The Vertical Location of Net Radiometers

I. The Effects of the Underlying Air Layer*

By S.B. Idso and K.R. Cooley

U. S. Water Conservation Laboratory, Phoenix, Arizona

Abstract

Theory indicated that for surfaces with temperatures significantly different from that of the ambient air, net radiation measurements become increasingly less representative of surface conditions with increasing height above the surface. This effect of the intervening air layer between the net radiometer and the surface was found experimentally to create a 7% discrepancy between the net radiation measured at 50 cm above a dry, bare soil and that measured at 215 cm for the daylight hours. On a 24-hour basis the discrepancy amounted to 11% of the total net radiation. In this situation, true net radiation is obtained only at the surface.

1. Introduction

In research work dealing with energy balances of bare or vegetation covered surfaces, there appears to have been little uniformity in the vertical placement of net radiometers. Some examples of height placement, for instance, have been 0.1 m by van Bavel and Fritschen (1965); 0.3 m by van Bavel (1967); 0.5 m by Rosenberg (1966), and Stanhill, Hofstede, and Kalma (1966); 0.75 m by Idso, Baker, and Blad (1969); 1.0 m by Davies and Buttimor (1969), Fritschen (1967), Stanhill and Fuchs (1968), and Thompson and Boyce (1967); 1.5 m by Ekern (1965), Fitzpatrick and Stern (1966), Fuchs and Tanner (1967), and Monteith and Szeicz (1961); 2.0 m by Begg *et al.* (1964), Denmead (1969), Morgan, Pruitt, and Lourence (1970), and Rosenberg (1969); and 2.5 m by Stanhill, Hofstede, and Kalma (1966).

In practically all of these studies, no reason was given for the height placement of the net radiometers. Only Stanhill, Hofstede, and Kalma (1966) indicated that they worked at 2.5 m to obtain representative readings over incomplete or non-homogenous vegetation; and van Bavel and Fritschen (1965) stated that they positioned their net radiometers at 0.1 m to minimize any vertical divergence of the net radiation. Neither of these

teams, however, gave any *quantitative* reasons for the particular heights chosen.

Reifsnyder (1967) was one of the first investigators to elucidate a rational approach to the vertical placement of net radiometers. Elaborating quantitatively upon the reasoning used by Stanhill, Hofstede, and Kalma (1966), he reviewed some of the heat transfer literature dealing with view factors for radiant energy interchange between diffusely emitting surfaces. His end product was a method for determining percentages of radiation received from various size areas under radiometers at different heights. Nowhere in his analysis, however, did he make allowance for the intervening air layer between the radiometer and the surface. Thus, in this paper, we explore the significance for net radiometry of the fact that the intervening air layer between the net radiometer and the underlying surface is a participating medium in the radiation exchange process.

2. Theory

Consider a net radiometer located at a reference level (optical thickness $u = u_r$) above some underlying surface ($u = u_s$). In the long-wave or thermal energy region, this radiometer receives a downward flux of radiation, $F_{\downarrow}$, emitted by the atmosphere above it, and an upward flux of radiation, $F_{\uparrow}$, emitted by the underlying ground surface and the intervening air layer.

Following Fleagle and Businger (1963), the downward flux of radiation may be written as

* Contribution from the Soil and Water Conservation Research Division, Agricultural Research Service, U.S. Department of Agriculture.

$$F\downarrow = \int_{u_r}^{u_{\infty}} \gamma(u) \sigma T_A(u)^4 du \quad (1)$$

and the upward flux of radiation as

$$F\uparrow = \int_{u_r}^{u_s} \gamma(u) \sigma T_A(u)^4 du + (1 - \epsilon_{fs}) \sigma T_s^4 \quad (2)$$

where T_A and T_s are the air and surface temperatures, σ is the Stefan-Boltzmann constant, γ is a constant of proportionality which is only a function of optical thickness (u), and ϵ_{fs} is the flux emissivity of the air layer between the reference level and the underlying surface, given by

$$\epsilon_{fs} = \int_{u_r}^{u_s} \gamma(u) du \quad (3)$$

Now it is evident from equations (1, 2, 3), first of all, that there is a possibility for net radiation variation with height if surface temperature is significantly different from air temperature, due primarily to the changing contributions of the two terms of (2) to $F\uparrow$ with height. In particular, consider two net radiometers located at two different reference levels, $r1$ and $r2$. It is evident from (1) that $F\downarrow$ for these two net radiometers will be nearly identical if T_A is fairly constant between the two levels. For $F\uparrow$, however, the situation is somewhat different. If we write equation (2) as it would apply at levels $r1$ and $r2$ for instance, we get

$$F\uparrow(r1) = \int_{u_{r1}}^{u_s} \gamma(u) \sigma T_A(u)^4 du + \sigma T_s^4 - \sigma T_s^4 \int_{u_{r1}}^{u_s} \gamma(u) du \quad (4)$$

$$F\uparrow(r2) = \int_{u_{r2}}^{u_s} \gamma(u) \sigma T_A(u)^4 du + \sigma T_s^4 - \sigma T_s^4 \int_{u_{r2}}^{u_s} \gamma(u) du \quad (5)$$

For the situation where surface temperature is significantly greater than air temperature, equations (4) and (5) may be simplified somewhat by assuming that $T_A(u_{r1}) \approx T_A(u_{r2}) \approx T_A(u_s) \approx$ constant. Then, σT_A^4 may be removed from behind the integral signs in equations (4, 5) and equations (5) subtracted from equation (4) to yield

$$\begin{aligned} F\uparrow(r1) - F\uparrow(r2) \\ = \left[\int_{u_{r1}}^{u_s} \gamma(u) du - \int_{u_{r2}}^{u_s} \gamma(u) du \right] [\sigma T_A^4 - \sigma T_s^4] \quad (6) \end{aligned}$$

For $r1 > r2$, equation (6) implies that for $T_s > T_A$, $F\uparrow(r2)$ will be greater than $F\uparrow(r1)$, since

the first integral will then always be larger than the second, making the right-hand side of equation (6) permanently negative. Thus, since the downward flux at each of the two levels is practically identical, the net radiation at level $r1$ will be greater than that at $r2$ by the amount specified by equation (6).

3. Experiment

From the foregoing theoretical analysis, it is evident that if surface temperature is significantly different from air temperature, the true net radiation at the surface may only be measured there, and that as one moves higher above the surface, the net radiation measured becomes less and less representative of that at the surface.

To determine the validity of this hypothesis and the magnitude of net radiation errors involved, if true, we devised the following experiment. Using two pairs of Fritschen (1963, 1965) net radiometers, we positioned one set at 50 cm above a dry, bare soil surface and another set at 215 cm. All four of these net radiometers had been carefully calibrated for both short- and long-wave radiation by the techniques described by Idso (1970, 1971), and demonstrated to yield identical results by pairs. Nevertheless, to insure that no bias was present, the radiometers were operated for a full 24-hour period in one arrangement, and then the two pairs were interchanged for a second 24-hour period. Concurrently, soil temperature was also monitored by thermocouples in two places, plus air temperature at the two heights.

Upon completion of the two days of data collection over the dry, bare soil, the instruments were all relocated over a dense bermudagrass sod. The grass was clipped, raked, and then given two irrigations of 15 cm water on each of two successive days. Immediately thereafter, a second two-day experiment similar to the first one was run over the bermudagrass. In both this experiment and the first one, data were collected at 10-minute intervals and stored on punched tape by a Vidar data acquisition system. These data were then analyzed for every 10-minute period during the day, and every half-hour at night.

4. Results

The results of the experiment run over the dry, bare soil are portrayed graphically in Fig. 1. Throughout most of the daylight hours when

Fig. 1. Net radiation at 50 and 215 cm over a dry, bare soil.

$T_s > T_A$, net radiation at 215 cm was substantially greater than that at 50 cm. This is consistent with the hypothesis that the lower radiometers receive proportionally more radiation from the soil than do the upper radiometers. Since the soil radiation is greater than the air radiation, the net

incoming radiation is lower at lower levels.

Since equation (6) and its commentary indicated that the difference in net radiation (R_N) between two heights should be directly proportional to $\sigma T_s^4 - \sigma T_A^4$, if T_A is fairly constant with height, we have plotted ΔR_N against $\sigma T_s^4 - \sigma T_A^4$ in Fig. 2,

Fig. 2. Net radiation difference between 50 and 215 cm over a dry, bare soil surface as a function of the difference between blackbody radiation at soil surface and air temperatures.

where T_s is the average of two soil surface temperatures and T_A is the air temperature at 50 cm. Results of a linear regression run on these data are also included in the figure. Although there is a fair amount of scatter in the data, the regression is quite satisfactory. It approaches the origin to within a value less than the accuracy of the instruments and also defines a good straight line as predicted. The scatter is due chiefly to three separate effects: variations in specific humidity with time, difficulties in representing the mean surface temperature of an extended area with but two point values (which at times were more than 2°C different), and variations of T_A with height and this factor's variation with time.

The results of the experiment run over the bermudagrass sod are portrayed graphically in Fig. 3. On the first day of this experiment the irrigation water remained in a small depres-

sion just under the lower net radiometers until about 1500. Since the reflection coefficient of water for solar radiation is much less than that of grass (Sellers, 1965), the net radiation measured by the lower radiometers prior to 1500 was greater than that measured by the higher radiometers, which viewed only a small portion of open water. After 1500, however, and throughout the next day, the expected results were obtained: when the two sets of net radiometers viewed an identical surface type, net radiation did not vary with height.

5. Discussion

The net radiation above a surface whose temperature is significantly different from that of the overlying air is a strong function of height. For the situation we investigated, a dry, bare soil, at the peak $T_s - T_A$ temperature differential

Fig. 3. Net radiation at 50 and 215 cm over an irrigated bermudagrass sod.

(25°C), a mean net radiation difference between 50 and 215 cm of $0.06 \text{ cal cm}^{-2} \text{ min}^{-1}$ was recorded. This amounted to practically 10% of the absolute net radiation reading at that time. For the two daylight periods the discrepancy was 7%, and for the entire 48-hour period it was 11%.

It is evident from the theory considered, that the true net radiation at the surface was most likely even lower than that measured at 50 cm. However, as the surface is approached much closer than 50 cm, the presence of the net radiometer alters the conditions of the surface, due primarily

to shading. Thus, before a final statement can be made as to the proper vertical location of net radiometers, an analysis must be made of the effects of a net radiometer upon the underlying surface. Such a study has been carried out by Idso and Cooley (1971), and final conclusions as to optimum vertical placement of net radiometers are reached there.

We thus conclude here only that when net radiation measurements are made over a surface such as a dry, bare soil which may become significantly hotter than the ambient air during times of intense solar radiation, that significant errors may be introduced when measurements are made at heights greater than 50 cm. If the surface is an irrigated sod or crop, however, whose temperature never departs too greatly from that of the air, the requirement of making measurements close to the surface may be relaxed. In fact, for most irrigated crops, surface temperature is probably close enough to air temperature that net radiation measurements may be made at almost any height above the surface. In this case, it would be the view factor of the radiometer for the surface being studied that would define the maximum height allowable

Acknowledgements

We would like to acknowledge the able assistance of Mr. K.G. Mullins in the collection and reduction of the field data.

References

- Begg, J.E., J.F. Bierhuizen, E.R. Lemon, D.K. Misra, R.O. Slatyer, and W.R. Stern, 1964: Diurnal energy and water exchanges in Bulrush millet in an area of high solar radiation. *Agr. Meteor.* **1**, 294-312.
- Davies, J.A. and P.H. Buttmore, 1969: Reflection coefficients, heating coefficients and net radiation at Simcoe, Southern Ontario. *Agr. Meteor.* **6**, 373-386.
- Denmead, O.T. 1969: Comparative micrometeorology of a wheat field and a forest of *Pinus radiata*. *Agr. Meteor.* **6**, 357-371.
- Ekern, P.C. 1965: The fraction of sunlight retained as net radiation in Hawaii. *J. Geophys. Res.*, **70**, 785-793.
- Fitzpatrick, E.A. and W.R. Stern, 1966: Estimates of potential evaporation using alternative data in Penman's formula. *Agr. Meteor.* **3**, 225-239.
- Fleagle, R.G., and J.A. Businger, 1963: *An Introduction to Atmospheric Physics*. Academic Press, New York, 346 pp.
- Fritschen, L.J., 1963: Construction and evaluation of a miniature net radiometer. *J. Appl. Meteor.* **2**, 165-172.
- , 1965: Miniature net radiometer improvements. *J. Appl. Meteor.* **4**, 528-532.
- , 1967: Net and solar radiation relations over irrigated field crops. *Agr. Meteor.* **4**, 55-62.
- Fuchs, M. and C.B. Tanner, 1967: Evaporation from a drying soil. *J. Appl. Meteor.* **6**, 852-857.
- Idso, S.B., 1971: The relative sensitivities of polyethylene-shielded net radiometers for short- and long-wave radiation. *Rev. Sci. Instr.* **41**, 939-943.
- , 1971: A simple technique for the calibration of long-wave radiation probes. *Agr. Meteor.* **8**, 235-243.
- , D.G. Baker, and B.L. Biad, 1969: Relations of radiation fluxes over natural surfaces. *Quart. J. Roy. Meteor. Soc.* **95**, 244-257.
- , and K.R. Cooley, 1971: The vertical location of net radiometers. II. The effects of the net radiometers shadow. *J. Meteor. Soc. Japan*. In press.
- Monteith, J.L. and G. Szeicz, 1961: The radiation balance of bare soil and vegetation. *Quart. J. Roy. Meteor. Soc.* **87**, 159-170.
- Morgan, D.L., W.O. Pruitt, and F.J. Lourence, 1970: Radiation data and analyses for the 1966 and 1967 micrometeorological field runs at Davis, California. *R & D. Tech. Rept.* ECOM 68-G10-2, 55 pp.
- Reifsnnyder, W.E. 1967: Radiation geometry in the measurement and interpretation of radiation balance. *Agr. Meteor.*, **4**, 255-265.
- Rosenberg, N.J. 1966: Microclimate, air mixing and physiological regulation of transpiration as influenced by wind shelter in an irrigated bean field. *Agr. Meteor.* **3**, 197-224.
- , 1969: Advective contribution of energy utilized in evapotranspiration of alfalfa in the east central great plains. *Agr. Meteor.* **6**, 179-184.
- Sellers, W.D. 1965: *Physical Climatology*. The Univ. of Chicago Press, Chicago, 272 pp.
- Stanhill, G. and M. Fuchs, 1968: The climate of the cotton crop: physical characteristics and microclimate relationships. *Agr. Meteor.* **5**, 183-202.
- , G.J. Hofstede, and J.D. Kalma, 1966: Radiation balance of natural and agricultural vegetation. *Quart. J. Roy. Meteor. Soc.* **92**, 128-140.
- Thompson, G.D. and J.P. Boyce, 1967: Daily measurements of potential evapotranspiration from fully canopied sugarcane. *Agr. Meteor.* **4**: 267-279.
- van Bavel, C.H.M., 1967: Surface energy balance of bare soil as influenced by wetting and drying.

Tach. Rept. ECOM 2-67P-2, 72pp.
van Bavel, C.H.M. and L.J. Fritschen, 1965: Energy
balances of bare surfaces in an arid climate.

UNESCO, Methodology of plant Eco-physiology.
Proc. of the Montpellier Symp., 99-107.

放射収支計の垂直位置 1.

——下に横たわる空気層の効果——

S. B. イドソー・K. R. クーリー

米国水資源管理研究所

地表面温度が周囲の気温とかなり異なる場合、放射収支量の測定値は地上よりの高さによって異なり、測定点が高くなると、地上の値を代表し得なくなる。放射計と地表面間に介在する空気層の効果は、日中、乾燥した裸地上 50 cm および 215 cm で測定した放射収支量に約 7 % の差異を生ずることが実験的に見出された。24 時間単位では、差異は全放射収支量の 11 % に達する。この状況では、地表面の真の放射収支量は地表面上においてのみ得られる。