Modeling reaction of non-sorted circles to changes in climate and vegetation cover

D. J Nicolsky[1], V. E. Romanovsky[1], G. S. Tipenko[1], D. A. Walker[2], R. Daanen[1], P.P. Overduin[3]

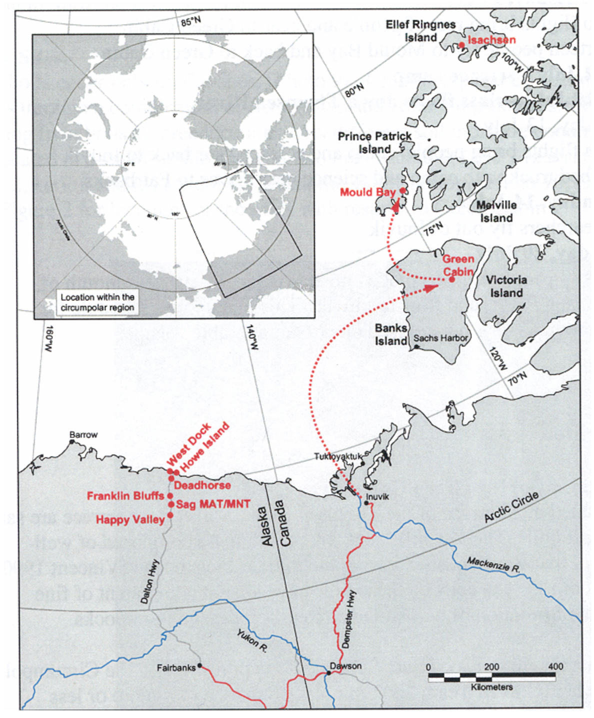
1. Permafrost Laboratory, Geophysical Institute, University of Alaska Fairbanks 2. Alaska Geobotany Center, Institute of Arctic Biology, University of Alaska Fairbanks, 3. Alfred Wegener Institute for Polar and Marine Research

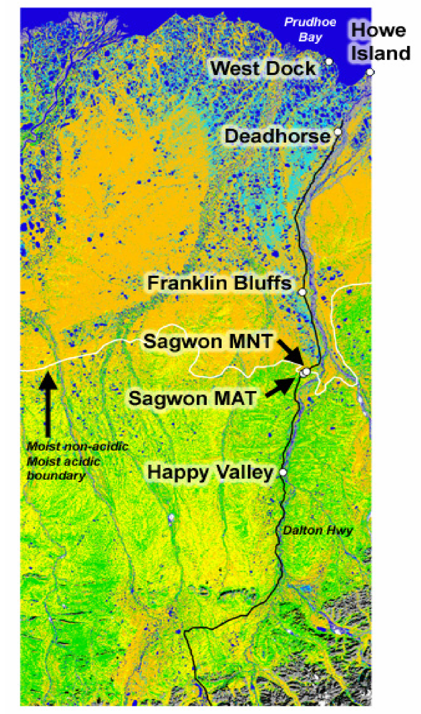
Abstract

We examine sensitivity of a general model of the frost boil dynamics with respect to changes in thermal, rheological and hydraulic properties of the ground material and boundary conditions. We apply the model to non-sorted circles along the low Arctic Climate gradient and investigate the seasonal dynamics of them. This investigation allows evaluation/detemination of physical mechanisms and driving forces that play the most decisive role in creating the differential frost heave in the non-sorted circles. Using this model we explore interactions between vegetation cover and thermo-mechanical processes. As the conclusion, we investigate the reaction of the non-sorted circles at several sites along the Dalton highway in the Arctic tundra in Alaska to changes in climate, in the active layer depth and in vegetation cover.

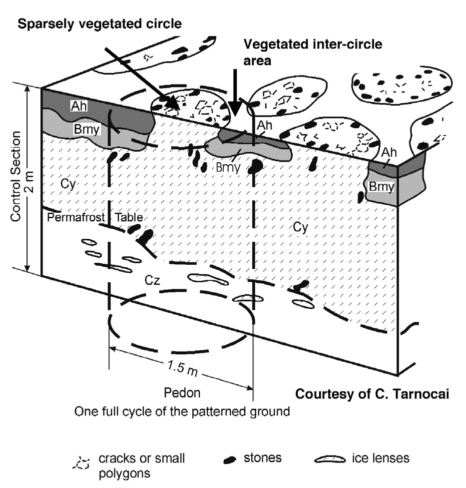
Frost boil: "a patterned ground form that is equidimensional in several directions with a dominantly circular outline which lacks a border of stones…" van Everdingen 1998

Area of study





Soil horizons



Non-sorted circles are defined as circular patterned ground features without a border of stones, usually with barren or sparsely vegetated central area 0.5 to 3.0 m in diameter.

[h]-A horizon enriched with organic matter.

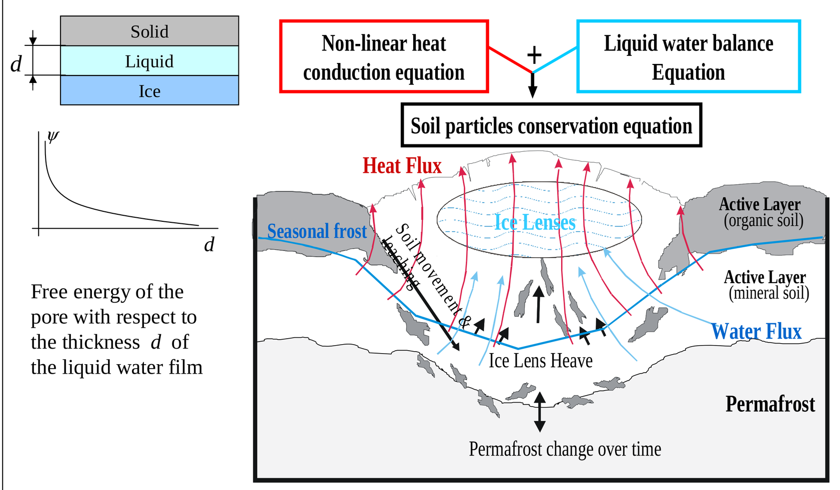
[m]-A horizon slightly altered by hydrolysis, oxidation, or solution, or all three to give a change in color or structure, or both.

[y]-A horizon affected by cryoturbation as manifested by disrupted and broken horizons, incorporation of materials from other horizons, and mechanical sorting in at least half of the cross section of the pedon.

[z]-A frozen layer.

The non-sorter circles occur on Turbic Cryosols.

Thermo-Mechanical Model of Non-sorted circles



Free energy of the pore with respect to the thickness d of the liquid water film

The model

Mass conservation law for the water and mineral skeleton components:

$$\frac{\partial n}{\partial t}-\nabla\cdot\left((1-n)\frac{\partial U}{\partial t}\right)=0 \qquad \theta_w+\theta_i=n$$

θ_w,θ_i – volumetric fraction of water and ice

n – porosity

Energy conservation principle for a multi-component system

$$C\frac{\partial T}{\partial t}-\rho_i L\frac{\partial \theta_i}{\partial t}-\rho_i L\nabla\cdot\left(\theta_i\frac{\partial U}{\partial t}\right)=\nabla\cdot(k\nabla T) \qquad \theta_w=\begin{cases} n & T\ge T_0\\ \min\left[n, n_e\left(\frac{T_0-T}{T_0-T_e}\right)^{-B}\right] & T<T_0\end{cases}$$

where the unfrozen water content θ_w is a function of temperature and porosity

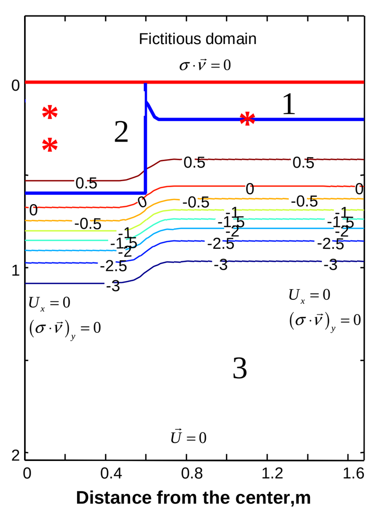
Liquid moisture conservation principle, derived from the generalized Darcy's law

$$-(1-\delta)\frac{\partial \theta_i}{\partial t}-\nabla\cdot\left(((1-\delta)\theta_i-1)\frac{\partial U}{\partial t}\right)=\nabla\cdot\left(k_f\left[\nabla\left(P+\rho_w\theta_w\frac{LT}{T_*}\frac{\partial f}{\partial \theta_w}\right)+\rho_w\frac{LT}{T_*}\nabla f\right]\right), \qquad \delta=\frac{\rho_i}{\rho_w}$$

Linear elasticity model is adopted for the soil

$$\nabla\cdot(\mu\nabla U)+\nabla((\lambda+\mu)\nabla\cdot U)=\nabla P$$

Computational geometry, boundary and initial conditions



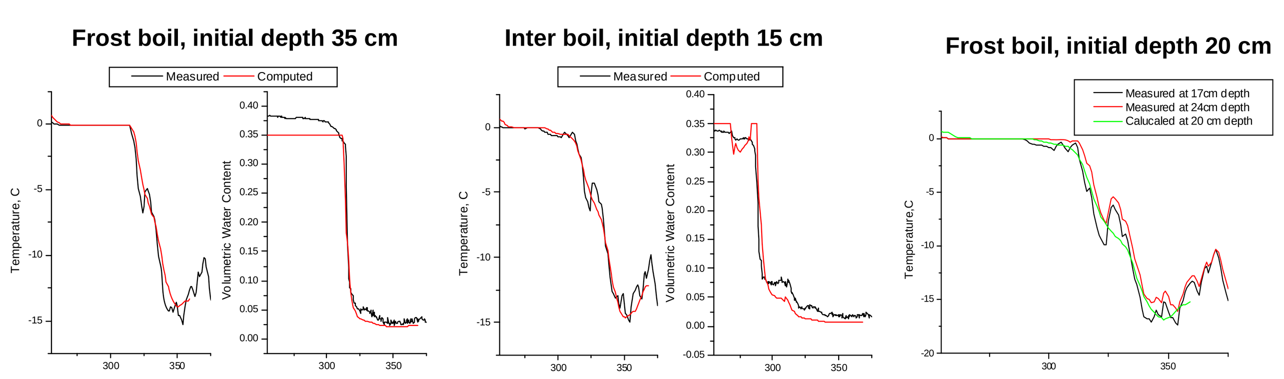
A fictitious domain is separated from a real one (soil) by a red line which plays a role of the ground surface.

* are points at which temperature and moisture are compared with experimental data.

The soil consists of three parts, namely, 1,2,3 which have common and distinctive properties.

Heat conduction coefficient		Young modulus	"Cryogenic Suction"
$\lambda_{1f}=0.8$	$\lambda_{1t}=0.4$	$E_1=2\cdot10^6$	$a_1=2\cdot10^{-5}$
$\lambda_{2f}=1.45$	$\lambda_{2t}=1.1$	$E_2=2\cdot10^6$	$a_2=2\cdot10^{-4}$
$\lambda_{3f}=1.45$	$\lambda_{3t}=1.1$	$E_3=20\cdot10^6$	$a_3=2\cdot10^{-4}$

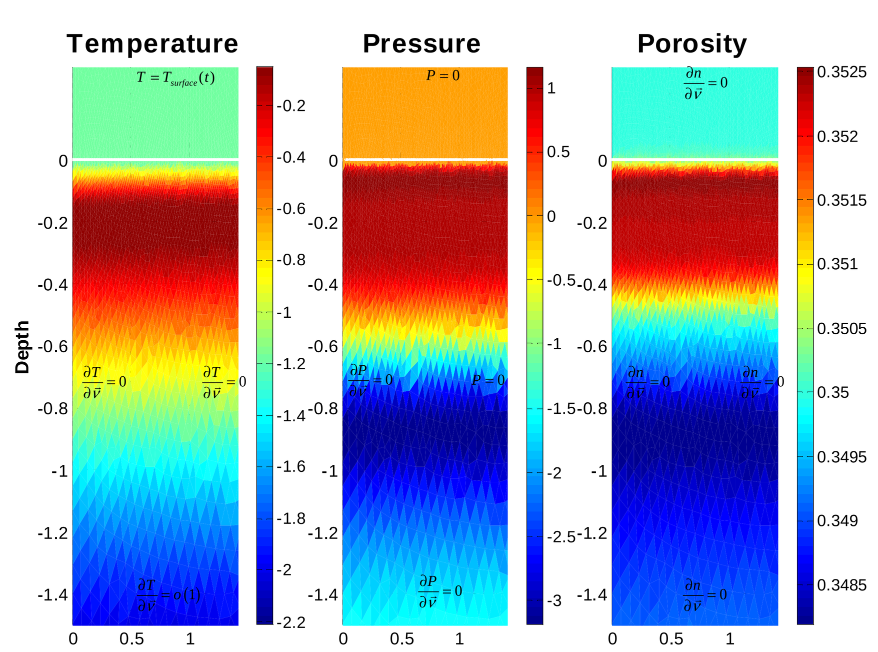
Measured and calculated temperature and water content at some points (*)



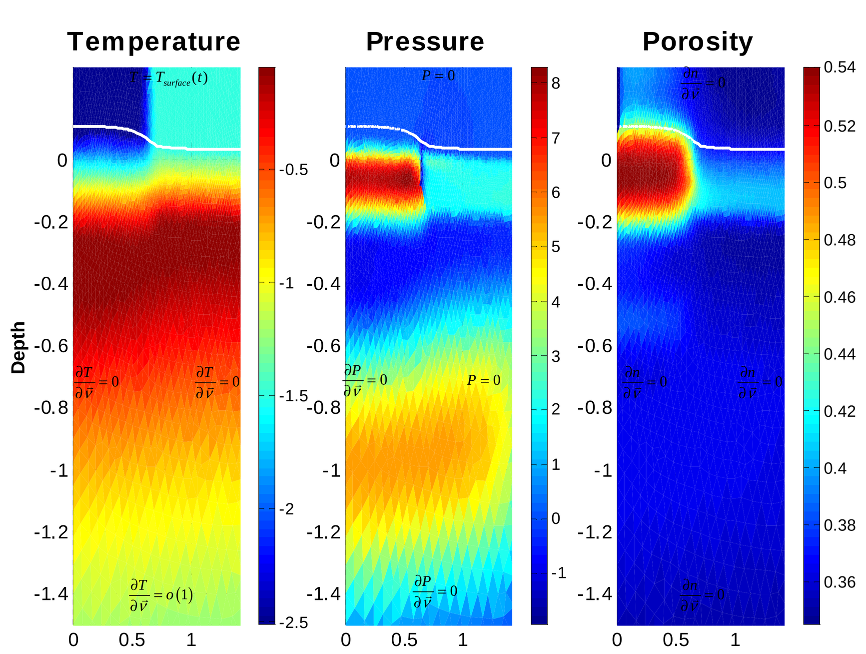
A departure of the calculated temperature and moisture from the measured one is small and can be partially explained by uncertainties in boundary conditions and soil properties.

- **Phase change occurs around –0.05 C.**
- **Pore pressure correlates with temperature, and shows sinks and sources of water.**
- **If the system is open then water migrates from the outer boundary through an unfrozen region to the so-called "frozen fringe", where the cryogenic suction makes the majority of liquid water migrate upwards. If the system is closed then water merely redistributes.**
- **Increase in porosity in a frozen region is associated with ice lens formation. Just the volumetric expansion of water due to the phase change cannot explain an observed frost heave. Cryogenic suction plays an important role.**

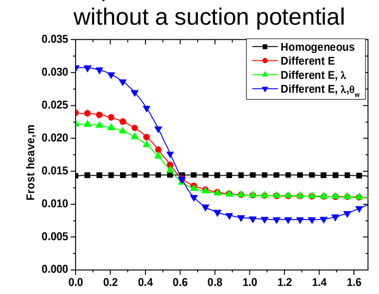
Ideal fluid



Hydraulically permeable boundary with suction potential



Modeling differential frost heave for water impermeable external boundary without a suction potential



Each curve represents the maximal displacement of the ground surface and is computed for different combinations of soil properties.

$$\boxed{heave=nd\left(1-\frac{\rho_i}{\rho_w}\right)}$$

n – porosity

d – active layer depth

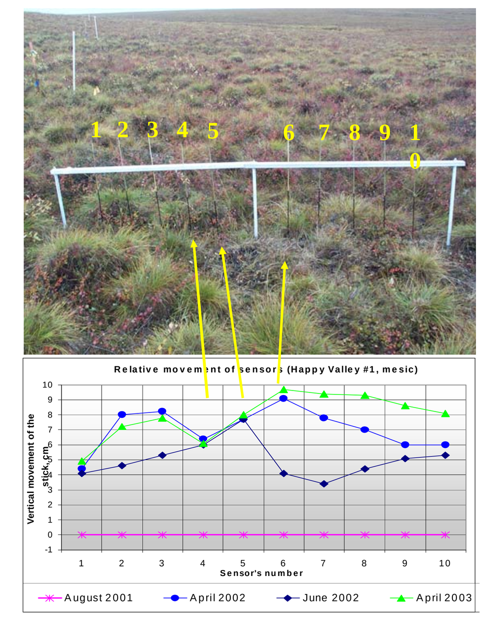
ρ_w,ρ_i – water and ice density

$0.35*0.55*0.09\approx0.017$

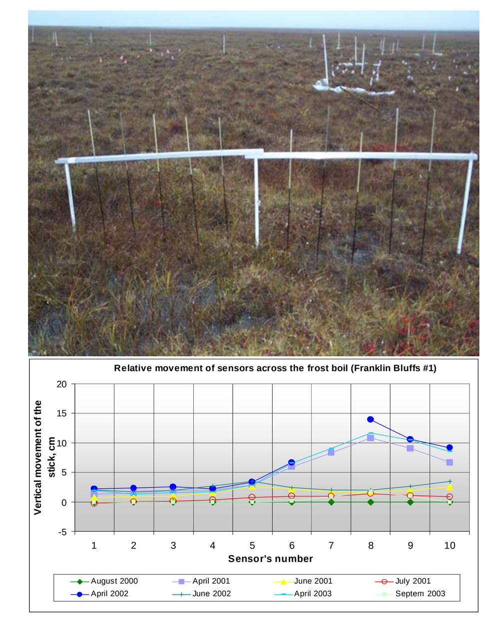
Temperature, pore pressure and porosity (from the left to the right) distribution at the same moment of time in the entire computational domain, the ground is below the white line.

Field measurements along Artic climate gradient

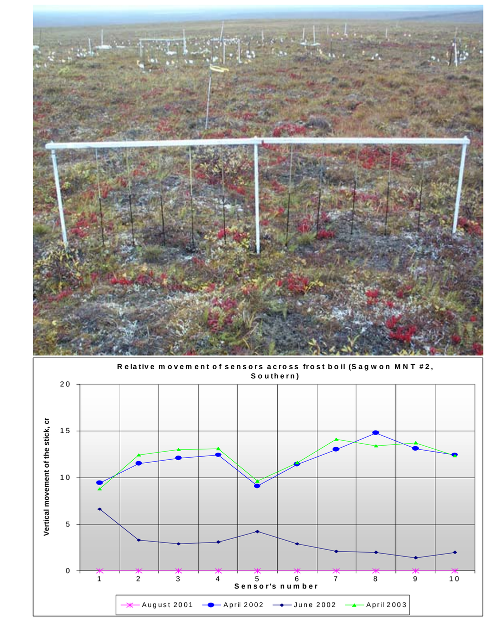
Happy Valley

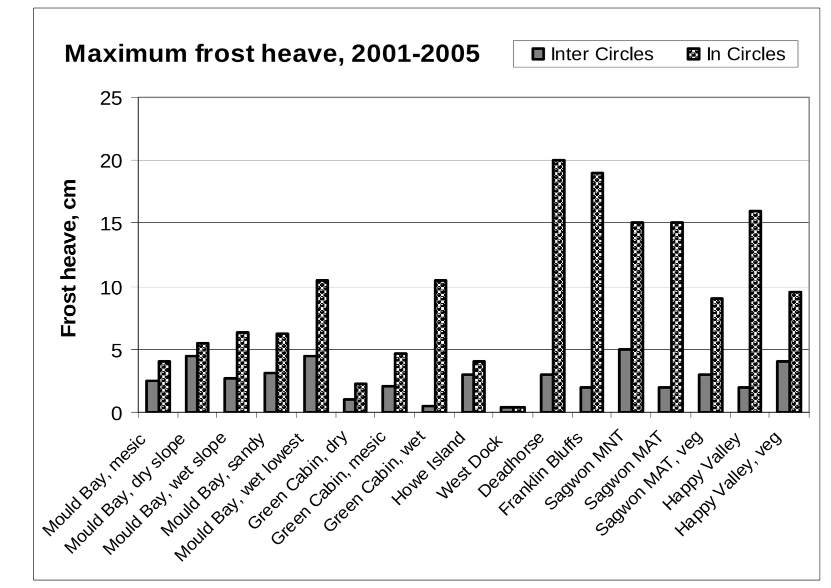


Franklin Bluffs



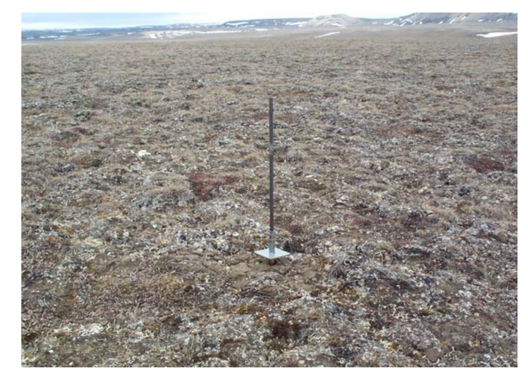
Sagwan



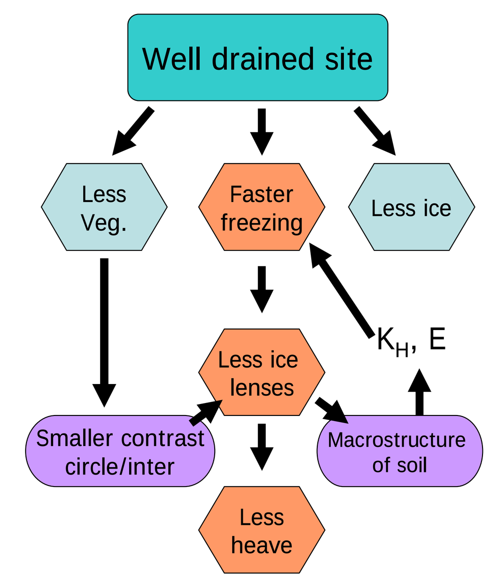


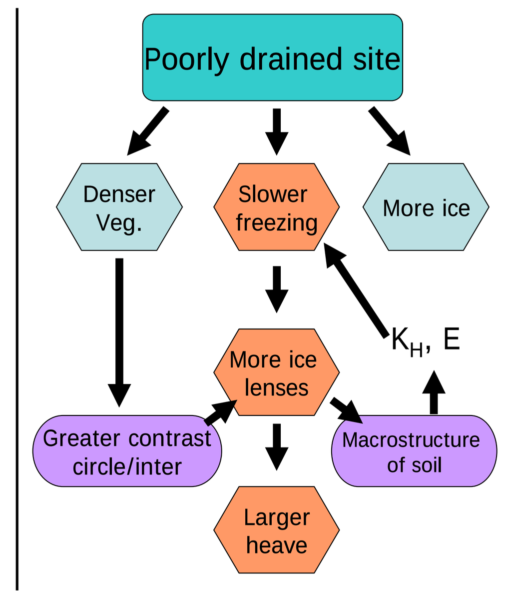
Water availabilty and its effect on non-sorted circle system

Mould Bay, mesic



4 cm frost heave

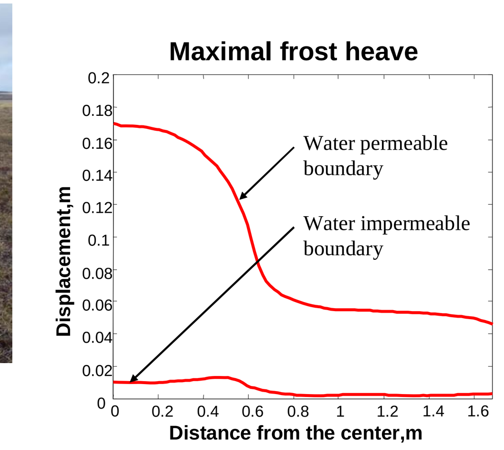




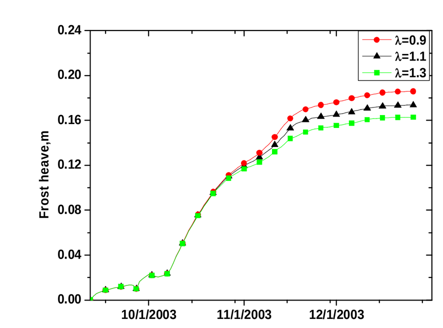
Green Cabin, wet

11 cm frost heave

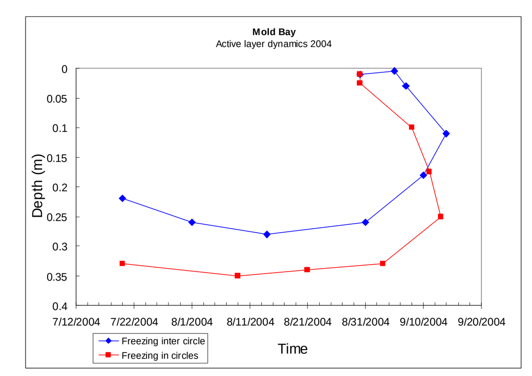
Results from numerical model



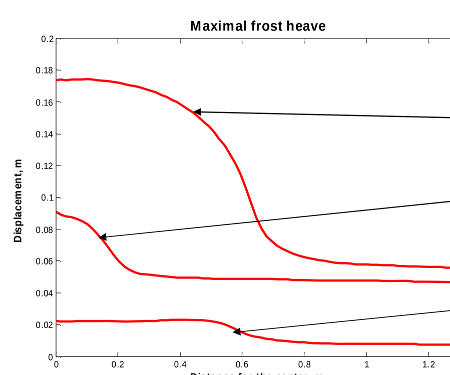
Modeled displacement of the soil surface in the center of the frost boil



Measured active layer depth



Simulated displacement of the soil surface for circles at typical sites along the climate gradient

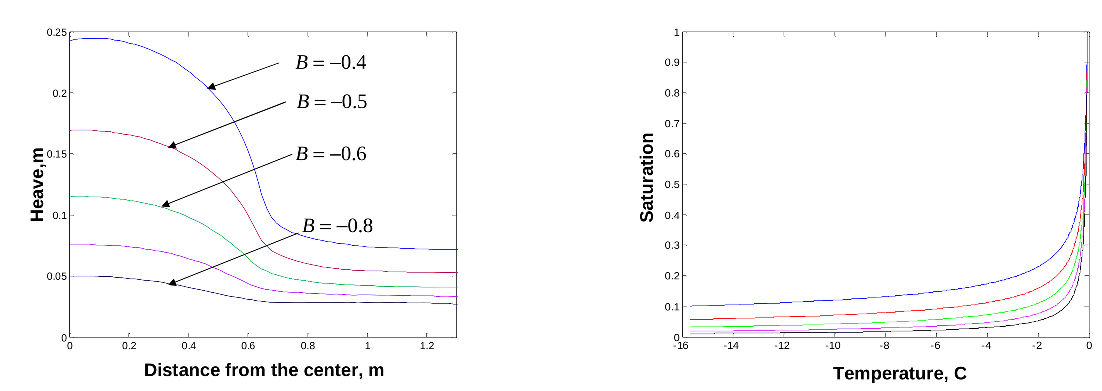


Franklin Bluffs, poorly drained and non-vegetated

Happy Valley, moderately drained and well vegetated

Howe Island, well drained and non-vegetated

Unfrozen water content

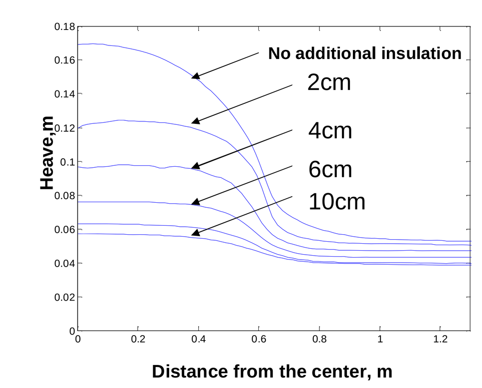


$B=-0.4$ – fine grained, i.e. silt

$B=-0.8$ – coarse grained, i.e. sand, organic matter, moss

Higher values of B correspond to higher amount of liquid water in partially frozen pores, and larger body forces caused by the "cryogenic suction".

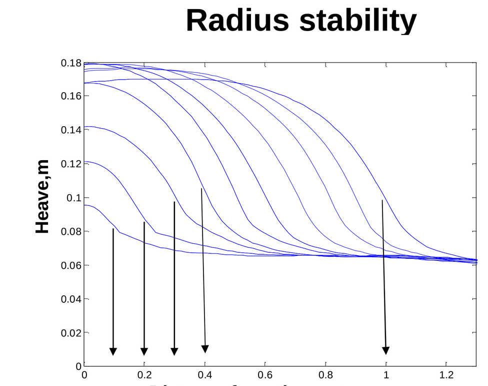
Additional insulation layer



Each blue line corresponds to the different depth of an additional insulation layer over frost and inter boil areas. The insulation simulates the effect of vegetation cover on frost heave.

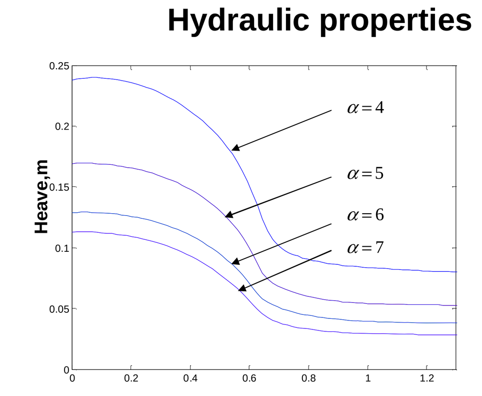
Thicker vegetation layer causes better thermal insulation and lower values cryogenic suction, hence the smaller frost heave of the ground.

Radius stability



The value of maximal frost heave non-linearly depends on the radius of the frost boil.

Hydraulic properties



Hydraulic permeability is

$$k=k_0\chi^{\alpha},$$

where

k_0 – unfrozen state

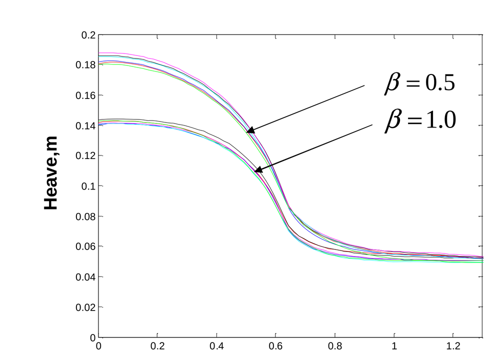
χ – saturation

α – 'rate'

$k\in\left[10^{-10},10^{-8}\right]\frac{m}{s}$

Higher values of the hydraulic permeability implies higher liquid water fluxes in the unfrozen region and more available water to form ice in the partially frozen area.

Effect of snow and temperature



The effect of snow is modeled by increasing the surface temperature in the inter boil area by

$$T_{inter\,boil}=\beta T_{frost\,boil}$$

Location of the frost boil system on the Arctic gradient, can be modeled by specifying the surface temperature

$$T_{frost\,boil}=\alpha T_{Frunkin\,bluff}$$

$$\alpha=0.6,0.8,\dots,1.6$$

The value of the maximal frost heave does not depend on the surface temperature explicitly, but rather on the difference between $T_{inter\,boil}$ and $T_{frost\,boil}$.

ACKNOWLEDGEMENTS: This research was funded by ARCSS Program and by the Polar Earth Science Program, Office of Polar Programs, National Science Foundation (OPP-0120736, OPP-9732126, OPP-9870635, IARC-NSF CA: Project 3.1 Permafrost Research), and by the State of Alaska.