Determination of Subsurface Soil Evaporation using a Heat Pulse Probe Array

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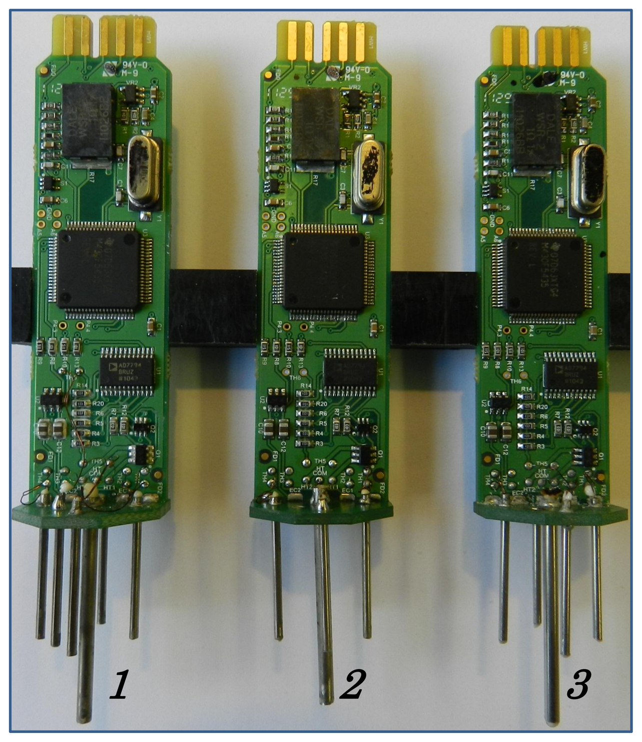
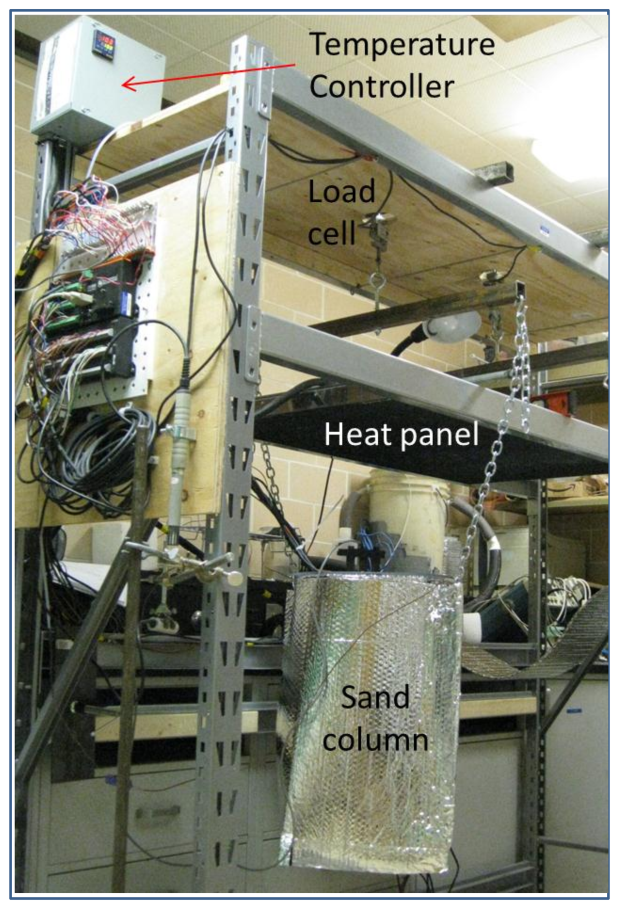
Introduction

Soil water evaporation is a critical component of both the surface energy balance and the hydrologic cycle, coupling heat and water transfer between land and the atmosphere. Recently introduced heat pulse probes (HPP) allow in-situ measurements of subsurface stage-2 soil water evaporation (Heitman et al., 2008a,b).

In the presented study, soil water evaporation was measured with an array of heat pulse probes embedded in a soil column.



Heat pulse probe array

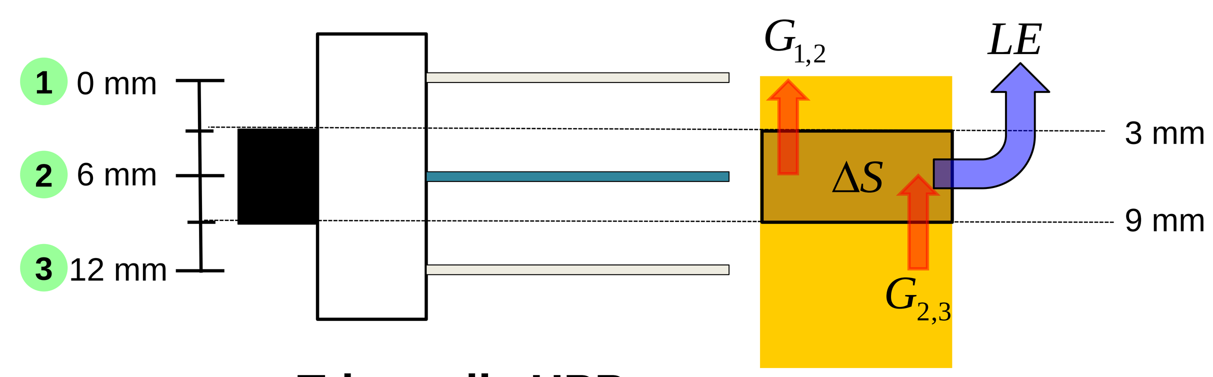


Soil column setup

A penta-needle heat pulse probe (PHPP) is a sensor used to make measurements for estimating subsurface evaporation. A PHPP consists of 5 needles. One needle contains a resistance heater for applying a small heat input, while the remaining needles contain thermocouples for measuring temperature response at a fixed distance (typically 6.5 mm) from the heater.

Subsurface Evaporation Rate

HPP method (Heitman et al., 2008a,b)



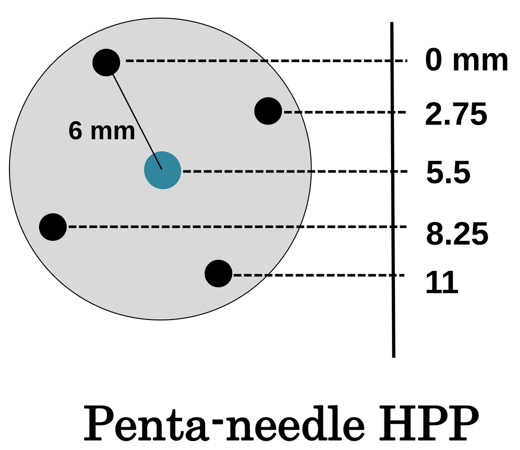
Tri-needle HPP

Energy Balance

$$LE = G_{2,3} - G_{1,2} - \Delta S \qquad (1)$$

$$G_{1,2} = -\lambda\left(\frac{T_1 - T_2}{z_1 - z_2}\right) \qquad \Delta S = C\left(T_2^j - T_2^{j-1}\right)\frac{z_{1,2} - z_{2,3}}{t^j - t^{j-1}}$$

LE :Latent heat flux
G :Sensible heat flux of conduction
S :Sensible heat storage
L :Latent heat of vaporization
E :Subsurface evaporation rate
T :Soil Temperature
λ :Thermal conductivity
C :Heat capacity of soil
z :Depth
t :Time
j :Time step

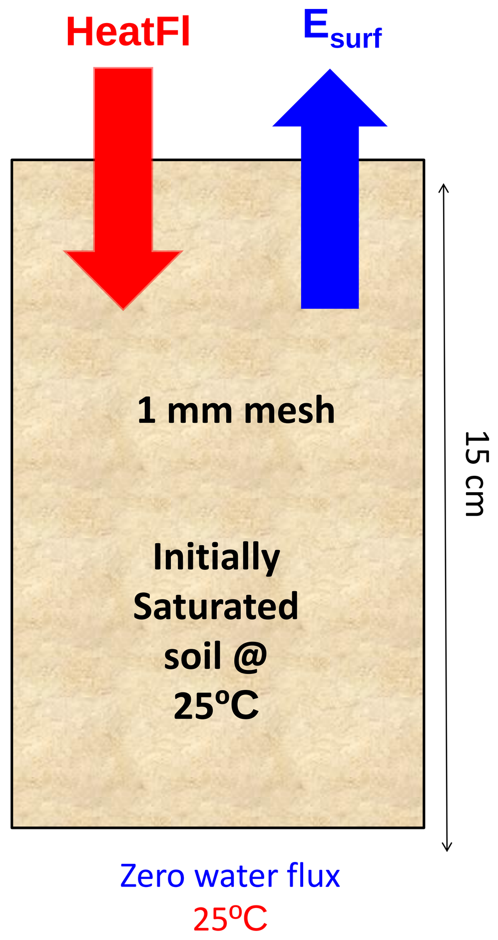


Penta-needle HPP

(Temperature resolution of HPP is 0.001 ºC)

Experimental Setup

Simple evaporation process from a saturated soil column.



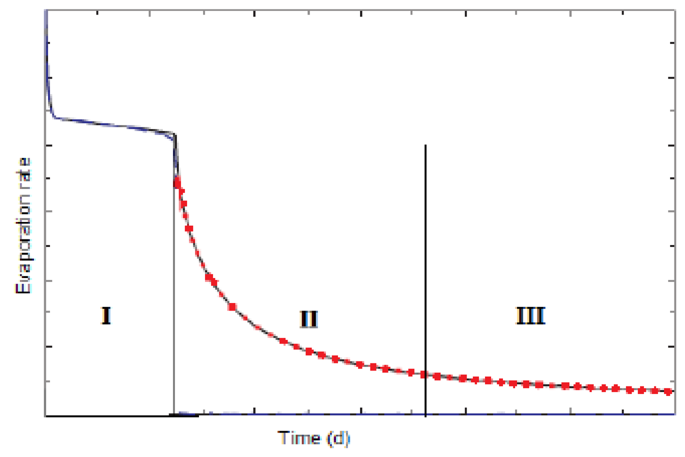
Surface boundary conditions are influenced by continuous supply of heat and a uniform wind velocity over the surface. Subsurface evaporation rates are calculated based on the sensible heat balance determined using the equation:

$$LE = \left[\left(-\lambda\frac{T_i - T_{i+1}}{z_i - z_{i+1}}\right) - \left(-\lambda\frac{T_{i-1} - T_i}{z_{i-1} - z_i}\right)\right] - \Delta S$$

E = Subsurface evaporation rate (m/s)
L = volumetric latent heat of vaporization(J/m^3)
λ = Soil thermal conductivity (Wm^{-1}°C^{-1})
T = Soil temperature (℃)
Z = soil depth (m)

The PHPP array is rotated 27.3° from a horizontal orientation to make temperature measurements every 3 mm within the soil profile.

Stages of Evaporation



Stages of evaporation with respect to time (in days)

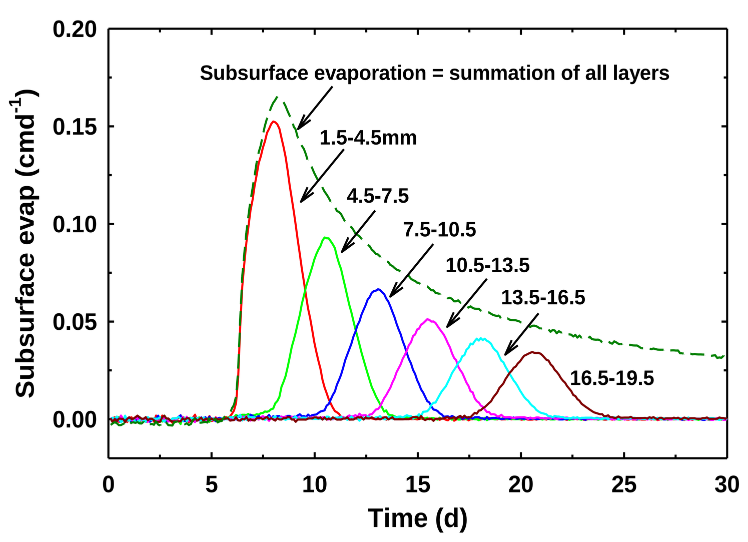
I. Rate of water loss remains nearly constant

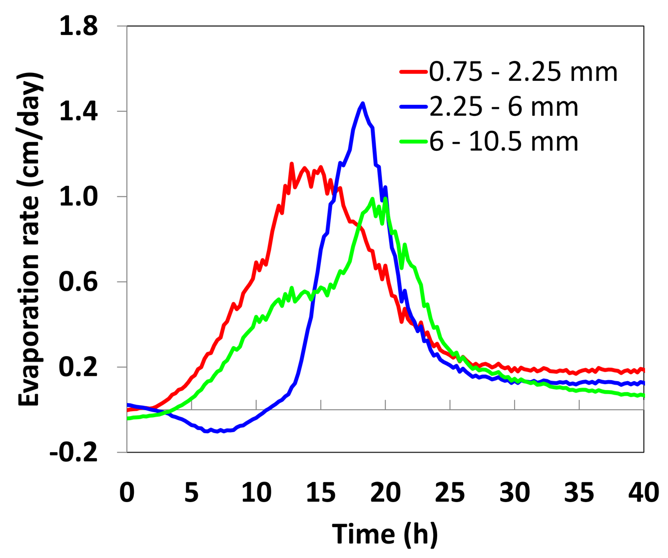
II. Intermediate falling-rate stage with lower drying rate

III. Residual slow rate stage

Results and Discussion

Subsurface evaporation rates were calculated with Eq.(1) from soil temperatures with different observation grids (1.5mm, 3mm, 6mm) using a Heat pulse probe array in a soil column.

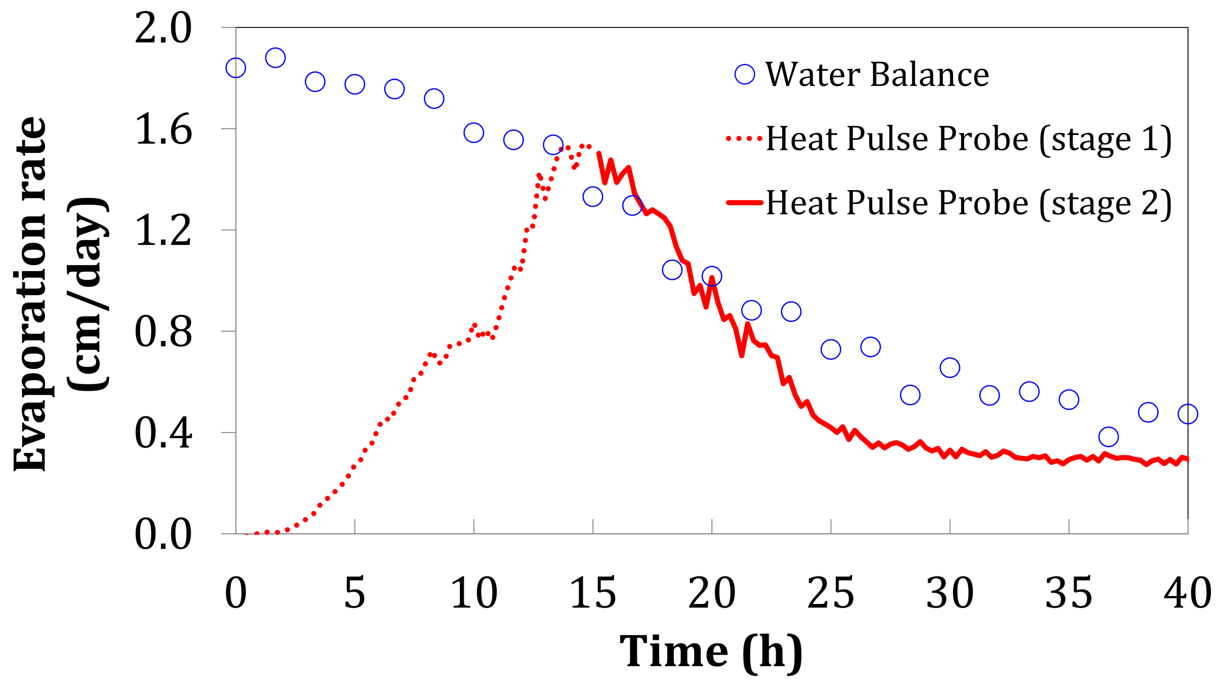




- *Simulated subsurface evaporation rates determined by the heat balance method*
- *Column measured subsurface evaporation drying rates for each of the temperature observation grids*

✓ The determined graph is distorted due to noise potentially due to averaging thermal conductivity across both sides of a heater needle.
✓ Discrepancies among 1, 3, and 6 mm observation results are largest for stage 2 evaporation.
✓ As the drying front deepens with time, these differences diminish.

HPP v/s Water Balance Method



Integrating all subsurface evaporation rates within each individual layer, total evaporation rate was calculated. The results are compared to the water balance method (i.e., from load cell readings).

As expected, HPP fails to measure stage-one evaporation. As discussed by Sakai et al. (2011), HPP cannot detect evaporation occurring within the "undetectable zone" (i.e., from the surface down to the first midpoint of the two top sensors).

As soon as the vaporization plane falls below the undetectable zone, HPP results agree reasonably well with the water balance results. However, there are still some discrepancies which may be due to inaccuracy of spacing and temperature readings.

Summary

- A PHPP provides estimates of soil thermal properties and heat flux.
- Subsurface evaporation estimates are derived from thermal property assessment with measurable depth dependent on number of PHPP in the array.
- A PHPP array experiment is underway to determine the level of accuracy for subsurface evaporation estimates.

This approach provides a new opportunity for determining in-situ soil water evaporation.

Future Work

- A laboratory evaporation experiment using diurnal atmospheric boundary conditions is underway.
- The PHPP can be used a multi-purpose research tool combining soil evaporation monitoring with estimates of soil water flux (e.g., from irrigation or precipitation).

References

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- Heitman, J.L., X. Xiao, R. Horton, and T.J. Sauer (2008b): Sensible Heat Measurements indicating depth and magnitude of subsurface soil water evaporation, Water Resour. Res., 44: W00D05.
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Acknowledgements

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