# Model estimates of the process of complete permafrost degradation under warming in the region of the Yamal Peninsula

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The climate at high latitudes is characterized by great variability and sensitivity to natural and anthropogenic forcings, with rapid warming in recent decades. Particularly significant climatic changes occur in the cryolithozone during the permafrost degradation and the violation of the methane hydrates stability. Here, changes in the permafrost and methane hydrates stability zone (MHSZ) under conditions of future warming over a long period of time of 20 000 years in the region of the Yamal Peninsula from model simulations are presented.

To calculate the thermal state of the permafrost and thermobaric conditions of the existence of gas hydrates, the one-dimensional model of the thermophysical processes in soils was used [2,3]. The changes in the monthly mean surface temperature for the northern regions of Western Siberia were set as the upper boundary conditions for heat transfer in the soil. Changes in the permafrost and MHSZ over the last 130 000 years were estimated with the use the changed boundary conditions on the basis of the CLIMBER-2 global climate model simulations before 1850 [4,5]. The permafrost state and MHSZ for the Yamal Peninsula region from 1850 to 2300 were calculated numerically using the results of the CMIP6 ensemble of the climatic model simulations. The results of calculations of the surface temperature and precipitation with the CanESM5, IPSL-CM6A-LR, ACCESS-ESM1-5 and MRI-ESM2-0 climate models under “historical” and SSP5-8.5 scenarios for the 21st century with the ScenarioMIP long-term extention up to 2300 [1] were used (Fig. 1). In addition, permafrost and MHSZ were calculated for the next 20 000 years with the boundary conditions using climate model simulations with the boundary conditions fixed at the level of 2300 (temperature and precipitation, simulated under the SSP5-8.5 scenario until 2100 and ScenarioMIP CMIP6 for the period of 2100–2300) [5]. Different values of the heat flux from the Earth interior were used: 50 mW/m$^2$ and 75 mW/m$^2$.

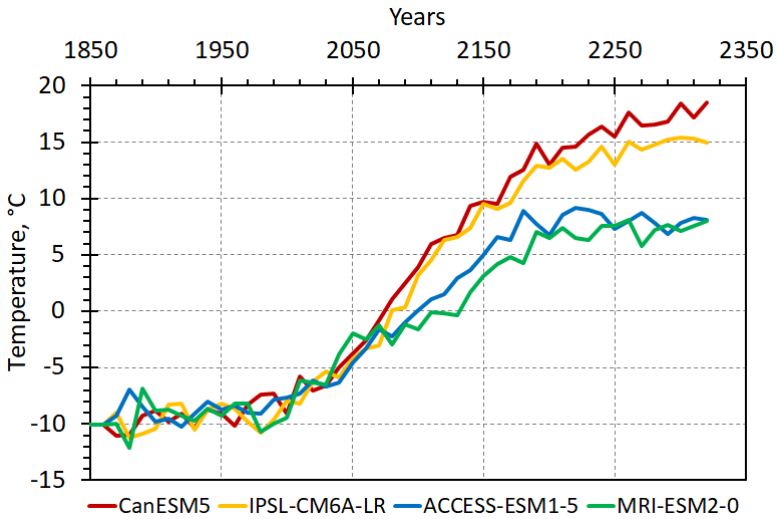


**Figure 1.** Changes in the annual mean surface temperature in the Yamal Peninsula region, used as the boundary conditions for the period of 1850–2300 according to the climate model simulations (CanESM5, IPSL-CM6A-LR, ACCESS-ESM1-5 and MRI-ESM2-0) under “historical” and SSP5-8.5 scenarios for the 21st century with the ScenarioMIP long-term extention up to 2300.

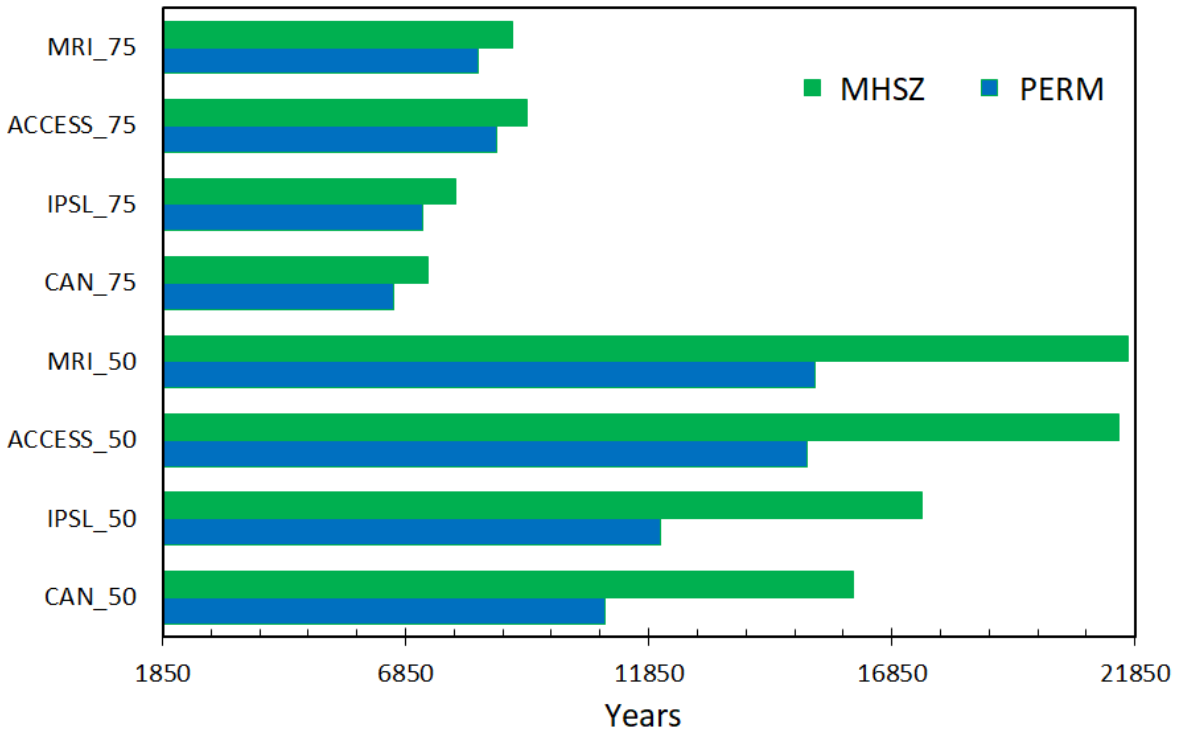


**Figure 2.** Time of the disappearance of permafrost (PERM) and of the methane hydrates stability zone (MHSZ) from model simulations with different geothermal heat flux: 50 mW/m$^2$ (CAN_50, IPSL_50, ACCESS_50 and MRI_50) and 75 mW/m$^2$ (CAN_75, IPSL_75, ACCESS_75 and MRI_75).

The estimates of the limiting conditions for the existence of permafrost at different depths and the conditions for the stability of methane hydrates were obtained. According to model simulations under historical" and SSP5-8.5 scenarios for the 21$^{st}$ century with the ScenarioMIP long-term extention up to 2300 the permafrost survives, at least, for 5 millennia after present conditions or even longer provided that heat flux 75 mW/m$^2$. For smaller geothermal flux (50 mW/m$^2$) the period of complete degradation of permafrost increases to 11-15 millennia, depending on the scenario (Fig. 2). According to simulations methane hydrate stability zone disappears not earlier that at 7300-9300 for the heat flux 75 mW/m$^2$. For smaller geothermal heat flux, 50 mW/m$^2$, the moment of complete disappearance of the MHSZ ranges from 16 to 21.7 millennia, depending on the forcing scenario (Fig. 2).

## References

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