In Situ Monitoring of Soil Thermal Properties and Heat Flux during Freezing and Thawing

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Significance and challenges

- Accurate representation of freeze/thaw processes needed for
  - climate models and projections
  - hydrologic models and forecasts
  - wintertime energy balance studies
- Few methods for monitoring soil thermal properties during freeze/thaw
- Few methods for monitoring soil heat flux during freeze/thaw

Theory (Fuchs et al., 1978)

$$C\frac{\partial T}{\partial t}-L_f S_i=\frac{\partial}{\partial z}\left(\lambda\frac{\partial T}{\partial z}\right)-J_l C_l\frac{\partial T}{\partial z} \qquad [1]$$

where C is soil volumetric heat capacity (MJ m^{-3} K^{-1}), T is temperature (K), t is time (s), L_f is the latent heat of fusion for water (J kg^{-1}), S_i is the mass rate of ice formation (kg m^{-3} s^{-1}), z is depth (m), λ is the soil thermal conductivity (W m^{-1} K^{-1}), J_l is the liquid water flux (m^3 m^{-2} s^{-1}), and C_l is the volumetric heat capacity of liquid water (MJ m^{-3} K^{-1}).

Theory (Fuchs et al., 1978)

$$S_i=-\rho_l\frac{\partial J_l}{\partial z}-\rho_l\frac{\partial \theta_l}{\partial t} \qquad [2]$$

where ρ_l is the density of liquid water (kg m^{-3}) and θ_l is the soil liquid water content (m^3 m^{-3}). By the chain rule, we can then write

$$L_f S_i=-L_f\rho_l\frac{\partial J_l}{\partial z}-L_f\rho_l\frac{\partial \theta_l}{\partial T}\frac{\partial T}{\partial t} \qquad [3]$$

Theory (Fuchs et al., 1978)

Inserting Eq. [3] into Eq. [1] and grouping similar terms gives

$$\left(C+L_f\rho_l\frac{\partial \theta_l}{\partial T}\right)\frac{\partial T}{\partial t}=\frac{\partial}{\partial z}\left(\lambda\frac{\partial T}{\partial z}-L_f\rho_l J_l\right)-J_l C_l\frac{\partial T}{\partial z} \qquad [4]$$

The complete term in parentheses on the left-hand side of Eq. [4] is the apparent volumetric heat capacity, C_a, which may be interpreted as the quantity of heat required to raise the temperature of a unit volume of soil by 1 K while a phase change between liquid water and ice is occurring.

Theory (Fuchs et al., 1978)

$$J_l=-K\left(\frac{\partial \psi_l}{\partial z}+\frac{\partial \psi_g}{\partial z}\right) \qquad [5]$$

where K is the soil hydraulic conductivity, ψ_l is the matric potential, and ψ_g is the gravitational potential. Omitting the gravity-driven water flux, which is of minimal significance in freezing soil (Fuchs et al., 1978), and applying the chain rule again, we obtain

$$J_l=-K\frac{\partial \psi_l}{\partial T}\frac{\partial T}{\partial z} \qquad [6]$$

Theory (Fuchs et al., 1978)

Inserting Eq. [6] into Eq. [4] gives

negligible

$$C_a \frac{\partial T}{\partial t} = \frac{\partial}{\partial z}\left(\lambda_a \frac{\partial T}{\partial z}\right) + K\frac{\partial}{\partial T}\left(\frac{\partial T}{\partial z}\right) \quad [7]$$

where the apparent thermal conductivity, λ_a, is defined as

$$\lambda_a = \lambda + \rho_l L_f K \frac{\partial \psi_l}{\partial T} \quad [8]$$

The apparent thermal conductivity may be interpreted as the heat flux per unit temperature gradient that occurs while temperature gradients are driving liquid water flow in soil at subfreezing temperatures.

Theory (Fuchs et al., 1978)

heat transfer in partially frozen soil can be approximated by

$$C_a \frac{\partial T}{\partial t} = \frac{\partial}{\partial z}\left[\lambda_a \frac{\partial T}{\partial z}\right] \quad [9]$$

and the soil heat flux, G, by

$$G = -\lambda_a \partial T / \partial z \quad [10]$$

which includes both sensible heat transfer by conduction and latent heat transfer due to thermally induced liquid water flow.

Measurements

- University of Minnesota research farm
- Rosemount, Minnesota, USA, 44.7°N, 93.1 °W

Field experiment

- Silt loam soil
- No tillage, soybean residue
- 4 heat pulse sensors each at 2.5 and 5 cm depths
- Temperature measurements at 5 minute intervals
- Thermal properties measured at 30 minute intervals
- Freezing, Nov.-Dec.
- Thawing, Feb.-Mar.

Thermal property measurements

$$C = \frac{q' t_0}{e\pi r^2 T_m}\left(1 - \frac{\varepsilon^2}{8}\left\{\frac{1}{3} + \varepsilon\left[\frac{1}{3} + \frac{\varepsilon}{8}\left(\frac{5}{2} + \frac{7\varepsilon}{3}\right)\right]\right\}\right) \quad [12]$$

where q' is the heating rate (W m^{-1}), t_0 is the heating duration (s), e is the base of the natural logarithm, T_m is the maximum temperature rise (K) at a distance r (m) from the heater, and ε is t_0/t_m with t_m being the time (s) from the beginning of heating until T_m occurs (Knight and Kluitenberg, 2004).

$$\alpha = \frac{r^2}{4t_m}\left(\frac{t_0}{t_m - t_0}\right)\left[\ln\left(\frac{t_m}{t_m - t_0}\right)\right]^{-1} \quad [13]$$

Soil temperatures during freezing

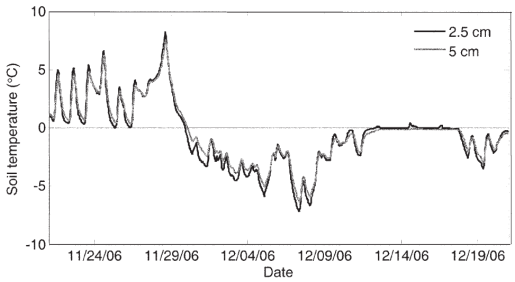

Fig. 1. November and December 2006 soil temperatures at 2.5- and 5-cm depths in Waukegan silt loam under soybean residue in Field G19.

Soil thermal properties during freezing

- Abrupt, large increase in C_a as *T* falls below freezing point,
  - due to latent heat of fusion
- Abrupt, large increase in λ_a
  - due to latent heat transfer by liquid flow
- Abrupt, large decrease in α_a
- Good agreement between measured and modeled values for C_a, less so for λ_a and α_a
  - extended monitoring period required

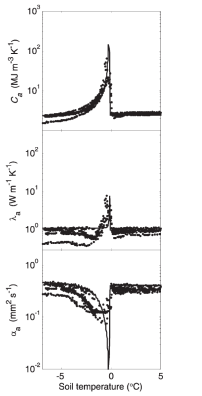

Fig. 2. Soil apparent heat capacity (C_a), apparent thermal conductivity (λ_a), and apparent thermal diffusivity (α_a) during a November and December 2006 freezing event. Data (symbols) are from 2.5- and 5-cm depths. The model (line) is that of Fuchs et al. (1978).

Soil temperatures and thermal properties during thawing

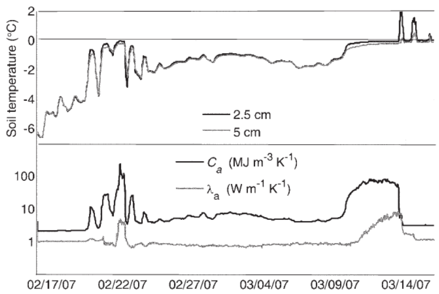

Fig. 3. February and March 2007 soil temperatures (top panel), and measured soil apparent heat capacity (C_a) at 2.5-cm depth and apparent thermal conductivity (λ_a) at 5-cm depth (bottom panel).

Soil thermal properties during thawing

- Maximum C_a ~800 MJ m^{-3} K^{-1}
- Narrow spike in λ_a just below freezing point
  - confirmation of theoretical model
  - Maximum value ~100 W m^{-1} K^{-1}
- 5-minute monitoring period allowed α_a measurements down to 0.03 mm^2 s^{-1}

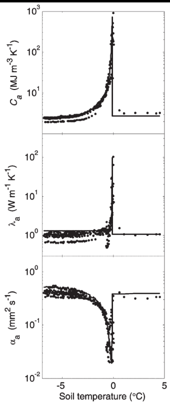

Fig. 4. Measured (symbols) and modeled (line) soil apparent heat capacity (C_a), apparent thermal conductivity (λ_a), and apparent thermal diffusivity (α_a) during a February and March 2007 thawing event.

Measured vs modeled thermal properties

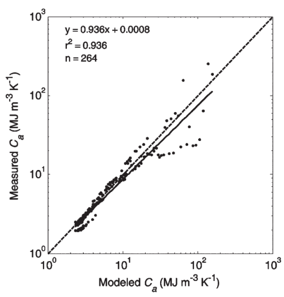

Fig. 6. Measured vs. modeled soil apparent heat capacity (C_a) during a February and March 2007 thawing event.

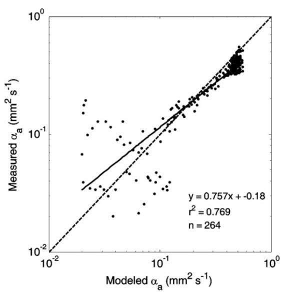

Fig. 7. Measured vs. modeled apparent thermal diffusivity (α_a) during a February and March 2007 thawing event.

Heat pulse curves during thawing

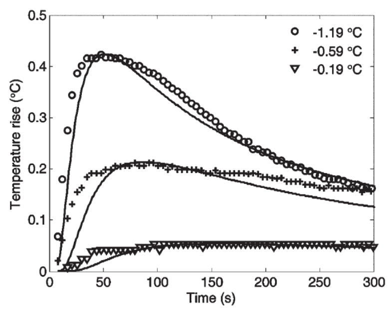

Fig. 5. Selected heat pulse curves recorded by a single sensor at 2.5-cm depth on 21 Feb. 2007 for three different ambient temperatures (symbols). Corresponding modeled heat pulse curves (lines) were based on the assumptions discussed in relation to Eq. [11–13].

Soil heat flux during thawing

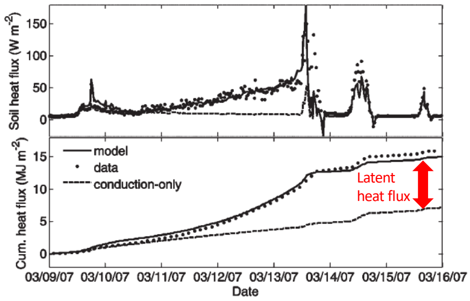

Fig. 8. March 2007 instantaneous (upper panel) and cumulative (lower panel) heat fluxes at the soil surface.

Final thoughts

- Challenging measurements
  - Temperature rise due to heat pulse may be <0.005°K
  - Two-point running harmonic mean used here for effective noise reduction
- Mean absolute differences between measured and modeled thermal properties, 20-37%
- Accurate in situ soil heat flux measurements during freeze/thaw are possible
- Latent heat flux due to snowmelt infiltration detectable with this approach

For more details:

Ochsner, T.E. and J.M. Baker. 2008. In Situ Monitoring of Soil Thermal Properties and Heat Flux during Freezing and Thawing. Soil Sci. Soc. Am. J. 72: 1025-1032.

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