Surface Temperature Measurements of Bare Soils

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Measurement of the surface temperature of bare soils by contact thermometry is subject to serious error. It is difficult to maintain good thermal contact between the sensor and the surface without disturbing the conditions at the surface. Accordingly, with the near zero wind velocity in the immediate vicinity of the surface, large radiation errors may obtain even with very small sensors, if they are exposed to sun and sky radiation. Fuchs and Tanner (1967) have reported that under sunlight conditions, five thermocouple wires lying on the surface yielded measurements 2–4C higher than the temperature obtained by infrared (IR) thermometers. If the sensor is covered with a thin layer of soil, the temperature also will differ from that at the surface much of the time.

The IR thermometer is accurate to 0.3C, provided measurements of the background radiation and the emissivity of the surface, weighted for the IR thermometer's bandpass are available (Fuchs and Tanner, 1966; Conaway and Van Bavel, 1967). The change of water content of a drying soil will cause a change in the surface emissivity since the emissivity of water is different from the emissivity of the soil material. A value of 0.97 is generally accepted for the emissivity of water (Anderson, 1954). The emissivities of clayey and loamy soils are close to 0.96 (Hovis, 1966), and changes in moisture content of these soils hardly modify their emissivity. In the case of dry, predominantly quartz sand with an infrared emissivity near 0.90 (Falckenberg, 1928), the water content of the surface significantly affects the emissivity.

Buettner and Kern (1965) measured an emissivity of 0.936 for wetted coarse quartz sand in the bandpass of an IR thermometer similar to the one we used. The value of 0.916 they found for the dry quartz sand is probably too high as discussed in a later paragraph.

We report here comparisons between thermocouple and infrared measurements of soil temperature and give the variation of the emissivity of Plainfield sand surface with moisture content.

The emissivity ϵ of the soil surface in the wave bandpass of the IR thermometer may be expressed as

$$\epsilon=(\sigma T_r^4-B_s^*)/(\sigma T^4-B_s^*), \tag{1}$$

where σ is the Stefan-Boltzmann constant, T_r the "apparent" Kelvin temperature of the soil surface, T the absolute Kelvin temperature and B_s^* a parameter proportional to the background radiation. The range of validity of (1) and the method for determining B_s^* are discussed in detail in a previous article (Fuchs and Tanner, 1966).

The computation of B_s^* implies the constancy of the spectral emissivity in the bandpass of the IR thermometer. In the case of quartz, which has a strong reflection band near 9 μ (Lyon, 1965; Hovis, 1966), this assumption fails. The resulting error can be minimized if B_s^* is small with respect to the other terms of (1). In the "emissivity box" used by Buettner and Kern, B_s^* is large and results in an overestimate of the emissivity. This error is substantiated by their comparison of the emissivities of various quartzitic materials measured in the "emissivity box" with the emissivity obtained from an integration of the spectral curves.

The emissivity of Plainfield sand was computed from (1) for various moisture conditions of the soil surface. The measurement of T was made with an IR thermometer through the apex of an aluminum cone 35 cm high with a base diameter of 26 cm that covered the soil for less than 5 sec. During this time lapse, the temperature drift traced on a strip chart recorder connected to the output of the IR thermometer was approximately 0.1C. The apparent temperature T_r was obtained by taking a measurement of the bare soil exposed to the cold sky which minimizes B_s^*.

As shown by Table 1, the emissivity decreases when the moisture content of the soil layer between 0 and 2.5 cm decreases. The relationship is only approximate because the average water content in this layer may not represent well the amount of water present at the surface; however, it does show the trend we are concerned with. We note that the largest value of ϵ was not obtained for the highest moisture content in the 2.5-cm layer; this measurement, however, was taken at night with condensation occurring at the surface. When a thin, dry, sand layer at the surface is continuous, the emissivity equals 0.90, regardless of the moisture content beneath the surface layer. A spectral reflectivity curve[1] has confirmed this value for the dry Plainfield sand, and also indicates that the colloidal coating of the sand grain considerably reduces the reflection band of quartz near 9 μ.

TABLE 1. Relationship between the emissivity (8–13 μ) of Plainfield sand and the volumetric water content of the soil layer between 0 and 2.5 cm.

Emissivity	Water content (%)
0.94	8.4
0.96*	7.6
0.92	6.2
0.92	5.8
0.90	3.5
0.90	0.7
0.88**	0.7

* Condensation at the surface.
** Coarse quartz sand.

Soil temperature measurements were made with differential, 5-junction, copper-constantan thermopiles of 0.25-mm diameter wire. Differential temperatures were measured between −0.1, −2.5, −7.5 and −30.0 cm. The absolute temperature of the soil was measured within 0.2C by a diode in a close thermal contact with the deepest thermocouple junctions. The soil temperature profiles obtained in this manner allow a meaningful comparison between the temperature at −0.1 cm and the temperature at the true surface, which was measured by the IR thermometer. The depth of −0.1 cm is the shallowest depth at which good thermal contact between the sensors and the soil can be obtained on this soil without disturbing severely the surface conditions. Radiation errors on the thermocouples were considerably reduced by this procedure.

A typical diurnal trend of the temperature is shown in Fig. 1. The net radiation measured with a Suomi type ventilated radiometer is also shown. In the early morning, the soil surface was wet, but dried very rapidly. A thin film of dry soil appeared locally over the surface around 0800 CST. At the end of the day, the dry layer had an average thickness of 0.2 cm. The arrows in Fig. 1 mark the timing of the emissivity measurements; the values obtained are also indicated.

During the hours of high net radiation, the surface temperature is higher than the temperature measured at −0.1 cm and is lower in the early morning and late afternoon. However, in both cases, the surface temperature is in the correct relationship with respect to the curvature of the soil temperature profile. The maximum difference between T_0 and $T_{-0.1}$ is 3.3C and occurs at 1100 when the soil heat flux reaches its maximum. On the other hand, when the top layer of the soil is nearly isothermal, both temperatures are well within the absolute accuracy of the measurements. Better agreement obtained during the afternoon than in the morning. The IR measurement in the morning could be slightly low because the fast change in the moisture content of the surface caused the emissivity to decrease more rapidly than expected.

It appears that covering the thermocouples with a thin layer of soil causes about the same size of departures from the surface temperature as leaving the wires exposed to radiation. Although the extrapolation of the soil temperature profile to the surface may be

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[1] This determination was made by W. A. Hovis, NASA, Goddard Space Flight Center, Greenbelt, Md.

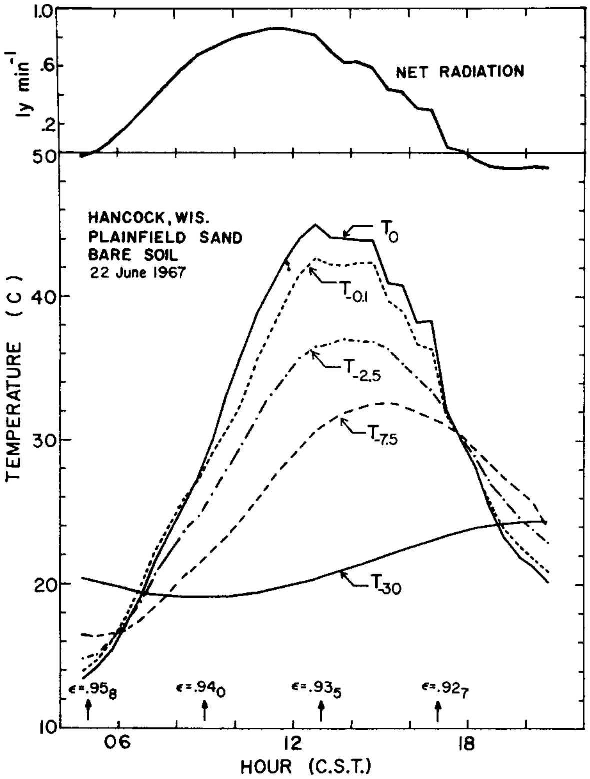

Fig. 1. Diurnal variation of the soil temperature. The subscripts on the curve labels indicate the depth (cm) of the measurement.

misleading because of the vertical heterogeneity of the soil thermal properties, the curvature of the temperature profile indicates whether the covered thermocouples will either overestimate or underestimate the actual surface temperature.

Addendum. A reviewer of our manuscript raised the point that the aluminum cone we use to obtain the absolute surface temperature T is not a perfect reflector, and consequently, that a temperature difference between the surface and the aluminum would result in an error in the measurement of T, owing to a departure from blackbody emission. Considering a diffuse cone cavity of hemispherical apparent emissivity ϵ_a toward the base of the cone, and temperature T_a, covering a surface of emissivity ϵ and temperature T, the effective emissivity ϵ_f through a small orifice at the cone apex is given by

$$\epsilon_f = 1 - 4\epsilon_a(1-\epsilon)(T-T_a)T^{-1}(\epsilon_a+\epsilon-\epsilon_a\epsilon)^{-1}. \qquad (2)$$

The apparent emissivity ϵ_a of the aluminum cone depends upon the emissivity of the aluminum itself (taken as 0.10) and the angle θ of the cone apex (for our cone $\theta = 41°$). Approximating an analysis by Sparrow and Jonsson (1963) for a cone with diffuse inner surface, ϵ_a was found to be 0.24. Assuming for the soil an emissivity of 0.90, (2) yields

$$\epsilon_f = 1 - 0.103(T-T_a)T^{-1}.$$

For $T - T_a = 10\text{K}$, and $T = 300\text{K}$, ϵ_f is 0.997. The resulting error in T is

$$\delta T = [0.003/0.997]T/4.$$

At $T = 300\text{K}$, $\delta T = 0.2\text{K}$ which is close to the limit of resolution of our infrared thermometer. It should be noticed that in practice this error is smaller because at a wavelength around 10 μ, the emissivity of aluminum is less than 0.1 and also because aluminum has strong specular behavior.

However, as a result of the calculations made following Sparrow and Jonsson (1963), we recommend that aluminum cones with apex angles of 120° or larger, or shallow cylindrical cavities which have smaller apparent emissivities (Kelly and Moore, 1965) be used to improve the accuracy of the measurements.

We acknowledge the reviewer's criticism which has forced us into this more detailed analysis and leads to an improvement of our surface temperature measurement technique.

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