Stability of relic methane hydrates under climatic changes in the Holocene

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Abstract. The results of numerical modeling of the thermal regime of high-latitude permafrost regions of Western Siberia (the Yamal Peninsula) for the last 6 thousand years are presented. Thermobaric conditions for stability and dissociation of continental methane hydrates are defined. It is shown that at the present time relict methane hydrates can exist at depths of up to 150 m in the strata of frozen soil of Yamal above the modern boundary of the stability zone, having “survived” warming in the Mid-Holocene warm period (about 6,000-5,000 years ago) at negative temperatures in the permafrost. According to the results obtained, the current warming in Yamal region exceeds the warming of the Mid-Holocene. The increase of the temperature of the permafrost layer can reduce the strength of the soil and lead to dissociation of the near-surface gas hydrates.

1. Introduction

The most significant growth of the near-surface temperature occurs in the high and middle latitudes of the Northern Hemisphere and may continue in the 21st century and the next few centuries [1, 2]. According to observational data and simulation results, the spatial structure of the permafrost temperature response to near-surface warming has regional maxima in the north of Western Siberia [3-5]. The maximum increase in the active layer depth in the 21st century is also associated with this region, according to calculations with global climate models [6-8].

The raise of the soil temperature reduces the strength of frozen soil and can lead to dissociation of relict methane hydrates located above the modern boundary of the hydrate stability zone, which are sensitive to changes in the soil temperature. A probable reason for the formation of hydrates in the upper horizons of the cryolithozone is the baric factor that might be explained by the pressure of overlying ice sheet or by marine transgression. The results of calculations with a dynamic model of thermophysical processes in the glacier-soil system show that the upper boundary of the stability zone of methane hydrates could reach the soil surface [12 -14] in Yamal region during glaciation periods about 95-80 and 70-60 thousand years ago [9-11].

The warming that began more than 10 thousand years ago with a maximum about 6 thousand years ago led to the fact that the southern boundary of the permafrost in Western Siberia moved northward towards about 68th degree north [5, 15], but Yamal region remained in the permafrost. Due to the soil temperature increase, gas hydrates located in the frozen soil could have existed above the modern boundary of the stability zone (at depths of up to 100-150 m), and remain in a metastable state as a result of the self-preservation effect at negative temperatures. In particular, experimental data indicate
that methane hydrates can exist in a metastable state at a negative temperature of about \(-6^\circ C\) in the pore space of frozen soil for a considerable time [16, 17].

According to one of the hypotheses, the current warming can lead to dissociation of the underlying surface gas hydrates and can be one of the causes of gas emissions into the atmosphere. This hypothesis is supported by the fact that since 2014 craters with a diameter of about 10–20 m with traces of discarded rocks have been found on the Yamal Peninsula and in neighboring regions. This may be a consequence of an increase in the near-surface temperature in the recent years with dissociation of shallow deposits of relict methane hydrates [18–20]. The absence of traces of external exposure and combustion, as well as an increased concentration of methane in the funnel, serve as an evidence of gas release into the atmosphere [18]. Gas emissions in this region are not related to the gas flow from the underlying lithospheric layers because, according to isotope analysis, the gas taken from sediments to depths of about 120 m on Yamal contains nitrogen, which is of biochemical origin and is formed as a result of microbial processing of the organic matter contained in soil [21]. Large gas flows, as well as the composition, structure, and properties of the frozen soil in Yamal region indicate possible existence of gas accumulations in hydrate form [21]. Small depths and location above the boundary of the stability zone indicate that the gas emissions may be a result of dissociation of relict methane hydrates.

The aim of this study is to assess the response of the permafrost thermal state to the most significant climatic changes of the Holocene, in particular, in the Mid-Holocene, and at the end of the 20th - beginning of the 21st centuries.

2. Numerical simulations

To obtain estimates of the soil temperature regime and the thermobaric conditions for the existence of methane hydrates in the permafrost of the Yamal Peninsula in the Holocene (during the last 6 thousand years), calculations with the model of heat transfer in the soil were performed [22, 23]. The results of the calculations with the global climate model CLIMBER-2 [24] in the period from 6 thousand years ago to the middle of the 20th century (1950) were used as external atmospheric forcing. For 1950-2010, CERA-20C reanalysis data were used [25] for Yamal region (66N–73N; 65E–75E). This reanalysis reproduces the temperature anomalies in the Northern Hemisphere most realistically [25]. It reproduces the spatial structure of the temperature changes, as well as the periods of warming and cooling, in particular, in the 1970s [26].

In the numerical experiments, the depth of the computational area in the soil was taken to be 1500 m. The soil thermal characteristics were chosen to correspond to clay loam in accordance with the drilling data from Yamal region [27]. The concentration of salts in the pore solution, lowering the water freezing point in the permafrost were also taken into account, and the temperature of the water-ice phase transitions during the modeling of the soil thermal regime was assumed to be \(-1^\circ C\). At the initial time, the soil temperature profile was determined by solving the stationary heat transfer equation for the average annual surface air temperature at the specified heat flux at the lower boundary of the computational domain. For the upper boundary of the region, the temperature of the surface soil (or snow, if any) was taken to be equal to the surface temperature for this region, according to the CLIMBER-2 model calculation results and reanalysis data. The geothermal flux at the lower boundary was assumed to be 50 mW/sq.m, which corresponds to the average heat flux for this region [28]. The snow accumulation dynamics was taken into account according to the CLIMBER-2 model precipitation data and from the CERA-20C reanalysis.

The equilibrium equations for the existence of methane hydrates in thawed and frozen environments were used during the simulations of the stability zone of methane hydrates [29]. In the model, the soil pressure is calculated as hydrostatic.

3. Results and discussion

Analysis of the results of calculations with CLIMBER-2 and reanalysis data revealed a negative trend in the surface temperature in Yamal region starting from the Mid-Holocene to the modern period, which is consistent with paleo reconstructions based on palynological data [30]. The average monthly
surface temperatures on the Yamal Peninsula in the Mid-Holocene (5,500 years ago) and in the mid-20th century (1950-1960) according to the CLIMBER-2 model results and in the first decade of the 21st century using CERA-20C reanalysis are presented in Figure 1a. The temperature in the middle of the 20th century is lower than the temperature in the Mid-Holocene in summer, as well as in winter in January and February. In the spring and autumn periods in the middle of the 20th century the surface temperature is higher compared to the Mid-Holocene.

![Figure 1. CLIMBER-2 model surface temperature and CERA-20C reanalysis data (a), snow depth (b), seasonal thawing depth (c), and soil temperature at a depth of 10 m (d) for Mid-Holocene (blue curve), mid-20th century (green curve), and the modern period (red curve).](image)

A comparison of the results of calculations with the CLIMBER-2 model and reanalysis data showed that the current near-surface warming exceeds the warming in the Mid-Holocene. The greatest difference (about 5°C) was obtained for the winter period. In the autumn seasons the values of the near-surface temperature at the beginning of the 21st century are also higher by 2-3°C compared to the Mid-Holocene. The temperatures for the summer periods for the beginning of the 21st century and for the Mid-Holocene are almost equal.

The trend of surface temperature increase in the region for 1950-2010 is 0.03°C/year according to CERA-20C reanalysis, which is consistent with the observational data [5] (0.02-0.03°C/year). The results of calculations obtained in [31] demonstrate that the global surface temperature at the beginning of the 21st century (2000–2009) could also exceed the Mid-Holocene temperatures by 0.3°C.

The calculated snow depth for the beginning of the 21st century exceeds that of the middle of the 20th century and the Mid-Holocene. The underestimation of the snow depth in the Mid-Holocene in CLIMBER-2 calculations is associated with an underestimation of precipitation by the model. This
underestimation leads to the disappearance of the snow cover in May in the Mid-Holocene and, therefore, to earlier permafrost thawing, according to the simulations.

The maximum thawing depth is dependent on the air temperature in the warmest season and is estimated to be about 1.1 m at the beginning of the 21st century and in the Mid-Holocene. Higher autumn temperatures at the beginning of the 21st century compared to the Mid-Holocene lead to later soil freezing during this period. The model estimates of the maximum thaw depth do not correlate with the snow cover thickness. This is due to the numerical scheme specifications, which consider the major amount of heat loss during the thawing of ice-containing soil to be consumed by the ice-water phase transition. The energy amount needed for heating the ice-saturated soils depends on the initial soil temperature, but even for low-temperature permafrost it does not exceed 5-10% of the energy amount required for ice melting. The snow cover has a heat insulating effect on the permafrost in winter.

The soil temperature of the upper horizons at the beginning of the 21st century exceeds the temperature in the middle of the 20th century and in the Mid-Holocene (Figure 1d) due to the higher average annual air temperature and the greater snow cover thickness in the 21st century. Thus, the obtained estimates of the soil temperature at a depth of 10 m are about -5°C for the beginning of the 21st century, which is consistent with observations [32]. For all three periods simulated, the minimum annual temperature values for 10-m depth are reached in summers due to thermal inertia, which creates a phase shift between the temperature fluctuations at different depths.

Figure 2 presents the results of the calculation of the average annual soil temperature for Yamal region over the past 6 thousand years. The soil temperature in the upper 100-150 m of the permafrost in the Mid-Holocene was about -6°C – -7°C. Starting from about 4000 thousand years ago, the temperature of the soil drops to -7°C – -8°C in the upper 20 m and to -6°C at a depth of 100 m.

At the same time, the trend of soil temperature decreases with depth. A significant increase in the soil temperatures in the upper layers of 50-60 m was obtained for the modern climatic conditions (Figure 2).

Figure 3 shows the soil temperature profiles for the Mid-Holocene, mid-20th and early 21st centuries. According to the results obtained, the current near-surface warming in the north of Western Sibe-
ria exceeds the warming in the Mid-Holocene about 6 thousand years ago. The current soil temperature in the upper few tens of meters exceeds the soil temperature in the Mid-Holocene, and may exceed the threshold temperature for the dissociation of methane hydrates. In addition, near-surface warming, particularly in Yamal region, also contributes to the permafrost degradation. As a result, this can lead to the dissociation of gas hydrates and gas emissions with the destruction of frozen soil [13]. One can also see that the permafrost thickness in the region simulated decreases from 500 m about 6 thousand years ago to 430 m under the current climatic conditions.

Based on the model estimates for the vertical temperature and pressure distribution in the permafrost, the temperature and pressure conditions for the equilibrium state of methane hydrates were calculated, and the depth of the upper and lower boundaries of the stability zone was determined. It was found that the upper boundary depth of the stability zone of methane hydrates in the Mid-Holocene drops from 194 m to 220 m as a result of warming during this period. With a subsequent decrease in the air temperature, the model depth of the stability zone boundary remains almost unchanged and is located within the frozen strata. The results of the calculation of the thermobaric conditions show that at the present time stable methane hydrates may exist at depths of more than 200-250 m in the frozen soil masses of Yamal, together with relict methane hydrates that persist at depths of up to 150 m [9] at negative temperatures below -7°C over the past 6 thousand years, including the Mid-Holocene. The disruptions of stability of methane hydrates near the surface may be a result of the current climate change.

4. Conclusions
The above analysis of the calculation results of the global climate model CLIMBER-2, the CERA-20C reanalysis and the calculation results of the permafrost thermal regime revealed that the current warming may exceed the warming in the Mid-Holocene, particularly in Yamal region. The average annual near-surface temperature in this region at the beginning of the 21st century can be higher than the temperature in the Mid-Holocene due to warmer winters and autumns. According to the results of the calculations, modern climatic changes lead to an increase in permafrost temperatures. At the same time, soil temperatures in the upper horizons (several tens of meters below the surface) can exceed the equilibrium temperature of metastable methane hydrates. This affects the stability of the relict hydrates of
the continental cryolithozone gases which are located above the present-day stability zone boundary. Near-surface warming also contributes to reducing the strength of the frozen soil. As a result, this leads to frozen soil destruction and dissociation of the gas hydrates which "survived", in particular, the Mid-Holocene warming.

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