On the Performance of Pyrgeometers with Silicon Domes[1]

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ABSTRACT

Net radiation and the individual components of incoming and outgoing solar and longwave radiation were measured over alfalfa (*Medicago sativa, L.*). Solar radiation was measured with precision spectral pyranometers and longwave radiation with pyrgeometers fitted with silicon rather than KRS-5 domes. Direct measurement of incoming longwave irradiance was compared with the value calculated as the residual of the terms comprising net radiation. Shading the pyrgeometer indicated heating of the dome and under calm, sunny conditions, errors as large as 98 W m^{-2} were observed. Visual inspection of the dome indicated no deterioration.

1. Introduction

After the introduction of the Eppley pyrgeometer in the early 1970's, two problems associated with the dome became evident: 1) the quality of the dome constructed of KRS-5 deteriorated after long periods of exposure and 2) an additional source of longwave radiation developed as the dome was heated by the sun. Albrecht *et al.* (1974) proposed that the dome temperature be monitored with a thermistor and the longwave radiation be calculated on the basis of energy balance considerations as follows:

$$L = CE + \epsilon_0\sigma T_s^4 + k\sigma(T_d^4 - T_s^4), \qquad (1)$$

where L is the incident irradiance, C the calibration constant of the thermopile, E the voltage output from the thermopile, ϵ_0 the emissivity of the thermopile surface, σ the Stefan-Boltzmann constant, T_s the temperature of the thermopile cold junction, T_d the temperature of the dome and k a constant determined during calibration procedures. The commercially available pyrgeometer has a circuit that simulates the second term in Eq. (1) and combines it with the thermopile output to yield a signal proportional to the longwave radiation assuming $T_s = T_d$. Additional improvements in the pyrgeometer, by removing the battery circuit which simulates the second term in Eq. (1), were suggested by Albrecht and Cox (1977). This would eliminate the variability in the output voltage of the battery and the inability of the circuit to accurately produce a signal at extreme temperatures. They further suggested that the thermopile temperature be measured directly with a thermistor and that this temperature be used in Eq. (1).

Enz *et al.* (1975) directly vented air onto the dome in order to minimize heating. While this technique is helpful, it cannot completely eliminate the dome

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as an additional source of longwave radiation. Campbell *et al.* (1978) redesigned the aluminum housing of the pyregeometer to act as a heat sink for the dome and utilized a different type of thermopile. A net pyrradiometer and a pyranometer were modified to measure all-wave incoming radiation and with a pyranometer, the resulting longwave radiation from these sensors was compared with the modified pyrgeometer. They also derived a relationship similar to Eq. (1). In 1976, Eppley Laboratory, Inc. introduced a pyrgeometer with a silicon dome in order to eliminate the problems described above.

2. Instrumentation

An evaluation of the performance of a pyrgeometer with a silicon dome was conducted from 14 July to 9 September 1978 at the Scottsbluff Agricultural Laboratory of the University of Nebraska Panhandle Station (41°59′N; 103°41′W; 1225 m MSL, ~9 km northwest of Scottsbluff, Nebraska). Individual measurements of incoming (↓) and outgoing (↑) solar (S) and longwave (L) radiation were made near the center of a 4 ha alfalfa (*Medicago sativa, L.*) field at a height of 2 m above ground. The precision spectral pyranometers and pyrgeometers used in this experiment were constructed so that the upward and downward facing sensors shared a common housing (Fig. 1). Sensors were leveled with the assistance of a bubble level, mounted on a hollow cylinder placed over each dome, followed by adjustments of spring mounted bolts. Because of the diffuse nature of longwave radiation, leveling of the pyrgeometers is not as crucial as leveling of the pyranometers (Albrecht *et al.*, 1974). Temperature of the cold junction of the thermopile of the pyrgeometer was measured directly with a thermistor. Net radiation (R_n) was measured with two Swissteco net pyrradiometers.

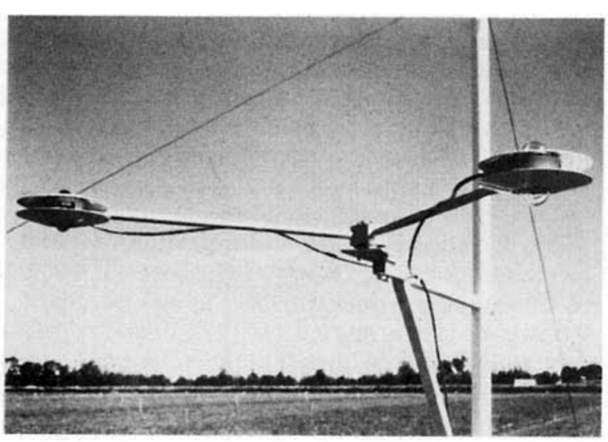

FIG. 1. Eppley precision spectral pyranometers on the right and pyrgeometers on the left. The spring mounted bolts in the center of the support system are used for leveling the sensors.

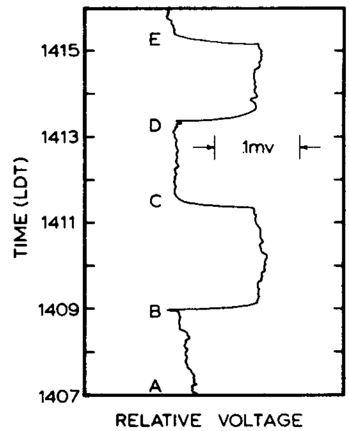

FIG. 2. The effect on the thermopile output of alternatively shading (BC and DE) and exposing (AB and CD) the pyrgeometer dome to sunlight. The polarity of the output was reversed during this test.

Air temperature was measured at 2 m with a shielded, naturally ventilated thermocouple. The sensors were sampled every 10 min and the output recorded on paper tape for later analysis. This sampling time was based on local daylight time (LDT) and then converted to solar time (ST) during the data analysis.

3. Pyrgeometer performance

Prior to the start of this evaluation, the pyrgeometer was alternatively exposed and shaded from the sun with a 30 cm disk held ~1.3 m above the pyrgeometer (Fig. 2). The polarity of the thermopile output was reversed during this test so that periods of shading, BC and DE should indicate a decrease in this output. The pyrgeometer output during periods of shading was 363 W m^{-2} while during periods of exposure to the sun (AB and CD) it was 377 and 384 W m^{-2}, respectively. This simple test conducted under windy, cool conditions, indicated the potential influence of solar loading on the silicon dome but nothing about the diurnal variation of the pyrgeometer performance under different sky conditions. The results of shading experiments of this type will vary as a function of incoming solar radiation, wind speed and air temperature.

Incoming longwave radiation was measured with the pyrgeometer, utilizing Eq. (1) and ignoring the dome heating term and was compared to the "corrected" longwave radiation calculated by

$$L_c\downarrow = \bar{R}_n - S\downarrow + S\uparrow + L\uparrow. \qquad (2)$$

It was assumed that heating of the downward facing pyrgeometer measuring $L\uparrow$ occurred for only brief intervals near sunrise and sunset and was negligible. Enz *et al.* (1975) only found a 2–3% difference in the output from an inverted pyrgeometer, with a

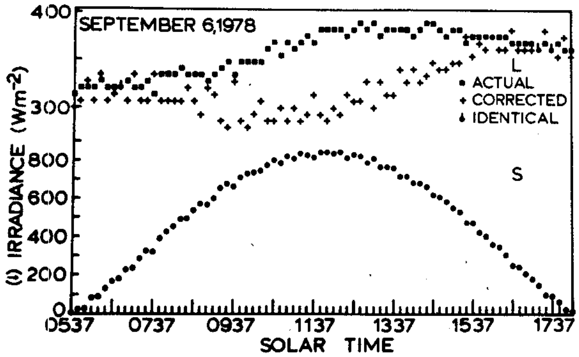

FIG. 3. Comparison of measured and corrected incoming longwave irradiance for 6 September 1978. Incoming solar irradiance is also shown.

KRS-5 dome, compared to the longwave radiation determined by an infrared thermometer. The calibration constants for the newly purchased pyranometers were those supplied by the manufacturer. The net pyrradiometers were calibrated against a "standard" pyrradiometer, i.e., a similar pyrradiometer used only for calibration purposes. The difference between the measured and calculated values of long wave radiation, therefore, could be due to the heating of the upward facing pyrgeometer dome.

A "worst-possible" case of the behavior of the pyrgeometer under cloud-free conditions is illustrated in Fig. 3. On 6 September a record breaking air temperature of 38°C (100°F) was recorded at the Scotts Bluff County Airport, 12.5 km southeast of the field site. The maximum air temperature recorded at the field site was 32°C.

Measured and calculated values were in good agreement under low levels of solar irradiance, but disagreement was great when irradiance was high. This latter period occurred from approximately 0907 to 1527 ST when the elevation angle of the sun was ~38 and 33°, respectively. The maximum difference in the determination of longwave irradiance was ~98 W m^{-2} at 1157 ST.

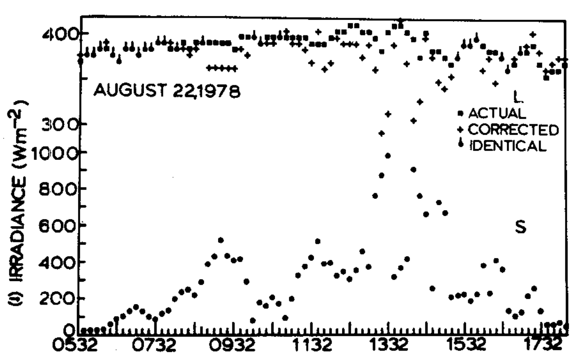

FIG. 4. As in Fig. 3 except for 22 August 1978.

TABLE 1. Daily integrated values (W m^{-2})* of $\bar{R}_n$, $S\downarrow$, $S\uparrow$, $L\uparrow$, $L_c\downarrow$ and $L\downarrow$ and the absolute E_a and probable E_p errors associated with $L_c\downarrow$.

	$\bar{R}_n$	$S\downarrow$	$S\uparrow$	$L\uparrow$	$L_c\downarrow$	$L\downarrow$	E_a	E_p
22 August	66	156	38	411	359	364	12	9
6 September	108	266	65	416	324	345	16	9

* 1 cal cm^{-2} min^{-1} = 697.3 W m^{-2}; 1 cal cm^{-2} day^{-1} = 0.4843 W m^{-2}.

Another perspective on the problem of solar loading on the pyrgeometer dome can be gained from observations under cloudy conditions on 22 August (Fig. 4). There is much better agreement between the two methods of determining longwave irradiance during periods of low solar irradiance. However, during breaks in the cloudiness, as indicated by peak values of solar radiation centered at 0912, 1142, 1332, 1412 and 1452 ST, discrepancies between the two methods occurred. Thus, heating of the silicon dome can be a problem even on generally cloudy days.

The absolute and probable errors associated in the determination of $L_c\downarrow$ may be defined as

$$E_a = \Delta r R_n + \Delta s\downarrow S\downarrow + \Delta s\uparrow S\uparrow + \Delta l\uparrow L\uparrow \quad (3)$$

and

$$E_p = (\Delta r R_n)^2 + (\Delta s\downarrow S\downarrow)^2 + (\Delta s\uparrow S\uparrow)^2 + (\Delta l\uparrow L\uparrow)^2, \quad (4)$$

respectively. The Δ terms are the uncertainties in the absolute accuracy of the measured quantities R_n, $S\downarrow$, $S\uparrow$ and $L\uparrow$ and are taken as 3, 1, 2 and 2%, respectively. Using 24 h integrated values of these parameters (Table 1), the difference between the incoming calculated ($L_c\downarrow$) and measured ($L\downarrow$) longwave radiation is less than the probable error on 22 August but is greater than the absolute error on 6 September. Using a similar analysis for the data at 1157 ST on 6 September yields absolute and probable errors of 36 and 20 W m^{-2}, respectively, while as previously noted the difference between $L\downarrow$ and $L_c\downarrow$ was 98 W m^{-2}. These calculations indicate that the pyrgeometer with silicon domes can have significant errors on a calm, sunny day and that $L_c\downarrow$ on 6 September was probably real and not due to the residual method of calculation.

The difference in the diurnal variation of the corrected longwave radiation on 6 September may be attributed partially to the "center of gravity" hypothesis first proposed by Paltridge (1970). The center of gravity of atmospheric emission is ~200–300 m above the earth's surface. During the day when lapse conditions normally predominate, the temperature of this layer is cooler than the temperature at the 2 m level, while during inversion conditions, the opposite is true. While this hypothesis does not give a quantitative distribution of incoming longwave radiation during daytime clear-sky conditions, it does indicate that predicted incoming longwave radiation during this period from empirical formula (e.g., Swinbank's equation) will overestimate actual values. Since these data were collected in a heavily irrigated valley, additional water vapor in the atmosphere may have influenced the distribution of $L_c\downarrow$.

Stanhill *et al.* (1968) used a similar residual procedure as employed in this analysis to calculate $L\downarrow$ with the exception of the measurement of leaf temperatures and the calculation of $L\uparrow$ rather than the direct measurement of $L\uparrow$. Their clear sky calculations of $L\downarrow$ are similar to the corrected values presented in Fig. 3 as is the data of Campbell *et al.* (1978).

On 14 August a thunderstorm with peak gusts reaching 30 m s^{-1} deposited 2.74 cm of water in 30 min at the field site. The domes of the pyrgeometers were not damaged by the storm. The domes, which have a mirrorlike finish, were visually inspected at the end of the experiment and no deterioration in their condition was observed.

4. Conclusion

With the introduction of the silicon domes for their pyrgeometers, Eppley Laboratory hoped to eliminate two problems associated with the KRS-5 domes: deterioration and heating. The former problem has been solved but the latter problem remains. It appears that a solution to this heating problem may be obtained from the results of either Albrecht and Cox (1977) or Campbell *et al.* (1978).

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