Quantifying soil ice content with a heat pulse probe for an entire range of temperature during soil freezing and thawing

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Soil freezing and thawing is important for winter hydrology. Despite its importance, measuring in-situ soil ice content θ_I has been difficult. Volumetric heat capacity measurement with a heat pulse probe (HPP) has been used to quantify θ_I (hereafter, VHC method). The VHC method determines θ_I only when soil temperature is below -5°C. In this study, we propose a new method to determine θ_I from HPP by considering sensible heat balance in soils (hereafter, SHB method). We tested both VHC and SHB methods for θ_I determination.

A HPP measures soil temperature *T*, volumetric heat capacity *C*, and thermal conductivity λ. For the VHC method, only *C* is used to determine θ_I. For the SHB method, a HPP is inserted into soil such that each needle is located at a different depth. When the heat balance of a thin soil layer which has boundaries at the middle of each HPP needle is considered, there is conductive heat flux at the first boundary H_1, conductive heat flux at the second boundary H_2, change in sensible heat storage ΔS, and latent heat flux *L, i.e.,* $H_1-H_2-\Delta S=L$. H_1, H_2 and ΔS can be estimated from HPP measurements and equations, thus, *L* can be calculated. When *T* is < 0°C, *L* is associated with soil freezing and thawing. Thus, change in θ_I can be determined by dividing *L* by latent heat for water freezing L_f. θ_I can be determined by integrating $\Delta\theta_I$ with respect to time once *T* drops below 0 °C.

Soil was packed into 0.3 m long PVC columns with 0.28 m^3 m^{-3} water content. A HPP was inserted through the column wall. Additional columns were prepared for destructive sampling to determine total soil water content after soil freezing. Upper boundary temperature was initially 5°C, and then it was decreased to -15°C gradually within 24 hours. After 6 days, the temperature was increased to 5°C within 24 hours. The temperature for the lower boundary was maintained at 5°C. Transient θ_I was estimated with VHC and SHB methods.

θ_I determined by sampling was around 0.20 m^3 m^{-3}. θ_I estimated with the VHC method was close to 0.20 m^3 m^3 when *T* was < -5 °C. The SHB method could additionally estimate transient θ_I when *T* was between 0 and -5 °C but failed at *T* < -5°C. Thus, we measured θ_I for a whole *T* range by using the SHB method with *T* between 0 and -5°C and using the VHC method with *T* < -5°C.

A combination of SHB and VHC methods allowed determination of transient θ_I for the entire range of temperature during freezing. Accordingly, a HPP can be a useful sensor for monitoring θ_I under freezing and thawing conditions.

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