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

*Yuki Kojima¹, Joshua L. Heitman², Robert Horton³

1.The University of Tokyo, 2.North Carolina State University, 3.Iowa State University

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

A HPP measures soil temperature $T$, volumetric heat capacity $C$, and thermal conductivity $\lambda$. For the VHC method, only $C$ is used to determine $\theta_I$. 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 $\Delta S$, and latent heat flux $L$, i.e., $H_1 - H_2 - \Delta S - L$. $H_1$, $H_2$ and $\Delta S$ 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 $\theta_I$ can be determined by dividing $L$ by latent heat for water freezing $L_f$. $\theta_I$ 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 m³ 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 $\theta_I$ was estimated with VHC and SHB methods.

$\theta_I$ determined by sampling was around 0.20 m³ m⁻³. $\theta_I$ estimated with the VHC method was close to 0.20 m³ m⁻³ when $T$ was $< -5 °C$. The SHB method could additionally estimate transient $\theta_I$ when $T$ was between 0 and -5 °C but failed at $T < -5°C$. Thus, we measured $\theta_I$ 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 $\theta_I$ for the entire range of temperature during freezing. Accordingly, a HPP can be a useful sensor for monitoring $\theta_I$ under freezing and thawing conditions.