ISSN 1028-334X, Doklady Earth Sciences, 2012, Vol. 446, Part 1, pp. 1132–1137. © Pleiades Publishing, Ltd., 2012.
Original Russian Text © V.I. Sergienko, L.I. Lobkovskii, I.P. Semiletov, O.V. Dudarev, N.N. Dmitrievskii, N.E. Shakhova, N.N. Romanovskii, D.A. Kosmach, D.N. Nikol'skii, S.L. Nikiforov, A.S. Salomatin, R.A. Anan'ev, A.G. Roslyakov, A.N. Salyuk, V.V. Karnaukh, D.B. Chernykh, V.E. Tumskoi, V.I. Yusupov, A.V. Kurilenko, E.M. Chuvilin, B.A. Bukhanov, 2012, published in Doklady Akademii Nauk, 2012, Vol. 446, No. 3, pp. 330–335.

The Degradation of Submarine Permafrost and the Destruction of Hydrates on the Shelf of East Arctic Seas as a Potential Cause of the "Methane Catastrophe": Some Results of Integrated Studies in 2011

Academician V. I. Sergienko, Corresponding Member of the RAS L. I. Lobkovskii, I. P. Semiletov, O. V. Dudarev, N. N. Dmitrievskii, N. E. Shakhova, N. N. Romanovskii, D. A. Kosmach, D. N. Nikol'skii, S. L. Nikiforov, A. S. Salomatin, R. A. Anan'ev, A. G. Roslyakov, A. N. Salyuk, V. V. Karnaukh, D. B. Chernykh, V. E. Tumskoi, V. I. Yusupov, A. V. Kurilenko, E. M. Chuvilin, and B. A. Bukhanov

Received March 15, 2012

Abstract—On the basis of the analysis of published data and in the course of the authors' long-term geochemical and acoustic surveys performed in 1995–2011 on the East Siberian shelf (ESS) and aimed to research the role of the Arctic shelf in the processes of massive methane outbursts into the Earth's atmosphere, some crucially new results were obtained. A number of hypotheses were proposed concerning the qualitative and quantitative characterization of the scale of this phenomenon. The ESS is a powerful supplier of methane to the atmosphere owing to the continued degradation of the submarine permafrost, which causes the destruction of gas hydrates. The emission of methane in several areas of the ESS is massive to the extent that growth in the methane concentrations in the atmosphere to values capable of causing a considerable and even catastrophic warning on the Earth is possible. The seismic data were compared to those of the drilling from ice performed first by the authors in 2011 in the southeastern part of the Laptev Sea to a depth of 65 m from the ice surface. This made it possible to reveal some new factors explaining the observed massive methane bursts out of the bottom sediments.

DOI: 10.1134/S1028334X12080144

Several hypotheses have been proposed to understand the causes of drastic climate changes occurring on the Earth [1]. One of the hypotheses as such was advanced by Kenneth et al. and called the Clathrate Gun hypothesis. It consisted in the assumption that a variation in thermal conditions of bottom methane hydrates under a change of climatic epochs could cause massive methane outbursts into the Earth's atmosphere, which should, in turn, cause drastic climate changes and even biosphere collapse [2]. This hypothesis encountered difficulty at two points. First, the mechanism of bottom hydrate destabilization is not understood, for oceanic hydrates are known to remain stable within wide ranges of temperature and pressure. Second, the factors preventing oxidation of methane supplied into the water are not evident, in view of the fact that the primary condition to form oceanic hydrates is a water column over 700 m in depth.

On the other hand, concerning formation of the Earth's climate, the Arctic region was always considered exclusively as a cooler destined to start the thermohaline cycle of the World Ocean [1]. The possible role of the Arctic in the global carbon cycle and its contribution to the carbon dioxide effect were not even considered despite the fact that the soils and sediments in the Arctic region contain over 30% of the global resources of carbon, and the mobility of these resources is associated with the stability of long-year frozen masses (below the permafrost). This stability is determined by the thermal conditions of the climatic epoch (glacial or interglacial). Even the names of these epochs should point to the fact that a change in thermal conditions under the transition from a cool period to a warm epoch would affect the most sensible part of the geosphere, i.e., the cryosphere. The most pronounced variations in thermal conditions were traced precisely in the Arctic region, and the so-called atmo-

Presidium of the Far East Branch, RAS, Vladivostok, Russia
Ilichev Pacific Oceanological Institute Far East Branch, RAS, Vladivostok, Russia
International Arctic Research Center, University of Alaska Fairbanks, USA
Shirshov Institute of Oceanology, Russian Academy of Sciences, Moscow, Russia
Moscow State University, Moscow, Russia
Geophysical Institute, University of Alaska, Fairbanks, USA
Institute of Problems of Laser and Information Technologies, RAS, Troitsk, Moscow Oblast

spheric maximum of methane was registered in the atmosphere of the Arctic region just for interglacial epochs. It is manifested in the fact that the methane concentrations in the Arctic atmosphere are the highest in the world and exceed those for Antarctica by 10% on average.

All these facts came to the attention of specialists of the Far East Branch, Russian Academy of Sciences, which started in the early 1990s with studies of the greenhouse gas cycle in the Arctic region. The first noticeable results of these studies showed the role of Arctic lakes as perennial methane suppliers to the atmosphere and were published in 1996 and 1997 [3, 4]. Afterwards, the studies were concentrated on studies of the East Siberian Shelf (ESS). The latter is not only the broadest and shallowest shelf of the World Ocean, but also undergoes pronounced transformations under the change of climatic epochs [5, 6]. The shelf is also characterized by the location of over 80% of the existing submarine permafrost, as well as of the bulk of shallow-water gas hydrates [7].

The most distinctive characteristics of the Arctic compared to oceanic gas hydrates are the following: (1) high density of the spatial deposition; the thickness of the layer of pure gas hydrates may be as high as 100 m or more, unlike the oceanic hydrates occurring mainly in disseminated form, (2) the presence of deposits is more likely by several times at the Arctic shelf compared to the Arctic land, (3) the high interstitial saturation with gas hydrate (from 20 to 100% of the interstitial volume against 1–2% for oceanic gas hydrates), (4) the lower thermal capacity of the phase transition (a third of that for oceanic hydrates), and (5) high sensitivity to further warming, because of the profound changes in thermal conditions of the submarine permafrost proceeding as long as 5000–6000 years [5, 6].

In the course of the studies, the following hypotheses were tested. (1) The degradation of submarine permafrost results in the formation of gas-permeable channels within its structure, which causes methane emission from bottom deposits, as well as the growth of methane production in melted sediments. (2) The East Siberian shelf is a methane supplier to the atmosphere; its intensity should grow under the continued degradation of the submarine permafrost. (3) The degradation of submarine permafrost causes the degradation of gas hydrates, which determines a character of methane emission in several areas of the ESS. (4) Methane emission might be massive at several areas of the ESS, which does not exclude the potential growth of methane concentrations in the atmosphere to the levels sufficient to cause pronounced and even catastrophic global warming, as had already taken place in the remote past [2, 8].

Based on many years (2003–2010) studies it was shown that the ESS is a methane supplier to the atmosphere of the Arctic region, and its contribution is comparable to that of the whole World Ocean. It was also found that the methane emission amounted to 3 mg/(m^2 day), on average, over the main part of the ESS and to 13 mg/(m^2 day) in the aquatic area of local methane plumes. The area of the plumes as such is equal to ~10% of that of the ESS, whereas their contribution to the annual emission amounts to ~53%.

The primary task of the present project was to reveal the degree of degradation of submarine permafrost and associated gas hydrates, as well as to evaluate methane fluxes into the atmosphere. The latter might be performed on the basis of the determined methane potential of the ESS (the methane resource in the forms of hydrates, free gas, and the methane producible from the organic matter of thawing sediments), as well as including the transformation rates of this potential into the methane emission at present.

To obtain the required data, two large-scale expeditions over the shelf of East Arctic seas were performed in 2011 by Russian scientists in collaboration with the International Arctic Research Center (IARC) of the University of Alaska, Fairbanks, and the University of Georgia, Athens: the 45-day expedition on board the R/V *Akademik Lavrent'ev* and the first Russian–American ice expedition used core drilling to characterize the methane potential of the ESS (Figs. 1a, 1b). This report presents some of the results of these studies.

One of the most important results is the discovery of numerous and powerful methane outbursts to 700 nM concentration in the form of bubble streams (so-called plumes) in the depth range of 60–110 m where the surveys were formerly quite confined. The most pronounced thawing of the submarine permafrost was previously supposed precisely within this depth range [5], which should cause the formation of through gas-effluent channels [9]. In some oceanographic sections, a number of plumes over 100 m in diameter were joined into a multirooted enormous plume over 1000 m in diameter (Fig. 2), which exceeds greatly the dimensions of plumes registered formerly in the Sea of Okhotsk and in other areas of the World Ocean where the typical plume diameter usually varied from a few meters to tens of meters. The integrated hydroacoustic and geophysical surveys permitted us to identify the plume roots going deep into the 15- to 20-km layer of the ESS sediments, which are enriched in organic matter. It is interesting that the area of methane streams researched in 2011 lies in the zone of the Gakkel Ridge juncture to the Laptev Sea shelf, i.e., in an area of abnormally high seismotectonic activity. At the same time, the discovered methane cloud with the concentrations of dissolved methane to 900 nM and over 200 nautical miles in size within the depth range of 40–60 m in the East Siberian Sea [10] is not associated with intense seismotectonic activity. This fact requires additional integrated studies.

The other important result consists in the validation of seismic data by those of core drilling from the ice surface that we first performed in 2011 in the southeastern part of the Laptev Sea [11] to a depth of

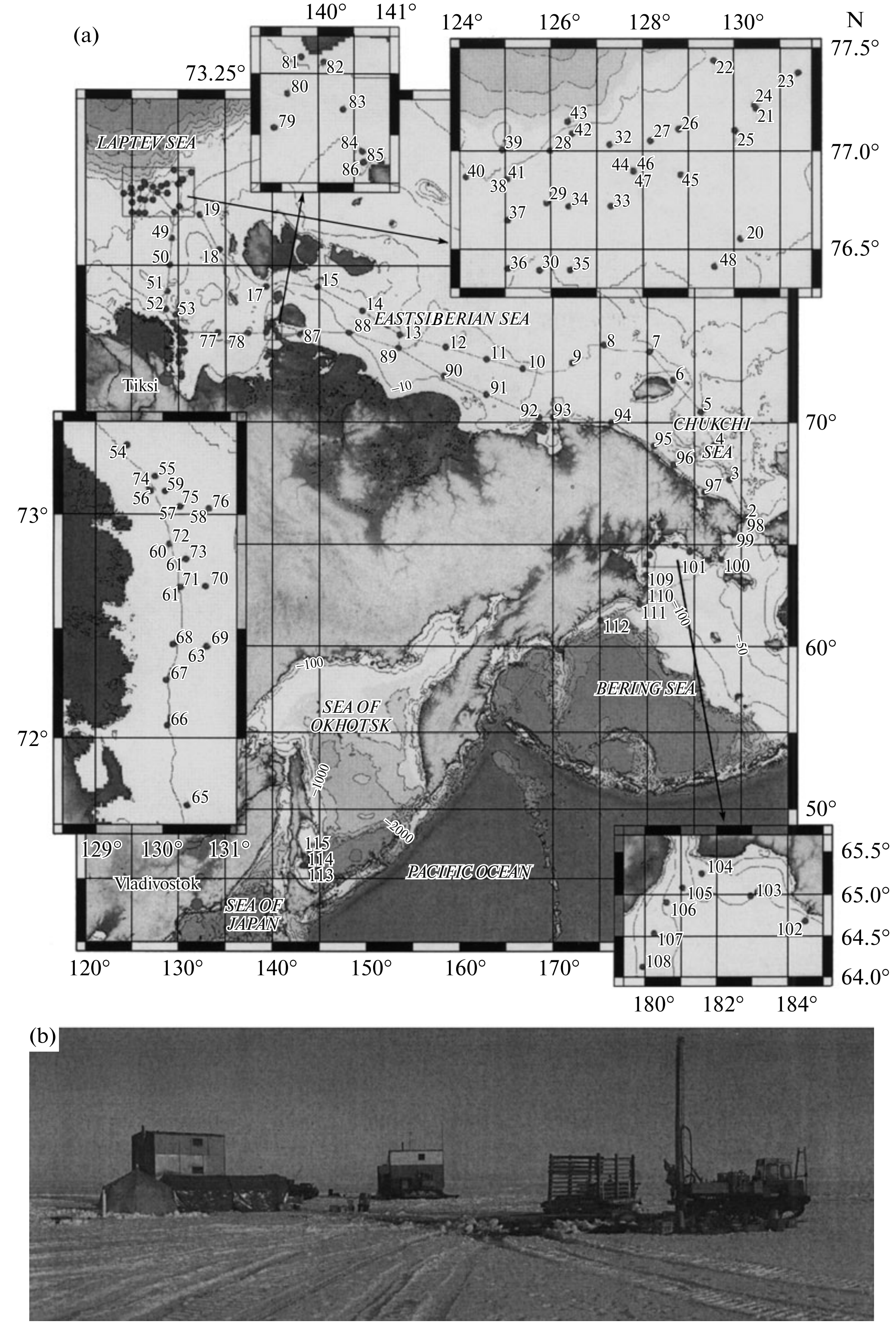

Fig. 1. Schematic map of the expedition on board the R/V *Akademik Lavrent'ev* in September–October of 2011 (a) and the drilling base of the first Russian–American winter expedition of 2011 in the Laptev Sea (b).

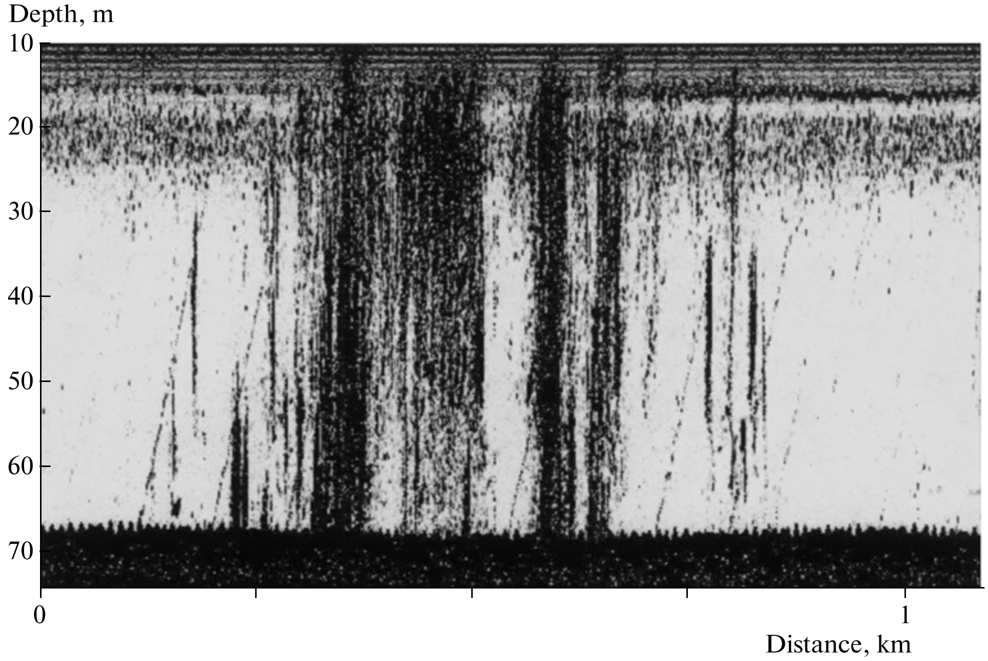

Fig. 2. One of 117 megaplumes discovered in the north of the Laptev Sea at the end of September 2011.

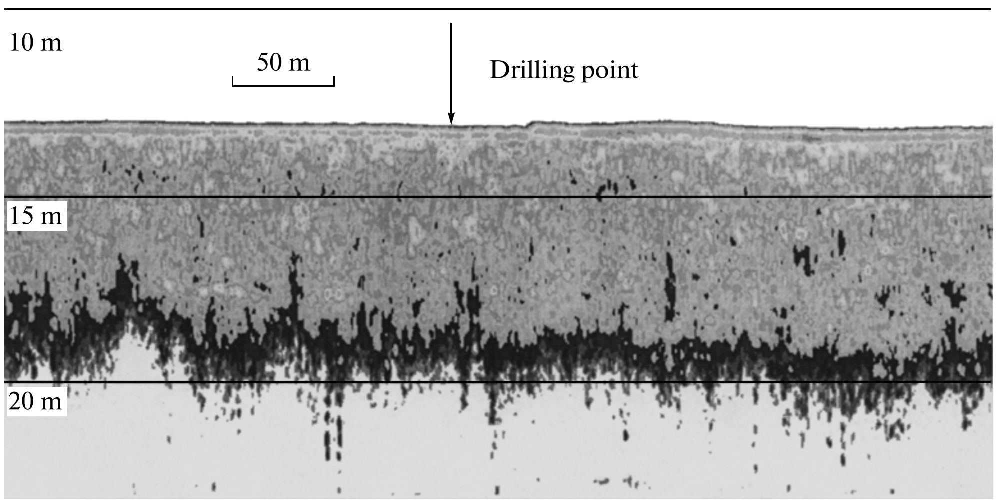

Fig. 3. A record by the high-resolution seismic profilograph obtained in the shallow part of the East Arctic sea shelf.

65 m under ice at a sea depth of 12 m. The comparison of drilling data to the obtained acoustic temporal section (Fig. 3) shows that the acoustic reflector, traced at a depth of about 5 m below the bottom surface and treated formerly as the roof of permafrost rocks, is really related to the lithological boundary between the Holocene silty–clayey oozes and their underlying alternation packet of sands and siltstones of the Upper Pleistocene. In this case, the shielding effect of this reflector upon the lower part of the section may be caused by a high gas concentration in sandy interlayers.

The first core hole we drilled in 2011 started up the studies aimed at geophysical mapping of the boundaries of submarine permafrost (with correction by new holes) and to evaluate the methane potential in typical areas of the East Arctic seas (the rift zones, the taliks of paleorivers and paleolakes, and the background areas).

It is significant that no submarine permafrost was found along the entire borehole to the sediment depth of 53 m. The minimum temperature of –0.9°C was registered in the upper layer of sediments in thermal equilibrium with the near-bottom water. Downwards through the core, the temperature increased to –0.3°C. The drilling point was selected in the zone of the Ust'-Lenskii rift about 30–40 km eastwards from the Byk-

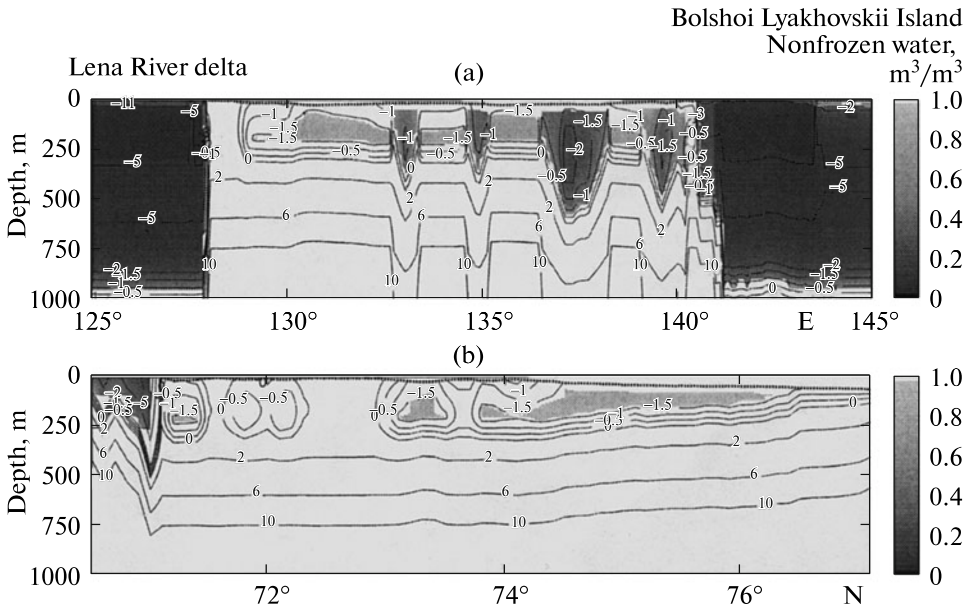

Fig. 4. The distribution of temperature (a) and the content of nonfrozen water (b) along the vertical section at 73.5° N from the Strait of Dmitrii Laptev (the East Siberian Sea) towards the Lena River delta (the Laptev Sea).

ovskaya channel of the Lena River where the thermal action of this river is pronounced.

Romanovskii [5] distinguishes two primary types of cryolite zones: those of the inner and outer parts of the shelf (the coastal shelf and the oceanic zone, respectively). Resulting from the modeling of the present conditions of submarine permafrost, Romanovskii concludes that the coastal shelf cryolite zone is stable to the isobath line of 50–70 m. At the same time, he considers the possibility of the appearance of though channels in rift zones. The other extreme viewpoint was expressed by Solov'ev et al. [7], who assumed the occurrence of insular (present and relict) submarine permafrost over the open part of the Laptev Sea. It is interesting that, by recent results of the modeling of submarine permafrost conditions including the salinity of sediments and the amount of nonfrozen water, on the basis of the approach by [8, 12] verified by the drilling data of 1980s, through channels and alternations of frozen and thawed rocks occur near the Lena River delta and in Dmitrii Laptev Strait (about 230–320 nautical miles from the delta). This seems to be necessary to explain the observed massive methane outburst from the bottom sediments (Fig. 2). The formation of through channels is most likely under the ancient thermokarstic lakes flooded during the Holocene transgression. As an illustration of recent modeling results obtained in the coastal shelf zone, Fig. 4 shows the distribution of temperature and nonrozen water content along the vertical section at 73.5° N from Dmitrii Laptev Strait toward the Lena River delta. The possible formation of a through channel in this area according to the modeling results is confirmed by [5, 7].

Note that the temperature of bottom sediments in the Dmitrii Laptev Strait increases to 3°C in summer owing to the wind-induced mixing of warm and desalinated waters of the Lena River flow to the bottom [13], which causes the formation of annual average temperatures of about 0°C for the near-bottom waters and permafrost in this area. Note that the submarine permafrost is naturally salinized to a degree that determines its thawing at negative temperatures (depending on the mineralization of sediments). Under the conditions of the observed abnormal warming of the East Siberian shelf, the acceleration of thawing of the upper layer of submarine permafrost and an increase of bottom erosion are inevitable. Their rates are projected to be studied by repeated drilling of the holes that were already being executed at the ESS in the 1970s–1980s. It is supposed that the present warming has already caused or might cause in the immediate future deepening of the shallow-lying roof of frozen masses, which is important for outflow of the gas (methane) front onto the surface. This front is often situated at depths of 3–6 m from the sediment surface and found everywhere in the East Arctic seas at depths to 40 m in high-resolution seismic profiles by the expeditions of 2008 and 2011. It is important to note that the existence of the acoustic gaseous (methane) front was first confirmed by the results of the analysis of the 53-m core obtained in 2011. We are planning the studies including repeated drilling for 2012–2014.

Moreover, the near-bottom water was sampled at the ESS to examine its chemical composition. This is required to reveal the intrusions of a deep fluid and/or of subpermafrost ground waters. The bottom sediments were also sampled to obtain the data on the stratigraphy, composition, and age of ancient organic matter and migrating deep-lying gases. This should allow us to know their genesis and to verify the geological history of the shelf of the East Arctic seas (the hard-to-get and therefore poorly explored northern area of Russia). These studies should preserve and strengthen the leading position of Russian scientists in the studies of the East Siberian shelf.

ACKNOWLEDGMENTS

The authors are grateful to Academicians N.P. Laverov and G.S. Golitsin, Academic Program 13(16), the Presidium of the Far East Branch of the Russian Academy of Sciences, the NSF and NOAA of the United States, the Knut and Alise Wallenberg Foundation, the IARC, and the Sweden Polar Research Secretariat for their long-term support of our studies. We are especially grateful to Academician V.Ya. Panchenko and to the Department of Targeted Basic Research of the Russian Foundation for Basic Research (project nos. 11-05-00781, 11-05-12021, 11-05-12027, 11-05-12028, 11-05-12032, 11-05-12026, and 11-05-12043) for their primary role in carrying out the present studies. Modern logistic provision of the studies would be impossible without the participation of the Scientific Agency for Marine Arctic Studies (E.N. Streletskaya).

REFERENCES

1. Intergovermental Panel on Climate Change (IPCC). The Scientific Basis. N. Y., Cambridge Univ. Press, 2007.
2. G. S. Golitsyn and A. S. Ginzburg, Doklady Earth Sciences **413A**, 487 (2007).
3. I. P. Semiletov, I. I. Pipko, N. Ya. Pivovarov, et al., Atmos. Environ. **30**, 1657–1671 (1996).
4. S. A. Zimov, Yu. V. Voropaev, I. P. Semiletov, et al., Science, No. 277, 800–802 (1997).
5. N. N. Romanovskii, A. A. Eliseeva, A. V. Gavrilov, et al., Kriosfera Zemli **10** (1), 29–38 (2006).
6. N. Shakhova, I. Semiletov, I. Leifer, et al., J. Geophys. Res., No. 115, C08007 (2010).
7. *Cryothermy and Natural Gas Hydrates in the Arctic Ocean,* V.A. Solov'eva, Ed. (Sevmorgeo, Leningrad, 1987) [in Russian].
8. N. E. Shakhova, D. Yu. Nikol'skii, and I. P. Semiletov, Doklady Earth Sciences **429A** (9), 1518–1521 (2009).
9. N. E. Shakhova, V. I. Sergienko, and I. P. Semiletov, Vestn. Ross. Akad. Nauk **79** (6), 507–518 (2009).
10. I. P. Semiletov and O. Gustafsson, EOS **90** (17), 145–146 (2009).
11. I. Semiletov, N. Shakhova, O. Dudarev, et al., First Drilling in the Ust' Lensky Rift Zone, Laptev Sea: Accomplishment and Preliminary Results. AGU Fall Meeting, GC51 (San Francisco, 2007).
12. D. Nicolsky and N. Shakhova, Environ. Res. Lett, No. 5, 015006 (2010).
13. I. P. Semiletov, N. E. Shakhova, V. I. Sergienko, et al., Environ. Res. Lett, No. 7, 015201 (2012).