ISSN 1028-334X, Doklady Earth Sciences, 2013, Vol. 449, Part 1, pp. 346–348. © Pleiades Publishing, Ltd., 2013.
Original Russian Text © S.N. Denisov, M.M. Arzhanov, A.V. Eliseev, I.I. Mokhov, 2013, published in Doklady Akademii Nauk, 2013, Vol. 449, No. 2, pp. 219–222.

GEOPHYSICS

Assessments of Stability of Methane Hydrates in the Lake Baikal System

S. N. Denisov, M. M. Arzhanov, A. V. Eliseev, and Corresponding Member of the RAS I. I. Mokhov

Received October 2, 2012

DOI: 10.1134/S1028334X13030112

Methane hydrates are widely spread in the permafrost regions and bottom sediment rocks of the ocean. The total reserves of carbon in the form of hydrates are estimated at 10^4 Gt C [1], which is one order of magnitude greater than its content in the atmosphere [2]. Large reserves of methane are also concentrated in the bottom deposits of hydrates in the largest inland reservoirs such as Lake Baikal and the Caspian Sea. In this paper we make assessments of the modern reserves of hydrates in the bottom sediments of Lake Baikal, their stability, and emissions of methane during dissociation of methane hydrates resulting from global warming.

The temperature increase during global warming facilitates destabilization and dissociation of aggregates of subaquatic hydrates and emissions of potentially large amounts of methane into the atmosphere. Such emissions can result in significant global and regional climatic consequences with accelerated dissociation of hydrates. Dissociation of methane hydrates could have been the cause of the rapid climatic changes in the past [3–5]. It is likely that significant temperature jumps during the last glacial period can be attributed to the sharp emissions of methane from methane hydrates [6].

The stability of hydrates in the bottom sediments of inland reservoirs depends on temperature and pressure. Hydrostatic pressure at the bottom in the locations of methane hydrates exceeds the pressure needed for the stability of hydrates at the temperature of the bottom water. Hydrates are usually not formed over the bottom owing to the insufficient concentration of methane. As the depth below the bottom increases, hydrostatic pressure and temperature increase linearly (in the equilibrium conditions), while the pressure needed for the stability of methane hydrates exponentially depends on temperature. Owing to this fact, the lower boundary of the stability zone exists. An increase in the bottom water temperature leads to a change in the temperature profile in the bottom sediments and to the corresponding displacement of the stability zone boundaries.

The bottom water temperature in Lake Baikal is currently approximately 3.5°C at depths exceeding 200 m [7]. The geothermal gradient is equal to 0.08°C/m (which is within the limits 0.06–0.1°C/m characteristic of Lake Baikal [8]; hence a hydrate stability zone (HSZ) should exist at present in the bottom sediments if the depth is greater than ~380 m). The thickness of the HSZ increases from ~20 m at a depth of 400 m to 180 m at a depth of 1600 m. If we assume that the porosity of the bottom sediments is 0.4 [8], we can use the data of the area of isobaths in Lake Baikal [9] and estimate similarly to [10] the modern volume of reserves of hydrates at approximately 52 km^3 of methane under standard conditions: 7×10^{12} m^3 (4 Gt C).

If the bottom temperature increases by 1°C, one can expect that the thickness of the HSZ would decrease at all depths on average by approximately 15 m, and the area of its spreading would decrease by approximately 5%. This would lead to a decrease in the reserves of methane in the hydrates by 14% up to 6×10^{12} m^3 (3.5 Gt C). The estimate of the amount of released methane (~0.5 Gt C) corresponds to a total methane emission into the atmosphere by all anthropogenic and natural sources over one year [11]. However, dissociation of hydrates corresponds to the spreading of the thermal wave in the bottom sediments and occurs quite slowly.

We carried out numerical experiments using the method for calculation of methane reserves in the bottom deposits of gas hydrates similarly to [10] to estimate the time intervals needed for the dissociation of hydrates. We specified the temperature gradient that corresponds to the equilibrium state at the geothermal flux equal to 0.09 W/m^2 characteristic of the deep water part of Lake Baikal as the initial condition for the model of bottom sediments [12]. We specified the thermal conductivity of bottom sediments according to [12], and the modern bottom water temperature was based on profile [7]. We calculated the thicknesses of HSZ for a period of 15 000 years at a temperature increase by 1°C (numerical experiment E1) and 3°C (experiment E2) relative to the modern bottom temperature as the upper boundary condition. The conductive thermal flux in the Baikal Depression varies in

---

Obukhov Institute of Atmospheric Physics, Russian Academy of Sciences, Pyzhevskii per. 3, Moscow, 109017 Russia
e-mail: mokhov@ifaran.ru

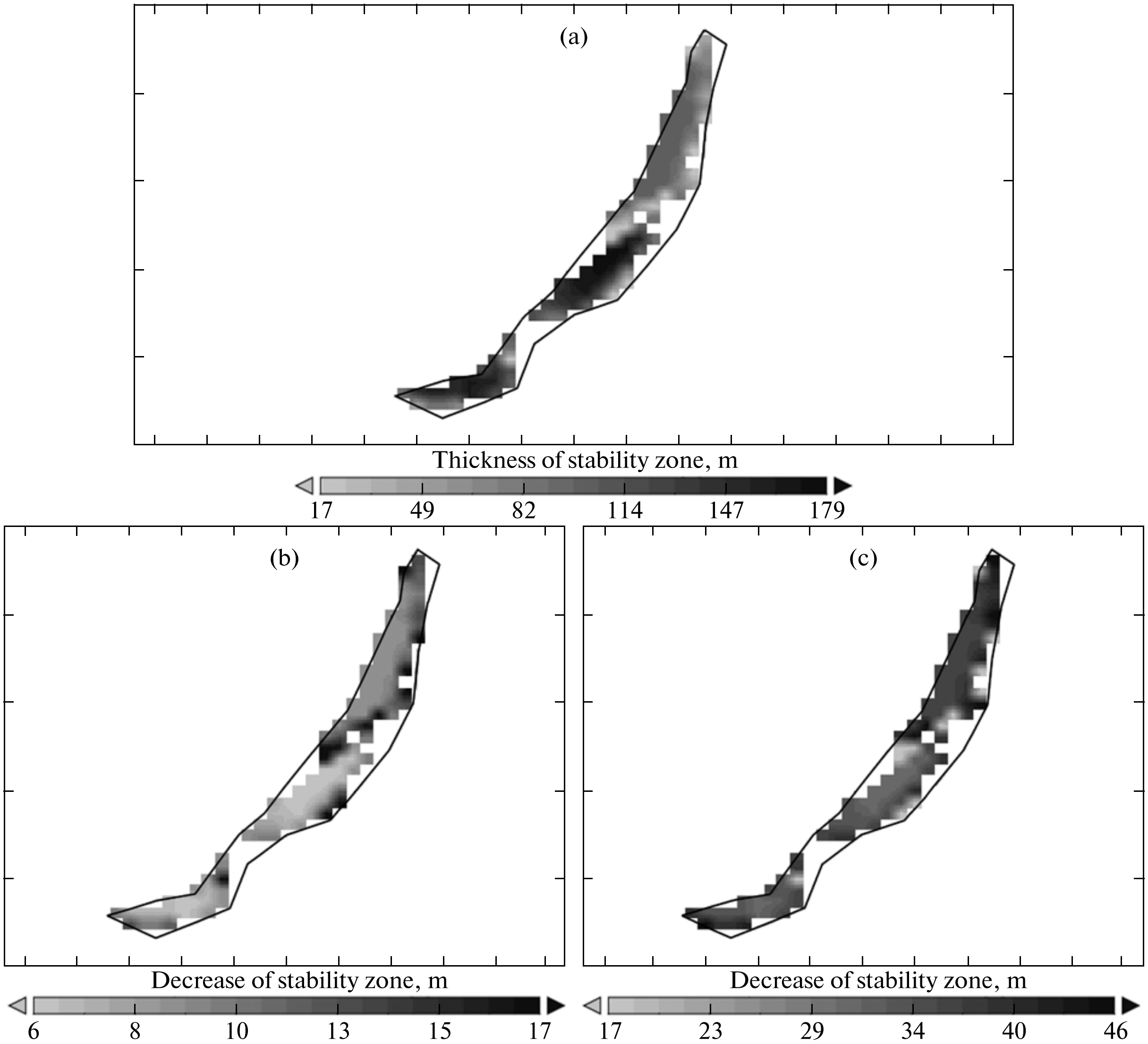

Fig. 1. Calculated thickness of the stability zone of hydrates in Lake Baikal under modern conditions (a) and its possible decrease if the bottom temperature increases by 1°C (b) and by 3°C (c).

wide limits from 0.05 to 0.12 W/m^2 [12]. Therefore, in order to estimate the sensitivity of the model, we carried out calculations with the geothermal flux equal to 0.07 W/m^2 (experiments E1_C and E_C) characteristic of the central part of the Baikal Depression [13].

According to the model calculations, the methane reserves in the deposits of gas hydrates in Lake Baikal based on experiments E1 and E2 are on the order of 60 km^3 of hydrates or more than 8000 km^3 of methane under standard conditions (approximately 5 Gt C). The difference between these estimates and those obtained earlier is related to accounting for the temperature gradient in the water column in the model and the small difference between the calculated and specified values of the geothermal gradient and spatial resolution (the model calculations were made using the latitudinal and longitudinal resolutions of 0.25° × 0.125°). In the modern conditions, the thickness of the HSZ based on the calculations is between 20 and 180 m depending on the depth of the lake (Fig. 1).

The HSZ thickness in numerical experiment E1 decreases by the end of the calculation period by 6–17 m depending on the depth, while in experiment E2 it decreases by 17–46 m. In this case, the reserves of gas hydrates decrease by 8% (up to 55 km^3) and by 32% (up to 40 km^3), respectively, with methane emissions in the approximate amounts of 0.4 and 1.6 Gt C, respectively.

Figure 2 characterizes the dynamics of HSZ shrinking based on the model calculations. More than half of the methane emissions in both experiments occur during the first thousand years. The average flux of methane during the first thousand years of calculation for the entire lake system of Lake Baikal is approximately 0.35 Mt CH_4 per year and 1.1 Mt CH_4 per year for experiments E1 and E2, respectively. The corresponding mean fluxes per unit area of the surface

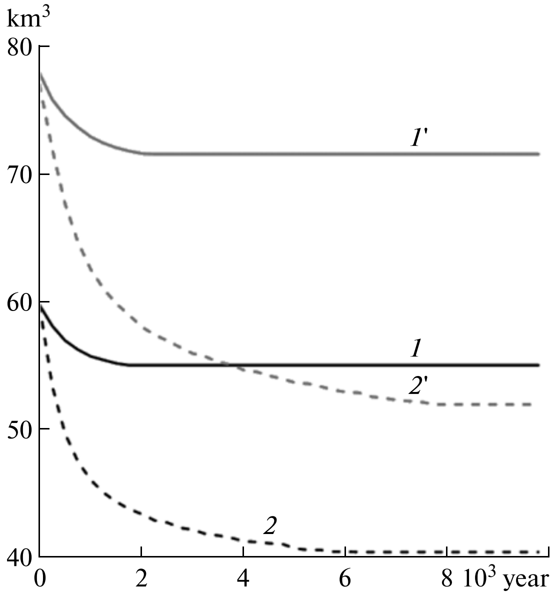

Fig. 2. Variations in the methane hydrate reserves in the system of Lake Baikal based on calculations for the condition of bottom temperature increase by 1°C (*1*, *1'*) and by 3°C (*2*, *2'*) in experiments E1 and E2 (*1*, *2*) and in experiments E1_C and E2_C (*1'*, *2'*).

of Lake Baikal are approximately 10 and 32 g CH_4 per year, which is comparable with the methane fluxes from the swamps in Western Siberia [14, 15] and exceeds by more than one order of magnitude the methane fluxes caused by dissociation of hydrates owing to the sedimentation in Lake Baikal (0.2–0.9 g CH_4 per year [8]). Later, the rate of HSZ degradation gradually decreases, and after 1.7–6 thousand years, experiments E1 and E2 reach a new equilibrium state.

The modern methane reserves based on experiments E1_C and E2_C are on the order of 78 km^3 of hydrates (greater by 30% than in experiments E1 and E2) or more than 10 000 km^3 of methane under standard conditions (approximately 6 Gt C). By the end of the calculation period, the methane reserves decrease in experiments E1_C and E2_C (similarly to E1 and E2) by 8% (up to 72 km^3) and by 33% (up to 52 km^3), respectively. In these experiments, the mean methane flux for the first thousand years of calculation compared to experiments E1 and E2 is greater; it is equal to 0.42 and 1.26 Mt CH_4 per year in experiments E1_C and E2_C, respectively. The new equilibrium state is reached later: after 2000 and 7500 model years. The obtained changes correspond to the sensitivity of the volume of gas hydrate reserves in Lake Baikal to the geothermal heat flux: approximately 1 km^3/(mW/m^2) (1.5% of reserves decrease per 1% of the geothermal flux increase).

It is noteworthy that when the stability zone decreases mainly from below, a significant part of methane cannot reach the bottom because it has to pass the stability zone of hydrates. In addition, the major part of methane that reached the surface dissolves in the water and does not spread into the atmosphere. However, many regions of methane emissions have been found in Lake Baikal including its deep-water parts with the height of the plume up to 950 m over the bottom [8], which indicates that there is a large methane flux from the bottom layers of the bottom sediments and its concentration near the bottom is high.

ACKNOWLEDGMENTS

This study was supported by the Russian Foundation for Basic Research, Programs of the Russian Academy of Sciences (74_OK/11-4), Programs of the Ministry of Education and Science of the Russian Federation (GK 11.519.11.5004, 16.525.11.5013, 21.519.11.5004, and 11.519.11.5006), and the President of the Russian Federation (grant no. NSh-5467.2012.5).

REFERENCES

1. K. A. Kvenvolden, Chem. Geol. **71**, 41–51 (1988).
2. *Climate Change 2001: The Scientific Basis*, Intergovernmental Panel on Climate Change, Ed. by J.T. Houghton, Y. Ding, D.J. Griggs, et al. (Cambridge Univ. Press, Cambridge, 2001).
3. G. R. Dickens, J. R. O'Neil, D. K. Rea, R. M. Owen, Paleoceanography **10**, 965–971 (1995).
4. I. I. Mokhov, V. A. Bezverkhnii, and A. A. Karpenko, Izv. RAN, Fiz. Atmos. Okeana **41** (5), 579-592 (2005) [Izv. Atmosph. Ocean. Phys. **41**, 523 (2005)].
5. G. S. Golytsyn, A. S. Ginzburg, Dokl. Akad. Nauk **413**, 816–821 (2007) [Dokl. Earth Sci. **413**, 487–490 (2007)].
6. H. Renssen, C. J. Beets, T. Fichefet, et al., Paleoceanography **19**, PA2010 (2004).
7. M. N. Shimaraev, R. Yu. Gnatovskii, V. V. Blinov, and V. G. Ivanov, Dokl. Akad. Nauk **438**, 121–124 (2011) [Dokl. Earth Sci. **438**, 652–654 (2011)].
8. N. G. Granin, S. I. Muyakshin, M. M. Makarov, et al., Geo-Mar. Lett. **32**, 453–464 (2012)
9. P. P. Sherstyankin, S. P. Alekseev, A. M. Abramov, et al., Dokl. Akad. Nauk **408**, 564–570 (2006) [Dokl. Earth Sci. **408**, 102–107 (2006)].
10. S. N. Denisov, M. M. Arzhanov, A. V. Eliseev, and I. I. Mokhov, Dokl. Akad. Nauk **441**, 685–688 (2011) [Dokl. Earth Sci. **441**, 1706–1710 (2011)].
11. J. Lelieveld, P. J. Crutzen, and F. J. Dentener, Tellus **50B** (2), 128–150 (1998).
12. A. Y. Golmshtik, A. D. Duchkov, D. R. Hutchinson, S. B. Khanukaev, Intern. Earth Sci. **89** (2), 193–211 (2000).
13. V. A. Golubev, Dokl. Akad. Nauk **433**, 684–688 (2010) [Dokl. Earth Sci. **433**, 1083–1088 (2010)].
14. S. N. Denisov, A. V. Eliseev, and I. I. Mokhov, Meteorologiya Gidrologiya, No. 2, 55–62, (2010).
15. H.-S. Kim, S. Maksyutov, M. V. Glagolev, et al., Environ. Res. Lett. **6** (3), 035201 (2011).