NUMERICAL SIMULATION OF OFFSHORE PERMAFROST DEVELOPMENT IN THE LAPTEV SEA, SIBERIA

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Abstract
Seismic reflection surveys by BGR during cruises in 1993, 1994 and 1997 to study the tectonic structure of the Laptev Sea, Siberia, have detected a strong reflective unit extending to depths of typically 300 m to 850 m, which is tentatively interpreted to image the vertical extent of permafrost. This shelf area with water depths of in general less than 60 m must have existed under subaerial conditions during the lower sea level stages of the last cold stages, thus permitting permafrost growth. Assuming for this region a plausible scenario for the sea level change and climatic change during the last 160,000 years, the time-dependent development of permafrost growth is calculated. The numerical analysis suggests the development of several hundreds of meters of permafrost during the last cold stages, whereby rivers across the formerly dry Laptev shelf region may have caused permafrost-free channels.

Introduction
The tectonic structure of the Laptev Sea, Siberia, has been intensively investigated by BGR with seismic reflection methods during offshore-geophysical cruises in 1993, 1994 and 1997, whose results are described in more detail in Hinz et al. (1998). One aspect of this work was the detection of seismic information on submarine permafrost thickness and extent in the Laptev Sea. This paper concentrates on the presentation of ideas on the development of the thermal field of the Laptev Sea shelf during the last 160,000 years in response to climatic and sea level changes.

Geology of the Laptev Sea shelf
The Arctic Mid Ocean Ridge runs at right angle to the Siberian land mass and causes landwards of the point of contact, crustal extension and the formation of graben and horst systems under the Laptev Sea shelf since the Early Tertiary (Figure 1). Several rivers, in particular the Lena River, discharge their terrestrial sedimentary load into the developing depressions. The sediments at the sea bottom of the shelf region are characterized by sandy and silty deltaic deposits of the Lena River with an increasing clayey content towards the shelf slope (Dehn and Kassens, 1995). Extensive occurrence of submarine permafrost in the shallow offshore regions between the coast and 77°N of the Laptev Sea was reported by Soloviev et al. (1987). The upper boundary of the permafrost layer is typically within 1 dm depth below sea floor as determined by Kassens et al., (1994) and again by piston coring attempts of the author in 1997. This find is in strong contrast to the situation found in Arctic Canada, where the top of ice bonded permafrost was observed at depths between 5 to 90 m (Taylor et al., 1996). Only two 1.1 m long cores were obtained in 1997 by BGR in the immediate vicinity of pock marks. The offshore-seismic reflection surveys by BGR have detected a strong reflective unit extending to depths of typically 300 m to 850 m, which is tenta-
Mathematical simulation of permafrost growth/degradation

In preparation for further scientific investigations of the Laptev Sea area, numerical models were employed to develop a conceptual understanding of the dynamics of the permafrost layer. The principal difficulty in numerically simulating permafrost growth and decay is the accurate description of the heat exchange at the moving phase change boundary during growth and decay of permafrost. The principal approach chosen here is based on the small scale discretization of the space, through which the permafrost boundary will migrate. Two processes are considered at each element, through which the permafrost boundary moves:

- What is the amount of latent heat liberated (permafrost growth) or taken up (permafrost decay) in each element.

- How much heat flows into and out of this element.

The amount of latent heat contained in each element at any time is given by the amount of water in the pore space that will undergo freezing, the volume of the element and the amount latent heat already lost (or gained) by heat flow through the element boundaries. The latter quantity is controlled by the temperature gradients through the element boundaries.

The temperature field of the space containing the permafrost zone is calculated using equations (1) and (2):

\[
\frac{dT}{dt} = \frac{\lambda}{\rho c} \text{div} \left( \nabla T \right) \tag{1}
\]

\[
\lambda \left( \frac{dT_1}{dz} - \frac{dT_2}{dz} \right) = L I_c P \frac{dX}{dt} \tag{2}
\]

where
\( \lambda \) is the thermal conductivity (W/mK);
\( \rho \) is the density of rock (kg/m³);
\( c \) is the specific heat capacity of rock (Ws/kgK);
\( L \) is the latent heat (Ws/kg);
\( I_c \) is the amount of ice per m³ sediment (kg/m³);
\( P \) is the percent moisture by wet weight;
\( dX/dt \) is the rate of movement phase change boundary (m s⁻¹);
\( t \) is the time (s);
\( T \) is the temperature (K).

Equation (2) describes the rate by which latent heat is lost or gained by each element containing the phase change boundary. The time dependent change of the temperature field is calculated by an explicite finite difference scheme.

For simplicity, the temperature at the soil surface is equated with the mean annual air temperature \( T_{\text{mean}} \) at the Earth’s surface according to the applied climatic curve (see below). The annual fluctuation of the soil temperatures within the uppermost meters (active layer) is not considered.

The phase change boundary was set at 0°C, since predominantly freshwater deposits are modelled. The actual boundary in the marine environment today might be slightly lower. The bottom waters of today with temperatures between -1.5°C to -2.2°C are, however, too cool to degrade the top of the submarine permafrost.

A uniform thermal conductivity of 2.2 W m⁻¹ K⁻¹ is assumed for the frozen and unfrozen subsurface materials, corresponding to slightly compacted silty to sandy sediments (see Kappelmeyer and Haenel, 1974). A uniform water content of 20% in the sediments is assumed to participate in the phase change. An additional, but small fraction of water will remain unfrozen in permafrost depending on the type of sediment (Nixon, 1985).

The models

The results of the analysis of two different scenarios will be presented:

In model A, the time dependent growth and degradation of permafrost thickness as function of climate was investigated.

In model B, the potential thermal influence of arms of the Lena River flowing across the Lena delta and the subaerial shelf region northwards during cold stages was modelled.

MODEL A: GROWTH/DEGRADATION OF PERMAFROST AS FUNCTION OF CLIMATE

The first model incorporates a climate curve for the last 160,000 years which was adapted and modified from a paper by Maximova and Romanovsky (1988). The curve was modified for the time periods of 125 - 105 ka and 5 - 0 ka before present and, alternatively for 125 - 70 ka and 5-0 ka before present, for which complete flooding of the shelf area by the Laptev Sea is assumed. During these time periods, a uniform mean temperature of -1.5°C at the sea floor (equivalent to the mean annual temperature of the sea water) is assumed. These time periods are equivalent to a massive warming of the top of the permafrost layer by the incursion of sea water. The chosen time periods of flooding events of the shelves are admittedly to some extent speculative. The onset of subaerial conditions depends on the onset of large scale glaciation in the Northern hemi-
sphere as the cause for the worldwide lowering of the sea level. It is unknown, if the climatic deterioration at the end of the Eemian did initiate ice sheet growth sufficiently to drop sea levels worldwide to a significant extent. Two model calculations presented below consider this possibility. As an alternative, sea level lowering as a result of the dramatic cooling event around 70 ka is analysed.

Two different values for the terrestrial heat flow $q$ from depth are assumed. The Laptev Sea covers the zone where the Arctic Mid Ocean Ridge meets at a 90° angle with the old continental shield of Siberia. The permafrost model was run for $q = 40$ mW m$^{-2}$ and 60 mW m$^{-2}$ (Lee and Uyeda, 1965); the former value represents the shield situation and the latter one the evolving transition from continental crust to a horst and graben structure under the extensional forces exerted by the adjacent ridge complex (see Figure 1).

**MODEL B: THERMAL INFLUENCE OF RIVERS ON PERMAFROST BODIES**

The second model considers the thermal effect of the Lena River on the thickness of permafrost. The temperature at the upper surface of the permafrost is assumed to be $-10^\circ$C at $t=0$, linearly decreasing by 0.5°C per 1000 years. However in the case of the presence of a river, the water temperature at the river bed is the controlling factor of the thermal field in the ground below. Flowing fresh water rivers have a positive mean annual temperature, which in the present calculations is assumed to be 2°C.

A 9300 m long vertical section through permafrost is modelled. The numerical model considers

- case a) four river arms flowing across the permafrost region;
- case b) again four river arms, three of which shift their position after $t>5000$ years. As a consequence, the thawed zone under the former river bed will refreeze and a new thawed zone will develop under the new beds.

The lateral extent of the rivers within the permafrost profiles are indicated in Figures 4a and 4b.

**Results and discussion**

**PERMAFROST THICKNESS VS. CLIMATE (MODEL A)**

The average permafrost thickness according to model A averages around 750 m given a heat flow of 40 mW m$^{-2}$ and around 550 m given a heat flow of 60 mW m$^{-2}$ (Figures 2a and 2b), except during periods of sea water incursion onto the Laptev Sea shelf. The amplitude of climatic signals arriving at the permafrost base diminishes with increasing permafrost thickness.

The thermal effect of the sea water incursions during warm stages modifies the permafrost significantly. A decrease in permafrost thickness by 200 m is predicted for the case of $q = 40$ mW m$^{-2}$ and by 350 m for the case of 60 mW m$^{-2}$, given a flooding period of 20 ka (125-105 ka before present) initiated by the Eemian warm stage (130 - 115 ka ago). The temperature distribution within the permafrost zone, as well as the lower phase boundary are shown in Figures 3a and 3b for the selected time instants of 150 ka, 110 ka, 20 ka and today. During cold stages the temperature curve is mostly linear from the sediment surface to depth. During warm
stages, a nearly isothermal situation near the melting point in the permafrost body will develop with time.

Even in the case of the lengthy marine incursion from 125 - 70 ka before present, a permafrost thickness in the order of about 70 m (given a high regional heat flow of 60 mW m$^{-2}$) should have existed at the end of this incursion (Figure 2c). The permafrost should have grown again to about 500 m during the last glacial maximum.

The third example of model A demonstrates regrowth of thin permafrost to values $> 400$ m within 1500 years. On this basis it is suspected that, even if the last period of marine incursion onto the Laptev Sea shelf was shorter than assumed above - maybe only on the order of 20 ka - permafrost thicknesses today beneath the Laptev Sea shelf should be not less than 350 m to 400 m. This result compares favourably with the findings by Hinz et al., (1998), which on the basis of sea-seismic work predict a permafrost thickness of 300 m in the shelf region and up to 850 m in near-shore positions.

**Influence of Rivers on Permafrost (Model B)**

The analysis of the thermal influence of flowing rivers on the thermal field of the permafrost zone demonstrates in principle the dependence of depth of the thawed zone on the width of rivers and the time dependence of thaw development. Thaw beneath roughly the 100 m wide rivers is unable to penetrate the on-average 400 m thick permafrost layer within 9000 years, while a 1 km wide river is able to do so within 1500 years.

Figure 3. Temperature distribution within the permafrost zone as well as below the phase change boundary for (a) the case of 40 mW m$^{-2}$ (left) and (b) 60 mW m$^{-2}$ (right).
Figure 4. (a) River arms of km-width that shift their beds on fully developed permafrost, are able to produce thawing below their new beds within 1500 years.
Figure 4(b). Numerical simulation of permafrost decay and growth in a scenario of shifting river beds (see top of drawing) in a permafrost region.

- Position of rivers for $t < 5000$ years
- Position of rivers for $t > 5000$ years

$t = 4000$ years

$t = 6000$ years

$t = 7000$ years

$t = 8000$ years
(Figure 4a). The shift of a 2.2 km-wide river arm from one position to an adjacent one (new width of river is now 1.3 km) will thaw the underlying permafrost zone within slightly less than 3000 years (Figure 4b), while permafrost regrowth in the old position is to a large extent completed within the same time period.

Conclusions

The permafrost thickness in the Laptev Sea area is only substantially reduced in phases of sea water incursions, which are induced by flooding due to rising sea level during warm stages. The likely permafrost thickness at the end of a warm stage, which in our case is equivalent to the time period of flooding of the shelf area by sea water, is in the order of 70 m to 400 m depending on the regional terrestrial heat flow $q$ and on the time length of the marine incursions.

The thickness of the submarine permafrost today does depend essentially on the climatic curve of the last cold stage, and to a lesser extent on the time period of the marine incursion onto the Laptev Sea shelf as long as the incursion lasted for more than 20 ka.

On the basis of the numerical simulation, a current minimum permafrost thickness of > 350 m under the shallow water region of the Laptev Sea is expected.

During the flooding periods, a nearly isothermal temperature field near the mean annual sea water temperature will develop in the permafrost body. Under subaerial conditions, arms of the Lena River which are of km-width, are likely to melt the permafrost of the shelf area existing under their beds within a time period on the order of 1500 to 3000 years, depending on the width of the river bed. It appears that the permafrost layer during cold stages is more prone to the existence of thaw zones than during warm stages depending on the extent of side arm development of the Lena River. If, and to what extent, thawed zones under former beds of the Lena River refreeze during phases of flooding depends critically on the salt content in the sediments. If the freezing point in the “thaw zone” is above the mean annual temperature of the sea water, refreezing will occur. In that case, the permafrost layer in the Laptev Sea today potentially forms a tighter seal for vertical gas and fluid transport from below than during cold stages.

References


