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Estimation of the methane release intensity from the Arctic shelf bottom sediments

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ABSTRACT

Large reserves of carbon are preserved under conditions of subsea permafrost in the bottom sediments of the Arctic shelf. The existence of permafrost has created the necessary conditions for the thermodynamic stability of methane hydrates. Using a mathematical model that describes the thermal state of the sediment, we analyzed the dynamics of the permafrost and methane hydrates stability zone of the Arctic shelf bottom sediments for 100 thousand years in the future. Climate changes are considered under an idealized scenario of CO_2 emissions into the atmosphere and changes in the parameters of the earth's orbit. The simulations for the next 100 kyr found that at the middle and shallow parts of the shelf the subsea permafrost survives, at least, for 9 kyr after the emission onset or even for several tens of kiloyears. Model estimates of methane emission from the Arctic shelf sediments to the water amounts up to 10 g/m^2 per year.

Keywords: methane emission; methane flux; subsea permafrost; Arctic Shelf; climate change; modeling

1. INTRODUCTION

The existence of subsea permafrost in the bottom sediments of the Arctic shelf has created the necessary conditions for the thermodynamic stability of methane hydrates in the so-called methane hydrate stability zone (MHSZ) [1, 2]. The permafrost and methane hydrates on the Arctic shelf were formed during the Pleistocene glaciations when the sea level was significantly lower than the present one, and this shelf was in direct contact with the cold atmosphere [1, 3-8]. Both subsea permafrost and methane hydrates associated with permafrost have survived until the present [1, 7].

Subsea permafrost is degrading and hydrates can become destabilized, especially where geothermal flux is high, i.e., at fault zones [1, 7] or paleo-river beds [9]. Methane (CH_4) trapped in the subsea permafrost of the shelf, as well as under its base, can serve as the main source of this greenhouse gas in the atmosphere of the region. Frozen deposits are a substrate for biogenic CH_4. Methane can also migrate upward from dissociating hydrates or free gas layers as a result of increased permeability of the frozen layer.

In recent years, the East Siberian Arctic Shelf has attracted attention as a potentially important source of methane into the atmosphere [10-15]. To date, atmospheric CH_4 fluxes throughout the shelf are uncertain, and estimates in the literature vary significantly [13, 16]. Uncertainties arise from the lack of data coverage. This problem is mainly associated with the degradation of modern permafrost, the dissociation of hydrates, and the gaseous release from the sediments into the water and further into the atmosphere [16-20]. Methane fluxes may increase closer to the time of complete local disappearance of permafrost and hydrate layers, especially considering the upper estimate of the methane reserve in flooded hydrates associated with subsea permafrost at 1400 PgC [10, 21].

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The goal of our study is to obtain a quantitative estimate of methane emissions from the sediments of the Arctic shelf as a result of the degradation of methane hydrates that exist in subsea permafrost.

2. METHODS

To study the processes of the permafrost formation in the sediment of the Arctic shelf, we used the model of long-term variability of permafrost sediment (SMILES) [7, 22]. The one-dimensional Stefan problem was solved in the sediment column of depth 1500 m. The vertical size of the computational domain exceeded the freezing depth, which ensures that the lower limit of the domain does not affect the background permafrost dynamics. The boundaries of the methane hydrate stability zone in shelf sediments are calculated using the relations from the model [23], taking into account the decrease in the dissociation temperature caused by the salt effect [22].

At the sediment interface, we set time-varying boundary conditions represented by the curve of temperature changes [7]. The boundary condition on the sediments top is determined by periods of transgression-regression, taking into account changes in sea level over the past 400 thousand years. The temperature on the top of bottom sediments (*Tb*) is given as air temperature *Ta* (during periods of regressions) or as the temperature of bottom water *Tw*, taking into account the depth of the shelf (during periods of ocean transgressions). The time-dependent *Ta* corresponds to the mean monthly atmospheric temperature obtained from Climber-2 simulations for the time interval from 400 kyr B.P. to $t = 0$ [24], as described in detail in [7].

We believe that when the shelf is flooded with seawater, there is salinization. The intensity of the geothermal flux in the numerical experiments has been estimated to be 60 mW/m^2, which corresponds to the average value of the heat flux for the given region. The modeling was performed in relation to the Laptev Sea Shelf area with water depths of 10, 50 and 100 m. More detailed description of SMILES is available in [7, 22].

In this study, modeling continues over 100 thousand years for the upcoming period. It is assumed that the shelf is always covered with water. Thus, the temperature on the sediments surface for the future period is $Tb = Tw + \Delta T$. We use the continuation of the Climber-2 simulation, taking into account changes in the parameters of the Earth's orbit and anthropogenic CO_2 emissions [24]. These emissions begin in 1950 and continue for 300 years until the target cumulative emission level of 3000 PgC is reached. Thereafter, anthropogenic CO_2 emissions were set to zero and the Climber-2 simulation continued with a free-running carbon cycle. We have performed two numerical experiments describing extreme possibilities, with the lowest and highest seafloor water warming.

- TR0 does not take into account changes in the temperature of the bottom water layer, $\Delta T = 0$.
- TR3000 takes into account bottom layer warming, which corresponds to atmospheric warming, $\Delta T(t) = Ta(t) - Ta(0)$.

The content of methane in volume units of gas hydrates is estimated as [25, 26]:

$$m(CH_4) = C \cdot R \cdot \varphi \cdot Sh,$$

where C – the gas expansion coefficient from the sediment condition to the standard temperature and pressure, $C = 140$ [26]; φ is sediment porosity exponentially decreased downward from the value 0.4 at the top of the sediments; $R = 0.7168$ kg/m^3 methane density; $Sh = 0.05$ is fraction of pore volume occupied by hydrates [25, 27]. Then, total methane content per unit area of the sediments (1 m^2) is calculated by integrating $m(CH_4)$ over the estimated MHSZ.

When estimating methane emissions from bottom sediments to seawater, we assume that:

1) Methane, which is released during the dissociation of the hydrate due to the violation of the conditions for the stability of the hydrate, is instantly transferred to the interface between the bottom and water. In doing so, it undergoes chemical losses in the sulfate reduction zone. This loss is represented by the coefficient $K_S = 0.5$.

2) In the TR0 and TR3000 numerical experiments, we assumed that methane escapes as a result of hydrate dissociation both in the upper part of the MHSZ and at the bottom of the MHSZ.

3. RESULTS

As a result of the calculation carried out using the developed scenario, we estimated the dynamics of the frozen layer of bottom sediments on the Arctic shelf over the past 400 thousand years similarly to the previous result [22]. We have found that in the upper sediment's permafrost degrades at negative temperatures. Due to salt diffusion, the upper boundary of the subsea permafrost is located at a depth of 10-25 m below the seabed, depending on the water depth. The formation and existence of the methane hydrate stability zone correlates with the dynamics of the lower permafrost boundary. The thickness, as well as the thickness of the permafrost, increases with a decrease in the water depth on the shelf. However, for the MHSZ this increase is less pronounced than for the permafrost thickness. This is due to the stabilizing effect of pressure increase due to the weight of the water column.

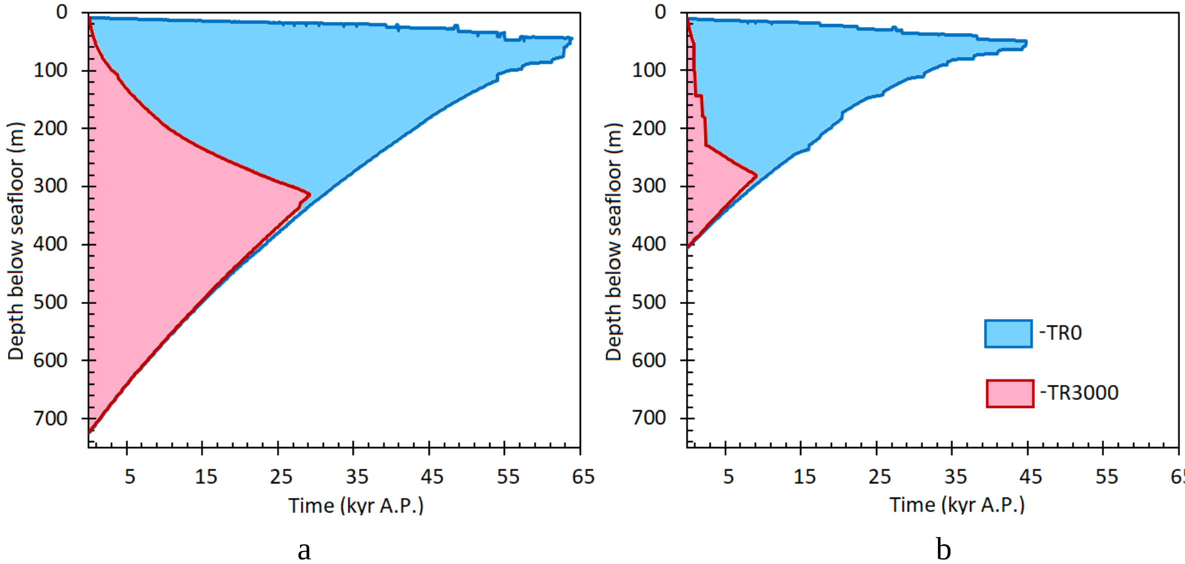

Figure 1. Evolution of the subsea permafrost in bottom sediments of the shelf, obtained in the numerical experiments TR0 and TR3000 for the shelf area with water depth: a) 10 m; b) 50 m.

On the outer shelf (water depth 100 m), permafrost and MHSZ disappear before the start of the warming period. After the onset of caused by CO_2 warming, the subsea permafrost begins to thaw at the top and the base (Fig.1). Thawing at the permafrost base is largely independent of the used warming scenario, and it is a continuation of the response to the onset of the Holocene and shelf flooding [7,22]. The average rate of thawing of the frozen layer at the base in TR0 was 10.5 and 8 m/kyr for the shallow (water depth 10 m) and middle (water depth 50 m) shelves, respectively. In the TR3000, this rate went up slightly, at 14 and 13.5 m/kyr. The thaw rate of the top permafrost, on the contrary, is heavily dependent on external emissions of CO_2 into the atmosphere. For the TR0, this rate is always less than 1 m per thousand years, irrespective of the depth of the shelf. In TR3000, the simulation rate was 10 to 30 m/kyr. Subsea permafrost persists for a long period at the middle and shallow parts of the shelf in our simulation TR0. The permafrost disappears after 45-64 thousand years, according to the water depth (Fig.1). The time until permafrost disappears from the Arctic Shelf is highly dependent on the water depth of the shelf and the intensity of CO_2 emissions (Fig. 1). Timings of the disappearance of subsea permafrost decreases with increasing thickness of the water layer, since the shallower modern depth of the shelf leads to a thinner layer of permafrost at $t = 0$. In the middle and shallow parts of the shelf in the TR3000 experiment, the frozen layer completely disappears after 9-29 thousand years.

The decrease of MHSZ in the absence of warming in the bottom water layer (TR0) occurs mainly at the base. This process is primarily a consequence of the Holocene sea transgression, as a result of which both permafrost and methane hydrates found themselves in non-equilibrium conditions of existence. For a shallow shelf, the model thickness of MHSZ was about 1150 m (Fig. 2a). The period of possible existence of MHSZ for this part of the shelf in the future does not exceed 40 thousand years. The thickness of the MHSZ on the middle shelf reaches 550 m (Fig. 2b). Here it disappears twice as fast in 20 thousand years. In TR3000, after the start of CO_2 emission, MHSZ starts to decrease from the side of the upper boundary at a faster rate (Fig.2). In the shallow and middle parts of the shelf during the first thousand years after the beginning of the emission, the MHSZ reduction rate varies from 1 to 4 m per thousand years. This is in agreement with the scale predicted in works [28, 29].

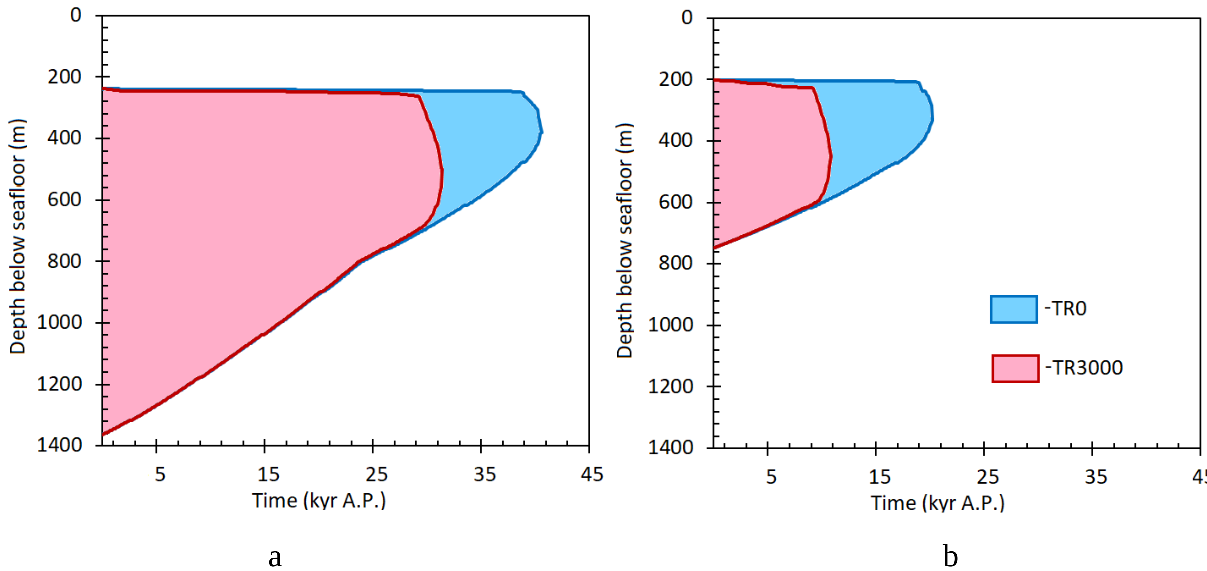

Figure 2. Evolution of the methane hydrate stability zone in bottom sediments of the shelf, obtained in the numerical experiments TR0 and TR3000 for the shelf area with water depth: a) 10 m; b) 50 m.

The MHSZ reduction leads to the degradation of gas hydrates and the emission of methane from bottom sediments into the water. The calculated methane fluxes for the next 45 thousand years, averaged over 1000-year intervals, are shown in Fig. 3. Methane emission for the current period was 2-4 g/m^2 per year.

Accounting for warming in the near-bottom water layer (TR3000) has led to an increase in methane emissions both on the shallow and on the middle shelf. The methane flux in the next millennium amounted to 3–10 g/m^2 per year. The maximum methane emissions are timings of complete disappearance of MHSZ. Thus, the methane flux from bottom sediments of the middle shelf can be up to 70-90 g/m^2 per year in 10 thousand years according to the results of TR3000 and after 20 thousand years in TR0.

4. CONCLUSION

In the simulations for next 100 kyr forced by the output of an Earth System model with internally calculated ice sheets as driven by idealized scenarios of CO_2 emissions and by changes of the parameters of the Earth orbitwe found that at the outer shelf permafrost and the methane hydrate stability zone disappear either before the emission onset or during few centuries in future. In contrast, for the middle and shallow parts of the shelf the subsea permafrost survives, at least, for 9 kyr after the emission onset or even during several tens of kiloyears.

In the shallow and middle parts of the shelf, the methane hydrate stability zone disappears no earlier than after 10-30 thousand years. In the scenario without taking into account warming, the MHSZ remains in the bottom water layer for up to 20-40 thousand years.

We estimated the methane emission from bottom sediments to water for the current and future. Accounting for warming in the bottom water layer has led to an increase in methane emissions both on the shallow and the middle shelf. Our modeling suggests that the methane emission in the water amounts to 3–7 g/m^2 per year.

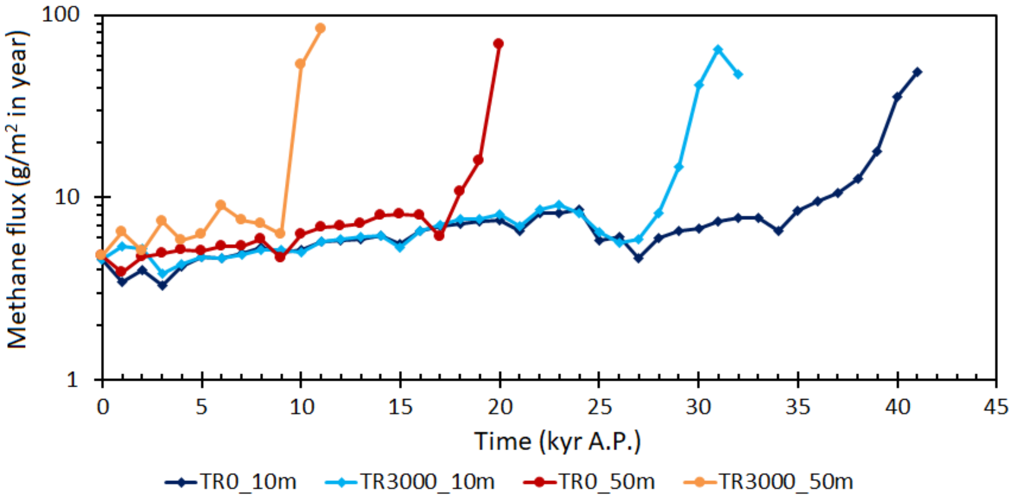

Figure 3. Methane flux from sediments to the ocean obtained in the numerical experiments TR0 and TR3000 for the shelf area with water depths of 10 m and 50 m.

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