Soil subsidence associated with permafrost degradation in the Arctic

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Abstract

Arctic sources of greenhouse gas associated with permafrost degradation constitute a large uncertainty in existing climate models. Greenhouse gas release from the arctic subsurface is mediated by numerous interconnected physical processes; one facet of these is the interplay between surface deformation and melting of subsurface ice. We study this interplay via numerical modeling of subsidence due to post-thaw fluid drainage from an initially frozen, fluid saturated, porous, 2D matrix. We include an initially ice-rich zone by setting the porosity in a 6 x 20 m^2 rectangular shaped region near the surface to one and a half that of the surrounding medium (0.6 vs 0.4). With the surface temperature fixed at 5°C, a thaw front propagates to ≈10 m depth within 20 years, and drainage of fluid from the pore space leads to a zone of soil depressed by ≈3 meters above the initially ice-rich zone. Soil underlying this depressed zone may have its permeability reduced by between one and two orders of magnitude; this reduction in permeability can act as a negative feedback to thawing. In addition to these numerical results, an analytic model provides the porosity and permeability as functions of time in a 1D column, as well as a group of model parameters that determines a characteristic time scale for soil subsidence.

Motivation

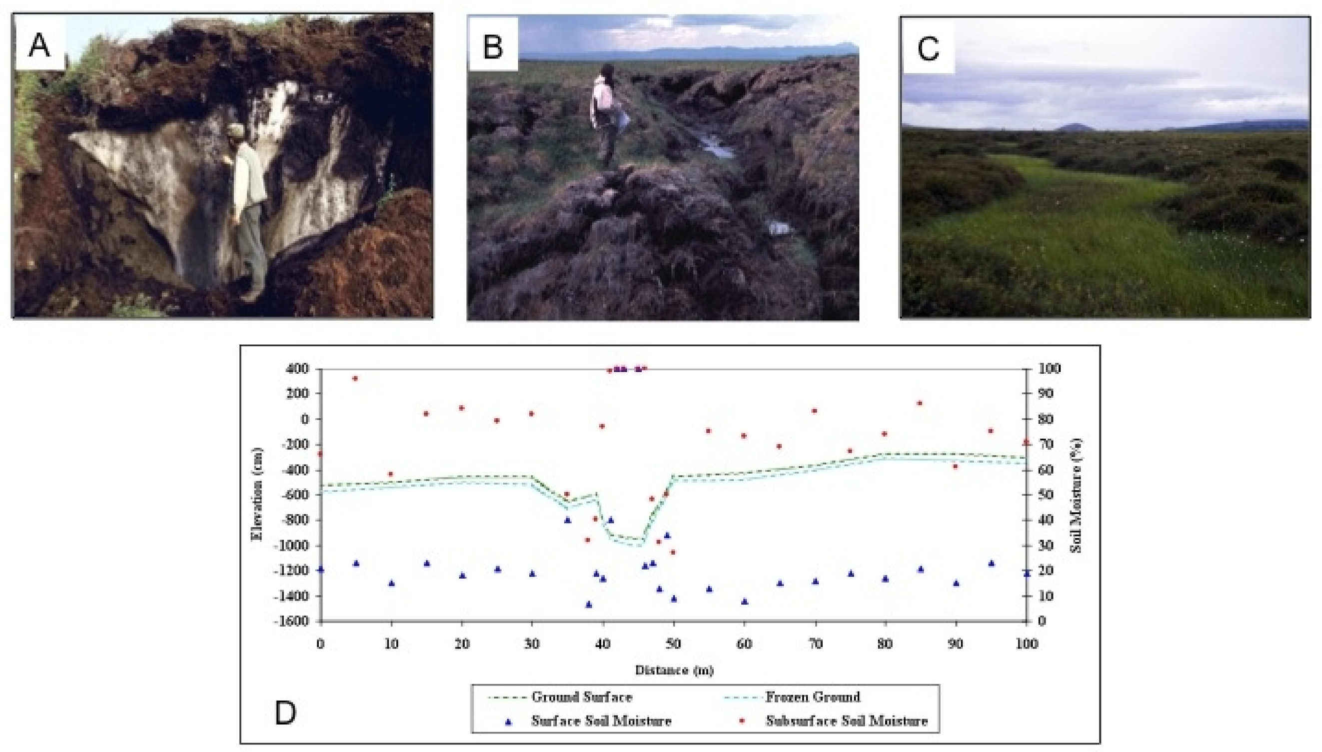

Figure 1: When massive ground ice and ice wedges (A) in permafrost melt the land surface deforms (B). This process, called thermokarst, drives changes in surface and subsurface hydrology (D), biogeochemistry and vegetation (C).

Ice model

We use the computational framework FEHM (Finite Element Heat and Mass Transfer) to generate numerical fluid flow solutions in this study. The equations of FEHM governing fluid flow require expressions for the density, enthalpy, and viscosity of each thermodynamic phase present in a mixture. Because the freezing curve for water has a steep slope in the thermodynamic regime of interest (i.e. -10 °C $< T <$ 5 °C, 0.1 MPa $< P <$ 0.5 MPa), we model the ice-liquid phase transition as a step function in T located at 0 °C. We approximate the step function as a hyperbolic tangent located between -0.25 and 0.25 °C. Fluid properties in the single phase regions are treated linearly as

$$\xi \approx \xi_{ref}(\alpha \Delta T + \beta \Delta P) \tag{1}$$

where ξ is density, enthalpy, or viscosity, ξ_{ref} is a reference value, and α and β are empirical constants representing respectively the rate of increase of ξ with increasing temperature and pressure. For temperatures between -0.25 and 0.25 °C, we interpolate between the endpoints by using the step function approximated as $tanh$.

Soil subsidence model

An initially frozen and fluid saturated soil column will collapse subsequent to thawing and fluid drainage if its elastic moduli fall below some minimum allowed thresholds. As an initial condition, we assume a saturated and frozen porous soil matrix with a thin outflow region located at depth. This region, hereafter referred to as the drainage face, is held at atmospheric pressure to allow fluid flow out of the system. The drainage face can be envisioned as a flow route that leads to the surface someplace outside of the system. As the soil is thawed from the top, ice within the pore space melts and fluid in the resulting melt layer leaves the system when it reaches the drainage face. We assume that the overlying thawed soil is weak enough to collapse continuously upon drainage. If all overlying fluid were to drain, steady state pressures in the soil column would be atmospheric and porosities would be at consolidated values. This consideration suggests modeling the soil collapse via the relation

$$\phi = \phi_{ref} - \gamma(p - p_{ref}) \tag{2}$$

where ϕ is the porosity, p is the pressure, and the subscript ref indicates reference values. The coefficient γ is spatially dependent, being set to force consistency between (2) and initial pressures and porosities. We employ a similar relation between the rock permeability k and the pressure. In addition to the effect encapsulated in (2), we include the volume change upon melting due to greater specific volume of ice compared to liquid water.

Geometry, boundary, and initial conditions

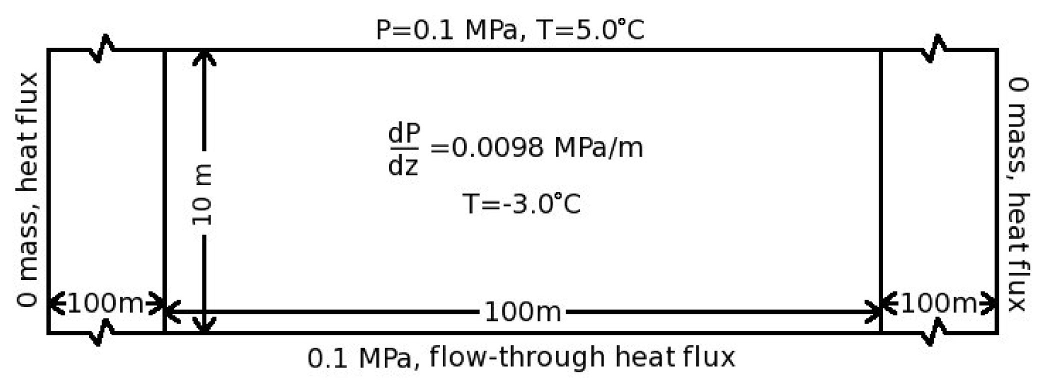

Figure 2: The system is assumed fully saturated, while the region of interest is the central 100 m. The total system is 300 m wide to minimize edge effects. The sides are set to allow zero fluid flow and heat transfer. Internal temperatures increase with depth at a rate of 0.0375 °C/m, consistent with an imposed basal heat flux of 0.0625 W/m^2.

Porosity structure

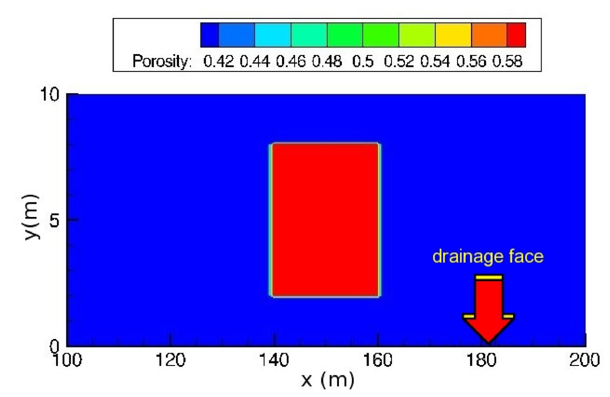

Figure 3: We model a central ice-rich region via a zone of heightened porosity in a fluid saturated porous medium. The pressure along the drainage face is held at atmospheric (0.1 MPa). Although the system is 2D, the drainage face allows fluid to exit the system via a plane perpendicular to that of the figure. We impose a constant 5°C heat source at the top boundary and allow the system to evolve for 20 years.

Simulation results

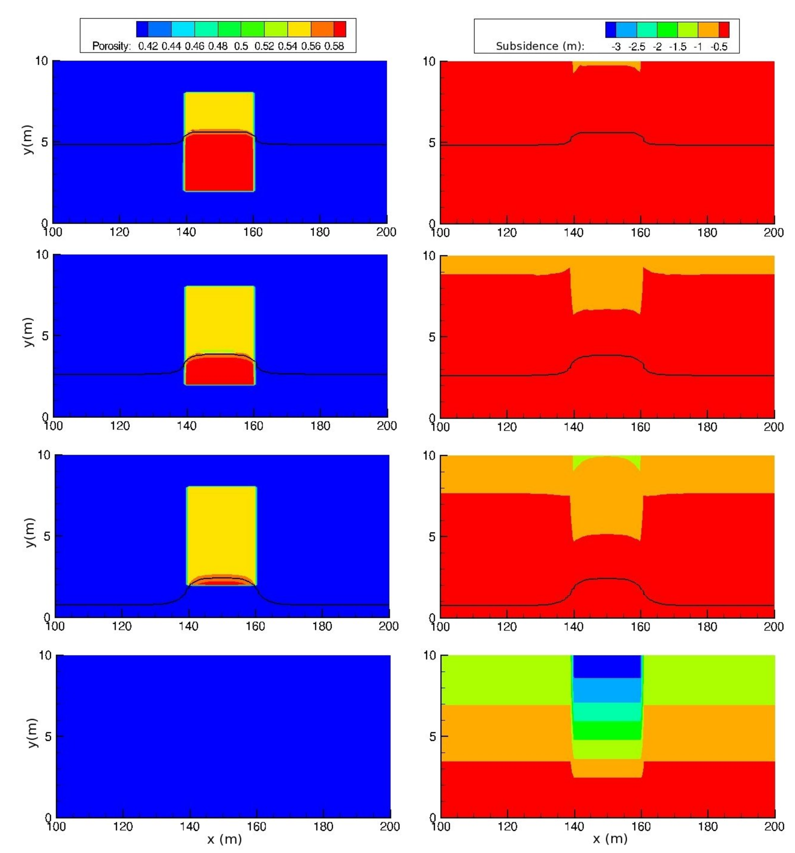

Figure 4: Porosity and subsidence (m) after 5, 10, 15, and 20 years (top to bottom) of simulation time.

Analytic model

For fluid of constant density in a 1D soil column, mass conservation is governed by

$$\frac{\partial \phi}{\partial t} - \frac{1}{\mu}\frac{\partial}{\partial z}\left(k\frac{\partial p}{\partial z}\right) + \frac{\rho g}{\mu}\frac{\partial k}{\partial z} = 0 \tag{3}$$

where k is the soil permeability, μ is the fluid dynamic viscosity, ρ is the fluid density, and g is the gravitational acceleration constant. Putting (2) and a similar expression relating k to p into (3) and nondimensionalizing yields

$$\frac{\partial \mathcal{P}}{\partial \tau} - (1+\epsilon)\frac{\partial^2 \mathcal{P}}{\partial \chi^2} - \epsilon\frac{\partial \mathcal{P}}{\partial \chi}\left(1 - \frac{\partial \mathcal{P}}{\partial \chi}\right) = 0 \tag{4}$$

where $\mathcal{P}$ is nondimensional pressure and ϵ is a small parameter when the dependence of k on p is weak. This equation can be solved via the method of regular perturbations, where the first order solution has a decay time proportional to

$$t_{subs} \propto \frac{\mu \gamma l^2}{k_{ref}} \tag{5}$$

where l is the distance between the surface and the drainage face. Equation 5 gives the characteristic time scale for soil subsidence, once all soil above the drainage face has been thawed.

Conclusions

Soil subsidence associated with post-thaw drainage of saturated frozen soils can be modeled assuming linear proportionality between porosity and pressure as well as between permeability and pressure. The resulting simulation results show a nontrivial surface subsidence profile. Furthermore, an analytic model can be used to calculate the time evolution of pressure, porosity, and permeability in a 1D column, and gives a first order characteristic post-thaw subsidence time scale.