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Climatic impact of Arctic Ocean methane hydrate dissociation in the 21st-century

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Abstract

Greenhouse gas methane trapped in sub-seafloor gas hydrates may play an important role in a potential climate feedback system. The impact of future Arctic Ocean warming on the hydrate stability and its contribution to atmospheric methane concentrations remains an important and unanswered question. Here, we estimate the climate impact of released methane from oceanic gas hydrates in the Arctic to the atmosphere towards the end of the 21st century, integrating hydrate stability and atmospheric modeling. Based on future climate models, we estimate that increasing ocean temperatures over the next 100 years could release up to 17 ± 6 Gt C into the Arctic Ocean. However, the released methane has a limited or minor impact on the global mean surface temperature, contributing only 0.1 % of the projected anthropogenic influenced warming over the 21st century.

1. Introduction

Methane is a greenhouse gas, which has a global warming potential ~28 times greater than CO_2 over 100 years (Myhre et al., 2013). The gas contributes significantly to the recent increase in global temperature and increasing atmospheric greenhouse gas levels (Hartmann et al., 2013;Saunois et al., 2016). A large amount of methane in the ocean is trapped in sediments in the form of gas hydrates, an ice-like crystalline substance made of water and gas (Sloan and Koh, 2008), which occurs in the pore space of sediments in continental margins all

over the world (Collett et al., 2009). Gas hydrates are generally stable under high-pressure and low-temperature but are extremely sensitive to slight variations in these conditions. The release of methane from dissociating hydrates in response to a warming ocean has been suggested to have major implications for past and rapid warming events (Dickens et al., 1997) resulting in a positive climate feedback (Berbesi et al., 2014;Kroeger and Funnell, 2012). The potential impact of hydrates on global climate and its consideration as an unconventional energy resource lead to numerous studies trying to estimate the amount of methane trapped in hydrates beneath the ocean floor (Archer et al., 2009;Buffett and Archer, 2004;Burwicz et al., 2011;Dobrynin et al., 1981;Kretschmer et al., 2015;Kvenvolden, 1988;Milkov, 2004). Furthermore, there is a concern that ongoing global warming could result in the dissociation of ~2% of the existing global sub-sea hydrates over the next 800 years (Hunter et al., 2013). However, the fate of the released methane and its impact on the atmosphere and climate remains very uncertain and a quantitative assessment is therefore deemed important for climate projections.

In particular, the Arctic environment is a very climatically sensitive region, which is warming fast and twice as much than the rest of the world. This phenomenon is called the Arctic amplification (Screen and Simmonds, 2010). Under the RCP8.5 "*business as usual*" scenario (Stocker et al., 2013), the Arctic temperature could rise as much as 10-12 degrees by 2100 in certain areas. The Arctic Ocean hosts numerous methane seeps that are presently very active and gas hydrate accumulations that are widespread but with a patchy distribution (Bünz et al., 2012;Paull et al., 2007;Ruppel, 2015;Phrampus et al., 2014;Shakhova et al., 2010;Sahling et al., 2014). Some of the methane seeps are directly connected with dissociating methane hydrates (Westbrook et al., 2009;Berndt et al., 2014;Portnov et al., 2016) and/or thawing subsea permafrost (Portnov et al., 2013) after ice sheet retreats. Although the suggested gas hydrate storage in the Arctic represents only a fraction of the global repository of methane

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stored in hydrates (Kretschmer et al., 2015;Marín-Moreno et al., 2016), the rapid loss of sea ice (Boe et al., 2009), thawing subsea permafrost, and a warming ocean (Ferré et al., 2012) could potentially result in accelerated release of methane from dissociating hydrates. This study presents a quantitative analysis of the impact of methane hydrate dissociation on the atmosphere and climate over the 21st century. To this end, we analyze methane hydrate dissociation in the Arctic Ocean and potential methane emissions to the atmosphere due to ocean warming. The approach utilizes an ensemble of nine Coupled Model Intercomparison Project (CMIP5) (Taylor et al., 2012) climate predictions to model the transient evolution of hydrate stability with variations in ocean bottom water temperature. The impact of methane emissions resulting from gas hydrate dissociation on the atmosphere is then analyzed through atmospheric chemistry and transport modeling. Finally, we calculate the radiative forcing of the atmospheric perturbation resulting from the release of methane from hydrate dissociation over the next 100 years.

2. Methods

2.1 Quantification of the present-day methane hydrate reservoir in the Arctic

The amount of methane trapped as gas hydrates is calculated based on the thickness of methane hydrate stability zone, hydrate saturation in the sediments, and the porosity. Methane hydrate stability thickness in the Arctic sediments north of 65° N is estimated using the CSMHYD program (Sloan and Koh, 2008) for pure methane gas and a pore-water salinity of 35 ‰. The input data for the hydrate stability modeling include the IBCAO bathymetry (Jakobsson et al., 2012) and thermal gradient measurements over the Arctic (Bugge et al., 2002;Phrampus et al., 2014;Damm et al., 2013;Pollack et al., 1993) (See S1 for more details).

Estimation of hydrate saturation in the sediment pore space involves direct methods such as drilling or indirect methods which involve analysis of seismic data. As there are no direct

measurements of hydrate saturation in the Arctic Ocean, we adopt hydrate saturation estimates derived from analysis of ocean-bottom seismic data from offshore Svalbard (Hustoft et al., 2009;Chabert et al., 2011;Westbrook et al., 2008). Based on these studies, we apply a constant hydrate saturation of 9 ± 3 % of pore space throughout the gas hydrate stability zone in the Arctic sediments. We assume a constant hydrate-free sulfate reduction zone extending from the seafloor to a depth of 5 m in the sediments (Riedel et al., 2006), where anaerobic oxidation consumes methane. The gas hydrate stability zone is adjusted based on the global sediment thickness map in areas where the base of hydrate stability zone exceed the thickness of sediments (Laske and Masters, 1997). We employ a porosity curve, with values from available ocean drilling data (for locations of the drill holes, see Fig. S3) (IODP database, http://iodp.tamu.edu/janusweb/links/links_all.shtml) for the estimation of available pore-space for hydrate formation. To estimate the volume of methane trapped in hydrates, we consider 163 m^3 of methane trapped in 1 m^3 of hydrates with a 94 % cage occupancy based on observations from Blake Ridge (Lorenson and Collett, 2000). The number of moles of methane estimated stems from the methane volume using the ideal gas law at STP.

2.2 Transient evolution of methane hydrate reservoir

To estimate the evolution of methane hydrate stability in the Arctic during the 21st century (2006-2100), we consider seafloor temperature variations from nine different CMIP5 climate models (Arora et al., 2011;von Salzen et al., 2013;Gent et al., 2011;Hurrell et al., 2013;Dunne et al., 2012;Dunne et al., 2013;Schmidt et al., 2006;Schmidt et al., 2014;Collins et al., 2011;Martin et al., 2011;Dufresne et al., 2013;Watanabe et al., 2011;Jungclaus et al., 2013;Stevens et al., 2013) (Table S1) based on the RCP 8.5 scenario (Riahi et al., 2011). Using an ensemble of models illustrates the uncertainty range in model simulations and the multi-model mean generally agrees more favorably with observations than the individual models (Flato et al., 2013). It also increases the robustness of results and estimates for the 21st

century. The climate models have a temporal resolution of one year which allows analysis of hydrate stability evolution at a high temporal resolution. A 3D finite-difference heat flow model is used to estimate the diffusive transport of seafloor temperature variation through the sediments (Turcotte and Schubert, 2002;Spiegelman, 2004;Gerya, 2010;Phrampus and Hornbach, 2012) (see S4 for more details). Afterwards, the resulting subsurface temperature profile for each year allows estimating the thickness of the methane hydrate stability zone and the methane stored within the zone as hydrates.

2.3 Radiative forcing of released methane from methane hydrates

The estimated yearly average methane emissions to the atmosphere from methane hydrate dissociation as predicted by the transient hydrate model were added as an additional emission source in a simulation using the Oslo CTM3 model (Dalsøren et al., 2016;Søvde et al., 2012). The lifetime of methane is longer than the time-scale for interhemispheric exchange, it is therefore not critical for the climate impact study to know exactly where the extra Arctic Ocean gas emissions occur. Emissions are therefore distributed evenly over the ocean north of 70° N. The initialization of the atmosphere started with the year 2006 concentrations of methane and other chemical compounds affecting the atmospheric chemistry as described in Dalsøren et al. (2016). See also Dalsøren et al. (2016) for further details on model setup, chemical reactions, and applied meteorological fields. The model was then run with the extra methane flux until the atmospheric methane burden reached a new equilibrium. The calculated change in tropospheric methane concentration was used to quantify the radiative forcing using simplified equations for methane (Myhre et al., 1998).

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3. Results and Discussion

3.1 Methane hydrates in the Arctic and its response to a warming ocean

The present-day hydrate stability zone in the Arctic modeled using present-day pressure-temperature conditions is shown in figure 1. On the continental shelves off northern Norway, Svalbard, Russia, and Alaska, the pressure-temperature conditions are not suitable for the widespread occurrence of methane hydrate accumulations, except for relatively smaller areas in the Barents Sea. Gas hydrates could be stable under the submarine permafrost off the coast of Russia and Alaska. Permafrost conditions are not considered in this model, however, the hydrate accumulations are relatively small in the marine permafrost regions (Ruppel, 2015). Even today, the depth of the hydrate stability zone may reach a substantial 700 m thickness beneath the seafloor (dark blue) as seen in the Canada Basin, where water depths reach approx. 4000 m (Fig.1).

Based on the thickness of the modeled gas hydrate stability zone and hydrate saturation within the sediments we estimate a methane hydrate volume of 29 ± 12 (1-σ) trillion m^3, which is equivalent to 4777 ± 1901 (1-σ) trillion m^3 of methane or 2524 ± 1005 (1-σ) Gt of carbon. The model does not include hydrates trapped under submarine permafrost on Arctic continental shelves, which may amount to approx. 20 Gt of carbon (Ruppel, 2015). Our estimate falls within the range of values reported previously, with its lowest at 110 Gt of carbon (Kretschmer et al., 2015) and highest at 9000 Gt of carbon (Biastoch et al., 2011).

The impact of non-linear variations in the ocean bottom temperature on methane hydrate stability during the 21st century is evaluated by employing an ensemble of nine CMIP5 climate models (from 2006-2100) under the RCP8.5 scenario (Fig.2a). The model data were compared to measured bottom water temperatures for the period 1960-2013 at three different locations (Fig.2a). More than half of the selected climate models agree well with the observed

bottom water temperature, except in the Beaufort Shelf, but there the number of measurements is relatively low. The values predicted by the model are yearly averages hence the mismatch between seasonal measurements and model predictions are expected. The climate models reveal bottom water temperatures variations up to 11 ^{0}C (e.g., HadGEM2-ES) in the Barents Sea over the 94 years from 2006-2100 (Fig.2a). The lowest variation in bottom water temperature over this period (an increase of <1 ^{0}C) is projected by the GISS-E2-R model.

In the model, the thickness of the hydrate stability zone varies in response to the changes in bottom water temperature. Due to the non-linearity of bottom water temperature variations, shallow hydrates may form or dissociate if the bottom water gets colder or warmer, respectively. However, since the bottom water temperature increases overall over the investigated period, the total volume of methane hydrates in the Arctic is lower in the year 2100 than 2006. We estimate ~0.7 % ± 0.25 (1-σ) of the initial hydrate volume could dissociate until 2100 (Fig. 2b). This corresponds to 32.48 ± 11.6 (1-σ) trillion m^{3} (22884 ± 8173 Tg) of methane or 17.15 ± 6.13 (1-σ) Gt of carbon that could be released into the water column of the Arctic over the course of 94 years, until the year 2100. The amount of methane dissociated from hydrates varies from year to year with a maximum of 428 ± 217 Tg yr^{-1} of methane during the year 2081 (Fig.3). These variations are mainly due to the fluctuations in ocean bottom temperatures (Fig.2a) resulting in a rapid response of the shallow hydrate system, typically 1-50 m below the seafloor.

Our calculations show a mean value of 220 ± 160 Tg yr^{-1}of methane released from hydrate dissociation at the Arctic seabed to the ocean. In our estimate, we assume no heat changes during hydrate dissociation or gas retention in sediments, and no delay in the time taken for the gas to migrate through the sediments to the seafloor. These effects may slow-down methane flux to the water column in the short term (100 years) by up to >70% (Stranne et al.,

166 2016b), hence we present an upper estimate. Biastoch et al. (2011) predicted a mean emission
167 of 162 Tg yr^{-1} of methane release from the Arctic seabed. A more recent study using a single
168 climate model predicted a reduction of up to 0.12 % of the existing gas hydrate reservoir by
169 the end of the century (Kretschmer et al., 2015). Both these results are of the same order of
170 magnitude as our estimations.

171 The distribution of the methane releases from methane hydrates to the ocean until 2100 are
172 not uniform in the Arctic (Fig.4a). The Arctic continental slopes are hotspots for hydrate
173 dissociation due to ocean warming. The area affected most is the SW Barents Sea, where up
174 to 16000 moles m^{-2} of methane (0.25 tons m^{-2}) (or a lower limit of 4800 moles m^{-2}, based on
175 Stranne et al. (2016b)) could be released into the water column before 2100 (Fig.4a). Most of
176 the hydrate dissociation occurs in the 350-450 m seafloor depth range. Reported methane
177 seeps from Arctic regions (Fig.4a, red dots), generally match predicted locations of hydrate
178 dissociation, except in permafrost areas which are not considered in our model. From very
179 active methane seep areas on the West Svalbard margin, a methane bubble flow of 4-50 x 10^6
180 mol yr^{-1} is reported at a water depth of around 380-390 m using a bubble catcher during the
181 year 2012 (Sahling et al., 2014). This is at least an order of magnitude lower than our mean
182 estimate of 384 x 10^6 mol yr^{-1}. Modeling conducted over the same area (Marín-Moreno et al.,
183 2015) estimate a methane flow from the seabed (420-450 m water depth) of about 25–35 mol
184 yr^{-1} m^{-2} from dissociating hydrates. It is comparable to our mean estimate of about 27 mol yr^{-1}
185 m^{-2} at that location. These estimates are close to methane bubble emissions from thawing sub-
186 sea permafrost in the East Siberian Shelf (Shakhova et al., 2014).

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3.2 Methane release from the Arctic Ocean and its potential impact on the atmosphere and climate

The migration of methane from the seabed to the surface water can be either through bubbles or as dissolved methane. Modeling studies suggest that for water depths more than 100 m, methane gas bubbles may not be able to reach the surface water (McGinnis et al., 2006). In addition, methane gas can diffuse out of bubbles, so that most of the methane gas dissolves within the water column before reaching the surface (McGinnis et al., 2006). Various microbial processes and oceanic conditions control the fate of dissolved methane in the water column (AMAPAssessment, 2015). Aerobic microbial oxidation can consume dissolved methane in the water column, the rate of which depends on the amount of methane available and hydrodynamic conditions (Valentine et al., 2001). In addition, water mass stratification is a potential barrier for upward migration of dissolved methane (Graves et al., 2015;Geprägs et al., 2016;Steinle et al., 2015). Recent studies from Western Svalbard identified efficient methane filtering by oxidation and water mass stratification in the water column (Graves et al., 2015;Steinle et al., 2015), and very little to no methane flux into the atmosphere from waters offshore western Svalbard during the 2015 summer season despite high concentrations of methane above the seabed (Myhre et al., 2016).

Nevertheless, methane released at seabed could still reach the surface waters under favorable oceanographic conditions as stormy seas, and winter time, and in shallow seas (< 50m) (Shakhova et al., 2014). Analysis of water column methane concentration measurements from the Arctic (Table S2) show that the amount of methane that reaches surface waters is a function of the water depth (Fig.4b) (Mau et al., 2015;Shakhova et al., 2010;Schneider von Deimling et al., 2011;Damm et al., 2008;Damm et al., 2007;Damm et al., 2005;Myhre et al., 2016;Gentz et al., 2014;Lammers et al., 1995;Steinle et al., 2015;Graves et al., 2015). More than 50 % of the methane released at the seabed seem to reach the surface waters when the

water depth is lower than 20 m (Fig. 4b, Table S2). However, the amount of methane that reaches the surface water reduce drastically as the water depth increases. Around the water depth of 300-400 m, where most of the hydrate dissociation areas are located (Fig. 4a), the amount of methane that reached surface water was between 0.1 and 7.5% of the amount released at the seabed (Fig. 4b, Table S2). The ocean surface water-atmosphere methane flux depends greatly on the wind conditions and the equilibrium concentration of methane in seawater (Shakhova et al., 2014;Graves et al., 2015). Offshore west Svalbard, sea water-atmosphere methane flux was up to ~50 % of the surface water concentration over two seasons (Graves et al., 2015). Based on this we propose that 1% (0.1 to 10%) of the methane released at the seafloor reaching the atmosphere. This translates to an emission of 2.2 Tg CH_4 yr^{-1} (0.2 – 22) to the atmosphere from hydrate dissociation in the Arctic. This is about five times lower than the anthropogenic methane emissions in the Arctic in the year 2005 from fossil fuel industry, agriculture, and wastewater sectors, which is estimated to ~56 Tg yr^{-1} (ranging from 56 – 67 as per three different agencies) of CH_4 and predicted to increase up to 103 Tg $yr^{-1}$of CH_4 by 2050 (based on GAINS CLE) (AMAPAssessment, 2015).

To assess the atmospheric changes and calculate the additional radiative forcing due to methane emissions from hydrates dissociation until 2100, we have added emissions of 2.2 Tg CH_4 yr^{-1} (0.2 – 22) to a detailed global chemistry-transport model (Dalsøren et al., 2016) for calculations of the corresponding changes in the atmospheric CH_4 concentration. The simulated global mean increase in atmospheric CH_4 concentration over the period 2006-2100 is estimated to be 13 ppb (1.3 – 130). We calculate a radiative forcing of 0.005 Wm^{-2} (0.0005 to 0.05) from this change in atmospheric methane abundance (Myhre et al., 1998). A change in atmospheric CH_4 also changes ozone and stratospheric water vapor. Based on previous simulations, we quantify our upper limit to be less than 50% of the CH_4 radiative forcing (Isaksen et al., 2011). The radiative forcing due to the release of methane from hydrate

dissociation to the atmosphere is therefore estimated to be in an upper range of 0.007 Wm^{-2} (0.0007 to 0.07) up till 2100. To put such a change into perspective, this is less than 0.1% of the total radiative forcing in the RCP8.5 scenario. This conclusion holds even with a 25% increase in the radiative forcing of methane recently estimated, mainly due to the inclusion of shortwave absorption by methane (Etminan et al., 2016).

Our study suggests that even under strong global warming (RCP 8.5) projections, Arctic methane hydrate dissociation and fluxes to the atmosphere may have a negligible impact on the global climate and thus on a climate feedback loop in the near future (within this century). The added 13 ppb of methane to the atmosphere from hydrate dissociation is comparable to the annual yearly increase in recent years (The global mean increase from 2014-2015 was 11 ppb (WMO, 2016)). To reach a 1-degree additional increase in global temperature, it would require three to four times increase in the methane concentration, i.e., on the order of 800 Tg yr^{-1} of methane release from the Arctic Ocean to the atmosphere over the course of 21st century (Isaksen et al., 2011;Samset et al., 2016). Based on our study, a maximum amount of only 380 Tg yr^{-1} of methane might release into the Arctic atmosphere due to hydrate dissociation, considering no ocean filter.

The contribution of marine methane seepage to the global methane emission is estimated to be ~20 Tg yr^{-1} (Kvenvolden et al., 2001), with a global contribution of 2-10 Tg yr^{-1} from hydrates (Ciais et al., 2013). Airborne observations of methane in the Arctic Ocean suggest a methane efflux of 10.2 Tg yr^{-1}(Kort et al., 2012). These values, along with the reported emissions on the East Siberian Arctic Shelf (Shakhova et al., 2010), are within our estimated range of 0.2 - 22 Tg yr^{-1}. Based on our climate impact analysis and other recent studies (Stranne et al., 2016a;Ruppel and Kessler, 2017), gas hydrate dissociation in the Arctic Ocean appears to be a minor methane source to the atmosphere in the near future.

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4. Impact of model uncertainties

As with any modeling exercise analyzing a complex system, the modeling presented here also involve large uncertainties. Some of these uncertainties arise from the lack of data coverage, whereas a few are inherent due to the complex nature of the Earth system. The uncertainties that arise from the lack of data include heat flow data and sediment porosity. These parameters have a significant impact on the estimation of gas hydrate volume within the Arctic Ocean sediments as presented in the supplementary material (S2, fig. S5). As such, this manuscript is not an effort to improve on the methodology or the estimate of hydrate volume in the Arctic marine sediments. We utilize the volume of hydrates as a marker to evaluate potential scenarios of hydrate dissociation in the 21st century and try to evaluate its impact on climate. The most significant parameters that have a larger impact are hydrate saturation and transport of methane through the sediments and water column.

The nature of hydrate distribution through the hydrate stability zone is almost impossible to estimate or model over large regions such as the Arctic Ocean. Hence, we have considered a constant hydrate saturation throughout the hydrate stability zone. This might inflate the gas hydrate volume within the sediments, and the estimates presented here should be taken as a first-order estimate. However, this does not necessarily affect our conclusion, as even with very high estimates of hydrate volume or methane release, the impact on the atmosphere remains minor.

As previously mentioned, our study does not account for methane release from permafrost-degradation in the Arctic shelves (e.g., Shakhova et al., 2017;Shakhova et al., 2015). Increasing ocean temperatures, seawater transgression, and seafloor erosion are contributing to rapid degradation of marine permafrost which could potentially release methane into shallow water column (Shakhova et al., 2017). Approximately 20 Gt of carbon (~26 Pg of

287 CH_4) might be trapped as methane under the thawing Arctic shelves (<200 m) (Ruppel,
288 2015). Complete destabilization of permafrost generally takes ~5-7 kyr, based on modeling
289 results (Romanovskii et al., 2005). If we consider a rapid degradation of permafrost within a
290 1 kyr period (e.g., Shakhova et al., 2014), the maximum amount of methane that could be
291 released in to the water column is ~26 Tg yr^{-1}. This is well within the uncertainty limits of
292 our estimated 220 ± 160 Tg yr^{-1} emission from gas hydrate dissociation.

293 As detailed in sections 3.1 and 3.2, the transport of methane is slow through the sediments
294 and methane is consumed both in the shallow sediments as well as within the water column.
295 Methane oxidation in the water column can add to the CO_2 budget of the Ocean. However,
296 additional CO_2 generated through this process is at least seven orders of magnitude lower
297 than the CO_2 influx into the Ocean (e.g., Takahashi et al., 2009;Mau et al., 2013) and has
298 negligible impact on the earth system model used in this study. This is not accounted in our
299 study, as the additional CO2 generaConsidering that most of the hydrate dissociation occur
300 over water depths of 300-400 m, little to no methane might be reaching the atmosphere, as
301 evidenced offshore Svalbard (Myhre et al., 2016). Thus, our model here might be
302 overestimating the methane flux into the atmosphere, as well as its radiative forcing.
303 However, this also does not affect our conclusions as our estimates show that even if the
304 effect of the water column is neglected, the methane flux to the atmosphere is too low to have
305 a significant impact on global temperatures.

306 ## 5. Conclusions

307 Here we present the climate impact of methane emissions from dissociating gas hydrates over
308 the Arctic Ocean in the 21st century by integrating hydrate stability, seafloor temperature
309 variations, and atmospheric modeling. The mean present-day carbon reservoir within Arctic
310 sediments is estimated to be ~2524 ± 1005 Gt. Transient modeling of hydrate stability shows

311 that up to 32 ± 12 trillion m^3 of methane (17 ± 6 Gt C) could release into the Arctic Ocean in
312 the 21st century as a result of warming ocean waters. However, microbial methane filter
313 processes and oceanic conditions restrict the methane release to the atmosphere to about 1%
314 (0.1 – 10%) of the expelled methane at the seafloor. This amounts to methane emission of 2.2
315 Tg CH_4 yr^{-1} (0.2 – 22) to the atmosphere, which results in a radiative forcing of 0.007 Wm^{-2}
316 (0.0007 to 0.07) Wm^{-2} up until 2100. This represents less than 0.1 % of the total radiative
317 forcing in the RCP8.5 scenario, suggesting that climate impact of methane release from
318 hydrate dissociation appears to be minor in the Arctic Ocean during the 21st century.

319 ## Data Availability

320 The climate models are available from the sources mentioned in Table S1. The bottom water
321 temperature data, heat flow data, porosity values are accessible from the websites of NOAA-
322 NODC, International Heatflow Commission, and the Ocean Drilling Program respectively.
323

324 ## Competing interests

325 The authors declare that they have no conflict of interest.
326

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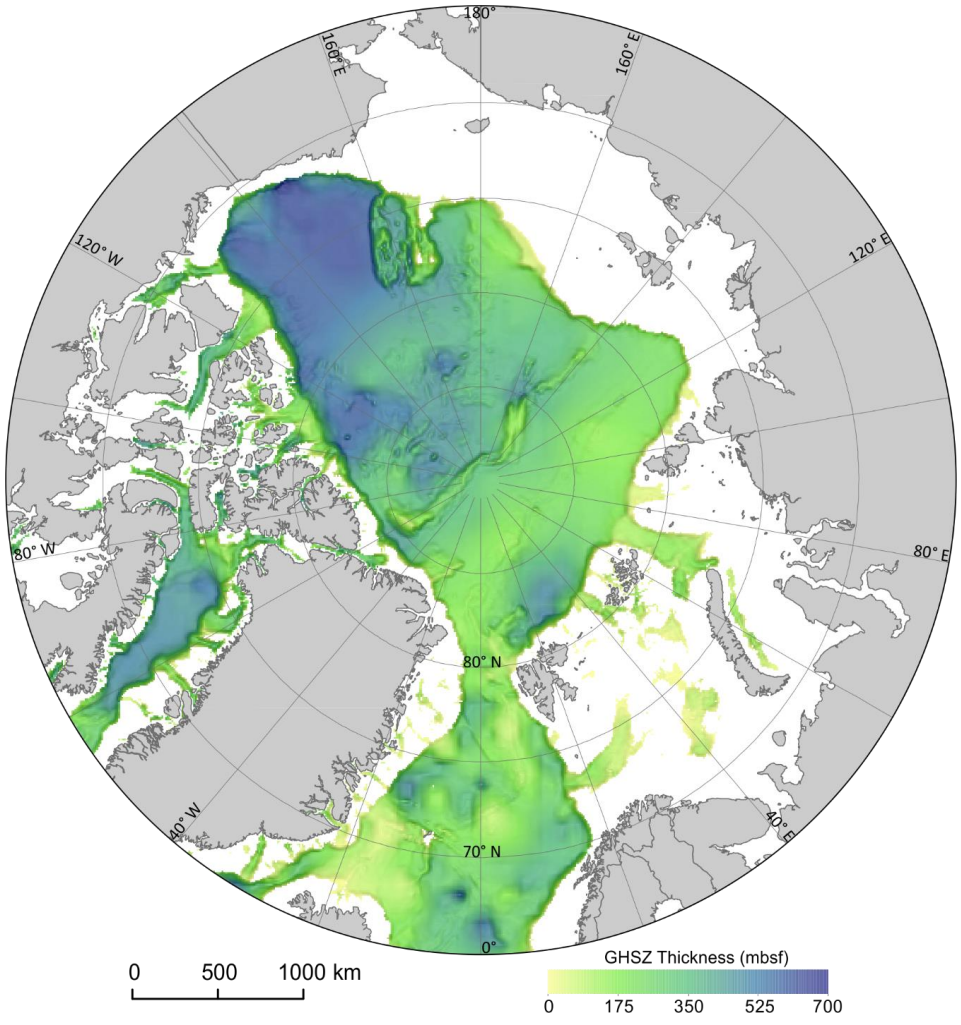
Discussion started: 18 December 2017

719 FIGURE 1



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721 **Figure 1.** Present-day gas hydrate stability zone over the Arctic region modeled in this study

722 (see supplementary S1 for details).

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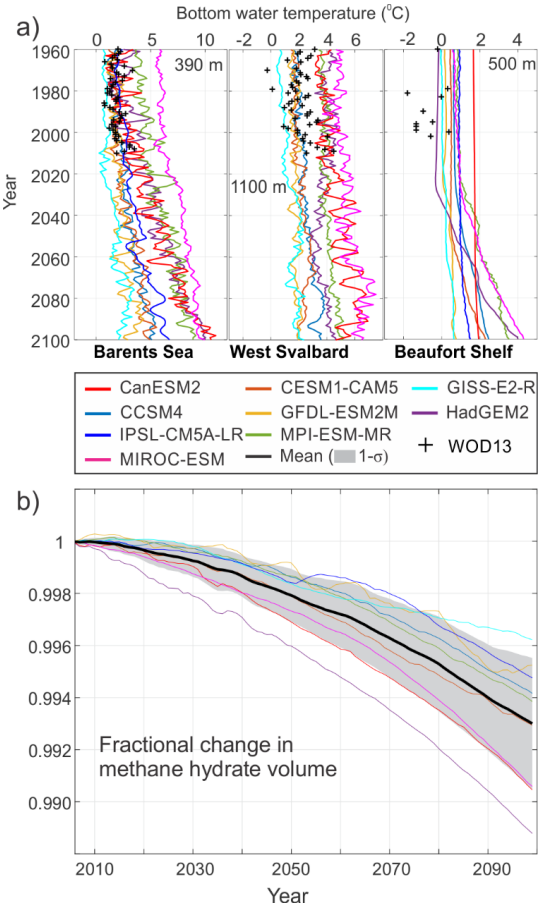

Figure 2. a) Comparison between temperature predictions from 9 CMIP5 models and measurements of bottom water temperature from high-resolution CTD (Conductivity, Depth, Temperature) data shown as black '+' symbols (See S1 and S3 for more details). The measured water depth is indicated in meters. b) Variation in the potential volume of methane hydrates within the hydrate stability zone with the changes in ocean bottom temperatures based on multiple climate models until the year 2100.

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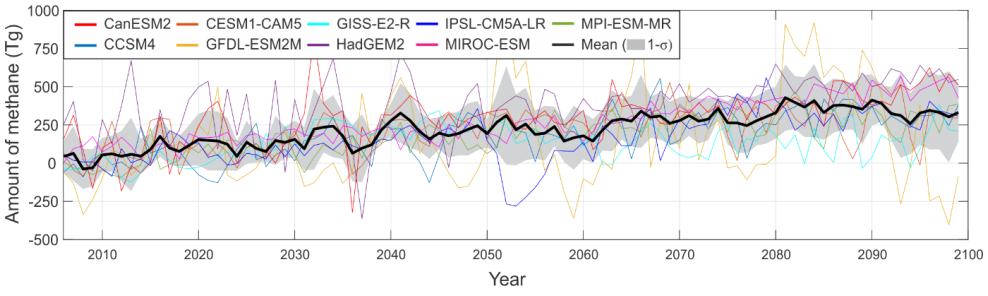
736 FIGURE 3



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738 **Figure 3.** Amount of methane (Tg) released per year from methane hydrates to the ocean over
739 the whole Arctic for each climate model. The mean represents the average amount of methane
740 released each year as predicted by the nine different modeling scenarios. The shaded area
741 represents the standard deviation (1-sigma) for each year.

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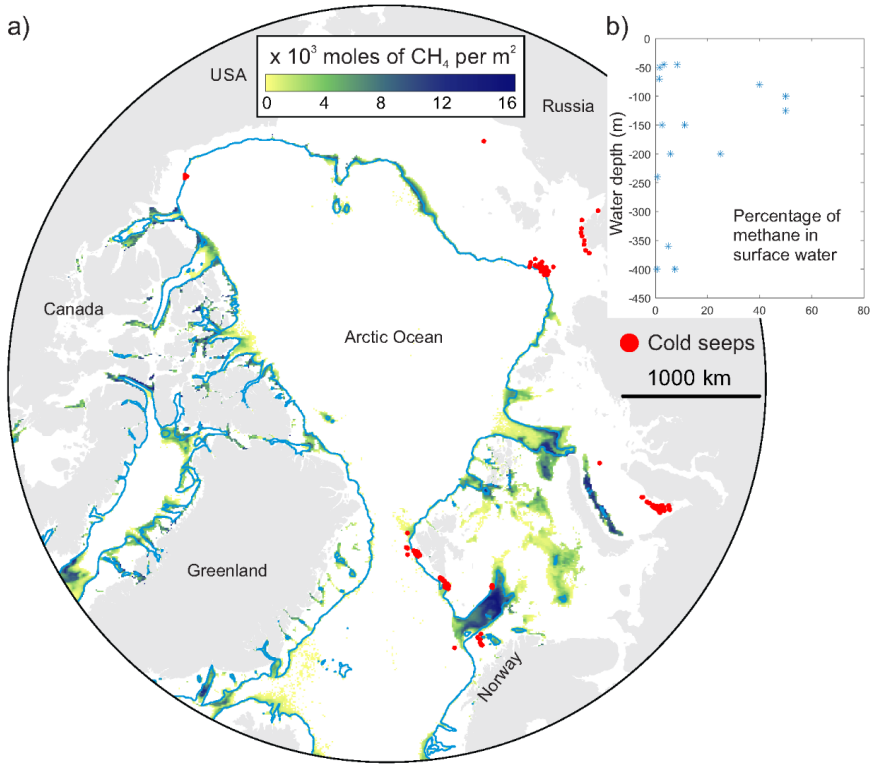
753 FIGURE 4



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755 **Figure 4.** a) Map showing the regions and mean value of total amount of methane released
756 until 2100. Identified methane seeps in the Arctic are also marked. The light-blue line denotes
757 360 m isobath which we identify as the hotspot for future methane release in the Arctic. b)
758 Percentage of methane observed (blue stars, as a function of observed bottom water
759 concentrations) in surface water of Arctic seep locations (See table S2 in supplementary).