Modelling subsurface heat flow in permafrost during a marine transgression in the Western Laptev Sea

F. Kneier, M. Langer, K. Froeb & P.P. Overduin
Alfred Wegener Institute for Polar and Marine Research, Potsdam, Germany

Introduction

The transition from onshore to offshore permafrost

Most submarine permafrost is relict terrestrial permafrost that was inundated by seawater as a result of sea level rise and/or coastal erosion. The marine transgression brings about a change from sub-aerial to submarine boundary conditions for permafrost: sea bottom temperature is generally warmer than ground surface temperature, and salt water infiltration thaws pore space ice. Permafrost degradation rates in the near-shore zone (< 10 m water depth) are complicated by sedimentation, water column heat and mass transport, sea ice dynamics (especially the timing and duration of bottom-fast ice) and diffusive transport processes within the sediment column. As a result of the interaction between these processes, the transition of terrestrial permafrost to offshore permafrost remains poorly understood [*Taylor et al., 1996*]. This study focuses on modelling results for this transition.

Modelling efforts

Several studies have employed numerical modelling to the transition of permafrost to offshore conditions. An early quantitative investigation was carried out for two sites in the Beaufort Sea, Alaska [*Harrison & Osterkamp, 1978*]. Therein, the system of partial differential equations describing the underlying processes of submarine permafrost aggradation and degradation including salt diffusion was solved analytically for a simple limiting case to the conditions at Elson Lagoon and Prudhoe Bay to discuss the breakdown of the diffusive regime in salt and heat transport. Taylor et al. [*1996*] employ a one-dimensional thermal diffusion model in order to interpret the paleoenvironmental history of the Beaufort Shelf, Canada. Geothermal modelling of the temperature profiles and best fit comparison with offshore drill holes allowed for local dating of the time of marine transgression. Romanovskii and Hubberten [*2001*] calculated the evolution of permafrost thickness through the last four climatic cycles (400 ky) on the scale of the Laptev Sea Region, Russia. Leaving out short-term temperature fluctuations as well as salt diffusion and their influence on the upper permafrost horizon, they showed that permafrost has been preserved throughout all transgressions as ice-bearing permafrost for the larger part of the shelf depending on water-depth isobaths and geothermal heat flux. Recent work [*Dmitrenko et al., 2011*] has shown that extended summer-ice free periods in the eastern Siberian shelf, containing the Laptev Sea, have led to an increase of bottom water temperature of 2.1°C since the mid 1980s. Modelling suggests that significant effects on permafrost thickness and gas stability from the current warming can be expected by the end of the next millennium.

Open questions and objectives

Submarine permafrost degradation from above occurs most rapidly in the near-shore coastal zone of the shelf (< 10 m depth) [*Rachold, 2000*]. Our objectives are to employ meso-scale numerical calculations (10^1 to 10^2 m, 1000s of years) in connection with borehole data to model the transition of permafrost from onshore to offshore conditions. In order to identify key processes driving the degradation of permafrost following inundation in the near-shore zone, an initial simple approach neglecting known key aspects, e.g. mass transfer and sedimentation, is used. We seek to explain whether the observed temperature profiles are consistent with stable permafrost conditions or may be indicative of rapid degradation in the Laptev Sea region. Future refinements to the model are discussed below.

Study Site

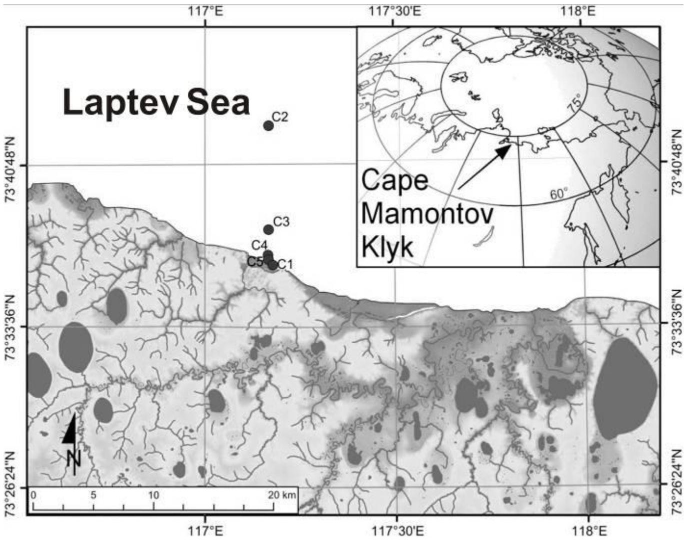

Figure 1. Location of Cape Mamontov Klyk and the series of five boreholes in the western Laptev Sea.

Five boreholes were drilled into the permafrost in the western Laptev Sea in 2005. Cores recovered onshore (C1, terrestrial, 100 m from the coastal bluff) and offshore (C2 to C5, marine, up to 11.5 km from the coastline) were analyzed for composition, including grain-size, and organic, ice and water contents. These composition data are used in this study to parameterize the numerical model of heat flow.

Modelling

The initial temperature profile from the terrestrial borehole C1 is taken as upper portion of the terrestrial permafrost temperature profile and initial condition for the transgression model. Initial coastal erosion of the top 25 m layer of ice-complex rich soil and changed surface temperatures are taken into account when numerically solving the heat transfer equation

$$c_{eff} \cdot \frac{\partial T}{\partial t} = \frac{\partial}{\partial z}\left(\lambda \frac{\partial T}{\partial z}\right) \qquad (1)$$

Freeze-thaw processes are considered in a three phase heat capacity / conductivity model

$$c_{eff} = \sum_i c_i \theta_i + L_f \frac{\partial \theta_w}{\partial T} \qquad (2)$$

where c is capacity, θ_i volumetric fraction of phase *i*, L_f latent heat of freezing, and λ thermal conductivity parameterized according to De Vries [*1963*] based on measured sediment properties and temperature.

Upper boundary conditions following transgression are given by the change in profile height due to initial coastal erosion and the bottom water temperature in the Laptev Sea shelf of -1.5°C. Sediment composition parameters are derived from field and laboratory analysis and are supplemented by data from Yershov [*1998*] for depths without measurements. The lower boundary is set to a constant geothermal flux of Q = 53 mW/m^2 as appropriate for the study region [*Romanovskii & Hubberten 2001*].

Table 1. Description of observed core sedimentological units, their ice saturation and the mean thermal conductivities (λ_{mean}) calculated or estimated based on sediment composition and temperature.

Depositional environment	Ice saturation	Elevations [m a.s.l.]	λ_{mean}
Marine, interglacial	0	offshore: -35 to -6	0.7-1.5*
Terrestrial, interglacial	0.4-0.9	onshore: +26 to +27	0.1-1.2*
Ice complex, glacial	0.4-1.0	onshore: +5 to +26	2.2*
Terrestrial, glacial	0.1-0.6	onshore: -34 to +5 offshore: -64 to -35	2.6 ±0.1 (n = 175) 2.6 ±0.1 (n = 50)
Lagoonal, glacial	0-0.1	offshore: -77 to -64	0.6-1.0*

* values taken from Yershov (1998)

Analysis and Outlook

In order to analyze details of the transition to offshore permafrost, measured temperature profiles will be compared to the modelled sediment temperature development between the times t_1 & t_2 corresponding to the time of sea transgression from location C2 to C1. Of special interest is the thaw depth or, more accurately, the evolution of the depth of the ice-bearing permafrost table as the one most discernible observable in the field.

Additionally, a best fit analysis is attempted of the C2 temperature profile to the simulated temperature evolution in time to give estimates about transgression rates and whether currently observed erosion rates have persisted throughout the inundation process of several thousand years.

As expected, results indicate deviations from measured field data. These deviations, especially of the position of ice-bearing permafrost table, are interpreted as the consequence of important processes, such as salinity diffusion and its contribution to permafrost degradation from above, that were not accounted for in the model. Including these processes, e.g. marine sedimentation rates, salt infiltration, and possibly even bottom-fast ice effects in the very near-shore area (< 2 m depth), will be subsequent steps in order to attempt a convincing picture of the transgression from one borehole position to the other.

References

Dmitrenko, I.A., Kirillov, S.A., Tremblay, L.B., Kassens, H., Anisimov, O.A., Lavrov, S.A., Razumov, S.O. & Grigoriev, M.N. 2011. Recent changes in shelf hydrography in the Siberian Arctic: Potential for subsea permafrost instability. Journal of Geophysical Research 116(C10027).

Harrison, W.D. & Osterkamp, T.E. 1978. Heat and Mass Transport Processes in Subsea Permafrost, 1. An Analysis of Molecular Diffusion and Its Consequences. Journal of Geophysical Research 83(C9): 4707-4712.

Rachold, V., Grigoriev, M.N., Are, F.E., Solomon, S., Reimnitz, E., Kassens, H. & Antonov, A. 2000. Coastal erosion vs riverine sediment discharge in the Arctic Shelf seas. International Journal of Earth Sciences. 89(3): 450-460.

Romanovskii, N.N. & Hubberten, H.W. 2001. Results of Permafrost Modelling of the Lowlands and Shelf of the Laptev Sea Region, Russia. Permafrost Periglac. Process. 12: 191-202.

Taylor, A.E., Dallimore, S.R. & Outcalt, S.I. 1996. Late Quaternary history of the Mackenzie-Beaufort region, Arctic Canada, from modelling of permafrost temperatures. 1. The onshore – offshore transition. Canadian Journal of Earth Sciences 33: 52-61.

De Vries, D.A. 1963. The thermal properties of soils. *Physics of Plant Environment* (ed. R.W. van Wijk), 210-235. North Holland, Amsterdam.

Yershov, E.D. 1998. General Geocryology. *Cambridge University Press.*