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Climate
of the Past
Discussions

Interactive comment on “Modeling of stability of gas hydrates under permafrost in an environment of surface climatic change – terrestrial case, Beaufort-Mackenzie basin, Canada” *by* J. Majorowicz et al.

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Response to Reviewers: Reviewer # 1 We are grateful for the time that Alan Taylor has taken to read and review our paper. We are very pleased that he approves of the manuscript (cit. “This is a good paper describing the development of methane hydrate and permafrost bodies during the Quaternary”) and that he recommends publication after our considering the detailed list of suggestions to improve the text and figure captions.. We would like to thank Alan for his detailed and helpful comments which we are attending all. We have addressed all of his specific editorial comments, many of

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which are minor, but beneficial into the final revised manuscript.

Reviewer # 2 We appreciate the time Reviewer #2 has dedicated to our paper and his positive Assessment (cit: “I have no doubts that the paper should be published in Climate of the Past with minor revisions“)

A specific comment of Reviewer #2 relates to the problem of the choice of a suitable ground surface temperature history.

As Rev. #2 correctly notices, we have used global reconstruction of air surface temperature change that was adapted for the investigated area. We realize that the assumed surface forcing model is not 100% reliable data , however, our calculations require that we employ a continuous numerical model of ground surface temperature within our model. Therefore we have used the global reconstruction of air surface temperature change model which is likely a most comprehensive, continuous and plausible reflection of the major changes of the past temperature variations. We are aware of a voluminous discontinuous and qualitative literature from both paleontological and glacial history regarding climate zones and specific incidents in the study region, but these are typically limited in both duration and non-quantitative unlike the global reconstruction of air surface temperature changes. Therefore we are aware of these other sources but find them impossible to reconcile with the global reconstruction of air surface temperature change record and other data. The most obvious example of this is the observation of rare sedimentary records interpreted as thin glacial till in the Mackenzie Delta succession as described by Dallimore et al. (2005,[0]). Both the GST history from the shallow borehole inversion record and the geodynamic record indicate that the interpreted till-forming event must be neither characteristically nor persistently indicative of the climate within the region studied. In the absence of other comprehensive and continuous models we use global reconstruction of air surface temperature change as a ‘plausible’ model to see how such variations effects stability of the permafrost and specifically, how the latent heat of permafrost changes of state preserve hydrate below when considering the latent heat model for hydrates.

Still we have attempted to accommodate this comment by adding additional model runs to the revised paper. As a result, in the revised paper we show that the present temperature - depth distribution is not very sensitive to the remote GST history and that the results obtained by the 14 Myr history for the last ice age are not materially biased by the use of the global reconstruction of air surface temperature change, which the reviewer suggested resulted in the use of a possibly and arguably too cold surface temperatures between 14 and 3 Myr ago. We have done simulation for the Mallik site (shown here in Fig.1 for the first case, when hydrate is considered below 900 m only). We have started 3 Myr ago with steady-state T-z profile corresponding to GST of 0 °C. GST had been decreasing linearly from 0 °C at 3 Myr ago to -10 °C at the beginning of the large 100 ka glacial cycles 0.9 Myr ago.As one can see, the differences between the two GST models in the position of the ice bonded permafrost and gas hydrate bases are of the order of tens of metres in the last 0.9 Myr, when the GST history was the same. Despite our use of quite a general surface temperature histories the agreement between the two model predictions and the observed bases of gas hydrate and ice bonded permafrost is reasonably good.

Reiterating the above; we have recalculated the models over a different time interval and considered a warmer previous climate, as suggested by reviewer #2. Again the effects of the changes in the model inputs have not produced a significant effect on the model results nor do they require that we modify any of the conclusions that were draw from the modeling. We also wish to point out that there is no well established or consensus model for the local temperature history in the region. Therefore we conclude it is entirely appropriate to adapt the well studied and more globally relevant temperature histories and employ them in our models. The use of these more regional temperature histories in our models provided testable predictions of the current conditions. Re. Demezhko comment:”During the glaciation periods the investigated area probably was covered by ice sheets. At least the north margin of the Laurentide Ice Sheet (95 – 20 kyr ago) extended to the shelf of the Beaufort Sea. It is known that temperature regime at the bed of ice sheet may be substantially different from that at its upper surface.”

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We agree that the temperature at the ice bed may be different from surface temperature , however, in our study case we have focused on gas hydrate occurrences in Beaufort-Mackenzie terrestrial environment that are near the Canadian margin of the Amerasian Basin of the Arctic Ocean, the contiguous onshore area. The MD-BS is not inferred to have been either persistently or thickly glaciated and it lacks significant post-glacial isostatic uplift [1]. This is unlike the Queen Elizabeth Island Group QEIG Arctic Archipelago to the North which was persistently and thickly glaciated as indicated by a strong post-glacial isostatic uplift record [2].

Also, in the revised paper we will add more detailed well constrained terrestrial case model of Taylor at al (Taylor et al. (2005, their Fig. 3b [3]) to model changes of permafrost and hydrate of the latest 0.5Myr history (Fig.2). The models are based on the surface temperature forcing effect on ice bonded permafrost and gas hydrates, which currently have observed bases at about 600 m and about 1160-1170 m, respectively.

Re. Demezhko comment: “Page 2879, lines 24,25. Authors used the term “thermal inertia” in the everyday sense, as it has a definite physical meaning. The “thermal inertia” (or “thermal effusivity”) is defined as the square root of the product of the bulk thermal conductivity and volumetric heat capacity. This parameter is displayed in problems where the heat exchange in a system of contacting bodies is considered. In the context of the paper is better to use the term “low thermal diffusivity” “.

We agree here with Demezhko and admit that term was used more in a common sense of the work rather than its scientific meaning. In the revised paper we use expression “low thermal diffusivity “instead.

We have attended small editorial changes of Demezhko and these improved the revised manuscript to be submitted.

Reviewer # 3 In response to Rev.#3 comments , we would like to thank for his positive assessment of our work i.e. “The paper in review could be published in the “Climate of the Past Discussions” after minor revision““.

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Re Rev.#3 general comment 1:” It would be beneficial for readers if the authors would provide more explanation how the salinity of the pore water (9g/L) was chosen. “

Concerning the salinity, shortly said, the salinity of 9 g/L was used so that the liquidus temperature at the permafrost base in Malik (-1 °C at 600 m) corresponds with the value given by formula T = 0 °C - 0.073*Pressure(MPa)-0.064*salinity(NaCl,KCl..)(g/L).This formula was taken from paper by Galushkin (1997),[4]. If there is a fresh water within Mallik sediments, the liquidus temperature would be by 0.58 °C higher. If there is a sea water with 40 g/L, the liquidus would be by 1.98 °C lower. For temperature gradient 20K/km it would mean a shift of the permafrost base by 30 m downward and by 100 m upward, respectively.

Re. Rev.#3 general comment 2: “ to recognize and adequately discuss in the paper the limitations of the used one-dimensional modeling approach with a very restricted range of used physical properties and implied simplifications in boundary conditions (including the lower boundary conditions). “

We agree with Rev 3’s request and this is discussed in the revised version.

Re. Rev.#3 general comment 3: “ to restrict conclusions about the possible impact of changes in sub-permafrost gas hydrates on climate to the area where research was conducted and not to try to generalize these conclusions to the entire Arctic domain where variety of paleo-environmental conditions and geological settings may easily prove these conclusions wrong”.

In fact we have pointed this problem in our paper writing that “The hypothesis that gas hydrates destabilize rapidly in response to environmental change, late in glacial intervals, and that they serve, at other times, as a sink for, and barrier to the migration of, methane into the atmosphere applies mainly to marine non-ice bonded permafrost gas hydrates “ Our study shows that sub-ice bonded permafrost gas hydrates below thick ice bonded permafrost vary in thickness in response to surface temperature history changes, but that terrestrial thermal inertia conserves both ice bonded permafrost and

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sub-ice bonded permafrost gas hydrates delaying and reducing methane release.

As the reviewer suggests we now have revised and limited our conclusions to the thick permafrost and hydrate areas like the one we model for Mallik. We recognize that areas in marginal position to thick permafrost become destabilized much more quickly and easier, or by other mechanisms, such as thermal karst below ephemeral lakes.

Also, in response to Rev. 3 concern about the possible de-stabilization of gas hydrates we are adding model of future warming projected by the IPCC 2007 [5] in the revised paper. The "marine transgression" effect upon hydrate stability is also considered (see Fig 3 below) as results when hydrate is destabilized after ‘terrestrial’ -15C conditions are succeeded by ‘warmer’ subsea conditions that are near 0oC, as such conditions currently exists in limited marginal portions of the Beaufort Sea.

The future warming of the sea bottom was assumed for the extreme global warming case scenario [5], (Figure 11).

We have added dicussion of the assumed salinity.

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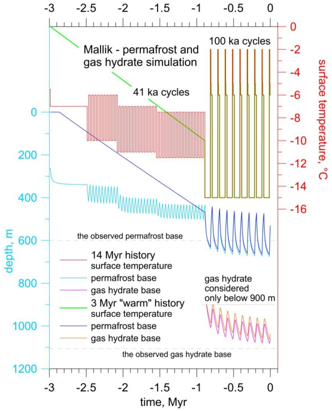

Figure 1. Comparison of the results of the two GST models (“warmer” and “colder” shown for Malik, when occurrence of gas hydrate is possible only below the depth of 900 m. 3 Myr history is warmer than the 14 Myr model by up to 6 K for most of the period between 3 Myr and 0.9 Myr ago. Note: the simulated thicknesses of the ice bonded permafrost and the gas hydrate layer differ between the two models by tens of meters at most. It means that the present temperature – depth distribution is not very sensitive to the remote history and that the results obtained by the 14 Myr history for the end of Pleistocene and Holocene are not biased substantially by possibly arguable too cold surface temperatures assumed for the period between 14 and 3 Myr ago.

Fig. 1.

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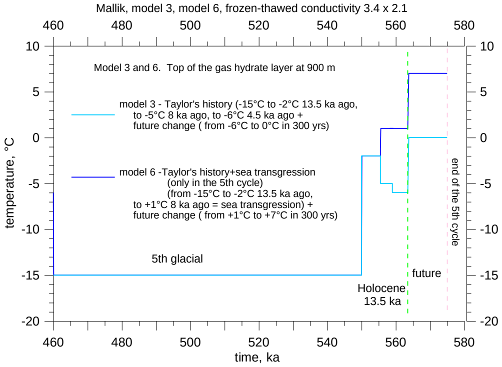

Figure 2. Model considering sea transgression and related temperature changes from land to sub-sea (warmer).

Fig. 2.

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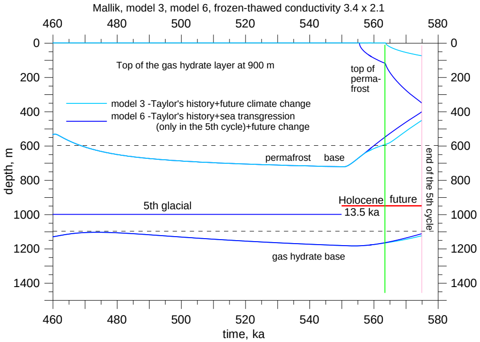

Figure 3. Consequences in changes in hydrate and permafrost as related to model in Fig. 2 (transgression plus global warming).

Fig. 3.

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