the actual field configuration and acquired data are used. It is recommended that the full Eq. (2) be explored when the input information is available, but simpler forms of that equation may be sufficient to remove all identifiable offset errors.

Typical daytime offset errors in several types of SBD pyranometers were determined and then verified by comparison to B&W pyranometers, the Rayleigh limit for clearest-sky cases, and capped instrument zeros. The typical offset errors are on the order of 5–20 W m^{-2} (95% limits), with extreme cases of 30 W m^{-2} observed less than 0.1% of the time. These errors can be corrected to within 4 W m^{-2} (in the daytime mean) when using verified correction functions determined from the relationship between nighttime offsets and net IR thermal forcing. All methods of validating the offset corrections suggest that the contributions from the conductive and convective terms in the mean are negligibly small. This is in part due to the engineering design of the instruments and in part because such errors would tend to be random. It should be noted, however, that abrupt changes in ambient temperature can lead to transient errors (Kuhn 1973) in SBD instruments because of error-producing internal conductive and convective effects. Our experience is that certain SBD instruments are less sensitive to sudden ambient temperature changes because of ''radiative equilibrium'' (low thermal mass) reference detector elements. Without such reference elements, thermal transients in SBD pyranometers can cause temporary errors as great as 40 W m^{-2}.

Instruments with factory ventilation systems still can have significant thermal offset errors, while preliminary tests with one particular new ventilation system appears to have virtually eliminated detectable thermal offsets under the conditions investigated. In general, ventilation stabilizes instrument characteristics and helps prevent buildup of condensation on the dome.

Close agreement was shown between computed Rayleigh diffuse irradiance values and the observed diffuse using corrected SBD or B&W pyranometer data under near-Rayleigh conditions. This strongly suggests that the fundamental measurement of 2π sr diffuse-sky irradiance can be properly implemented to an absolute accuracy to within about 2 W m^{-2}, both in calibration and application for the low-aerosol, no-cloud conditions. The mean agreement between the offset-free B&W pyranometers and corrected SBD instruments under cloudy conditions is within 5 W m^{-2}, suggesting comparable accuracy in each instrument or compensating biases. Further implied from the apparent success of the application of this offset correction procedure to the instruments and sites shown is that the net IR term of the energy budget of the pyranometer dome dominates under the conditions that existed over the extend time during which the data were acquired. Locations and installations where environmental conditions are significantly different might not yield as satisfactory results.

It should be noted that this work has not addressed thermal offset errors in pyranometers when used to measure total solar irradiance measurements in clear skies.

This is because the relationship between nighttime determined offsets and daytime values cannot be readily established because of intense solar heating of the interior of the instrument.

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APPENDIX

Error Sources Not Considered in the Pyranometer Detector Energy Budget Analysis

a. Cosine response

For a pyranometer used for diffuse irradiance measurements the directional response for diffuse irradiance is of secondary concern as diffuse response is the product of the directional response, $\sin(2\theta)$ where theta is the zenith angle, and the sky radiance distribution (Forgan 1984a; Kuhn 1973). Therefore, the directional response for diffuse instruments in clear conditions is typically equivalent to the cosine response at zenith angles between 45° and 60°. Provided one has diffuse instruments with small deviation cosine response errors (say less that ±3%) between 0° and 70° zenith angle and monotonic trends in this zenith angle range, the resulting variation in the diffuse response is small (less that 1%). The magnitude for these directional errors can be minimized in conditions of scattered cloud conditions (with associated anisotropic sky radiance distributions) by choosing a detector with minimal variations in cosine response. To derive an appropriate calibration coefficient for diffuse sensors requires both the true directional response and estimates of the typical sky radiance distributions. Unless inversion methods (Forgan 1984a) are used, the calibration methods typically produce weighted directional cosine responses derived in total solar irradiance (global) conditions. These methods underestimate the deviation from ideal directional response as the ratio of diffuse to direct solar irradiance increases (Forgan 1984b, 1996). However, calculations indicate that for instruments with directional responses varying by less than ±3% from ideal (ISO 1990) over 0°–70° zenith angle, the directional-induced error would be much less than 4 W m^{-2} for diffuse irradiance measurements.

b. Calibration

Quantitatively, the offset-correction validation results using comparisons to B&W instruments depend on the uncertainty of the calibration assigned to both types of pyranometers. The calibrations of the NOAA pyranometers were assigned using standard total solar irradiance calibration procedures (e.g., Nelson 2000; ISO 1990; McArthur 1998). It is important to assess the impact of any uncorrected offset errors that exist in the instruments at the time of calibration. The instrument characteristic most crucial to the transfer of the calibration accuracy at low signal levels is the linearity of the detector output (ISO 1990; Kuhn 1973). If this linearity is maintained and the offset bias magnitude is less than 20 W m^{-2}, then performing calibrations at the larger signal levels of a typical total solar irradiance calibration, introduces only a relatively small percentage error (<2%) in the linear thermopile sensitivity determination. For example, an offset error of 15 W m^{-2} is more than 30% of a high-sun Rayleigh diffuse signal but less than 2% of the total solar irradiance in clear-sky conditions near solar noon. Therefore, an offset error at the time of total solar irradiance calibration introduces <1 W m^{-2} error in a typical clear-sky diffuse reading of 50 W m^{-2}. If the offsets in the pyranometer being calibrated are similar to the offsets in the diffuse pyranometer used in the calibration, and both are small in relation to the total irradiance, the impact of offsets on calibration are minimal.

Ideally, all known biases would be accounted for in the calibration process (ISO 1993). However, offset errors determined here are not valid for pyranometers exposed to total solar irradiance as the internal heating and resulting thermal exchanges are different than under the dark conditions inherent to the determination of the correction expressions developed here. To make the necessary corrections, accurate knowledge of the sensor's internal temperatures, specifically the detector surface and the inner dome's inner surface are required. Even then, it is necessary to separate and identify the temperature effects that would result in an offset error and those that are part of the shortwave response of the sensor (Kuhn 1973). In practice, the offset error in a total solar irradiance pyranometer is partially compensated for at the time of calibration by referencing to an absolute standard.

c. Time response

The *e*-folding time response (or time constant) of the instruments used is on the order of 1–5 s except for the B&W standard where this response is about 15 s. This characteristic of the B&W instrument is one reason why it is not more widely used for total solar irradiance measurements. However, for diffuse measurements the irradiance field does not vary as fast as the total irradiance (with the highly variable direct beam component). Under clear-sky conditions the diffuse irradiance variations can be captured by instruments with 30-s time constants.

d. Spectral response

The spectral response of a SBD is determined by the absorption properties of the detector surface and the transmission of the glass domes. Typically the black detector surface is uniformly near-optically black well into the thermal IR, while the dome transmission becomes nonzero near 0.3 μm and has a cutoff near 3.0 μm (Robinson 1966). The B&W instruments depend on the optical properties of both detector surface types as well as the dome (Robinson 1966). Ideally, the white surface would be highly reflective over the same spectral range as the dome transmits and nearly black outside that range. One characteristic of the B&W pyranometers that has diminished their desirability for routine total solar irradiance applications is the problematic spectral response of the instrument, because of the significantly different spectral responses in the near IR cutoff (Robinson 1966). The spectrum of diffuse irradiance, clear and cloudy, is weighted well toward the shorter wavelengths compared to the direct solar beam such that the exact longwave cutoff of the glass dome is not crucial in capturing the complete energy integral. However, white materials can have high emissivities well below 2.0 μm. The B&W pyranometer's sensitivity to solar irradiance is decreased as the white surface's emissivity increases. Samples of the white surfaces of current models of the B&W instruments used in this study showed reflectance values of 80% or greater out to 2.5 μm.

e. Shade geometry

Finite detector areas and view-limiting mechanisms for radiometers used for either diffuse or direct solar irradiance measurements are a source of differences between theoretically calculated and measured irradiance quantities, and between measurements at different measurement installations. As to the results in this paper, this error source is 1) not significant when near-Rayleigh conditions are present because the lack of a solar aureole, 2) not a factor when capping radiometer to get a daytime zero offset, 3) potentially a factor when comparing between two diffuse instruments with different shade geometries. Although identical shade devices were used for both the SBD and B&W diffuse measurements that are compared here, the much larger (three times the diameter) B&W detectors will tend to see more of the solar aureole and hence also accounts for the B&W irradiances tending to be greater under certain aureole conditions. The mean geometrical effect for results reported here is apparently less than about 2–3 W m^{-2}, but does account for occasional greater differences.

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