Biogeosciences Discuss., 11, C6019–C6026, 2014
www.biogeosciences-discuss.net/11/C6019/2014/

Biogeosciences
Discussions

Interactive comment on "A model of the methane cycle, permafrost, and hydrology of the Siberian continental margin" *by* D. Archer

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Received and published: 20 October 2014

The author has chosen a very important topic which definitely needs further thorough study. In this manuscript, a simple 2-D model of the passive continental margin is applied to simulate processes in the tectonically active environment of the Russian Arctic Shelves. The developed model considers a single latitudinal cross-section, employs greatly simplified physics assumptions and is eventually used to quantify methane emissions from the entire Siberian continental margin. I encourage the author to improve the model in order to consider the realistic tectonic settings and conduct a thorough sensitivity study, then re-submit their manuscript for possible publication in a later time.

Specific Comments:

»>First, the authors apply a model of the methane cycle in a passive sedimentary accretionary wedge to the entire Russian Arctic Shelves. The applied model is called SpongeBOB and it was developed "to simulate an accumulating passive continental margin, such as the east coast of the United States, which has been accumulating sediment since rifting of the Atlantic about 200 million yr ago (Archer et al., 2012)." Despite some modifications to simulate salt and temperature dynamics, the employed model is still far from realistic representation of physical processes occurring in the Russian Arctic Shelves.

The tectonic history of the Russian Arctic is completely different from the tectonic environment of the east cost of the United States. In the applied model, after the initial model spin-up, the sedimentary cover is about 8-10 km thick. A quick look at the "International Tectonic Map of the Arctic at 1:5M scale – TeMAr-5000" (http://www.vsegei.ru/en/intcooperation/temar-5000/index.php) reveals some regions with a considerable sedimentary cover, depicts no uniform coverage across the shelves. Note that the sedimentary cover at significant areas of the shelf is thinner than 1-2 km. The deep sedimentary basins at the shallow parts of the Shelves are formed by the active rifting processes, not by the passive sediment accumulation. For example, the above-mentioned tectonic map as well as research e.g. by Drachev et al., (2010), and Shephard et al., (2013) illustrates a reach tectonic history of the Arctic. Thus applying a simple 2-D model of the accumulating passive margin to the Russian Arctic Shelves is simply erroneous.

The Laptev Sea Region consists of the series of wide extensional horsts and narrow grabens (eg. Drachev, Franke, Sekretov). It is believed that the warm and moist climate of Paleocene facilitated the weathering of horsts and transportation of sediments to grabens. Oligocene was marked by the global climate cooling that resulted in deposition of coal-bearing sediments, which are now buried by about 200-400 meter of sediments in near-coastal areas Grinenko et al. [1989]. The active tectonic processes responsible for the horst and graben development as well as for the formation of the coal bearing deposits are not considered in the present model. Moreover, Drachev et al. (2010), provide an in-depth review of the gas-prone and oil-prone source rocks, their age and possible distribution across the Laptev, East Siberian and Russian Chukchi Sea. The impact of these sediments and the rifting processes must be considered in order to obtain a more realistic picture of the methane cycle in the Russian Arctic Shelves. The simple 2-D model is too simple to account for the realistic description of the tectonic processes on the Arctic shelf. On page 7865, the author states "The sediment cover on the horsts is much thicker than it is in the grabens." An opposite statement is generally true, please review Drachev et al. (2010).

»»Water pump mechanism. It is a belief of the present reviewer that the proposed model is neither verified or validated to simulate the large scale freshening of the Arctic Shelves. The developed model is also too general in the underlying assumptions. Pockets of soil with anomalous salinity are possible and would complicate any generalization of seabed soil salinity. For example, in an evaluation of well-logs from oil fields on the North Slope of Alaska, Collett and Bird [1993] showed that the ice-bearing permafrost has numerous vertical discontinuities, marked by horizons in which ice content is greatly diminished or absent. The most prominent horizon lays between 50 and 250 meters below the ground surface and is laterally continuous over an area of at least 1000 km2. According to the well-logs, the ground temperature within this horizon is -8°C, and thus the pore water salinity was calculated to be at least 130 g/L. These brines are thought to be formed below the freezing front as it advances downward during glacial cycles, and finally trapped above a low permeability, clay-rich sedimentary sequence.

The SpongeBob model only considers a freshening action by the large hydrologic scale flow, when the sea level was low, but excluding salt diffusion, salt fingering and buoyancy-driven flows, when the sea level is high (or at least I could not find the mentioning a potential impact of these processes in the manuscript). The omitted processes can be important on the geological scale, however the author simply ignores

them. It must be emphasized that an extensive validation of the "fresh water pump" mechanism is necessary. Although the author cites Post et al., 2013 "Offshore fresh groundwater reserves as a global phenomenon" most of the vast meteoric groundwater reserves are shown to be located in temperate climate. The Mackenzie basin site may have some ground freshening according to Post et al., 2013, however Post et al., 2013 also states that the connection of the Mackenzie basin to the onshore water supply is unclear. The other cited research in (Post et al., 2013) was conducted offshore of Norway and indicated that there was some freshening at depths of 1000-1500 meters below the sea level, but the connection of the reported water freshening with the terrestrial water supply is unclear. Therefore, there is no single validated example of the ground water freshening in the Arctic Ocean.

The author greatly simplifies the "general process by subjecting the nearly complete sediment column to a one-time sea level lowering". The Oligocene global climate cooling contributed to formation of the ice sheets in Antarctica [Bowen, 2007] and the associated ocean regression 30-33 Mya [Patyk-Kara and Laukhin, 1986; Miller et al., 2011]. The regression was followed by a Oligocene-Miocene ocean transgression and then by a series of rapid sea-level changes in the Pliocene and Quaternary periods. During these periods, an almost continuous widespread horizontal cover of sediments several tens to several hundreds of meters thick formed over the present-day Laptev Sea shelf [Drachev et al., 1998]. A study of the sedimentary cover in the North American Arctic by Blasco et al. [1990]; Blasco [1995], reveal layering of marine and continental sediments in the Canadian Beaufort Shelf. The layers are identified within a 467-meter deep borehole near the Mackenzie River Delta. The data extracted from core samples show eight distinct regressive/transgressive fluvial sand/marine mud cycles e.g. Osterkamp [2001]. This findings reveal that the geologic shelf can be a very complicated environment with periodic marine transgression (salt diffusion into the upper horizons), ocean regression (salt exclusion due to shelf freezing) The effect of the fresh water pump needs to be further verified, as well as the salt transport needs to be better described. However, a problem is a model parameterization, that is a huge unknown in all quantitative studies.

»»>Modeling permafrost dynamics: Modeling the temperature and permafrost dynamics is completed with an ad-hoc approach. No references are provided whether or not this approach works. It looks like that the author is proposing to use a kinetic approach to model the rate of the ice production, i.e. the mass of ice production is proportional to the difference in the Gibbs free energy of ice and liquid water. The author mentions that the permafrost dynamics is important in estimation of the methane dynamics, but no validation of this method is provided. Moreover, on page 7864, line 24, the author states "in the model, this effect was simulated by stopping gas transport completely when a grid cell exceeds 50% ice fraction." This statement needs further justification, or at least the sensitivity analysis of the modeling results with respect to the major parameters. No mentioning of the geothermal heat flux, however it is known that it is a primary controlling factor to the permafrost dynamics.

Overall, the permafrost modeling fails the test of reproducibility. So little detail is provided that it is difficult to determine exactly what was done; the modeling is also simpler in many ways than work previously done in (Archer et al., 2012). The presented modeling is entirely deterministic and oversimplifies the reality. It is not enough to say what was assumed for a given parameter. There has to be easy-to-follow justification for the assumptions.

»»>If one is going to develop a highly deterministic model like this one, it would be helpful to close out the paper by comparing the results with constraints from field data. The authors claim that they are consistent with observations by Kort et al., (2012). However, Archer's estimate is an order of magnitude smaller than the estimate by Kort et al., (2012). Archer also states that according to Kort et al., (2012) "the total atmospheric methane flux from the Siberian margin is a small fraction of the global flux of methane to the atmosphere, and thus represents only a minor climate forcing." However, (Kort et al., 2012) "suggest that the surface waters of the Arctic Ocean represent a potentially important source of methane, which could prove sensitive to changes in

sea-ice cover". Therefore, it is not clear how Archer draws his conclusions. Moreover, comparing the global scale modeling results with data collected during five field seasons is not methodologically correct. What if in the next field expedition some other significantly different values of the methane flux are obtained. Climate, temporal and spatial variability of the methane flux from the five flights over is merely not enough to draw this far-reaching statement as in the manuscript.

It has been shown by multi-year observations that the current atmospheric venting methane flux from the Russian Arctic Shelves sediments is an important source of methane. The diffusive component is on par with previous estimates from methane venting from the entire World Ocean (Shakhova et al., 2010), while including ebullition component that estimation is increased at least twice (Shakhova et al., 2014). The proposed model is merely not capable to reproduce the vastly heterogeneous environment currently present on the shelf and thus is not capable to provide any reliable estimations of the methane flux.

»»>** I cannot emphasize this too much** » There is almost no sensitivity analysis « In highly deterministic models like this one, it is important to determine which of the many assumptions play the greatest role in controlling the results. The paper does not provide the reader with fundamental insight about physical processes. The earlier modeling paper by Archer et al., (2012) and Archer and Buffet (2012) in BG did a much better job presenting results.

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Interactive comment on Biogeosciences Discuss., 11, 7853, 2014.