Reply to comment by J. Wang and R. L. Bras on "Estimating the soil temperature profile from a single depth observation: A simple empirical heatflow solution"

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[1] We welcome the comments by *Wang and Bras* [2009] on our recent paper [*Holmes et al.*, 2008]. The comments by the authors indicate that the way we presented our novel approach, which considers the effect of extending part of the surface energy balance components to below the ground surface, raises questions and warrants a more comprehensive discussion. With this reply we take the opportunity to elucidate and clarify the theoretical concepts of our approach with more rigor and to discuss the underlying assumptions and limitations in greater detail.

[2] Continuity of energy flux (E) at a horizontal surface is given by

$$E^+ = E^-, \tag{1}$$

where the plus and minus represent the upper and lower side of that surface. Arranging the classical surface energy balance in this form yields

$$R_N - LE - H = G, \tag{2}$$

with net radiation (R_N), latent heat flux (LE), and sensible heat flux (H) at the upper side and soil heat flux (G) at the lower side of the surface. Continuity of total energy flux is illustrated in Figure 1. By convention, R_N and G are defined as positive when directed downward, and LE and H are positive when directed upward. A comparison of equations (1) and (2) shows that $G = E^-$ and therefore represents the total soil energy flux at the surface.

[3] The essence of our approach is that we explicitly separate the belowground term G into three components: the conductive heat flux (G_C), latent heat flux by the movement of water vapor (G_L), and a sensible heat flux (G_H). Note that G_C and G_H together constitute the total subsurface sensible heat flux, which we explicitly separate into a conductive and a nonconductive term. The latter term (G_H) is the least tangible. However, it is included for the sake of completeness and accommodates, for example, advection of heat through the movement of air or water. With these terms, equation (2) now becomes

$$R_N - LE - H = G_C - G_L - G_H. \tag{3}$$

Note that G_L and G_H are defined as positive in the upward direction, matching the sign conventions of LE and H, whereas G_C is positive downward.

[4] Flux continuity not only applies to the total energy flux (E) but also to the vapor flux and hence to latent heat flux

$$LE = G_L. \tag{4}$$

This continuity principle is implied in equation (2) of *Holmes et al.* [2008] by the integral over depth of the latent heat production term.

[5] The implication of continuity of LE and G_L is that equation (3) can be reduced to

$$R_N - H = G_C - G_H. \tag{5}$$

This result basically shows that at the surface, the conductive part of the ground heat flux, G_C, is not affected by subsurface evaporation and is only determined by R_N, H, and G_H:

$$G_C = R_N - (H - G_H). \tag{6}$$

[6] Figure 2 illustrates the above relationships between the various energy flux terms. Continuity of LE and G_L (equation (4)) is illustrated in Figure 2a. The other two plots show discontinuity between G_H and H (Figure 2b) and G_C and R_N (Figure 2c). Because of continuity of the total energy flux (E), the discontinuities in Figures 2b and 2c are of the same magnitude.

[7] Aiming to develop a practical method to describe the near-surface temperature profiles for remote sensing applications, *Holmes et al.* [2008] made two assumptions. First, energy storage in the near-surface layer is assumed to be negligible in comparison to the total energy flux. Second, the difference ($H - G_H$) is small in comparison to R_N.

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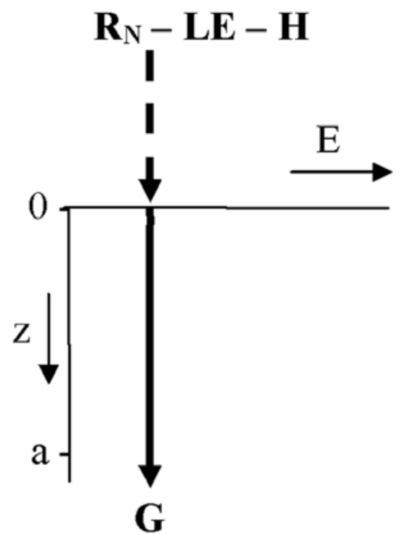

Figure 1. A theoretical daytime example of continuity of energy fluxes at the surface and steady state situation within the ground.

[8] The first assumption is depicted by the uniform G from the surface to depth a in Figure 1, where a represents the depth at which both G_L and G_H become negligible. As G_H is expected to approach zero within several millimeters and vapor transport has been shown to be significant to depths up to several centimeters, a would be typically of the order of centimeters. The above implies that at $z = a$ the total ground heat flux approaches soil conductive heat transport:

$$G(a) = G_C(a). \tag{7}$$

[9] In Figure 2 uniformity of G within the surface layer is schematically depicted by constancy of the sum of G_C, G_L, and G_H. In field experiments, ground heat flux plates only measure G_C, and the depth at which these plates are installed in relation to a could affect the extent to which energy closure is achieved. Commonly reported depths of ground heat flux plates are 2 and 5 cm, and the 2 cm depth in particular might well be too shallow for energy balance approaches.

[10] The second assumption is required to derive the surface temperature gradient directly from net radiation by reducing equation (6) to

$$G_C(0) = R_N, \tag{8}$$

and hence,

$$\lambda \frac{\partial T}{\partial z}(0) = R_N. \tag{9}$$

Equation (8) should help to clarify the admittedly unconventional expression of the energy balance as formulated in equation (2) of *Holmes et al.* [2008]. The use of R_N rather than $G_C(0)$ in the latter equation should not be interpreted as implying that we extend the net radiation term to below the ground surface. We do agree with *Wang and Bras* [2009] that the second assumption, i.e., neglecting the term $H - G_H$ in equation (6), may not be justifiable in general, and the implications for the proposed approach could have been more explicitly discussed in our original contribution.

[11] H is a well-known energy balance component that under favorable conditions accounts for a large part of the surface energy balance. In the absence of similar observational evidence of G_H, we do not have a clear insight into the significance of this term in comparison to H in natural soils. It is likely that under most circumstances this term will be small in comparison to H, and $G_C(0)$ should therefore preferably be described by equation (6), not equation (8). For example, in nonporous media G_H will clearly be zero, and discontinuity of G_H and H is apparent. On the other hand, in a medium with large connected pores like gravel or a recently ploughed field, G_H could well be significant.

[12] *Holmes et al.* [2008] developed an empirical approach with minimal data requirement, and the relative contribution of G_H and H may be considered to be accounted for, albeit in a coarse way, in the fitting of the sigmoid between $G_C = R_N$ at $z = 0$ and $G_C = G$ at $z = a$. Incorporating H might well yield a more accurate fit to measured temperature profiles; however, the use of H would render the method much less practical for many remote sensing applications. Figure 3 is a reprint of Figure 3 from *Holmes et al.* [2008] with extra information on the uncertainty of the calculated G_C. From Figure 3 it can be seen that the uncertainties below 1.5 cm

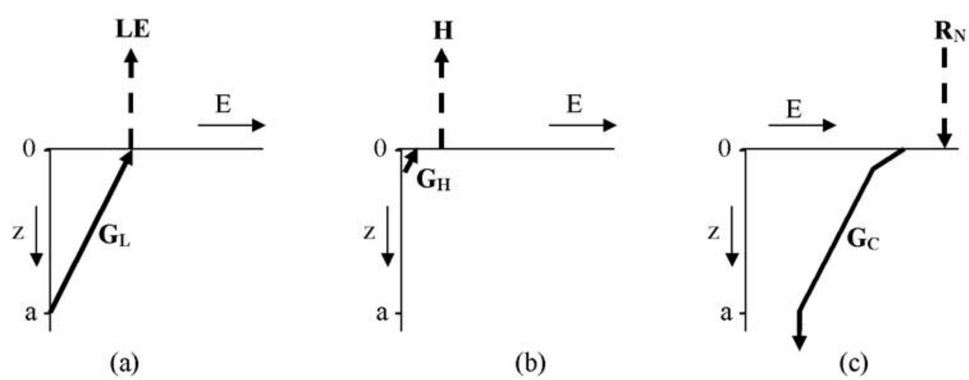

Figure 2. Components of the ground heat flux: (a) the latent heat flux G_L, (b) the heat transported by air in both advective and conductive terms G_H, and (c) the conductive heat flux G_C. Theoretical daytime example expanded from Figure 1.

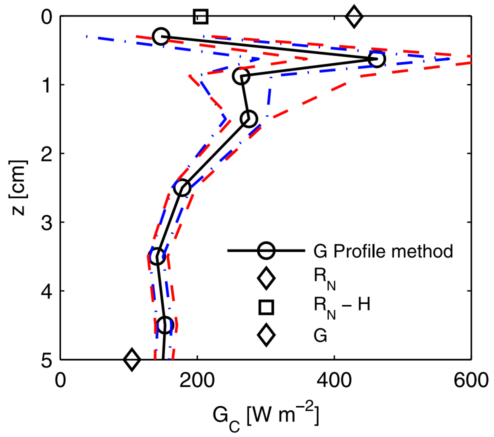

Figure 3. Conductive ground heat flux profiles at noon, redrawn from Figure 3 of *Holmes et al.* [2008], indicating the effect. Error bounds shown are calculated for a deviation in soil moisture of ±0.04 m^3 m^{-3} (blue dash-dotted line) and a deviation in temperature measurement depth of ±1 mm (red dashed line). The measured value of $R_N - H$ is indicated at the surface. (The reported value of H that is used is likely associated with large uncertainty and is included only for reference.)

are low and G_C deviates markedly from the more uniform behavior that would be expected in the absence of contributions from subsurface evaporation. To what extent G_C trends toward R_N or $R_N - H$ at the surface cannot be ascertained because of the increase in uncertainty (error bounds) toward the surface. Although the shallowest calculated G_C appears to approximate $R_N - H$, this is considered to be an artifact resulting from exposure of the uppermost temperature sensor to the air. Extremely shallow temperature measurements, in this case reported at 2 mm depth, are notoriously susceptible to systematic errors.

[13] Notwithstanding the fairly crude modeling of the G_C profile, the instantaneous temperature profile in the near-surface layers can be modeled effectively thanks to the approximation $G_C(0) = R_N$. This approach only requires single depth measurements of soil moisture and soil temperature in addition to net radiation and is therefore suitable for remote sensing applications.

[14] Finally, we should mention a note on term convention. *Holmes et al.* [2008, paragraph 7] specified the ground heat flux G as "the conduction of heat vertically into the profile", and in the above terms this exclusively refers to G_C. The term G in equation (1) of Holmes et al. should therefore be understood as the $G_C(a)$ at a depth where both G_L and G_H are negligible. Furthermore, the divergence of G_L and G_H in Figures 2a and 2b is represented by the production terms *le* and *h* in the work by *Holmes et al.* [2008].

References

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