Modelling of long-term permafrost evolution in the discontinuous permafrost zone of North-West Siberia

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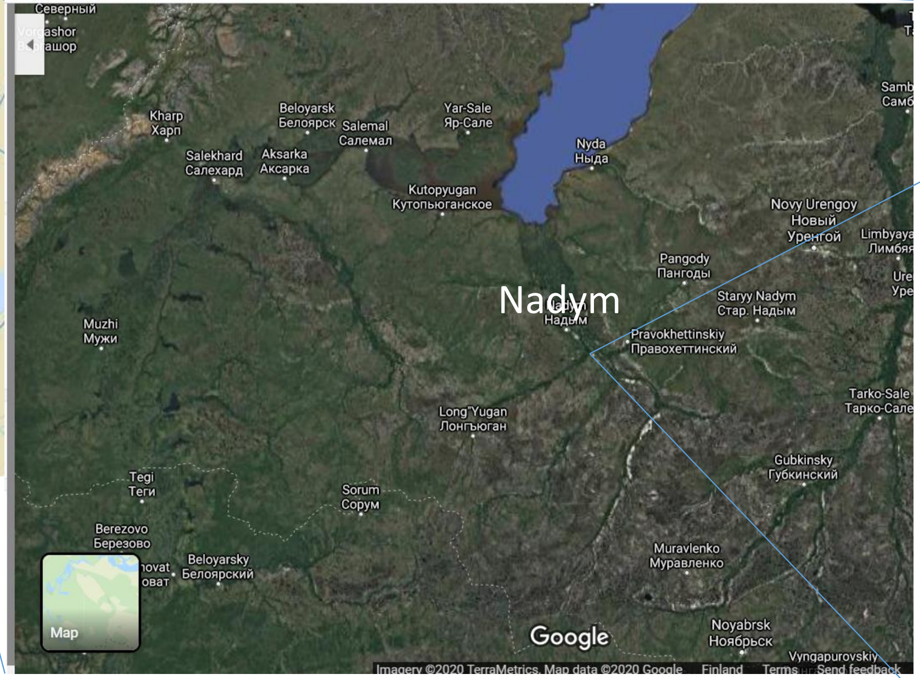
Motivation

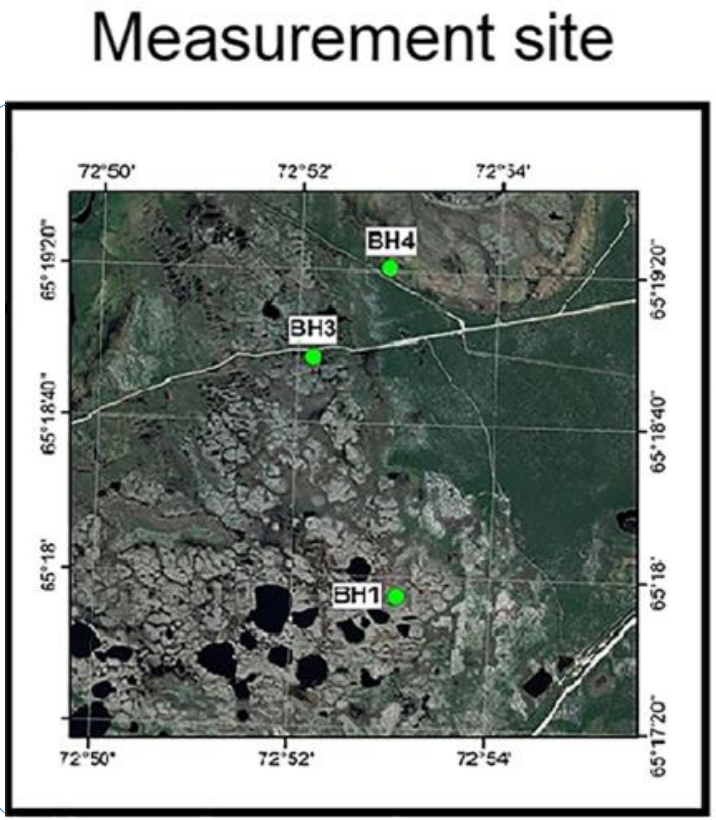
- The rate of climate warming in North-West Siberia in summer (0.8-1.0°C per decade, 1972-2012) is double that for the entire Arctic.
- Prolongation of the warm season + increase in the summer mean temperature -> increase in thawing degree-days -> thawing of permafrost.
- We study decadal temperature observations from three boreholes near Nadym, North-West Siberia.
- We use temperature measurements and cryolithological structure of soils in two boreholes to model 300-yr evolution of the deep permafrost under two climate scenarios: RCP2.6 (climate action, fast reduction of CO_2 emissions) and RCP8.5 ('business as usual').

Location of boreholes

The data sets (temperature at different depths, soil properties, 2009-2017) are from 3 boreholes in the discontinuous permafrost area, located within 1 km.

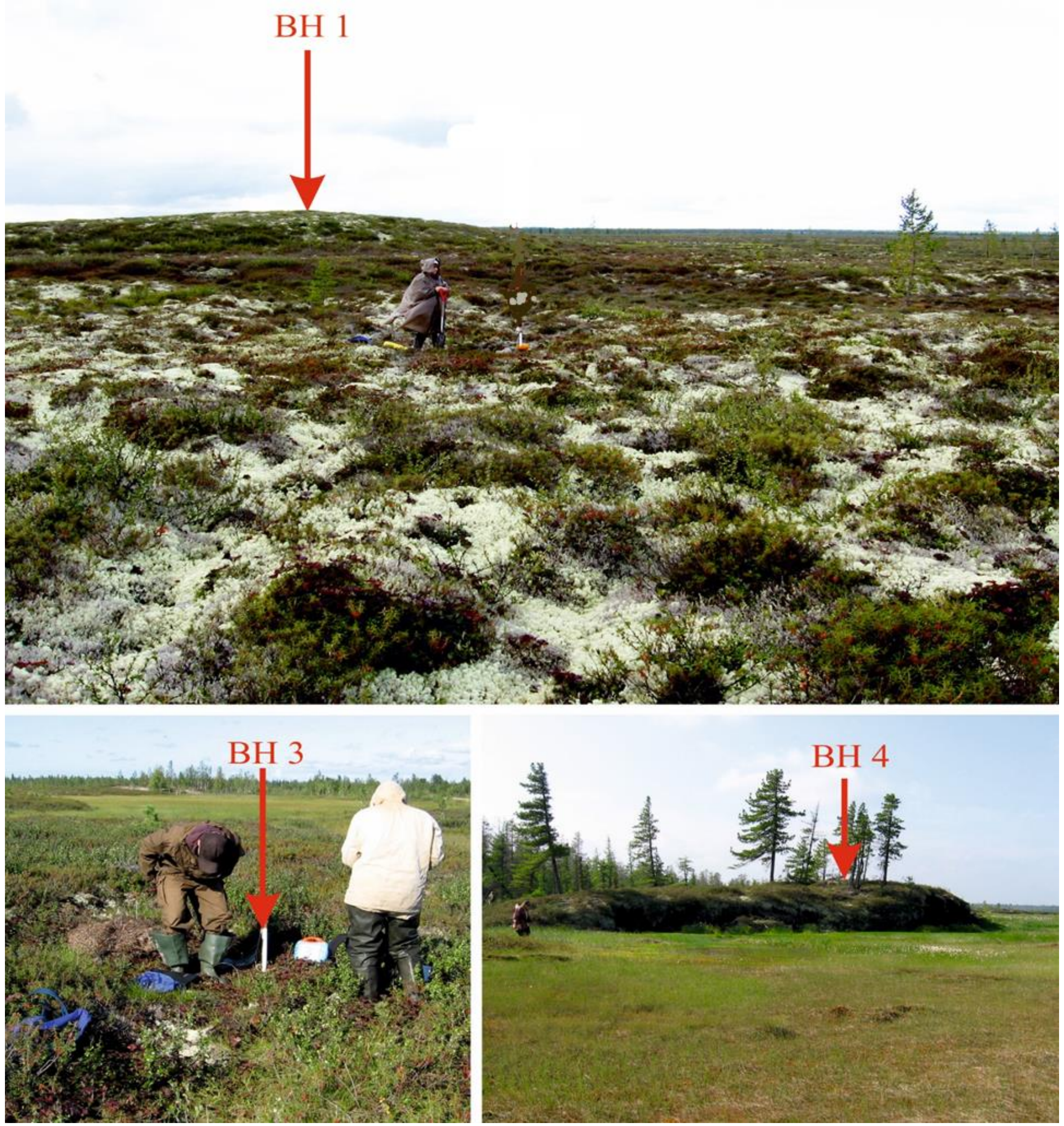
Brown et al., 1997





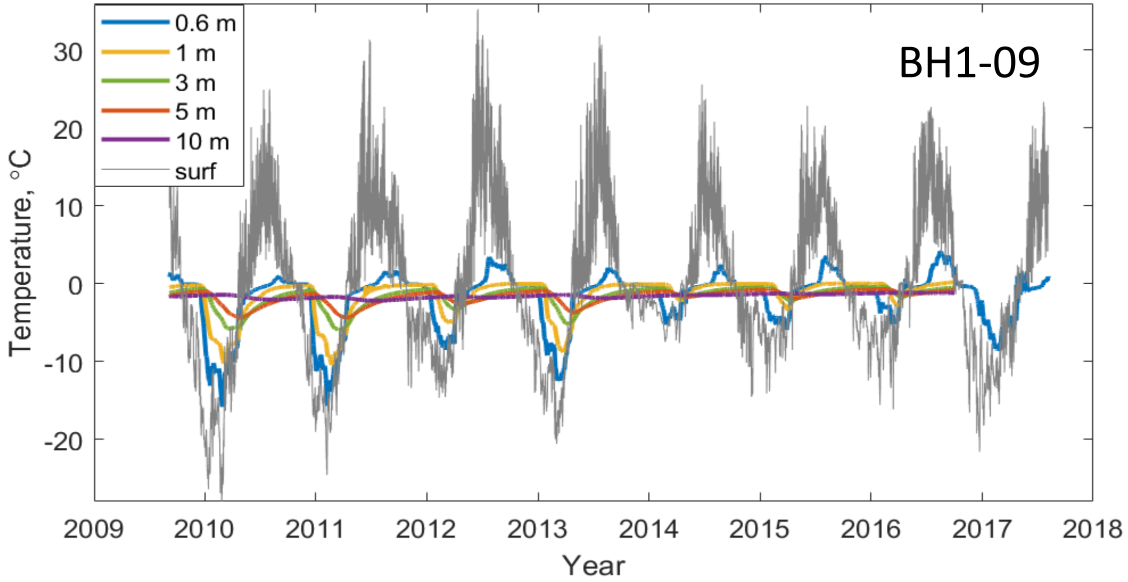
Borehole data

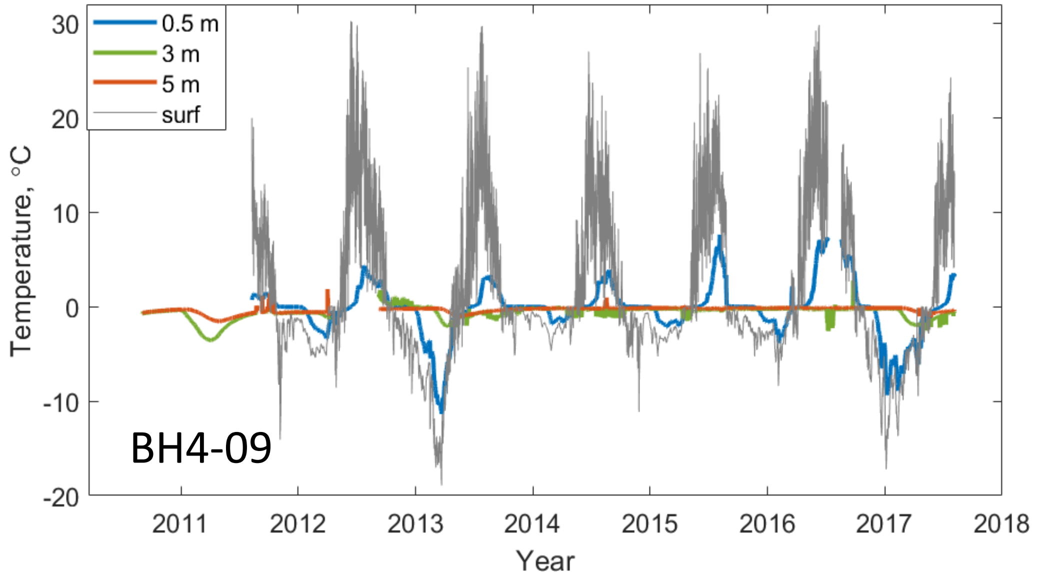
Borehole code	Coordinates	Landscape	Drill core, m
1-09	65°17'54.5''N 72°53'03.6''E	Alluvial/lacustrine plain, top of the frost mound	Lichen on the surface 0 – 0.6 peat 0.6 – 1.55 loamy sand 1.55 – 7.2 inequigranular sand 7.2 – 10.2 loam
3-09	65°18'57.5''N 72°52'08.7''E	Alluvial/lacustrine plain, flat peatland	Moss layer on the surface, 0 – 0.6 peat 0.6 – 1.0 peaty sand 1.0 – 1.7 loamy sand 1.7 – 6.7 sand 6.7 – 10.15 loam
4-09	65°19'21.3''N 72°52'54.3''E	Edge of floodplain of the River Kheygiyakha, frost mound	Lichen on the surface 0 – 6.3 peat 6.3 - 10 loam

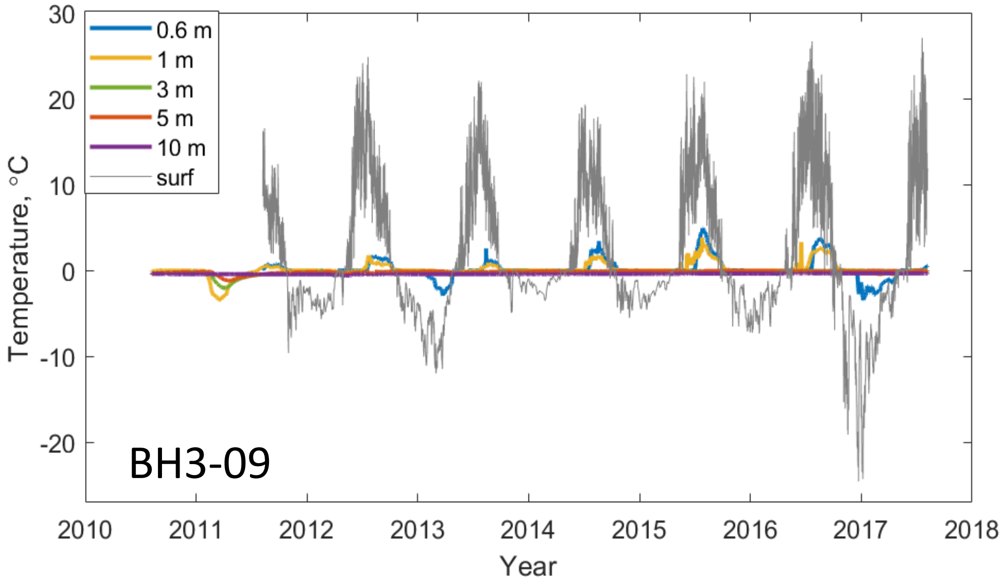


Temperature dynamics

- Most effective freezing in BH1-09
- Almost no freezing in BH3-09
- BH1 is located on the hill: deeper freezing in winter, warmer in summer

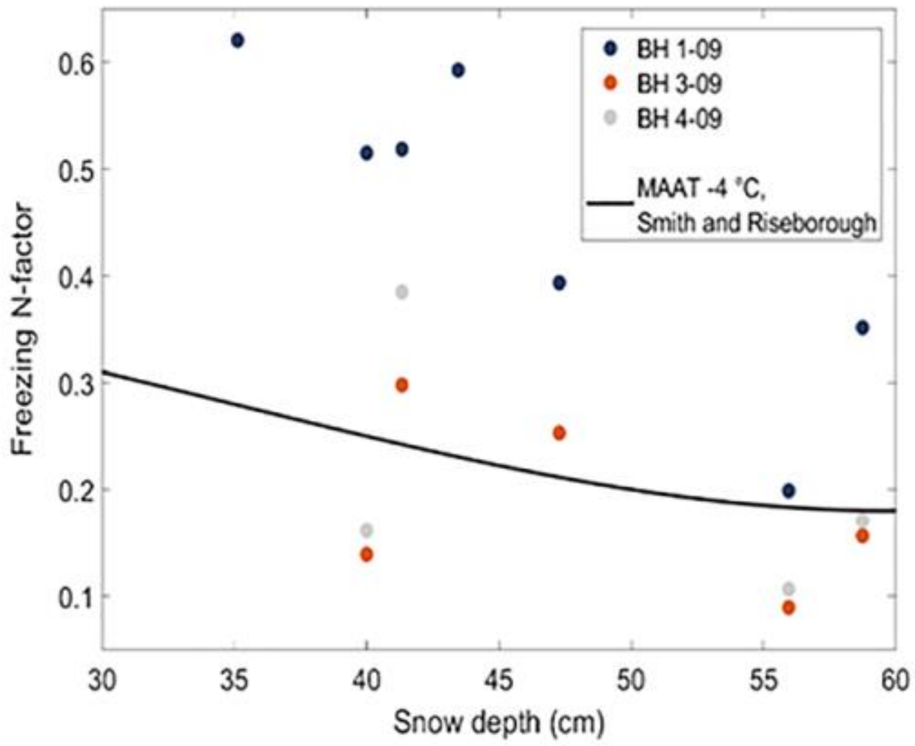






Effect of snow at different boreholes

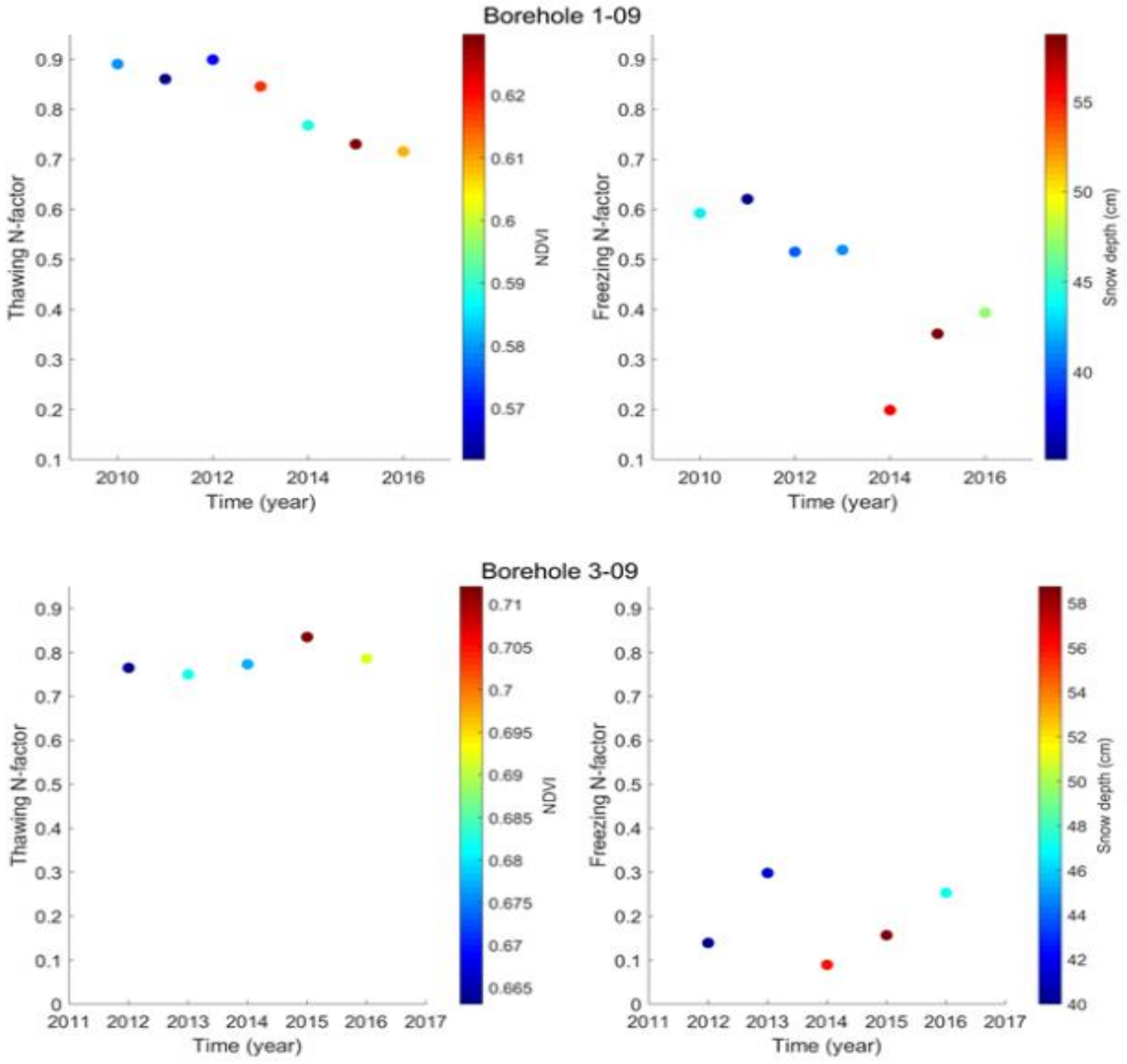
- Snow thickness was estimated as an average over 5 neighboring meteostations.
- Freezing n-factor was estimated from MAAT and snow thickness following model by Smith and Riseborough, 2002 (grey curve).
- Calculated n-factors for BH 3-09 are close to the curve, whereas n-factor for BH 1-09 is higher pointing at thinner snow cover.



Thawing and freezing n-factors

- $N_{f(t)} = I_{f(t)s} / I_{f(t)a}$,
- $I_{f(t)s}$ – surface freezing (thawing) degree-days
- $I_{f(t)a}$ – air freezing (thawing) degree-days

- Color map: NDVI in summer, snow thickness in winter
- Freezing n-factors are lower when snow cover is thicker
- NDVI increases at BH1 -> greening and possible decrease of surface temperature.
- We use n-factors for modelling



Model: Shemat, Clauser C., 2003

$$\nabla\left(\underline{\lambda}\,\nabla T-\rho_f\, c_f\, T\, \mathbf{v}\right)=\frac{\partial T}{\partial t}\left(\phi\, \rho_f\, c_f+(1-\phi)\, \rho_m\, c_m\right)-H\,,$$

- λ is thermal conductivity tensor, ρ is density, *c* is specific heat capacity, *H* is volumetric heat production
- The subscripts *f* and *m* account for the two-phase mixture of solid material (m) and fluid-filled pore space (f). This mixture is characterized by porosity ϕ.

$$\phi_m = 1-\phi,\ \phi_f = \phi\cdot\Theta,\ \phi_i = \phi-\phi_f$$

Θ – unfrozen water content

$$\Theta=\begin{cases}\exp\left[-\left(\dfrac{T - T_L}{w}\right)^2\right]; & T\le T_L \\ 1 ; & T>T_L\end{cases}.$$

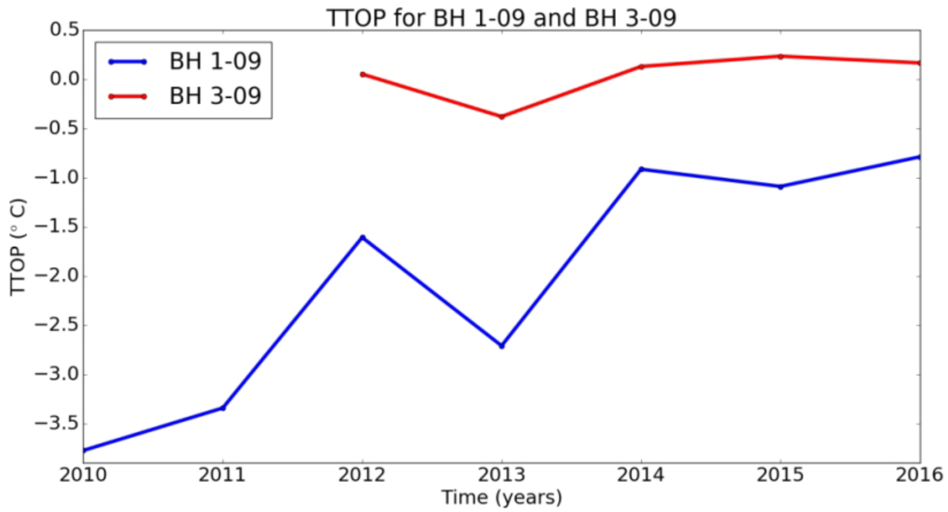
- Used as 1D model

Boundary conditions and porosity

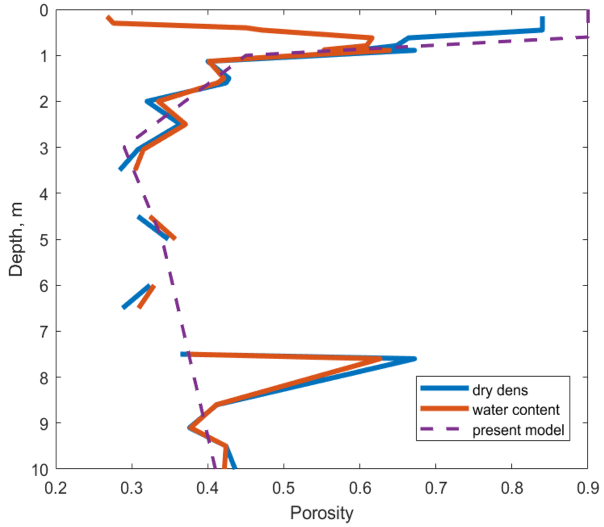
- TTOP (temperature on the top of permafrost) was used as an upper boundary condition
- Temperature trends for RCP scenarios were recalculated into TTOP trends

$$TTOP = \frac{\left(\frac{\lambda_w}{\lambda_i}\right)^{\phi} n_t I_{t,a} - n_f I_{f,a}}{P}$$

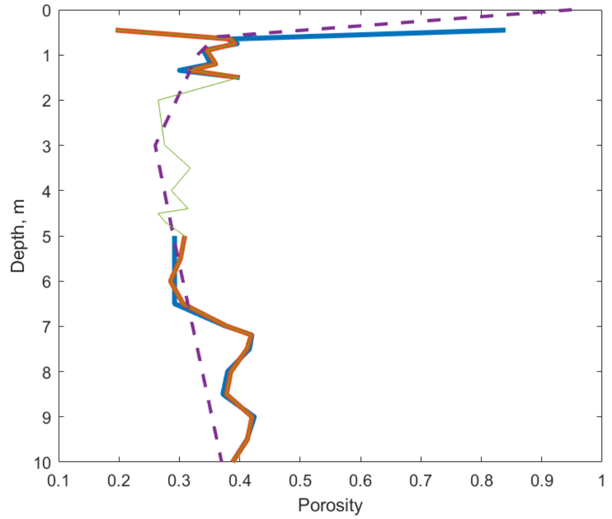
- We calculated porosity from measurements of water content and dry density
- The bottom boundary condition: geothermal heat flux 65 mW m^{-2}



Porosity BH1-09

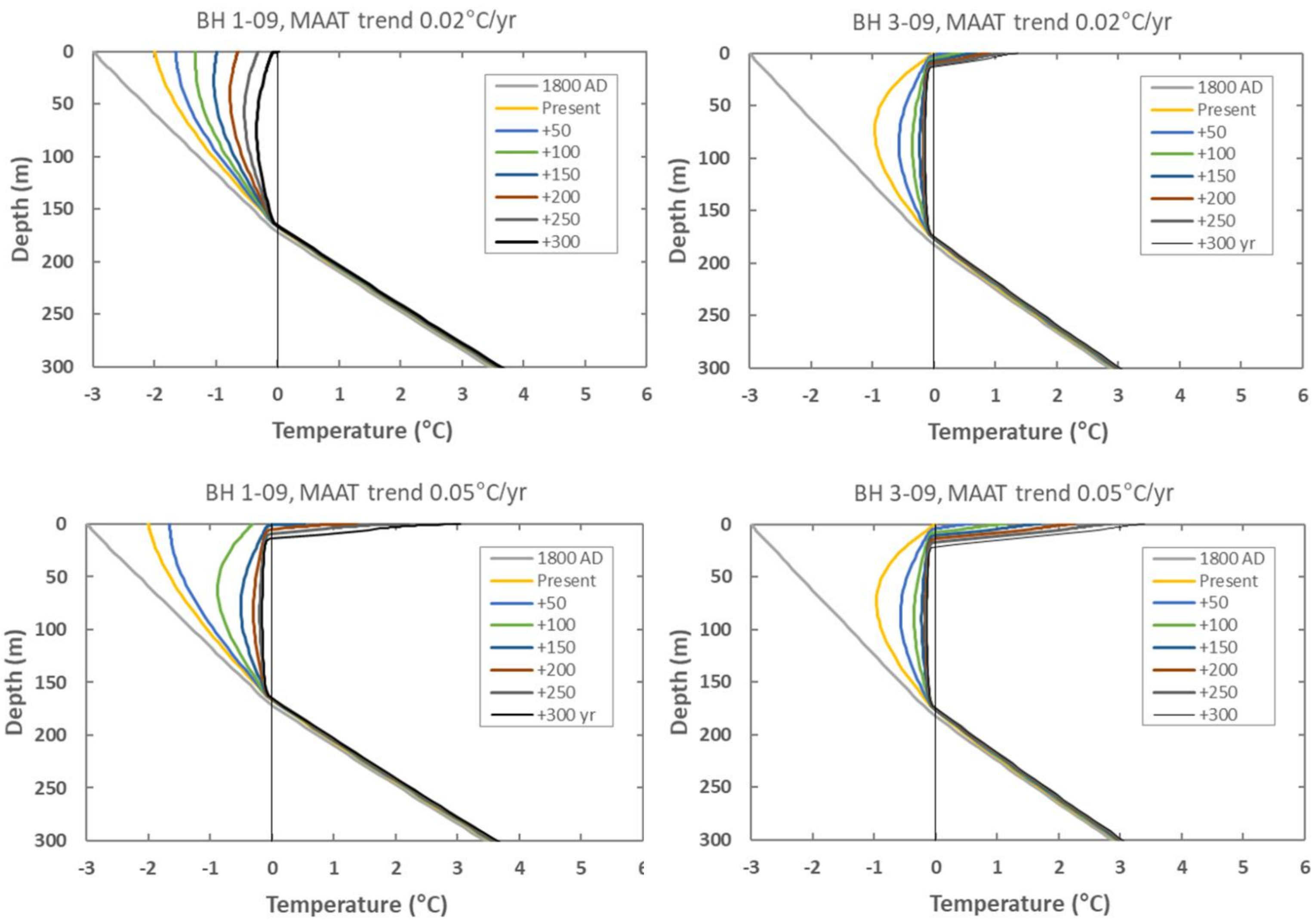


Porosity BH 3-09



Modelling of temperature dynamics: BH1 vs BH3

- Permafrost at BH1 remains under RCP2.6 scenario. But we took *mean global* temperature *trend*, while *local trend* in Nadym is close to 0.05 C/yr.
- 0°C isotherm will be
- at 5 m after 200 years at BH1,
- at 3 m after 50 years at BH3.



Conclusions

- The boreholes' freezing in winter is different despite close location. The difference is presumably due to local snow cover.
- In 300 years, under RCP8.5 scenario, permafrost in our sites will degrade. Under RCP2.6 scenario, permafrost will not degrade in the borehole on the top of the hill, although the permafrost temperatures are eventually above -1°C.

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