Answer to reviewer comments 1 (by Alexey V. Eliseev, 2021-09-16)

We, the authors, of „Strong Increase of Thawing of Subsea Permafrost in the 22nd Century Caused by Anthropogenic Climate Change“ appreciate very much the acknowledgement of the novelty of our work by the reviewer and the fast reply. Below we attempt to answer the points of critics from the reviewer more or less point by point.

Major comments:

The reviewer points out that our spin-up procedure, change of models (from SuPerMAP to JSBACH) at the year 1850 and thereby resultant transient model drifts may limit the value of our results.

The SuPerMAP points were initialized at 50 ka BP with steady state vertical profiles calculated using the geothermal heat flux at 2 km depth and averaged surface temperatures from 400 ka long runs from a limited number points as boundary conditions (see Overduin et al. (2019) for more details). By using these long term averages – longer than the time scale proposed by Malakhova and Eliseev (2017) to be neccesary for the deep sediments to become into equilibrium - this approach rules out transient effects in the deeper parts of the sediments. In the period 50 ka BP to the LGM 23.5 ka BP the SuPerMAP model was run using the boundary conditions as described in Overduin et al (2019). To diminish initial shocks and transient effects from changing the model from SuPerMAP to JSBACH in year 1850, several different ways of doing the transition from the idealized upper boundary conditions described in Overduin et al. (2019) to the “realistic” forcing from MPI-ESM (assuming that the benthic temperatures from the preindustrial period (1850-1873) of the CMIP6 runs are representative for the entire holocene), were tested (Fig. RA1). The approach resulting in the least “noise” turned out to be an interpolation from 23.5 ka BP to 1 ka BP, keeping the forcing constant over the last 1000 years of the SuPerMAP runs. How this interpolative approach exactly compares to the O(10^4) year time scale proposed by Malakhova and Eliseev (2020) for adjusting the sediments to the forcing is not completely clear, but it is at least at the same order of magnitude.

In the manuscript, it may it may not have been made sufficiently clear, that our runs reuse the SuPerMAP runs before the LGM, only modifying the last part of the forcing compared to the experiment presented in Overduin et al. (2019). This may have given rise to the impression that our total spin-up length is only 23.5ka, which would, indeed, limit the usage of our study. We will clarify this in the revised version of the manuscript.

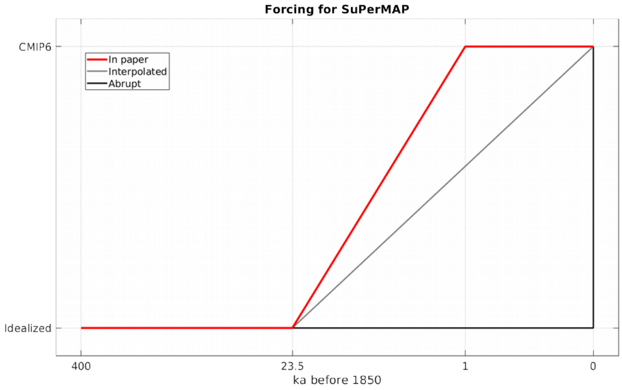

Fig. RA1: Tested forcing pathways for the SuPerMAP spin-up runs.

The two models used (SuPerMAP and JSBACH) have very different purposes. Whereas JSBACH is the land component of the MPI-ESM and thus a state-of-the-art terrestrial land and vegetation model with a (normally shallow) soil model designed for typical climate projection time scales of approximately 100-1000 years with high temporal resolution, SuPerMAP is a specialized permafrost, deep soil, model with the capability of repeated ocean transgression/regression cycles, designed for very long time scales. The focus of SuPerMAP is to determine the melting of sub-sea permafrost by geo-thermal heat flux (i.e. from below) and our present work is mainly on the additional melting from above caused by anthropogenic climate change. To be able to extent a very long spin-up to get sensible soil temperature and ice content with climate projections at high temporal resolution (both of forcings and results), this two-model approach has been necessary despite the issues about differences in model physics and interpolation of initial conditions, eventually leading to transient effects.

The two approaches sketched in gray/black colors in Fig. RA1 indeed lead to severe transient effects within the JSBACH runs. In has not been possible to completely eliminate these effects, which are visible as a slightly higher initial melting rate in Figs. 2 and S7 in the manuscript. In Fig. RA2 we used the pmt_pre experiment (which was run with cyclic forcing) to quantify these effects by showing the average melting rate for each for the 24 year forcing cycles. In this experiment a small decrease in Sub-Sea Permafrost (SSPF) ice melting should be expected over time, since individual point may loose all SSPF ice. Despite this small effect, we take the SSPF ice melting from the average from cycle 8 (starting in 2018) to the end of the experiment as the best guess value for the “true” steady state melting rate corresponding to the preindustrial (or holocene) forcing. This average is about 7.4 km^3/a. Indeed specially the first cycle (1850-1873) has a melting rate almost twice as high as this average, but already in the second the difference is much diminished (25% additional melting). The average additional melting during the first 7 cycles is about ~1.8 km^3/a, only ~25% of the best guess. For comparison the peak melting in pmt_ssp585 is >100 km^3/a. Calculating the average melting rates from the pmt_sspXXX experiments for the same 24 year intervals reveals that these exceeds those of pmt_pre already for the third “cycle”, i.e. from the year 1898 (not shown), indicating that the climatic signal from here on exceeds the initial “noise”. Since our focus is on the inter-SSP differences (after 2010), these transient effects have been considered unimportant, but of course deserve to be mentioned in the discussion in the revised manuscript.

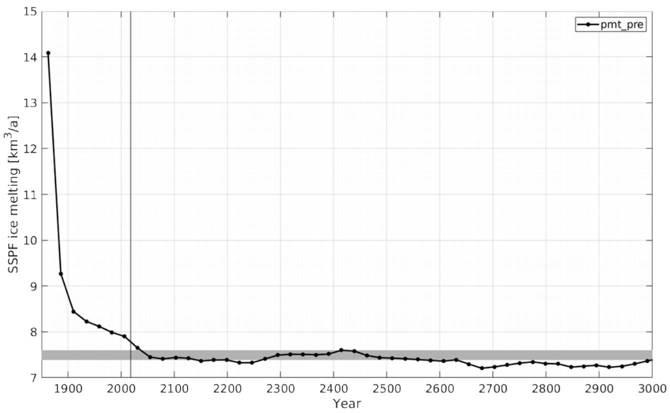

Fig. RA2: SSPF ice melting in the pmt_pre experiments averaged over each 24 year forcing cycle. Each point mark the average of one forcing cycle. Gray hatch is the mean +/- two standard deviations of the melting from 2018 (forcing cycle 8) to the end of the experiment (to the right of the vertical line).

The reviewer has the opinion that SuPerMAP produces too much SSPF ice.

It is true that SuPerMAP produces subsea permafrost in some regions which probably lack it. However, it is important here to be specific about the nuances of terminology. The permafrost definition used in the SuPerMAP study corresponds to terrestrial permafrost (cryotic for more than 2 consecutive years) and will therefore cover a larger spatial region than permafrost defined by ice content. This issue is addressed in the Overduin et al. (2019) (“*...Both effects lead to an overestimation of the areal extent of cryotic sediments...*”). The validation data sets for SuPerMAP nonetheless fit observed data in Alaska and the Kara Sea reasonably well at the scale of the modelling. These data sets are based on seismic velocity and therefore ice content, suggesting that discrepancies between defined permafrost domains are small and/or site specific. For example, SuPerMAP underestimates permafrost determined by borehole investigations in the Canadian Beaufort, where ice cover histories and the influence of fluvial water may be poorly constrained. Strong benthic warming might exaggerate the speed with which permafrost reaches its thawing temperature, but the rate of permafrost thaw is more strongly dependent on sediment ice content. This is unlikely to be relevant for permafrost that is cryotic but ice poor.

Minor comments:

The reviewer suggest for clarity to show the temporal development of the benthic temperature only for points with SSPF in Fig. S5.

We acknowledge that this is a good idea. The resultant figure is shown here as Fig. RA3:

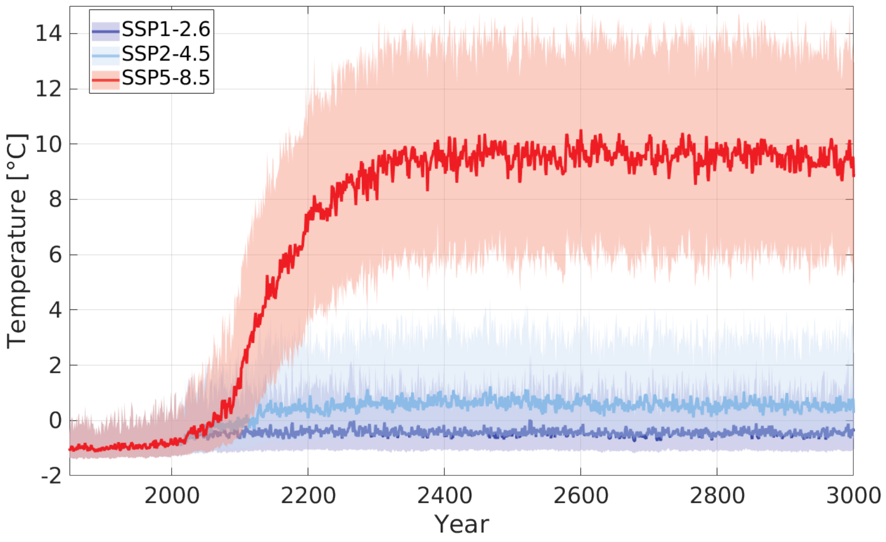

Fig. RA3: Benthic temperature development. As supplemental figure S5 but average only done over points with SSPF in 1850.

The reviewer miss a clear definition of which area is defined as SSPF area.

In our study we regard a grid cell with an ice concentration >0 anywhere in the sediment column as a SSPF cell, which is counted with it’s total area in the SSPF area. We have an implicit depth limit by the limit of our sediment depth (1km) but no further limit on the depth range in which ice has to appear to be counted. Due to the geothermal heat flux and the freezing history anyhow, no ice is found below 700m (i.e. in our lowest layer). We will include a more accurate definition in the final manuscript.

Bibliography

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