Supplementary Material for

Development of perennial thaw zones in boreal hillslopes enhances potential mobilization of permafrost carbon

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Contents of this file: Text S1; Additional references; Figures S1- S3**;** Tables S1, S2, and S3

Introduction

In this document, we provide details on the model construction (Figure S1, Table S1), model simulation/scenarios tested (Table S2) and select model results (Figure S2, Figure S3, Table S3) not included in the main text.

Text S1.

Various model simulations are described in Table S2. “High mineral soil k” and “low mineral soil k” showcase the influence of (thawed) permeability (k) by varying k an order of magnitude higher and lower than the basecase. Likewise, “high slope” and “low slope” incorporate ground slopes of 0.1 and 0.01 compared with the basecase 0.05 slope. The thickness of the organic layer (OL) was varied, which affects both thermal and hydraulic property configuration among the simulations.

Model results shown in Figure S2 demonstrate the importance of organic layer thickness to thaw vulnerability (a-c) and the resulting changes through time in seasonal groundwater discharge from the modeled hillslopes in response to thaw development. Though increased organic layer thickness reduces the rate of thaw and perennial thaw zone development, the higher permeability of the organic soil relative to the mineral soil results the in greatest groundwater discharge in the thick organic soil case. These results are also reflected in Figure 2 of the main text that displays annual groundwater discharge through time for five simulations, including the no organic layer and thick organic layer cases.

Model results shown in Figure S3 demonstrate the importance of the organic layer thickness to thaw vulnerability in cases where the mineral soil permeability (k) is an order of magnitude greater than the basecase. The non-parallel configuration of the PTZ that develops in settings with high mineral soil k compared with the hillslope-parallel PTZ for the basecase reflects the influence of advective heat transport in high permeability substrate.

Model presented in Table S3 and in addition to those presented in the main text confirm that variants on the thermal parameters (n-factors, organic layer thickness) have the greatest effect on permafrost thaw rates and development of perennial thaw zones, whereas hydraulic parameters (slope, mineral soil permeability) have minimal effect. However, hydraulic parameters do exert substantial control on groundwater discharge.

Additional references

All references provided in the supplemental material are listed in the reference list of the main text with the exception of:

Beringer J, Lynch A H, Chapin F S III, Mack M, and Bonan G B 2001 The representation of arctic soils in the land surface model: the importance of mosses J. Climate 14 3324-3335

French H M 2007 The Periglacial Environment, Third Edition, John Wiley & Sons

Hinzman L, Kane D L, Gieck R E, and Everett K R 1991 Hydrologic and thermal properties in the active layer in the Alaskan Arctic Cold Regions Sci. Techol. 19 95-110

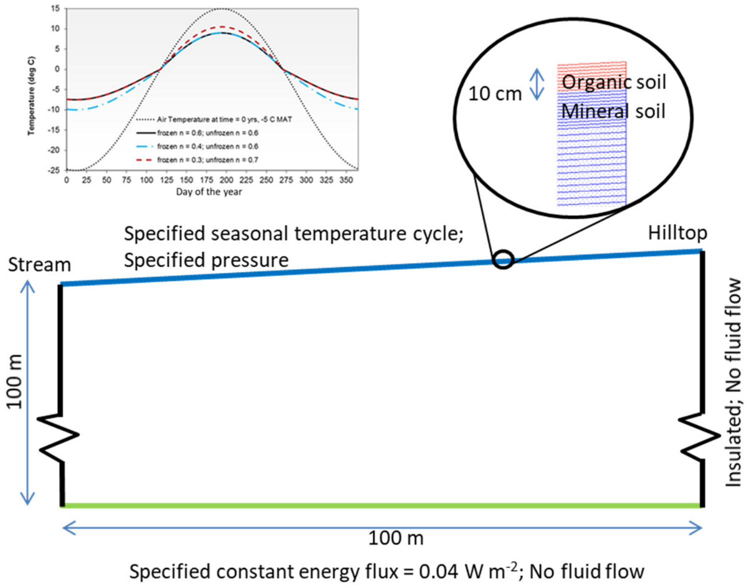

Figure S1. Model geometry and boundary conditions.

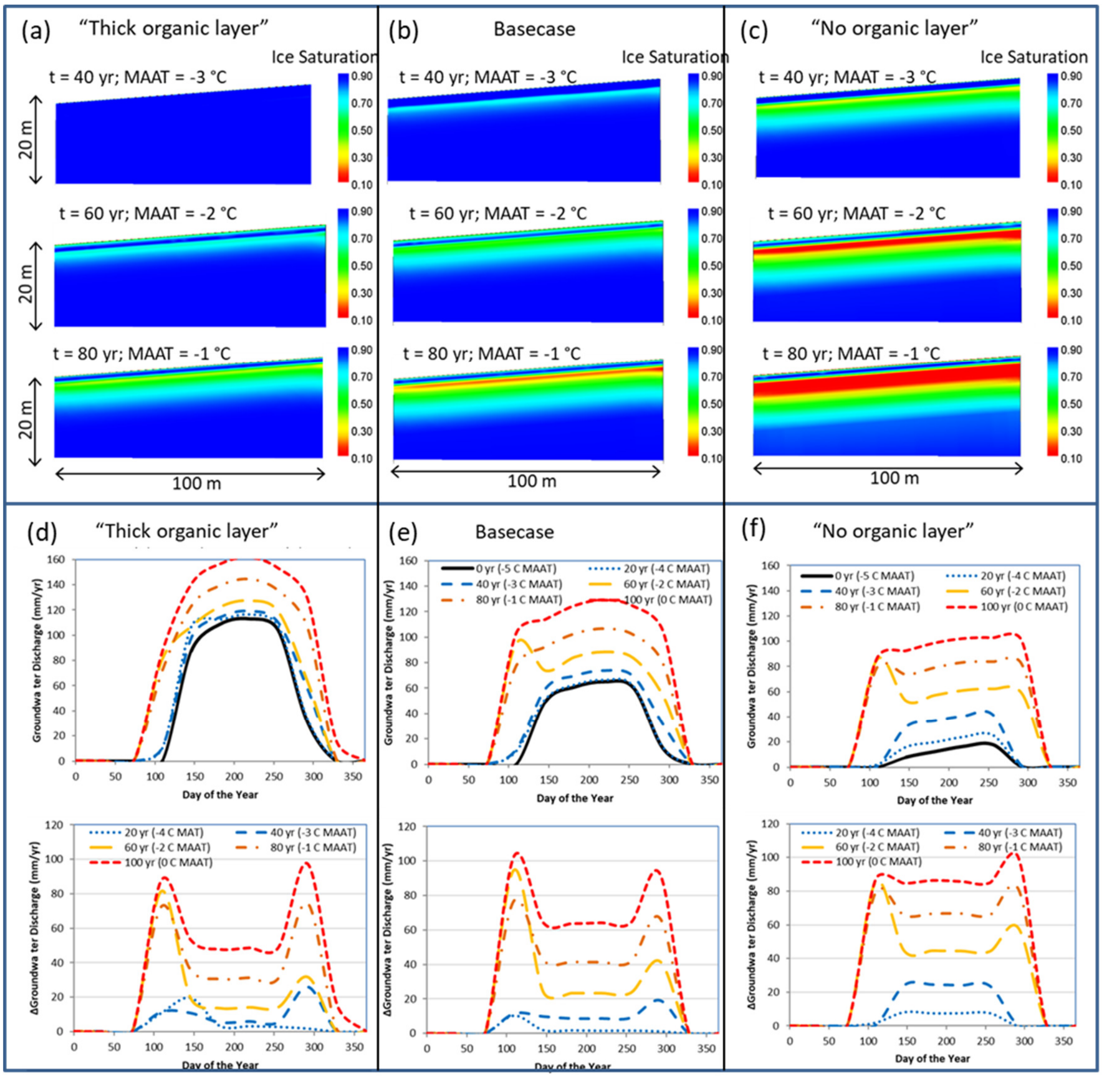

Figure S2. Cross-sectional model results for ice saturation at maximum frozen conditions at t = 40, 60, and 80 years for (a) thick organic layer, (b) basecase, and (c) no organic layer cases. Seasonal groundwater discharge (baseflow) results at 20-yr intervals are shown for (d) thick organic layer, (e) basecase, and (f) no organic layers cases. Bottom graphs in d-f display differences in groundwater discharge from t = 0 years. Day 1 of the year = January 1.

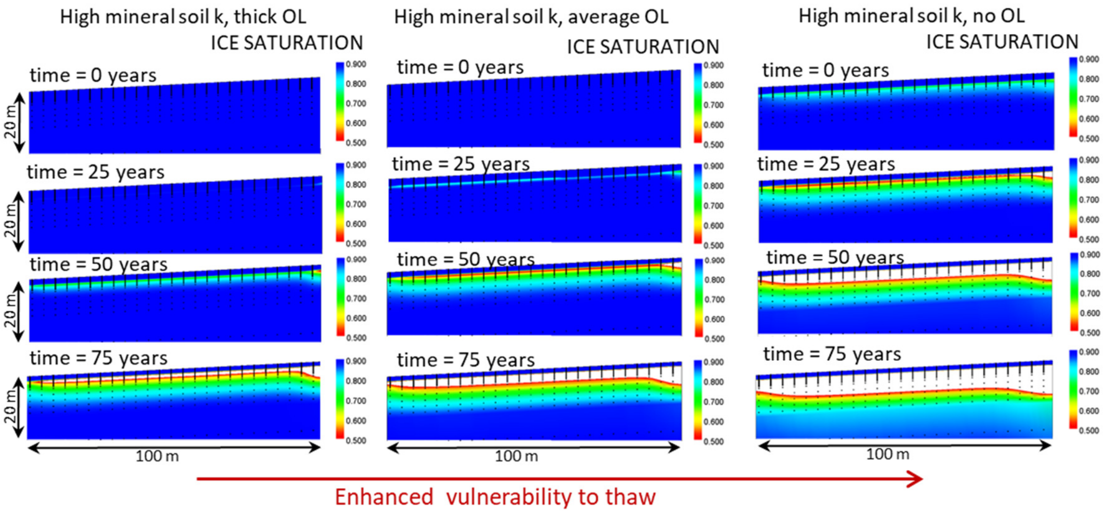

Figure S3. Cross-sectional model results of ice saturation at maximum frozen conditions for “High mineral soil k, thick OL” (left), “High mineral soil k, average OL” (center), “High mineral soil k, no OL” (right) at t = 0, 25, 50, and 75 years. Regions in white indicate conditions in which ice saturation is < 0.5 thus indicative of a perennial thaw zone at the 0.5 liquid saturation threshold.

Table S1. Model description and parameter values used in SUTRA simulations

General parameters	**Value**	**Reference/Notes**
Ice specific heat (J kg^{-1})	2,108	McKenzie and Voss, 2013; Wellman et al., 2013
Liquid water specific heat (J kg^{-1})	4,182	McKenzie and Voss, 2013; Wellman et al., 2013
Ice thermal conductivity (Js^{-1} m^{-1} °C^{-1})	2.14	French, 2007
Liquid water thermal conductivity (Js^{-1}m^{-1} °C^{-1})	0.6	French, 2007
Ice density (kg m^{-3})	920	McKenzie and Voss, 2013; Wellman et al., 2013
Liquid water density at 20 °C (kg m^{-3})	1000	McKenzie and Voss, 2013; Wellman et al., 2013
Solid grain density (kg m^{-3})	2600	Wellman et al., 2013
Latent heat of fusion (J kg^{-1})	334,000	Wellman et al., 2013
Freezing function	linear	McKenzie and Voss, 2013
Minimum liquid saturation	0.1	Kurylyk et al., 2016
Temperature at which minimum liquid sat occurs	-1.0	Wellman et al., 2013
Relative permeability function	linear	McKenzie and Voss, 2013
Liquid saturation at which minimum relative permeability occurs	0.1	Kurylyk et al., 2016
Minimum relative permeability	10^{-5}	model results insensitive to values < 10^{-4}
Model discretization	**Value**	**Reference/Notes**
Horizontal distance, x, (m)	100	
Vertical distance, z, (m)	100-110	depends on slope
Slope	0.01-0.1	0.05 for the Basecase
Horizontal node spacing (m)	1	results for 0.1-m node spacing were comparable
Vertical node spacing (m)	0.05-10	0.05 to 1 m in upper 20 m; 10 m spacing below
Timestep (yr)	0.01	results for 0.001-yr timesteps were comparable
Solver for pressure solution	iterative	IC-preconditioned conjugate gradient
Solver for temperature solution	iterative	ILU-preconditioned conjugate gradient

Table S1. Model description and parameter values used in SUTRA simulations (continued)

Organic soil thermal and hydraulic properties	**Value**	**Reference/Notes**
Solid grain specific heat (J kg^{-1} $°C^{-1}$)	1880	Engineering Toolbox online http://www.engineeringtoolbox.com/specific-heat-capacity-d_391.html
Solid grain thermal conductivity (J $s^{-1}m^{-1}$ $°C^{-1}$)	0.25	Beringer et al., 2001; Kurylyk et al., 2016
Porosity	0.7	Hinzman et al., 1991; Beringer et al., 2001
Permeability, k, (m^2)	5 x 10^{-12}	Hinzman et al., 1991; Beringer et al., 2001
Anisotropy (k_x/k_z)	1	no anisotropy
Mineral soil thermal and hydraulic properties	**Value**	**Reference and Notes**
Solid grain specific heat (J kg^{-1})	840	Wellman et al., 2013
Solid grain density (kg m^{-3})	2600	Wellman et al., 2013
Solid grain thermal conductivity ($Js^{-1}m^{-1}$ $°C^{-1}$)	3.5	Beringer et al., 2001
Porosity	0.4	Beringer et al., 2001
Permeability, k, (m^2)	10^{-13}- 10^{-11}	10^{-12} for Basecase (typical silty sand)
Anisotropy (k_x/k_z)	1	no anisotropy

Table S2. Description of model simulations presented in the main text (first five rows) and in the supplemental material (remaining rows). Variations from the basecase parameters are shaded in grey. k = permeability; OL = organic layer

Model simulation/scenario	**Organic layer thickness (m)**	**Mineral soil permeability (m^2)**	**Slope**	**n_F**	**n_{UF}**
Basecase	0.1	10^{-12}	0.05	0.3	0.6
Reduced snow	0.1	10^{-12}	0.05	0.4	0.6
Reduced shading	0.1	10^{-12}	0.05	0.3	0.7
Thick organic layer	0.2	10^{-12}	0.05	0.3	0.6
No organic layer	0.0	10^{-12}	0.05	0.3	0.6
Low slope	0.1	10^{-12}	0.01	0.3	0.6
High slope	0.1	10^{-12}	0.1	0.3	0.6
Low mineral soil k	0.1	10^{-13}	0.05	0.3	0.6
High mineral soil k, average OL	0.1	10^{-11}	0.05	0.3	0.6
High mineral soil k, thick OL	0.2	10^{-11}	0.05	0.3	0.6
High mineral soil k, no OL	0.0	10^{-11}	0.05	0.3	0.6

Table S3 Supplemental model results. GW = Groundwater; PTZ = perennial thaw zone; NA = not applicable.

Model	**Time (yrs)**	**GW discharge (mm yr^{-1})**	**Depth to permafrost (m)**	**Depth to PTZ top (m)** ***>0.3 perennial liquid saturation criteria***	**Depth to PTZ base (m)** ***>0.3 perennial liquid saturation criteria***	**Depth to PTZ top (m)** ***>0.5 perennial liquid saturation criteria***	**Depth to PTZ base (m)** ***>0.5 perennial liquid saturation criteria***
Thick Organic Layer	0	45	0.95	NA	NA	NA	NA
	20	49	1.10	NA	NA	NA	NA
	40	51	1.25	NA	NA	NA	NA
	60	62	1.40	NA	NA	NA	NA
	80	72	1.70	1.4	5.5	2.1	2.9
	100	85	2.10	1.2	8.5	1.5	5
No Organic Layer	0	6	1.5	NA	NA	NA	NA
	20	9	1.65	NA	NA	NA	NA
	40	15	2.0	1.7	6.5	2.4	3.4
	60	38	2.9	1.55	9.0	1.7	6.0
	80	48	4.5	1.45	11.0	1.6	8.0
	100	58	7.0	1.35	13.0	1.55	10.0
Low slope	0	5	1.2	NA	NA	NA	NA
	20	5	1.3	NA	NA	NA	NA
	40	6	1.4	NA	NA	NA	NA
	60	9	1.7	1.7	4.5	NA	NA
	80	11	2.1	1.4	8.0	1.7	4.5
	100	14	3.6	1.3	10.0	1.5	7.0
High slope	0	50	1.3	NA	NA	NA	NA
	20	54	1.4	NA	NA	NA	NA
	40	65	1.5	NA	NA	NA	NA
	60	99	1.8	1.6	5.5	NA	NA
	80	115	2.5	1.4	8.0	1.6	5.0
	100	143	3.9	1.3	10.5	1.45	7.5

Model	**Time (yrs)**	**GW discharge (mm yr^{-1})**	**Depth to permafrost (m)**	**Depth to PTZ top (m) *>0.3 perennial liquid saturation criteria***	**Depth to PTZ base (m) *>0.3 perennial liquid saturation criteria***	**Depth to PTZ top (m) *>0.5 perennial liquid saturation criteria***	**Depth to PTZ base (m) *>0.5 perennial liquid saturation criteria***
Low mineral soil k	0	21	1.2	NA	NA	NA	NA
	20	23	1.3	NA	NA	NA	NA
	40	24	1.4	NA	NA	NA	NA
	60	30	1.7	1.7	5.0	NA	NA
	80	31	2.3	1.4	7.5	1.7	4.5
	100	34	3.7	1.3	10.0	1.5	7.0
High mineral soil k, average OL	0	59	1.2	NA	NA	NA	NA
	20	64	1.3	NA	NA	NA	NA
	40	104	1.5	NA	NA	NA	NA
	60	202	1.8	1.7	5.0	NA	NA
	80	307	2.3	1.4	8.0	1.6	5.0
	100	433	3.7	1.3	10	1.5	7.0
High mineral soil k, thick OL	0	68	0.95	NA	NA	NA	NA
	20	75	1.05	NA	NA	NA	NA
	40	91	1.15	NA	NA	NA	NA
	60	151	1.3	NA	NA	NA	NA
	80	237	1.65	1.4	5.5	2.1	2.7
	100	341	2.1	1.2	8.0	1.45	6.0
High mineral soil k, no OL	0	61	1.5	NA	NA	NA	NA
	20	100	1.7	NA	NA	NA	NA
	40	157	2.1	1.8	6.5	2.3	3.6
	60	357	3.1	1.55	9.0	1.7	6.0
	80	480	4.5	1.45	11.5	1.6	8.5
	100	602	6.5	1.35	13.0	1.55	10