Seasonal Freeze-Thaw Modelling for Short Duration and Midwinter Melt Events in Mineral Soils

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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, especially in cold regions. Midwinter thaw events are often the cause of flooding due to the coupled impact of rain-on-snow, 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 soil without having to solve a discrete form of the coupled partial differential equations describing freeze-thaw and soil water content. The model tracks pore ice formation and soil cold content in terms of enthalpy. It is tested against data collected in Southern Saskatchewan and is shown to 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 over-winter streamflow and flooding 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). The prairie region is especially important agriculturally, and the fill-and-spill hydrology of prairie wetlands is highly sensitive to antecedent conditions, changes in precipitation timing and volume, and tends to have a memory extending beyond a single hydrologic year (Shaw et al., 2012; K. R. Shook & Pomeroy, 2011; K. Shook et al., 2013). This behaviour leads to hysteresis in the hydrologic response of these systems, and makes hydrologic prediction challenging (K. R. Shook & Pomeroy, 2011; Shanley & Chalmers, 1999). When coupled with an increase in climate variability and extreme climate events, this complex behaviour can lead to significant challenges in predicting streamflow, flooding, groundwater supply and water quality. These challenges are not limited to Prairie and Boreal systems which are the focus of this paper, but other regions that undergo freeze/thaw processes are affected by these and other modelling challenges.

The limitations of current hydrological modelling are, in part, due to a lack of representation of soil ice content. 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. 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). However, a recent increase in midwinter thaw events and short duration freeze/thaw events in the shoulder seasons make these predictions less and less accurate, to the point where they are insufficient to represent they hydrology of these systems (Pavlovskii et al., 2019). This change is increasingly important as more extreme precipitation, especially rain-on-snow events, can lead to severe flooding. Prediction of flood timing and extent is dependent on infiltrability and hydraulic conductivity of partially frozen soils (M. Seyfried & Murdock, 1997). To adequately simulate runoff in hydrologic models, it is crucial to have a sense of the infiltrability of soils (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). It is also demonstrated that including some representation of frozen soils is beneficial in temperate regions, and a significant improvement over the null hypothesis that frozen soils are impermeable (Pomeroy et al., 2007; Qi et al., 2019). 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). 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.

The present work fills a gap in the existing spectrum of modelling tools (physically-based discrete continuum models vs. purely empirical models) by proposing a semi-analytical physical model that efficiently predicts freeze/thaw processes and ice content in soils, focusing on midwinter melt events and short-duration freeze/thaw events in the shoulder seasons that are currently not captured well. Specifically, the objectives of this paper are to (1) extend the method presented in Devoie and Craig (2020) to mineral soils without permafrost (2) evaluate the new model against a continuum model benchmark, and (3) apply the model intermittently flrozen soil data collected at the Kenaston Field site, with a focus on partial freezing in the near-surface soil.

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.

2.1 Interface Model

The interface model used 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 for the specified soil parameters. This interface-based modelling approach, where the location 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. However, the approach was not applicable to lower porosity mineral soils with low moisture content, did not readily support intermittent freeze/thaw cycles, and presumed the presence of permafrost at depth.

[Figure 1 about here.]

In this work, the interface model is extended to represent seasonally frozen mineral soils. The interface model reports the water table position as well as the freeze/thaw fronts that exist in the subsurface (see figure 1). The model also includes a surface "buffer" layer of fixed depth that is allowed to contain fractional ice content, accounting for the near-surface soil behaviour and preventing the non-physical formation of many freeze/thaw interfaces. In this work the buffer layer is taken to be 85 mm, which aligns with the depth of the field measurements used in model validation. To adequately represent unsaturated, seasonally frozen mineral soils, some elements of the original interface model were modified from Devoie and Craig (2020). Most importantly, the bottom boundary condition was modified to reflect the thawed soil. The bottom boundary of the soil profile is fixed at a constant temperature, either 0.1 °C, just above the freezing point for comparison with the continuum model discussed in section 2.2, or a specified temperature based on field measurements. Mineral soils with lower hydraulic conductivity challenged the original assumption that the water table was in equilibrium, but some modifications were made to water content representation, and this led to adequate results as the model did not seem to be sensitive to small changes in water content (as discussed in section 4). The numerical implementation details and derivation are included in appendix 5.1. The model structure is otherwise unchanged from Devoie and Craig (2020), though the formulation of soil layers was modified to accommodate seasonal freeze/thaw cycles congruent with the system shown in figure 1.

For comparison with field data, the model domain was extended to a depth of 15 m and a fixed soil temperature of 5 °C was prescribed at the base of the profile, consistent with data collected near Edmonton, Canada (Toogood, 1976). An initial water table position was assigned at 1 m below the ground surface, based on soil moisture data collected in the filed. A no-flow boundary condition was assigned at the base of the soil column to represent the near-impermeable bedrock underlying this system. The surface temperature boundary condition was drawn from soil temperature collected at a depth of 5 cm in the field sites near Kenaston, Canada, 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 sites 16 and 18 which were started in summer 2013 due to lack of data. 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 content 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 9 and a 1 day timestep otherwise. Other soil parameters were homogeneous and independent of depth, and are summarized in table 5.2 in Appendix 5.2 both for organic and mineral soils.

2.2 Continuum Model

The interface model above 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 discussed in Devoie et al. (2019). This 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 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 physics of the system. Identical initial conditions and boundary conditions were used in this model, and a spatial discretization of 1 cm and 2 cm were compared, both for 1 hour time steps. 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 for a freezing range of -0.005 to 0 °C.

2.3 Kenaston Data-driven Model

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 moisture (permitivity) and temperature data to establish a site-specific freezing point depression and uncertainty range for both freezing and thawing. 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 us to consistently estimate 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 flag.

2.3.1 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). 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 (K. Shook et al., 2013).

Soil moisture was measured using "HydraProbes", commercially available electromagnetic sensors which report permittivity (M. S. 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 installation of these probes, it is assumed that they are sensitive to water and ice 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. A depth of 85 mm was assigned to the buffer in the interface model to correspond to this near-surface layer for model validation. Soil temperature was measured alongside soil moisture (as part of the soil moisture measurement) at three depths: 5, 20 and 50 cm below the ground surface (Burns et al., 2016). Precipitation was also measured at each site using tipping bucket rain gauges. All data was collected at 30-minute intervals (Tetlock et al., 2019).

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 a near-saturated peat soil column, followed by another purely numerical comparison in an unsaturated system more typical of mineral soils in the semi-arid climate of Southern Saskatchewan. In both cases, boundary conditions and soil parameters were obtained from field data, but no direct measurements of soil moisture or freeze/thaw status are available; these tests are purely to demonstrate numerical accuracy of the method. Finally, the interface model predictions are compared to the data-derived freeze/thaw status at sites in the Canadian prairies in order to evaluate the practical efficacy of the method.

3.1 Near-Saturated peat soils

This first test of the accuracy of the interface model was a comparison of the interface model to the benchmarked continuum model simulates a near-saturated peat soil column with a soil porosity of 0.8. The bottom boundary was fixed at a temperature of 0.1 °C at a depth of 3 m, and the profile was initially treated as thawed below the base of the active layer. The surface boundary condition was drawn from field data collected in the Scotty Creek Research Basin (Quinton et al., 2019), and is consistent with soil surface temperatures of peat soils in a cold region. This data and details on model parameterization can be found in Devoie and Craig (2020), and specific peat soil characteristics are included in table 5.2 in the Appendix. As seen in figure 2, the model agreement is good with respect to water saturation, total integrated ice content (RMSE of 0.14 between ice content of interface and continuum models) and location of the freeze/thaw interface. The largest discernible discrepancy between the models being that the interface model freezes slightly deeper than the continuum model at the end of the freezing season (see figure 6), indicating that perhaps the assumption of a linear (equilibrium) temperature profile in the bottom-most layer may not be adequate to fully represent this model domain.

[Figure 2 about here.]

3.2 Unsaturated conditions

Many temperate mineral soils maintain a water table between 0.25 and 5 m from the ground surface (Fan et al., 2013). The interface model was therefore compared to the continuum model for unsaturated mineral soil conditions where the water table was initially at 2 m below the ground surface as seen in Figure 3. Specific mineral soil characteristics were drawn from Kurylyk et al. (2014), and are included in table 5.2 in the Appendix. Again, the agreement between continuum and interface model is generally of high quality, without the deeper freezing anomaly seen in the saturated peat soil test case, improving the RMSE between the ice content of the interface model and continuum model to 0.004. This improved agreement is likely due to the increased diffusivity of the soil matrix.

[Figure 3 about here.]

3.3 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 2.1. Figure 4 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 4 (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 2.3.1, and compares favourably with the reported freeze/thaw timing. The use of field data resulted in an increase in RMSE to 0.04, which is still excellent agreement. The simulation was re-run using finer discretization in the continuum model (shown in figure 5) to capture the exact timing of a specific freeze/thaw event.

[Figure 4 about here.]

[Figure 5 about here.]

The comparison of the interface and continuum model for the short-duration event in figure 5 was generated using the same model configuration as figure 4, but with finer spatial and temporal discretization of both models. The comparison of computational efficiency can also be established in figure 5 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 same size timestep and simulation setup. The model performance of the interface model is arguably better than the continuum model: when the spatial step of the continuum model is refined, it tends toward the interface model solution. Larger spatial steps lead to a lack of convergence in the continuum model, and smaller temporal discretization was computationally impractical. The interface model also shows better timing and more gradual and physical response to freeze/thaw events. Neither model captures the initial freezing event near day 7, likely due to the choice of freezing point depression (-0.005 $^\circ$ C) and the freezing range between 0 and -0.01 $^\circ$ 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.

3.4 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. 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 permitivity 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) sensitivity of the soil moisture probes used to collect the field data (Pardo Lara et al., 2021). 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” flag indicating residual water content only, these are assigned the same colours as the field data. Example results for the entire 5 year simulation at Kenaston site 3 are shown in figure 6, 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 6, the agreement is 92%, indicating that the 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.

[Figure 6 about here.]

4 Discussion

Figure 6 demonstrates agreement in the timing of broad seasonal events between the modelled data and data collected in the field, and figure 7 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 layer tend to occur sooner than in the measured data (Figure 7 & 8), perhaps due to an under-estimate of the water content (and hence effective heat capacity) of the soil, alternatively an under-estimate or mismatch of the depth of influence of soil water content on the measurements made in the field. These explanations are also supported by the tendency of the interface model to exit and enter the phase change state 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 7 and 8), 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 extent 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 7 about here.]

Figures 7 and 8 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 data. It is thought that this is due to the single freezing point depression that is assigned to the data. It is known that there is hysteresis in the freeze-thaw process, and that the freezing point is generally lower than the thawing point (Saberi & Meschke, 2021). This leads to more rapid modelled thaw as it is initiated at a colder temperature than would realistically be observed in the field. More work including hysteretic behaviour in freeze/thaw modelling is needed.

[Figure 8 about here.]

The small difference in freeze/thaw timing may also be driven by a mismatch in near-surface soil water content. The error in estimated soil water content may arise because an equilibrium soil moisture profile is implemented in the interface model, as detailed in Appendix 5.1. The equilibrium assumption was first established for near-saturated peat soils in which infiltration events were expected to be rapid due to the high hydraulic conductivity of these soils. The transition 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. This boundary condition was chosen for convergence reasons in the continuum model. Secondly, the quantity of interest is the frozen state of the near-surface soil. When freezing is occurring, 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.

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 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 hydrology of the system. Water movement in the landscape is expected to be much more strongly affected by the fully frozen 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 meaningful physically speaking, as there is evidence for the development of a surface layer symmetric to the buffer layer concept 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 9 about here.]

The interface model is notably better at representing early fall freezing events (Figure 9) which are of much higher hydrological importance as the underlying soil is ice-free and the surface ice layer has the greatest impact on runoff partitioning. These results are promising for their potential improvement to hydrologic modelling.

5 Conclusion

An interface model is presented that simulates 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.

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Figure 1. Schematic diagram showing model domain. Interface model tracks the buffer layer (where fractional ice content is permitted) and the interface between frozen and thawed soil. The water table is also computed separately and updated through an equilibrium mass balance.

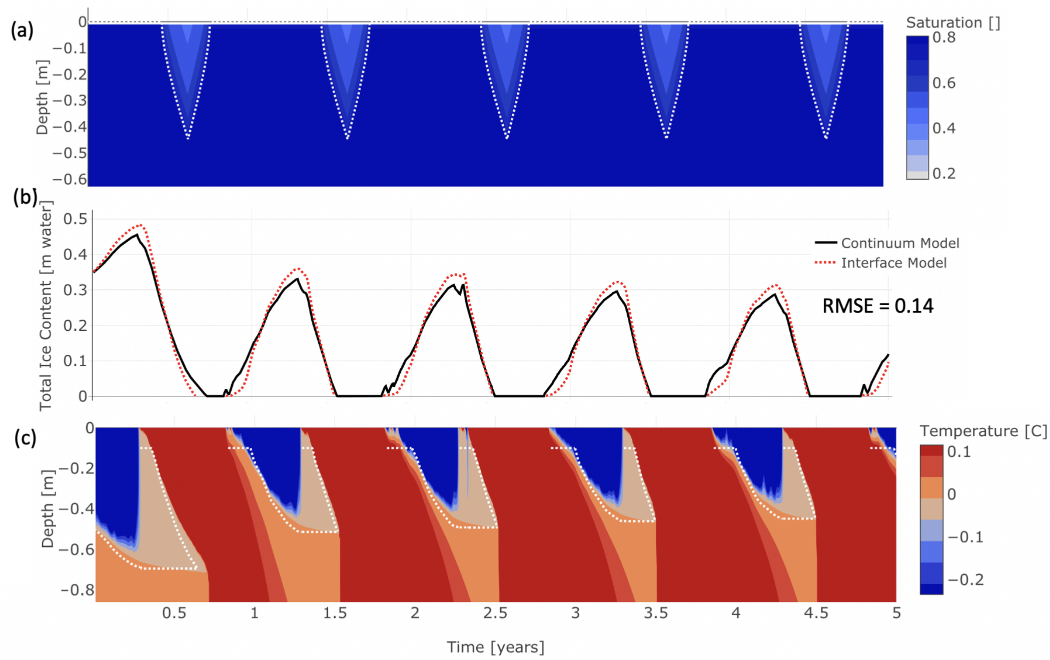

Figure 2. (a) Contour plot of continuum model saturation with water table position of interface model superimposed; (b) comparison of total ice content for each model and (c) contour plot of continuum model temperature with interface position (dashed white line) superimposed.

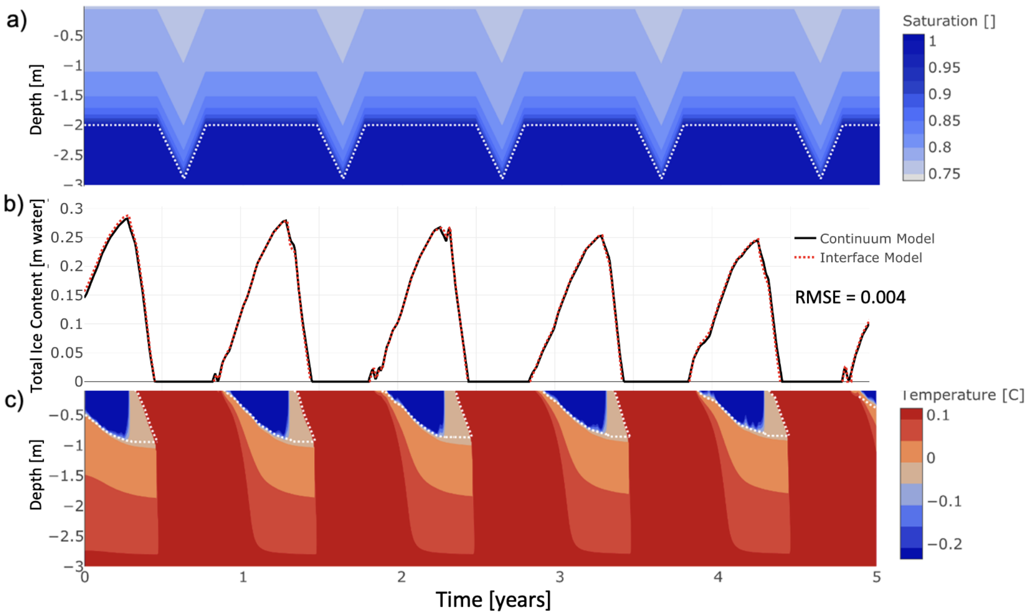

Figure 3. (a) Contour plot of continuum model saturation with water table position of interface model superimposed for mineral soils (b) comparison of total ice content for each model and (c) contour plot of continuum model temperature with interface position superimposed all for mineral soils. Depths are relative to the ground surface.

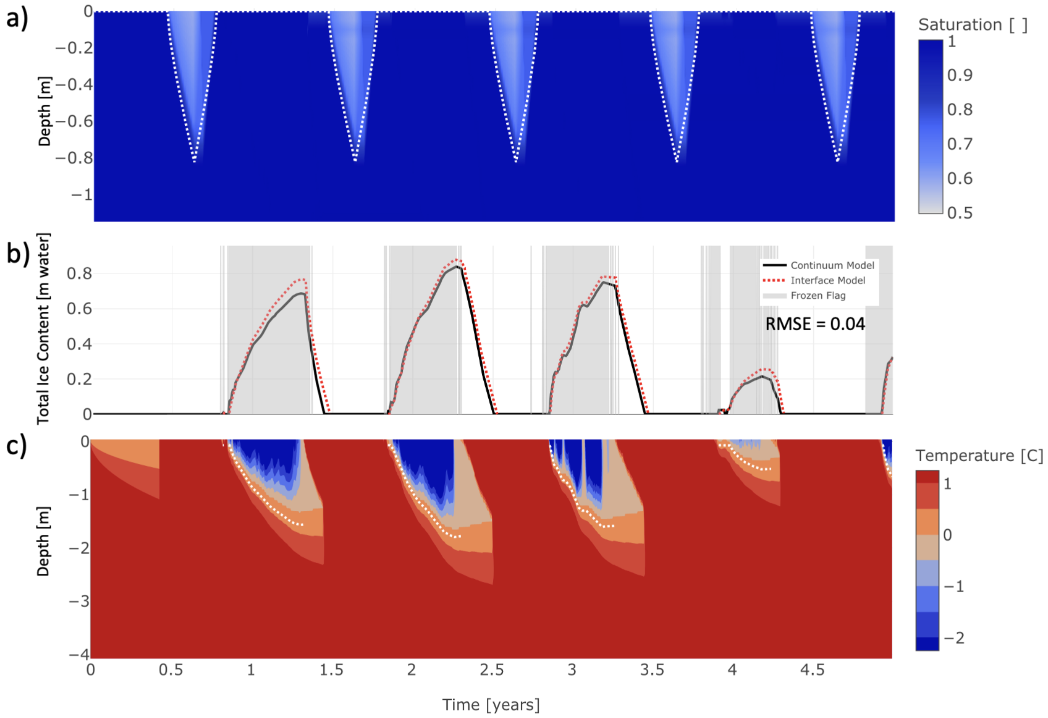

Figure 4. (a) Comparison of water content for interface and continuum model (b) comparison of total ice content for continuum model (black), interface model (red) and field-based near-surface frozen flag (shaded grey) and (c) contour plot of continuum model temperature with freeze/thaw interface position from interface model superimposed. 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 5.2 of Appendix

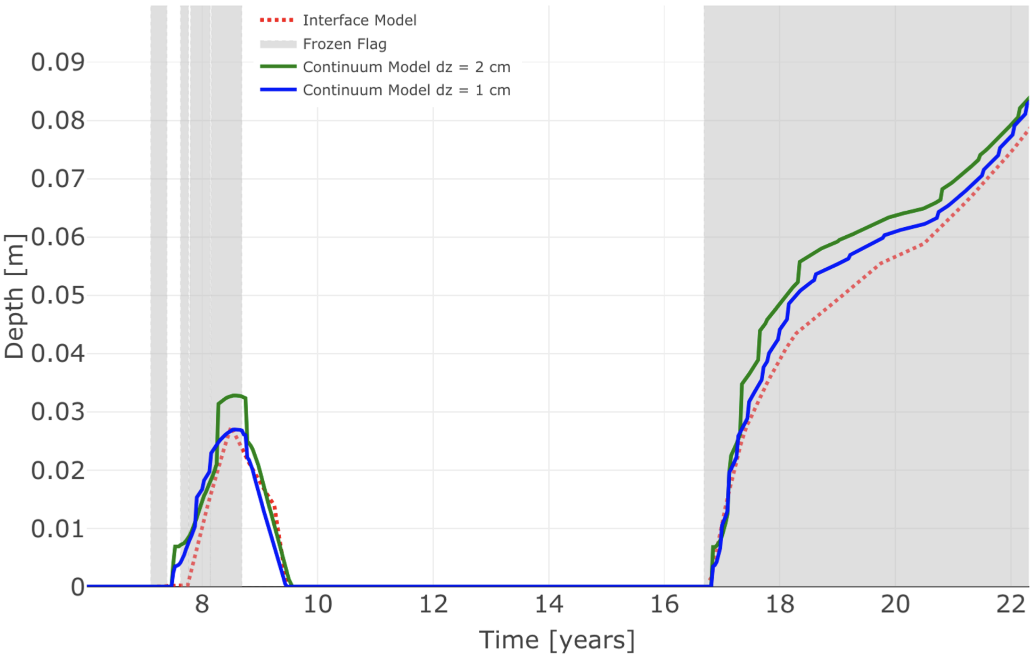

Figure 5. Short duration freeze/thaw initiation. Comparison of interface model (with 6 hour timesteps) to continuum model with varying timesteps. This short duration initiation of freezing results in a small quantity of near-surface ice, hence the small total ice content. Simulation duration for continuum model with 1 cm spatial discretization was 2 hours and 22 minutes, while the interfqce model ran in 4.5s. Continuum model does not converge for larger spatial or temporal steps than those shown. Grey shaded region indicates soil freezing according to the field-data based flag. Soil texture data drawn form Kenaston Site 1 in table 5.2 of Appendix

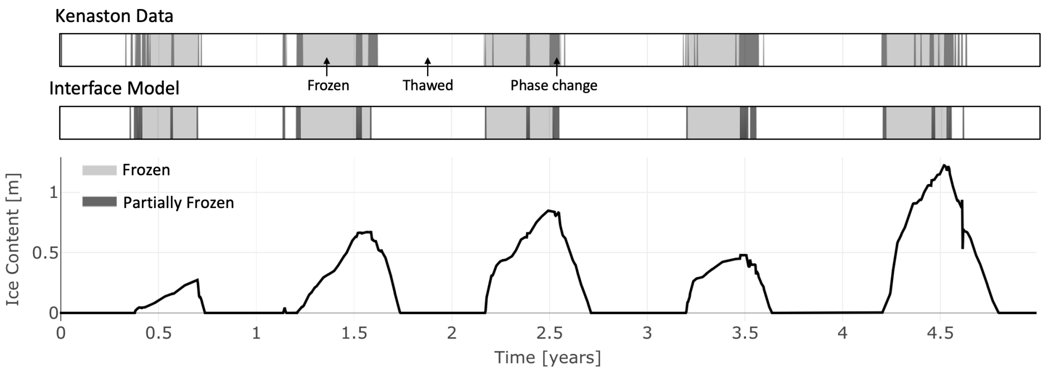

Figure 6. Comparison of Kenaston field-data and interface model generated near-surface ice content indicating phase change (dark grey) and frozen soil (light grey). Total ice content from interface model shown along bottom axis. Soil texture data drawn form Kenaston Site 3 in table 5.2 of Appendix

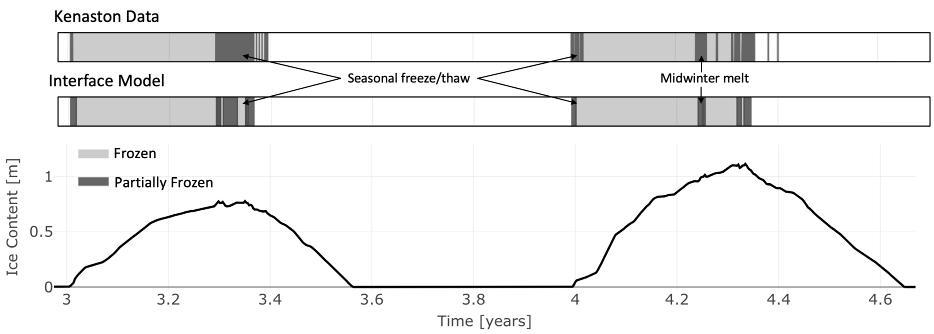

Figure 7. Comparison of Kenaston field-data and interface model generated near-surface ice content indicating phase change (dark grey) and frozen soil (light grey). This 2 year subset from 5 year simulation drawn from Kenaston site 15. Seasonal freeze thaw at the near surface occurs in fall and early 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.

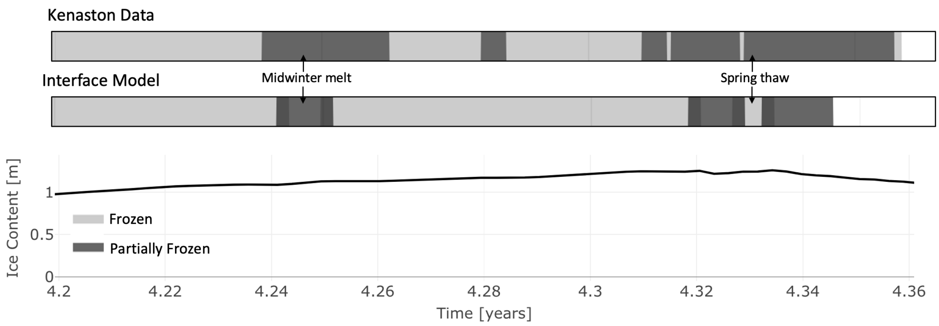

Figure 8. Comparison of Kenaston field-data and interface model generated near-surface ice content indicating phase change (dark grey) and frozen soil (light grey). Interface model phase change takes less time, perhaps because of an under-estimate of the freezing point. Overall agreement between the 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.

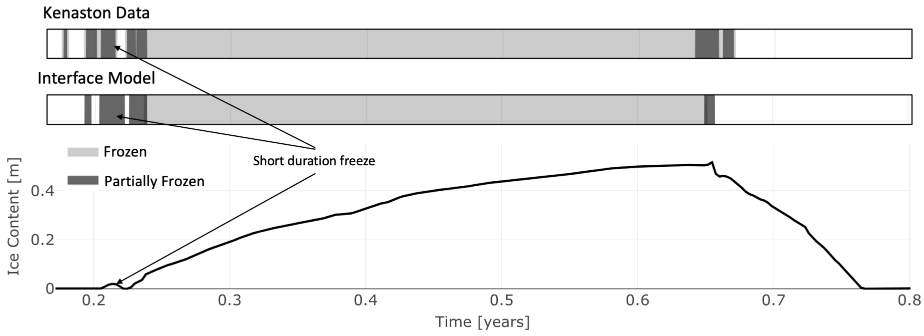

Figure 9. Early season short-duration freeze/thaw event comparison between field-data and interface-model generated freeze/thaw. The overall agreement between freeze/thaw states was 95%, while the interface model correctly identified 96% of the frozen period. Single year of data drawn from 5 year simulation of Kenaston site 10.