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Valentina V. Malakhova, Alexey V. Eliseev, "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 11208, 25th International Symposium on Atmospheric and Ocean Optics: Atmospheric Physics, 112086Q (18 December 2019); doi: 10.1117/12.2539017

Event: XXV International Symposium, Atmospheric and Ocean Optics, Atmospheric Physics, 2019, Novosibirsk, Russian Federation

# Influence of the uncertainty of the sea level data for the Pleistocene glacial cycles on the analysis of the subsea sediments thermal state

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## ABSTRACT

The estimates of the uncertainty for the model simulated subsea permafrost characteristics relative to the uncertainty of paleoclimatic reconstructions of ocean level are obtained. This is done by using the model for thermophysical processes in the subsea sediments. This model is driven by four time series of temperature at the sediment top, $T_B$, which is constructed for the last 400 kyr by using different combinations of the same reconstruction of the past surface air temperature but different sea level reconstructions. At each time instant $t$ and each variable $Y$, the uncertainty metric is defined as a ratio $\Delta Y(t) / Y_m(t)$, where $\Delta Y(t)$ is spread of the values of $Y$ for different $T_B$ time series, and $Y_m(t)$ is the mean of $Y$ over different realizations corresponding to different $T_B$. The root-mean-square calculated value of thus defined metric for different time intervals is $\leq 50\%$ for permafrost base depth with the exception of isolated time intervals and / or the deepest part of the shelf. This uncertainty is not symmetric with respect to the sign of the sea level uncertainty. In turn, uncertainty for the hydrate stability zone thickness is small for shallow shelf but becomes pronounced for intermediate and deep shelves. The most uncertainty is due to uncertainty of dates for oceanic regressions and transgressions.

**Keywords:** submarine permafrost; subsea permafrost; Arctic shelf; methane hydrates; glacial cycles; sea level

## 1. INTRODUCTION

It is believed that the contemporary subsea permafrost at the shelf developed during the Pleistocene glaciations [1, 2]. Thus, any simulation of past changes of the subsea permafrost is conditioned by time series of past climate changes [3-6]. This uncertainty basically increases back in time.

For instance, [7] reviewed uncertainty of different sea level reconstructions. They stated that typical uncertainty of these reconstructions may be as large as few tens of meters. The most accurate reconstructions are those based on corals [8-12]. Their uncertainty for the last interglacial is few meters, but increases back in time. The typical uncertainty for reconstructions based on $^{18}O$ content in the benthic foraminifera is ±20 m [13] (here and below, 1 standard error is reported as an uncertainty metric). Similar uncertainty is obtained for planctonic foraminifera-based reconstructions ± 6 m for the last glacial cycle but is large as ±18 m for the middle Pleistocene [14]. The uncertainty amounting to ±13 m is estimated for the combined coral - bentic $^{18}O$ content reconstruction [15] as well as for the inverted ice model reconstructions [16].

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25th International Symposium On Atmospheric and Ocean Optics: Atmospheric Physics, edited by Gennadii G. Matvienko, Oleg A. Romanovskii, Proc. of SPIE Vol. 11208, 112086Q
© 2019 SPIE · CCC code: 0277-786X/19/$21 · doi: 10.1117/12.2539017

The uncertainty estimates for two known reconstructions based on hydraulic control models of semi-isolated basins are ± 12 m [17] and ± 20 m [18] (but decrease at coarser, millennium-scale time resolutions). In turn, the reported uncertainties for the reconstruction [7] is ± 7 m for the Last Glacial Maximum but increases up to ± 25 m back in time.

All these uncertainty estimates are non-negligible in comparison to the depth of the contemporary shelf depths. When they are used to construct time series of temperature at the sediment top, $T_B$, their uncertainty is translated into uncertainty of dates of sea transgression and regressions. These dates, in turn, impose a primary control on the subsea permafrost dynamics during the Pleistocene [2, 3, 19].

The goal of the present paper is to study uncertainty of the Pleistocene subsea permafrost on past sea level changes with a model for thermophysical processes in the sediments.

## 2. MATERIALS AND METHODS

We use the model for heat propagation in the subsea sediments [20, 21, 22]. The model solves the one-dimensional equation for heat diffusion in the sediments subject to boundary conditions for temperature at the sediments top and to prescribed heat flow from the Earth interior at the bottom of the computational domain. The depth of the latter is set to 1.5 km, and the heat flow intensity is $G$ = 60 mW m$^{-2}$, which is estimated as a typical value of geothermal flux at the Eurasian shelf [23, 24].Temperature diffusivity in the sediments depends on their state and is set equal to $1.06 \cdot 10^{-6}$ m$^2$ s$^{-1}$ ($0.64 \cdot 10^{-6}$ m$^2$ s$^{-1}$) in the frozen (unfrozen) part of the sediment column. The sediment pores are completely filled with water. The freezing and melting temperature of the water in pores is set equal to $T_F$ = -1$^o$C [25, 26]. In the model, the latent heat of fusion during because of formation and melting of the pore ice is taken into account, but neglect the respective heat released during dissociation of hydrates ignored. The difference of the latent heat of fusion between pure ice and ice with hydrates is ignored as well. Model equations are solved by using the sweep method at a vertical grid with the vertical step 0.5 m. Time stepping is implicit with the time step 1 month. Annual cycle is not resolved. Initial temperature distribution is prescribed as being in equilibrium with the initial temperature at the sediment top and with the time-invariant value of $G$ [27]. Methane hydrates stability zone (HSZ) is further computed by employing the equilibrium pressure-temperature curve from the TOUGH+HYDRATE reservoir simulator model [28].

Temperature $T_B$ at the sediment top is constructed as follows. When shelf is covered with water, $T_B$ = -1.8$^o$C [2, 5]. When shelf is in direct contact with the air, $T_B = T_A = T_{A,R} + T_P$, where $T_{A,R}$ = -12°C is equal to the present-day annual mean surface air temperature in the East Siberian shelf region [25], and $T_P$ is a time-varying anomaly obtained from the EPICA (The European Project for Ice Coring in Antarctica) Dome C ice-drilling project data [29] (Fig. 1a). In previous studies [3, 4, 19], anomalies were used from Vostok borehole data for the last 400 kyr [30]. In present paper, these data are replaced by a newer data from EPICA.

To study the uncertainty with respect to prescribed sea level reconstructions, we combine the EPICA-derived $T_P$ with four different sea level time series available for the last 400 kyr (Fig. 1b). The first one is the combined coral - bentic $^{18}$O content reconstruction [15] (WLB02 thereafter). Other three reconstructions are obtained from the supplementary information to [7] and in their paper referred to as 'PC1', '2.5%' and '97.5%' in their paper. Thereafter, we denote the latter three datasets as SP16PC1, SP16MIN, and SP16MAX correspondingly. In turn, the time series for $T_B$ are labeled by using the same names as for sea level dataset used in constructing these time series.

All simulations are performed for three values of the contemporary shelf depth $H_B$: 10 m (shallow shelf), 50 m (intermediate-depth shelf), and 100 m (deep shelf). For each time instant $t$ and for each simulated variable $Y$, we define the following uncertainty metric

$$R_Y = \left| \max_K Y - \min_K Y \right| \Big/ \left( \frac{1}{4} \sum_K Y \right)$$

where maximum, minimum and mean are calculated over the subscript $K$, which stands for a specific sea level reconstruction (thus, for specific $T_B$). The uncertainty representative for a given time interval is calculated as a root-mean-square (RMS) value for $R_Y$ over this time interval.

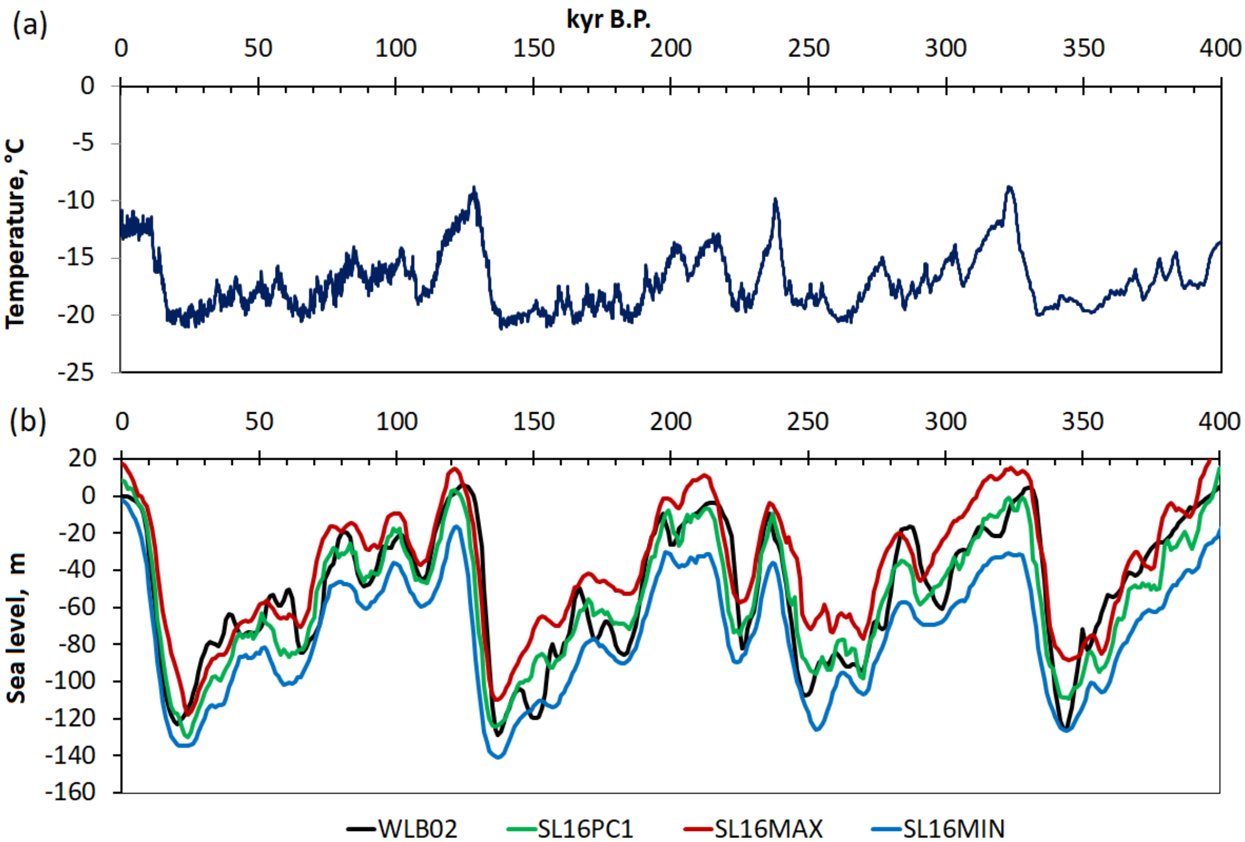


Figure 1. Change of surface air temperature $T_A$ (a) and sea level (b) employed in the present paper.

## 3. RESULTS

Subsea permafrost base depth $h_p$ appears rather sensitive to sea level prescription (Fig. 2). This sensitivity is larger for larger $H_B$. We note that this sensitivity is symmetric with respect to sign of the sea level difference between different datasets. This is visible if one compares simulations SL16PC1 as a central estimate and SL16MIN and SL16MAX as lower and upper sea level limits. At shallow and intermediate-depth shelf, differences are larger when $h_p$ is smaller - thus, near glacials ends (with a caveat for delay in $h_p$ response to changing $T_B$ [2, 3]. Because the same surface air temperature curve is prescribed for different runs, this means that the most uncertainty come from the dates of the oceanic regressions and transgressions. For the deep shelf, differences are large irrespective of time instants. They are differ by a factor around 1.5 for the Last Glacial maximum and by about twofold for the present day.

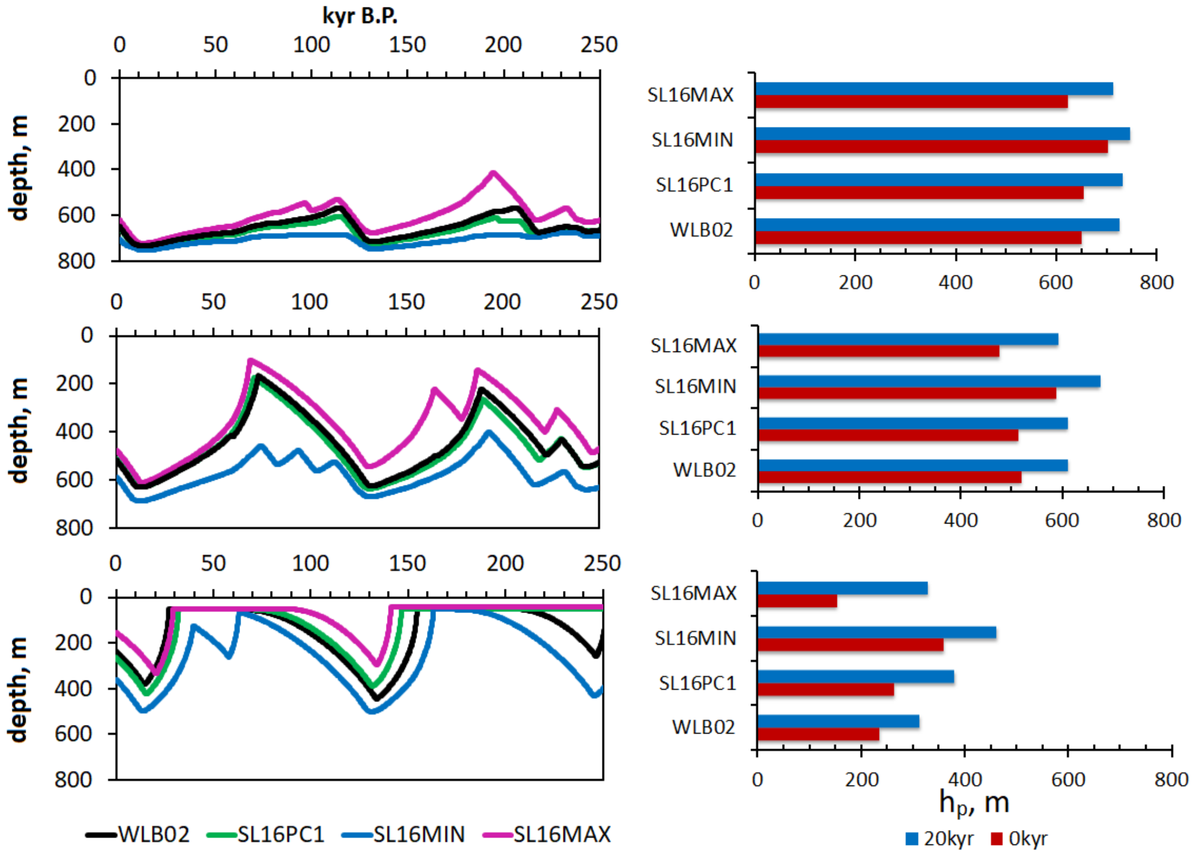


Figure 2. Depth (below the oceanic floor) of the subsea permafrost bas for shelf with the contemporary depth $H_B$ = 10, 50, and 100 m (upper, middle and lower rows correspondingly). Left column shows the respective time series vs. time. Right column shows the values for two to time instants: 20 kyr B.P. and for the present (0 kyr B.P.).

Impact of sea level uncertainty on the results of our simulations is further illustrated by using RMS values either for the last 20 kyr (last deglaciation and the Holocene) and for the last 120 kyr (last glacial cycle) (Fig. 3). At first, for both time intervals, RMS uncertainty is much larger for $H_B$ = 100 m than for shallow and intermediate-depth shelves. Irrespective of the contemporary shelf depth, root-mean-square uncertainty is much larger for the whole glacial cycle than only for its deglaciation-Holocene part.

Similar to that it was obtained for the subsea permafrost bas, the uncertainty for the HSZ thickness *D* is not larger than few per cent for shallow shelf (Fig. 4). However, it becomes pronounced for intermediate depth shelf when it shrinks. Again, this is a delayed response to warmings. The most marked examples are time intervals around 70 kyr B.P. and 180 kyr B.P. Hydrate stability thickness uncertainty further exaggerates for the deep shelf. The most pronounced difference is around 50 kyr B.P., when HSZ exists for SL16MIN but is absent for other sea level reconstructions.

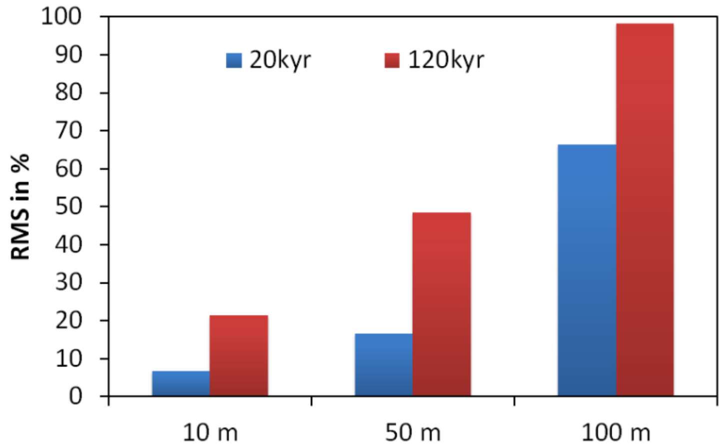


Figure 3. Root-mean-square uncertainty of the subsea permafrost thickness for shelf with the present-day depth indicated as abscissas. Calculations are done for the last 20 kyr and for the last 120 kyr.

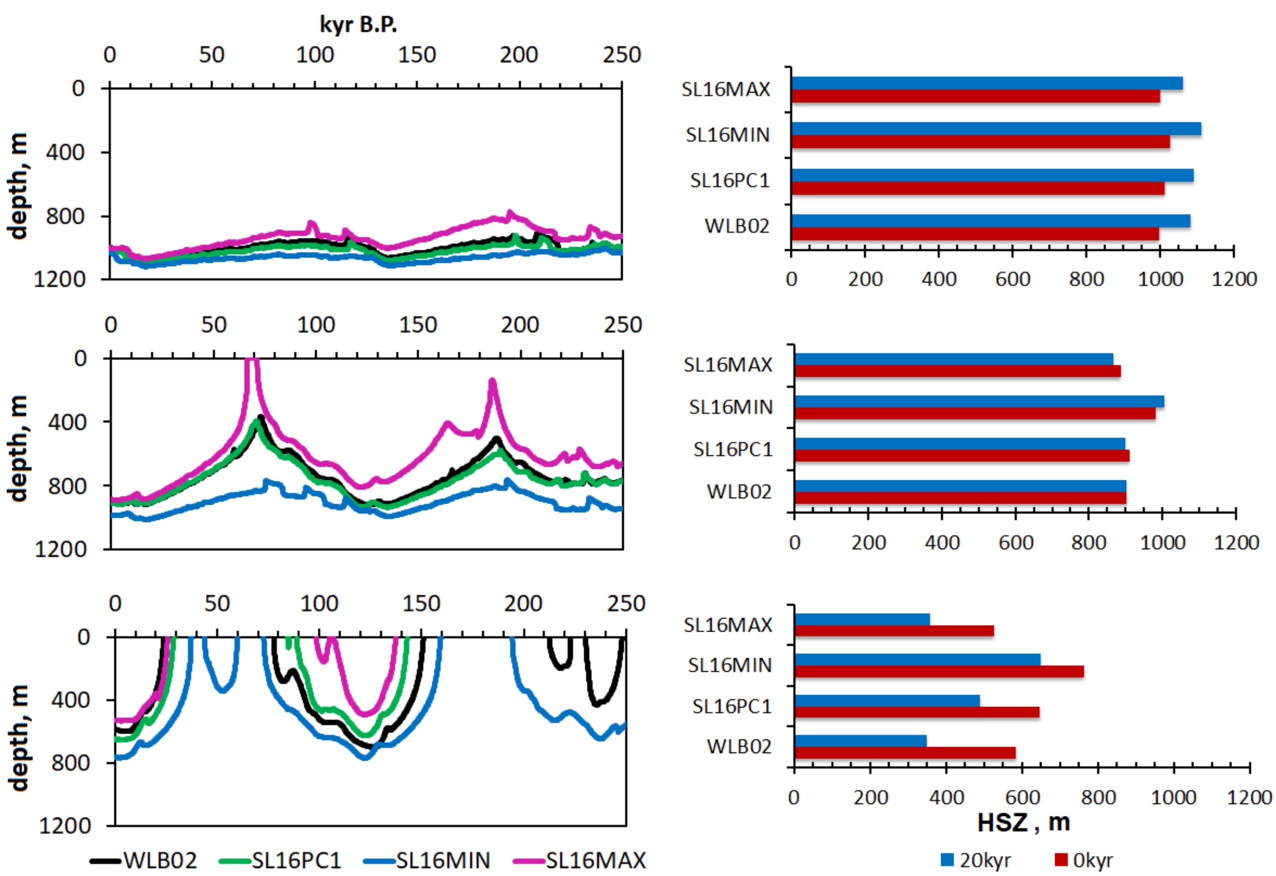


Figure 4. The thickness of the hydrate stability zone for shelf with the contemporary depth $H_B$ = 10, 50, and 100 m (upper, middle and lower rows correspondingly). Left column shows the respective time series vs. time. Right column shows the values for two to time instants: 20 kyr B.P. and for the present (0 kyr B.P.).

## 4. CONCLUSION

In this paper, we quantified uncertainty of the simulated subsea permafrost characteristics relative to the uncertainty of paleoclimatic reconstructions. This was done by using the model for thermophysical processes in the subsea sediments. This model is driven by four time series of temperature at the sediment top, $T_B$, which is constructed for the last 400 kyr by using different combinations of the same reconstruction of the past surface air temperature but different sea level reconstructions. At each time instant $t$ and each variable $Y$, the uncertainty metric is defined as a ratio $\Delta Y(t) / Y_m(t)$, where $\Delta Y(t)$ is spread of the values of $Y$ for different $T_B$ time series, and $Y_m(t)$ is the mean of $Y$ over different realizations corresponding to different $T_B$.

The root-mean-square of thus defined metric calculated for different time intervals for permafrost base depth is $\leq 50\%$ with the exception of isolated time intervals and / or the deepest areas of the shelf. It is not symmetric with respect to the sign of the sea level uncertainty. In turn, uncertainty for the hydrate stability zone thickness is small for shallow shelf but becomes pronounced for intermediate and deep shelves. The most uncertainty is due to uncertainty of dates for oceanic regressions and transgressions.

## ACKNOWLEDGEMENT

This work has been supported by the Russian Foundation for Basic Research (grants 17-05-00396, 18–05–00087, 18-05-60111). A new version of the permafrost model was obtained within the framework of the budget project 0315-2019-0004 for ICMMG SB RAS. It was also funded by the government program for federal support of Kazan (Volga region) Federal University for enhancing its competitiveness among the world's leading scientific and educational centers.

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