Longwave radiation at the ground: III. A radiometer for the 'representative angle'

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SUMMARY

The construction of a directional radiometer for measuring longwave radiation from the atmosphere is described. The instrument had a filter of black polyethylene to exclude solar radiation, and the detector was a thermopile. By analysis of the radiation and heat balances of the thermopile, correction terms are derived for (i) the flux density of radiation received by the thermopile from the filter, and (ii) the dependence of instrument sensitivity on temperature. Measurements with the new instrument of the equivalent flux density below cloudless skies at zenith angle 52·5° agree well with measurements of hemispheric flux density derived from simultaneous measurements with a Linke–Feussner actinometer.

1. INTRODUCTION

Longwave radiation received from the earth's atmosphere is a major term in the heat balance of the earth's surface. Accurate spot measurements are possible with a Linke–Feussner actinometer and similar commercial instruments which receive radiation from a small fraction of the hemisphere, but the filter technique for distinguishing between longwave and shortwave fluxes is cumbersome and the instruments cannot be conveniently adapted for continuous recording. An estimate of the *net* longwave flux at the ground can be obtained from the difference between net radiation and net solar radiation, both of which can be measured with standard instruments, but such estimates may have large uncertainties by day when solar radiation is large. Instruments fitted with filters to absorb and reflect solar radiation, such as the Eppley pyrogeometer, are prone to errors because thermal emission of the filter is increased when it is heated by the sun (Enz *et al.* 1975; Albrecht and Cox 1977). Paltridge (1969) tried to minimize the uneven heating of a spherical black polyethylene filter surrounding a net radiometer by rotating the filter rapidly about a horizontal axis.

The instrument described in this paper exploits the existence of a 'representative zenith angle', z, at which the longwave radiance from the atmosphere is equal to the mean radiance for the whole hemisphere. Experimental evidence reviewed in the first paper of this series (Unsworth and Monteith 1975) confirmed that for both cloudless and overcast skies, z has a value of 52·5° irrespective of the amount of water vapour in the atmosphere (Dines and Dines 1927; Robinson 1947, 1950). The same value of z is appropriate for the emission by any gas where apparent emissivity is a linear function of the logarithm of the optical path length.

2. DESIGN AND THEORY

(a) Construction of the instrument

The instrument, shown in Fig. 1(a), was constructed from a solid cylinder of aluminium 17 cm long by 9 cm diameter. A truncated conical opening machined in the block subtended a half-angle of 10° at its base where the detector, D, a constantan-copper thermopile, was fixed. A filter, F, of black polyethylene, 38 μm thick, was fixed across the top of the cone.
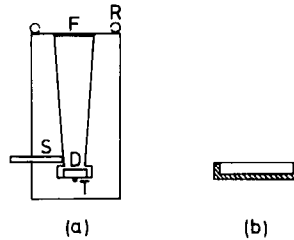
Figure 1.   (a) Cross-section of radiometer showing thermopile detector D, diode thermometer T, zero slide S, polyethylene filter F and ventilation ring R. (b) Cross-section of thermopile former.

The filter temperature was maintained close to air temperature by blowing air from a perforated ring R fixed to the end of the instrument; this arrangement also kept the filter clear of dust and avoided the formation of dew.

The thermopile, wound on an anodised aluminium former 20 mm square, was designed for large power output (Funk 1962). Eighty turns of 50 s.w.g. constantan wire, 25 μm diameter, were wound on the former and partly copper-plated to produce a thermopile as described by Monteith (1959). The upper row of junctions was suspended over the bridge of the former whereas the lower junctions were in good thermal contact with its base (Fig. 1(b)). The suspended junctions were covered with thin tissue paper which was painted with Parson's optical black paint. The lower junctions were varnished for electrical insulation and the thermopile was bolted to the solid base of the instrument. To check the zero offset, i.e. the output of the thermopile when the incident radiation from the atmosphere was zero, a manually operated slide, S, consisting of two layers of aluminium separated by a layer of perspex, was incorporated. The upper surface of the slide was covered with reflecting foil and the lower surface was coated with optical black paint.

The thermopile temperature was measured with a diode thermometer T, calibrated against a National Physical Laboratory standard mercury thermometer, and fixed close to the lower junctions.

(b)   Theory

It is convenient to express the longwave and shortwave radiation received by the radiometer as the equivalent flux densities $\mathscr{L}$ and $\mathscr{S}$ which would be received from a hemisphere radiating uniformly like the part of the sky at which the radiometer is pointing (Unsworth and Monteith 1975; Steven 1977).

Let f be the view factor of the radiometer (Reifsnyder 1967), and let the thermopile temperatures be T_u for the upper junctions and T_l for the lower junctions. Assume that the body of the instrument has emissivity ε_i and is at temperature T_i, and the filter temperature is T_p.

Ignoring heat transfer by conduction along the wires of the thermopile, the heat balance of the surface of the thermopile is

$$tf\mathscr{L} + \varepsilon_i(1-f)\sigma T_i^4 + f\varepsilon\sigma T_p^4 + \varepsilon_i\sigma T_i^4 - \sigma T_u^4\{\varepsilon_i(2-f)+f(1-r)\} = h_c(T_u - T_i) \qquad (1)$$

where h_c is a convective heat transfer coefficient and t, r and ε are the transmissivity, reflectivity and emissivity of the filter (here assumed identical for atmospheric and black-body radiation) so that $\varepsilon = 1-t-r$. By assuming that $T_i - T_u$ and $T_p - T_u$ are small, it may be shown from Eq. (1) that

$$\mathscr{L} = CV + \sigma T_i^4 - \delta\mathscr{L} \qquad . \qquad . \qquad . \qquad (2)$$

where the calibration factor of the thermopile is

$$C = (T_u - T_i)[4\sigma T_i^3\{\varepsilon_i(2-f)+f(1-r)\} + h_c]/ftV \quad . \qquad . \qquad (3)$$

V being the e.m.f. generated by the thermopile, and

$$\delta\mathscr{L} = 4\varepsilon t^{-1}\sigma T_i^3(T_p - T_i) \qquad . \qquad . \qquad . \qquad (4)$$

Eq. (3) shows that CV is not a linear function of $T_u - T_i$; the relative contributions of the radiative and convective terms to the non-linearity depend on the geometry of the instrument and on the optical properties of the filter. The term $\delta\mathscr{L}$ in Eq. (4) may be regarded as a correction term which would be zero for an ideal filter with $t = 1$ and $\varepsilon = 0$. Typically $4\sigma T_i^3 \simeq 5\cdot5\,\mathrm{W\,m^{-2}K^{-1}}$ and it will be shown later that εt^{-1} for black polyethylene $\simeq 1\cdot2$ so that $\delta\mathscr{L} \simeq 6\cdot6(T_p - T_i)\,\mathrm{W\,m^{-2}}$.

(c) Optical properties of the filter

Fig. 2 shows the spectral transmission of the filter, measured with spectrophotometers in the waveband $0\cdot3$–$40\,\mu$m. When a piece of filter material was held in front of a Linke–Feussner radiometer pointing at the sun, about $0\cdot7\%$ of incident radiation was transmitted, in agreement with calculations based on Fig. 2 and typical solar spectra (Gates 1965). The transmission of diffuse solar radiation could not be measured but would be smaller than $0\cdot7\%$ because the radiation is mainly in the waveband $0\cdot3$–$0\cdot8\,\mu$m (Gates 1965).
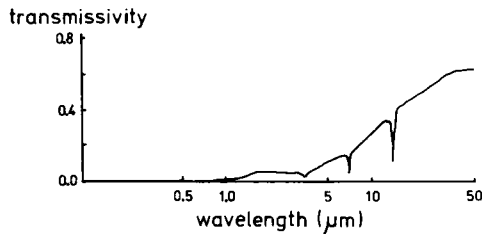

Figure 2. The transmissivity of black polyethylene, $38\,\mu$m thick.

Similar experiments using a black-body source at 20°C showed that the transmissivity for longwave radiation was $0\cdot44$; the estimated transmissivity for radiation from a black body at -20°C was $0\cdot48$.

Kyle (private communication) estimated that the reflectivity of polyethylene was about $0\cdot04$ and was almost independent of wavelength. Experiments with longwave radiation confirmed this value. Thus the emissivity at 20°C is $1 - 0\cdot44 - 0\cdot04 = 0\cdot52$.

When the sky is cloudless, typical values of $\mathscr{S}$ and $\mathscr{L}$ are 150 and $300\,\mathrm{W\,m^{-2}}$ respectively, and transmitted solar radiation would introduce an error of about $1\,\mathrm{W\,m^{-2}}$. The worst case arises when the instrument views an isolated cloud reflecting the sun. Assuming $\mathscr{S} = 600\,\mathrm{W\,m^{-2}}$, transmitted solar radiation would be about $4\,\mathrm{W\,m^{-2}}$.

To calculate the correction term $\delta\mathscr{L}$ in Eq. (2), the temperature T_p of the filter must be measured or estimated. In the field, we were unable to measure T_p continuously, but laboratory experiments showed that, when the instrument was exposed to longwave radiation, T_p was close to air temperature T_a because of the forced convection from the ventilation ring. When shortwave radiation is absorbed by the filter, T_p exceeds T_a. In these circumstances values of $\delta\mathscr{L}$ calculated on the convenient assumption that $T_p = T_a$ are likely to be underestimated by less than $4\,\mathrm{W\,m^{-2}}$ when skies are cloudless and by up to $10\,\mathrm{W\,m^{-2}}$ in the worst case of scattered cloud. Laboratory experiments showed that the underestimations would be approximately doubled without forced ventilation.

3. CALIBRATION

The instrument was calibrated by two methods. In the laboratory the radiometer received radiation from a conical black-body source operated at temperatures up to $T_i +$ 30°C. Fig. 3 shows the dependence of instrument output voltage V on net longwave radiation. The y intercept of the best straight line through the points does not differ significantly from zero, and the line forced through the origin has slope $1 \cdot 07 \pm 0 \cdot 01 \, Wm^{-2} \mu V^{-1}$ ($r = + \cdot 999$).

In the field the output of the radiometer was compared on cloudless nights with the output from a Linke–Feussner actinometer pointing at the same zenith and azimuth angles. The actinometer was calibrated against an Ångström pyrheliometer at Bracknell. Fig. 3 shows the radiometer output V as a function of net longwave radiation determined by the actinometer. The best line through the origin has slope $1 \cdot 04 \pm 0 \cdot 12 \, Wm^{-2} \mu V^{-1}$. As the field calibration did not differ significantly from the laboratory calibration, the more precise value was applied in all cases.
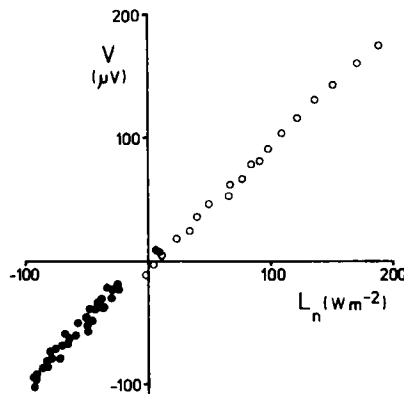

Figure 3. Dependence of output voltage V of the radiometer on net longwave radiation L_n: ○ laboratory measurements, ● field measurements.

4. FIELD OPERATION

When operated automatically in the field, corrections were made for filter emission, assuming that filter temperature was equal to air temperature, and for the signal from the thermopile when the slide was closed (Fig. 1). To examine the factors determining this zero
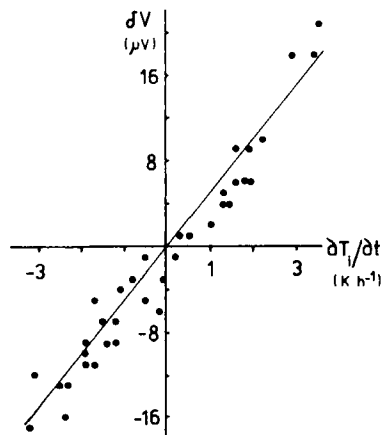

Figure 4. Dependence of zero offset δV of the radiometer on the rate of temperature change $\partial T_i / \partial t$.

offset, the radiometer was left outside with the zero slide inserted and instrument temperature and voltage output were recorded at ten-minute intervals on a data logger for three periods of 48 hours each. Fig. 4 shows that the hourly average of the zero offset δV was linearly related to the rate of change of T_i with time, and the relationship $\delta V/(\partial T_i/\partial t) = 5\cdot1 \pm 0\cdot2\,\mu V/(\mathrm{K\,h^{-1}})$ $(r = +\cdot97)$ was used to make corrections to all subsequent records.

5. RESULTS

On cloudless days the diurnal variation of $\mathscr{L}(z)$ measured with the radiometer was compared with values of L_d determined by integrating values of $\mathscr{L}$ measured with a Linke–Feussner radiometer at seven zenith angles as described by Unsworth and Monteith (1975). Corrections for zero offset and for filter emission of the new instrument were applied.
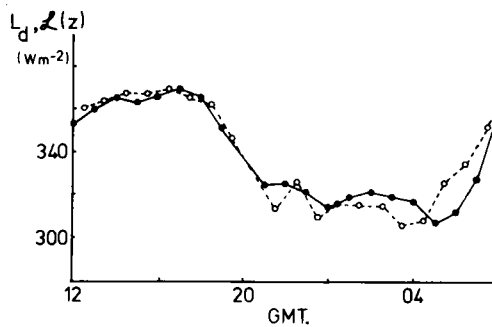

Figure 5.   Variations of hemispheric flux density L_d (—●—) of longwave radiation and of equivalent flux density $\mathscr{L}(z)$ (--○--) with time during the cloudless period 25–26 June 1975.
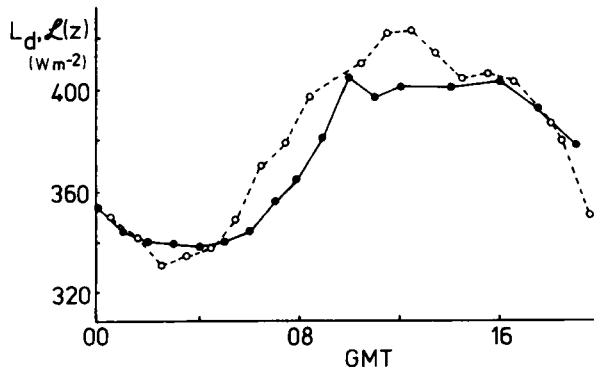

Figure 6.   Variations of hemispheric flux density L_d (——●——) of longwave radiation and of equivalent flux density $\mathscr{L}(z)$ (--○--) with time during the cloudless day 3 August 1975.

Typical results are shown in Figs. 5 and 6. The instruments agree well within the uncertainties in their calibrations and in the corrections described earlier. There is some evidence that $\mathscr{L}(z)$ exceeds L_d when instrument temperature lags behind air temperature so that the zero offset correction may have been underestimated.

6. CONCLUSIONS

This simple instrument measures the equivalent flux density $\mathscr{L}(z)$ at $z = 52\cdot5°$ with a potential accuracy of better than 5%, and there is strong evidence supporting the equality of $\mathscr{L}(z)$ and the hemispheric flux density on a horizontal surface, L_d. When used as described here, the absorption of solar radiation by the filter may cause systematic overestimation of

$\mathcal{L}(z)$, but the error would not exceed $5\,\mathrm{W\,m^{-2}}$ when skies are cloudless and $15\,\mathrm{W\,m^{-2}}$ below scattered cloud. Measurements of filter temperature would remove this source of error. A number of further improvements are possible to increase accuracy, at the expense of simplicity. A thermostat would reduce offset errors; a pyroelectric detector would produce a larger signal and the filter could be placed closer to the detector to restrict the solid angle from which the filter receives solar radiation. Further studies are necessary to establish whether the radiometer can also be used to measure $\mathcal{L}(z)$ below overcast and partial cloud. However, no reliable standard methods exist for determining L_d in such conditions.

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