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The role of heat transfer time scale in the evolution of the subsea permafrost and associated methane hydrates stability zone during glacial cycles

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ABSTRACT

Climate warming may lead to degradation of the subsea permafrost developed during Pleistocene glaciations and release methane from the hydrates, which are stored in this permafrost. It is important to quantify time scales at which this release is plausible. While, in principle, such time scale might be inferred from paleoarchives, this is hampered by considerable uncertainty associated with paleodata. In the present paper, to reduce such uncertainty, one-dimensional simulations with a model for thermal state of subsea sediments forced by the data obtained from the ice core reconstructions are performed. It is shown that heat propagates in the sediments with a time scale of ~ 10–20 kyr. This time scale is longer than the present interglacial and is determined by the time needed for heat penetration in the unfrozen part of thick sediments. We highlight also that timings of shelf exposure during oceanic regressions and flooding during transgressions are important for simulating thermal state of the sediments and methane hydrates stability zone (HSZ). These timings should be resolved with respect to the contemporary shelf depth (SD). During glacial cycles, the temperature at the top of the sediments is a major driver for moving the HSZ vertical boundaries irrespective of SD. In turn, pressure due to oceanic water is additionally important for SD ≥ 50 m. Thus, oceanic transgressions and regressions do not instantly determine onsets of HSZ and/or its disappearance. Finally, impact of initial conditions in the subsea sediments is lost after ~ 100 kyr. Our results are moderately sensitive to intensity of geothermal heat flux.

1. Introduction

It is believed that most of the present-day methane hydrates (which are also referred to as methane clathrates) at continental shelves are formed in the subsea permafrost (MacDonald, 1990; Buffett, 2000; O'Connor et al., 2010). This permafrost has developed during Pleistocene glaciations (O'Connor et al., 2010; Behseresht and Bryant, 2012). Response of these hydrates to climate changes during warm epochs (i.e., interglacials), including the Holocene, is not well known. In particular, there is an uncertainty about origins of the measured large fluxes of methane from the marginal Arctic seas to the atmosphere (Westbrook et al., 2009; Shakhova et al., 2010a; Shakhova et al., 2010b; Semiletov et al., 2012; Berndt et al., 2014). While Shakhova et al. (2010a,b) and Semiletov et al. (2012) attribute the observed methane release to the contemporary climate warming, it might be related to the processes of much longer time scales, e.g., to the glacial cycles (Dmitrenko et al., 2011; Anisimov et al., 2014; Malakhova, 2016). The uncertainty in drivers of methane release has important implication for the release rate from hydrates over next coming centuries (O'Connor et al., 2010).

Understanding may be improved, in principle, by employing numerical models for thermal state of subsea sediments. Such modelling, however, contains its own uncertainties associated with its parameterisations (e.g., thermophysical properties of the sediment column or intensity of the geothermal heat flux) as explored by Eliseev et al. (2015), and with initial state originating from sea level changes during glacial cycles.

Timings of the oceanic regressions and transgressions depend on the contemporary shelf depth (e.g., Bauch et al., 2001). For instance, it is well known that the subsea permafrost top is deeper for locations which are more distant from the shoreline and, therefore, were earlier covered by water during the last glacial termination (Overduin et al., 2015). Previous studies, however, sometimes assume either instantaneous exposition and flooding over the entire shelf (Portnov et al., 2014; Razumov et al., 2014) (Nicolsky et al., 2012 is an exception though). Another somewhat unrealistic assumption, which is frequently employed is that the permafrost, which was developed during last glaciations, remains unchanged up to the present (Denisov et al., 2011;

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