The response of the Arctic Ocean gas hydrate associated with subsea permafrost to natural and anthropogenic climate changes

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Abstract. We present an assessment of changes in the gas hydrates stability zone of the Arctic Ocean associated with subsea permafrost conditions. To evaluate the formation and dissociation of gas hydrates under the climatic conditions of the last glacial cycle, it is necessary to understand how the thickness of the permafrost has changed after flooding by the sea. To do this, we have combined two numerical models: a model of permafrost dynamics based on the paleoclimatic scenario of changes in temperature and ocean level, and a model of the methane hydrates stability zone (MHSZ). Calculations of changes in the thickness of the submarine permafrost and the MHSZ were carried out for the period of 120 thousand years. Our results show that, although changes in the bottom water temperature over the last-decades period affect the hydrate stability zone, the main changes with this zone occurring after flooding the Arctic shelf with the seawater. As a result of the combined simulation of the permafrost and state of MHSZ, it was found that in the shallow shelf areas (lower 50 m water depth) after flooding, the hydrate presence conditions in the upper 100-meter layer of the MHSZ are violated. This suggests that the methane coming from this reservoir is concentrated in the bottom sediments of the shelf, and then released into the water, continuing to adapt to changing sea levels, rising bottom water temperatures, and subsea permafrost melting.

1. Introduction
Gas hydrates are crystalline compounds of gases and water of a variable composition and have similar to the ice physical properties [1]. Gas hydrates are formed upon the contact of gas and water under certain thermobaric conditions. Natural gas hydrates, found in large quantities in the bottom sediments of the seas and oceans [2], are a possible source of methane, which can manifest as a result of an increase in the bottom water temperature or a decrease in the ocean level.

A large amount of methane is preserved in gas hydrates of the marine sediments of the Arctic Ocean [3-5]. Due to the dissociation of hydrates, a gas flux in the offshore areas can result in gaseous precipitates with a greater compressibility than the same sediment without gas. This can cause certain problems in the process of offshore gas and oil production [6]. Methane hydrates can also be dangerous for the climate due to the release of methane in the course of the decomposing hydrates [7]. Since methane is a greenhouse gas, the release of methane into the atmosphere may have the global warming effect.
The hydrate dissociation can occur for many reasons. One of them is an increase in ocean temperature. The submarine methane hydrates of the Arctic Ocean are subject to thermal effects during the warming of the bottom water layer [7-11]. Submarine hydrate deposits existing in bottom sediments at the sea depths of 250-300 m are sensitive to current climate changes. The earlier calculations [12, 13] confirm that the shallow marine gas hydrate deposits could be affected by climate changes, mainly, by a temperature increase. In [14], based on an analysis of satellite data, it was concluded that methane emissions from the Arctic Ocean are slightly less than those of methane from the continental Arctic.

The shallow continental shelves of the Arctic (with a depth of less than 120 m) are underlain by permafrost [15-18]. The permafrost formed in the continental conditions and was subsequently submerged as a result of the postglacial sea-level rise and the inundation of the permafrost tundra. Conservative assumptions yield an estimated 20 Gt C sequestered in arctic permafrost-associated gas hydrates [19]. As was noted above, the marine gas hydrates can form in the Arctic Ocean with a water layer exceeding thickness ~ 250-300 m. The gas hydrates associated with the submarine permafrost are currently in sediments covered with a maximum of 100-120 m of water. This determines their destabilization caused by the warming of bottom sediments after flooding. Thawing of the subsea permafrost and the methane hydrates destabilization in the sediment of the East Siberian Arctic shelf are considered to be responsible for very high concentrations of dissolved methane in the water column (> 500 nM) and for increased methane flux into the atmosphere up to 17 Tg per year [20]. However, simultaneous measurements of methane in the atmosphere and surface water, during July and August 2014, show flux of methane from the Siberian shelf seas to the atmosphere of 2.9 Tg per year [21]. The processes that regulate the degradation of gas hydrates associated with the subsea permafrost on the shallow Arctic shelf are not well understood [22, 23].

In this study, we estimate the thickness and propagation of the methane hydrates stability zone (MHSZ) and the climate change impact on its condition. We consider methane hydrates associated with the subsea permafrost on the shallow Arctic shelf with a water depth of less than 120 m. To study the evolution of gas hydrates of the Arctic shelves associated with the subsea permafrost, it is necessary to understand what the thickness of the permafrost has changed after flooding by the sea. To this end, we have combined two numerical models: the dynamics permafrost model [17, 24], which is based on the paleoclimatic scenario of changes in the temperature and ocean level, and the model of the gas hydrates stability zone [25]. We use a one-dimensional model because most hydrates are found in hydrated reservoirs, in which there is no significant lateral spread [26]. It is assumed that methane is the only gas component in the system; therefore, all the values used refer to hydrate of pure methane.

2. Methods
It is assumed that the subsea permafrost was formed on land in the cold age during a period of the ocean regression and the drying of the shelf. We proceed from the assumption that the shelf area with depths of up to 120 m during the ice ages was land [16]. On it, as a result of freezing under the influence of low temperatures of the atmosphere, the permafrost was formed, in whose structure methane could be included in the form of gas hydrates. In the process of subsequent ocean transgressions, the flooding of frozen sediments is specified.

To analyze the climate change effect on the thermohaline structure of the Arctic Ocean, the subsea permafrost of the Arctic shelves, and the methane hydrates stability zone, we use a set of interacting numerical models. We have combined two numerical models: the model of thermophysical processes in the bottom sediments of the ocean [24], based on the model of ground permafrost; the model for calculating the thermobaric conditions for the existence of methane gas hydrates [27].

2.1. Modeling of thermal processes
We use the model for thermal state of subsea sediments [17, 24]. The model solves the one-dimensional equation for heat diffusion in sediment column for the unfrozen and frozen layers subject to prescribed temperature at the sediment–ocean interface and prescribed heat flux at the bottom
boundary. In addition, the present study considers the influence of the pore water salinity on the rate of destruction of frozen sediment. We add diffusion of salt to the existing model [17].

We determine bottom boundary condition using a global heat flux database which is presented on 2x2 equal area grid [28]. The depth of the latter boundary is set to 1500 m. The model for thermal state of subsea sediments was run at a discrete vertical grid with the step of 0.5 m. Time stepping scheme is implicit with the time step equal to 1 month.

2.2. Methane hydrate stability zone

To identify the part of the sediments, where there are appropriate conditions for the existence of methane hydrates, we use the thermobaric model that determines the pressures and temperatures at which the phase changes between the frozen gas hydrate and free gas occur. The code version [25] was used to calculate pressures at which hydrates are stable based on a given temperature and salt concentration.

\[ \ln(P_H) = \sum_{n=0}^{3} a_n (T + T_D)^n \]  \hspace{1cm} (1)

where \( P_H \) is the phase equilibrium pressure (MPa), \( T \) is the sediment temperature (K), \( T_D \) is the salt induced temperature depression (K) and \( a_n \) are empirical constants for the unfrozen and frozen layers [25]. The relationship (1) covers a wide temperature range and is a general regression expression based on data from several researchers.

The dissolved substances, including salts, such as sodium chloride, can have a significant effect on the thermodynamic stability of methane hydrates [29]. The equilibrium temperature decreases relative to the pure water temperature [30]. Since the hydrate stability is closely linked with temperature, a corresponding shift in the equilibrium pressure also takes place. This shift in the equilibrium temperature can be solved as follows [31]: \( T_D = 0.6825 T_F \). This temperature depression is incorporated into the pressure-temperature equilibrium relationship for methane–hydrate system (1). Temperature of initiating water freezing:

\[ T_F = -0.073 \cdot P - 0.064 \cdot S \]

Here \( T_F \) is the freezing temperature of water in the sediments pores, \( P \) is the pressure (MPa), \( S \) is the pore water salinity (‰).

2.3. Surface forcing

The model of thermophysical processes in bottom sediments is supplemented by the scenario of a climate change on the Arctic shelf for the last 120 thousand years [24]. The surface temperature of the bottom sediments is set depending on the conditions in which the shelf is located. When a shelf is exposed to the atmosphere, this temperature is calculated as the sum of the present-day annual mean surface air temperature at the near shore and is a time-varying anomaly constructed from the Vostok ice core data [32]. It is assumed that after the flooding of the shelf by the sea, the sea water temperature does not significantly differ from that of today, corresponds to the average annual values for the shelf seas [33, 34], and depends on the coordinates and varies from the coast towards the edge of the shelf.

To assess the current state of the subsea permafrost and the MHSZ for the period 1948-2015, the temperature and salinity of the bottom water were obtained from the numerical model of the ocean and sea ice (SibCIOM) [35-37]. The model reproduces the variability of the state of the Arctic Ocean with forcing by the daily atmospheric fluxes, calculated with the NCEP/NCAR reanalysis (http://www.esrl.noaa.gov/psd/data/reanalysis/ reanalysis.shtml) [38]. The model of thermophysical processes in the bottom sediments of the Arctic seas was adapted to the computational grid of the ocean-ice model. In this study, we proceed from the assumption that the main differences in the physical and geographical conditions on the shelf are the scheme of transgressions - regressions,
geothermal flow [28], temperature and salinity fields (based on the average climatic data [39]) for paleo conditions. The main differences for present-day conditions, starting from 1948, are the simulated temperature and salinity field of bottom water [37, 40]. This approach allows us to analyze the temporal and spatial changes in the state of the stability zone of gas hydrates in the Arctic Ocean, as well as to identify the areas that are most sensitive to possible climatic changes.

3. Results

The calculations have been carried out for the interval ranging from 120 thousand years ago (BP) up to the present. When setting the initial conditions, it is assumed that the shelf is below the sea level and there are no frozen rocks. A change in the shelf surface temperature over the calculation period of 20 thousand years is shown in Figure 1 for shelf with a depth of 20 m and 70 m. A strong dependence of the duration of the transgression or regression periods on the current shelf depth determines the formation of permafrost of various thicknesses. The duration of the periods of transgression and the corresponding periods of degradation of submarine permafrost increases with an increasing depth (Figure 1).

![Figure 1](image)

**Figure 1.** Temperature at the top of sediments (black line), depth of the permafrost base (blue line) and top (red line), and depth of the MHSZ top in the sediment (green line) in simulation with a present-day water depth, (a) 20 m, (b) 70 m.

According to the calculations, the thickness of the permafrost layer in the bottom sediments of the shelf depends on the depth of the sea, geothermal flux, salinity pore water and ranges from 0 to 700 m, Figure 2. The obtained thickness of the permafrost decreases with an increasing distance from the coast. Large heat fluxes in the rift areas and on the outer shelf bring about more severe permafrost degradation. The edge of the current submarine permafrost is located on the outer shelf with a water
depth of ~ 100 m in the seas of the East Siberian shelf. A more limited distribution of the relict permafrost is observed under the continental shelves of the Kara Sea. A minimum spread of the permafrost distribution in the bottom sediments of the Barents Sea probably means that the permafrost has already dissociated because of the onset of the flood after the last glacial maximum or was influenced by the cover glaciation [41, 42].

Figure 2. The simulated depth of the subsea permafrost bottom boundary (in meters) for 1948 over the Arctic region. The extent of the subsea permafrost is assumed to be the 120 m isobaths.

The position of the upper permafrost boundary in the bottom sediments depends on the depth of the sea and the salt content. In the numerical experiment, it was found that the upper boundary of the subsea permafrost is located at a depth of 12 - 27 m below the seabed, depending on the shelf area (Figure 1).

When the thickness of the permafrost reaches a value of about 250 m, the formation of the MHSZ begins. Like the dynamics of the permafrost, the dynamics of the MHSZ boundaries characteristics depends on the current shelf depth. However, for hydrates, this increase is less pronounced than for the permafrost thickness. This is due to the stabilizing effect of an increased pressure due to the weight of the water column. As a result of the study, conducted, for the Arctic shelves, the thickness of the MHSZ was obtained as 0 - 800 m depending on the water depth on the shelf, Figure 3a. At the same time, the upper boundary of the MHSZ is at a depth of 120 - 220 m under the seabed, Figure 3b, which makes the gas hydrate layer weakly sensitive to an increase in the temperature of the bottom water. The influence of salt on the characteristics of the stability zone of methane hydrates in subsea permafrost is insignificant due to their large depth in the shelf sediments.

An increase in pressure in the case of transgression on the shallow shelf has an insignificant short-term effect on the gas hydrates associated with the subsea permafrost (Figure 1a, 2a). It should be noted that in the initial period of transgression (with a corresponding increase in pressure on the bottom), the MHSZ is increasing over several centuries, Figure 1. Subsequently, an increase in temperature in the bottom sediments leads to a reduction in the MHSZ. The most pronounced deepening of the upper boundary of the MHSZ for this period is characteristic of the shallow shelf and amounts to 85 m, Figure 1a, Figure 4a. Thus, in spite of significant sea level variations in the Pleistocene glacial cycles, the main role in the formation of the MHSZ response is played by a change in the sediment temperature in these cycles.
Figure 3. The simulated gas hydrate stability zone (in meters) for 1948 over the Arctic region: a – the thickness of the MHSZ, b - depth of the MHSZ top in the sediment.

The shift of the upper boundary of the MHSZ for the period from 1948 to 2015 did not exceed 6 m due to changes in temperature in the sediment, Figure 4b. The gas hydrate layer remains a frozen soil layer isolated from the surface of the seabed. At the obtained permafrost degradation rates, the MHSZ will remain isolated for several thousand years.

Figure 4. The map showing the regions where the position of the upper boundary of the MHSZ is changing (in meters). Positive values mean a shift of the upper boundary downward and negative values mean a shift upward or a complete disappearance of the MHSZ. (a) A change of the depth of the MHSZ upper boundary value for 1948 minus the value for 20 year ago, (b) the value for year of 2015 minus the value for 1948.

4. Conclusion

The created combination of the numerical models: the dynamics model of permafrost, and the model of the gas hydrates stability zone, which are based on the paleoclimatic scenario of changes in temperature and ocean level, makes it possible to identify the stable state areas and degradation of both the subsea permafrost and the methane hydrates layer. The analysis made does not confirm that the intensity of degradation of the subsea permafrost and methane hydrates on the shelf of the Arctic seas is present day due to modern climate changes. The submarine permafrost degradation occurs as a result of the oceanic transgression and its intensification is manifested in the areas where the thermokarst lakes have developed [34].
The results of the simulation of the dynamics of the stability zone of methane hydrate in sediments of the Arctic Ocean associated with the submarine permafrost are presented. The time scales of the response of methane hydrates of the Arctic shelf to a climate change in the glacial cycles are estimated. Our results show that although changes in the bottom water temperature over the modern period affect the hydrate stability zone, the main changes with this zone occur after flooding the shelf with the sea water. As a result of the combined modeling of the permafrost and the state of MHSZ, it was found that in the shallow shelf areas (less than 50 m water depth) after flooding the hydrate existence conditions in the upper 100-meter layer of the MHSZ are violated.

It was found that the temporal scale of the propagation of a thermal signal in the subsea permafrost layer is 5–15 thousand years [16, 24]. This time scale exceeds the duration of the Holocene. The large time scale of the response of characteristics of the subsea permafrost and the hydrate stability zone of the Arctic shelf indicate to the fact that globally significant releases of methane from hydrates, either in the past or in the future require millennia. This suggests that methane from hydrate associated with the submarine permafrost is concentrated in the bottom sediments of the shelf, and then released into the water, continuing to adapt to the changing sea levels, rising bottom water temperatures, and subsea permafrost melting.

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