Analysis of the subsea permafrost dynamics at the Arctic shelf accounting for climate change uncertainty during glacial cycles

Malakhova, Valentina, Eliseev, Alexey

Valentina V. Malakhova, Alexey V. Eliseev, "Analysis of the subsea permafrost dynamics at the Arctic shelf accounting for climate change uncertainty during glacial cycles," Proc. SPIE 11560, 26th International Symposium on Atmospheric and Ocean Optics, Atmospheric Physics, 115606D (12 November 2020); doi: 10.1117/12.2575081

Event: 26th International Symposium on Atmospheric and Ocean Optics, Atmospheric Physics, 2020, Moscow, Russian Federation

Analysis of the subsea permafrost dynamics at the Arctic shelf accounting for climate change uncertainty during glacial cycles

Valentina V. Malakhova*[a], Alexey V. Eliseev[b,c,d]

[a]Institute of Computational Mathematics and Mathematical Geophysics of SB RAS, Prospect Academika Lavrentieva, 6, Novosibirsk, Russia, 630090; [b]Lomonosov Moscow State University, Faculty of Physics, 1-2 Leninskiye Gory, Moscow, Russia 119991; [c]A.M. Obukhov Institute of Atmospheric Physics RAS, 3, Pyzhevsky, Moscow, Russia, 119017; [d]Kazan Federal University, 5 Tovarishcheskaya, Kazan, Russia, 420097

ABSTRACT

The changes in the characteristics of submarine permafrost within the ocean shelf have been analyzed using a mathematical model describing the thermal state of the soil and supplemented with the salt diffusion equation. The model is complemented with reconstructions of climate changes at the Arctic shelf over the past 400 thousand years with two combinations of air temperature and sea level reconstructions. The estimates of the subsea permafrost sensitivity to the uncertainty of paleoclimatic reconstructions of air temperature and ocean level have been obtained. The time scales of the Arctic shelf submarine permafrost response to climate change in the glacial cycles have been estimated. The temporal scale of the propagation of the thermal signal in the permafrost layer of the shelf sediment amounted to 4-12 thousand years.

Keywords: submarine permafrost; subsea permafrost; Arctic shelf; glacial cycles; sea level; paleoreconstruction

1. INTRODUCTION

Based on the instrumental data there have been increases in the global near-surface atmospheric temperature over the past 150 years. A linear trend of atmospheric surface temperature under global averaging over the 20th century is estimated as 0.6–0.8 K/century [1]. It is commonly accepted that such warming is caused by the anthropogenic impact, primarily, by greenhouse gas emissions into the atmosphere. It is of crucial importance to place the current changes in the climate and in the biogeochemical cycles characteristics into the context of the climatic changes known for the past.

One of the potentially important biogeochemical processes is the methane release out of permafrost and gas hydrates of the Arctic shelf under climate warming [2]. The estimates of the response periods of submarine permafrost and gas hydrate stability zone amount to at least several thousand years [3, 4]. This time scale significantly exceeds the time scale associated with current climate warming (decades and centuries) and suggests that this methane flux us due to adjustment of the Earth system to the termination of the last glaciation. It should be pointed out that such time scales combined with limited knowledge of the thermophysical condition of bottom sediments in the Pleistocene require numerical calculations to be conducted within long time periods. In particular, at least one complete glacial cycle (120 thousand years) is necessary to study the submarine permafrost and methane hydrates evolution [3, 4].

In order to analyze the evolution of submarine permafrost of the Arctic shelf and to evaluate its current state, the paleogeographic reconstructions of climatic conditions development in the region are to be set up [3-8]. There are significant quantitative differences between the available temperature reconstructions for the Pleistocene glacial cycles. According to the MARGO project [9], the range of decrease in the average annual ocean surface temperature for the Last Glacial Maximum relative to the pre-industrial period amounts to 1.9 ± 1.8 K.

*malax@sscc.ru; phone 7 383 330-64-50; fax 7 383 330-87-83

26th International Symposium on Atmospheric and Ocean Optics, Atmospheric Physics, edited by Gennadii G. Matvienko, Oleg A. Romanovskii, Proc. of SPIE Vol. 11560, 115606D
 · doi: 10.1117/12.2575081

Within some regions such uncertainty is significantly higher compared with global estimates. For example, as far as the shelf of Eastern Eurasia is concerned, the uncertainty for the Last Glacial Maximum (LGM) temperature change ranges from 4 to 8 K based on the simulations [10]. Considering the aforementioned uncertainty with regard to the past climate changes, it is important to understand sensitivity of the subsea permafrost response to the temperature and sea level changes being used [11-16].

Salt transport processes significantly influence the condition of marine cryolithozone [17]. Most studies of the submarine permafrost condition disregard explicit salt transport. The simulation is performed with prescribed negative freezing temperature, which is selected for certain salts concentration and the assumption of constant salinity in the context of bottom sediments. So, in the papers [3, 4], when exploring permafrost layer evolution, the freezing temperature was set to -1 or -2 ° C with no change at different depth.

The changes in the characteristics of submarine permafrost within the ocean shelf have been analyzed using a physical and mathematical model describing the thermal state of the soil [4, 5] and supplemented with the salt diffusion equation [18]. The model is complemented with reconstructions of climate changes on the Arctic shelf over the past 400 thousand years with two combinations of air and sea level temperature reconstructions [19-21]. The time scales of the Arctic shelf submarine permafrost response to climate change in the glacial cycles have been estimated.

2. MATERIALS AND METHODS

We have applied a soil heat transfer model with due account for phase transitions to calculate thermal field in a sedimentary layer and to determine the lower and upper boundaries of the cryolithozone. The one dimension mathematical model is based on the formulation of the Stefan`s problem with mixed boundary conditions. Our modeling framework includes the heat conduction equations for thawed and frozen layers of a geological cross section (under the condition of their contacts junction) [4]. The model is supplemented with the salt diffusion equation [18]. Salinity impact on the freezing temperature entails a relation between the heat transfer and salt transfer equations for a frozen layer, meanwhile heat and salt transfer in unfrozen soil is independent relative to each other [18]. It is assumed that bottom sediments are moisture-saturated. The salt diffusion coefficient was taken equal to 10^{-9} m^2/s in accordance with the estimates based on the drilling data from the Laptev Sea [22, 23]. The thermophysical properties in the model (thermal conductivity in thawed and frozen state, volumetric heat capacity of thawed and frozen rocks, volumetric latent heat of fusion, and unfrozen water) are set depending on rock composition in accordance with [22].

The lower boundary of the model domain was defined at a depth of 1.5 km. According to preliminary theoretical assessment, such region dimensions ensure the lower boundary of the equilibration region not to influence dynamics of the permafrost base [24]. At the lower boundary of the equilibration region we set a geothermal flow as 60 mW / m^2 that is average for a given region, [25, 26].

To set the upper boundary conditions we used the paleogeographic scenarios of the rock surface temperature variation, with difference in the shelf depth. In the calculations the surface temperature $T_B = T(z_0, t)$ is given in the form $T_B = T_W$ during ocean transgressions periods. T_W, the average temperature of the bottom water on the Laptev Sea shelf, which depends on the water layer thickness during shelf flooding, was set based on the average climatic data for the Laptev Sea region [27, 28], see Table 1. Within the regression period, when the shelf is under the atmospheric influence, this temperature is calculated as $T_B = T_S + T_{A.k}$. In this case, T_S = -12°C is the present-day average annual surface air temperature in the coastal zone of the Laptev Sea, and $T_{A.k}$ is the time-varying anomaly derived from temperature reconstructions for the Pleistocene (the lower index k indicates such various reconstructions). Thus obtained surface temperature variations depend on changes in the average annual temperature of the water layer, changes in sea level, changes in sediment surface temperatures in subaerial areas, Figure 1. Latitudinal and sectoral changes in climatic characteristics are disregarded.

Taking into account the uncertainty about past climatic changes, we have studied the permafrost layer response sensitivity to the used paleoclimatic reconstructions over the past 400 thousand years, particularly, to the changes in atmosphere, water temperature, sea level. Two numerical experiments were conducted using the different data from the paleotemperature reconstructions and sea level changes. The description of the numerical experiments is as follows:

- ANTAR – continuous recording for air temperature from the Antarctica ice cores (400 thousand years) [19]. In the scenario-related calculation we have used the sea level change reconstruction based on the data on foraminifera [20].
- CLB – the simulated data for air temperature and sea level obtained in the course of the calculations through CLIMBER-2 [21] were used.

We would like to note that the applied temperature and sea level reconstructions are closely related to each other. For example, the coefficient of correlation between two time series of the sea level [20, 21] amounts to 0.93 for the past 123 thousand years and 0.87 for the past 250 thousand years. The temperature reconstructions also correlate with each other, however, their values for certain time intervals may differ from each other by 8 °C, especially, when the glacial maxima were reached (Figure 1).

To perform quantitative assessment of the permafrost thickness (h_p) uncertainty to selection of a paleoclimatic changes data set, we have introduced the uncertainty coefficient ratio R:

$$R = 2 \cdot \left| h_{p1} - h_{p2} \right| / \left(h_{p1} + h_{p2} \right) \cdot 100\%.$$

Table 1. Temperature (T_W) and salinity (S_W) used as the upper boundary condition during transgression periods [27, 28].

H_W, m	T_W, °C	S_W, ‰
$H_W < 5$	-0.5	25
$5 \le H_W < 10$	-1.2	25
$10 \le H_W < 20$	-1.3	27
$20 \le H_W < 30$	-1.4	28
$30 \le H_W < 50$	-1.5	33
$50 \le H_W < 70$	-1.7	33.5
$70 \le H_W < 100$	-1.8	34
$100 \le H_W$	-1.9	34

We also estimated the apparent response timescale τ for the permafrost thickness. This variable was estimated as a lag at which the modulus of the cross-correlation function between h_p and T_B is at the maximum [4, 29].

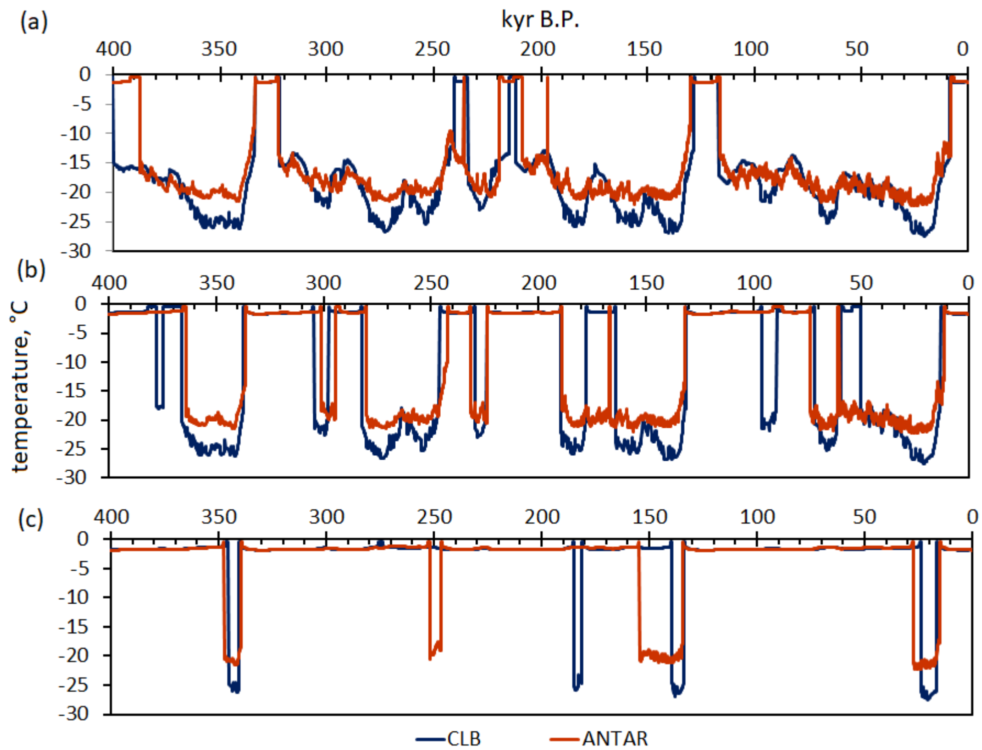

Figure 1. Variation of mean annual ground temperature on shelf during transgression and regression periods employed in the present paper: a) 10 m , b) 50 m, c) 100 m.

3. RESULTS

All numerical experiments were performed for three values of the current shelf isobaths (H_W): 10 m, 50 m and 100 m. In accordance with the considered depth, we apply the names for the shelf areas: at H_W = 10 m - shallow shelf, H_W = 50 m - medium and at H_W = 100 m - deep shelf.

Some time periods are characterized by high permafrost thickness sensitivity to the used temperature and level-related dataset. For instance, within the time span of 50-80 thousand years ago for the medium shelf, Figure 2, the difference in permafrost layer thickness reaches 100-200 m and is primarily determined by the data used for the sea level. The simulation results are highly dependent on the time period and the uncertainty coefficient *R* sometimes exceeds 50% for the deep and medium shelf. For H_W = 10 m the uncertainty coefficient is R <18% during last 250 thousand years.

During the LGM, permafrost thickness in shallow shelf could have ranged between 750 m and 830 m according to model results ANTAR and CLB. The modeled LGM permafrost thickness corresponds well with the 700–800 m estimate in the northern (arctic) region [24]. Over the last 15 thousand years, permafrost thawed on 100-110 m to leave an estimated 650 to 720 m in the present epoch.

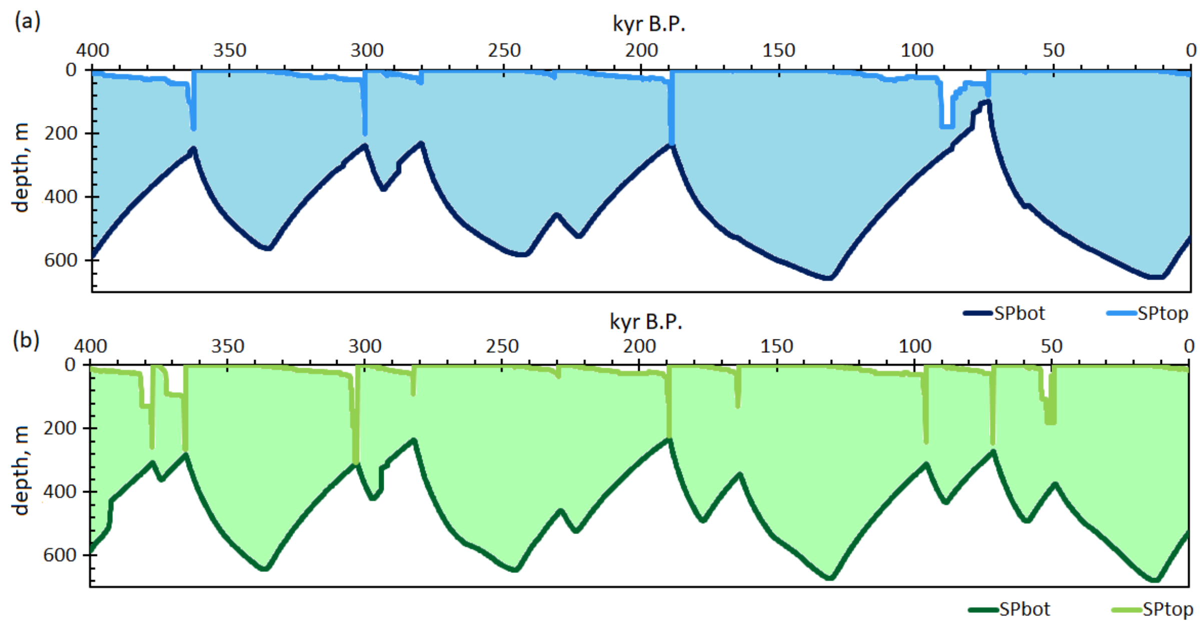

Figure 2. Evolution of offshore permafrost thickness during 400,000 years with recent seawater depth H_W = 50 m: a) for ANTAR; b) for CLB

It is shown that in the upper bottom sediment layers the permafrost degrade under subzero temperatures. The permafrost thickness reduction following the degradation on the top depends on shelf depth that is determined by the period of the sea postglacial transgression and the water layer temperature (Figure 2).

The main interest lies in the quantitative estimates for the current submarine permafrost thickness obtained at the end of the calculation, Figure 3. The permafrost base depth for the shallow shelf is considered as the largest and amounts to h_p = 650 - 720 m (R = 10%), for the medium shelf h_p = 526 - 528 m (R <1%) and for the deep shelf h_p = 68 - 82 m (R = 18%), Figure 3b. For the permafrost base depth the impact turns to be slight and leads to results uncertainty not exceeding 18%.

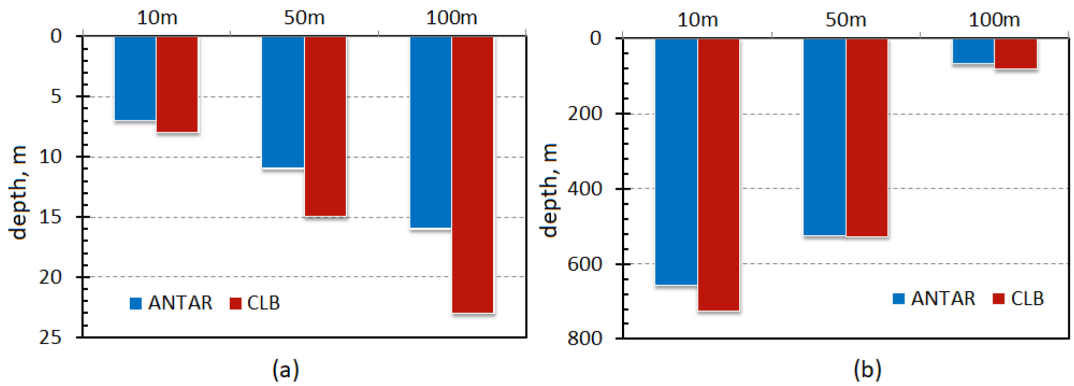

Figure 3. Depth of the current permafrost upper boundary (a) and base (b) below the seafloor in the simulations ANTAR and CLB.

The present-day permafrost upper boundary is located at a depth of 7-23 m below the seabed depending on the sea depth on the shelf, due to bottom sediments salinization, Figure 3a. For the depth of the permafrost upper boundary, the impact turns to be more significant and leads to results uncertainty of 1-34%, increasing for the medium and deep shelf. This is defined by the influence of sea level changes that indicates its importance for the permafrost thickness and degradation rate to be determined [15].

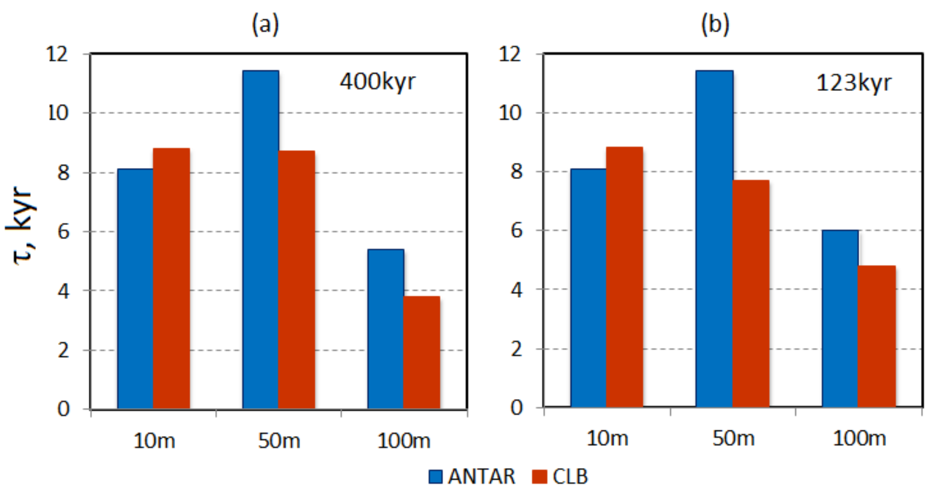

Figure 4. Apparent response time scales of the subsea permafrost base depth to surface sediment temperature changes in simulations ANTAR and CLB. Calculations are done for the last 400 kyr and for the last 123 kyr.

Figure 4 shows the response time τ calculated for the submarine permafrost base depth within two time periods. It lies in the range from 8 to 8.8 thousand years for the shallow shelf (H_W = 10 m), from 7 to 12 thousand years for the medium shelf (H_W = 50 m) and from 4 to 6 thousand years for the deep shelf (H_W = 100 m). We have obtained the result that the calculated response time for the shallow shelf is slightly sensitive to the paleogeographic scenarios used. With that, higher values of τ for the shallow shelf were obtained in a numerical experiment CLB with the largest changes in temperature during regression periods. The lower values of the permafrost base response to surface changes were obtained in the numerical experiment CLB for the medium and deep shelf.

4. CONCLUSION

The changes in the characteristics of submarine permafrost within the ocean shelf have been analyzed using a mathematical model describing the thermal state of the soil and supplemented with the salt diffusion equation. The model is supplemented by climate change scenarios on the Arctic shelf over the past 400 thousand years, using various combinations of reconstructions of air temperature and sea level. To reconstruct air and sediment paleotemperatures the continuous ice core records from Antarctica [19], as well as the simulated data [21] have been used. We have used the data on the sea level changes [20] as well.

The existing paleotemperature data reconstructions, empirical and model ones are characterized by the significant uncertainty determined by spatial and temporal variability. Despite perceptible difference in the temperature and sea level data, we have obtained the limitation in the response of the submarine Arctic shelf permafrost condition. For the permafrost base depth the impact turns to be slight and leads to results uncertainty not exceeding 18% for the deep shelf and 10% for the shallow shelf.

The time scale of thermal signal propagation in the shelf permafrost layer amounts to 4-12 thousand years. We have not discovered any systematic dependence of the results on temperature variability recording on a millennial scale. Despite the noticeable differences between the data sets used, the submarine permafrost response uncertainty coefficient does not exceed 15% for the shallow shelf.

ACKNOWLEDGEMENT

A new version of the permafrost model with the salt diffusion equation was obtained within the framework of the Russian Foundation for Basic Research (grant № 20-05-00241). The paleogeographic scenario to study the evolution of submarine permafrost was obtained within the framework of the Russian Science Foundation (grant № 20-11-20112) in ICMMG SB RAS.

REFERENCES

[1] Intergovernmental Panel on Climate Change, [Climate Change 2013], Cambridge; N.Y.: Cambridge Univ. Press, 1535 p. (2014). https://doi.org/10.1017/CBO9781107415324

[2] Frederick, J. M., Buffett, B. A., “Taliks in relic submarine permafrost and methane hydrate deposits: pathways for gas escape under present and future conditions,” J. Geophys. Res. Earth 119, 106–122 (2014).

[3] Romanovskii, N. N., Hubberten, H. W., Gavrilov, A. V., Eliseeva, A. A., Tipenko, G. S., “Offshore permafrost and gas hydrate stability zone on the shelf of East Siberian Seas,” Geo Mar. Lett. 25, 167–182 (2005).

[4] Malakhova, V.V., Eliseev, A.V., “The role of heat transfer time scale in the evolution of the subsea permafrost and associated methane hydrates stability zone during glacial cycles,” Global Planet. Change 157, 18-25 (2017).

[5] Malakhova, V.V., Eliseev, A.V., “Influence of rift zones and thermokarst lakes on the formation of subaqueous permafrost and the stability zone of methane hydrates of the Laptev sea shelf in the Pleistocene,” Ice and Snow 58(2), 231-242 (2018).

[6] Nicolsky, D. J., Romanovsky, V. E., Romanovskii, N. N., Kholodov, A. L., Shakhova, N. E., Semiletov, I. P., “Modeling sub-sea permafrost in the East Siberian Arctic Shelf: The Laptev Sea region,” J. Geophys. Res. 117, F03028 (2012).

[7] Overduin, P. P., Schneider von Deimling, T., Miesner, F., Grigoriev, M. N., Ruppel, C. D., Vasiliev, A., Lantuit, H., Juhls, B., Westermann, S., ”Submarine permafrost map in the Arctic modeled using 1-D transient heat flux (SuPerMAP),” Journal of Geophysical Research: Oceans 124(6), 3490– 3507 (2019). https://doi.org/10.1029/2018JC014675

[8] Arzhanov, M. M., Malakhova, V. V., Mokhov, I. I., “Simulation of the Conditions for the Formation and Dissociation of Methane Hydrate over the Last 130 000 Years,” Doklady Earth Sci. 480(2), 826-830 (2018).

[9] MARGO Project Members, "Constraints on the magnitude and patterns of ocean cooling at the Last Glacial Maximum," Nature Geoscience 2, 127–132 (2009).

[10] Annan, J., Hargreaves, J., "A new global reconstruction of temperature changes at the Last Glacial Maximum," Climate of the Past 9, 367–376 (2013).

[11] Clark, P. U., Dyke, A. S., Shakun, J. D., Carlson, A. E., Clark, J., Wohlfarth, B., Mitrovica, J. X., Hostetler, S. W., McCabe, A. M., "The Last Glacial Maximum," Science 325, 710–714 (2009). doi:10.1126/science.1172873

[12] Lambeck, K., Rouby, H., Purcell, A., Sun, Y., Sambridge, M., "Sea level and global ice volumes from the Last Glacial Maximum to the Holocene," P. Natl. Acad. Sci. USA 111, 15296–15303 (2014). https://doi.org/10.1073/pnas.1411762111

[13] Kopp, R. E., Simons, F. J., Mitrovica, J. X., Maloof, A. C., Oppenheimer, M., "Probabilistic assessment of sea level during the last interglacial stage," Nature 462, 863–867 (2009). https://doi.org/10.1038/nature08686

[14] Kindler, P., Guillevic, M., Baumgartner, M., Schwander, J., Landais, A., Leuenberger, M., "Temperature reconstruction from 10 to 120 kyr b2k from the NGRIP ice core," Climate of the Past 10, 887–902 (2014).

[15] Malakhova, V.V., Eliseev, A.V., "Influence of the uncertainty of the sea level data for the Pleistocene glacial cycles on the analysis of the subsea sediments thermal state," Proc. SPIE: 25th International Symposium on Atmospheric and Ocean Optics: Atmospheric Physics 11208 (112086Q), (2019).

[16] Spratt, R. M., Lisiecki, L. E., "A Late Pleistocene sea level stack," Clim. Past 12, 1079-1092 (2016). https://doi.org/10.5194/cp-12-1079-2016

[17] Rachold, V, Bolshiyanov, D. Yu, Grigoriev, M.N., Hubberten, H-W, Junker, R., Kunitsky, V.V., Merker, F., Overduin, P., Schneider, W., "Near-shore Arctic subsea permafrost in transition," EOS Trans Am Geophys Union 88(13), 149–156 (2007).

[18] Malakhova, V.V., "Estimation of the subsea permafrost thickness in the Arctic Shelf," Proc. SPIE: 24nd International Symposium on Atmospheric and Ocean Optics: Atmospheric Physics 10833 (108337T), (2018).

[19] EPICA Community Members, "Eight glacial cycles from an Antarctic ice core," Nature 429, 623–628 (2004). https://doi.org/10.1038/nature02599

[20] Waelbroeck, C.C., Labeyrie, L.L., Michel, E.E., Duplessy, J.J., McManus, J.J., Lambeck, K.K., Balbon, E.E., Labracherie, M.M., "Sea-level and deep water temperature changes derived from benthic foraminifera isotopic records," Quat. Sci. Rev. 21 (1–3), 295–305 (2002).

[21] Ganopolski, A., Calov, R., "The role of orbital forcing, carbon dioxide and regolith in 100 kyr glacial cycles," Climate of the Past 7, 1415–1425 (2011).

[22] Razumov, S. O., Spektor, V. B., Grigoriev, M. N., "Model of the post-Cenozoic evolution of the cryolithozone of the shelf of the western part of the Laptev Sea," Oceanology 54 (5), 637–649 (2014).

[23] Angelopoulos, M., Westermann, S., Overduin, P. P., Faguet, A., Olenchenko, V., Grosse, G., Grigoriev, M. N., "Heat and salt flow in subsea permafrost modeled with CryoGRID2," Journal of Geophysical Research: Earth Surface 124, 920–937 (2019). https://doi.org/10.1029/2018JF004823

[24] Kitover, D. C., van Balen, R. T., Roche, D. M., Vandenberghe, J., Renssen, H., "New Estimates of Permafrost Evolution during the Last 21 k Years in Eurasia using Numerical Modelling," Permafrost and Periglacial Processes 24, (2013). https://doi.org/10.1002/ppp.1787

[25] Davies, J. H., "Global map of Solid Earth surface heat flow," Geochem. Geophyst. Geosyst. 14(10), 4608–4622 (2013).

[26] Pollack, H. N., Hurter, S. J., Johnson, J. R., "Heat flow from the Earth's interior: Analysis of the global data set," Rev. Geophys. 31(3), 267–280 (1993).

[27] Steele, M., Morley, R., Ermold, W., "PHC: A global hydrography with a high quality Arctic Ocean," J. Climate 14(9), 2079–2087 (2001).

[28] Dmitrenko, I., Kirillov, S., Tremblay, L., Kassens, H., Anisimov, O., Lavrov, S., Razumov, S., Grigoriev, M., "Recent changes in shelf hydrography in the Siberian Arctic: Potential for subsea permafrost instability," J. Geophys. Res. 116, C10027 (2011).

[29] Muryshev, K., Eliseev, A., Mokhov, I., Timazhev, A., "Lead–lag relationships between global mean temperature and the atmospheric CO2 content in dependence of the type and time scale of the forcing," Glob. Planet. Change 148, 29–41 (2017).