

# **A model of the methane cycle, permafrost, and hydrology of the Siberian continental margin**

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## **Author's response**

First I want to acknowledge my gratitude to the editor and the reviewer. On the editor's part, I imagine that this paper might have required more time to sort through the contentious issues than is usual. I am deeply grateful. I hope I have taken advantage of the reviewers' suggestions in a way that would be more to his/her satisfaction than I did last time.

I have restructured the whole document, and rewritten it quite extensively, along the suggestions of the editor and the reviewer. The reviewer suggested a section describing the outline of the paper, which I have now added. An alternative possibility would be a table of contents. I added both; the editor can decide which of these options is preferable, or maybe both. I restructured the body of the text so that it made more sense as an outline or TOC, makes it easier to find things and know where one is. I relegated a substantial amount of text to supplemental sections (about 15%), along with four figures. I completely rewrote the abstract as suggested. The reviewer asked for a section on critical issues for further model development, which I would not have thought to include, but it did help focus the conclusions section, and so was another good suggestion. In the end the main text of the paper is substantially shorter and I hope more accessible.

1 **A model of the methane cycle, permafrost, and hydrology of the Siberian**  
2 **continental margin**

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5  
6 **Abstract**

7 A two-dimensional model of a sediment column, with Darcy fluid flow,  
8 biological and thermal methane production, and permafrost and methane  
9 hydrate formation, is subjected to glacial / interglacial cycles in sea level,  
10 alternately exposing the continental shelf to the cold atmosphere during  
11 glacial times, and immersing in the ocean in interglacial times. The glacial  
12 cycles are followed by a “long tail” 100-kyr timescale warming due to  
13 fossil fuel combustion.

14 The salinity of the sediment column in the interior of the shelf can be  
15 decreased hydrological forcing, to depths well below sea level, when the  
16 sediment is exposed to the atmosphere. There is no analogous advective  
17 seawater-injecting mechanism upon resubmergence, only slower diffusive  
18 mechanisms. This hydrological ratchet is consistent with the existence of  
19 fresh water beneath the sea floor on continental shelves around the  
20 world, left over from the last glacial time.

21 The salt content of the sediment column affects the relative proportions  
22 of the solid and fluid H<sub>2</sub>O-containing phases, but in the permafrost zone  
23 the salinity in the pore fluid brine is a function of temperature only,  
24 controlled by equilibrium with ice. Ice can tolerate a higher salinity in the  
25 pore fluid than methane hydrate can at low pressure and temperature,  
26 excluding methane hydrate from thermodynamic stability in the  
27 permafrost zone. The implication is that any methane hydrate existing  
28 today will be insulated from anthropogenic climate change by hundreds of  
29 meters of sediment, resulting in a response time of thousands of years.

30 The strongest impact of the glacial / interglacial cycles on the  
31 atmospheric methane flux is due to bubbles dissolving in the ocean when  
32 sea level is high. When sea level is low and the sediment surface is  
33 exposed to the atmosphere, the atmospheric flux is sensitive to whether  
34 permafrost inhibits bubble migration in the model. If it does, the

35 atmospheric flux is highest during the glaciating, sea-level regression (soil  
36 freezing) part of the cycle, rather than during deglacial transgression  
37 (warming and thawing).

38 The atmospheric flux response to a warming climate is small, relative to  
39 the rest of the methane sources to the atmosphere in the global budget,  
40 because of the ongoing flooding of the continental shelf. The increased  
41 methane flux due to ocean warming could be completely counteracted by  
42 sea level rise of tens of meters on millennial time scales due to loss of ice  
43 sheets, decreasing the efficiency of bubble transit through the water  
44 column. The model results give no indication of a mechanism by which  
45 methane emissions from the Siberian continental shelf could have a  
46 significant impact on the near-term evolution of Earth's climate, but on  
47 millennial timescales the release of carbon from hydrate and permafrost  
48 could contribute significantly to the fossil fuel carbon burden in the  
49 atmosphere / ocean / terrestrial carbon cycle.

51	<u>1. Introduction.....</u>	<u>5</u>
52	<u>1.1 The Siberian Continental Shelf System .....</u>	<u>5</u>
53	<u>1.1.1 Permafrost .....</u>	<u>6</u>
54	<u>1.1.2 Salt .....</u>	<u>7</u>
55	<u>1.1.3 Carbon.....</u>	<u>8</u>
56	<u>1.2 Models of Methane Hydrate in the Permafrost Zone .....</u>	<u>8</u>
57	<u>1.3 Outline of This Work.....</u>	<u>8</u>
58	<u>2. Model Description.....</u>	<u>9</u>
59	<u>2.1 SpongeBOB Application to the Siberian Continental Margin .....</u>	<u>9</u>
60	<u>2.2 New Model Development: Groundwater Hydrology.....</u>	<u>11</u>
61	<u>2.2.1 Pressure Head .....</u>	<u>11</u>
62	<u>2.2.2 Pore Fluid Flow .....</u>	<u>12</u>
63	<u>2.2.3 Canyons.....</u>	<u>13</u>
64	<u>2.3 Permafrost.....</u>	<u>14</u>
65	<u>2.3.1 Thermodynamics of Ice and Hydrate.....</u>	<u>14</u>
66	<u>2.3.3 Other Impacts .....</u>	<u>16</u>
67	<u>2.4 Atmospheric Methane Fluxes .....</u>	<u>16</u>
68	<u>2.5 Initial Condition.....</u>	<u>18</u>
69	<u>2.5.1 Rational for Spinup.....</u>	<u>18</u>
70	<u>2.5.2 Sediment Column Salt Content.....</u>	<u>18</u>
71	<u>2.6 Glacial Cycle Forcing .....</u>	<u>19</u>
72	<u>2.6.1 Sea Level.....</u>	<u>19</u>
73	<u>2.6.2 Glacial Climate.....</u>	<u>19</u>

74	<u>2.6.3 Deposition of Carbon on Land .....</u>	<u>20</u>
75	<u>2.7 Anthropogenic Global Warming Forcing .....</u>	<u>20</u>
76	<u>2.7.1 Long-Term Climate Impact from CO<sub>2</sub> Addition .....</u>	<u>20</u>
77	<u>2.7.2 Long-Term Behavior of Sea Level.....</u>	<u>20</u>
78	<u>2.8 Sensitivity Studies.....</u>	<u>21</u>
79	<u>3. Results.....</u>	<u>21</u>
80	<u>3.1 Glacial Cycles .....</u>	<u>25</u>
81	<u>3.1.1 Salinity.....</u>	<u>25</u>
82	<u>3.1.2 Pressure and Flow .....</u>	<u>26</u>
83	<u>3.1.3 Methane Cycle.....</u>	<u>26</u>
84	<u>3.2 Anthropogenic Global Warming.....</u>	<u>31</u>
85	<u>3.3 Sensitivity Studies.....</u>	<u>33</u>
86	<u>3.3.1 Sediment Salt Content.....</u>	<u>33</u>
87	<u>3.3.2 Methane Production Rates .....</u>	<u>34</u>
88	<u>3.3.3 Geothermal Temperature Gradient .....</u>	<u>34</u>
89	<u>3.3.4 Thermodynamic Competition Between Ice and Hydrate .....</u>	<u>34</u>
90	<u>3.3.5 Permafrost Inhibition of Gas Migration .....</u>	<u>34</u>
91	<u>3.3.6 Vertical flow heterogeneity .....</u>	<u>35</u>
92	<u>3.3.7 Ground water Flow .....</u>	<u>35</u>
93	<u>3.4 Comparison with Observations.....</u>	<u>35</u>
94	<u>4. Discussion .....</u>	<u>36</u>
95	<u>4.1 Limitations of the Model Results and Critical Issues for Future</u>	
96	<u>Development.....</u>	<u>36</u>
97	<u>4.1.1 Methane Production Rates .....</u>	<u>36</u>
98	<u>4.1.2 Gas Transport in the Sediment Column .....</u>	<u>36</u>
99	<u>4.1.3 Atmospheric Flux Efficiency.....</u>	<u>37</u>
100	<u>4.1.4 Uncertainty in Model Output.....</u>	<u>37</u>
101	<u>4.2 Robust Features of the Simulation.....</u>	<u>39</u>
102	<u>4.2.1 Arctic Ocean Methane Fluxes are Small in the Global Budget ..</u>	<u>39</u>
103	<u>4.2.1 The Hydrological Salinity Ratchet .....</u>	<u>39</u>
104	<u>4.2.2 Salinity (Water Activity) and Hydrate Stability in the Permafrost</u>	
105	<u>Zone .....</u>	<u>39</u>
106	<u>4.2.3 Sea Level Dominates the Glacial Cycle of Methane Flux.....</u>	<u>40</u>
107	<u>4.2.3 Methane Emission Response to Anthropogenic Climate Change</u>	<u>40</u>
108	<u>5. Acknowledgements.....</u>	<u>43</u>
109	<u>6. Bibliography.....</u>	<u>43</u>
110	<u>7. Figure Captions .....</u>	<u>50</u>
111	<u>8. Tables.....</u>	<u>55</u>
112	<u>9. Supplemental Text .....</u>	<u>57</u>
113	<u>S1. Vertical Flow.....</u>	<u>57</u>

114 S2. Ice Formation..... 58

115 S3. Thermodynamics of Ice and Hydrate..... 58

116 S4. Construction of the Pre-Freshened Sediment Column..... 59

117 negligible impact of canyons ..... 60

118 120 m same as 30 ..... 60

119 10. Supplemental Figure Captions ..... 60

120

121 ~~A two-dimensional model of a passive continental margin was adapted to~~  
 122 ~~the simulation of the methane cycle on Siberian continental shelf and~~  
 123 ~~slope, attempting to account for the impacts of glacial / interglacial~~  
 124 ~~cycles in sea level, alternately exposing the continental shelf to freezing~~  
 125 ~~conditions with deep permafrost formation during glacial times, and~~  
 126 ~~immersion in the ocean in interglacial times. The model is then subjected~~  
 127 ~~to a potential future climate warming scenario.~~

128 ~~Pore fluid salinity plays a central role in the model geochemical dynamics.~~  
 129 ~~In the permafrost zone, pure water ice tolerates a higher fluid salinity~~  
 130 ~~than methane hydrate can, eliminating hydrate as an equilibrium phase.~~  
 131 ~~An analogous region in the ice – hydrate – brine phase diagram excludes~~  
 132 ~~ice in favor of hydrate, but the two phases can coexist at a sub-saturated~~  
 133 ~~methane concentration. In the permafrost zone (cold and low pressure),~~  
 134 ~~in contrast, the dissolved methane concentration cannot be higher than~~  
 135 ~~equilibrium with gas, so the hydrate exclusion from this zone is~~  
 136 ~~inescapable. This thermodynamic constraint restricts methane hydrate to~~  
 137 ~~at least 300 meters depth below the sediment surface, precluding a fast~~  
 138 ~~hydrate dissolution response to sea-floor warming.~~

139 ~~The initial salinity of the sediment column may have been affected by~~  
 140 ~~previous hydrological forcing, because freshwater invasion driven by a~~  
 141 ~~pressure head is probably much faster than salinity invasion due to~~  
 142 ~~convective-diffusive processes. This has a ratcheting effect, leaving relict~~  
 143 ~~fresh water lenses below sea level in many parts of the world. The pore~~  
 144 ~~fluid salinity determines the relative volumes of the ice, brine, and~~  
 145 ~~hydrate phases in the sediment column, and therefore the timing of ice~~  
 146 ~~formation and melting, but the chemical composition, in particular the~~  
 147 ~~salinity of the brine phase, is fixed, in equilibrium, by the local~~  
 148 ~~temperature. The model hydrate inventory on the shelf is however~~  
 149 ~~sensitive to the initial salinity of the sediment column.~~

150 ~~Through the glacial / interglacial cycles, the atmospheric methane flux is~~  
151 ~~affected most strongly by changes in sea level, because bubbles dissolve~~  
152 ~~in the ocean when sea level is high. Methane emissions to the~~  
153 ~~atmosphere are highest during the sea-level fall part of the cycle (as soil~~  
154 ~~is freezing), rather than during the warming deglaciations. Timings of the~~  
155 ~~atmospheric methane flux changes are sensitive to assumptions made~~  
156 ~~about bubble transport inhibition by permafrost. The atmospheric flux is~~  
157 ~~sensitive to biogenic and thermogenic methane production rates, but the~~  
158 ~~hydrate inventory is only sensitive to thermogenic methane production.~~  
159 ~~The geothermal heat flux affects the thickness of the hydrate stability~~  
160 ~~zone (primarily the depth of its base), but not the inventory of hydrate in~~  
161 ~~the model until a low-gradient threshold is passed. The model produces~~  
162 ~~methane inventory changes of 50 Gton C as bubbles, and as much as~~  
163 ~~hundreds of Gton C as hydrate, but these reservoir changes interact~~  
164 ~~mostly with pore water dissolved methane rather than driving immediate~~  
165 ~~methane loss from the sediment column.~~

166 ~~The model-predicted methane flux to the atmosphere in response to a~~  
167 ~~warming climate is small, relative to the global methane production rate,~~  
168 ~~because of the ongoing flooding of the continental shelf. The~~  
169 ~~atmospheric methane flux response to sudden warming takes thousands~~  
170 ~~of years, because of the slow thermal diffusion time to the hydrate~~  
171 ~~stability zone, and because a warming perturbation beginning now would~~  
172 ~~follow a much larger warming perturbation that started thousands of~~  
173 ~~years ago, when the sediment surface flooded. On time scales of~~  
174 ~~thousands of years in the future, the increased methane flux increase due~~  
175 ~~to warming could be completely counteracted by sea level rise, which~~  
176 ~~decreases the efficiency of bubble transit through the water column.~~

## 177 **1. Introduction**

### 178 **1.1 The Siberian Continental Shelf System**

179 The Siberian Arctic continental shelf has been the focus of attention from  
180 scientists and the public at large for its potential to release methane, a  
181 greenhouse gas, in response to climate warming, a potential amplifying  
182 positive feedback to climate change [Shakhova, 2010; Westbrook,  
183 2009]. The goal of this paper is to simulate the geophysical and carbon  
184 cycle dynamics of the Siberian continental margin within the context of a  
185 basin- and geologic time-scale mechanistic model of the coastal margin  
186 carbon cycle called SpongeBOB [Archer *et al.*, 2012]. An initial condition

187 for the glacial cycle simulations was generated by spinning the up at low  
188 resolution over 62 million simulated years. Then the model at higher  
189 resolution is driven by cyclic changes in sea level and air temperature  
190 resulting from glacial cycles, to simulate the impact of the hydrological  
191 pressure head and permafrost formation on the fluid flow and methane  
192 cycle on the shelf. Finally, an 100,000-year interglacial interval in the  
193 simulation is subjected to anthropogenic warming of the overlying water  
194 and potential 60-meter changes sea level. Sensitivity studies are  
195 presented for the biogenic and thermogenic methane production rates,  
196 initial salinity, geothermal temperature gradient, rates of hydrological  
197 flow, and permafrost impact on gas mobility.

### 198 **1.1.1 Permafrost**

199 One component of the simulation is a wedge of frozen sediment  
200 (permafrost) submerged beneath the ocean on the continental shelf of  
201 Siberia, left behind from glacial time when the shelves were exposed to  
202 the frigid atmosphere by lowered sea level [*Romanovskii and Hubberten,*  
203 2001]. The ice is thought to provide a seal to upward migration of  
204 methane gas [*Shakhova et al., 2009*], especially where ancient fresh  
205 groundwater flow produced a layer of very high saturation ice infill, a  
206 formation called the Ice Complex in Siberia [*Romanovskii et al., 2000*],  
207 although there are high ice saturations found in the Alaskan Arctic as well  
208 [*Zimov et al., 2006*].

209 With inundation by the natural sea level rise over the last 10+ thousand  
210 years, the permafrost is transiently melting, although the time constant  
211 for this is generally long enough that significant frozen volume remains,  
212 especially in shallower waters which were flooded more recently  
213 [*Khvorostyanov et al., 2008a; Nicolosky and Shakhova, 2010; Romanovskii*  
214 *and Hubberten, 2001; Romanovskii et al., 2004; Shakhova et al., 2009;*  
215 *Taylor et al., 1996*]. Even overlying water at the freezing temperature  
216 can provoke subsurface melting by providing a warmer boundary  
217 condition against which geothermal heat establishes the subsurface  
218 temperature profile, but with climate warming, the waters could surpass  
219 the freezing temperature, allowing heat to flow from above as well as  
220 below [*Khvorostyanov et al., 2008b*].

221 Elevated methane concentrations have been measured in the water  
222 column over the Siberian shelf, even in areas of shallow water where the  
223 permafrost should still be strongly intact [*Shakhova, 2010; Shakhova et*

224 *al.*, 2005]. Chemical and isotopic signatures of hydrocarbons adsorbed  
225 onto surface sediments indicate a thermal origin [*Cramer and Franke,*  
226 2005], suggesting that the methane is produced many kilometers deep in  
227 the sediment column. The apparent ability for this methane to transverse  
228 the barrier of the Ice Complex has been attributed to hypothesized  
229 openings in the ice (called “taliks”), resulting from lakes or rivers on the  
230 exposed shelf, or geologic faults [*Nicolosky and Shakhova, 2010;*  
231 *Romanovskii et al., 2004; Shakhova et al., 2009*].

232

### 1.1.2 Salt

233 Dissolved salt in the pore waters can ~~have a strong~~ impact ~~on~~ the timing  
234 of thawing permafrost [*Nicolosky and Shakhova, 2010; Shakhova et al.,*  
235 2009]. When sea level drops and exposes the top of the sediment  
236 column to the atmosphere and fresh water, the salinity of the subsurface  
237 pore waters can be flushed out by hydrological groundwater flow, driven  
238 by the pressure head from the elevated terrestrial water table above sea  
239 level. The boundary between fresh and salty pore water tends to  
240 intersect the sediment surface at the water’s edge [*Moore et al., 2011*].  
241 From there, the boundary tends to dip landward, to a depth of  
242 approximately 40 meters below sea level for every 1 meter of elevation  
243 of the table water. The ratio of water table elevation to freshwater lens  
244 depth is driven by the relative densities of fresh and salt water, as the  
245 fluid seeks an isostatic balance in which the fresh water displaces an  
246 equal mass of salt water [*Verrjuit, 1968*].

247 The SpongeBOB model has been modified to simulate the processes  
248 responsible for these observations. We do not attempt to simulate a  
249 detailed outcropping history over 62 million-year spinup time of the  
250 sediment column, but rather demonstrate the general process by  
251 subjecting the nearly complete sediment column to a one-time sea level  
252 lowering, exposing the continental shelf to groundwater forcing ([see  
253 Supplemental Text S4](#)). After a few million years, the sediment column  
254 subsides, due to compaction and absence of sediment deposition,  
255 resulting in a sediment column that has been considerably freshened by  
256 the atmospheric exposure. This freshening persists in the model for  
257 millions of years, because there is no corresponding “salt-water pump”  
258 during high sea-level stands. This behavior is consistent with the  
259 discovery of vast nearly fresh aquifers in currently submerged continental  
260 shelf regions around the world [*Post et al., 2013*], left over from  
261 groundwater forcing during glacial time.



262

### 1.1.3 Carbon

263 Another component of the simulation is the Yedoma, deposits of wind-  
264 blown dust and organic carbon that accumulated on the coastal plains of  
265 exposed continental shelves during glacial times [Zimov *et al.*, 2006].  
266 The deposits contain a substantial fraction of organic carbon, consisting  
267 of grass roots and remains, preserved by the freezing conditions. When  
268 they thaw, they begin to release CO<sub>2</sub> and methane to the atmosphere  
269 [Dutta *et al.*, 2006; Schuur *et al.*, 2008; Zimov *et al.*, 2006]. Oxidation  
270 of the carbon can give off enough heat to accelerate the melting driven  
271 by primary climate forcing [Khvorostyanov *et al.*, 2008b].

### 272 1.2 Models of Methane Hydrate in the Permafrost Zone

273 The dynamics of the permafrost layer, and its present state, have been  
274 extensively modeled within detailed maps of the crust and sediment  
275 structure [Gavrilov *et al.*, 2003; Nicolsky and Shakhova, 2010; Nicolsky *et*  
276 *al.*, 2012; Romanovskii and Hubberten, 2001; Romanovskii *et al.*, 2005].  
277 Methane hydrate modeling has been done in the Arctic applied to the  
278 Siberian continental slope [Reagan, 2008; Reagan and Moridis, 2009;  
279 Reagan *et al.*, 2011], but only one calculation has been done in the  
280 context of permafrost formation [Romanovskii *et al.*, 2005], as found on  
281 the shelf. Romanovski [2005] modeled the extent of the methane  
282 hydrate stability zone through glacial cycles, but based the calculations  
283 on marine salinity values when calculating the stability of hydrate. I will  
284 argue that in sub-freezing conditions (in the permafrost zone) the only  
285 water available for hydrate formation will be in a saline brine that would  
286 be in equilibrium with ice at the local temperature. This formulation  
287 restricts hydrate stability from the permafrost zone to greater depth  
288 below the sea floor than if the salinity was unaffected by formation of ice.

### 289 1.3 Outline of This Work

290 The model description in Section 2 begins with a description of the  
291 previously published aspects of the SpongeBOB model as it is applied to  
292 the Siberian margin (2.1). New developments in the code include  
293 pressure-head driven groundwater flow (2.2), permafrost formation and  
294 its impacts on the thermodynamics of ice and hydrate (2.3), and the  
295 calculation of the methane flux to the atmosphere (2.4). The procedure  
296 for generating the initial condition sediment column for the glacial /  
297 interglacial cycles (2.5) is presented along with a description of the  
298 forcings imposed to generate the glacial / interglacial cycles (2.6), and

299 the subsequent anthropocene (2.7). The formulation and rationale for  
300 the sensitivity studies is given in Section 2.8.

301 The Results in Section 3 include a discussion of the model behavior  
302 through the glacial / interglacial cycles (3.1), and in response to  
303 anthropogenic global warming scenarios (3.2). A summary of model  
304 sensitivity study results is given in Section 3.3, and comparison with field  
305 observations in Section 3.4.

306 The Discussion in Section 4 includes the model limitations and critical  
307 issues for future development (4.1), followed by the robust features of  
308 the model simulations (4.2).

## 309 **2. Model Description**

### 310 ***2.1 Previously Published Model Formulation***

#### 311 ***2.1 SpongeBOB Application to the Siberian Continental Margin***

312 SpongeBOB is a two-dimensional basin spatial-scale and geological time-  
313 scale model for the methane cycle in continental margin sediments. The  
314 model, configured for a passive margin basin, was described by Archer et  
315 al [2012], ~~as~~-applied to the Atlantic coast of the United States. The  
316 bottom boundary is bedrock, and accumulation time scales are millions of  
317 years, as sediment is introduced as coastal riverine material, and settles  
318 on the sea floor. Isostatic adjustment and crustal subsidence make room  
319 for the accumulation of 5-10 km of sediment, which progrades seaward in  
320 sigmoidal packages, driven by a maximum sediment accumulation rates  
321 just off the shelf break.

322 Here the model framework is used as a representation of the continental  
323 shelf of Siberia, although the tectonic and depositional histories of the  
324 region are heavily impacted by vertical tectonic motions not represented  
325 in the model. The crust underlying the continental shelf area has been  
326 alternately rising and subsiding in blocks called horsts and grabens  
327 [Nicol'sky et al., 2012]. The sediment cover on the grabens is thick much  
328 thicker than it is in the horsts, thick enough for thermal methane  
329 production. The thickness of the sediment cover in the model ranges  
330 from 5 - 10 kilometers throughout the domain, reminiscent of the  
331 grabens (subsiding blocks), because thermogenic methane is an essential  
332 part of the simulations.

333 The model maintains a concentration of particulate organic carbon, with  
334 which it predicts rates of methanogenesis. However, because the  
335 depositional histories and organic carbon concentrations in the Siberian  
336 continental margin are not well constrained, the rates of biological and  
337 thermal methane production predicted by the model are unreliable  
338 predictors of reality. For this reason, methanogenesis rates in the model  
339 are scaled arbitrarily as tunable model inputs. The depth distributions of  
340 the sources depend mostly on temperature, an easier variable to predict  
341 than organic carbon degradation activity.

342 ~~The model attempts to “grow” a sediment column based on first principles~~  
343 ~~or parameterizations of sediment and pore water physical and chemical~~  
344 ~~dynamics. The approach integrates processes of the carbon and methane~~  
345 ~~cycles within the evolving sediment column matrix, providing constraints~~  
346 ~~to the rates and processes that may inform the response of the system to~~  
347 ~~future changes in climate. Where model parameterizations or parameters~~  
348 ~~are poorly constrained, sensitivity studies are used to assess which of the~~  
349 ~~uncertainties are the most significant.~~

350 ~~Sediment is delivered from the coast of the model as riverine material,~~  
351 ~~and it settles according to a parameterization of grain size, with finer~~  
352 ~~material advecting further offshore before deposition. The organic~~  
353 ~~carbon concentration of the depositing material is determined in the~~  
354 ~~model as a function of water depth at the time of sedimentation. Rather~~  
355 ~~than attempt to simulate the complex biogeochemical dynamics of the~~  
356 ~~ocean and surficial sediments (early diagenesis), the POC fraction and the~~  
357 ~~H/C ratio of the organic matter are specified by a parameterization based~~  
358 ~~on water depth to reproduce the observed patterns of sediment surface~~  
359 ~~POC deposition, as a driver to the subsurface model.~~

360 ~~The H/C ratio of the depositing organic matter limits the potential extent of~~  
361 ~~methane production from the organic matter. The degradation rate of~~  
362 ~~organic carbon is estimated based on its age, a relationship that captures~~  
363 ~~many orders of magnitude of variability in the natural world [Middelburg et~~  
364 ~~al., 1997]. The reaction pathways presume a reactive intermediate H<sub>2</sub>,~~  
365 ~~which either reduces SO<sub>4</sub><sup>2-</sup> if it is available or it reacts with DIC to produce~~  
366 ~~methane. Isotopic fractionation of CO<sub>2</sub>, CH<sub>4</sub>, and radioiodine are simulated~~  
367 ~~by maintaining parallel concentration fields of different isotopologs, and~~  
368 ~~applying fractionation factors to the chemical kinetic rate constants or~~  
369 ~~equilibrium conditions. Dissolved methane in the pore water has the~~  
370 ~~potential to freeze into methane hydrate or degas into bubbles, depending~~  
371 ~~on the temperature, pressure, salinity, and CH<sub>4</sub> concentration.~~

372 ~~Sediment compaction drives pore fluid advection through the sediment~~  
373 ~~column, but the fluid flow is also focused in some simulations by ad hoc~~  
374 ~~vertical channels of enhanced permeability, to simulate in at least a~~  
375 ~~qualitative way the impact of heterogeneity in the fluid flow on the~~  
376 ~~characteristics of the tracer field. Methane hydrate is concentrated in~~  
377 ~~these channels by focused upward flow, and the pore-water tracers in the~~  
378 ~~channels resembles that of hydrate-bearing regions (in SO<sub>4</sub><sup>2-</sup>~~  
379 ~~concentration and <sup>129</sup>Iodine ages).~~

380 ~~Most of the model configuration and formulation was described by Archer~~  
381 ~~et al. [2012]. The new modifications required to simulate groundwater~~  
382 ~~hydrological flow and permafrost formation are described in detail below.~~

## 383 ***2.22 New Model Development: Groundwater Hydrology***

### 384 **2.22.1 Pressure Head**

385 When the sediment column is exposed to the atmosphere, the pressure  
386 field from the variable elevation of the water table (the pressure head)  
387 begins to affect the fluid flow. The pressure head for a fluid particle at  
388 the depth of the water table varies as

$$389 \quad P_{\text{head}}(z) = g \int_z^{z_{\text{wt}}} \rho_{\text{fluid}} dz$$

390 where  $z_{\text{wt}}$  is the elevation of the water table, which affects the pressure  
391 throughout the fluid column, and the integral of the fluid density allows  
392 the pressure at depth to be affected by the. ~~The pressure head at each~~  
393 ~~depth in the domain is a function of the physical water table height above~~  
394 ~~it and the density anomalies integrated from the water table to the depth~~  
395 ~~of the point in question. The pressure head resulting from a varying~~

396 ~~water table can therefore be altered at depth by variations in pore fluid~~  
397 ~~density driven by salinity or and temperature of the water above. The~~  
398 ~~depth of the water table is a pronostic variable in the model. In these~~  
399 ~~simulations, however, the water table remains very close to the sediment~~  
400 ~~surface, as unsaturated soil produced by subsurface flow is quickly~~  
401 ~~replenished by hydrological recharge.~~

## 402 **2.22.2 Pore Fluid Flow**

403 The pressure head acts in concert with the excess pressure  $P_{\text{excess}}$ , ~~as~~  
404 ~~defined by Archer et al. [2012],~~ to drive horizontal Darcy flow through  
405 the sediment. The value of  $P_{\text{excess}}$  is determined from the porosity and  
406 sediment load of the sediment in each grid box, ~~as described in Archer et~~  
407 ~~al [2012].~~ An assumed sediment rheology is used to calculate the load-  
408 bearing capacity of the solid matrix within a given grid cell.  $P_{\text{excess}}$  is  
409 calculated by assuming that the load of the solid phase overlying the grid  
410 cell that is not carried by the solid matrix must be carried by the  $P_{\text{excess}}$  in  
411 the fluid phase.

412 ~~When ice forms (described below), it leaves  $P_{\text{excess}}$  unchanged, but the~~  
413 ~~flow is inhibited by scaling the permeability  $k$  by the decrease in fluid~~  
414 ~~porosity.~~

415 ~~The horizontal flow is, as~~

$$416 \quad u_{\text{Darcy},i \rightarrow i+1} = \frac{k_{h,i} + k_{h,i+1}}{2\mu} \frac{(P_{\text{excess},i} - P_{\text{excess},i+1}) + (P_{\text{head},i} - P_{\text{head},i+1})}{(\Delta x_i + \Delta x_{i+1})/2}$$

417 while the vertical flow in the model is driven only by compaction pressure

$$418 \quad w_{\text{Darcy},j \rightarrow j+1} = \frac{k_{v,j}}{\mu} \frac{P_{\text{excess},j} - P_{\text{excess},j+1}}{(\Delta z_j + \Delta z_{j+1})/2}$$

419 ~~In previous versions of the SpongeBOB model, the fluid flow was~~  
420 ~~calculated explicitly, each time step, as a function of  $P_{\text{excess}}$  at the~~  
421 ~~beginning of the time step. Numerical stability motivated a modification~~  
422 ~~of the vertical flow to an implicit numerical scheme, which finds by~~  
423 ~~iteration an internally consistent array of vertical flow velocities and~~  
424 ~~resulting  $P_{\text{excess}}$  values from a time point at the end of the time step.~~  
425 ~~Ocean and atmosphere models often use this methodology for vertical~~  
426 ~~flow. A benefit to this change is stability in the vertical flow field,~~

427 ~~reducing numerical noise that can cause trouble with other aspects of the~~  
428 ~~model such as ice formation. Implicit schemes can be more efficient~~  
429 ~~computationally, but in this case the execution time is not improved by~~  
430 ~~the implicit method, just the stability.~~

431 ~~Note that the flow scheme in its formulation is entirely elastic, whereas in~~  
432 ~~reality, pore fluid excluded by the pressure of a sediment column above~~  
433 ~~sea level, for example, where it is uncompensated by buoyancy in~~  
434 ~~seawater, should remain excluded when sea level rises again, like~~  
435 ~~toothpaste from the tube. However, my attempts to embed this plastic~~  
436 ~~behavior into an implicit solver failed to converge.~~

### 437 ~~2.2.3 Water Table Depth~~

438 ~~The model maintains  $z_{wt}$ , the elevation of the water table within the~~  
439 ~~sediment column, as a continuous variable that ranges through the~~  
440 ~~discreet vertical grid of the model. The formulation allows boxes to be~~  
441 ~~empty of water or partially “saturated” at the top of the fluid column. In~~  
442 ~~these simulations, however, the water table remained very close to the~~  
443 ~~sediment surface, as unsaturated soil produced by subsurface flow is~~  
444 ~~quickly replenished by hydrological recharge.~~

445 ~~where  $k_{h,i}$  is the horizontal permeability at horizontal cell index  $j$ ,  $k_{v,j}$  is~~  
446 ~~vertical permeability at vertical index  $j$ ,  $\mu$  is the viscosity, and  $\Delta x$  and  $\Delta z$~~   
447 ~~are cell dimensions. Notes on numerical issues are given in Supplemental~~  
448 ~~Text S1.~~

### 449 ~~2.22.34 Canyons~~

450 The model as described so far represents a laterally homogeneous slab, a  
451 poor approximation for hydrology above sea level because of the  
452 formation of canyons and river networks in a real drained plateau. The  
453 depth of the water table in a river canyon is depressed, relative to the  
454 surroundings, to the depth of the canyon. The water table is higher in  
455 between the canyons because of recharge, and the difference in head  
456 drives lateral flow, the canyons acting to drain the sediment column.

457 The model formulation has been altered to represent this mechanics in a  
458 simplified way. Rather than expand the model into the full third  
459 dimension, the 2-D field of the model is held to represent the sediment  
460 column at a hypothetical ridge crest, as altered by an adjacent canyon.

461 The canyon elevation is represented by  $z_{\text{canyon}}$ , and its width by a scale  
462  $\Delta y_{\text{canyon}}$ . A cross-column flow velocity  $v_{\text{Darcy},j}$  is calculated as

463 
$$v_{\text{Darcy},j} = \frac{k_{h,j} (P_{\text{head,canyon}} - P_{\text{head}})}{\mu \Delta y_{\text{canyon}}}$$

464 where  $P_{\text{head,canyon}}$  is the pressure head as a function of depth in the  
465 hypothetical canyon, calculated assuming that the water table outcrops  
466 at  $z_{\text{canyon}}$ , and that the temperatures in the sediment column have  
467 adjusted to the formation of the canyon, such that the near-surface  
468 geothermal gradient is the same between the hypothetical canyon and  
469 the bulk sediment column. The lateral “drainage” flow ( $v_{\text{Darcy},j}$ ) drives  
470 vertical velocities by continuity.

471 The horizontal distance scale  $\Delta y_{\text{canyon}}$  is somewhat arbitrary and difficult to  
472 constrain, given that in the reality of river networks the distance to the  
473 nearest canyon from any point in the domain is likely to be a function of  
474 altitude, distance from the coast, and time. Another poorly resolved  
475 factor is the depth of the canyon. In reality, canyons cut into a plateau  
476 following a dynamic that erosion is proportional to slope, ~~but stoppings~~  
477 at sea level. As a simplification the model is set to hold the canyon depth at  
478 current sea level throughout the simulation.

479 ~~The canyon mechanism accelerates the freshening of the sediment~~  
480 ~~column by providing a pathway for the escape of the salt water, although~~  
481 ~~it was found that the net effect in the model is not dramatic (results~~  
482 ~~shown below), in part because the canyon drainage mechanism only acts~~  
483 ~~on pore fluids above sea level, while the hydrological freshwater pumping~~  
484 ~~mechanism reaches much deeper than sea level.~~ In the real fractal  
485 geometry of canyons, the spacing between canyons across a plain is  
486 similar to the width of the plain (length of the canyons), so the Base  
487 simulation assumes a canyon width of 100 km, based on the 100+ km  
488 width scale of the continental shelf.

## 489 **2.33 Permafrost**

### 490 **2.3.1 Thermodynamics of Ice and Hydrate**

491 The ice model is based on an assumption of thermodynamic equilibrium, in  
492 which the heat content of the cell is distributed between the pure ice,  
493 hydrate, and brine phases, while the salt content is restricted to the

494 brine. Notes on numerical implementation are given in Supplemental Text  
495 S2.

496 In the permafrost zone where ice is present, and the salinity of the brine  
497 drives-creates an ice--freezing point depression to that matches the local  
498 temperature. This equilibrium salinity is higher than methane hydrate can  
499 tolerate, excluding hydrate from thermodynamic stability. For a more  
500 detailed examination of the role of the brine salinity in determining the  
501 relative stabilities of ice and hydrate, see Supplemental Text S3.

## 502 **2.4 Thermodynamic competition between ice and hydrate**

503 ~~The high salinity (low activity of water) in the permafrost zone has the~~  
504 ~~practical impact of excluding methane hydrate from permafrost soils that~~  
505 ~~are significantly colder than freezing. The thermodynamics are illustrated~~  
506 ~~in Figure 1. When the system consists only of ice and fluid phases, the~~  
507 ~~equilibrium salinity  $S_{eq}$  increases with decreasing temperature below~~  
508 ~~freezing (Figure 1a, left). Above the melting temperature, ice is unstable, as~~  
509 ~~indicated by the nonzero values of the disequilibrium temperature,  $\Delta T_{eq,ice}$~~   
510  ~~$= T - T_{eq,ice}$ , in contours, even in zero-salinity water (right). For a system~~  
511 ~~consisting of only the hydrate and fluid phases (assuming that ice~~  
512 ~~formation is disallowed, and also gas saturation for methane) (Figure 1b),~~  
513 ~~the behavior is similar but with an added pressure dependence due to the~~  
514 ~~compressibility of the gas phase. When both solid phases are allowed, the~~  
515 ~~overall equilibrium salinity will whichever is higher between  $S_{eq,ice}$  and  $S_{eq}$~~   
516 ~~hydrate. Whichever phase can seize water at its lowest activity (highest~~  
517 ~~salinity) will be the stable phase. The salinity of the brine excluded from~~  
518 ~~that phase will be too high to permit the existence of the other solid phase~~  
519 ~~at that temperature. The contours show  $\Delta T_{eq}$  for hydrate (solid) and ice~~  
520 ~~(dashed), which are also plotted in color in Figures 1d and e. This is~~  
521 ~~illustrated in Figure 1d, in colors of  $\Delta T_{eq,hydrate}$  and contours of the excess~~  
522 ~~salinity relative to hydrate equilibrium,  $S_{max} - S_{eq,hydrate}$ . Hydrate is only~~  
523 ~~stable when  $\Delta T_{eq,hydrate}$  is zero (purple color). Under permafrost conditions~~  
524 ~~of low pressure and low temperature (upper left corner),  $\Delta T_{eq,hydrate}$  is~~  
525 ~~greater than zero, indicating that hydrate is unstable, coinciding with the~~  
526 ~~salinity forcing from the ice, in overlain contours. A similar exclusion of~~  
527 ~~ice in part of the hydrate stability zone is seen Figure 1e, but this would~~  
528 ~~only happen in nature in conditions of unlimited methane. The resulting~~  
529 ~~phase diagram for ice and methane hydrate is shown in Figure 1f. Hydrate~~  
530 ~~stability is suppressed in the permafrost zone by this thermodynamic~~  
531 ~~mechanism.~~

532 ~~This model formulation implies that the salinity of pore fluid in subfreezing~~  
533 ~~conditions (the permafrost zone) is independent of the original salinity of~~



534 ~~the bulk sediment column, but is rather determined only by the freezing-~~  
535 ~~point depression implied by the temperature. If the original column is~~  
536 ~~relatively fresh, there will be a smaller volume of pore fluid at a~~  
537 ~~subfreezing temperature than if it is originally salty (see for example~~  
538 ~~Figure 4 in [Nicol'sky and Shakhova, 2010]), but the activity of the water~~  
539 ~~(a correlate of the salinity) is set by the temperature and the~~  
540 ~~thermodynamics of pure ice, which are the same in the two cases. Layers~~  
541 ~~of high-salinity unfrozen brines called cryopegs [Gilichinsky et al., 2005;~~  
542 ~~Nicol'sky et al., 2012] are consistent with this formulation.~~

543 ~~**2.3.3 Other** [The ice content in a grid cell relaxes toward equilibrium,~~  
544 ~~quickly enough to approximate an equilibrium state through the slow~~  
545 ~~temperature evolution in the model (which neglects a seasonal cycle at the~~  
546 ~~surface), but slowly enough to avoid instabilities with other components of~~  
547 ~~the model such as fluid flow and methane hydrate formation. A limiter in~~  
548 ~~the code prevents more than 99% of the fluid in a grid cell from freezing,~~  
549 ~~but the thermodynamic equilibrium salinity is used to calculate, for~~  
550 ~~example, the stability of methane hydrate, to prevent the numerical limiter~~  
551 ~~from affecting the thermodynamic availability of water to drive chemical~~  
552 ~~reactions.~~**mpacts**

553 Permafrost formation has several impacts on the methane cycle in the  
554 model. Biogenic methanogenesis is assumed stopped in the ice fraction  
555 of a grid cell (which approaches unity but never reaches it in the model,  
556 due to exclusion of salt into brine). Bubble transport in the model  
557 balances bubble production, driven by a small and not very well  
558 constrained standing bubble concentration within the pore space. It is  
559 generally assumed [Shakhova et al., 2010b] that permafrost inhibits gas  
560 transport through the sediment column, both based on sediment column  
561 carbon and hydrogen budgets [Hunt, 1995] and on the tight seal  
562 provided by the ice complex. The seal provided to Arctic lakes, which can  
563 drain overnight if the seal is breached, also lends credence to this idea. In  
564 the model, this effect was simulated by stopping gas transport  
565 completely when a grid cell exceeds 50% ice fraction (with sensitivity  
566 runs assuming 10%, 30%, 70%, and 90%).

## 567 **2.45 Atmospheric Methane Fluxes**

568 Bubbles emerging from the sediment column into the water column of the  
569 ocean may dissolve in the water column, or they may reach the sea  
570 surface, a direct methane flux to the atmosphere [Westbrook et al.,  
571 2009]. In the model, bubble dissolution in the water column is assumed

572 to attenuate the bubble flux according to the water depth with an e-  
573 folding attenuation scale of 30 meters [*Gentz et al.*, 2014; *Portnov et al.*,  
574 2013; *Westbrook et al.*, 2009]. In reality, a low-flux gas seep, producing  
575 small bubbles, will probably not reach as far into the water column as a  
576 30-meter scale height, while a faster seep can reach further. Methane  
577 dissolved in the water column, in reality, may survive oxidation (time  
578 constant of about a year), and degas to the atmosphere, but this  
579 possibility is not included in the model. For land grid points (exposed to  
580 the atmosphere by lowered sea level), any upward bubble flux at the  
581 sediment surface is assumed 100% released to the atmosphere. The  
582 model neglects methane oxidation in soils, as well as many other  
583 terrestrial processes such as thaw bulbs beneath bodies of water [*Walter*  
584 *et al.*, 2006], and the seasonal cycle of melting and thawing in the  
585 surface active layer. [See discussion in Section 4.1.](#)

~~586 In short, the methane fluxes to the atmosphere computed from the model  
587 runs are crude, and underlain by a sedimentary methane cycle with large  
588 uncertainties, intended to capture the main sensitivities to various  
589 processes rather than to provide strong quantitative constraint to the  
590 fluxes in the real world.~~

## 591 ***2.6 Comparison with Previous Models***

~~592 The dynamics of the permafrost layer, and its present state, have been  
593 extensively modeled within detailed maps of the crust and sediment  
594 structure [*Gavrilov et al.*, 2003; *Nicol'sky and Shakhova*, 2010; *Nicol'sky et*  
595 *al.*, 2012; *Romanovskii and Hubberten*, 2001; *Romanovskii et al.*, 2005].  
596 The crust underlying the continental shelf area has been alternately rising  
597 and subsiding in blocks called horsts and grabens [*Nicol'sky et al.*, 2012].  
598 The sediment cover on the grabens is much thicker than it is in the  
599 horsts. SpongeBOB, an idealized two-dimensional model, does not  
600 address this complexity, but the thickness of the sediment cover on the  
601 shelf ranges from 5 – 10 kilometers, reminiscent of the grabens  
602 (subsiding blocks). A thin sediment column would not reach the  
603 temperature required for thermogenic methane production. The rates of  
604 thermogenic methane production are not predicted or constrained by the  
605 model, because of the different depositional histories of the sediment  
606 columns. However, we can gauge the sensitivity of the methane cycle in  
607 the near-surface sediments to thermogenic methane production by  
608 scaling the model-predicted rate (by factors of 10 and 100).~~

609 ~~Methane hydrate modeling has been done in the Arctic applied to the~~  
610 ~~Siberian continental slope [Reagan, 2008; Reagan and Moridis, 2009;~~  
611 ~~Reagan et al., 2011], but only one calculation has been done in the~~  
612 ~~context of permafrost formation [Romanovskii et al., 2005], as found on~~  
613 ~~the shelf. Romanovski [2005] modeled the extent of the methane~~  
614 ~~hydrate stability zone through glacial cycles, but based the calculations~~  
615 ~~on marine salinity values when calculating the stability of hydrate, while I~~  
616 ~~argue that in sub-freezing conditions (in the permafrost zone) the only~~  
617 ~~water available for hydrate formation will be in a saline brine that would~~  
618 ~~be in equilibrium with ice at the local temperature. This formulation~~  
619 ~~restricts hydrate stability from the permafrost zone to greater depth~~  
620 ~~below the sea floor than predicted by Romanovski [2005]. In the~~  
621 ~~Mackenzie Delta, hydrate was detected in a core drilled into onshore~~  
622 ~~permafrost soils [Dallimore and Collett, 1995], but only at depths greater~~  
623 ~~than 300 meters, near the base of the permafrost zone.~~

## 624 2.5 Initial Condition

### 625 2.5.1 Rational for Spinup

626 The point of the spinup phase is to generate an initial condition for the  
627 glacial cycle simulations. The more usual approach in modeling hydrates  
628 is to start with an ad-hoc initial condition [Reagan, 2008; Reagan and  
629 Moridis, 2009; Reagan et al., 2011]. For SpongeBOB the model state at  
630 any time is the result of the time-history of sedimentation, which is driven  
631 by the time-evolving depth of the sea floor, and interacting with isostatic  
632 adjustment of the crust. The simplest way to generate an initial condition  
633 in the model without a startup transient is to spin the model up from  
634 bedrock. The duration of the spinup phase is 62 million years, roughly  
635 consistent with the time scale since the opening of the Laptev Rift. The  
636 first 60 Myr used a relatively coarse resolution as shown in Figure 1a. For  
637 the glacial / interglacial experiments, the initial condition was interpolated  
638 to a higher resolution grid in the vertical, as shown in Figure 1b.

### 639 2.5.2 Sediment Column Salt Content

640 When sea level drops such that the surface of the sediment column  
641 outcrops to the atmosphere, the pore fluid becomes subject to the  
642 pressure head driving it seaward, and to fresh water recharge from  
643 precipitation. The pressure head forcing and the buoyancy of the  
644 sediment fluid column combine to create a mechanism to excavate  
645 salinity from the upper sediment column, to depths well below sea level.

646 The salinity of the sediment column tends to be ratcheted down by  
647 exposure to the atmosphere, because there is no comparable advective  
648 pump for reinvasion of seawater when sea level rises.

649 A “pre-freshened” sediment column was constructed by dropping sea  
650 level by 120 meters and holding it there for millions of years. The  
651 sediment column subsides back into the ocean over a few million years,  
652 but the fresh imprint of the hydrological flow persist for millions of years  
653 (Figure 2a and Supplemental Text S4). If the sediment surface never  
654 outcrops, the pore salinities remain nearly uniform and marine (Figure 2b).  
655 Particulate organic carbon (POC) concentrations are highest just off the  
656 shelf break (Figure 3), because this is where most of the sediment is  
657 deposited, and because the sedimentary material is richest in POC in  
658 shallow ocean water depths [Archer et al., 2012]. Methane concentration  
659 (Figure 4a) closely mirrors the solubility of dissolved methane, resulting in  
660 near saturation concentrations through most of the model domain (Figure  
661 4b). The pre-freshened (Fr) versus marine (Mr) initial conditions are  
662 taken as end member salinity sensitivity runs (see Table 1).

## 663 **2.6 Glacial Cycle Forcing**

664 Beginning from an entirely submerged initial condition, the model is  
665 subjected to 100-kyr sawtooth cycles of sea level ranging between -120  
666 to +20 meters from the initial sea level (starting at -120 for  
667 prefreshened, 0 for pure marine) (Figure 5a). The model forcing scenarios  
668 are summarized in Table 1.

### 669 **2.6.1 Sea Level**

670 The simplest scenario (SL) varies the sea level while keeping the air and  
671 water temperatures time-invariant. The sea-level air temperature is  
672 maintained at 0 °C. This simulation is nearly permafrost-free, with a small  
673 exception where the altitude of the sediment surface is much higher than  
674 sea level (due to the lapse rate in the atmosphere). There is no  
675 deposition of sediment above sea level in this simulation.

### 676 **2.6.2 Glacial Climate**

677 Permafrost formation is added in simulation GL, in which the air  
678 temperature ramps down to -16 °C at sea level, linearly with the glacial  
679 sea level fall (Figure 5b). In the ocean, shelf waters are always -1.8 °C,

680 but an interglacial subsurface temperature maximum of 1 °C at 200  
681 meters decreases to -1.8 °C during glacial times.

### 682 **2.6.3 Deposition of Carbon on Land**

683 Deposition of organic-rich sediments when the surface is exposed to the  
684 atmosphere (Yedoma: represented as accumulation of 10 meters in 100  
685 kyr, with 30% POC) is added in scenarios SL+LD and GL+LD (LD for land  
686 deposition).

## 687 **2.7 Anthropogenic Global Warming Forcing**

### 688 **2.7.1 Long-Term Climate Impact from CO<sub>2</sub> Addition**

689 The global warming (GW) scenario begins from a high sea-level interglacial  
690 state, and raising the temperature following the climate impact of the  
691 “spike and long tail” time distribution of a slug of new CO<sub>2</sub> added to the  
692 atmosphere [Archer et al., 2009] (Figure 8). There is a stage of fast  
693 atmospheric drawdown as CO<sub>2</sub> invades the ocean, but once the ocean,  
694 atmosphere, and land surface reach equilibrium (after a few hundred  
695 years), the CO<sub>2</sub> content of the entire biosphere begins to relax toward an  
696 initial “natural” value, on time scales of hundreds of thousands of years,  
697 by weathering reactions with carbonate and siliceous solid rocks. The net  
698 result is a CO<sub>2</sub> drawdown that can be expressed as the sum of several  
699 exponential functions in time, with time scales ranging from 10<sup>2</sup> – 10<sup>6</sup>  
700 years.

701 Changes in water column temperature are assumed equal to those of the  
702 atmosphere, following paleoceanographic reconstructions [Martin et al.,  
703 2002] and long-term coupled ocean / atmosphere circulation model  
704 experiments [Stouffer and Manabe, 2003]. The GW scenario imposes this  
705 temperature change on the water column, relaxing toward equilibrium  
706 with the atmospheric CO<sub>2</sub> trajectory with a time constant of 100 years.

### 707 **2.7.2 Long-Term Behavior of Sea Level**

708 The effect of sea level rise is added to create a second global warming  
709 scenario GW+SL. On time scales of thousands of years the sea level  
710 response to changing global temperature is much stronger than the sea  
711 level response over the coming century, as prominently forecast by the  
712 IPCC. Reconstruction of sea level and global temperature covariation in  
713 the geologic past (glacial time to Eocene hothouse) reveals a covariation

714 of 10-20 meters per °C [Archer and Brovkin, 2008]. The global warming  
715 with sea level scenario assumes an equilibrium sea level response of 15  
716 meters / °C, which it relaxes toward with a time constant of 1000 years.

## 717 **2.8 Sensitivity Studies**

718 A strategy for dealing with the many uncertainties in the model  
719 formulation and parameterization is to do sensitivity studies, to  
720 determine which of the unknowns are most significant. The model  
721 sensitivity studies are summarized in Table 1. Sensitivity studies to the  
722 rates of methane production have already been mentioned, as have the  
723 pre-freshened versus marine initial conditions, representing uncertainty in  
724 the salt content of the sediment column. Other model sensitivity runs  
725 include the geothermal temperature gradient, and a parameterization of  
726 permafrost inhibition of bubble migration. Several altered-physics runs  
727 were done, one adding vertical permeable channels, one disabling  
728 horizontal flow, and several to evaluate the impact of ice formation on  
729 methane hydrate stability.

## 730 **3. Results**

### 731 ***3.1 Initial Spinup***

#### 732 **3.3.1 Setup and Forcing**

733 ~~Beginning from an entirely submerged initial condition, the model is~~  
734 ~~subjected to 100-kyr sawtooth cycles of sea level ranging between -120~~  
735 ~~to +20 meters from the initial sea level (starting at -120 for~~  
736 ~~prefreshened, 0 for pure marine) (Figure 9a).~~

737 ~~The model scenarios and sensitivity studies are summarized in Table 1.~~

738 ~~The simplest scenario (SL) varies the sea level while keeping the air and~~  
739 ~~water temperatures time-invariant. The sea-level air temperature is~~  
740 ~~maintained at 0 °C. This simulation is nearly permafrost-free, with a small~~  
741 ~~exception where the altitude of the sediment surface is much higher than~~  
742 ~~sea level (due to the lapse rate in the atmosphere). There is no~~  
743 ~~deposition of sediment above sea level in this simulation. Permafrost~~  
744 ~~formation is added in simulation GL, in which the air temperature ramps~~  
745 ~~down to -16 °C at sea level, linearly with the glacial sea level fall (Figure~~  
746 ~~9b). In the ocean, shelf waters are always -1.8 °C, but an interglacial~~  
747 ~~subsurface temperature maximum of 1 °C at 200 meters decreases to~~

748 ~~-1.8 °C during glacial times. Deposition of organic-rich sediments when~~  
749 ~~the surface is exposed to the atmosphere (Yedoma: represented as~~  
750 ~~accumulation of 10 meters in 100 kyr, with 30% POC) is added in~~  
751 ~~scenarios SL+LD and GL+LD (LD for land deposition). The atmospheric~~  
752 ~~temperature impact of a global warming scenario (GW) is also shown in~~  
753 ~~Figure 9b, beginning at 400 kyr, and compared with an extended-~~  
754 ~~interglacial control forcing (Ctl). The potential impact of geologic-time~~  
755 ~~scale sea level rise is added to the global warming scenario in simulation~~  
756 ~~GL+SL.~~

757 ~~Other model sensitivity runs used varying values of the thermogenic and~~  
758 ~~biogenic methane production rates, the geothermal temperature gradient.~~  
759 ~~Several altered-physics runs were done, one adding vertical permeable~~  
760 ~~channels, one disabling horizontal flow, and several to evaluate the impact~~  
761 ~~of ice formation on methane hydrate stability.~~

### 762 **3.3.2 Salinity and Ice**

763 ~~In the “prefreshened” initial condition (Fr), millions of years have elapsed~~  
764 ~~since the previous exposure of the sediment to hydrological forcing, but a~~  
765 ~~core of fresh water remains. Salinities near the sediment surface have~~  
766 ~~grown saltier due to diffusive contact with seawater (Figure 10, left). A~~  
767 ~~fully marine initial condition (Mar) (Figure 10, right) was initialized from~~  
768 ~~the unfreshened case, in which sea level was held at a fixed value~~  
769 ~~throughout the 65 Myr spinup of the sediment column. The salinities are~~  
770 ~~nearly uniform in this case.~~

771 ~~When the sediment surface is re-exposed to the atmosphere during an~~  
772 ~~interval of sea level, in the absence of ice formation (simulation SL), the~~  
773 ~~surface layer tends to freshen relatively quickly due to the hydrological~~  
774 ~~forcing, but a subsurface salinity maximum persists (Figure 10c and d).~~  
775 ~~However, if the air temperatures are cold enough to form ice (simulation~~  
776 ~~GL), surface salinities in the model increase to up to nearly 190 psu, in~~  
777 ~~both prefreshened and pure marine cases (Figure 10e and f). By the next~~  
778 ~~interglacial time (Figure 10g and h), ice near the sediment surface has~~  
779 ~~melted enough for near-surface pore waters to reach relatively low~~  
780 ~~salinities.~~

781 ~~For the glacial / interglacial experiments, the initial condition was~~  
782 ~~interpolated to a higher resolution grid in the vertical, as shown in Figure~~  
783 ~~2b. Particulate organic carbon (POC) concentrations are highest just off~~

784 ~~the shelf break (Figure 3), because this is where most of the sediment is~~  
785 ~~deposited, and because the sedimentary material is richest in POC in~~  
786 ~~shallow ocean water depths [Archer et al., 2012]. The unchanging sea~~  
787 ~~level in the spinup period kept the sediment surface from outcropping,~~  
788 ~~resulting in nearly uniform marine salinity throughout the model domain~~  
789 ~~(Figure 4a). Methane concentration (Figure 5a) closely mirrors the~~  
790 ~~solubility of dissolved methane, resulting in near saturation~~  
791 ~~concentrations through most of the model domain (Figure 5b). As in the~~  
792 ~~previous model simulations [Archer et al., 2012], the imposition of~~  
793 ~~permeable channels has a strong effect on the chemistry of the~~  
794 ~~permeable grid cells (Figure 5d), although the impact on the integrated~~  
795 ~~model behavior, such as the methane flux to the atmosphere, was small in~~  
796 ~~these simulations.~~

797 ~~The point of the spinup phase is to generate an initial condition for the~~  
798 ~~glacial cycle simulations. The more usual approach in modeling hydrates~~  
799 ~~is to start with an ad-hoc initial condition [Reagan, 2008; Reagan and~~  
800 ~~Moridis, 2009; Reagan et al., 2011]. For SpongeBOB the model state at~~  
801 ~~any time is the result of the time-history of sedimentation, which is driven~~  
802 ~~by the time-evolving depth of the sea floor, and interacting with isostatic~~  
803 ~~adjustment of the crust. The simplest way to generate an initial condition~~  
804 ~~in the model without a startup transient is to spin the model up from~~  
805 ~~bedrock at low resolution. Because of the over-simplicity of the tectonic,~~  
806 ~~sea level, and sedimentation forcing of the spinup phase, its POC~~  
807 ~~concentrations and methane production rates do not constrain those of~~  
808 ~~the real Siberian shelf. The sensitivity of the glacial methane cycles to~~  
809 ~~methane production rates will be evaluated by scaling the model~~  
810 ~~methanogenesis rates from the spinup result. The model setting was~~  
811 ~~grown for 62 million years of model time. The initial spinup used a~~  
812 ~~relatively coarse resolution as shown in Figure 2a.~~

### 813 **3.2 Impact of Freshwater Hydrology**

814 ~~**When sea level drops such that the surface of the sediment column**~~  
815 ~~**outcrops to the atmosphere, the pore fluid becomes subject to the**~~  
816 ~~**pressure head driving it seaward, and to fresh water recharge from**~~  
817 ~~**precipitation. The pressure head forcing and the buoyancy of the sediment**~~  
818 ~~**fluid column combine to create a mechanism to excavate salinity from the**~~  
819 ~~**upper sediment column. Initially after sea level fall, there is a pressure head**~~  
820 ~~**gradient extending throughout the sediment column, provoking lateral flow**~~  
821 ~~**at all depths. As the pore fluid at the surface is replaced by fresh runoff,**~~  
822 ~~**the lighter density of that fluid tends to diminish the pressure head**~~



823 gradient in the deeper sediment column. The deeper pressure gradient and  
824 flow approach zero as the fresh water lens in the outcropping region  
825 approaches an isostatic equilibrium condition known as the Ghyben-  
826 Herzberg relation [Moore *et al.*, 2011], in which each meter elevation of the  
827 water table is compensated for by about 40 meters of fresh water below sea  
828 level, determined by the difference in densities of fresh and salt water.

829 To create this condition within the model, two simulations are presented in  
830 which sea level was decreased by 30 and 120 meters, respectively, and  
831 held there for millions of years (Figure 6). The 30-meter drop experiment  
832 produced land outcrop in about 1/4 of the model domain, with the predicted  
833 equilibrium Ghyben-Herzberg halocline reaching about 1200 meters  
834 maximum depth. The model salinity relaxes into close agreement with the  
835 predicted halocline, lending support to the model formulation for density,  
836 pressure head, and fluid flow. As time progresses further, the outcropping  
837 land surface subsides (there is no land deposition in this scenario), until it  
838 drops below the new lowered sea level value after about 2.5 Myr.

839 Variants of this experiment were done with differing values of the lateral  
840 distance to drainage canyons in the model, which provide a pathway for  
841 fluid loss in sediments above sea level. When a hypothetical canyon is  
842 located 10 km from the SpongeBOB slab, the model salinity approaches  
843 equilibrium on an e-folding time scale of about 400 kyr (Figure 7). When  
844 the canyon is 100 km distant or nonexistent, the equilibration time scale is  
845 about 600 kyr. Based on the idea that canyons of order 100 km long should  
846 be about 100 km apart, the Base simulation in this paper assumes canyon  
847 spacing of 100 km.

848 When sea level is lowered by 120 m, the sequence of events is similar,  
849 except that the pressure head is so high that to satisfy the Ghyben-  
850 Herzberg relation would require fresh pore waters at many kilometers  
851 depth, even deeper than bedrock on the “continental” side of the model  
852 domain. Because of the low permeability of the deepest sediment column,  
853 the freshwater pumping groundwater mechanism is unable to reach these  
854 deepest pore waters, which therefore remain salty. The time scale for  
855 establishing a significant freshening of the upper kilometer of the sediment  
856 column is still on the order of 100-500 kyr, and the subsequent subsidence  
857 time of the sediment column in the model, until it drops below the new  
858 lowered sea level, takes about 10 Myr. In both cases, subsidence of the  
859 exposed sediment column prevents the sediment surface in the model from  
860 remaining above sea level indefinitely (without land deposition).

861 The sequence of events leaves behind a fresh water lens below sea level  
862 that persists in the model for millions of years (Figure 6). Groundwater  
863 flow, driven by the pressure head, provides an advective means of

864 ~~pumping fresh water into the subsurface sediment column that has no~~  
865 ~~counterpart for salty ocean water. The model lacks the mechanism of salt~~  
866 ~~fingering, which can enhance the diffusion of salt from above into a fresh~~  
867 ~~water aquifer [Kooi et al., 2000]. However, higher-resolution models of~~  
868 ~~smaller domains that accounted for salt fingering also show a time~~  
869 ~~asymmetry, with faster fresh water invasion on sea level drop than salt~~  
870 ~~invasion on sea level rise [Lu and Werner, 2013; Watson et al., 2010].~~  
871 ~~As the size of the domain increases with increasing sea level change,~~  
872 ~~advective processes such as hydrological flow should become even more~~  
873 ~~dominant over diffusive processes such as salt fingering. The recent~~  
874 ~~discovery of vast freshwater aquifers on global continental shelves [Post~~  
875 ~~et al., 2013], persisting since the time of lowered sea level 20,000 years~~  
876 ~~ago, and the lower-than-marine salinities of the pore waters measured in~~  
877 ~~submerged surface Arctic sediments (summarized by [Nicolisky et al.,~~  
878 ~~2012]) are also consistent with the existence of a fresh-water~~  
879 ~~hydrological pump which has a significant impact on sediment column~~  
880 ~~salinities. The hydrological pumping generates a low-methane plume that~~  
881 ~~also persists for millions of years in the model (Figure 8). Two states,~~  
882 ~~called “prefreshened” and “pure marine”, serve as end-member initial~~  
883 ~~conditions for glacial / interglacial simulations (Figure 4b), to evaluate the~~  
884 ~~sensitivity of the model glacial cycles to the initial salinity of the sediment~~  
885 ~~column.~~

### 886 **3.13 Glacial Cycles**

#### 887 **3.1.1 Salinity**

888 In the “prefreshened” initial condition (Fr), millions of years have elapsed  
889 since the previous exposure of the sediment to hydrological forcing, but a  
890 core of fresh water remains. Salinities near the sediment surface have  
891 grown saltier due to diffusive contact with seawater (Figure 6, left). A  
892 fully marine initial condition (Mar) (Figure 6, right) was initialized from the  
893 unfreshened case, in which sea level was held at a fixed value throughout  
894 the 65 Myr spinup of the sediment column. The salinities are nearly  
895 uniform in this case.

896 When the sediment surface is re-exposed to the atmosphere during an  
897 interval of low sea level, in the absence of ice formation (simulation SL),  
898 the surface layer tends to freshen relatively quickly due to the  
899 hydrological forcing, although a subsurface salinity maximum persists  
900 (Figure 6c and d). If the air temperatures are cold enough to form ice

901 (simulation GL), surface salinities in the model increase to up to nearly  
902 190 psu, in both prefreshened and pure marine cases (Figure 6e and f).  
903 By the next interglacial time (Figure 6g and h), ice near the sediment  
904 surface has melted enough for near-surface pore waters to reach  
905 relatively low salinities.

### 906 **3.13.23 Pressure and Flow**

907 The effect of the glacial / interglacial sea level and permafrost-climate  
908 forcing on the pressures and flow velocities are shown in Figure Z11. On  
909 a spatial scale of the entire model domain (Figure Z11, left), the highest  
910 driving pressures are found at the base of the sediment column,  
911 underneath the region of maximum sediment accumulation (the  
912 depocenter just off the shelf break). Changes in sea level drive large  
913 fluctuations in the pressure head (contours) extending to bedrock. In the  
914 near-surface continental shelf (Figure Z11, right), the driving pressure  
915 variations are dominated by the pressure head, driven by sea level  
916 changes. The formation of permafrost (GL, Figure Z11 e and f) seals the  
917 upper sediment column to fluid flow.

918 When sea level rises again, in the model configuration including  
919 permafrost, there is a strong pulse of downward flow following partial  
920 melting of the permafrost (Figure Z11 h). It is possible that this flow,  
921 which lasts a few thousand years, is an artifact of the elastic model  
922 configuration, in which the release of a load (by submergence of the  
923 upper sediment column into the ocean) provokes the expansion of pore  
924 spaces in the sediment. The anomalous flow, integrated over its duration,  
925 could displace the pore fluid by about 40 meters, which is less than one  
926 grid cell. The model configuration without the sealing effect of permafrost  
927 (SL) does not show this pulse of invasive flow on sea level rise.

### 928 **3.13.34 Methane Cycle**

929 There are multiple ways in which the glacial cycles of sea level and air and  
930 water temperature might impact the flux of methane to the atmosphere.  
931 Submergence in the ocean is one modulating factor, because the  
932 emerging bubbles dissolve in the ocean rather than reaching the  
933 atmosphere. Another factor is the deposition of high-POC surface soils  
934 during low sea level stands, and its exposure to degradation later when  
935 the permafrost soils melt. A third factor is permafrost, impeding gas and  
936 fluid flow and excluding dissolved methane and salt from ice formation.

937 The impacts of these processes are assessed by comparing the results  
938 from model configurations with and without each process in question.

939

940 **Ice vs. Hydrate.** The impact of phase competition between ice and  
941 hydrate is shown in [Figure 812](#). In the Base scenario ([Figure 812a and c](#))  
942 hydrate stability is excluded from the permafrost zone as described  
943 ~~above and in [Supplemental Text S3Figure 1](#)~~. Preventing ice from forming  
944 in an altered-physics simulation (+ No Ice) decreases the fluid-phase  
945 salinity relative to the Base simulation, and allows the methane hydrate  
946 stability zone to nearly reach the sea floor ([Figure 812b and d](#)), during  
947 strongest glacial conditions. Another altered-physics simulation was done  
948 in which ice is allowed to form, but not affect the salinity as it drives  
949 methane hydrate stability (which was hard-wired to marine salinity).  
950 Methane hydrate is still unstable in the permafrost zone through most of  
951 the simulation (see movie files in supplemental material), indicating that  
952 thermal interaction must also have a strong impact on methane hydrate  
953 stability in the permafrost zone.

954

955 **Dissolved Methane.** The evolution of the dissolved methane  
956 disequilibrium condition ( $\text{CH}_4 / \text{CH}_{4 \text{ sat}}$ ) is shown in [Figure 913](#). At the  
957 initiation of the glacial cycles, methane is undersaturated in near-surface  
958 sediments on the continental shelf, by diffusive contact with the  
959 methane-free ocean upper boundary condition. In the prefreshened  
960 sediment column scenario (Fr), methane concentrations in the depth  
961 range of 100-1000 meters are lower than in the marine case (Mar, [Figure](#)  
962 [913b](#)), due to the ventilation by the hydrological pump ([Figure 913a](#)).  
963 Further freshening of the pore waters in the ice-free case (SL+LD) tends  
964 to deplete methane in the upper sediment column ([Figure 913c-e](#)), while  
965 methane exclusion from the permafrost ice leads to supersaturation in  
966 simulation GL+LD ([Figure 913-f-h](#)). The hydrate stability zone is  
967 somewhat expanded in the prefreshened sediment column relative to the  
968 marine case ([Figure 913 g vs. h, heavy black contour](#)).

969 **Methane Sources.** [Figure 104](#) shows snapshot sections of various  
970 aspects of the shelf carbon cycle, beginning from a prefreshened initial  
971 condition. Sections of POC concentration in [Figure 1410](#), left show the  
972 accumulation of POC-rich Yedoma deposits on land ([Figure 14-10g and j](#)).

973 The rate of methane production in the model (Figure 1410, right)  
974 depends on temperature and organic carbon age, but it is also attenuated  
975 by permafrost formation in the model, scaling to zero in the completely  
976 frozen case. Methanogenesis rates are near zero in the permafrost zone  
977 during glacial time (Figure 14h10h), but partially recover during  
978 interglacial time (Figure 14k10k) even though permafrost is still present.

979

980

981 **Hydrate.** A zone of methane hydrate stability exists below the  
982 permafrost zone when permafrost is present, and some methane hydrate  
983 accumulates in that zone. The highest pore-fraction values are found  
984 near the continental slope, where the shelf stability field outcrops within  
985 the slope depocenter. Dissolved methane concentrations exceed  
986 saturation within the stability zone in the model (Figure 913), but the  
987 accumulation of methane hydrate (Figure 104, right) is limited by the  
988 rate of methane production.

989 Time series plots of the inventory of methane as hydrate on the shelf are  
990 shown in Figure 115. The integration cuts off at x=560 km to exclude  
991 the sediment depocenter on the continental slope. Hydrate inventories  
992 reach maximum values during deglaciations. There is more hydrate when  
993 the pore water is fresher, and there would be more if ice were excluded  
994 from forming (Figure 115a). The hydrate inventory is much more  
995 sensitive to thermogenic methane production, deep in the sediment  
996 column, than Yedoma deposition (Figure 115b). The impact of the  
997 geothermal heat flux is to change the depth of the bottom of the hydrate  
998 stability zone (Figure 182 e and f), but the impact is small on the hydrate  
999 inventory, unless the temperature gradient is so low that hydrate persists  
1000 through the entire glacial cycle (Figure 115c). The hydrate forms from  
1001 the dissolved methane pool, which exceeds 1000 Gton C in shelf  
1002 porewaters of the model.

1003

1004 **Permafrost, Ocean, and Atmospheric Methane Flux.** The impact  
1005 of the glacial cycles on the methane pathway to the atmosphere in the  
1006 model is shown in Figure 126. When sea level is high, the efficiency of  
1007 bubble transport across the sediment-water interface reaching the  
1008 atmosphere ranges from about 75% near the coast to about 10% at the

1009 shelf break (Figure 126a). Most of the methane flux from the sediment is  
1010 located just off the shelf break (Figure 126e), where the escape  
1011 efficiency is low, so not much methane makes it to the atmosphere  
1012 during the interglacial. During glacial times, the sediment column is  
1013 exposed to the atmosphere, and the escape efficiency in the model is  
1014 100% (Figure 16b12b). Permafrost inhibits the terrestrial methane flux  
1015 (Figure 16i12i) relative to the case without permafrost (Figure 16f12f).  
1016 During some deglaciations, the release of pent-up gas by permafrost  
1017 degradation leads to a spike of excess methane flux to the atmosphere  
1018 (Figure 16j12j-k relative to 16g12g-h).

1019

1020 **Budget.** Time series plots of the major fluxes of the methane cycle on  
1021 the continental margin are shown in Figure 137. The methanogenesis  
1022 rates in the model output are in units of moles per meter of coastline,  
1023 since it is a 2-D model. We scale this up to the Siberian continental  
1024 margin by assuming a width of 1,000 km. The area of the shelf is then  $5$   
1025  $\cdot 10^{11}$  m<sup>2</sup>, roughly comparable to the real shelf area of 460,000 km<sup>2</sup>  
1026 [Stein and Fahl, 2000]. The biological rate of methane production on the  
1027 continental shelf evolves through time in Figure 17b13b. Yedoma  
1028 deposition (case SL+LD) tends to slowly increase the total shelf  
1029 respiration rate in the model, relative to a case with no land deposition  
1030 (case SL). The formation of permafrost, during glacial periods of case  
1031 GL+LD, attenuates methanogenesis by inhibiting biological activity in the  
1032 frozen soil.

1033 The solid regions in Figure 17-13\_c-h are cumulative methane sinks for six  
1034 different model scenarios, plotted underneath red lines showing biogenic  
1035 methane production. In time average, where sinks balance sources, the  
1036 colored areas should fill up the region below the red line.

1037 Trapping of methane by impermeable permafrost leads to a spike of  
1038 methane fluxes at the ends of deglaciations in simulations with  
1039 permafrost (Figure 17-13\_c and e). The spikes happen as sea level  
1040 approaches its highest extent, stifling the offshore groundwater flow by  
1041 decreasing the pressure head, but early in the interglacial time while  
1042 permafrost is the most intact. The spikes are stronger for the first glacial  
1043 cycles than the last, apparently due to long-term adjustment of the  
1044 methane cycle on the shelf (a growing together of the production rate

1045 (red lines in [Figure 17-13 c-f](#)) and the various methane sinks (colored  
1046 areas).

1047 Permafrost formation blocks methane emission during times of low sea  
1048 level. This can be seen in the collapse of the blue regions in [Figure 17-13](#)  
1049 [c vs. d and e vs. f](#) during times of low sea level. Blocking horizontal flow  
1050 disrupts offshore flow, the only significant methane sink on the shelf  
1051 during glacial periods ([Figure 17-13h](#)), resulting in somewhat higher  
1052 deglacial spikes of methane emission than predicted by the models  
1053 including transport. There is no direct link between ice fraction and  
1054 methane oxidation in the model, which is driven only by coexisting  
1055 concentrations of sulfate and methane, but the rate of methane oxidation  
1056 also drops to negligible during glacial times in the simulations with  
1057 permafrost (grey in [Figure 17-13 c and e](#)). The absolute rates of  
1058 methane loss differ between the Prefreshened vs. Marine initial conditions,  
1059 but this is in part due to differences in the width of the continental shelf  
1060 between the two simulations. The patterns of the methane cycle are  
1061 very similar, however, between the two cases, and also not much  
1062 affected by the imposition of permeable vertical channels ([Figure](#)  
1063 [17g13g](#)).

#### 1064 **atmospheric fluxes**

1065 Atmospheric Flux. Fluxes of methane to the atmosphere are shown in  
1066 [Figure 18-14](#). In the absence of permafrost ([Figure 18-14 a and b](#)), or  
1067 assuming that bubble migration is blocked only if the ice fraction exceeds  
1068 90%, a condition rarely attained in the model ([Figure 18e14e](#)), the  
1069 highest methane fluxes to the atmosphere are found during glacial (cold)  
1070 times, rather than warm interglacials. This is due to dissolution of  
1071 methane gas into the ocean when the sediment column is submerged.  
1072 When permafrost blocks methane gas fluxes in the sediment column, the  
1073 highest atmospheric fluxes are generally found during the time of early  
1074 sea level fall, when unfrozen sediment is exposed to the atmosphere  
1075 before it has a chance to freeze. The timing of the variations in  
1076 atmospheric flux through the glacial cycles is very sensitive to the critical  
1077 ice fraction for blocking gas transport ([Figure 18e14e](#)).

1078 The impacts of the pore water salt inventory are most apparent during  
1079 the time of sea level fall, with permafrost formation (red lines). The  
1080 saltier sediment column takes about 20 kyr to choke off the methane flux  
1081 to the atmosphere ([Figure 18a14a](#)), while the pre-freshened sediment

1082 column stops the methane flux more abruptly, in just a few thousand  
1083 years (Figure 18b14b).

1084 Atmospheric emissions also scale with methane production rates,  
1085 generally maintaining the temporal patterns of emission as set by  
1086 permafrost and submergence in the ocean.

### 1087 **3.24 Anthropogenic Global Warming**

~~1088 The global warming (GW) scenario begins from a high sea-level interglacial  
1089 state, and raising the temperature following the climate impact of the  
1090 “spike and long tail” time distribution of a slug of new CO<sub>2</sub> added to the  
1091 atmosphere [Archer et al., 2009] (Figure 8). There is a stage of fast  
1092 atmospheric drawdown as CO<sub>2</sub> invades the ocean, but once the ocean,  
1093 atmosphere, and land surface reach equilibrium (after a few hundred  
1094 years), the CO<sub>2</sub> content of the entire biosphere begins to relax toward an  
1095 initial “natural” value, on time scales of hundreds of thousands of years,  
1096 by weathering reactions with carbonate and siliceous solid rocks. The net  
1097 result is a CO<sub>2</sub> drawdown that can be expressed as the sum of several  
1098 exponential functions in time, with time scales ranging from 10<sup>2</sup> – 10<sup>6</sup>  
1099 years.~~

~~1100 Changes in water column temperature are assumed equal to those of the  
1101 atmosphere, following paleoceanographic reconstructions [Martin et al.,  
1102 2002] and long-term coupled ocean / atmosphere circulation model  
1103 experiments [Stouffer and Manabe, 2003]. The GW scenario imposes this  
1104 temperature change on the water column, relaxing toward equilibrium  
1105 with the atmospheric CO<sub>2</sub> trajectory with a time constant of 100 years.~~

~~1106 The effect of sea level rise is added to create a second global warming  
1107 scenario GW+SL. On time scales of thousands of years the sea level  
1108 response to changing global temperature is much stronger than the sea  
1109 level response over the coming century, as prominently forecast by the  
1110 IPCC. Reconstruction of sea level and global temperature covariation in  
1111 the geologic past (glacial time to Eocene hothouse) reveals a covariation of  
1112 10-20 meters per °C [Archer and Brovkin, 2008]. The global warming with  
1113 sea level scenario assumes an equilibrium sea level response of 15 meters  
1114 /°C, which it relaxes toward with a time constant of 1000 years.~~

1115 The atmospheric methane fluxes, shown in Figure 1915, increase in the  
1116 global warming (GW) model run, as they also do in the control (Ctl)  
1117 simulation, which is essentially an extended but unwarmed interglacial



1118 period. The permafrost melts on a time scale of about 10,000 years for  
1119 the GW simulation, and about 50,000 for the Ctl. The rates of methane  
1120 production, and flux to the atmosphere, both increase with the loss of the  
1121 permafrost, if there is no change in sea level. However, the new methane  
1122 flux comes not as a sudden burst, but rather as a slow transition toward a  
1123 new, higher, chronic release rate.

1124 When sea level is also changed (GW+SL), bubbles dissolve in the water  
1125 column, which more than counteracts the increase in methane flux due to  
1126 the extended interglacial (Ctl) or warming (GW) scenarios.

### 1127 ***3.5 Summary of Model Sensitivity Studies***

1128 ~~**Sediment Porewater Salinity.** Ice freezes until the salinity of the~~  
1129 ~~residual brine brings about a freezing point depression equal to the in situ~~  
1130 ~~temperature. A saltier initial sediment column will reach this condition~~  
1131 ~~with a lower ice fraction, its melting is accelerated, and its hydrate~~  
1132 ~~inventory is lower (Figure 18). The equilibrium salinity in the permafrost~~  
1133 ~~zone is not affected by the salt inventory of the column, only the relative~~  
1134 ~~volumes of the solid and fluid phases.~~

1135 ~~**Methane Production Rates.** The atmospheric flux increases with~~  
1136 ~~increases in either shallow, biogenic methane production, driven by~~  
1137 ~~deposition of Yedoma, and thermogenic methane production in the deep~~  
1138 ~~sediment column (Figure 19). Biogenic methane is produced too shallow~~  
1139 ~~in the sediment column to impact the inventory of methane hydrate~~  
1140 ~~(Figure 15). The timing through the glacial cycles of atmospheric~~  
1141 ~~methane emissions from these scenarios parallel each other, because they~~  
1142 ~~are controlled in common by the transport-blocking effects of permafrost~~  
1143 ~~and sediment submergence in the ocean.~~

1144 ~~**Geothermal Temperature Gradient.** When the heat flux is higher, the~~  
1145 ~~temperature gradient is steeper, pivoting about the sediment surface~~  
1146 ~~temperature, which is set by the ocean. The base of the methane~~  
1147 ~~hydrate stability boundary gets shallower, while the top remains at about~~  
1148 ~~the same depth, resulting in a thinning of the stability zone (Figure 12).~~  
1149 ~~The hydrate inventory through the glacial cycles however is not much~~  
1150 ~~affected, unless the heat flux gets small enough for hydrate to persist~~  
1151 ~~through the glaciations (Figure 15).~~

1152 ~~**Ice vs. hydrate thermodynamic competition.** When ice is included~~  
1153 ~~as a competing phase, it excludes methane hydrate from the low-~~

1154 ~~pressure, very cold permafrost zone. The hydrate stability zone thins~~  
1155 ~~(from above and below in the model: Figure 12), and the hydrate~~  
1156 ~~inventory decreases (Figure 15). When ice formation is disallowed, the~~  
1157 ~~hydrate stability zone approaches the sediment surface during coldest~~  
1158 ~~glacial time, but by the time of an interglacial-based global warming~~  
1159 ~~climate perturbation, the stability zone boundary has retreated to several~~  
1160 ~~hundred meters below the sea floor, precluding a sudden hydrate~~  
1161 ~~dissolution response to a suddenly warming ocean.~~

1162 ~~**Permafrost inhibition of gas migration.** When the ice fraction of~~  
1163 ~~the model exceeds a critical threshold, gas migration is blocked.~~  
1164 ~~Changing the value of this threshold has a strong impact on the rates of~~  
1165 ~~methane emission during glacial versus interglacial times. This process is~~  
1166 ~~therefore a high priority for future model refinement.~~

1167 ~~**Vertical flow heterogeneity.** The chemistry of continental margin~~  
1168 ~~sediments in this model [Archer *et al.*, 2012] showed a strong sensitivity~~  
1169 ~~to flow heterogeneity, achieved by increasing the vertical permeability of~~  
1170 ~~every fifth grid cell. In the configuration presented here, the impact of~~  
1171 ~~the channels is much smaller. The dynamics of this simulation are~~  
1172 ~~thermally driven, rather than by sediment deposition driving fluid flow in~~  
1173 ~~the continental margin case. Atmospheric methane fluxes are spikier when~~  
1174 ~~the channels are included, but the mean rate is not much changed.~~

1175 ~~**Ground water flow.** Groundwater flow carries enough methane to be a~~  
1176 ~~significant sink during times of low sea level. However, disabling that flow~~  
1177 ~~has only subtle impacts on the other aspects of the methane cycle on the~~  
1178 ~~shelf. Spikes of methane emission during late deglaciation get somewhat~~  
1179 ~~more intense.~~

### 1180 **3.3 Sensitivity Studies**

#### 1181 **3.3.1 Sediment Salt Content**

1182 Ice freezes until the salinity of the residual brine brings about a freezing  
1183 point depression equal to the in situ temperature. A saltier initial  
1184 sediment column will reach this condition with a lower ice fraction, its  
1185 melting is accelerated, and its hydrate inventory is lower (Figure 14).  
1186 The equilibrium salinity in the permafrost zone is not affected by the salt  
1187 inventory of the column, only the relative volumes of the solid and fluid  
1188 phases.

1189

### **3.3.2 Methane Production Rates**

1190 The atmospheric flux increases along with either shallow, biological  
1191 methane production, driven by deposition of Yedoma, or thermal methane  
1192 production in the deep sediment column (Figure 15). Biogenic methane  
1193 production is too shallow in the sediment column to impact the inventory  
1194 of methane hydrate (Figure 11). The timing through the glacial cycles of  
1195 atmospheric methane emissions from these scenarios parallel each other,  
1196 because they are controlled in common by the transport-blocking effects  
1197 of permafrost and sediment submergence in the ocean.

1198

### **3.3.3 Geothermal Temperature Gradient**

1199 When the heat flux is higher, the temperature gradient is steeper,  
1200 pivoting about the sediment surface temperature, which is set by the  
1201 ocean. The base of the methane hydrate stability boundary gets  
1202 shallower, while the top remains at about the same depth, resulting in a  
1203 thinning of the stability zone (Figure 8). The hydrate inventory through  
1204 the glacial cycles however is not much affected, unless the heat flux gets  
1205 small enough for hydrate to persist through the glaciations (Figure 11).

1206

### **3.3.4 Thermodynamic Competition Between Ice and Hydrate**

1207 When ice is included as a competing phase, it excludes methane hydrate  
1208 from the low-pressure, very cold permafrost zone. The hydrate stability  
1209 zone thins (from above and below in the model: Figure 8), and the  
1210 hydrate inventory decreases (Figure 11). When ice formation is  
1211 disallowed, the hydrate stability zone approaches the sediment surface  
1212 during coldest glacial time, but by the time of an interglacial-based global  
1213 warming climate perturbation, the stability zone boundary has retreated  
1214 to several hundred meters below the sea floor, precluding a sudden  
1215 hydrate dissolution response to a suddenly warming ocean.

1216

### **3.3.5 Permafrost Inhibition of Gas Migration**

1217 When the ice fraction of the model exceeds a critical threshold, gas  
1218 migration is blocked. Changing the value of this threshold has a strong  
1219 impact on the rates of methane emission during glacial versus interglacial  
1220 times. This process is therefore a high priority for future model  
1221 refinement.

1222

### **3.3.6 Vertical flow heterogeneity**

1223 The chemistry of continental margin sediments in this model [Archer et  
1224 al., 2012] showed a strong sensitivity to flow heterogeneity, achieved by  
1225 increasing the vertical permeability of every fifth grid cell. In the  
1226 configuration presented here, the impact of the channels is much smaller.  
1227 The dynamics of this simulation are thermally driven, rather than by  
1228 sediment deposition driving fluid flow in the continental margin case.  
1229 Atmospheric methane fluxes are spikier when the channels are included,  
1230 but the mean rate is not much changed.

1231

### **3.3.7 Ground water Flow**

1232 Groundwater flow carries enough methane to be a significant sink during  
1233 times of low sea level. However, disabling that flow has only subtle  
1234 impacts on the other aspects of the methane cycle on the shelf. Spikes  
1235 of methane emission during late deglaciation get somewhat more intense.

1236

### **3.4 Comparison with Observations**

1237 The model bubble flux to the atmosphere in the base case in analog  
1238 present-day conditions is 0.02 Tg CH<sub>4</sub> per year, which is an order of  
1239 magnitude lower than an estimate of the total methane emission rate  
1240 from the sea surface (bubbles + gas exchange) [Kort et al., 2012] of 0.3  
1241 Tg CH<sub>4</sub> / yr. The model does not include gas exchange evasion of  
1242 methane from the sea surface, which could be significant. Concentrations  
1243 of methane in the water column of 50 nM are common [Shakhova et al.,  
1244 2010a], which, if they were unimpeded by sea ice, could lead to a flux  
1245 from the region of 0.4 Tg CH<sub>4</sub> / yr (assuming a typical gas exchange  
1246 piston velocity of 3 m/day). Gas exchange is impeded by sea ice, but it  
1247 can be enhanced by storms [Shakhova et al., 2013]. Once released to  
1248 the water column, the fate of a methane molecule will depend on its  
1249 lifetime with respect to oxidation, which could be up to a year in the open  
1250 water column [Valentine et al., 2001], versus its lifetime with respect to  
1251 gas exchange, which for ice-unimpeded conditions would be just a few  
1252 months for a 50-meter deep water column. Thus the methane in bubbles  
1253 dissolving in the water column has some chance of making it to the  
1254 atmosphere anyway, depending on stratification in the water column and  
1255 the extent of ice, and the gas exchange flux has the potential to be  
1256 significant in the regional total flux.

1257 Methane fluxes into the water column range up to 0.4 Tg CH<sub>4</sub> / yr during  
1258 times of relatively high sea level. This is much lower than the Shakhova  
1259 et al. [2013] estimate of 17 Tg CH<sub>4</sub> / yr from hot-spot ebullition fluxes  
1260 to the water column. The model fluxes are comparable to these  
1261 observations when the thermal methane flux is increased by a factor of  
1262 100 (see Section 3.3.2), but the model lacks the physical or mechanistic  
1263 detail required to focus the emissions into hot spots of concentrated  
1264 methane flux as observed (Section 4.1).

#### 1265 **4. Discussion Implications of the Model Results for the Real Siberian** 1266 **Continental Margin**

##### 1267 ***4.1 Limitations of the Model Results and Critical Issues for Future*** 1268 ***Development***

1269 This is the first simulation of the full methane cycle on the Siberian  
1270 continental margin, or any other location with embedded permafrost soils,  
1271 including hydrate formation and transient fluxes. It is internally  
1272 consistent, linking processes from the ocean, the sea floor, and the deep  
1273 Earth, within constraints of sediment accommodation and conservation of  
1274 carbon, through geologic time. As such it has some lessons to teach  
1275 about the real Siberian continental margin. However, many of the model  
1276 variables are not well known, such as the methaneogenesis rates or soil  
1277 permeabilities, meaning that in some aspects the model results are not a  
1278 strong constraint on reality. These uncertainties illuminate critical issues  
1279 for future model refinement.

##### 1280 **4.1.1 Methane Production Rates**

1281 The rates of biological and thermal methane production on the Siberian  
1282 continental shelf are not well constrained by laboratory measurements or  
1283 field inferences. These rates are treated as tunable model parameters,  
1284 and the sensitivity studies show that they are important ones to  
1285 ultimately get right.

##### 1286 **4.1.2 Gas Transport in the Sediment Column**

1287 Simulating the hot-spot behavior of bubble emission from the sea floor  
1288 will also require more detailed treatment of the mechanisms by which gas  
1289 moves around in the sediment column. The model lacks faults and  
1290 permeable layers that act as transport highways and hydrate  
1291 deponents, and may concentrate the flow into a hot-spot ebullition

1292 region. The model also lacks the ability to episodically “blow out”,  
1293 producing the sedimentary wipe-out zones observed seismically in the  
1294 subsurface [Riedel et al., 2002], and the pockmarks at the sediment  
1295 surface [Hill et al., 2004]. The steady-state hydrate inventory in the  
1296 model is extremely sensitive to the bubble vertical transport spatial scale  
1297 [Archer et al., 2012], which determines how far a bubble can get through  
1298 unsaturated conditions before it redissolves. This result demonstrates  
1299 the importance of gas transport to predicting the methane hydrate or  
1300 bubble inventories.

### 1301 **4.1.3 Atmospheric Flux Efficiency**

1302 On land, the model lacks seasonal melting of surface permafrost, and the  
1303 thaw bulbs underneath lakes and rivers. In the ocean, the fraction of the  
1304 sea-floor gas flux which dissolves in the water column intensity of water  
1305 column dissolution of rising bubbles depends on the bubble sizes, which  
1306 depend on the gas emission rate, ultimately driven by details of gas  
1307 transport in the sediment.

### 1308 **4.1.4 Uncertainty in Model Output**

1309 These uncertainties affect the flux of methane to the atmosphere, and  
1310 model predictions of the standing stocks of methane as gas and hydrate  
1311 in the sediment column.

1312 ~~The model bubble flux to the atmosphere in the base case in analog~~  
1313 ~~present-day conditions is only 0.02 Tg CH<sub>4</sub> per year, which is an order of~~  
1314 ~~magnitude lower than an estimate of the total methane emission rate~~  
1315 ~~from aircraft [Kort et al., 2012] of 0.3 Tg CH<sub>4</sub>/yr. However, the model~~  
1316 ~~only accounts (crudely) for the bubble flux to the atmosphere, and does~~  
1317 ~~not include gas-exchange evasion of methane from the water column,~~  
1318 ~~which could be significant. Concentrations of methane in the water~~  
1319 ~~column of 50 nM are common [Shakhova et al., 2010a], which, if they~~  
1320 ~~were unimpeded by sea ice, could lead to a flux from the region of 0.4 Tg~~  
1321 ~~CH<sub>4</sub>/yr (assuming a typical gas exchange piston velocity of 3 m/day).~~  
1322 ~~Methane fluxes into the water column range up to 0.4 Tg CH<sub>4</sub>/yr during~~  
1323 ~~times of relatively high sea level. Once released to the water column, the~~  
1324 ~~fate of a methane molecule will depend on its lifetime with respect to~~  
1325 ~~oxidation, which could be up to a year in the open water column~~  
1326 ~~[Valentine et al., 2001], versus its lifetime with respect to gas exchange,~~  
1327 ~~which for ice-unimpeded conditions would be just a few months for a 50-~~

1328 ~~meter deep water column. Thus the methane in bubbles dissolving in the~~  
1329 ~~water column has some chance of making it to the atmosphere anyway,~~  
1330 ~~depending on stratification in the water column and the extent of ice, and~~  
1331 ~~the gas exchange flux has the potential to be significant in the regional~~  
1332 ~~total flux.~~

1333 ~~This is the first simulation of the full methane cycle on the Siberian~~  
1334 ~~continental margin, or any other location with embedded permafrost soils,~~  
1335 ~~including hydrate formation and transient fluxes. It is internally~~  
1336 ~~consistent, linking processes from the ocean, the sea floor, and the deep~~  
1337 ~~Earth, within constraints of sediment accommodation and conservation of~~  
1338 ~~carbon, through geologic time. As such it has some lessons to teach us~~  
1339 ~~about the real Siberian continental margin. However, many of the model~~  
1340 ~~variables are not well known, such as the methaneogenesis rates or soil~~  
1341 ~~permeabilities, meaning that in some aspects the model results are not a~~  
1342 ~~strong constraint on reality.~~

1343 ~~The absolute values of the methane inventories in the system, as hydrate~~  
1344 ~~and bubbles, are not well constrained theoretically. The rate of methane~~  
1345 ~~production in shallow sediments is not well characterized. In reality there~~  
1346 ~~might be some flux of methane from the crust, but this is not included in~~  
1347 ~~the simulation. The transport of bubbles through the sediment column is~~  
1348 ~~mechanistically poorly understood, therefore not well represented in the~~  
1349 ~~code, which affects the inventories of bubbles in the sediment.~~  
1350 ~~Ultimately the bubble concentration in the model reaches a rough steady~~  
1351 ~~state where production of methane gas balances its escape through the~~  
1352 ~~sediment column, but the steady state value from the model could be~~  
1353 ~~wrong. The model lacks faults, permeable layers, or the ability to “blow~~  
1354 ~~out”, producing the sedimentary wipe-out zones observed seismically in~~  
1355 ~~the subsurface [Riedel et al., 2002], and the pockmarks at the sediment~~  
1356 ~~surface [Hill et al., 2004]. On land, the model lacks seasonal melting of~~  
1357 ~~surface permafrost (to form the active layer) and the thaw bulbs~~  
1358 ~~underneath lakes and rivers. In the ocean, the intensity of water column~~  
1359 ~~dissolution of rising bubbles depends on the bubble sizes, which depend~~  
1360 ~~on the gas emission rate, ultimately driven by details of gas transport in~~  
1361 ~~the sediment, which are neglected in the model.~~

1362 ~~These uncertainties all affect the flux of methane to the atmosphere,~~  
1363 ~~which is therefore not well constrained by the model. However, the~~  
1364 ~~model is consistent with observations [Kort et al., 2012], that the total~~  
1365 ~~atmospheric methane flux from the Siberian margin is a small fraction of~~

1366 ~~the global flux of methane to the atmosphere, and thus represents only a~~  
1367 ~~minor climate forcing. The model would have to be pushed very hard (as~~  
1368 ~~would the measurements) to fundamentally change this conclusion.~~

## 1369 4.2 Robust Features of the Simulation

### 1370 4.2.1 Arctic Ocean Methane Fluxes are Small in the Global Budget

1371 The model is consistent with observations [Kort et al., 2012], that the  
1372 total atmospheric methane flux from the Siberian margin is a small  
1373 fraction of the global flux of methane to the atmosphere, and thus  
1374 represents only a minor climate forcing. The model would have to be  
1375 pushed very hard (as would the measurements) to fundamentally change  
1376 this conclusion.

### 1377 4.2.1 The Hydrological Salinity Ratchet

1378 Groundwater flow, driven by the pressure head, provides an advective  
1379 means of pumping fresh water into the subsurface sediment column that  
1380 has no counterpart for salty ocean water. The model lacks the mechanism  
1381 of salt fingering, which can enhance the diffusion of salt from above into  
1382 a fresh water aquifer [Kooi et al., 2000]. However, higher-resolution  
1383 models of smaller domains that accounted for salt fingering also show a  
1384 time asymmetry, with faster fresh water invasion on sea level drop than  
1385 salt invasion on sea level rise [Lu and Werner, 2013; Watson et al.,  
1386 2010]. As the size of the domain increases with increasing sea level  
1387 change, advective processes such as hydrological flow should become  
1388 even more dominant over diffusive processes such as salt fingering. The  
1389 recent discovery of vast freshwater aquifers on global continental shelves  
1390 [Post et al., 2013], persisting since the time of lowered sea level 20,000  
1391 years ago, and the lower-than-marine salinities of the pore waters  
1392 measured in submerged surface Arctic sediments (summarized by  
1393 [Nicolisky et al., 2012]) are also consistent with the existence of a fresh-  
1394 water hydrological pump which has a significant impact on sediment  
1395 column salinities.

### 1396 4.2.2 Salinity (Water Activity) and Hydrate Stability in the Permafrost Zone

1397 In the simulations the porewater salinities in the permafrost zone did not  
1398 depend on the total salt content of the sediment column, but only on the  
1399 temperature (and secondarily pressure) condition. A saltier sediment  
1400 column will end up with a larger volume of brine in equilibrium than a



1401 fresher sediment column would have, but the salinities of the brines would  
1402 be the same.

1403 In the permafrost zone (low temperature and pressure), ice can tolerate  
1404 higher salinity (lower water activity) than methane hydrate can. As long  
1405 as there is no kinetic impediment to ice formation, bubbles of methane  
1406 rising into this zone should encounter brine salinities too high to permit  
1407 formation of methane hydrate.

1408

#### 1409 **4.2.3 Sea Level Dominates the Glacial Cycle of Methane Flux**

1410 The methane flux to the atmosphere through the glacial / interglacial  
1411 cycles is highest during cold times, because sea level is low, rather than  
1412 providing a positive climate feedback by releasing methane during warm  
1413 (high sea level) intervals. Atmospheric methane concentrations were  
1414 lower during glacial times than interglacials, but since the Arctic Ocean is  
1415 a small fraction of the total methane budget (Section 4.1.2), the  
1416 atmospheric concentration does not necessarily reflect Arctic fluxes.

#### 1417 **4.2.3 Methane Emission Response to Anthropogenic Climate Change**

1418 There is a warming positive feedback in the simulated future from climate  
1419 warming, with fluxes rising gradually on a time scale of thousands of  
1420 years. Shakhova et al [2010b] proposed that 50 Gton C as methane  
1421 could erupt from the Arctic on a time scale of a few years. However, the  
1422 thermodynamic exclusion of methane hydrate from the permafrost zone  
1423 (Section x.xx) ensures that methane hydrate will be isolated from  
1424 changes in ocean temperature by ~400 meters of mud and ice. A  
1425 warming perturbation at the sea floor today will not reach this depth for  
1426 hundreds or thousands of years. A complex model is not really required  
1427 to conclude that methane hydrate will probably not produce a methane  
1428 eruption of this scale so quickly.

1429 Could an abrupt methane release arise from release of trapped bubbles  
1430 from melting ice? The model actually does produce a glacial cycle in  
1431 bubble inventory, with changes exceeding 50 Gton over a cycle,  
1432 apparently driven by methane exclusion from ice formation (Figure 115).  
1433 But the model does not deliver an abrupt release in response to  
1434 anthropogenic warming for any of its sensitivity studies (Figure 148). We  
1435 would get a faster initial response to global warming if the transition from

1436 glacial to global warming sediment surface temperatures hadn't mostly  
1437 happened thousands of years ago.

1438 ~~Shakhova et al [2010b] proposed that 50 Gton C as methane could erupt~~  
1439 ~~from the Arctic on a time scale of a few years. However, one seemingly~~  
1440 ~~robust model result is the thermodynamic exclusion of methane hydrate~~  
1441 ~~from the permafrost zone, by competition for water between ice and~~  
1442 ~~hydrate. Thermodynamics does not control everything, especially at low~~  
1443 ~~temperature, but kinetic inhibitions are more often found for nucleation~~  
1444 ~~steps rather than decomposition. To find an accumulation of "metastable"~~  
1445 ~~hydrate would also require some sort of transport mechanism of hydrate~~  
1446 ~~into the region where it is unstable, which does not exist. There is no~~  
1447 ~~reason to imagine that hydrate could form in situ when thermodynamic~~  
1448 ~~conditions are wrong for it. A kinetic inhibition of water-ice formation~~  
1449 ~~would work, but ice does not tend to super-cool in a dirty, nucleation-site-~~  
1450 ~~rich environment like sediments. Therefore it seems as though methane~~  
1451 ~~hydrate should not be expected in sediment depths shallower than about~~  
1452 ~~300 meters. A warming perturbation at the sea floor today will not reach~~  
1453 ~~this depth for hundreds or thousands of years.~~

1454 ~~As has been acknowledged, t~~he model provides poor constraint on the  
1455 standing stock of bubbles or methane hydrate in the sediment column,  
1456 and neglects many of the mechanisms that could come into play in  
1457 transporting methane quickly to the atmosphere, such as faults, channels,  
1458 and blowouts of the sediment column. ~~Permafrost melting driven by~~  
1459 ~~deglacial sea level rise has already been going on for thousands of years.~~  
1460 ~~In this span of time a temperature anomaly has diffused quite deep into~~  
1461 ~~the sediment column. In order for the abrupt temperature anomaly of~~  
1462 ~~global warming to further accelerate the ongoing ice or hydrate melting,~~  
1463 ~~it will have to diffuse down in the sediment column to where the ice still~~  
1464 ~~is. In the real world, geological features such as faults and permeable~~  
1465 ~~layers dominate the methane cycle in the sediments.~~ A continuum model  
1466 such as this one predicts a smooth methane release response to a  
1467 warming, growing in on some e-folding time-scale. A world dominated by  
1468 features that each represent a small fraction of the total methane  
1469 reservoir will release methane more episodically, but the statistical  
1470 distribution of the response in time should still show the e-folding time  
1471 scale of the underlying driving mechanism, the diffusion of heat into the  
1472 sediment column.

1473 The way to deliver 50 Gton of methane to the atmosphere on a short  
1474 time scale is for it all to be released from a single geologic feature pent

1475 up by ice. But 50 Gton of C represents a large fraction of all the  
1476 traditional natural gas deposits on Earth (about 100 Gton C). The place  
1477 to look for such a large unstable gas reservoir is in the field, not in this  
1478 model, but until such a thing is found it remains conjecture.

1479 On time scales of thousands of years and longer, carbon from deep  
1480 methane hydrates and frozen organics on the Siberian continental shelf  
1481 could reach the atmosphere / ocean carbon cycle, potentially significantly  
1482 amplifying the “long tail” climate impact of anthropogenic carbon release.  
1483 Methane that is oxidized in the ocean would eventually equilibrate with  
1484 the atmosphere, so it is much easier for escaping methane to impact the  
1485 long tail as CO<sub>2</sub> than it is to affect the near future as methane.

1486 The potential for future sea level change is much higher on millennial time  
1487 scales than the forecast for the year 2100, because it takes longer than  
1488 a century for ice sheets to respond to changes in climate. The model  
1489 finds that for the future, if sea level changes by tens of meters, as guided  
1490 by paleoclimate reconstructions [Archer and Brovkin, 2008], the impact  
1491 of sea level rise could overwhelm the impact of warming. The dominance  
1492 of sea level over temperature in the model of this area is due to  
1493 dissolution of methane in the water column, rather than a pressure effect  
1494 on hydrate stability, which is generally a weaker driver than ocean  
1495 temperature in deeper-water settings [Mienert et al., 2005].

1496

1497 ~~Another probably robust feature of the model is the dominant impact of~~  
1498 ~~sea level inundation of the sediment column on the atmospheric methane~~  
1499 ~~flux. The methane flux is highest during cold times, because sea level is~~  
1500 ~~low, rather than providing a positive climate feedback of releasing~~  
1501 ~~methane during warm (high sea level) intervals. There is a warming~~  
1502 ~~positive feedback in the simulated future from climate warming, but it is~~  
1503 ~~much smaller than the impact of sea level changes in the past. The~~  
1504 ~~potential for future sea level change is much higher for the deep future,~~  
1505 ~~thousands of years from now, than the forecast for the year 2100,~~  
1506 ~~because it takes longer than a century for ice sheets to respond to~~  
1507 ~~changes in climate. The model finds that for the future, if sea level~~  
1508 ~~changes by tens of meters, as guided by paleoclimate reconstructions~~  
1509 ~~[Archer and Brovkin, 2008], the impact of sea level rise could overwhelm~~  
1510 ~~the impact of warming. The dominance of sea level over temperature in~~  
1511 ~~the model of this area is due to dissolution of methane in the water~~

1512 ~~column, rather than a pressure effect on hydrate stability, which is~~  
1513 ~~generally a weaker driver than ocean temperature in deeper-water~~  
1514 ~~settings [Mienert et al., 2005].~~

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## 1749 **76. Figure Captions**

1750 ~~Figure 1. Thermodynamics of hydrate and ice. Top) Colors are salinities,~~  
1751 ~~which range from fresh if there is no solid phase, to saltier as the freezing~~  
1752 ~~point depression of the solid phase follows the in situ temperature.~~  
1753 ~~Contours indicate the extent of thermal disequilibrium,  $\Delta T_{eq} = T - T_{eq}$ . a)~~  
1754 ~~For the system of ice and fluid. b) Considering hydrate and fluid phases,~~  
1755 ~~excluding ice formation and assuming equilibrium with methane gas. c)~~  
1756 ~~Combined ice + hydrate + fluid system, where the salinity is controlled by~~  
1757 ~~the most stable solid phase. Solid contours are  $\Delta T_{eq, hydrate}$ , dashed  $\Delta T_{eq, ice}$ .~~  
1758 ~~d and e) Colors are  $\Delta T_{eq}$ , where 0 (purple) indicates stability, and contours~~  
1759 ~~are the excess salinity relative to a solid phase, e.g.  $S_{max} - S_{eq, hydrate}$  in (d),~~  
1760 ~~for hydrate, and e) ice. f) Phase diagram for the ice + hydrate + brine~~  
1761 ~~system. Hydrate is excluded from the ice phase space by the high salinity~~  
1762 ~~of the brine. Ice is ideally also excluded from part of the hydrate stability~~  
1763 ~~zone by a similar mechanism, but this would only happen in nature under~~  
1764 ~~conditions of unlimited methane availability. Thus it is easier to envision~~  
1765 ~~coexistence of hydrate and ice within the hydrate stability zone, under~~  
1766 ~~conditions of limited methane availability, than it is to imagine hydrate in~~  
1767 ~~the permafrost zone, where ice has no impediment for formation.~~

1768 Figure 12. Domain of the model as applied to the Laptev Sea continental  
1769 shelf and slope. This is the result of 62 million years of sediment  
1770 accumulation on the crust, isostatic subsidence, pore fluid flow, and

1771 thermal diffusion, used as the initial condition for glacial / interglacial  
1772 cycle and climate change simulations. Color indicates temperature. a)  
1773 Full view. Black line shows the bottom of the crust, which grades  
1774 smoothly from continental on the left into ocean crust through most of  
1775 the domain on the right. b) Zoom in to see increased model resolution in  
1776 the upper kilometer of the sediment column.

1777 Figure 24. Pore water salinity a) The fully marine case, in which the  
1778 sediment column has always been submerged underneath a time-invariant  
1779 sea level. b) Result of sediment column freshening by hydrological  
1780 groundwater flow, driven by the pressure head resulting from a water  
1781 table higher than sea level. A movie of the transition from marine to  
1782 freshened (the origin of b) can be seen at  
1783 [http://geosci.uchicago.edu/~archer/spongebob\\_arctic/fig24.movie.gif](http://geosci.uchicago.edu/~archer/spongebob_arctic/fig24.movie.gif)

1784 Figure 3. Particulate Organic Carbon (POC) concentration. Highest values  
1785 are found in the sediment depocenter just off the continental shelf break.

1786 Figure 45. Initial distribution of dissolved methane. a) Concentration in  
1787 moles/m<sup>3</sup>. b-d)  $\Omega = \text{CH}_4 / \text{CH}_{4(\text{sat})}$  deviation from equilibrium, b) of the  
1788 Marine (salty) initial condition; c) of the pre-freshened initial condition  
1789 (note depletion in near-surface near-shore sediments in the upper left);  
1790 d) including permeable channels every five grid points, plus pre-  
1791 freshening.

~~1792 Figure 6. Freshening the sediment column by hydrological groundwater  
1793 flushing. Color indicates salinity. Solid black line represents sea level in  
1794 the ocean (white space), and the equilibrium fresh-salty boundary given a  
1795 snapshot of the pressure head (the Ghyben-Herzberg relation). Left side:  
1796 results of dropping sea level 30 meters and holding it there. A freshwater  
1797 lens forms and strives to reach Ghyben Herzberg equilibrium as the  
1798 sediment column subsides, where atmospheric exposure decreases its  
1799 buoyancy and stops sediment accumulation. After the sediment column  
1800 subsides beneath the still-lowered sea level, the fresh water lens remains  
1801 for millions of years. A movie can be seen at  
1802 [http://geosci.uchicago.edu/~archer/spongebob\\_arctic/fig6a.movie.gif](http://geosci.uchicago.edu/~archer/spongebob_arctic/fig6a.movie.gif).  
1803 Right side: Result of dropping sea level 120 meters and holding it there  
1804 forever. Movie at  
1805 [http://geosci.uchicago.edu/~archer/spongebob\\_arctic/fig6b.movie.gif](http://geosci.uchicago.edu/~archer/spongebob_arctic/fig6b.movie.gif)~~

1806 ~~Figure 7. Time scale of depleting the salinity of the continental shelf~~  
1807 ~~sediment column after an instantaneous sea level drop of 30 meters. The~~  
1808 ~~effect of lateral canyons is to provide a pathway for saline fluid to be~~  
1809 ~~replaced by fresh groundwater in sediments above sea level. If the lateral~~  
1810 ~~canyon spacing is 10 km, they can have a significant impact on the time~~  
1811 ~~constant for ground water flushing. A more conservative 100-km canyon~~  
1812 ~~is adopted for the rest of the simulations.~~

1813 ~~Figure 8. Dissolved methane impact by hydrological freshening of the~~  
1814 ~~sediment column as described in Figure 5.  $\Omega = \text{CH}_4 / \text{CH}_{4(\text{sat})}$ . Movies can~~  
1815 ~~be seen at~~  
1816 ~~[http://geosci.uchicago.edu/~archer/spongebob\\_arctic/fig8a.movie.gif](http://geosci.uchicago.edu/~archer/spongebob_arctic/fig8a.movie.gif)~~  
1817 ~~and~~  
1818 ~~[http://geosci.uchicago.edu/~archer/spongebob\\_arctic/fig8b.movie.gif](http://geosci.uchicago.edu/~archer/spongebob_arctic/fig8b.movie.gif)~~

1819 Figure 59. Time-dependent forcing for the glacial / interglacial  
1820 simulations and the global warming scenarios. a) Sea level is imposed as  
1821 a sawtooth 100-kyr cycle, with interglacial intervals shaded. The GW+S  
1822 simulation tracks potential changes in sea level on long time scales due to  
1823 fossil fuel CO<sub>2</sub> release, following a covariation from the geologic past of  
1824 15 meters / °C. The GW and Control simulations hold sea level at  
1825 interglacial levels. b) Ocean temperature forcings.

1826 Figure 610. Colors indicate salinity in the unfrozen pore fluid of the  
1827 sediment column. Thin solid black contours show the frozen fraction of  
1828 the pore space. Heavy black stippled contour shows the stability  
1829 boundary of methane hydrate as a function of temperature, pressure, and  
1830 unfrozen pore fluid salinity. Left side: previously pre-freshened initial  
1831 condition. Right side: Pure marine initial condition. c-d) Lowered sea level  
1832 (from 70 kyr in Figure 8) but warm air temperatures prevent permafrost  
1833 formation. e-f) Glacial conditions of lowered sea level (70 kyr) and  
1834 atmospheric temperature of -17 °C driving permafrost formation. The  
1835 pre-freshened and the marine initial conditions differ in the frozen fraction  
1836 of sediment, but the salinity of the unfrozen fluid, a correlate of the  
1837 activity of water, depends only the temperature. g-h) Rising sea level (at  
1838 90 kyr in Figure 8) into an interglacial interval. Movies of the glacial  
1839 cycles (GL) with the prefreshened initial condition can be seen at  
1840 [http://geosci.uchicago.edu/~archer/spongebob\\_arctic/fig610a.movie.gif](http://geosci.uchicago.edu/~archer/spongebob_arctic/fig610a.movie.gif)  
1841 , and the marine initial condition at  
1842 [http://geosci.uchicago.edu/~archer/spongebob\\_arctic/fig610b.movie.gif](http://geosci.uchicago.edu/~archer/spongebob_arctic/fig610b.movie.gif)  
1843 .

1844 Figure [Z11](#). Pore fluid pressure forcing and flow through the glacial  
1845 cycles. Left) Colors indicate  $P_{\text{excess}} + P_{\text{head}}$ , solid contours are ice fraction,  
1846 dashed contours are  $P_{\text{head}}$ . Right) Colors indicate  $P_{\text{excess}} + P_{\text{head}}$ , note  
1847 different color scale from Left. Initial refers to the prefreshened initial  
1848 condition. “Low Sea Level” refers to simulation SL. “Glacial” and  
1849 “Interglacial” refer to simulation GL. Dashed contours indicate ice  
1850 fraction, vectors fluid velocity. Movies ~~of the prefreshened initial~~  
1851 ~~condition and glacial cycles (GL)~~ can be seen at  
1852 [http://geosci.uchicago.edu/~archer/spongebob\\_arctic/press\\_uw.65e6.nc](http://geosci.uchicago.edu/~archer/spongebob_arctic/press_uw.65e6.nc.ld2.gl.pf_eq.gw.compfig7a.movie.gif)  
1853 [c.ld2.gl.pf\\_eq.gw.compfig7a.movie.gif](http://geosci.uchicago.edu/~archer/spongebob_arctic/press_uw.65e6.nc.ld2.gl.pf_eq.gw.compfig7a.movie.gif) and  
1854 [http://geosci.uchicago.edu/~archer/spongebob\\_arctic/fig7bpressure\\_flow](http://geosci.uchicago.edu/~archer/spongebob_arctic/fig7bpressure_flow.65e6.nc.ld2.gl.pf_eq.gw.comp.movie.gif)  
1855 [.65e6.nc.ld2.gl.pf\\_eq.gw.comp.movie.gif](http://geosci.uchicago.edu/~archer/spongebob_arctic/fig7bpressure_flow.65e6.nc.ld2.gl.pf_eq.gw.comp.movie.gif).

1856 Figure [812](#). Sensitivities of the hydrate stability zone. Impact of the  
1857 competition between ice and hydrate phases (a-d), and the geothermal  
1858 temperature gradient (e-f). When ice is included as a potential solid  
1859 phase, the pore waters are salty in the permafrost zone (a), restricting  
1860 hydrate stability to at least 300 meters below sea level throughout the  
1861 simulation (c). When ice is forbidden to form, hydrate can be stable  
1862 nearly to the sediment surface during the height of the glaciation (b and  
1863 d). The base of the stability zone is sensitive to the geothermal  
1864 temperature gradient, while the shallowest reach of the stability zone  
1865 does not respond to changing heat fluxes, because the temperatures are  
1866 “anchored” at the ocean value at the top of the sediment column.

1867 Figure [913](#). Dissolved methane concentration relative to equilibrium ( $\Omega =$   
1868  $\text{CH}_4 / \text{CH}_{4(\text{sat})}$ ). Solid contours indicate ice fraction, dashed contours show  
1869 the methane hydrate stability boundary. Movies for the left, center, and  
1870 right columns, respectively can be seen at  
1871 [http://geosci.uchicago.edu/~archer/spongebob\\_arctic/fig913a.movie.gif](http://geosci.uchicago.edu/~archer/spongebob_arctic/fig913a.movie.gif)  
1872 ,  
1873 [http://geosci.uchicago.edu/~archer/spongebob\\_arctic/fig913b.movie.gif](http://geosci.uchicago.edu/~archer/spongebob_arctic/fig913b.movie.gif)  
1874 , and  
1875 [http://geosci.uchicago.edu/~archer/spongebob\\_arctic/fig913c.movie.gif](http://geosci.uchicago.edu/~archer/spongebob_arctic/fig913c.movie.gif).

1876 Figure [104](#). Carbon cycle through glacial cycles from a prefreshened  
1877 initial condition. Solid contours: Ice Fraction. Dashed contours: Methane  
1878 hydrate stability zone. Left) Particulate organic carbon (POC)  
1879 concentration. Movie at  
1880 [http://geosci.uchicago.edu/~archer/spongebob\\_arctic/fig104a.movie.gif](http://geosci.uchicago.edu/~archer/spongebob_arctic/fig104a.movie.gif).  
1881 Center) Biological methane production rate. Movie at

1882 [http://geosci.uchicago.edu/~archer/spongebob\\_arctic/fig104b.movie.gif](http://geosci.uchicago.edu/~archer/spongebob_arctic/fig104b.movie.gif)  
1883 Right) Methane hydrate concentration. Movie at  
1884 [http://geosci.uchicago.edu/~archer/spongebob\\_arctic/fig104c.movie.gif](http://geosci.uchicago.edu/~archer/spongebob_arctic/fig104c.movie.gif).  
1885 Movies of methane hydrate stability and concentration are given for the  
1886 sensitivity studies, in the supplemental material and at  
1887 <http://geosci.uchicago.edu/~archer/spongebob/>.

1888 Figure 115. Glacial cycle of methane hydrate inventory on the  
1889 continental shelf. a) Effects of salt and ice. b) Sensitivity to  
1890 methaneogenesis rates. c) Sensitivity to the column temperature  
1891 gradient. d) Glacial cycles of shelf bubble inventories, effects of salt and  
1892 ice.

1893 Figure 126. Spatial distribution and sea level impact of methane fluxes to  
1894 the atmosphere. a-d) Solid line shows the elevation of the sediment  
1895 surface relative to the sea level at the time. Grey lines (scale to right)  
1896 show the efficiency of bubble transport through the water column,  
1897 assuming a flux attenuation length scale of 30 meters. e-k) Dashed line:  
1898 Methane bubble flux across the sediment surface. Solid line: Methane  
1899 bubble flux to the atmosphere (dashed line multiplied by transport  
1900 efficiency). Most of the methane flux in the model occurs near the shelf  
1901 break, and submergence in the ocean has a strong impact on the flux to  
1902 the atmosphere. A related movie can be seen at  
1903 [http://geosci.uchicago.edu/~archer/spongebob\\_arctic/fig126.movie.gif](http://geosci.uchicago.edu/~archer/spongebob_arctic/fig126.movie.gif) .

1904 Figure 137. Glacial / interglacial cycle of methane fluxes on the  
1905 continental margin of the model. Sea level at top, grey regions indicate  
1906 interglacial intervals, pink the Anthropocene. a-e) Cumulative methane  
1907 fluxes. Red lines show production rate. Brown regions show lateral  
1908 transport of dissolved methane. Grey shows oxidation by  $\text{SO}_4^{2-}$  in the  
1909 sediment column. Blue shows bubble flux to the water column. During  
1910 interglacial times (e.g. far left) there is a small onshore transport of  
1911 methane, which is represented by a negative starting point for the  
1912 oxidation (grey) region. In equilibrium, the colored areas should fill in the  
1913 region under the red curve.

1914 Figure 148. Methane fluxes to the atmosphere. Sea level at the top,  
1915 interglacial intervals in vertical grey bars, the Anthropocene in pink. a)  
1916 From a pre-freshened initial condition, with and without permafrost  
1917 formation. b) From a pure marine initial condition. c and d) Sensitivity to  
1918 terrestrial organic carbon deposition during low sea-level stands, and to

1919 thermogenic methane flux. e) Sensitivity to the impact of ice fraction on  
1920 bubble mobility.

1921 Figure 159. Impact of anthropogenic warming on the methane cycle in  
1922 the model. a) Base cases, a warming scenario (GW), without and with a  
1923 geological time-scale sea level rise scenario (+SLR), and extended  
1924 interglacial control (Ctl). Warming plus increasing sea level decreases the  
1925 methane flux overall, due to bubble dissolution in a deeper water column.  
1926 b) Altered model physics impacts. c and d) Altered methanogenesis  
1927 rates. e) Sensitivity to the ice fraction at which bubble mobility is  
1928 assumed stopped.

1929

## 1930 **8. Tables**

1931 Table 1. Summary of Nomenclature describing the model scenarios and  
1932 sensitivity runs.

<u>Fr</u>	<u>The sediment column has been pre-freshened by previous exposure to hydrological forcing.</u>
<u>Mr</u>	<u>Initial salinities are close to marine.</u>
SL	Sea level changes with constant air and water temperatures
GL	SL + glacial cycles in air and water temperature
GW	A long-term global warming scenario, a peak and long tail temperature perturbation consistent with CO <sub>2</sub> release and cessation of the glacial sawtooth forcing.
<u>GW+SLR</u>	Adds geologic-timescale sea level rise due to anthropogenic climate change, based on correlation between temperature and sea level in the geologic past (10 meters / °C).
Ctl	An extended interglacial with no CO <sub>2</sub> release forcing.



+ LD	Land deposition of carbon-rich Yedoma. Base case is 10 m / 100 kyr, with sensitivity runs using 30 and 100 m / 100 kyr accumulation of 30% POC material. Movies in the supplemental material are identified by the tags Land30 and Land100.
+ TG	Thermogenic methane production rate sensitivity runs, scaling the rate from the spinup result by factors of 10 and 100. Movies in the supplemental material are identified by the tags TGenX10 and TGenX100.
+ Geotherm	Sensitivity of ice and hydrate cycles on the geothermal temperature gradient. Temperatures from the Base simulation were adjusted when calculating the stability of ice and hydrate, to simulate the impact of geothermal heat fluxes on hydrate stability. Note that other aspects of the sediment column, including the solubility of methane, retained the original temperatures. Heat fluxes simulated include 25 mW/m <sup>2</sup> , 37.5, 50 (Base), 62.5, and 75. Movies of the non-base runs are identified by tags HF050, HF075, HF125, and HF150.
Ice and Bubble Transport	When the ice fraction exceeds a threshold value methane gas flow is disabled. Base case is 50%, variants 10%, 30%, 70%, and 90%, identified with tags Ice10, Ice30, Ice70, and Ice90.
No Ice	The ice phase is disallowed in the thermodynamic calculation. Movies in the supplemental material include salinity. The files are tagged as Nolce

No Salt from Ice	Ice is allowed to form, but it does not affect the salinity as it determines methane hydrate stability. Movie files are tagged as NoSalFromIce.
Permeable Channels	Increasing vertical permeability by a factor of 10 every 5 <sup>th</sup> grid cell, to generate heterogeneity in the flow. Tagged as PermChan
No Horizontal Flow	Horizontal flow is disabled. Tagged as NoHFlow.

1933 Movies comparing altered scenario runs with the Base scenario are given  
1934 in the supplemental material, and at  
1935 <http://geosci.uchicago.edu/~archer/spongebob/>. Movies named  
1936 hydrate\* and bubbles\* show methane hydrate and bubble inventories and  
1937 stability zone changes. Files entitled salinity\* show salinities, and  
1938 bubb\_atm\* show bubble fluxes through and out of the sediment column,  
1939 into the ocean, and into the atmosphere, through time.

1940

## 1941 **9. Supplemental Text**

### 1942 **S1. Vertical Flow**

1943 In previous versions of the SpongeBOB model, the fluid flow was  
1944 calculated explicitly, each time step, as a function of  $P_{\text{excess}}$  at the  
1945 beginning of the time step. Numerical stability motivated a modification  
1946 of the vertical flow to an implicit numerical scheme, which finds by  
1947 iteration an internally consistent array of vertical flow velocities and  
1948 resulting  $P_{\text{excess}}$  values from a time point at the end of the time step.  
1949 Ocean and atmosphere models often use this methodology for vertical  
1950 flow. A benefit to this change is stability in the vertical flow field,  
1951 reducing numerical noise that can cause trouble with other aspects of the  
1952 model such as ice formation. Implicit schemes can be more efficient  
1953 computationally, but in this case the execution time is not improved by  
1954 the implicit method, just the stability.

1955 Note that the flow scheme in its formulation is entirely elastic, whereas in  
1956 reality, pore fluid excluded by the pressure of a sediment column above  
1957 sea level, for example, where it is uncompensated by buoyancy in  
1958 seawater, should remain excluded when sea level rises again, like  
1959 toothpaste from the tube. However, my attempts to embed this plastic  
1960 behavior into an implicit solver failed to converge.

## 1961 **S2. Ice Formation**

1962 The ice content in a grid cell relaxes toward equilibrium, quickly enough to  
1963 approximate an equilibrium state through the slow temperature evolution  
1964 in the model (which neglects a seasonal cycle at the surface), but slowly  
1965 enough to avoid instabilities with other components of the model such as  
1966 fluid flow and methane hydrate formation. A limiter in the code prevents  
1967 more than 99% of the fluid in a grid cell from freezing, but the  
1968 thermodynamic equilibrium salinity is used to calculate, for example, the  
1969 stability of methane hydrate, to prevent the numerical limiter from  
1970 affecting the thermodynamic availability of water to drive chemical  
1971 reactions.

## 1972 **S3. Thermodynamics of Ice and Hydrate**

1973 When the system consists only of ice and fluid phases, the equilibrium  
1974 salinity  $S_{eq}$  increases with decreasing temperature below freezing (Figure  
1975 1a, left). Above the melting temperature, ice is unstable, as indicated by  
1976 the nonzero values of the disequilibrium temperature,  $\Delta T_{eq, ice} = T - T_{eq, ice}$ ,  
1977 in contours, even in zero-salinity water (right). For a system consisting  
1978 of only the hydrate and fluid phases (assuming that ice formation is  
1979 disallowed, and also gas saturation for methane) (Figure 1b), the behavior  
1980 is similar but with an added pressure dependence due to the  
1981 compressibility of the gas phase.

1982 When both solid phases are allowed, the overall equilibrium salinity will  
1983 whichever is higher between  $S_{eq, ice}$  and  $S_{eq, hydrate}$ . Whichever phase can  
1984 seize water at its lowest activity (highest salinity) will be the stable  
1985 phase. The salinity of the brine excluded from that phase will be too high  
1986 to permit the existence of the other solid phase at that temperature.  
1987 The contours show  $\Delta T_{eq}$  for hydrate (solid) and ice (dashed), which are  
1988 also plotted in color in Figures 1d and e. This is illustrated in Figure 1d, in  
1989 colors of  $\Delta T_{eq, hydrate}$  and contours of the excess salinity relative to hydrate

1990 equilibrium,  $S_{\max} - S_{\text{eq, hydrate}}$ . Hydrate is only stable when  $\Delta T_{\text{eq, hydrate}}$  is zero  
1991 (purple color).

1992 Under permafrost conditions of low pressure and low temperature (upper  
1993 left corner),  $\Delta T_{\text{eq, hydrate}}$  is greater than zero, indicating that hydrate is  
1994 unstable, coinciding with the salinity forcing from the ice, in overlain  
1995 contours. A similar exclusion of ice in part of the hydrate stability zone is  
1996 seen Figure 1e, but this would only happen in nature in conditions of  
1997 unlimited methane. The resulting phase diagram for ice and methane  
1998 hydrate is shown in Figure 1f. Hydrate stability is suppressed in the  
1999 permafrost zone by this thermodynamic mechanism.

2000 There is an analogous exclusion of ice from part of the methane hydrate  
2001 stability zone, but this assumes unlimited methane; if the dissolved  
2002 methane concentration is less than gas saturation, both solid phases can  
2003 coexist. In the permafrost zone, the dissolved methane concentration  
2004 cannot exceed solubility with gas saturation, so the exclusion of methane  
2005 hydrate from thermodynamic stability is inescapable.

2006 **S4. Construction of the Pre-Freshened Sediment Column**

2007 If sea level falls, exposing the sediment column to the atmosphere for the  
2008 first time, there is a pressure head gradient extending throughout the  
2009 sediment column, provoking lateral flow at all depths. As the pore fluid at  
2010 the surface is replaced by fresh runoff, the lighter density of that fluid  
2011 tends to diminish the pressure head gradient in the deeper sediment  
2012 column. The deeper pressure gradient and flow approach zero as the  
2013 fresh water lens in the outcropping region approaches an isostatic  
2014 equilibrium condition known as the Ghyben-Herzberg relation [Moore et  
2015 al., 2011], in which each meter elevation of the water table is  
2016 compensated for by about 40 meters of fresh water below sea level,  
2017 determined by the difference in densities of fresh and salt water.

2018 To create this condition within the model, two simulations are presented  
2019 in which sea level was decreased by 30 and 120 meters, respectively, and  
2020 held there for millions of years (Supplemental Figure 2). The 30-meter  
2021 drop experiment produced land outcrop in about 1/4 of the model  
2022 domain, with the predicted equilibrium Ghyben-Herzberg halocline  
2023 reaching about 1200 meters maximum depth. The model salinity relaxes  
2024 into close agreement with the predicted halocline, lending support to the  
2025 model formulation for density, pressure head, and fluid flow. As time

2026 progresses further, the outcropping land surface subsides (there is no  
2027 land deposition in this scenario), until it drops below the new lowered sea  
2028 level value after about 2.5 Myr. The hydrological pumping generates a  
2029 low-methane plume that also persists for millions of years in the model  
2030 (Supplemental Figure 3).

### 2031 negligible impact of canyons

2032 Variants of this experiment were done with differing values of the lateral  
2033 distance to drainage canyons in the model, which provide a pathway for  
2034 fluid loss in sediments above sea level. When a hypothetical canyon is  
2035 located 10 km from the SpongeBOB slab, the model salinity approaches  
2036 equilibrium on an e-folding time scale of about 400 kyr (Supplemental  
2037 Figure 4). When the canyon is 100 km distant or nonexistent, the  
2038 equilibration time scale is about 600 kyr. Based on the idea that canyons  
2039 of order 100 km long should be about 100 km apart, the Base simulation  
2040 in this paper assumes canyon spacing of 100 km.

### 2041 120 m same as 30

2042 When sea level is lowered by 120 m, the sequence of events is similar,  
2043 except that the pressure head is so high that to satisfy the Ghyben-  
2044 Herzberg relation would require fresh pore waters at many kilometers  
2045 depth, even deeper than bedrock on the “continental” side of the model  
2046 domain. Because of the low permeability of the deepest sediment  
2047 column, the freshwater pumping groundwater mechanism is unable to  
2048 reach these deepest pore waters, which therefore remain salty. The time  
2049 scale for establishing a significant freshening of the upper kilometer of  
2050 the sediment column is still on the order of 100-500 kyr, and the  
2051 subsequent subsidence time of the sediment column in the model, until it  
2052 drops below the new lowered sea level, takes about 10 Myr. In both  
2053 cases, subsidence of the exposed sediment column prevents the  
2054 sediment surface in the model from remaining above sea level indefinitely  
2055 (without land deposition).

### 2056 10. Supplemental Figure Captions

2057 Supplemental Figure 1. Thermodynamics of hydrate and ice. Top) Colors  
2058 are salinities, which range from fresh if there is no solid phase, to saltier  
2059 as the freezing point depression of the solid phase follows the in situ  
2060 temperature. Contours indicate the extent of thermal disequilibrium,  $\Delta T_{eq}$   
2061 =  $T - T_{eq}$ . a) For the system of ice and fluid. b) Considering hydrate and

2062 fluid phases, excluding ice formation and assuming equilibrium with  
2063 methane gas. c) Combined ice + hydrate + fluid system, where the  
2064 salinity is controlled by the most stable solid phase. Solid contours are  
2065  $\Delta T_{eq, hydrate}$ , dashed  $\Delta T_{eq, ice}$ . d and e) Colors are  $\Delta T_{eq}$ , where 0 (purple)  
2066 indicates stability, and contours are the excess salinity relative to a solid  
2067 phase, e.g.  $S_{max} - S_{eq, hydrate}$  in (d), for hydrate, and e) ice. f) Phase diagram  
2068 for the ice + hydrate + brine system. Hydrate is excluded from the ice  
2069 phase space by the high salinity of the brine. Ice is ideally also excluded  
2070 from part of the hydrate stability zone by a similar mechanism, but this  
2071 would only happen in nature under conditions of unlimited methane  
2072 availability. Thus it is easier to envision coexistence of hydrate and ice  
2073 within the hydrate stability zone, under conditions of limited methane  
2074 availability, than it is to imagine hydrate in the permafrost zone, where  
2075 ice has no impediment for formation.

2076 Supplemental Figure 2. Freshening the sediment column by hydrological  
2077 groundwater flushing. Color indicates salinity. Solid black line represents  
2078 sea level in the ocean (white space), and the equilibrium fresh-salty  
2079 boundary given a snapshot of the pressure head (the Ghyben-Herzberg  
2080 relation). Left side: results of dropping sea level 30 meters and holding it  
2081 there. A freshwater lens forms and strives to reach Ghyben Herzberg  
2082 equilibrium as the sediment column subsides, where atmospheric  
2083 exposure decreases its buoyancy and stops sediment accumulation.  
2084 After the sediment column subsides beneath the still-lowered sea level,  
2085 the fresh water lens remains for millions of years. A movie can be seen at  
2086 [http://geosci.uchicago.edu/~archer/spongebob\\_arctic/supp\\_fig2a.movie](http://geosci.uchicago.edu/~archer/spongebob_arctic/supp_fig2a.movie)  
2087 .gif . Right side: Result of dropping sea level 120 meters and holding it  
2088 there forever. Movie at  
2089 [http://geosci.uchicago.edu/~archer/spongebob\\_arctic/supp\\_fig2b.movie](http://geosci.uchicago.edu/~archer/spongebob_arctic/supp_fig2b.movie)  
2090 .gif

2091 Supplemental Figure 3. Dissolved methane impact by hydrological  
2092 freshening of the sediment column as described in Supplemental Figure 2.  
2093  $\Omega = CH_4 / CH_{4(sat)}$ . Movies can be seen at  
2094 [http://geosci.uchicago.edu/~archer/spongebob\\_arctic/supp\\_fig3a.movie](http://geosci.uchicago.edu/~archer/spongebob_arctic/supp_fig3a.movie)  
2095 .gif and  
2096 [http://geosci.uchicago.edu/~archer/spongebob\\_arctic/supp\\_fig3b.movie](http://geosci.uchicago.edu/~archer/spongebob_arctic/supp_fig3b.movie)  
2097 .gif

2098 Supplemental Figure 4. Time scale of depleting the salinity of the  
2099 continental shelf sediment column after an instantaneous sea level drop

2100 of 30 meters. The effect of lateral canyons is to provide a pathway for  
2101 saline fluid to be replaced by fresh groundwater in sediments above sea  
2102 level. If the lateral canyon spacing is 10 km, they can have a significant  
2103 impact on the time constant for ground water flushing. A more  
2104 conservative 100-km canyon is adopted for the rest of the simulations.

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