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COMPARISON OF IRRADIANCE MEASUREMENTS MADE WITH THE MULTI-FILTER ROTATING SHADOWBAND RADIOMETER AND FIRST-CLASS THERMOPILE RADIOMETERS

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Abstract—The multi-filter rotating shadowband radiometer (MFRSR) uses a silicon photodiode sensor to measure shortwave global and diffuse horizontal irradiance from which direct normal irradiance is calculated. Silicon sensors are rugged, stable, and have a fast time response. However, silicon sensors are both thermally and spectrally sensitive. In addition they, as do all pyranometric sensors, have an imperfect cosine response, especially at high solar-incidence angles. In the MFRSR two of these sources of error are minimized: the cosine response of the MFRSR is measured, and the acquired data are corrected accordingly; an automatic heater maintains the MFRSR detector at a constant temperature near 40°C. This paper demonstrates that there is substantial agreement between first-class thermopile instruments and the MFRSR silicon sensor with the elimination of these two sources of error. Furthermore, this paper describes corrections, based on sky conditions, to lower the remaining errors. The data base for deriving and testing these corrections was collected in Albany, New York, during 1993. After correction equations are applied, the root-mean-square differences for 5 min averages of the global horizontal, diffuse horizontal, and direct normal irradiance are 8.8, 9.1, and 16.3 W/m^2, respectively. The differences in time response or time keeping between silicon and thermopile instruments may explain much of the remaining root-mean-square differences.

1. INTRODUCTION

Silicon sensors only respond between 300 and 1100 nm and have a peak response near 900 nm that is about twice that at 400 nm. In contrast, the WMO first-class thermopile instruments have a reasonably flat response over the whole shortwave spectrum between 300 and 3000 nm. The spectral distribution of solar radiation changes as the sun rises and sets with shifts to longer wavelengths as solar elevations decrease. Diffuse horizontal spectral irradiance is particularly sensitive to cloud cover: if the sky is clear, the spectral peak is at blue wavelengths with little near infrared radiation, but it shifts to a typical solar spectral distribution with clouds present. Consequently, typical calibrations of silicon sensors using thermopile standards with clear skies and high solar elevations will not strictly hold when clouds or geometry alter the solar spectra.

A methodology was developed by Michalsky *et al.* (1991) for the correction of the popular LI-COR 200 series pyranometer (LI-COR 1986) used in a rotating shadowband configuration. A temperature correction was first performed followed by a spectral/cosine-response correction based on solar geometry and sky conditions. The latter was achieved by developing ratios of thermopile response to silicon response for discreet values of these variables; sky clearness, proportional to the ratio of direct to diffuse irradiance; sky brightness, proportional to the ratio of diffuse to extraterrestrial irradiance, and solar-zenith angle. A table of corrections was developed for the three components: global and diffuse horizontal and direct normal irradiances.

The MFRSR differs substantially from the LI-COR 200 pyranometer. A complete description of the MFRSR is given in Harrison *et al.* (1994). Briefly, the instrument uses a computer-driven shading band to alternately shade and unshade the diffuser that illuminates the silicon sensor. These diffuse and global irradiance measurements are used to calculate the direct normal irradiance. The diffuser geometry is similar to the LI-COR pyranometer. In the LI-COR pyranometer, the silicon sensor is just below the acrylic diffuser. In the MFRSR, light that penetrates the diffuser enters an integrating cylindrical cavity with an exit port that illuminates seven sensors one of which is the same silicon detector used in the LI-COR pyranometer. The detector's housing temperature is controlled by heating to a setpoint temperature between 40 and 45°C. Temperature is held to within 1 or 2°C of the setpoint. Additionally, the cosine response of each MFRSR is measured in four azimuthal directions between incidence angles of 1 and 90° in 1° increments using our automated cosine response test bench (Michalsky *et al.*, 1995). Interpolations to other azimuths are made to correct the direct beam for cosine response. Global horizontal irradiance is corrected by summing the corrected horizontal component of the direct normal irradiance (direct horizontal irradiance) and the diffuse horizontal irradiance.

Instead of building a correction table as in Michalsky *et al.* (1991) for the LI-COR 200, four simple correction equations are derived using the sky condition variables as described earlier. In Michalsky *et al.* (1991), the thermopile global horizontal irradiance was measured by an Eppley PSP. The direct horizontal irradiance was calculated using the direct normal irradiance measured by an Eppley NIP multiplied by the cosine of the incidence angle. The diffuse horizontal was then derived by subtracting direct horizontal from the global horizontal irradiance. The problem with this procedure is that the imperfect cosine response of the global horizontal irradiance sensor introduces biases in both the global and diffuse irradiance measurements.

In this paper, the thermopile data base is improved by summing direct horizontal obtained from a pyrheliometer and diffuse horizontal taken under a tracking disk as a measure of the global horizontal irradiance, thus the cosine error associated with a standard pyranometer measurement of global horizontal irradiance is reduced. Furthermore, all of the thermopile calibrations are based on absolute cavity radiometer measurements performed on site.

2. INSTRUMENTS AND DATA

An MFRSR actually contains seven silicon cell sensors. Six of them are covered by narrow-band interference filters at different wavelengths. The remaining sensor uses no filter. We chose to use the EG&G UV-040BG silicon photodiode (EG&G 1990) that is used in the LI-COR 200 series pyranometer for this open channel. We used only data from this open channel in this paper to estimate irradiance.

Two World Meteorological Organization (WMO) first-class thermopile radiometers (Coulson and Howell, 1980) are used as the reference system. An Eppley NIP pyrheliometer mounted on an Eppley SMT-3 automatic solar tracker measures the direct normal irradiance. An Eppley PSP pyranometer under an Eppley tracking shading disk measures the diffuse horizontal irradiance. The global horizontal irradiance is calculated from direct normal times the cosine of the solar-incidence angle plus diffuse horizontal irradiance. The NIP is calibrated against an Eppley HF absolute cavity radiometer, and the PSP is calibrated by shading and unshading the PSP and comparing the difference to the direct horizontal irradiance derived from the measurement of the NIP.

All of the instruments are located atop the Atmospheric Sciences Research Center in Albany, New York. Data from the MFRSR and the thermopile instruments are collected by two separate, but otherwise identical data acquisition systems whose time keeping is closely monitored. The MFRSR is sampled every 15 s and 5 min averages are stored. The thermopile instruments are sampled every 15 s and 1 min averages are stored. These 1 min averages are summed to 5 min averages for comparison to the MFRSR data.

The experimental data base used for this paper includes data from 1 January 1993 to 31 December 1993. The second half year's data are used to derive the correction equations and the first half year's data are used as a test set for the equations. Since the cosine response of both the PSP and MFRSR becomes problematic at low elevation angles, only those points collected at elevation angles higher than 10° are used to derive the correction equations. Only those points with direct normal irradiance greater than 50 W/m^2 are used in the direct normal correction equation derivation.

3. SKY-CONDITION SENSITIVITY CORRECTION

We follow the Perez *et al.* (1990) approach to describe the sky conditions by introducing two parameters: the sky clearness parameter "ϵ" and the sky brightness parameter "Δ", defined as follows:

$$\epsilon = ((dif(hu) + dir(nu))/dif(hu) + 1.041*z^3)/(1 + 1.041*z^3)$$

$$\Delta = dif(hu)/(I_0 * \cos(z))$$

where *dif(hu)* is uncorrected diffuse horizontal and *dir(nu)* is uncorrected direct normal irradiance from the MFRSR. "z" is the solar-incidence angle in radians, and I_0 is the mean extraterrestrial solar irradiance in W/m^2. Physically, ϵ describes how clear (free of cloud and aerosol) the sky is. If the sky is cloud free and the aerosol burden is low, ϵ will be large because direct will be large and diffuse horizontal will be small. For clear skies, moderate aerosol reduces direct and increases diffuse, thus lowering ϵ. If it is overcast with no direct, ϵ will be 1. Δ indicates aerosol burden and cloud thickness. If the sky is clear and aerosol is low, Δ is low. If the sky is clear, but aerosol loading is high or there are thin cirrus clouds, Δ can be high. If it is heavily overcast, Δ will be low, however, low Δ in this case can be distinguished from low Δ when it is clear by ϵ. For all sky conditions in the data base used, the value of ϵ was found to lie between 1 and 9, and the value of Δ between 0 and 0.8.

We define the ratio of thermopile measurements to MFRSR measurements as the correction ratio "γ". Our object is to find a relationship between γ and the parameters ϵ and Δ for each solar component. Since the points are not evenly distributed in ϵ and Δ, we separated ϵ and Δ into several bins, respectively. Each bin contains about the same number of points. Table 1 shows the boundaries of the ϵ and Δ bins. Figures 1(a)–(c) show the relation between γ, ϵ and Δ for these bins. The unit of the clearness and brightness axes is bin number, not the value of ϵ and Δ. The lower the bin number, the cloudier for ϵ, the darker the sky for Δ. The vertical axis is the mean γ value of all the points that fall in that cell. γ is set to 1 if there are no points in a given cell. The data points for this derivation were collected between 1 July 1993 and 31 December 1993, and total 12,000 points.

Figure 1 shows that for global horizontal and diffuse horizontal irradiances, a "valley" of γ values is formed at low ϵ along the Δ axis. This suggests that under very cloudy conditions, the silicon photodiode is over sensitive relative to its calibration. (The calibration for all components measured by the silicon sensor is derived from a linear regression of silicon and thermopile direct normal irradiances.) Its measurement can be 10% higher than thermopile measurements. However, for high ϵ and low Δ values, corresponding to clear sky conditions, a "peak" is formed, indicating that the silicon photodiode's response is lower than its thermopile counterpart.

Table 1. The bin boundaries for sky clearness and brightness parameters

Parameter	Boundaries
ϵ	1, 1.065, 1.23, 1.5, 1.95, 2.8, 4.5, 6.2, 9
Δ	0, 0.075, 0.125, 0.2, 0.3, 0.425, 0.8

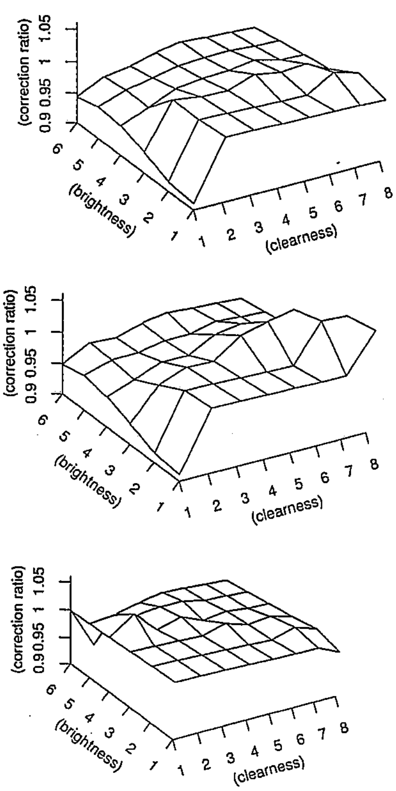

Fig. 1. Correction factors for global (top), diffuse horizontal (middle) and direct normal (bottom) irradiances.

By dividing ϵ and Δ into finer bins, we found that a large number of points fall between ϵ values 1 and 1.005. The sky is basically overcast and the direct irradiance is negligible. The points in this category show a uniform γ pattern that depends only on Δ. For partially cloudy and clear sky conditions, γ is a function of both ϵ and Δ. Four correction equations, using functions that satisfactorily approximate the data, are derived using least-squares-fits for the global horizontal, diffuse horizontal and direct normal irradiance as follows:

Global horizontal

when $\epsilon > 1.005$

$$\gamma = 1.0199 + 0.01188/\epsilon - 0.05913/\epsilon^2 - 0.03851*\Delta \quad (1)$$

when $\epsilon \leq 1.005$

$$\gamma = 0.9090 + 0.1646*\Delta. \quad (2)$$

Diffuse horizontal

when $\epsilon > 1.005$

$$\gamma = 0.9211 + 0.03120*\epsilon - 0.001517*\epsilon^2 + 0.005393/\Delta \quad (3)$$

when $\epsilon \leq 1.005$ use eqn (2).

Table 2. Root mean square errors between silicon and thermopile sensors before and after sky-condition sensitivity correction (5 min samples)

	Global (W/m_2)	Diffuse (W/m_2)	Direct (W/m_2)
Michalsky *et al.* (1991) (uncorrected)	10.4	24.4	40.0
This paper:			
Before correction	11.1	10.6	16.5
After correction	8.8	9.1	16.3

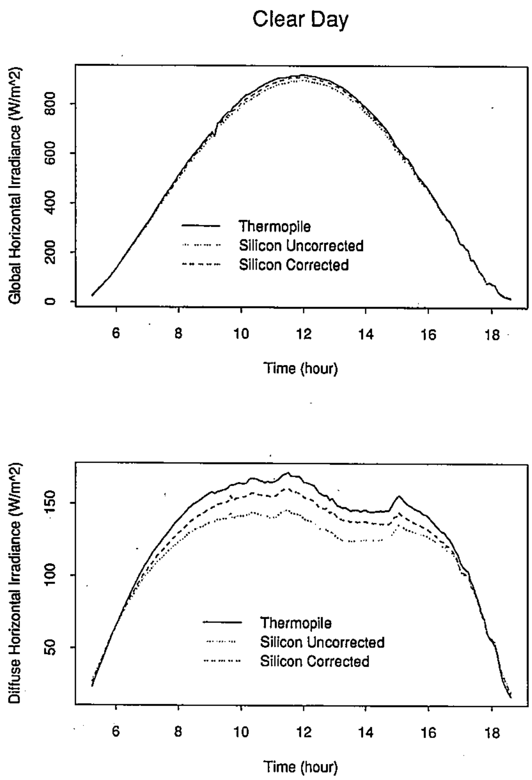

Fig. 2. Global horizontal irradiance (upper) and diffuse horizontal irradiance (lower) measured with the MFRSR before and after sky-condition sensitivity correction and measured with the reference thermopile instruments on a typical clear day.

Direct normal
for all ϵ

$$\gamma = 0.9895 + 0.07483/\epsilon - 0.2051/\epsilon^2 + 0.05701 * \Delta. \quad (4)$$

The correction eqns (1)–(4) were applied to the test data set collected between 1 January 1993 and 30 June 1993. In Table 2 lines 2 and 3 indicate the results of corrections on the entire test data set. Figures (2) and (3) show the MFRSR measurements vs thermopile measurements before and after the correction for a typical clear day (3 May 1993) and a typical overcast day (9 January 1993), respectively.

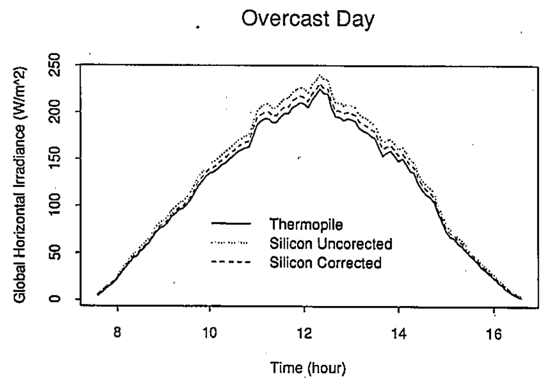

Fig. 3. Global horizontal irradiance measured with the MFRSR before and after sky-condition sensitivity correction and measured with the reference thermopile instruments on a typical overcast day.

4. DISCUSSION

In Michalsky *et al.* (1991) 5 min LI-COR 200 silicon cell and thermopile data were compared, as in this paper. The silicon cell data were not cosine response corrected and the temperature was not held constant, but data were temperature corrected using an experimental temperature response function. Additionally, the thermopile data base consisted of manufacturer calibrated direct normal and global horizontal irradiance data and the diffuse was calculated from the two measurements without a cosine correction of the global horizontal irradiance. Line 1 of Table 2 contains r.m.s. differences between thermopile and LI-COR 200 measurements before corrections. Line 2 of Table 2 contains r.m.s. difference between thermopile and MFRSR measurements before correction. Clearly the MFRSR silicon measurement of solar radiation is substantially improved over that measured by the LI-COR 200 series sensor used in Michalsky *et al.* (1991). There is some relative minor further improvement in the r.m.s. error for the global and diffuse irradiance after sky-condition correction (line 3).

There is no improvement for the direct normal irradiance. The basic calibration of the MFRSR is derived by regressing thermopile direct versus silicon direct irradiance. This process minimizes differences in this parameter. Although the r.m.s. difference is highest for the direct normal irradiance, we should note that the mean value of direct normal irradiance is much higher than global and diffuse horizontal irradiance. In the test data set, the means were 571, 346 and 168 W/m^2, respectively. The ratio of r.m.s. error to the mean value for the direct normal irradiance is (2.9%) compared to global horizontal (3.2%) and diffuse horizontal irradiance(6.3%).

We believe time constants are an important factor that should be considered when comparing silicon photodiode and thermopile instruments. One of the advantages of the silicon sensor is its ability to follow rapid changes in sky conditions because its time constant is small (10 μs). The thermopile sensors have longer time constants (measured in seconds). When radiation is changing dramatically under partly cloudy conditions the measurements from MFRSR and thermopile instruments show a significant discrepancy. If totally clear or totally overcast days are isolated, global and diffuse horizontal r.m.s. errors of 5–6 W/m^2 are typical. If partly cloudy days are isolated, r.m.s. errors of 10–11 W/m^2 are typical. Thus, time constant differences may account for much of the rms error difference in the comparisons of Table 2. Furthermore, if measurements are not made coincidentally, differences (that appear as r.m.s. errors) can become significant.

Finally, equations that are used to correct the data are necessarily weighted by the Albany solar conditions. Consequently, we should expect some modification to these if we incorporate a wider set of data from clearer or cloudier sites. However, this must await availability of those data.

5. CONCLUSIONS

From the research we have done, we have the following conclusions:

1. The MFRSR dramatically reduces the r.m.s. differences between silicon cell and thermopile measurements relative to the LI-COR 200 series pyranometer without correction.
2. With sky-condition corrections, the r.m.s. error of global and diffuse horizontal irradiance measurements from the MFRSR are further reduced by between 15 and 20%. Based on arguments made in the introduction and in reference to Fig. 1 we feel that this sky-condition sensitivity is largely the result of the spectral sensitivity difference in thermopile and silicon sensors.
3. Using sky condition parameters ϵ and Δ is a convenient and effective way to account for the sky-condition sensitivity of the silicon photodiode.
4. The correction results show how well the silicon sensors agree with thermopile instruments. We believe that a significant fraction of the remaining error is due to the response time or time keeping differences between the two types of instruments.

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