Implications of measurement metrics on soil freezing curves: A simulation of freeze-thaw hysteresis

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Abstract

Soil freeze-thaw events have important implications for water resources, flood risk, land productivity, and climate change. A property of these phenomena is the relationship between unfrozen water content and sub-freezing temperature, known as the soil freezing characteristic curve (SFC). It is documented that this relationship exhibits hysteretic behaviour when frozen soil thaws, leading to the definition of the soil thawing characteristic curve (STC). Although explanations have been given for SFC/STC hysteresis, the effect that "scale"—particularly "measurement scale"—may have on these curves has received little attention. The most commonly used measurement scale metric is the "grain" or "support," which is the spatial (or temporal) unit within which the measured variable is integrated—in this case, the soil volume sampled.

We show (1) measurement support can influence the range and shape of the SFC and (2) hysteresis can be, at least partially, attributed to the support and location of the measurements comprising the SFC/STC. We simulated lab measured temperature, volumetric water content (VWC), and permittivity from soil samples undergoing freeze-thaw transitions using Hydrus-1D and a modified Dobson permittivity model. To assess the effect of measurement support and location on SFC/STC, we masked the simulated temperature and VWC/permittivity extent to match the instrument's grain and location. By creating a detailed simulation of the intra- and inter-grain variability associated with the penetration of a freezing front, we demonstrate how measurement support and location can influence the temperature range over which water freezing events are captured. We show it is possible to simulate hysteresis in homogenous media with purely geometric considerations, suggesting that SFC/STC hysteresis may be more of an apparent phenomenon than mechanistically real. Lastly, we develop an understanding of how the location and support of soil temperature and VWC/permittivity measurements influence the temperature range over which water freezing events are captured.

1 Introduction

Over one third of Earth's land surface undergoes seasonal transitions between frozen and thawed states (Barry & Gan, 2011). The spatial and temporal occurrence of freeze-thaw events is seasonally variable and may be modified under a changing climate (Ireson, van der Kamp, Ferguson, Nachshon, & Wheater, 2013). These events are critical factors affecting terrestrial water, carbon, and energy balance with consequential effects on hydrological, climatic, ecological, and biogeochemical processes such as runoff, infiltration, SM (SM) and groundwater recharge, erosion, streamflow generation, and microbial respiration (Andersland et al., 2004; Christensen et al., 2013; Öquist et al., 2009). Thus, soil freeze/thaw phenomena have important implications for water resources, forest and agricultural productivity, flood risk, and climate change.

When soil freezes, not all liquid water transforms into ice. At temperatures above –80 °C a certain amount of water remains unfrozen due to adhesive and cohesive forces as well as solute concentration (Mousson 1858; Bouyoucos and McCool 1916). The unfrozen water content changes drastically near 0 °C, decreasing with temperature. This relationship between unfrozen water content and sub-freezing temperature is known as the soil freezing characteristic curve (SFC) and is a fundamental property of the physical processes involved in soil freeze-thaw phenomena (Ireson et al., 2013). The SFC is used for understanding the transport of heat, water, and solutes in frozen soils (Koopmans & Miller, 1966). The resilient modulus, shear strength, and segregation potential for frost heave can all be interpreted using SFC as a tool (Liu & Yu, 2014).

SFC have been well studied in laboratory settings using a variety of instrumentation and methods including dilatometers, calorimeters, tensiometers, heat capacity, X-ray diffraction, nuclear magnetic resonance, and various electromagnetic (EM) SM probes (Cheng, Sun, Xue, & Guo, 2014; Koopmans & Miller, 1966; Tian, Wei, Lai, & Chen, 2018; Wen et al., 2012; Yoshikawa & Overduin, 2005). Numerous empirical parameterizations have been developed and used to simulate unfrozen water content (Ge, McKenzie, Voss, & Wu, 2011; Kozlowski, 2007; Osterkamp & Romanovsky, 1997; Quinton, Shirazi, Carey, & Pomeroy, 2005; Romanovsky & Osterkamp, 1997). The most common parameterization used is the power function relationship between unfrozen water content and negative temperature (Hu et al., 2020; Tice, Black, & Berg, 1989)

During the thawing process of soil, the relation between the unfrozen water content and the temperature is generally different from the SFC. Various authors mention the existence of this hysteresis, but do not present or describe it in detail (Parkin, von Bertoldi, & McCoy, 2013). More recently, this hysteretic effect has been described as mainly occurring through the phase change and shown dependence on the initial water content and the curvature of the pores in soil particles (Lu, Liu, Zhang, Heitman, & Horton, 2017). In addition, rapidly thawed soils have displayed lower unfrozen water content than gradually thawed soils near 0 °C (Hu et al., 2020). The hysteretic behavior between the freezing and thawing processes has led to the definition of the soil thawing characteristic curve (STC; Zhou et al. 2019). Hu et al., (2020) warn the hysteresis phenomenon is significant when the negative temperature is close to 0 °C and its effect should not be ignored on unfrozen water content under these conditions.

Simultaneously, there has been growing interest in modelling soil permittivity by the microwave remote sensing community (e.g: Bindlish et al., 2018; Mialon et al., 2015; Tabatabaeenejad, Burgin, Duan, & Moghaddam, 2015). Bulk soil permittivity is an average of the permittivities of the soil constituents (water, ice, soil, air) with different dielectrics randomly distributed and oriented in a host. The primary driver for changes in soil permittivity is moisture content (Topp, Davis, & Annan, 1980). Permittivity models are used in remote-sensing algorithms to establish the relationship between surface radiation emission or scattering and geophysical parameters, such as SM. This way, microwave observations of the landscape can provide information about its physical state when coupled with radiative transfer models. Generally, these models do not cover phase change events. In fact, satellite missions presently classify the freeze/thaw (F/T) state of the upper soil layer using empirical models for radio brightness temperature partially due to the lack of appropriate permittivity models (X. Xu, Derksen, Yueh, Dunbar, & Colliander, 2016).

Mironov et al., (2017) and Zhang, Zhao, Jiang, & Zhao, (2010) have presented permittivity models which account for SM phase changes. Much like their SFC counterparts, these models describe the relationship by way of a power or exponential function based on soil characteristics as inputs. However, experimental data on frozen soil permittivity are very limited in the literature and there are still important discrepancies between in situ data and models estimates. Notably, no current model adequately accounts for hysteresis (Mavrovic et al., 2020). Although it is likely that existing permittivity models for frozen soils can be used in the algorithms for retrieving the moisture of frozen soils the task of developing permittivity models for frozen soils is still in the initial stage, due to scarcity of data (Mironov et al., 2017).

Various mechanisms for the hysteretic behavior of soil freeze/thaw have been proposed based on capillary theory, supercooling effects, and water migration toward the freezing front (Parkin et al., 2013; Petrov & Furó, 2006; Tian et al., 2018; Wang, Lai, Yu, & Li, 2018). Although hysteresis has been widely ascribed to sorptive and capillary processes, to the best of our knowledge, only Amiri, Craig, and Kurylyk (2018), have replicated hysteretic effects; hypothesizing soil heterogeneities are partially responsible for the existence of a “slushy zone” in freezing soil. Parkin et al., (2013), argued that hysteresis may be more an apparent phenomenon than mechanistically real. They also posited SFC measurements may be more problematic during freezing than thawing because water content and temperature sensors do not measure the same soil volumes.

Notably, all studies of SFC/STC hysteresis with daily measurements (or better) from undisturbed or in situ samples struggle to describe their behavior compared to more manipulated samples (He et al., 2015; Pardo Lara, Berg, Warland, & Tetlock, 2020; Parkin et al., 2013). He et al., (2015), defined the "soil freezing thawing curve" and attributed this difference to transient boundary conditions which do not allow thermal equilibrium and constant total water content. Parkin et al., (2013), isolated a near "ideal" freezing and thawing episode to analyze the phenomena. Pardo Lara et al., (2020), isolated permittivity SFC/STC from laboratory and in situ electromagnetic (EM) SM probes. These permittivity SFC/STC showed a sigmoidal shape a high degree of hysteresis. This sigmoidal relationship is in disagreement with the predictions from both permittivity and SFC models. Pardo Lara et al., (2020), proposed the hysteresis was due to the difference in support between the permittivity and temperature measurements and offered the possibility of experimental bias.

Although many explanations have been given for SFC/STC hysteresis, none of them have explored the effects of "scale"– specifically "measurement scale"– on these curves. Scale is often equated to some level of hierarchy; however, such a definition does not provide details on how phenomena of interest are characterized at the selected hierarchical level. These details about how measurements are made in natural systems (such as the volume sampled) often affect the results acquired. The literature around "measurement scale" offers a framework for the description of these details. The most commonly discussed observation characteristic is the length, area, volume, or duration within which the measurement procedures have integrated the measured variable. Such a spatial or temporal unit is called "support" or "grain" (Bloschl & Sivapalan, 1995; Dungan et al., 2002; Pachepsky & Hill, 2017; Pereira, 2002). Each grain provides a single value of the measured variable and no variation is considered within it. Unlike a hierarchical description, support is a metric of scale. Extent is another important scale metric that quantifies total length, area, volume, or time interval within which measurements have been taken. The level of hierarchy cannot be substituted for information on extent. One more scale metric, "spacing," is defined as the minimum distance between sampling locations and it characterizes variability. The "support – spacing – extent" triplet of metrics is designed to reflect possible scale-related effects of the experimental or monitoring design on soil variables or parameters (Bierkens, Finke, & de Willigen, 2000; Western & Blöschl, 1999). Few attempts have been made to determine how these scale factors determine the SFC/STC's shape and range.

In this study, we test the hypotheses that (1) measurement support (grain) can influence the range and shape of the SFC and; (2) hysteresis can be, at least, partially attributed to the grain (support) and location of the measurements comprising the SFC/STC. In these aims, we simulated the temperature, volumetric water content (VWC), and permittivity for soil samples undergoing freeze-thaw transitions in the laboratory (Pardo Lara et al., 2020) using Hydrus-1D (H1D) and a modified Dobson model for the permittivity (Zhang et al., 2010). We show it is possible to reconcile SFC models with empirical studies and simulate hysteresis in homogenous media solely by considering measurement scale and location.

2 Materials and Methods

Models for the simulation of freeze-thaw phenomena in soils must incorporate some form of an SFC to relate the unfrozen moisture content to sub-zero temperatures. Most existing models for simulating water and heat transport in freezing soils predict unfrozen VWC by analogy between the SFC and the soil-water characteristic curve (SWC; the relationship between pressure head and VWC). Alternatively, numerous SFC have been derived empirically. There is a marked difference between time-dense SFC/STC measurements from undisturbed soil samples and theoretical or empirical SFC. To reconcile this discrepancy, we assess the effect of support and location by comparing laboratory SFC/STC measured with the HydraProbe against those produced from H1D simulations and the semi-empirical model proposed by Zhang et al. (2010) coupled with H1D's temperature output (H1D+Z).

2.1 Permittivity Measurements

Electric permittivity (usually given as a multiple of the permittivity of free space; $\varepsilon_r=\varepsilon/\varepsilon_0$) describes the tendency of a charge distribution to be distorted from its normal shape by an external electric field. Permanent dipoles, like water's, respond to an applied electric field by lining up along its direction. As water freezes, the molecules become bound in a crystal lattice, reducing their response to applied electric fields. At frequencies above the kHz range, the permittivity of H_2O falls abruptly with the freezing process as molecular rotations cease. SM EM probes operate over frequencies (10^6 - 10^9 Hz) at which the permittivity of water (~80) contrasts strongly with that of soil solids (~4), ice (~3), and air (~1); allowing for accurate estimates of the soil VWC.

2.1.1 HydraProbe

The HydraProbe (HP) is a commercially available EM SM sensor that measures the real and imaginary components of permittivity. The HP has four stainless steel tines, 3 mm diameter and 57 mm long, that protrude from a metal base plate, 42 mm in diameter. A central tine is circumscribed by three outer tines at a radius of 13 mm. The HP is based on coaxial impedance dielectric reflectometry resulting in high measurement accuracy that does not require calibration for most soils (e.g: Rowlandson et al. 2013). The base plate is part of the cylindrical head that houses the electronics used to measure temperature and produce the EM signal transmitted to the protruding tines. This method fully characterizes the dielectric spectrum in the radio frequency at 50 MHz. The sensing device is robust under a wide variety of field conditions and provides simultaneous in-situ measurement values of soil permittivity, conductivity, and temperature (Seyfried, Grant, Du, & Humes, 2005). The real component of the permittivity is used to estimate soil water content by way of an empirical calibration equation.

A material with higher permittivity polarizes more in response to an applied electric field than a material with lower permittivity. Thus, the permittivity of a material expresses the capability of an electric field to permeate it, or how much an electric field decreases inside the material compared to vacuum, or alternatively how much potential energy is stored in it. This implies that the measurement support of the probe changes based on the permittivity of the soil in which it is embedded. In other words, the wetter the soil, the higher the permittivity, the smaller the integrated volume. On the other hand, the more frozen or dry the soil, the lower the permittivity, the larger the integrated volume, as shown on Fig. 1.

Although the official HydraProbe documentation lists a cylindrical sensing volume of approximately 4.0 $x10^4$ mm^3, the support includes the soil between as well as surrounding the tines and is estimated to increase up to approximately 3.5 $x10^5$ mm^3. In addition, neither the location nor support for the temperature measurement are provided. However, the manufacturer confirmed the thermistor is situated 13 mm radially from the central tine within a hole 2.4 mm in diameter. Assuming a homogeneous thermal conductivity, the steady-state measurement volume of a thermistor depends only on its radius. Under this assumption, 90% of the thermistor signal is expected to come from within 10 thermistor radii (12 mm; $7.2x10^3$ mm^3; Xu and Anderson 2001). We use these numbers as bounding values for the support radius of the HydraProbe's measurements. Note, the thermistor location is unmarked on the HP.

2.2 Laboratory Experiment

The experiments simulated were performed on soil collected from a private farm located near Dunnville, Haldimand County, Ontario (45°52'N, 79°44'W, 192 m) during a thaw event in winter 2018. Undisturbed mesocosms were extracted in a PVC cylinder 120 mm in height and 50 mm in radius, see Pardo Lara et al., (2020) for further details. The Ontario Institute of Pedology describes soil in the area as moderately well drained Smithville heavy clay, composed primarily of 50-100 cm of mainly lacustrine heavy clay over bedrock. The topography is classified as complex, with irregular but very gentle slopes graded 2–5% (Presant & Acton, 1984). Textural analysis of one of the samples using the hydrometer method yielded a composition of 33% sand, 28% clay, and 39% silt, indicative of a clay loam. The bulk density of the sample was measured as 1.40 g cm^{-3} and the initial SM content for the transition of interest was 0.26 m^3m^{-3}.

The experiment took place at the School of Environmental Science of the University of Guelph in a walk-in NorLake2 temperature-controlled chamber equipped with a CP7L control panel. An HP was embedded in the sample 25 mm below the surface. Heat pulse probes (HPP) were inserted orthogonally at the same depth to simultaneously measure the sample's thermal diffusivity (heat capacity and thermal conductivity; Ochsner and Baker 2008). To laterally insulate the mesocosms and mimic a 1-D freezing front in the vertical direction. The samples were placed in insulated cardboard boxes and filled with dry sand, as shown in Fig. 2. One mesocosm was oven dried at 105 °C for 48 hours to serve as a control. The soil samples were subjected to temperature transitions from +10 to –10 °C and vice versa at ~24-hour intervals. The temperature and permittivity of each mesocosm were measured every minute with the HP, simultaneously a Campbell T109 thermistor measured the air temperature in the environmental chamber. Meanwhile, the HPP captured the apparent heat capacity and thermal conductivity at 24 min intervals. These output signals were recorded with a Campbell Scientific dataloggers (CR800 CR1000). These particular samples underwent five freeze-thaw events, we selected the fourth event from the first mesocosm (for data availability see: Pardo Lara, Tetlock and Berg, 2020)

2.3 Models

2.3.1 Hydrus-1D

Hydrus-1D is a widely used software package for studying vadose zone flow and transport processes (Šimunek, van Genuchten & Šejna, 2012). This modeling environment was chosen due to the high resolution available, allowing us to set the support to 1 mm spatially and 15 s temporally. H1D employs a finite-element model to simulate the one-dimensional movement of water and heat in variably saturated media (Šimůnek, van Genuchten, & Šejna, 2016). The standard version of H1D consists of modules that numerically solve for heat and water transport using the Richards and convection-dispersion type equations. Standard add-on modules are provided to simulate solute transport, major ion reactions, general biogeochemical reactions and other specialized phenomena. In addition to the standard H1D add-on modules, several additional nonstandard modules expand the capabilities of the software.

Hansson et al. (2004) presented a non-standard H1D module for solving the coupled equations governing heat transport and variably saturated flow in the context of phase changes. The module accounts for the significant decrease in the hydraulic conductivity of soil as pore water transitions to ice as well as the difference in thermal conductivities between ice and water (Mizoguchi, 1990). The module is not standard in H1D because it only runs for unsaturated soils and becomes unstable when the medium reaches full saturation. The freezing and thawing module has been used in studies by Watanabe et al. (2007) and Kurylyk and Watanabe (2013). The unfrozen water content in freezing soils is predicted based on similarity theory between the SFC and the SWC. This procedure has two major assumptions: (1) the relationship between capillary pressure and temperature is defined by the generalized Clapeyron equation and (2) the osmotic and ice gauge pressure are both zero (Kurylyk & Watanabe, 2013). The Clapeyron equation is valid with no modification, provided equilibrium is achieved and pressure is measured directly rather than estimated from an SWC. This thermodynamic approach is commonly used in land surface models with minor variations (Cherkauer & Lettenmaier, 1999; Koren et al., 1999).

We employed Hydrus-1D's standard water flow and heat transport modules with the nonstandard freezing module. The modelling support was standardized to 1 mm spatially by creating a homogenous vertical soil profile to a depth of 100 mm and dividing it into 100 evenly spaced observation nodes. We used the water content and temperatures measured from the HydraProbe as initial conditions for the profile. The van Genuchten–Mualem single porosity soil hydraulic model was selected with and without hysteresis to no discernible difference. Water flow parameters were estimated using the neural network feature based on the textural composition and bulk density measured for the sample. The soil solid's heat capacity in the simulation was refined from its default value with the one measured from the oven-dried sample with the HPP given in §3.1. The empirically determined thermal conductivities were linearly fitted and incorporated in terms of the Chung and Horton (1987) model, the fit coefficients are given in §3.1. Iteration criteria were selected as per the examples of Hansson et al. (2004), except for the maximum time-step, which was set to 15 s; anything greater causes Hydrus-1D to fail as the ice doesn't melt.

A zero heat-flux boundary condition was used at the bottom of the soil column. We additionally applied zero flux boundary conditions at both ends of the column for the water flow calculations. The simulation was run for 600,000 seconds. For the first 523,420 s, Hydrus-1D was "spun up" using time variable upper boundary temperature conditions from the preceding freeze-thaw events. These boundary conditions were taken from the average air temperature measured using the T109 thermistor between temperature changes, outlined in §3.1. The output from the information nodes (e.g. water, ice, temperature, etc.) was printed every 600 s between 448,740 s and 597,540 s, for 249 observations–the maximum allowed by Hydrus-1D. To match the temporal spacing of the empirical measurements, the simulation was run as described above a total of ten times, shifting the start time by 60 s with every repetition. The results were collated, yielding a total of 2490 simulation observations.

2.3.2 Dielectric Model Coupled with Hydrus-1D

The soil permittivity models with phase state changes considerations most widely used by the remote sensing community are described in (Mironov et al., 2017; Zhang et al., 2010). The input parameters required by these models include SM content, temperature, dry bulk density, and textural composition. For SM phase transitions, the Mironov model behaves as a step function from 0 to –1 °C.

On the other hand, Zhang et al., (2010) developed a semi-empirical permittivity model for frozen soil based on the Dobson and Ulaby (1985) semiempirical dielectric mixing model for a soil-water mixture:

$$\varepsilon^{\alpha}=1+\left(\rho_b/\rho_s\right)\left(\varepsilon_s^{\alpha}-1\right)+\theta_w^{\beta}\varepsilon_w^{\alpha}-\theta_w+\theta_i\varepsilon_i^{\alpha}-\theta_i \qquad (1)$$

where θ indicates volumetric content, ρ is the density, and the subscripts *s, w,* and *i* refer to solid soil, water , and ice respectively.α is a constant shape factor (optimized to 0.74 in our case), and β is a soil textural composition dependent coefficient (set to 0.42). The dielectric mixing model captures the liquid water content decrease with temperature using an exponential relationship, specifically, $\theta_w=a\left|T_s\right|^{-b}$, where *a* and *b* are constants correlated to the soil specific surface area. This unfrozen water fraction is then used to calculate the frozen water fraction and these values are input in the modified Dobson mixing model, proposed by Zhang et al., (2010). We also consider SFC/STCs derived empirically by coupling the temperature profile output by the Hydrus-1D simulation to a modified Dobson model.

2.3.3 Scaling

In a good model either the individual scales match or the transformation between them is well known and incorporated into the model (Bloschl & Sivapalan, 1995). Hydrologically speaking we are operating at the local scale, in regard to soil science, we are focusing at the horizon scale. To test our hypothesis regarding the effect of the support on SFC/STC measurements, we masked H1D's output extent to match the grain of the HydraProbe. Note, we exploit the symmetry inherent with a 1-D front penetrating a volume to reduce the freezing front simulation into a 2-D problem. This reduces the complexity of the model from one requiring a million-pixels to simulate the permittivity and temperature measurement support, to one requiring a ten-thousand-pixels. To accomplish this, the profiles output by Hydrus-1D were replicated laterally 100-fold, creating a 2-D mesh 101x100 pixels wide (this includes a 0^{th} surface layer), each of these 10,100 pixels in effect represents 1^2 mm^2.

The mask created to match the model output to the observation support is dependent on four geometrical parameters that define two circles: the measurement depths (*z*) and support radii (*r*) for both the temperature and permittivity measurements (z_T, r_T andz_ε, r_ε). The SFC/STC were generated by averaging the masked temperature profile for the abscissa. The ordinate values were generated in two ways: averaging the masked VWC profile from Hydrus-1D (H1D) or averaging the masked permittivity surface from the coupled model (H1D+Z). Care was taken to avoid artifacts in the resultant SFC/STC that could be caused by boundary condition effects, discretization errors, and domain size issues. In effect, we are spatially scaling the SFC underlying H1D and the H1D+Z model to the grain of the HydraProbe and comparing it to the empirically acquired SFC/STCs.

3 Results

3.1 Permittivity and temperature measurements

Figure 3 shows permittivity data collected from a Dunnville clay loam soil sample during various freeze-thaw events against time and temperature. Notably, the sigmoidal relationship between permittivity and temperature was seen in every sample analyzed for both the freezing and thawing transitions (Pardo Lara et al. 2020). The samples were nearly saturated as they were collected during a mid-winter thaw. The water migration associated with the freezing front in conjunction with the holes machined in the holders to accommodate the instrumentation led to water loss around these junctions, despite our best efforts.

Although large changes in soil permittivity are temporally correlated with spikes in the apparent heat capacity, the measurements do not correlate in temperature space. The soil permittivity continues increasing/decreasing at temperatures higher/lower than those at which the apparent heat capacity measurements return to their constant values. Pardo Lara et al., (2020) hypothesized this bifurcation was due to the difference in support between the permittivity and temperature measurements, the possibility of experimental bias was also presented.

The boundary conditions for the Hydrus-1D simulation were taken from the average air temperature measured using the T109 thermistor between temperature changes. The six transitions (3 events) prior to the event analyzed presented the following values: –8.3 °C till 85,440 s; +9.7 °C till 164,580 s; –8.3 °C till 232,200 s; +9.4 °C till 319,140 s; –8.5 °C till 392,460 s; and +8.25 °C till 463,500 s. Note, the boundary condition imposed for the thaw leading to the transitions analyzed was reduced by 1.15 °C (from +9.4°C to +8.25 °C) to assimilate the HydraProbe measured initial temperature into the simulation. For the transitions of interest, the empirically measured temperature boundary conditions were –8.5 °C till 523,420 s, +9.7 °C till 600,000 s. The heat capacity and thermal conductivity measured from the oven-dried control were C_s = 1.32 J cm^{-3} °C^{-1} and λ_s = 0.33 W m^{-1} °C^{-1} respectively. We linearly fitted the average thermal conductivity measured after each thaw event, yielding the following coefficients in terms of the Chung and Horton (1987) model: b_1 = 332 , b_2 = 665, b_3 = 0.

3.2 Model of the HydraProbe's Measurement Scale

There are unknowns about the scale and location of the HydraProbe measurements (see §2.1). In regard to the temperature measurement, the precise thermistor location is not known, the depth of the thermistor bead within the metal plate is unknown, and the surface of contact between the bead and the plate may potentially vary for each probe. The first issue alone implies degeneracy in the location of probe's temperature measurement since the thermistor position is rotationally asymmetric and unknown. As shown in the legend of Figs. 4 and 5, for a probe centered 25 mm below the surface, the thermistor could be located anywhere between 12 and 38 mm below the surface ($z_\varepsilon = 25\,mm \Rightarrow z_T$ = [12, 38]).

Therefore, three depths representative of the thermistor range were masked while holding the permittivity support constant. Recall, for permittivity, the HydraProbe's grain changes with respect to the soil's moisture content. Thus, two support radii were considered: $r_{\varepsilon \min}$= 13 mm, based on the radial distance to the outer tines and; $r_{\varepsilon \max}$= 25 mm, based on limitations imposed by the installation depth and the higher permittivity associated with clay dominant soils. The resulting SFC/STCs and timeseries can be seen in Figs. 4 and 5 respectively.

As the depth of the temperature measurement increases, the SFC (blue) shifts to warmer temperatures (rightward). At the shallowest depth, the simulated freezing transition stabilized at approximately –5.7 °C. On the other hand, at the deepest thermistor location possible, the end of the freezing transition is simulated at approximately –0.4 °C. The inverse occurs with the STC (red), which shifts to cooler temperatures (leftward) with increasing thermistor depth. The end of the simulated transition occurs at approximately +6 °C at the shallowest depth and just above +0.3 °C at the deepest point. The rightward shift of the SFC and the leftward shift of the STC cause these curves to crossover once the temperature measurement deeper in the soil than the permittivity measurement.

The VWC/permittivity timeseries overlap since the modeling extent was held constant for these simulations. The temperature timeseries, on the other hand, shows that increasing measurement depth has a moderating effect on the temperature range observed. For instance, at the deepest thermistor location (z = 38 mm) the average temperature ranges between 7.5 and –7.2 °C, on the other hand the shallowest measurement location this value ranges between 6.7 and –4.3 °C. The deepest measurement exhibits richer behaviour than those nearer to the surface and shows the best match between the modeled and empirical temperature timeseries.

The SFC/STC produced when the HydraProbe's grain is maximized look like diagonally stretched versions of the SFC/STC acquired using a smaller modeling extent. The trends described earlier are still discernible, with changes to the transition temperature. For example, the SFC transition from the topmost temperature measurement occurs at approximately –6.3 °C and at around –1.2 °C when measured from the deepest point. On the other hand, the STC transitions from this larger permittivity measurement occur at around 6.8 °C and 1.7 °C for the topmost and deepest temperature measurements.

4 Discussion

Figs. 4 and 5 corroborate our hypotheses that (1) measurement support can influence the range and shape of the SFC and; (2) hysteresis can be, at least, partially attributed to the support scale and location of the measurements comprising the SFC/STC. In soil, the freeze/thaw interface has been described as a partially frozen 'slushy zone' (Amiri, et al., 2018). Contrary to this previous work, we characterize the representative elementary volume (REV) of the 'slushy zone' as an average (temperature, water content, permittivity) of several homogenous soil layers generated from differential equations for heat and water flow. In our case, the grain is a subset of the REV. We now seek to illuminate how these measurement details affect measured SFC/STC.

4.1 Coincident and congruent measurement supports

Figs. 4 and 5 suggest that hysteresis can be induced in the SFC/STC when the temperature measurements are offset relative to the permittivity measurements and/or when the soil volume measured by these instruments differs in size. We begin by examining the effects of varying the support radii of coincident (same location) and congruent (same shape and size) permittivity and temperature measurements at a constant depth, seen in Fig. 6.

One of the most striking findings is how similar the H1D and H1D+Z simulations are, considering how differently they are derived. The underlying similitude in the results can be attributed to the very similar functional shape of the SFCs. The functional form of the SFC used by H1D is revealed by masking the model's extent to a single 1^2 mm^2 element (the model support). Similarly, the H1D+Z model collapses to the exponential form underlaying the Zhang model. One of the differences between both approaches can be seen in the STC's water content from the H1D model, which is higher than that of the SFC. The H1D model accounts for the water migration associated with the freezing front. On the other hand, the H1D+Z model does not account for this, given its semi-empirical nature. Given the subtle change associated with this consideration, we reject this migration as a significant source of the hysteresis for the experiment at hand.

At the model support scale, slight hysteresis can be seen using H1D+Z which is not present in the H1D model—perhaps due to lack of temporal resolution during a very dynamic part of the thawing process. By enlarging the masked model extent, we see the overall effect of increasing the grain is a transformation of the SFC/STCs. At the scale of the model's support (1^2 mm^2 element) as water freezes or thaws, the water content/permittivity shows a concave up relationship with temperature. As the modeled instrumental grain increases, the range of these SFC/STC transitions is expanded; the hysteresis between the SFC and STC is emphasized; and their curvature changes, with the SFC transforming from upward to downward concavity. These findings further support our hypotheses that (1) measurement support scale can influence the range and shape of the SFC and; (2) hysteresis can be, at least partially, attributed to the support scale and location of the measurements comprising the SFC/STC.

A converse pattern is seen with the thawing VWC/permittivity temporally; as the modeled instrumental grain size increases the timeseries' curvature transforms from upward to downward concavity. This transposition speaks to "time reversal" that occurs when sequentially collected measurement are plotted against cyclically changing variable (such as the temperature in our case).

Lastly, with increasing measurement support the temperature timeseries shows negative bias during the freezing transition and positive bias during the thawing transition.

The effects of varying the measurement depth for coincident and congruent HydraProbe measurements at a constant grain size can be seen in Fig. 7. As would be expected, the increase in probe depth has a moderating effect on the simulated soil temperatures. This effect manifests itself in the "rejoining" of the SFC/STCs around 0°C with increasing depth. Although their shape form begins to resemble the upward concavity of the model scale SFC/STCs, an inflection is still evident for both curves. Temporally, the buffering effect of increased depth represents itself in the delay of the freezing/thawing front. The VWC/permittivity timeseries show that the empirical measurements taken at a depth of 25 mm are best represented by simulations at 50 mm and 65 mm of depth for freezing and thawing respectively. These findings are indicative of opportunities for improving the modeling of heat transport processes in soils undergoing phase transitions. In terms of freezing/thawing, the heat diffusivity seems to be overestimated, as the simulated freezing/thawing front penetrates at a faster rate than that seen empirically. Interestingly, this effect is not symmetric for the simulated freezing and thawing events, with the former penetrating faster than the latter.

4.2 Offset or Incongruous Measurement Support

The case of coincident (same location) measurements with incongruous support (differing grains) is presented on Fig. 8. Interestingly, the simulation with a larger temperature extent most closely tracks the empirical SFC/STCs. When the instrument's temperature grain is greater than the permittivity grain, there is a negative (leftward) temperature bias for SFCs and a positive (rightward) temperature bias for STCs. On the other hand, when the permittivity grain is greater than the temperature grain, a relatively small degree of hysteresis is seen in the permittivity simulations and none in the H1D output. Other simulations of larger permittivity grains (relative to the temperature grains) behaved similarly; the main difference being a more gradual change in liquid content with respect to temperature. Notably, increasing the permittivity grain expands the SFC/STC range further than increasing the temperature grain does. As the permittivity grain increases, the hysteresis decreases; conversely, as temperature support increases, the hysteresis is accentuated.

Temporally, increasing the permittivity grain had the effect of extending the duration in which the VWC/permittivity freezing transition was recorded. When the temperature grain is larger than the permittivity grain, the VWC/permittivity transitions are sigmoidal and similar in shape; although, again, the simulated freezing transition is of longer duration. On the other hand, when the permittivity grain is larger, the freezing transition exhibits upward concavity and the thawing transition exhibits downward concavity.

The case of congruous (same grain size) but offset (different location) measurements supports is shown in Fig. 9. The effects of decoupling the location of the permittivity and temperature measurements are diverse. In the simulations, when the temperature grain is located above the permittivity grain, the SFC stays to the left of 0 °C and the STC stays to the right of 0 °C. On the other hand, when the temperature grain is below the permittivity grain, the STC is now found to the left of 0 °C and the SFC is to the right of 0 °C. Since it is not possible to discern the thermistor's location within the instrument, we cannot ascertain the thermistor's location for the laboratory experiments. We can, however, say that in 176 transitions induced on multiple soil types in the laboratory, this SFC/STC "crossover" was not seen. Furthermore, the crossover was not seen in the analysis of over 750 in situ transitions (Pardo Lara et al., 2020). Based on the SFC/STC behavior associated with the measurement support so far, we infer that the temperature grain and location of the thermistor are such that the measured volume is located above and/or circumscribes the permittivity grain.

4.3 Equifinality of the SFC/STCs: Offset and Incongruent Measurement Supports

Four different geometric arrangements that successfully simulate the empirically measured SFC/STCs are presented in Fig. 10. These findings further substantiate our hypotheses that (1) measurement support can influence the range and shape of the SFC and; (2) hysteresis can be, at least, partially attributed to the support scale and location of the measurements comprising the SFC/STC. Although these figures show good agreement with the empirical SFC/STC, simulations centered at a permittivity depth of 25 mm showed poor temporal agreement with the laboratory. The freezing transition is best simulated temporally at a depth of 50 mm, and the thawing transition at 65 mm, as seen in Table 1. It is notable that while the modelled and measured temperature are highly correlated for all depths (R = [0.954, 0.996]), the correlation between the modeled and measured VWC/permittivity deteriorates with shallowness, with R = [0.440, 0.798] for measurements depths of 25 mm and R = [0.876, 0.996] for measurement depths of 50 and 65 mm. This speaks to sensitivity of VWC/permittivity to temperature during freeze/thaw transitions and the importance of refining the heat-transfer model and its parameters. The correlation between the modeled and measured VWC/permittivity was greatly improved by the use of an empirically determined thermal conductivity relationship, as opposed to H1D's default options.

The equifinality seen in these SFC/STCs is not exclusive to geometric considerations of homogenous soil. Amiri et al., (2018) demonstrated that factors beyond the SFC-SWC relationship can influence the potential range over which pore water phase change occurs. They provided a theoretical extension for the functional form of the SFC based upon the presence of spatial heterogeneity in both soil thermal conductivity and the freezing point depression of water. They generated SFC via averaging of the multiple realizations of 1-D freezing front propagation in both homogeneous and heterogeneous media. In homogenous media their SFC collapses to an abrupt phase transition for homogeneous media. Similarly, we've inferred the functional form of the SFC from the spatial averaging of multiple exponential models. We've shown that (1) factors completely independent of the soil samples such as measurement support (grain) can influence the range and shape of the SFC and; (2) hysteresis can be, at least partially, attributed to the support scale and location of the measurements comprising the SFC/STC. In effect, the SFC exhibit equifinality with respect to spatial averaging of a homogenous medium as well as spatial heterogeneity in both soil thermal conductivity and the freezing point depression. As of now, it seems that these two contribute to the SFC's functional form, but we cannot discern which dominates, if at all.

5. Conclusions

We have shown that (1) measurement support (grain) can influence the range and shape of the SFC and; (2) hysteresis can be, at least partially, attributed to the support (grain) and location of the measurements comprising the SFC/STC. Although many explanations have been given for SFC/STC hysteresis, none of them have explored the effects of measurement grain and/or location mismatch as a cause. By creating a detailed simulation of the intra- and inter-grain variability associated with the penetration of a freezing front, we were able to reconcile theoretical and empirical SFCs with time-dense results from undisturbed samples. We simulated the temperature and VWC from soil samples undergoing freeze-thaw transitions (Pardo Lara et al., 2020) using Hydrus-1D and a modified Dobson model for the permittivity. To assess the effect of measurement scale and location on SFC/STC, we masked the simulated temperature and VWC/permittivity extent to match the instrument's support and location. The resulting curves were compared with those acquired empirically. We also demonstrated how the location and support of soil temperature and VWC/permittivity measurements can influence the temperature range over which water freezing events are captured. The results presented support the suggestion by Parkin et al., (2013), that SFC/STC hysteresis may be more apparent than mechanistically real.

This "detail dependence" in statistics of environmental systems is commonly encountered (Dungan et al., 2002) and is tied to the notion of the MAUP (modifiable areal unit problem), Simpson's Paradox, and the ecological fallacy. Even so, it was unexpected that purely geometric consideration, leading to relatively small changes in the temperature profile, could produce the rich behavior seen in the simulated SFC/STCs. Although it is not possible to determine the location of the thermistor within the HydraProbe, this is a fundamental consideration for SFC/STC studies employing the instrument. None the less, correlating values measured at different supports is possible, if the mismatch is reconciled (Pachepsky & Hill, 2017). It follows that this type of analysis is not exclusive to the HydraProbe, as any other SM probe samples a particular volume and, in general, this does not match the support of the temperature measurements acquired. These questions are ubiquitous in environmental systems and are, for instance, relevant to the complementary HPP instrumentation used in these experiments.

The sensitivity of SFC/STC to slight changes in the collected timeseries may partially explain why hysteresis has been a confounding phenomenon in the literature. Although we have only presented the analysis for one freeze-thaw event in one soil type, we have had success modeling transitions from all soil types measured by Pardo Lara et al., (2020). Previous SFC and soil freezing permittivity studies have usually been limited in time and/or temperature resolution and based on measurements from few, relatively small, disturbed soil samples that are compacted then saturated or slurries. More notably, these experiments are also performed at or near thermal equilibrium, by quasi-static or rapid cooling processes that are not representative of field conditions. Fundamentally, it seems that in the quest for isolation of the freezing/thawing phenomena in the laboratory the result was a reduction of dimensionality. Note, the Clapeyron relationship is only valid during equilibrium, however, disequilibrium phase change can occur at the onset of soil freezing because temperatures can decrease more rapidly than equilibrium ice formation. This research delves into disequilibrium freezing as measured in rapid early-stage freezing.

Simply assuming that values measured at a different scale in the lab represent the same process and can be correlated in the SFC/STC is a naïve approach. The insights gleamed from these manipulations are applicable at a reduced dimensionality but must be scaled when more realistic circumstances are considered. This is an example of how to reconcile mismatched measurement supports, a necessary step for correlating values measured at different grains (Pachepsky & Hill, 2017). The scaling analysis performed on SFC/STC simulations has the appealing features that it (1) is determinable from measurable soil and water properties, (2) collapses into traditional SFC in 1-D, and (3) replicates the observed hysteretic behavior of freeze-thaw cycles in soils. This framework of reduction and reintegration of dimensionality in the study of phenomena in the lab and in situ may be applicable to measurements other than just permittivity and temperature.

We believe the work presented lays out a theoretical justification for the range of the independently derived SFCs, which has been called for (Amiri et al. 2018). However, questions remain about the transferability of these curves when pressures, water contents, or other conditions change. There are other questions that this investigation has not delved into. For example, this method does not allow us to clearly examine the effects of freezing point depression since Hydrus-1D does not account for it. Moreover, we assumed cylindrical symmetry of the temperature measurements, when this could display hemi-spherical symmetry. At the same time, the thermal response of the HydraProbe is not well understood. Almost certainly, the thermal dynamics imposed by the metal plate affect the temperature measurement support—perhaps explaining why the simulated “crossover” of the SFC and STC is not seen empirically.

A sound understanding of the relationship between unfrozen water content and temperature unfrozen water content is critical for broad applications ranging from engineering to climate change. Past studies have demonstrated that considering the unfrozen water content in cold regions can significantly improve accuracy in coupling heat and water transfer modeling in frozen soil (Hu et al. 2020). We expected this work will provide fertile testing ground for the further study of the unfrozen water content in frozen soil and its subsequent effects on hydrothermal transfer processes in cold regions.

Data Availability Statement

Data supporting this study can be found through the Polar Data Catalogue (PDC) metadata repository at https://dx.doi.org/10.20383/101.0200 (Pardo Lara, Tetlock and Berg,2020)

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References

Amiri, E. A., Craig, J. R., & Kurylyk, B. L. (2018). A theoretical extension of the soil freezing curve paradigm. *Advances in Water Resources*, *111*(August 2017), 319–328. https://doi.org/10.1016/j.advwatres.2017.11.021

Andersland, O. B., Ladanyi, B., Barber, M., Bruscantini, C., Grings, F., & Karszenbaum, H. (2004). Physical Properties. In C. R. Fitts (Ed.), *Frozen Ground Engineering* (Second Edi, Vol. 42, pp. 1–5). Hoboken, NJ: Wiley. https://doi.org/http://dx.doi.org/10.1016/B978-0-12-384705-8.00002-9

Barry, R. G., & Gan, T. Y. (2011). *The Global Cryosphere: Past, Present, and Future*. *The Global Cryosphere: Past, Present, and Future*. Cambridge University Press. https://doi.org/10.1017/CBO9780511977947

Bierkens, M. F. P., Finke, P. A., & de Willigen, P. (2000). *Upscaling and downscaling methods for environmental research*.

Bindlish, R., Cosh, M. H., Jackson, T. J., Koike, T., Fujii, H., Chan, S. K., … Coopersmith, E. J. (2018). GCOM-W AMSR2 soil moisture product validation using core validation sites. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, *11*(1), 209–219. https://doi.org/10.1109/JSTARS.2017.2754293

Bittelli, M., Flury, M., & Campbell, G. S. (2003). A thermodielectric analyzer to measure the freezing and moisture characteristic of porous media. *Water Resources Research*, *39*(2), 1–10. https://doi.org/10.1029/2001WR000930

Bloschl, G., & Sivapalan, M. (1995). Scale Issues In Hydrological Modelling: a Review. *Hydrological Processes*, *9*(February 1994), 251–290.

Bouyoucos, G. J., & McCool, M. M. (1916). *Further Studies on the Freezing Point Lowering of Soils*. East Lansing, Michigan.

Cheng, Q., Sun, Y., Xue, X., & Guo, J. (2014). In situ determination of soil freezing characteristics for estimation of soil moisture characteristics using a dielectric tube sensor. *Soil Science Society of America Journal*, *78*(1), 133–138. https://doi.org/10.2136/sssaj2013.03.0120n

Cherkauer, K. A., & Lettenmaier, D. P. (1999). Hydrologic effects of frozen soils in the upper Mississippi River basin. *Journal of Geophysical Research*, *104*(August 1999), 19599–19610. https://doi.org/10.1029/1999jd900337

Christensen, A. F., He, H., Dyck, M. F., Turner, E. L., Chanasyk, D. S., Naeth, M. A., & Nichol, C. (2013). In situ measurement of snowmelt infiltration under various topsoil cap thicknesses on a reclaimed site. *Canadian Journal of Soil Science*, *93*(4), 497–510. https://doi.org/10.4141/CJSS2012-048

Chung, S. −O, & Horton, R. (1987). Soil heat and water flow with a partial surface mulch. *Water Resources Research*, *23*(12), 2175–2186. https://doi.org/10.1029/WR023i012p02175

Cox, P. M., Betts, R. A., Bunton, C. B., Essery, R. L. H., Rowntree, P. R., & Smith, J. (1999). The impact of new land surface physics on the GCM simulation of climate and climate sensitivity. *Climate Dynamics*, *15*(3), 183–203. https://doi.org/10.1007/s003820050276

Daanen, R. P., Misra, D., & Thompson, A. M. (2011). Frozen Soil Hydrology. In V. P. Singh, P. Singh, & U. K. Haritashya (Eds.), *Encyclopedia of Snow, Ice and Glaciers* (pp. 306–311). Dordrecht: Springer Netherlands. https://doi.org/10.1007/978-90-481-2642-2_171

Dobson, M. C., & Ulaby, F. T. (1985). Microwave Dielectric Behavior of Wet Soil-Part Dielectric Mixing Models, (1).

Dungan, J. L., Perry, J. N., Dale, M. R. T., Legendre, P., Citron-Pousty, S., Fortin, M. J., … Rosenberg, M. S. (2002). A balanced view of scale in spatial statistical analysis. *Ecography*, *25*(5), 626–640. https://doi.org/10.1034/j.1600-0587.2002.250510.x

Flerchinger, G. N., Seyfried, M. S., & Hardegree, S. P. (2006). Using Soil Freezing Characteristics to Model Multi-Season Soil Water Dynamics. *Vadose Zone Journal*, *5*(4), 1143–1153. https://doi.org/10.2136/vzj2006.0025

Ge, S., McKenzie, J., Voss, C., & Wu, Q. (2011). Exchange of groundwater and surface-water mediated by permafrost response to seasonal and long term air temperature variation. *Geophysical Research Letters*, *38*(14), 1–6. https://doi.org/10.1029/2011GL047911

Hansson, K., Šimůnek, J., Mizoguchi, M., Lundin, L.-C. C., Van Genuchten, M. T., Simunek, J., … Van Genuchten, M. T. (2004). Water flow and heat transport in frozen soil: Numerical solution and freeze-thaw applications. *Vadose Zone Journal*, *3*(2), 693–704. https://doi.org/10.2136/vzj2004.0693

He, H., Dyck, M. F., Si, B. C., Zhang, T., Lv, J., & Wang, J. (2015). Soil freezing-thawing characteristics and snowmelt infiltration in Cryalfs of Alberta, Canada. *Geoderma Regional*, *5*(August), 198–208. https://doi.org/10.1016/j.geodrs.2015.08.001

Hu, G., Zhao, L., Zhu, X., Wu, X., Wu, T., Li, R., … Hao, J. (2020). Review of algorithms and parameterizations to determine unfrozen water content in frozen soil. *Geoderma*, *368*(September 2019), 114277. https://doi.org/10.1016/j.geoderma.2020.114277

Ireson, A. M., van der Kamp, G., Ferguson, G., Nachshon, U., & Wheater, H. S. (2013). Hydrogeological processes in seasonally frozen northern latitudes: understanding, gaps and challenges. *Hydrogeology Journal*, *21*(1), 53–66. https://doi.org/10.1007/s10040-012-0916-5

Koopmans, R. W. R., & Miller, R. D. (1966). Soil Freezing and Soil Water Characteristic Curves. *Soil Science Society of America Journal*, *30*(6), 680–685. https://doi.org/10.2136/sssaj1966.03615995003000060011x

Koren, V., Schaake, J., Mitchell, K., Duan, Q.-Y. Y., Chen, F., & Baker, J. M. (1999). A parameterization of snowpack and frozen ground intended for NCEP weather and climate models. *Journal of Geophysical Research: Atmospheres*, *104*(D16), 19569–19585. https://doi.org/10.1029/1999JD900232

Kozlowski, T. (2007). A semi-empirical model for phase composition of water in clay-water systems. *Cold Regions Science and Technology*, *49*(3), 226–236. https://doi.org/10.1016/j.coldregions.2007.03.013

Kurylyk, B. L., & Watanabe, K. (2013). The mathematical representation of freezing and thawing processes in variably-saturated, non-deformable soils. *Advances in Water Resources*, *60*(January), 160–177. https://doi.org/10.1016/j.advwatres.2013.07.016

Liu, Z., & Yu, X. (2014). Predicting the phase composition curve in frozen soils using index properties: A physico-empirical approach. *Cold Regions Science and Technology*, *108*, 10–17. https://doi.org/10.1016/j.coldregions.2014.09.003

Lu, Y., Liu, X., Zhang, M., Heitman, J., & Horton, R. (2017). of Soil Analysis Thermo – Time Domain Reflectometry Method : Advances in Monitoring In Situ Soil Bulk Density, (January). https://doi.org/10.2136/msa2015.0031

Mavrovic, A., Pardo Lara, R., Berg, A., Demontoux, F., Royer, A., & Roy, A. (2020). Soil dielectric characterization at L-band microwave frequencies during freeze-thaw transitions. *Hydrology and Earth System Sciences Discussions*, (July), 1–22. https://doi.org/10.5194/hess-2020-291

Mialon, A., Richaume, P., Leroux, D., Bircher, S., Bitar, A. Al, Pellarin, T., … Kerr, Y. H. (2015). Comparison of Dobson and Mironov dielectric models in the SMOS soil moisture retrieval algorithm. *IEEE Transactions on Geoscience and Remote Sensing*, *53*(6), 3084–3094. https://doi.org/10.1109/TGRS.2014.2368585

Mironov, V. L., Kosolapova, L. G., Lukin, Y. I., Karavaysky, A. Y., & Molostov, I. P. (2017). Temperature- and texture-dependent dielectric model for frozen and thawed mineral soils at a frequency of 1.4 GHz. *Remote Sensing of Environment*, *200*(June), 240–249. https://doi.org/10.1016/j.rse.2017.08.007

Mizoguchi, M. (1990). *Water, Heat and Salt Transport in Freezing Soil*. University of Tokyo.

Mousson, A. (1858). Einige Thatsachen betreffend das Schmelzen und Gefrieren des Wassers. *Annalen Der Physik Und Chemie*, *10*, 161–174.

Ochsner, T. E., & Baker, J. M. (2008). In Situ Monitoring of Soil Thermal Properties and Heat Flux during Freezing and Thawing. *Soil Science Society of America Journal*, *72*(4), 1025. https://doi.org/10.2136/sssaj2007.0283

Öquist, M. G., Sparrman, T., Klemedtsson, L., Drotz, S. H., Grip, H., Schleucher, J., & Nilsson, M. S. (2009). Water availability controls microbial temperature responses in frozen soil CO2 production. *Global Change Biology*, *15*(11), 2715–2722. https://doi.org/10.1111/j.1365-2486.2009.01898.x

Osterkamp, T. E., & Romanovsky, V. E. (1997). Freezing of the active layer on the coastal plain of the Alaskan Arctic. *Permafrost and Periglacial Processes*, *8*(1), 23–44. https://doi.org/10.1002/(sici)1099-1530(199701)8:1<23::aid-ppp239>3.0.co;2-2

Pachepsky, Y., & Hill, R. L. (2017). Scale and scaling in soils. *Geoderma*, *287*(September 2017), 4–30. https://doi.org/10.1016/j.geoderma.2016.08.017

Pardo Lara, R., Tetlock, E., Berg, A (2020). A soil permittivity and temperature dataset of Canadian agricultural soils acquired in laboratory and in situ, https://doi.org/10.20383/101.0200

Pardo Lara, R., Berg, A. A. A., Warland, J., & Tetlock, E. (2020). In Situ Estimates of Freezing/Melting Point Depression in Agricultural Soils Using Permittivity and Temperature Measurements. *Water Resources Research*, *56*(5), 1–16. https://doi.org/10.1029/2019WR026020

Parkin, G., von Bertoldi, A. P., & McCoy, A. J. (2013). Effect of Tillage on Soil Water Content and Temperature Under Freeze–Thaw Conditions. *Vadose Zone Journal*, *12*(1), vzj2012.0075. https://doi.org/10.2136/vzj2012.0075

Pereira, G. M. (2002). A typology of spatial and temporal scale relations. *Geographical Analysis*, *34*(1), 21–33. https://doi.org/10.1111/j.1538-4632.2002.tb01073.x

Petrov, O., & Furó, I. (2006). Curvature-dependent metastability of the solid phase and the freezing-melting hysteresis in pores. *Physical Review E - Statistical, Nonlinear, and Soft Matter Physics*, *73*(1), 1–7. https://doi.org/10.1103/PhysRevE.73.011608

Presant, E. W., & Acton, C. J. (1984). *Soils of the REGIONAL MUNICIPALITY OF HALDIMAND-NORFOLK*. *Report No. 57* (Vol. I).

Quinton, W. L., Shirazi, T., Carey, S. K., & Pomeroy, J. W. (2005). Soil water storage and active-layer development in a sub-alpine Tundra hillslope, southern Yukon Territory, Canada. *Permafrost and Periglacial Processes*, *16*(4), 369–382. https://doi.org/10.1002/ppp.543

Ren, J., Vanapalli, S. K., & Han, Z. (2017). Soil freezing process and different expressions for the soil-freezing characteristic curve Mearsurement of unsaturated Compressibility Charactersristics View project Desiccation Cracking in Cohesive Soils View project CITATIONS SEE PROFILE Soil freezing p, (July). https://doi.org/10.3724/SP.J.1226.2017.00221

Romanovsky, V. E., & Osterkamp, T. E. (1997). Thawing of the active layer on the coastal plain of the Alaskan arctic. *Permafrost and Periglacial Processes*, *8*(1), 1–22. https://doi.org/10.1002/(sici)1099-1530(199701)8:1<1::aid-ppp243>3.0.co;2-u

Rowlandson, T. L., Berg, A. A., Bullock, P. R., Ojo, E. R. T., McNairn, H., Wiseman, G., & Cosh, M. H. (2013). Evaluation of several calibration procedures for a portable soil moisture sensor. *Journal of Hydrology*, *498*, 335–344. https://doi.org/10.1016/j.jhydrol.2013.05.021

Seyfried, M. S., Grant, L. E., Du, E., & Humes, K. (2005). Dielectric Loss and Calibration of the Hydra Probe Soil Water Sensor. *Vadose Zone Journal*, *4*(4), 1070. https://doi.org/10.2136/vzj2004.0148

Šimůnek, J., van Genuchten, M. T., & Šejna, M. (2016). Recent Developments and Applications of the HYDRUS Computer Software Packages. *Vadose Zone Journal*, *15*(7), vzj2016.04.0033. https://doi.org/10.2136/vzj2016.04.0033

Šimunek, J., van Genuchten, M. T., Šejna, M., Th. van Genuchten, M., & Šejna, M. (2012). HYDRUS: Model Use, Calibration, and Validation. *Transactions of the ASABE*, *55*(4), 1263. https://doi.org/https://doi.org/10.13031/2013.42239

Smirnova, T. G., Brown, J. M., Benjamin, S. G., & Kim, D. (2000). Parameterization of cold-season processes in the MAPS land-surface scheme. *Journal of Geophysical Research Atmospheres*, *105*(D3), 4077–4086. https://doi.org/10.1029/1999JD901047

Spaans, E. J. A., & Baker, J. M. (1996). The Soil Freezing Characteristic: Its Measurement and Similarity to the Soil Moisture Characteristic. *Soil Science Society of America Journal*, *60*(1), 13–19. https://doi.org/10.2136/sssaj1996.03615995006000010005x

Stähli, M., & Stadler, D. (1997). Measurement of water and solute dynamics in freezing soil columns with time domain reflectometry. *Journal of Hydrology*, *195*(1–4), 352–369. https://doi.org/10.1016/S0022-1694(96)03227-1

Tabatabaeenejad, A., Burgin, M., Duan, X., & Moghaddam, M. (2015). P-band radar retrieval of subsurface soil moisture profile as a second-order polynomial: First AirMOSS results. *IEEE Transactions on Geoscience and Remote Sensing*, *53*(2), 645–658. https://doi.org/10.1109/TGRS.2014.2326839

Tian, H., Wei, C., Lai, Y., & Chen, P. (2018). Quantification of water content durinfreeze–Thaw cycles: A nuclear magnetic resonance based method. *Vadose Zone Journal*, *17*(1), 160124. https://doi.org/10.2136/vzj2016.12.0124

Tice, A. R., Black, P. B., & Berg, R. L. (1989). Unfrozen water contents of undisturbed and remolded Alaskan silt. *Cold Regions Science and Technology*, *17*(2), 103–111. https://doi.org/10.1016/S0165-232X(89)80001-1

Topp, G. C., Davis, J. L., & Annan, A. P. (1980). Electromagnetic Determination of Soil Water Content: Measurements in Coaxial Transmission Lines. *Water Resources Research*, *16*(3), 574–582.

Wang, C., Lai, Y., Yu, F., & Li, S. (2018). Estimating the freezing-thawing hysteresis of chloride saline soils based on the phase transition theory. *Applied Thermal Engineering*, *135*(November 2017), 22–33.

https://doi.org/10.1016/j.applthermaleng.2018.02.039

Watanabe, K., Toride, N., Sakai, M., & Simunek, J. (2007). Numerical Modeling of Water, Heat, and Solute Transport during Soil Freezing. *J. Jpn. Soc. Soil Phys.*

Wen, Z., Ma, W., Feng, W., Deng, Y., Wang, D., Fan, Z., & Zhou, C. (2012). Experimental study on unfrozen water content and soil matric potential of Qinghai-Tibetan silty clay. *Environmental Earth Sciences*, *66*(5), 1467–1476. https://doi.org/10.1007/s12665-011-1386-0

Western, A. W., & Blöschl, G. (1999). On the spatial scaling of soil moisture. *Journal of Hydrology*, *217*(3–4), 203–224. https://doi.org/10.1016/S0022-1694(98)00232-7

Xu, L. X., & Anderson, G. T. (2001). Thermal Clearance Techniques. In C. T. Leondes (Ed.), *Biofluid Methods in Vascular and Pulmonary Systems*. Boca Raton, FL: CRC Press.

Xu, X., Derksen, C., Yueh, S. H., Dunbar, R. S., & Colliander, A. (2016). Freeze/Thaw Detection and Validation Using Aquarius' L-Band Backscattering Data. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, *9*(4), 1370–1381. https://doi.org/10.1109/JSTARS.2016.2519347

Yoshikawa, K., & Overduin, P. P. (2005). Comparing unfrozen water content measurements of frozen soil using recently developed commercial sensors. *Cold Regions Science and Technology*, *42*(3), 250–256. https://doi.org/10.1016/j.coldregions.2005.03.001

Zhang, L., Zhao, T., Jiang, L., & Zhao, S. (2010). Estimate of phase transition water content in freeze-thaw process using microwave radiometer. *IEEE Transactions on Geoscience and Remote Sensing*, *48*(12), 4248–4255. https://doi.org/10.1109/TGRS.2010.2051158

Zhang, M., Pei, W., Li, S., Lu, J., & Jin, L. (2017). Experimental and numerical analyses of the thermo-mechanical stability of an embankment with shady and sunny slopes in permafrost regions. *Applied Thermal Engineering*, *127*, 1478–1487. https://doi.org/10.1016/j.applthermaleng.2017.08.074

Zhou, Y., Zhou, J., Shi, X. you, & Zhou, G. qing. (2019). Practical models describing hysteresis behavior of unfrozen water in frozen soil based on similarity analysis. *Cold Regions Science and Technology*, *157*(February 2018), 215–223. https://doi.org/10.1016/j.coldregions.2018.11.002