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Supplementary Material For: New permafrost is forming around shrinking Arctic lakes, but will it last?

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Introduction

This supplemental material includes: 1. text describing numerical modeling initial conditions, 2 table of model thermal parameters, 3. auxiliary figures and captions, and 4. animations of numerical modeling results. Items 1, 2, and 3 are included within this document, while the animations (4) are separate in .mov format, but descriptions of their content are listed at the end of this document.

Initial Model Condition Sensitivity Testing:

Models were tested for sensitivity to initial conditions by varying temperature and water table boundary. Model initial conditions were varied from fully to partially saturated, and warm to completely frozen. Initial conditions did not substantially affect subsequent ambient model temperatures after a few years, except in the fully saturated frozen model (constant -4 ◦C upper boundary), as the thick sequence of ice at depth required >40 yr to thaw. We know this initial frozen-solid condition to be unrealistic, as the airborne electromagnetic surveys showed an open-talik beneath Twelvemile Lake, Alaska.

Supplemental Table 1. Thermo-physical characteristics of liquid, ice, and solid matrix used for model simulations.

Ice Parameters	
Ice specific heat (J kg^{-1})	2,108
Ice thermal conductivity ($Js^{-1}m$-$1C^{-1}$)	2.14
Density of ice (kg m^{3})	920
Latent heat of fusion (J kg^{-1})	334,000
Liquid Water Parameters	
Fluid specific heat (J kg^{-1})	4,182
Fluid thermal conductivity ($Js^{-1}m^{-1}C^{-1}$)	0.6
Solid Matrix Parameters	
Solid grain specific heat (J kg^{-1})	840
Solid grain thermal conductivity ($Js^{-1}m^{-1}C^{-1}$)	1.0
Porosity	0.46

Supplemental Figures

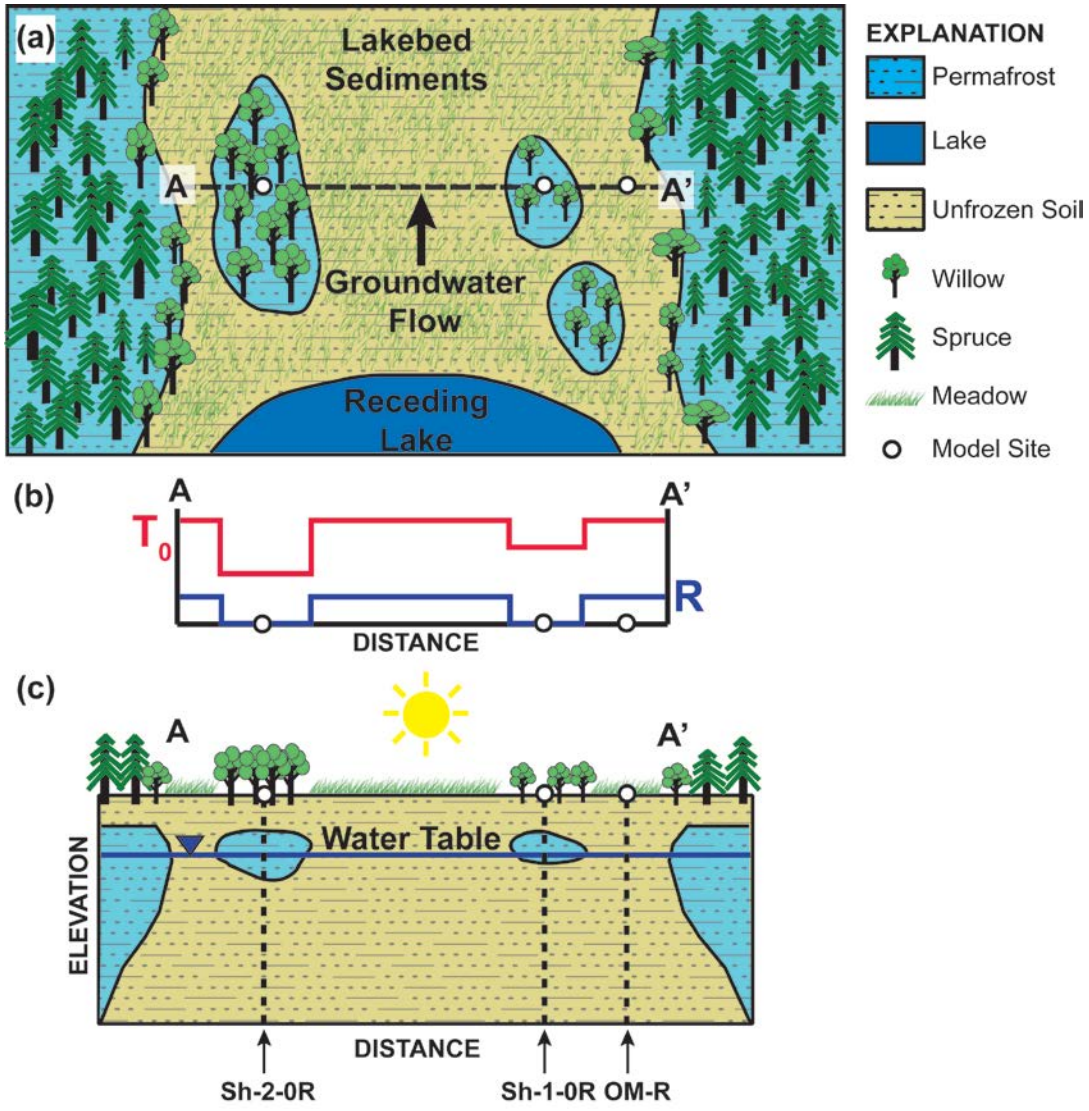

Figure 1. Supplemental Figure 1. A conceptual schematic of the study site within a dried lake boundary that shows the basic development of the numerical model framework to describe open-meadow and shrub-impacted conditions. (a) The plan view of the conceptual model, corresponding to the field photo in Figure 1B, shows discrete permafrost aggradation collocated with willow shrub as it develops within the dried lake margin; much thicker, older contiguous permafrost is found above the original lake level and overlain by spruce forest; (b) general summer temperature and recharge boundaries that coincide with various levels of shrub model shading (eg Sh-1 vs Sh-2) and the open meadow (no shading); (c) a cross section of the transect shown in (a), representing data presented in Figure 1C, shows discrete islands of permafrost forming in response to both magnitudes of shrub shading, though thicker permafrost that extends deeper into the saturated zone was found with the Sh-2-0R model, or "strongest" shrub effect.

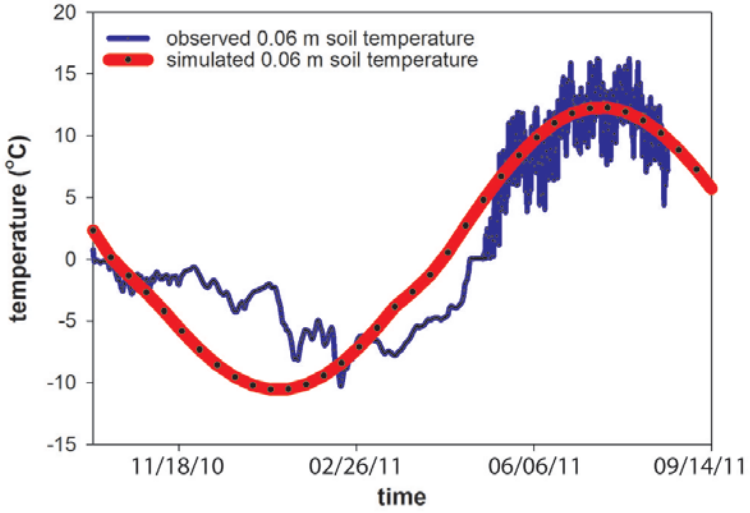

Figure 2. Supplemental Figure 2. The base open-meadow simulation (OM-R) thermal boundary was designed to reflect historical local conditions, and reproduces the cold winter maximum and summer thermal trend recorded in 2011 on the Twelvemile Lake margin.

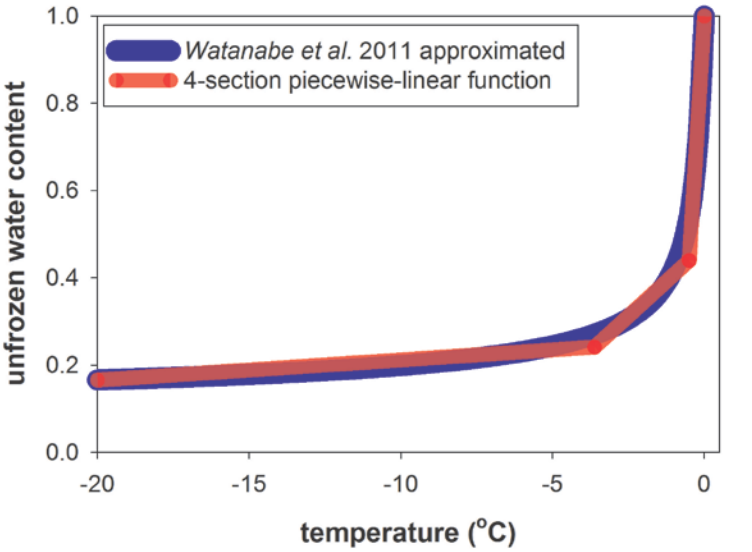

Figure 3. Supplemental Figure 3. Data collected by Watanabe et al. (2011) regarding the fraction of unfrozen water over a range of temperatures for “silt-loam” soils, such as those found at the Twelvemile Lake field site, is approximated here and extended to saturation then fit with a 4-section piecewise-linear function used for model simulations.

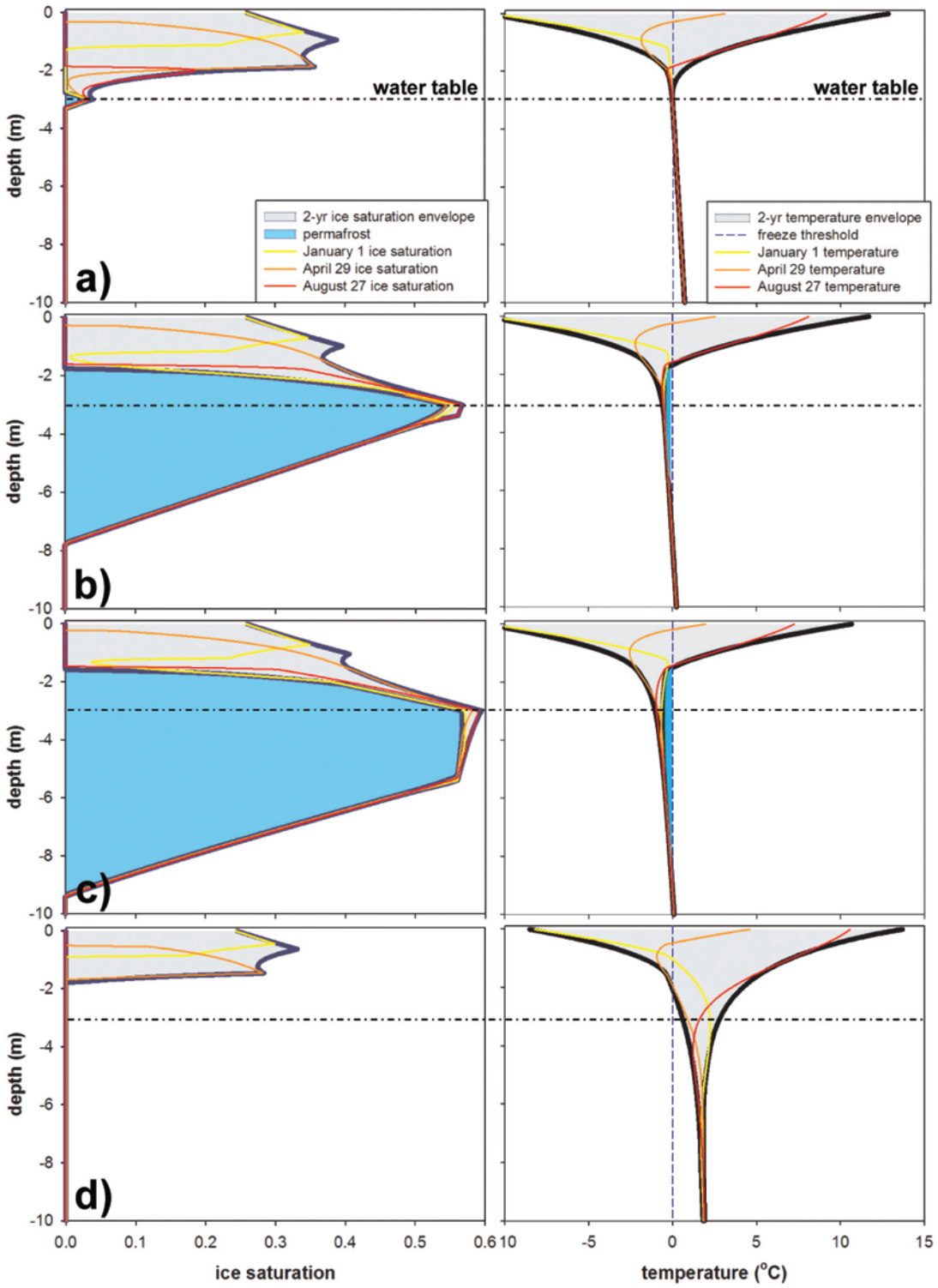

Figure 4. Supplemental Figure 4. Ice saturation and temperature envelopes encompassing annual variation (including 3 date-specific profiles) and aggraded permafrost ice saturation after 99 yr of simulation for models: (A) open-meadow (OM-R), (B) moderate shrub effect (Sh1-R), (C) strong shrub effect (Sh2-R), and (D) climate change (OM-CW); column 2 shows the corresponding 2-yr temperature envelopes.

Supplemental Animation Descriptions

Supplemental Video 1 (Sh1_0R):

This animation displays the 100-yr time lapse ice saturation for the simulation with 1◦C shading and zero summer recharge. The upper 5 m of the subsurface model domain are shown; the water table at -3 m is marked with the dashed line. Both panels show ice saturation through time, but the right-hand panel also illustrates the development of the ice saturation envelope, where the moving 2-yr range in ice saturation is shown in gray, specifying the range in ice saturation experienced at all depths as the simulation proceeds through annual freeze/thaw cycles. Ice content that lasts for at least 2 yr (permafrost) appears in magenta, shallow permafrost thickening and enhancement of ice saturation is notable throughout the simulation.

Supplemental Video 2 (Sh2_0R):

This animation displays the 100-yr time lapse ice saturation for the simulation with 2◦C shading and zero summer recharge, or the strongest vegetation effect considered. The upper 5 m of the subsurface model domain are shown; the water table at -3 m is marked with the dashed line. Both panels show ice saturation through time, but the right-hand panel also illustrates the development of the ice saturation envelope, where the moving 2-yr range in ice saturation is shown in gray, specifying the range in ice saturation experienced at all depths as the simulation proceeds through annual freeze/thaw cycles. Ice content that lasts for at least 2 yr (permafrost) appears in magenta, shallow permafrost thickening and enhancement of ice saturation is notably greater than for simulation Sh1_0R.

Supplemental Video 2 (Sh2_0R_CW):

This animation displays the 100-yr time lapse ice saturation for the simulation with 2◦C shading and zero summer recharge with climate warming of 3 ◦C/100 yr. The upper 5 m of the subsurface model domain are shown; the water table at -3 m is marked with the dashed line. Both panels show ice saturation through time, but the right-hand panel also illustrates the development of the ice saturation envelope, where the moving 2-yr range in ice saturation is shown in gray, specifying the range in ice saturation experienced at all depths as the simulation proceeds through annual freeze/thaw cycles. Ice content that lasts for at least 2 yr (permafrost) appears in magenta, shallow permafrost thickening and enhancement of ice saturation is initially similar to simulation Sh2_0R, but after 20 yr the simulations diverge, and by 69 yr all aggraded permafrost thaws, with a thinning of the annual active layer thereafter.