Modelling near-surface ice content and midwinter melt events in mineral soils

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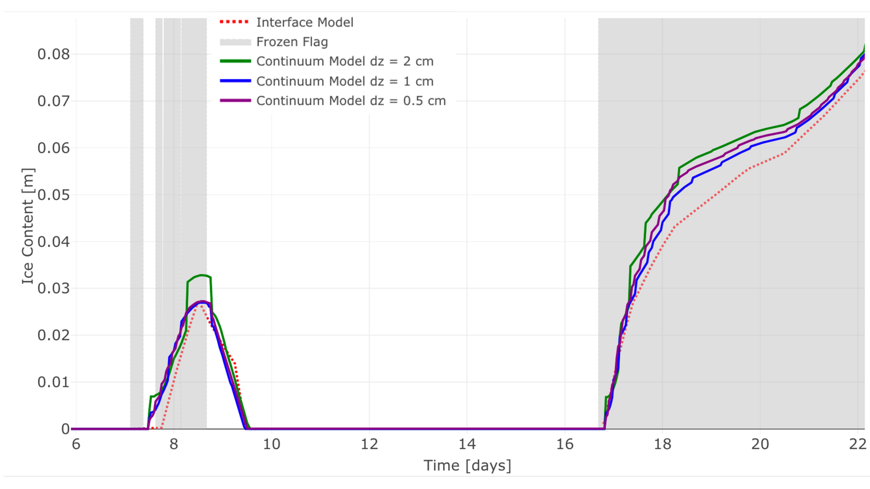
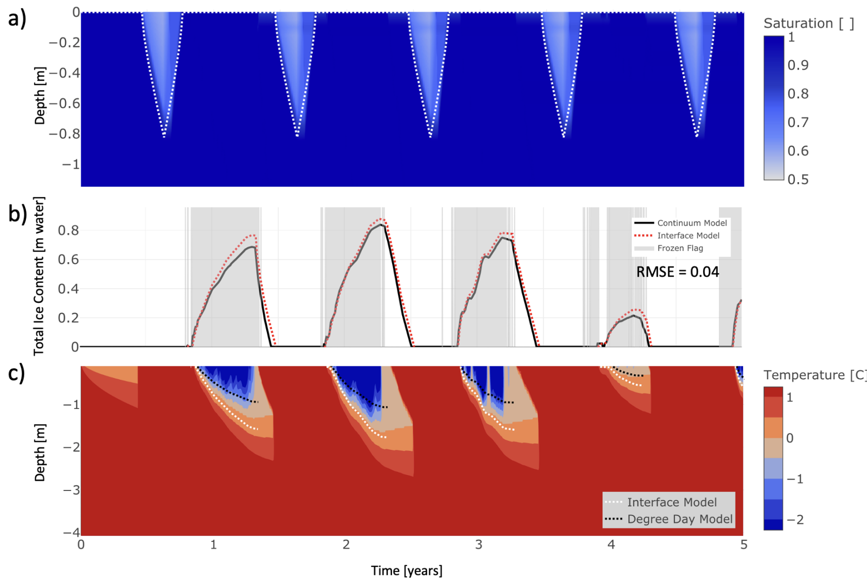
September 21, 2022

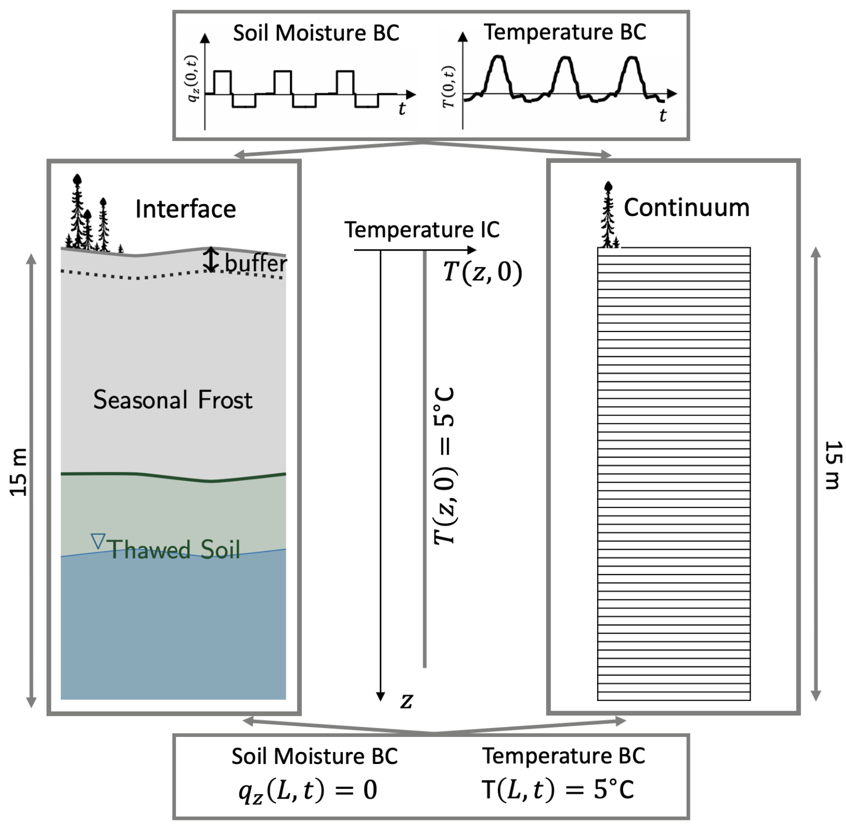
Abstract

Over winter freeze-thaw events are notoriously difficult to represent in hydrologic models and have serious implications for the hydrologic function of intermittently freezing regions. With changing climate leading to higher variability in observed weather patterns, it is anticipated that mid-winter thaw events may become more numerous at locales where intermittent thaw was previously rare. Midwinter thaw events are often the cause of flooding due to the combined impacts of snowmelt, precipitation, and limited soil infiltrability. A numerically efficient, semi-analytical coupled thermal and mass transport model is presented that is capable of representing the ice content of near-surface soil. This model allows for rapid and stable prediction of the ice content of frozen or partially frozen near-surface soil without having to solve a discrete form of the coupled partial differential equations describing the soil water and energy balance. The model tracks pore ice formation and mean soil temperature in terms of enthalpy. It is tested against data collected in Southern Saskatchewan and is shown to capably reproduce field observations. This model is efficient enough to be incorporated as a module into existing regional hydrologic models and is expected to improve predictions of soil ice content, which can later lead to improved estimates of over-winter streamflow and flood potential.

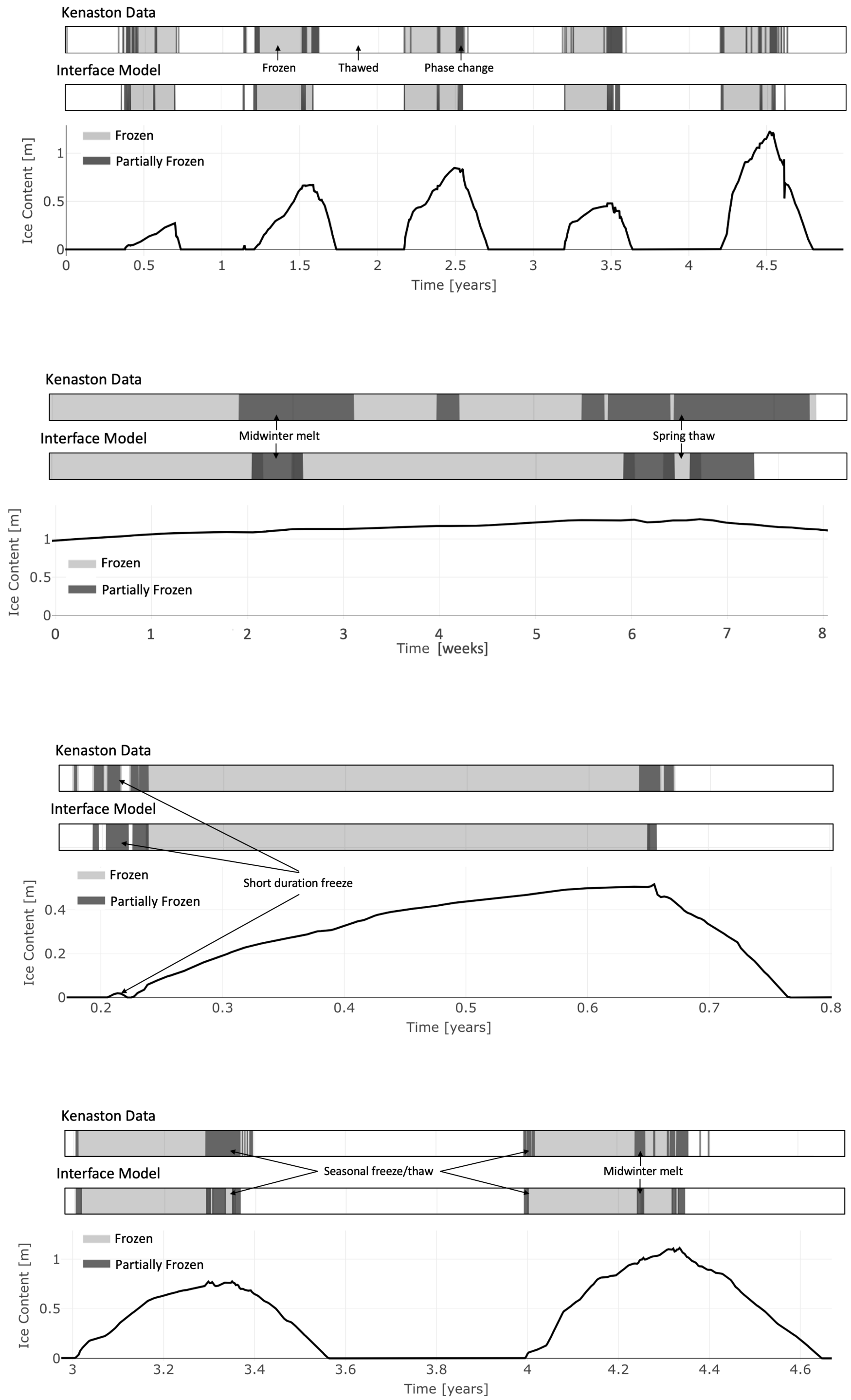




a)
b)
c)
Depth [m]
Saturation [ ]
Total Ice Content [m water]
Continuum Model
Interface Model
Frozen Flag
RMSE = 0.04
Temperature [C]
Interface Model
Degree Day Model
Time [years]



Soil Moisture BC
Temperature BC
$q_z(0,t)$
$T(0,t)$
t
Interface
buffer
Seasonal Frost
Thawed Soil
15 m
Temperature IC
$T(z,0)$
$T(z,0) = 5°C$
z
Continuum
15 m
Soil Moisture BC
$q_z(L,t) = 0$
Temperature BC
$T(L,t) = 5°C$


Kenaston Data
Interface Model
Frozen
Thawed
Phase change
Frozen
Partially Frozen
Ice Content [m]
Time [years]
Kenaston Data
Interface Model
Midwinter melt
Spring thaw
Frozen
Partially Frozen
Ice Content [m]
Time [weeks]
Kenaston Data
Interface Model
Short duration freeze
Frozen
Partially Frozen
Ice Content [m]
Time [years]
Kenaston Data
Interface Model
Seasonal freeze/thaw
Midwinter melt
Frozen
Partially Frozen
Ice Content [m]
Time [years]

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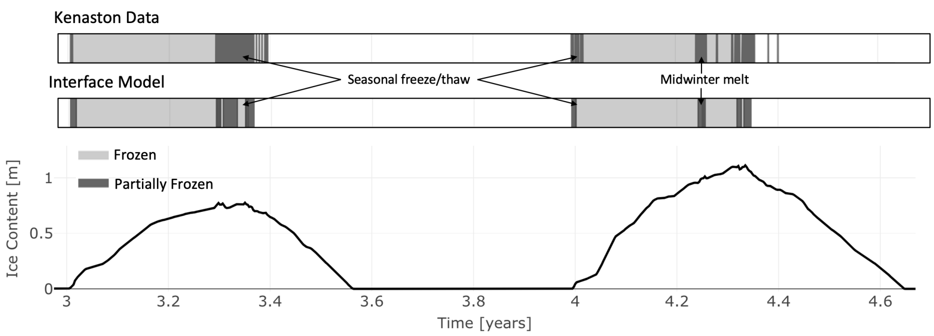
Key Points:

- An interface model is presented to predict ice content of near-surface soil
- Model is benchmarked and validated against midwinter freeze-thaw event data collected in Southern Saskatechewan
- Algorithm performs efficiently and accurately and is recommended for use in hydrologic models



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Abstract

Over winter freeze-thaw events are notoriously difficult to represent in hydrologic models and have serious implications for the hydrologic function of intermittently freezing regions. With changing climate leading to higher variability in observed weather patterns, it is anticipated that mid-winter thaw events may become more numerous at locales where intermittent thaw was previously rare. Midwinter thaw events are often the cause of flooding due to the combined impacts of snowmelt, precipitation, and limited soil infiltrability. A numerically efficient, semi-analytical coupled thermal and mass transport model is presented that is capable of representing the ice content of near-surface soil. This model allows for rapid and stable prediction of the ice content of frozen or partially frozen near-surface soil without having to solve a discrete form of the coupled partial differential equations describing the soil water and energy balance. The model tracks pore ice formation and mean soil temperature in terms of enthalpy. It is tested against data collected in Southern Saskatchewan and is shown to capably reproduce field observations. This model is efficient enough to be incorporated as a module into existing regional hydrologic models and is expected to improve predictions of soil ice content, which can later lead to improved estimates of over-winter streamflow and flood potential.

Key Words: Seasonal Freeze/Thaw, Freeze/Thaw Modelling, Cold Region Hydrology, Midwinter Melt, Semi-Analytical Modelling

1 Introduction

It is well established that anthropogenic climate change is leading to increased variability in climate and more frequent and severe weather events (Pörtner et al., 2019). The Prairie and Boreal climate regions of Canada are characterized by seasonally frozen soils, with significant snow accumulation over winter (accounting for more than one third of the seasonal precipitation), an annual hydrograph dominated by spring freshet, and complete thaw of frozen soils by early to mid-summer (Fang et al., 2007). Intermittent frozen soils are ubiquitous in the temperate regions of the northern United States and Southern Canada. With a changing climate, areas that were previously frozen through the entire winter have been observed to be affected by more midwinter melt events (Williams et al., 2015). The ability to simulate midwinter melt events can be important, especially in sensitive Prairie and Boreal Plains systems.

In many hydrologic models, frozen soils are either treated as strictly impermeable surfaces for the entire winter period (Niu & Yang, 2006) or empirical models are used to address the changes in infiltrability due to ice content fluctuations over the winter months (Luo et al., 2003). These approaches lead to an inability to accurately report the soil moisture, thermodynamic state, hydraulic conductivity, infiltrability, and water storage of the systems. Alternatively, many land surface schemes (e.g., Verseghy (2000)) explicitly simulate the full soil energy balance with freezing, which is typically accompanied by significant computational cost. In systems that are generally quiescent over the winter months, empirical models of over-winter processes have been found to be adequate (Luo et al., 2003). This has motivated the use of empirical models such as that presented by Zhao and Gray (1999), which improve model performance, but are not transferable to other study sites, nor are they applicable in non-stationary systems such as those affected by changing climates. A recent increase in midwinter thaw events and short duration freeze/thaw events in the shoulder seasons make empirical predictions less and less accurate, to the point where they may be insufficient to represent the hydrology of these systems (Pavlovskii et al., 2019). This change is increasingly important as more extreme precipitation, especially rain or rain-on-snow events over frozen ground, can lead to severe flooding. Prediction of flood timing and extent is sensitive to estimates of infiltrability and hydraulic conductivity of partially frozen soils (Seyfried & Murdock, 1997). To adequately simulate runoff in hydrologic models, it is crucial to understand infiltrability rates and patterns (Luo et al., 2003). The infiltrability is strongly controlled by the ice content of the soils, which in turn is dependant on the freeze/thaw history of the soils. Midwinter melt events are known to introduce ice lenses and layers which impede spring infiltration into froze soils (Pavlovskii et al., 2019). These melt events result in increased ice content in the near-surface soil which, upon re-freezing, also affects the soil thaw rate in the spring.

The representation of soil ice content is included in some hydrologic models, especially those applied in permafrost regions (e.g. Wang et al. (2010); Luo et al. (2003); Wang et al. (2017); Pomeroy et al. (2007)). It is shown that the accurate representation of frozen soils, including the coexistence of frozen and liquid water, improves hydrologic prediction in these regions (Niu & Yang, 2006), both for empirical and even more so for physically-based models (Wang et al., 2010). Representing soil freeze/thaw processes directly is a significant improvement over the null hypothesis that frozen soils are impermeable (Pomeroy et al., 2007; Qi et al., 2019). However, physically-based thermal models are notoriously demanding computationally, especially when coupled to mass transport of water in soils, and the representation of freezing and thawing often increases computational time more than ten-fold, and can also lead to instabilities and non-convergence of models (Wang et al., 2017).

We here propose a semi-analytical physical model that efficiently predicts freeze/thaw processes and ice contents in soils during midwinter melt and other short-duration freeze/thaw events that are currently not well captured by empirical models. As such, this model will fill the substantial gap separating physically-based, discrete continuum models from models that are purely empirical. The objectives of this paper are to (1) extend the methods developed for organic soils with permafrost by Devoie and Craig (2020) to mineral soils without permafrost, (2) evaluate the extended model against a continuum model benchmark, and (3) apply the model to intermittently frozen soil data collected at the Kenaston Field site in Saskatchewan, Canada, with a focus on short-duration freezing in the near-surface soil. Though the interface model is a front tracking model, the aim of this study is to evaluate its ability to efficiently predict freeze/thaw events to inform hydrologic models.

2 Methods

A combination of two modelling techniques and field-based measurements are used to establish the validity of the proposed interface model for the representation of freeze and thaw events in seasonally frozen mineral soils, especially for short duration midwinter melt events. Model governing equations are described in Appendix A, while model parameter definitions and values are summarized in Appendix D.

2.1 Field

2.1.1 Field Data

Soil moisture, temperature and precipitation have been monitored at 22 stations of the Kenaston Network located in the Brightwater Creek basin, east of Kenaston, SK, Canada (Tetlock et al., 2019). This is predominantly an agricultural region, dominated by annually cropped fields with some grazing land and without irrigation (Tetlock et al., 2019). The instrumented monitoring network spans 40 km^2, with most of the instrumentation within a flat 10 km^2 sub-region with slopes of less than 2%. The sites cover a soil textural composition of 10.5 - 61.7 % sand, 31.2 - 72.4 % silt and 1.2 - 41.1 % clay, for the base computational test, a representative soil (from Kensaton site 1) of 28 % sand, 53 % silt and 19 % clay was used (Pardo Lara et al., 2020, 2021). The mean annual air temperature in this region is 8 °C, and in the last three decades the mean annual precipitation has been 400 mm of which approximately 30% falls as snow (Meteorological Service of Canada, 2012). The catchment is semi-arid, and fluctuations in soil moisture follow a seasonal pattern (Burns et al., 2016), though some fill-and-spill and non-contributing areas are documented where water ponds in sloughs instead of contributing to the basin outflow (Shook et al., 2013).

Soil moisture was measured using "HydraProbes," commercially available electromagnetic sensors that report liquid water content from permittivity and temperature measurements (Seyfried & Murdock, 2004). The sensors have 4 metal tines which are 3 mm in diameter and 57 mm long. The zone of influence of the probe ranges approximately from 4.0 x 10^4 mm^3 to 3.5 x 10^5 mm^3, with a radial range of approximately 13 to 35 mm (Pardo Lara et al., 2021). Given the measurements from these probes installed at depths of 5, 20, and 50 cm below the ground (Pardo Lara et al., 2020), it is assumed that the near-surface probe is sensitive to water content in the top 50 $\pm$ 35 mm of soil, and this near-surface layer is used to report the frozen, thawed, or transitioning state of the soil. Soil temperature was measured alongside soil moisture and permittivity (as part of the soil moisture measurement) at three depths: 5, 20 and 50 cm below the ground surface (Burns et al., 2016). The mean annual soil surface temperature is approximately 5 °C. Precipitation was also measured at each site using tipping bucket rain gauges. All data was collected at 30-minute intervals (Tetlock et al., 2019).

2.1.2 Kenaston Data-driven Estimate

A field-based approach to determining the frozen or thawed state of the soil was used to generate validation data for the interface model discussed above. This approach uses soil permittivity and temperature data to establish a site-specific freezing point. The freezing temperatures were estimated using a logistic growth model fit to the soil freezing curve, as detailed in Pardo Lara et al. (2020). This allowed consistent estimates of when the soil is thawed, frozen, or undergoing phase change based upon the observation data. These data were used to validate the predicted freeze/thaw status from the interface model by specifying the field-data based freeze/thaw/transition flag. Though temperature and soil moisture data are available, the sensors are only proven to indicate if the soil is frozen, thawed or undergoing phase change (Pardo Lara et al., 2020). Extracting the exact ice content from the HydraProbe data is unfortunately not yet proven for these soils, and merits further investigation. This data was also used to identify midwinter melt events, in which the freeze/thaw flag transitioned from frozen to partially frozen and then returned to frozen.

2.2 Model

2.2.1 Interface Model

The interface model described here is a semi-analytical solution to the heat equation coupled to an equilibrium solution to a mass balance relationship based on the van Genuchten pressure-saturation relationship. This interface-based modelling approach, where the depth below the ground surface of the frozen-unfrozen interface is treated as a state variable, was first presented in Devoie and Craig (2020) in the context of active layer modelling in discontinuous permafrost peatlands environments. The model was described, benchmarked and validated in that paper, and applied to a specific case of thawing permafrost.

In this work, the interface model of Devoie and Craig (2020) is extended to represent seasonally frozen mineral soils. In this study, the bottom boundary condition of the soil profile was fixed at a constant temperature based on field measurements. In each of the simulations, the freezing point was specified based on field data. Mineral soils with lower hydraulic conductivity challenge the original assumption that the water table was in equilibrium, but modifications were made to water content representation (summarized in Appendix C), and this led to adequate results as the model was not sensitive to small changes in water content. The numerical implementation details and derivation are included in Appendix C. Finally, the modelled soil layers were modified to accommodate seasonal freeze/thaw cycles congruent with the system shown in figure 1.

Given these modifications, the interface model reports the water table position as well as the freeze/thaw fronts that exist in the subsurface (see figure 1). The updated model also includes a surface "buffer" layer of fixed thickness that may contain a fractional ice content (liquid water in excess of the residual unfrozen water content and solid water co-existing in soil pores). This enables a better approximation of the near-surface

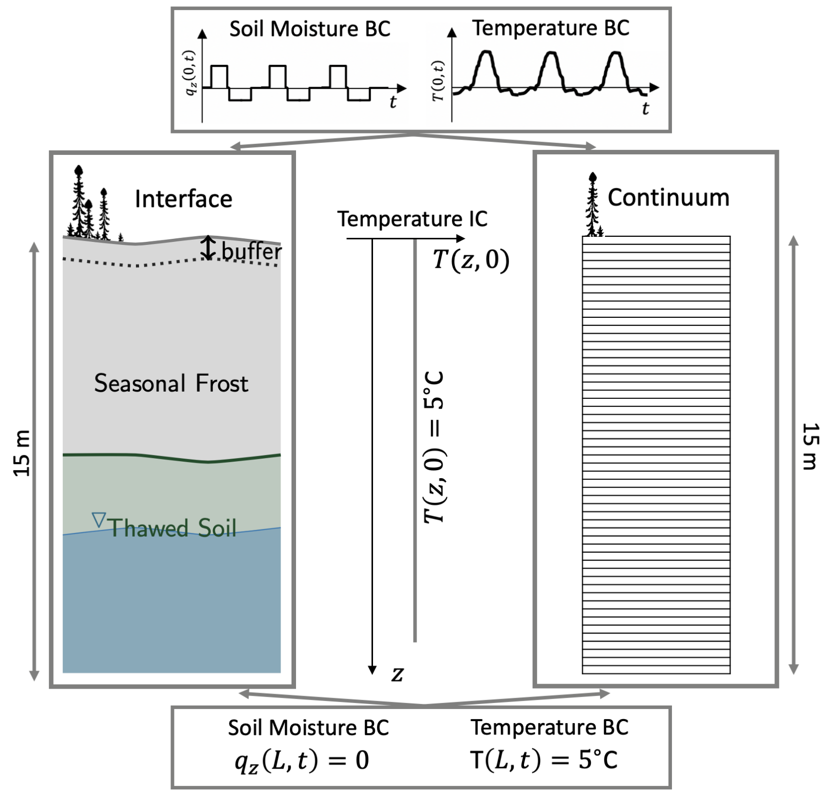

Figure 1. Schematic diagram showing model domain, boundary conditions (BCs) and initial conditions (ICs). The interface model (left) tracks the buffer layer (where fractional ice content is permitted) and the interface between frozen and thawed soil. The water table depth is also computed separately and updated through an equilibrium mass balance. The finite volume continuum model (right) used here for comparison uses operator splitting to solve the coupled PDEs describing heat and mass transport in 1D.

soil behaviour, and prevents the non-physical formation of many thin freeze/thaw interfaces that would have been required in the previous implementation. In this work the buffer layer is specified to be 85 mm, which aligns with the depth of the field measurements (section 2.1.1) of the near surface unfrozen water content used in model validation. This layer limits the fractional ice content to the near-surface, and is otherwise a purely front-tracking model with user-specified residual unfrozen water content. The limitations of this front-tracking approach are discussed in section 4.2. The interface model is appropriate for representing the total ice content in the soil column (without its exact spatial distribution), and estimating the freeze/thaw state of the near surface soil as is needed for predictions of soil infiltrability.

2.2.2 Continuum Model

To validate the details of its formulation, the interface model was directly compared to a coupled solution of the unsaturated Richards' equation and the energy balance equation solved via a finite volume method with operator splitting, as done previously in Devoie et al. (2019). This detailed numerical solution allows us to assess the impact of the simplifying assumptions made in the interface model while being forced with identical initial and boundary conditions, as well as test model representations of soil properties, pressure saturation relations, soil freezing characteristic curves and model domains. The comparison here is meant to ensure that the interface model adequately represents the most important physics. Identical initial conditions and boundary conditions were used in both models (described in section 2.2.3), and a spatial discretization of 1 cm and 2 cm were compared, both using 1 hour time steps in the continuum model. The same soil parameters were used for this model as were used in the interface model, with the addition of a linear soil freezing characteristic curve (SFCC) for a (theoretical) freezing range of -0.005 to 0 °C. This narrow range was chosen to match the interface model which does not include an SFCC as it tracks a sharp interface without a slushy region.

2.2.3 Initial and Boundary Conditions

For comparison with field data, the model domains of both models were extended to a depth of 15 m, using a fixed soil temperature of 5 °C at the base of the profile, consistent with the mean annual soil surface temperature of 5 °C, and the negligible geothermal gradient of 0.002 °C/m (Majorowicz & Grasby, 2021). This temperature also aligns with data collected at a depth of 15m near Edmonton, Canada (Toogood, 1976). This was the nearest geothermal data available to the study site, and at the depth of 15 m, the spatial variability of temperature is very low. This temperature is in agreement with data taken in Saskatoon, where the average soil temperature at 3.0 m was 6 °C, decreasing with depth, though there was still evidence of seasonal variation (Wittrock & Dunn, 2016). An initial water table position was assigned at 1 m below the ground surface, based on the water table data collected in the field in early spring. Mass flux at the surface was applied seasonally, with an average ET rate (-2.24$\times$10^{-3} mm/d) applied in spring/summer and an average recharge rate (2.88 $\times$ 10^{-3} mm/d) in the fall. The 15m depth was specified to be well below both the expected minimum water table depth and the extinction depth, but the precise choice of 15m is arbitrary: one of the benefits of the semi-analytical model is that a large vertical extent does not increase computation time. The net mass flux was zero annually. A no-flow boundary condition was assigned at the base of the soil column to represent the near-impermeable unweathered till underlying this system, and the bedrock beneath that (Shaw & Hendry, 1998). The surface temperature boundary condition was drawn from soil temperature collected at a depth of 5 cm in the field sites near Kenaston, and forced with a seasonally cyclic moisture boundary condition (reported in section 3) as direct application of the infiltration flux data collected in the field precluded convergence of the continuum model used for benchmarking. The soil column was initialized to a thawed uniform temperature of 5 °C, and the freeze/thaw discriminant temperature was assigned based on the specific freezing point depression determined from the field data, ranging between 0 and -0.4 °C (Pardo Lara et al., 2020). Simulations were started in the summer of 2012, except at sites 16 and 18 which were started in summer 2013 due to lack of data. All simulations were run for a duration of 5 years, with associated computational time of 11s for each simulation. As described in Devoie and Craig (2020), the surface layer of the interface model is a 'buffer layer' which may contain fractional ice content. The depth of this buffer layer was assigned based on the zone of influence of the soil moisture measurements made in the field. This allows the ice content of the buffer layer to be compared to the measured ice presence of the near-surface soil in the field. Below the buffer layer the freeze/thaw front is a moving sharp interface and fractional ice content is not permitted. Because of the moving interface, there is no spatial discretization of the interface model, however there is temporal discretization, and the simulations reported here are run with a 1 hour timestep for comparison with the finite volume model in figure 7 and a 1 day timestep otherwise. Other soil parameters were homogeneous and independent of depth, and are summarized in table 1 in Appendix D both for organic and mineral soils.

3 Results

The interface model presented in (Devoie & Craig, 2020) is extended to treat the case of seasonal ground ice, enabling it to represent seasonal freeze thaw in mid-latitude continental climates. Here, the simulation of seasonal freeze-thaw is first verified via a numerical benchmarking study in an unsaturated system typical of mineral soils in the semi-arid climate of Southern Saskatchewan. Boundary conditions and soil parameters were obtained from field data, but no direct measurements of freeze/thaw are available for the benchmark; these tests are purely to demonstrate numerical accuracy of the method. Finally, the interface model predictions are directly compared to the data-derived freeze/thaw status at sites in the Canadian prairies to evaluate the practical efficacy of the method. An additional comparison between the interface model and the continuum model in a near-saturated peat soil column is included in Appendix E for saturated and unsaturated organic soils.

3.1 Kenaston

The model was evaluated for a five-year simulation based on field data collected at one field site of the Kenaston Soil Moisture Network, with a 15 m vertical domain and realistic thermal initial and boundary conditions as detailed in section 2.2.1. Figure 2 shows the comparison between the continuum model, interface model, as well as field data indicating the 'frozen period' (shaded in grey). The shaded grey areas in figure 2 (b) indicate the period over which the near-surface soil (approximately 40 - 85 mm) at the field site was frozen. This data is drawn directly from field measurements using the methodology outlined in section 2.1.1, and compares favourably with the reported freeze/thaw timing. The use of field data resulted in an increase in RMSE to 0.04 between the total ice content simulated by the interface model and continuum model, which is still excellent agreement. The interface position in figure 2(c) tracks the zero degree isotherm relatively well, though the interface position is slightly deeper when compared to the discretized model. The performance of the interface model is however significantly better than a simple degree-day method from Fox (1992) which significantly under-estimates the thawing front, shown in black in figure 2(c). The simulation was re-run using finer spatial and temporal discretization in the continuum model (shown in figure 3) to capture the exact timing of a specific freeze/thaw event, which was not captured using the model setup used to simulate the entire period (5 cm spatial discretization and 3 minute timestep).

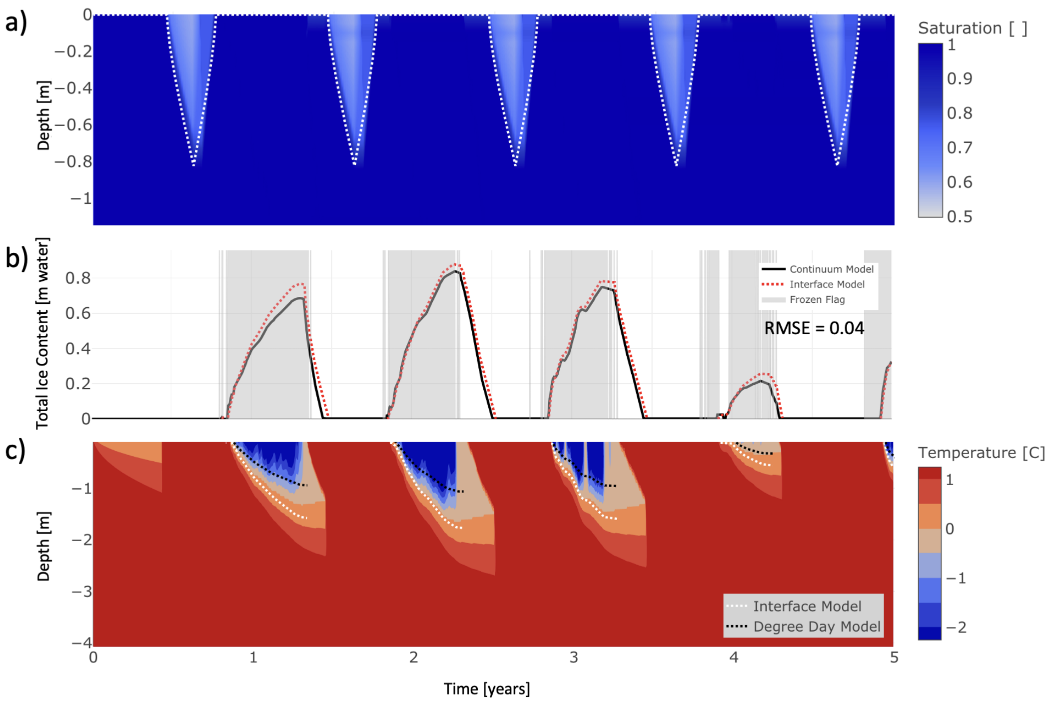

Figure 2. (a) Comparison of water content for interface and continuum model (b) comparison of total ice content for continuum model (black), interface model (red) and field-based near-surface frozen flag (shaded grey) and (c) contour plot of continuum model temperature with freeze/thaw interface position from interface model superimposed in white dashed line. Degree day model from Fox (1992) in black dashed line. Field-data driven with surface water flux approximated as seasonally uniform due to stability constraints for continuum model, soil texture data drawn form Kenaston Site 1 in Table 1 of Appendix D

The comparison of the interface and continuum model for the short-duration event in figure 3 was generated using the same model configuration as figure 2, but with finer spatial and temporal discretization of both models. The comparison of computational efficiency can also be established in figure 3 as the continuum model run took 2 hours and 22 minutes (in blue) while the interface model (red) only took 4.5 seconds for the

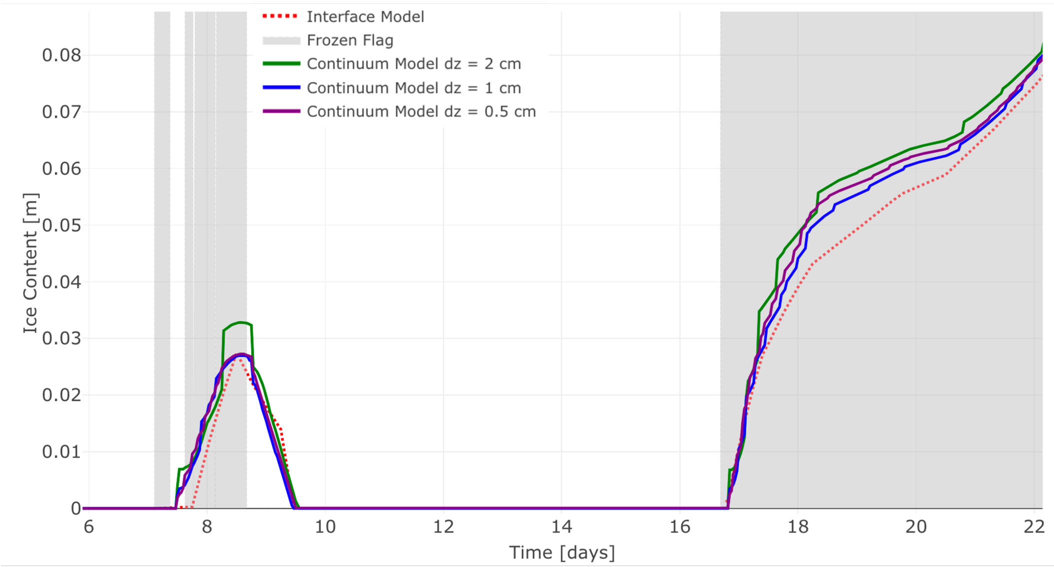

Figure 3. Short duration freeze/thaw initiation. Comparison of interface model (with 6 hour timesteps) to continuum model with timesteps chosen to satisfy convergence criteria given spatial discretization. This short duration initiation of freezing results in a small quantity of near-surface ice, hence the small total ice content. Spatial steps larger than 2 cm do not capture the near-surface freezing event in the continuum model. Model convergence is assumed based on the similarity between the 1 cm and 0.5 cm simulations. Grey shaded regions indicate soil freezing according to the field-data. Soil texture data drawn form Kenaston Site 1 in table Appendix D

same size time step and simulation setup. The performance of the interface model is arguably better than the continuum model: when the spatial discretization of the continuum model is refined, it tends toward the interface model solution. Larger spatial steps lead to a lack of identification of the freezing event in the continuum model, and smaller spatial (and associated temporal) discretization was computationally impractical. The interface model also shows better timing and more gradual response to freeze/thaw events. Neither model captures the initial freezing event near day 7, likely due to the choice of (theoretical) freezing point depression (-0.005 ° C) and the freezing range between 0 and -0.01 ° C for the interface and continuum models respectively. Subsequent figures generated using only the interface model without continuum model comparison use the freezing point depression determined from field measurements at the given field sites in order to better capture such events.

3.2 Midwinter Melt

The benchmarked interface model (but not the continuum model) was then applied to simulate all of the available data for similar mineral soil sites. A total of 22 sites were considered in which subsurface temperature and soil moisture were recorded for a duration of 4 - 6 years between 2014 and 2020. In 10 of these 22 sites clear mid-winder thaw events were identified, in which the soil temperature warmed above 0°C. The interface model was run using near-surface soil temperature data available at these sites, and compared to the freeze/thaw flag extrapolated from the field data. Here a second "transition" flag was added to the field data representing soils undergoing phase change; if the surface layer of soil contained fractional ice content based on its permittivity this flag was activated. This flag is shaded in dark grey in the subsequent figures, while entirely frozen near-surface soils (with only residual water content) were assigned a "frozen" flag, depicted in light grey and thawed near-surface soils were left as white bands. The interface model was compared to the two field-data based flags using the near-surface "buffer" layer in the model. The depth of this surface soil layer is 85 mm in accordance with the (maximal) depth of influence of the soil moisture probes used to collect the field data (Pardo Lara et al., 2021). Note that once this buffer layer is completely frozen, the total ice content is allowed to continue to increase as the freezing front moves downward beyond 85 mm. Two separate flags were also implemented in the model - the first "transition" flag representing fractional ice content in the near-surface, and the second "frozen"

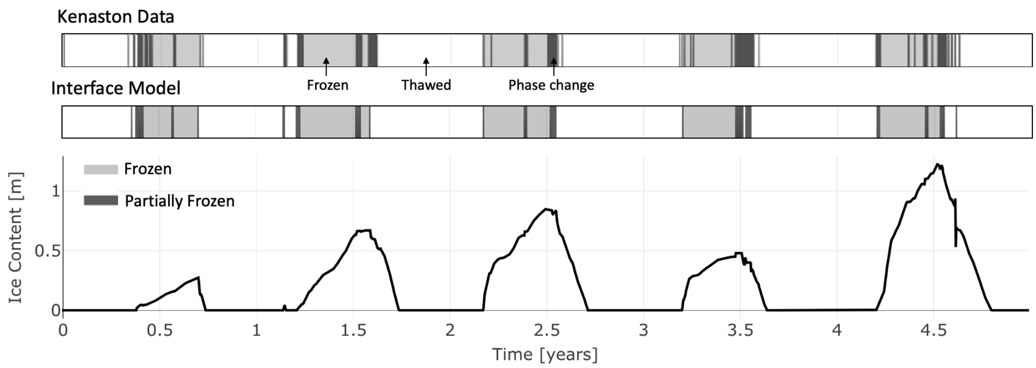

Figure 4. Comparison of Kenaston field-data and interface model generated near-surface ice content indicating phase change (dark grey) and frozen soil (light grey). Total ice content from interface model shown along bottom axis. Soil texture data drawn from Kenaston Site 3 in table 1 Appendix D

flag indicating residual water content only, these are assigned the same colours as the field data. Sample results for the entire 5 year simulation at Kenaston site 3 are shown in figure 4, showing agreement between the interface model and data-extrapolated freeze/thaw timing. Two error metrics are used to compare the simulated and observed near-surface ice content. The first indicates the overall agreement between the modelled and measured data including frozen, thawed and transitioning states. For the data in figure 4, the agreement is 92%, indicating that the measured and modelled soils did not have the same freeze/thaw state only 8% of the time. The second metric was conceived to identify the effectiveness of the interface model at identifying frozen soils, and so it compares the soil state only when the measured field data is frozen, and does not take into account partially vs. completely frozen soils. For this study case, there is 91% agreement, indicating that the interface model incorrectly identified frozen soil as thawed 9% of the time.

4 Discussion

4.1 Interface Model Limitations

The interface model used in this study is a front tracking model, and its greatest limitation is therefore that it does not have the capacity to represent a slushy zone beyond the buffer layer. It does not use a soil freezing characteristic curve (SFCC), and is therefore will not be as robust as a continuum model when detailed information on the fractional ice content is needed. This is especially true for soils with SFCCs having a wide temperature range such as clay-rich materials. The authors also caution against the use of this model in small-scale systems with significant groundwater recharge or discharge, as these processes depend on the detailed knowledge of distributed soil ice content to calculate fluxes. The interface model is however a good approximation of reality in sandy, coarse-grained soils where the SFCC is quite steep and the slushy zone is limited. It is also a valuable tool in the case of large-scale hydrologic simulations, which are limited by computational efficiency. In these cases, the approximation of freeze/thaw state in the near-surface provided by the interface model is superior to the current low-fidelity empirical models, as seen in figure 2(c) (Fox, 1992).

4.2 Model Evaluation: Near-surface buffer layer

Figure 4 demonstrates agreement in the timing of broad seasonal events between the modelled data and data collected in the field, and figure 5 shows a more detailed view that distinguishes the typical seasonal freeze/thaw (i.e. freeze in the fall/early winter and thaw in the spring) from midwinter melt events. The interface model is highly effective in detecting the timing of freeze/thaw initiation, however the freeze/thaw transitions of the near-surface buffer layer tend to occur sooner than in the measured data (Figure 5 & 6), in part due to the changing volume integrated in the HydraProbe's measurements and perhaps due to an under-estimate of the water content (and hence effective heat capacity) of the soil, alternatively an under-estimate of the volume integrated in the field measurements. As the soil freezes, its permittivity decreases, and the integrated volume of the HydraProbe measurement increases, delaying the observation of the frozen condition by the sensor. These explanations are also supported by the tendency of the interface model to begin to change phase more rapidly. An under-estimate or mismatch of the volume which must undergo phase change due to an under-estimate of the near-surface layer would result in more rapid freeze/thaw. It is also noteworthy that the total ice content in the soil column changes very little due to these short-duration freeze/thaw events. Generally we see a flattening of the slope during a midwinter melt (e.g. figures 5 and 6), where ice accumulation does not occur, however there is no clear evidence for significant ice loss during these events. It is difficult to establish the measured depth of thaw from the available field data, but there is no evidence that thaw extends beyond the first soil moisture and temperature sensor at a depth of 50 mm, limiting the anticipated ice loss to less than 25 mm given unsaturated soil conditions and a soil porosity not exceeding 0.5.

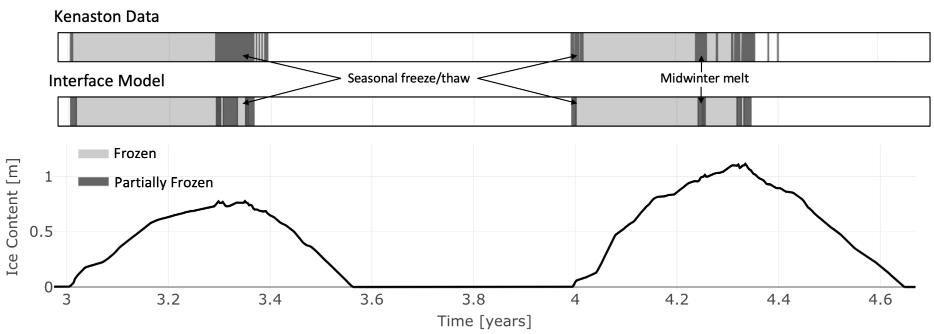

Figure 5. Comparison of Kenaston field-data and interface model generated near-surface ice content indicating phase change (dark grey) and frozen soil (light grey). This 2 year subset (2016 - 2017) from 5 year simulation (2013 - 2018) drawn from Kenaston site 15. Seasonal freeze thaw at the near surface occurs in fall and early spring, while a mid-winder melt event is highlighted in year 4. For this simulation, the overall agreement between freeze/thaw states was 94%, while the interface model correctly identified 95% of the frozen period.

4.3 Model Evaluation: Freezing point

Figures 5 and 6 also demonstrate that thaw occurs sooner in the interface model than in the extrapolated field data, though the interface model does accurately capture 96% of the frozen/thawed data. It is thought that this is due to the single freezing point depression used to interpret the data. It is known that there is hysteresis in the freeze-thaw process, and that the freezing point temperature is generally lower than the thawing point (Saberi & Meschke, 2021). This leads to more rapid initiation of modelled thaw as it is initiated at a colder temperature than would realistically be observed in the field. More work, including investigation of hysteretic behaviour in freeze/thaw modelling is needed, such as (Amiri & Craig, 2019) or the physical analysis of hysteresis, such as (Pardo Lara et al., 2021).

4.4 Model Evaluation: Near-surface water content

The small difference in freeze/thaw timing may also be driven by a mismatch in near-surface soil water content between simulated and observed. The error in estimated

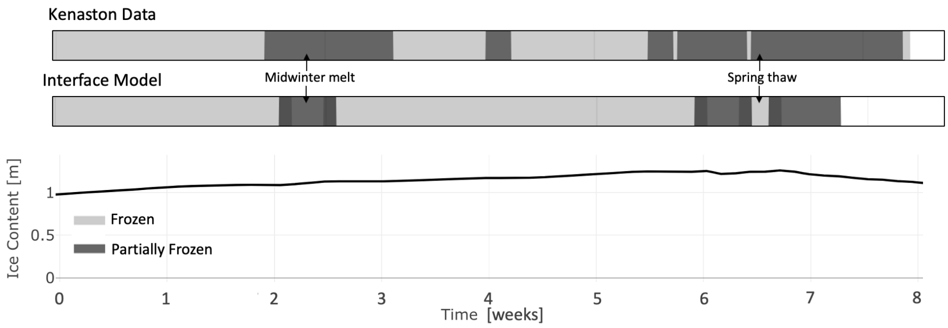

Figure 6. Comparison of Kenaston field-data and interface model generated near-surface ice content indicating phase change (dark grey) and frozen soil (light grey). Interface model phase change takes less time, perhaps because of an under-estimate of the freezing point. Overall agreement between the freeze/thaw states is 94%, while the interface model correctly identifies 96% of the frozen period. Detail view from 5 year simulation drawn from Kenaston site 20.

soil water content may arise because an equilibrium soil moisture profile is implemented in the interface model, as detailed in Appendix C. The application of the model to mineral soils was expected to require a more complex representation of infiltration events including plug flow and moisture redistribution, but these were not found to be necessary in the reproduction of the freeze/thaw conditions in field observations of near-surface soils. The equilibrium assumption seems to be adequate for two reasons; first, the surface mass balance used is based on seasonal trends and is very smooth. This results in near-equilibrium moisture conditions in the soil column over most of the freeze/thaw season. Secondly, the quantity of interest is the frozen state of the near-surface soil. When mineral soils freeze, the impedance of ice in the soil pores is such that infiltration and evapotranspiration are negligible, and therefore these processes have little effect on the model results.

4.5 Spring thaw

Measurements of spring thaw (and some midwinter events) lead to small and rapid fluctuations in ice content in the surface layer. Spring temperatures in the Kenaston region have strong diurnal fluctuations, where the daytime temperature is well above the freezing point, but the overnight low is around - 1 °C. In the interface model, the near-surface ice content is estimated in the top 85 mm of soil, deemed equivalent to the depth of soil characterized by the field based freeze-thaw flag. This layer was included in the model as a mathematical construct that would prevent the formation of very thin, non-physical frozen and thawed layers at the soil surface. Even with this layer, the interface model fails to capture many diurnal-fluctuation driven spring freeze/thaw events. However, these primarily occur when the underlying soil is frozen, and so the inability to track fractional ice content in the near-surface soil (especially when the ice content never freezes the pore water completely) likely has very little effect on the infiltration capacity and subsurface water movement. Water movement in the landscape is expected to be much more strongly affected by the fully frozen (less the residual water content) near-saturated layer at a depth of 10 - 15 cm below the soil surface. The relatively thin surface layer cannot store significant thermal energy, and the surface topography generally exceeds the scale of this layer, restricting the formation of flow pathways beyond the plot scale. The buffer layer may however still be physically meaningful, as there is evidence for the development of surface layer which undergoes freeze/thaw in a soil subject to midwinter thaw events. As noted by the temperature sensors in the soil profile, short thaw events do not extend beyond the top 100 mm of soil, though this surface layer experiences temperature cycling and freeze/thaw throughout the winter as well as the shoulder seasons when strong diurnal temperature cycles are common. The increased freeze-thaw cycling can lead to changes in soil structure (Alkire & Morrison, 1983) and changes in decomposition of soil organic matter (Yanai et al., 2004). Further investigation is required to establish if this layer is physically significant across landscapes experiencing freeze-thaw.

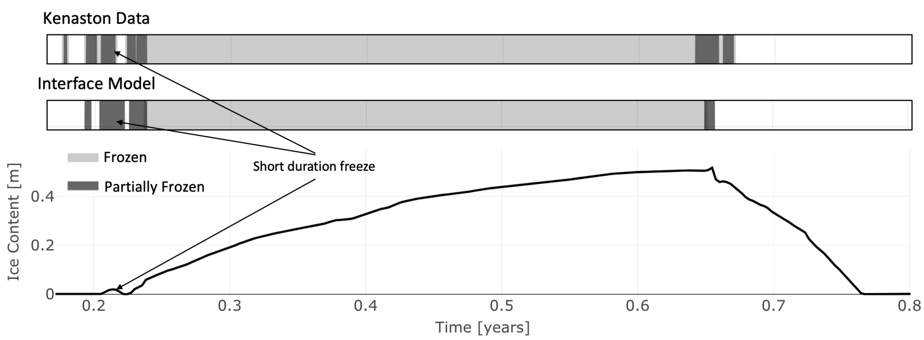

Figure 7. Early season short-duration freeze/thaw event comparison between field-data and interface-model generated freeze/thaw. The overall agreement between freeze/thaw states was 95%, while the interface model correctly identified 96% of the frozen period. Single year of data drawn from 5 year simulation of Kenaston site 10.

The interface model is notably better at representing early fall freezing events (Figure 7) which are of much higher hydrological importance as the underlying soil is ice-free and the surface (buffer) layer has the greatest impact on runoff partitioning. These results are promising for their potential improvement to runoff modelling.

5 Conclusion

An interface model was presented to simulate the ice content of variably saturated soils undergoing freeze/thaw processes. This model has been demonstrated to efficiently and stably reproduce the timing and magnitude of freeze/thaw events both on the inter-annual scale as well as on the sub-daily scale when compared to both a high-resolution finite volume model and to data collected at a site in Southern Saskatchewan. The interface model fills a utility gap between computationally intensive physically-based continuum models and low-fidelity empirical expressions for ground freeze-thaw, and its computational expediency lends itself towards integration into practical forecasting tools. Such a contribution is especially relevant in areas such as the Canadian prairies where an increase in midwinter freeze/thaw events of short duration is limiting the predictive ability of current hydrologic models.

Acknowledgements

We acknowledge the Liidlii Kue First Nation and the Jean Marie River First Nation for their continued support of the SCRS. We acknowledge the generous support of the Government of the Northwest Territories through their partnership agreement with Wilfrid Laurier University and of the Cold Regions Research Centre. We also acknowledge the support from ArcticNet through their support of the Dehcho Collaborative on Permafrost (DCoP), and Global Water Futures: Transformative sensor Technologies and Smart Watersheds for Canadian Water Futures (TTSW).

The data that support the findings of this study are openly available in the Federated Research Repository at `https://doi.org/10.20383/101.0116`.

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