ISSN 1019-3316, Herald of the Russian Academy of Sciences, 2009, Vol. 79, No. 3, pp. 237–246. © Pleiades Publishing, Ltd., 2009.
Original Russian Text © N.E. Shakhova, V.I. Sergienko, I.P. Semiletov, 2009, published in Vestnik Rossiiskoi Akademii Nauk, 2009, Vol. 79, No. 6, pp. 507–518.

Methane-containing sediments, accumulated everywhere along continental margins, are a powerful source of atmospheric methane, the third (after carbon dioxide and water vapors) most significant greenhouse gas. Meanwhile, until recently, scientific literature lacked data on the contribution of arctic continental margins to the formation of the global methane budget, as well as realistic forecast scenarios of future climate changes. The results of five-year-long (2003–2007) biogeochemical studies on the East Siberian shelf, which characterize the main arctic methane sources and reservoirs, including unique shelf gas hydrates, are presented in the article below. The studies were conducted by researchers of the Pacific Institute of Oceanology, RAS Far Eastern Division, with the participation of researchers of the International Arctic Research Center of the University of Alaska, Fairbanks.

DOI: 10.1134/S101933160903006X

The Contribution of the East Siberian Shelf to the Modern Methane Cycle

N. E. Shakhova, V. I. Sergienko, and I. P. Semiletov*

Far Eastern scientists began studying the methane land cycle on the basis of the East Siberian research station (village of Cherskii) of the Pacific Institute of Geography, RAS Far Eastern Division, in the 1990s. The all-season studies showed that Arctic water ecosystems actively participated in the carbon cycle by mobilizing fossil carbon buried in long-standing frozen strata and supplying methane to the Arctic atmosphere. The role of thermokarst lakes as suppliers of atmospheric methane was proved. Under these lakes, areas of melted sediments (unfrozen pockets) form with time, providing anaerobic conditions for methane production [1–3]. Lakes with such unfrozen pockets were attributed to sources of year-round methane atmospheric emissions because, in wintertime, methane can go to the atmosphere through the system of polynyas, built-up ice, and ice cracks. The achievements of Arctic microbiology in recent years also helped understand the processes of fossil carbon transformation and microbial methane production under conditions that were previously considered inadmissible for methanogenesis [4].

Hypothesis. On the basis of the initial findings, it was supposed that the all-round methane emission from the Arctic lakes could possibly contribute to the atmospheric methane maximum, recorded over the arctic–subarctic region exceptionally in interglacial epochs [5]. Further studies established that lake sources of this gas are insufficient to explain the stability of the methane winter maximum in the Arctic atmosphere because, in winter, the area of the lakes' open surface is incomparably smaller than the total area of the Arctic region and the gap between methane concentrations recorded in arctic and subarctic lakes is two to three orders of magnitude [3].

At the same time, attention was also paid to the fact that, in individual shallow regions of the East Siberian shelf, the concentration of methane in the surface water layer under ice is comparable with the concentration of this gas in large Arctic regions [3]. The regression–transgression model of the East Siberian shelf, which was developed by Russian permafrost scientists and is supposedly topical for the last four climatic cycles [6], showed that the huge area of the shelf had been land during glacial periods. As a result of subaerial freezing, the permafrost of mixed sea–land genesis was formed on this land; the structure of the permafrost could include methane of different geneses in the form of gas hydrates [7].

During warmings, structures of polygonal depressions developed on the permafrost surface (Fig. 1), which were typical of the initial stages of thermokarst; as for the subsequent stages, the formation of a broad network of thermokarst lakes was characteristic of them. The flooding of the East Siberian shelf owing to ocean transgression led to the submergence of the colossal areas of Arctic continental margins together with the existing depressions and lakes, as well as to the formation of thermokarst lagoons, characteristic features of the bottom relief, and the outlines of the East Siberian shelf (see Fig. 1).

After the transfer to the underwater state, the permafrost strata changed their thermal regime considerably:

*Natal'ya Evgen'evna Shakhova, Cand. Sci. (Med.), is a leading researcher at the Pacific Institute of Oceanology, RAS Far Eastern Division. Academician Valentin Ivanovich Sergienko is chair of the RAS Far Eastern Division. Igor' Petrovich Semiletov, Dr. Sci. (Geogr.), is a laboratory head at the Pacific Institute of Oceanology, RAS Far Eastern Division.

Fig. 1. Polygonal depressions: the initial thermokarst process (left) and the coastline relief with thermokarst lagoons (right).

stationary conditions were violated, and the subsequent transformation of the permafrost was targeted to reach a balance with the environment, which had become substantially warmer. Supposedly, the quasi-stationary state can be reached in 5000–10 000 years, depending on the duration of the previous period of freezing [8]. As a result of such transformation, the permafrost was degrading and turning insular and sporadic. However, already the first data on the methane content in East Siberian shelf waters made it possible to conclude that underwater permafrost was likely to degrade more actively than was admissible within the framework of mathematical modeling. The point is that anomalously high concentrations of methane were discovered everywhere on the shallow shelf [9–11], while, according to the modeling results, permafrost strata on the shallow part of the East Siberian shelf are stable, continuous, and impermeable for gas.

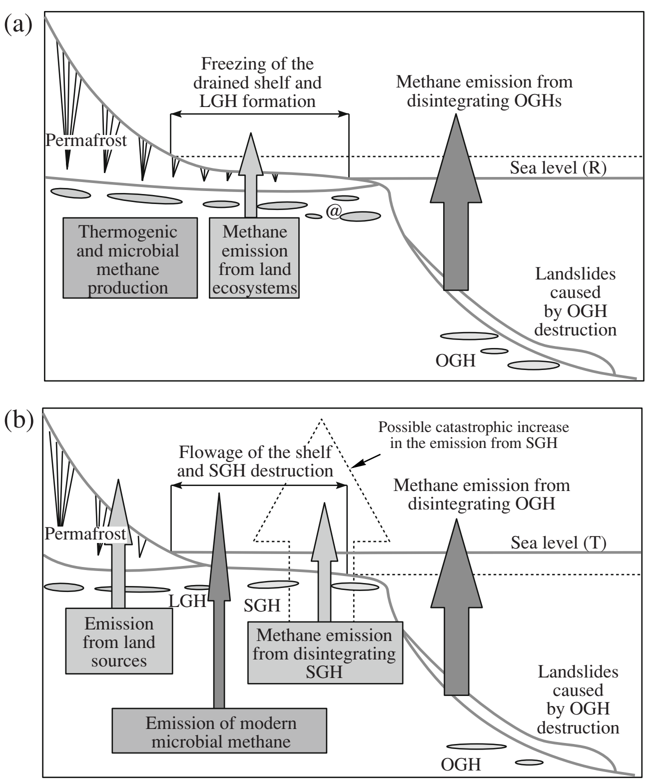

Fig. 2. Diagram of the cyclic transformation of methane sources on the East Siberian shelf depending on the climatic cycle. (a) Cold period, R is ocean regression; (b) warm period, T is ocean transgression; OGH, SGH, and LGH are oceanic, shelf, and land gas hydrates.

Obviously, the unique geographical position and geological background of this Arctic shelf favor the accumulation of a huge amount of deposits of a complex sea–land origin in its subsoil, as well as the creation of friendly conditions for methanogenesis. In cold epochs of climatic cycles, during ocean regression, the sedimentation masses of the East Siberian shelf outcrop and freeze epigenetically. Together with permafrost formation, conditions appear for the transformation of the methane synthesized in the sedimentation mass into land gas hydrates (LGH in Fig. 2a). In warm climate areas, the permafrost transfers to the underwater state and, thus, finds itself in nonstationary thermobaric conditions. Its further development is aimed at reaching the quasi-stationary state with the environment, the temperature of which is already 7–12°C higher. As a result, the permafrost temperature gradually grows, and balance is reached in the region of slightly negative temperatures, which border the points of phase transition "frozen salty deposits–warm salty deposits." However, the stability of gas hydrates, which, upon transferring to the underwater position, become shelf gas hydrates (SGH in Fig. 2b), is violated earlier than the permafrost begins to melt; as a result, an ascendant gas front is

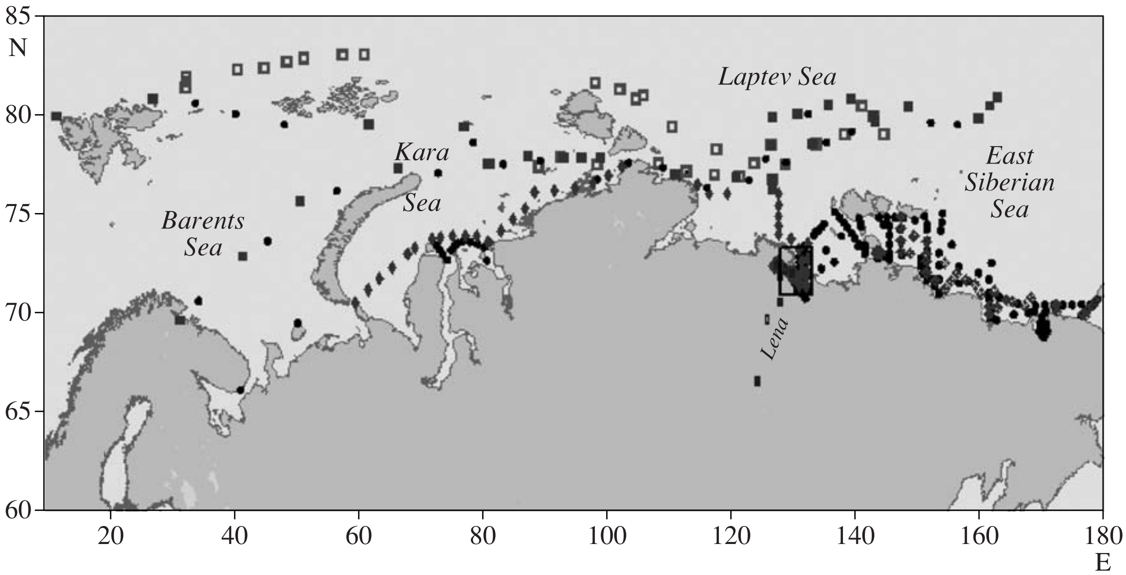

Fig. 3. Region of the biogeochemical studies on the East Siberian shelf in 2003–2007.
The signs show the locations of oceanographic stations and land measurements. The vessels *Moskovskii-11* (2003), *Ivan Kireev* (2003, 2004), *Auga* (2005), *TB-0012* (2006), *Kapitan Dranitsyn* (2006), and *Viktor Buinitskii* (2007) took part in the surveys.

formed. If continuous taliks form, the integrity of permafrost strata is violated, and conditions develop that allow methane to go through gas-conveying pathways into bottom water and then to the atmosphere.

Obviously, during "normal" warm climate cycles, the full degradation of the underwater permafrost is limited by time and/or total thermal impact on it; as a result, continuous taliks do not form on the larger part of the shallow shelf until the next climatic cooling. At present, when the natural climate cycle is obviously violated and warming continues, the degradation of frozen masses may become large-scale and even irreversible, which may lead to the mass destruction of the shelf gas hydrate stability zone and to a salvo emission of methane into water on the internal continental shelf (a depth of no less than 60 m). Since the East Siberian shelf is shallow and the emission of methane from the disintegrating hydrates may be in the form of a torch-like bubble emission, the probability of a subsequent emission of a considerable portion of methane to the atmosphere is very high. Taking into account that the methane potential of this shelf is colossal, the salvo emission of gas to the atmosphere may cause hardly predictable climatic consequences.

To confirm or reject this hypothesis, it is necessary to answer the following questions.

• What are the current scale and main characteristics of the methane emission on the East Siberian shelf?

• Does this emission affect considerably the concentration of atmospheric methane in the region?

• Are there proofs that bottom reservoirs of methane (gas hydrates and natural gas) are involved in the modern biogeochemical cycle?

• Can climate changes in the region cause an emission rate growth that could threaten the planet's climate?

Experimental data. A search for answers to the above questions was conducted during the 2003–2007 marine expeditions and land measurements from fast ice in the shallow part of the Laptev Sea in April 2007 (Fig. 3). More than 500 oceanographic stations were performed; more than 5000 water and bottom deposit samples were taken and analyzed; and the hydrologic and hydrochemical parameters of water, deposits' temperature, wind velocities and directions, and concentrations of methane and carbon dioxide in the water column and surface water atmospheric layer were measured. During a helicopter survey, the newest high-resolution analyzer DLT-100 was used (with a measurement frequency of up to 20 Hz and an error of no more than 0.02 ppm). The authors of this article processed the data statistically and graphically using the standard software application packages Statistics 6.0, Matlab 7.0, Grapher 6.0, and Surfer 8.0.

Since no areal measurements of dissolved methane had been conducted on the East Siberian shelf before our studies, in 2003 and 2004, we obtained primary data that made it possible to get an idea on the background concentrations of methane in the shelf waters and to single out areas with a high concentration of this gas. The measurements were carried out in the eastern part of the Laptev Sea and in the East Siberian Sea. Even the first results of the measurements were quite unexpected: the surface waters on a large part of the basin were supersaturated with methane, its concentration in individual regions reaching anomalously high values comparable with the concentration recorded in water areas where the destruction of oceanic gas hydrates took place [12].

The average content of methane in the surface layer was 10.5 nM and 14.4 nM, while in the bottom layer it was 13.5 nM and 15.5 nM in 2003 and 2004, respectively, reaching 440% supersaturation relative to the values equilibrium with the atmospheric concentration. At the same time, in Laptev Strait, the concentration of dissolved methane reached 154 nM, the concentrations in the bottom layer being practically the same as the surface ones, which, most likely, was due to the jet nature of the emission that helped methane avoid oxidation [10]. Since Laptev Strait is supposedly in the fracture zone, where, according to the mathematical modeling data, continuous taliks may form in the permafrost strata [7], it was decided to continue measurements with a focus on fracture zones.

In 2005, the expedition worked in the eastern part of the Laptev Sea and in the western part of the East Siberian Sea. We were especially interested in the regions near the Bel'kovsko-Svyatonosskii and Ust'-Lenskii fractures. On the shelf of the western end of Great Lyakhovsky Island, a high concentration of methane (138 nM) was recorded for the second time in both the bottom and surface layers. A high concentration of methane was discovered east of Great Lyakhovsky Island and near the coast in the vicinity of the Oyagosskii Yar, which are far from the above fractures. The highest concentration (reaching 520 nM, which is equivalent to 12 000% supersaturation relative to atmospheric concentrations) was discovered northeast of the estuary of the Lena River, whose main beds coincide with the position of the Ust'-Lenskii fracture. At the same time, we measured the concentrations of methane in the atmospheric surface layer. It was established that high concentrations of methane in the atmosphere (up to 8 ppm) correlate well with the high concentration of this gas in water. Thus, the conclusion that the source of air anomalies is the shelf was confirmed.

The findings made us consider the character of the source that supplies anomalously high concentrations of methane to the shelf waters. Methane can be supplied to the East Siberian shelf in two ways: from marine sources (production in situ or bottom reservoir discharge) and from land sources as a result of lateral transport by river waters. Methane sources involved in the modern biogeochemical cycle may be characterized according to the origin of methane and according to the type of the reservoir in question. As is known, methane in marine sediments may be of biogenic, thermogenic, and abiogenic origins. Biogenic methane is formed from the organic matter of the upper layer of bottom sediments under the following favorable conditions: a sufficient amount of available organic carbon, a suitable temperature and oxidation–reduction potential, and the absence of oxygen and competing oxidation–reduction processes [13]. Methane synthesized in deep sedimentary masses under the influence of high temperatures forms bottom reservoirs. On the East Siberian shelf, these are deposits of gas hydrates, as well as natural gas of normal reservoirs that accumulate methane ready for ascendant emission under the presence of respective gas-conducting routes and the absence of obstacles along them. Obviously, solid permafrost, impermeable for gases, is an insurmountable obstacle on the way of ascendant gas flows from bottom reservoirs.

To identify a methane source, it is necessary to use the most characteristic criteria typical of methane emissions from sources of different types. For example, biogenic methane is produced by methanogenic bacteria from the organic matter of bottom sediments at depths of 1 m or more. Consequently, biological production is possible only in the East Siberian shelf regions where the surface sediment layer either never freezes or defrosts in summer at a depth of no less than 1 m. Methanogenesis is characterized by the following: production areas correspond to the regions of the prevailing accumulation of deposits; and production velocities directly depend on sediment temperature, which inevitably manifests itself in seasonal variations of the concentration of dissolved methane. In addition, the distribution of the concentration in the water column depends on the velocity of the oxidation of dissolved methane under its diffuse transport to the surface of the water column and on hydrologic conditions.

In the regions adjacent to the Lena River estuary, biological production must be inevitable because the temperature of bottom sediments is never below 0°C even in winter. Nevertheless, the presence of clearly localized areas with anomalously high contents of methane under the sufficiently homogeneous distribution of lithologic, hydrochemical, and hydrologic parameters, as well as the significant excess of surface concentrations of methane relative to bottom concentrations may be determined by methane emissions from deep reservoirs. If there is no lateral transfer, such an inverse distribution of the methane concentration in the water column is uncharacteristic of biogenic methane sources.

In 2006, while differentiating methane sources, we, first of all, tried to find out the role of Siberian rivers that transport methane to the East Siberian shelf from the catchment regions. The lakes of the Kolyma–Indigirka Plains and the Primorskaya Lowland, which are enriched with methane that is formed in flooded landscapes and underlake taliks, may be a source of dissolved methane [2]. These lakes are linked with the rivers by channels and brooks. Previous studies showed that the content of dissolved methane in them might reach 360 μM [3]. Since methane transport by river waters takes place in aerobic conditions, a significant part of it undergoes oxidation. To determine the methane residuals that go to the shelf, we fulfilled measurements in one of the main channels of the Lena River, Bykovskaya. The maximum-recorded concentration of methane reached 120 nM there and decreased sharply

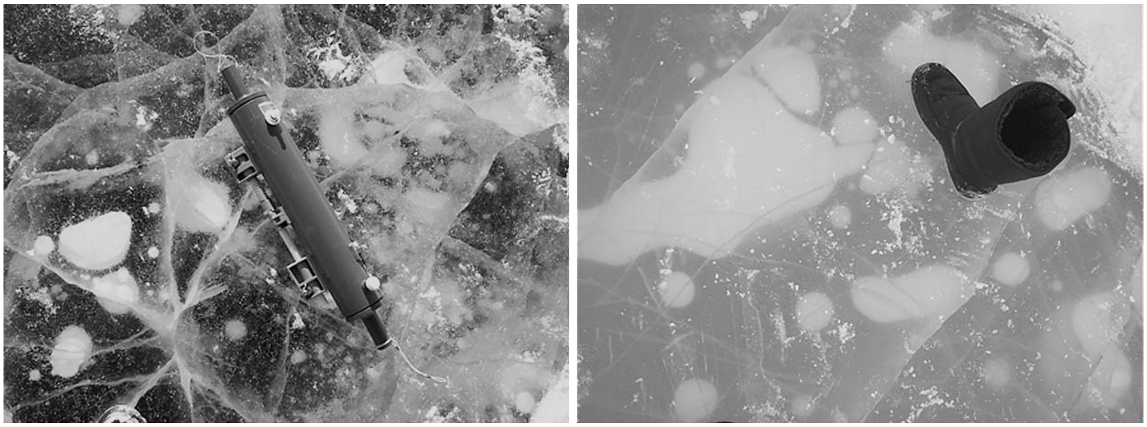

Fig. 4. Exterior of gas bubbles included in the ice composition.
The size of the bubbles may be evaluated by the length of the Niskin bathometer and a man's boot, size 13.

in the direction of the shelf. Thus, the conclusion was made that, although river waters do contribute to the formation of the near-estuary methane concentration, they leave room for another, more significant, source.

At the same time, the concentration of methane in the atmospheric ground layer was measured. The data were obtained through a helicopter survey, during which we were continually measuring the concentrations of methane, carbon dioxide, and water vapors. It was established that, in the water atmospheric layer at heights of 50–2000 m, the concentration of methane was approximately 10% higher than the average for these latitudes (1.85 ppm) [14]. Such an increase in the concentration of methane in air should be considered significant because an 8–10% difference between the concentrations of methane in the Antarctic and the Arctic is sufficient to record it as a phenomenon of the arctic methane maximum. It is noteworthy that the helicopter survey took place in late September, when deep fall convection and the massive discharge of methane to the atmosphere had already finished. Most probably, during the measurements, we managed to record a residual increase in the atmospheric concentration of methane.

To determine seasonal variations in the concentration of methane in the region adjacent to the Lena River estuary, we conducted a winter expedition on the Laptev Sea fast ice. The expedition obtained unique data that confirmed our assumptions concerning the possible emission of methane from a powerful deep source. The concentration of methane in the bottom water layer was 2.5 nM and 5 nM in the surface layer and eight to ten times exceeded the summer concentration. Numerous bubbles reaching 0.3 m in diameter, which were included in the ice structure (Fig. 4), testify to a powerful bubble emission, which, most probably, takes place year round and does not depend on the temperature and type of bottom sediments. Such emission may be observed under destruction of gas hydrates, a discharge of methane from the deposits of free gas, or a jet emission of gas from geofluid release zones. For example, an emission of methane in the form of colossal aggregations of bubbles, called torches, was discovered in the Sea of Okhotsk, where, along with methane releases, releases of methane gas hydrates to the surface were also recorded [12].

The bubble emission on the East Siberian shelf may be proved by an unexpected finding in September 2007. In the central part of the Laptev Sea, northwest of Kotelny Island, participants in the expedition on board the vessel *Viktor Buinitskii* discovered a gas torch analogous to those recorded in the Sea of Okhotsk in the zone of the supposed continuous underwater permafrost (Fig. 5). Taking into account that the finding was practically incidental, because the vessel echo sounder (with a frequency of about 30 kHz) had a very small beam width at these depths (no more than 10 m), and the chance to record such a torch was negligible, we can hardly exaggerate its significance. In the available literary sources, we found information on recording (based

Fig. 5. Methane torch recorded using an echo sounder in the central part of the Laptev Sea in September 2007.

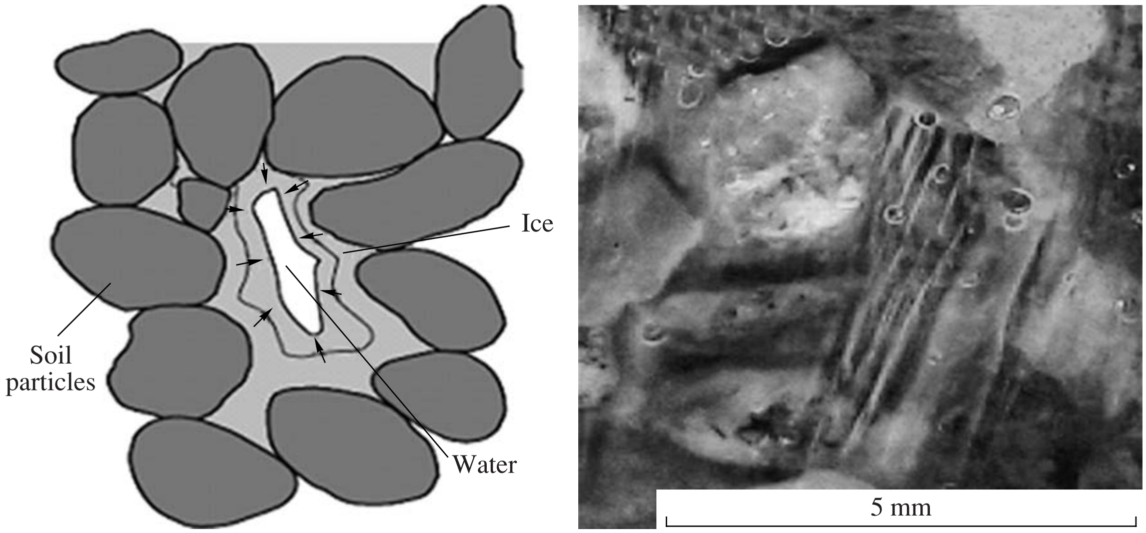

Fig. 6. Diagram of the formation of unfrozen water ductules in the frozen soil structure and a photo of the ductules, taken during the experiment.

on the profile shooting results) numerous cold methane jets in the central part of the Laptev Sea outside rift zones [15].

In our opinion, the emission of methane on the East Siberian shelf has characteristic features allowing for the possibility that not only modern biogenic methane but also methane from deep sources is released into the water. The larger part of the shelf territory is a source of methane in summer, keeping the emission to the region's atmosphere in the range from 2.6×10^4 to 39×10^4 g of CH_4/km^2. During the whole period of open water (90 days), the emission of methane may reach 4.5 Tg (1 Tg = 10^{12} g) [7]. The obtained quantitative assessments should be viewed as significantly underestimated because the calculations were performed on the basis of parameterizations applicable only to methane diffuse transport, which, under the conditions of a shallow shelf, may be no more than 5% in the transport structure; respectively, bubble transport, ignored in the calculations, may reach 95% [16]. In addition, it is necessary to take into account that, in individual regions of the East Siberian shelf, the discharge of methane into water in an anomalously high concentration takes place year round, including winter, which leads to the accumulation of methane under the ice, as well as to discharges to the atmosphere in the regions of coastal flaw polynyas occupying about 1% of the shelf's area, or 2.4×10^4 km^2. During the destruction of the ice sheet, a salvo emission of a considerable amount of methane to the atmosphere, comparable with its summer emission, is possible. Thus, the total emission of methane on the shelf may exceed 90 Tg, which is more than 16% of the annual global emission of methane to the atmosphere [17].

The discussion of the results. The modern state of permafrost strata on the East Siberian shelf may be assessed on the basis of the data of the mathematical modeling of permafrost transformation processes under changes in climatic cycles and, to a smaller degree, on the basis of experimental data. According to modeling, on the whole territory of the shelf, within isobathic lines of 60 to 70 m, the permafrost remains continuous, uninterrupted, and impermeable [18]. The exceptions are rift zones, where the formation of continuous taliks is possible at smaller depths. Meanwhile, the experimental data show that more than 80% of the area of the internal shallow shelf is a source of methane to the atmosphere.

Trying to explain this disagreement, we singled out three groups of factors that could tell on the modeling results if their impact was not fully accounted for.

Let us begin with *physical factors.* The mechanical properties of soils are influenced significantly by unfrozen water, the content of which depends on the soils' salinity, type, and temperature. Other conditions being equal, the temperature of the soils' initial freezing is determined by salinity. For example, it has been established that, at a 1% salinity, in the temperature range from –2.8 to –6.5°C, the content of unfrozen water increases by 22.3%; as a result, the temperature of the soil's initial freezing decreases down to –3°C [19]. According to the data of modern studies, under the freezing of definite types of salty soils (with a salinity of ≥2 g/l), unfrozen water accumulates in the center of the pore space, forming ductules in the structure of the frozen soil (Fig. 6) [20]. Together with air bubbles included in the composition of frozen rocks, the system of ductules of unfrozen water develops an original transport network, ensuring the movement of hydrocarbons inside the frozen soil (sandstone and gravel) on Barrow Point (Alaska) [21].

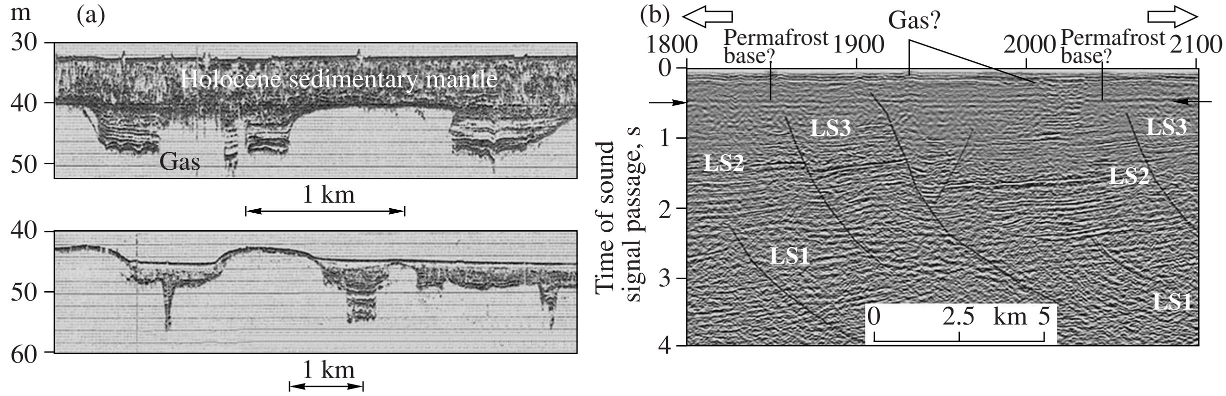

Fig. 7. Gas front formation and movement in the permafrost structure in two different sites of the shelf (a) [27] and the resultant breaks in permafrost continuity (b) [28].

Since the amplitude of annual temperature variations in Arctic regions is maximal, frozen soils are impacted destructively by respective compressions and spreads, which leads to local breaks in the continuity of frozen rocks and to the formation of a wide network of fractures and openings. This machinery explains the emergence of cuneate forms of ice formation, which are widely spread on the Arctic coast. From the point of view of the methane cycle, the possibility of an extensive network of cracks in the structure of frozen rocks means the presence of favorable conditions for forming routes of the migration of gases and gas-containing geofluids [22].

Let us now advert to the factors that can *destabilize underwater permafrost* and the associated *gas hydrates deposits.* Geologically, two categories of gas hydrate accumulations are isolated: oceanic and shelf. Oceanic ones have no analogues on the continents because they are syn- and diagenetic. Shelf hydrate accumulations (epigenetic and postaccumulation ones) are characteristic only of Arctic water areas and do not differ from hydrates located on the continents under the frozen zone [23]. In accordance with thermobaric conditions, the formation of the shelf gas hydrate stability zone necessarily takes place under the formation of permafrost rocks during the dewatering of the East Siberian shelf. This is favored, first, by a friendly condition of the gas hydrate-bearing capacity, which is determined by the multikilometer power of the sedimentary mantle, the relative stability of the basins, and the high share of organic carbon; and, second, by the ascendant migration of gas along fractures, as well as by enriching bottom deposits with diagenetic gas [8].

After the flooding of the continental margin during transgression, gas hydrates move to a nonstationary thermobaric situation because a sharp change in temperature conditions takes place: the temperature increases by 7–12°C. Such a change in temperature is a more significant factor than pressure growth owing to the rise of the water column [13]. As a result, the stability of gas hydrates is violated, and the upper border of the zone of their stability gradually shifts down [24]. Gas from the destructed gas hydrates accumulates between the lower border of permafrost and the upper border of the zone of gas hydrate stability [25]. A gas front is thus formed (Fig. 7a), i.e., a powerful accumulation of gas under pressure, which allows it to move both horizontally and vertically [25–27]. Under the influence of the high pressure of the ascendant gas front, the continuity of permafrost is violated and gas loss channels are formed (Fig. 7b) [28]. Following the gas loss and associated pressure changes, the frozen soil settles, which is recorded as endogenous seismicity; the latter, in turn, favors a release of additional amounts of gas [29].

It has been reliably established that the presence of rift zones is not necessary for the formation of wide regions of gas emission from disintegrating gas hydrates [25]. As a result of the lateral movement of the gas front, channels appear that allow gas to release in places where parallel resting deposits thin or their continuity is sharply violated, for example, on the slopes of underwater terraces, grabens, and ridges, as well as in hollows of thermokarst lakes. It is known that in the period that preceded the Holocene transgression of the sea, the shallow part of the East Siberian shelf, which was part of the land at that time, was affected by thermokarst processes more than the rest of the shelf. This led to the formation of numerous thermokarst lakes, in the hollows of which, after flooding, deposits with a thinned or even broken horizontal structure may form. River paleovalleys and other areas of sediment accumulation, where the horizontality of sediment layers is sharply abrupt, may play a similar role [26, 27]. In places where the mass is not lost but the pressure of gas-saturated water horizons reaches critical levels, structures resembling the structure of land permafrost, known as pingo, may form (Fig. 8) [30, 31]. Characteristically, such structures, widely spread in the relief of land permafrost, were first discovered in the bottom relief of the Laptev Sea more than ten years ago.

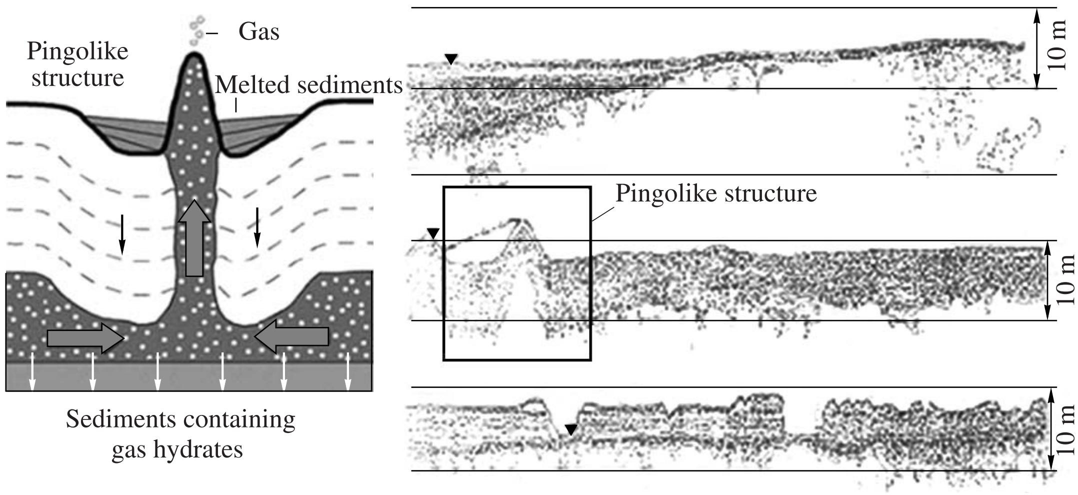

Fig. 8. The conceptual model of the formation of the pingo–gas-conveying collector for releasing methane from disintegrating gas hydrates [29] and a similar structure discovered in the Laptev Sea [31]. Seismoacoustic profiles shown in the figure were made in different parts of the shelf and in different periods.

As for *climatic factors*, Arctic regions, as is known, are subject to the influence of global climate changes to the greatest extent. It is established that, starting from 2007, the tendency towards the growth of atmospheric methane concentrations resumed both globally and in the Arctic regions (Fig. 9). In addition, according to the data of the US National Ocean and Atmosphere Administration (NOAA), average long-standing air temperatures over the Arctic have considerably increased over the past five years compared to the data of the 20th century. The sharpest growth (3–5°C) was recorded over the water area of the East Siberian shelf. Since its shallow part plays the role of the estuary of the great Siberian rivers, average annual water temperatures in the shelf's shallow regions differ significantly from those in deeper regions, reaching slightly positive values over quite wide territories [8].

An additional powerful warming impact on permafrost may be from the water horizons of its drainage system. Contacts with relatively warm waters of supra-, intra-, and subpermafrost horizons and their penetration into permafrost horizons accelerate the process of permafrost degradation [25]. Under such conditions, the structure and type of sediment, its density, the size of particles, and the degree of mineralization are of decisive importance because the position of the points of phase transitions from the permafrost state to the nonpermafrost state in sediments of different types may vary significantly, including in the region of slightly negative temperatures. The above information is reliably confirmed by the results of drilling on the East Siberian shelf, performed west of the Lena River estuary in a region distant from the influence of rift zones. In one of the core samples, obtained from bottom sediments at a distance of only 12 km from Cape Mamontov Klyk, starting from a depth of 10 m, the temperature of frozen deposits was from –1 to –1.4°C. Such a temperature corresponds to phase transitions of mineralized sediments into the nonpermafrost state; hence, melted deposits were discovered at a depth of up to 70 m [30]. Inside the permafrost, descendant taliks form additional channels that are permeable for ascendant gas and methane-bearing fluids. The horizons of the drainage system connect descendant and ascendant taliks into an integrated gas-conducting permafrost network.

Another factor of "anxiety" for the degrading permafrost is the earth's degassing processes, which are accompanied by a release of methane-bearing geofluids to the surface. It is believed that the release of geofluids takes place primarily in the zones where the continuity of the geological structure is destroyed, while release centers may be concentrated (under the influence of high geothermal gradients) or scattered (under the influence of low geothermal gradients). From the centers of the first type, the fluids are discharged through orifices of mud volcano, tectonic fractures, discontinuities in the anticline apex, and other disjunctives. From the centers of the second type, fluids are discharged through lithologic inhomogeneities (relatively more permeable layers), which may be drains for bordering deposits, as well as through pore and crack permeability [33].

The ratio of the concentrated centers to the scattered ones is determined by the ratio of the permeability of deposits in the massif to that in fluid-conducting zones. Occupying a small area, the centers of concentrated release collect a significant part of the total outflow of fluids. For example, in the Cascadia zone, such centers occupy only 0.2% of the total area but collect up to 60% of the total outflow of fluids [31]. On the East Siberian shelf, in the zones of fractures, regions of concentrated methane releases may form; through them, a massive discharge of methane from the ascendant gas front is

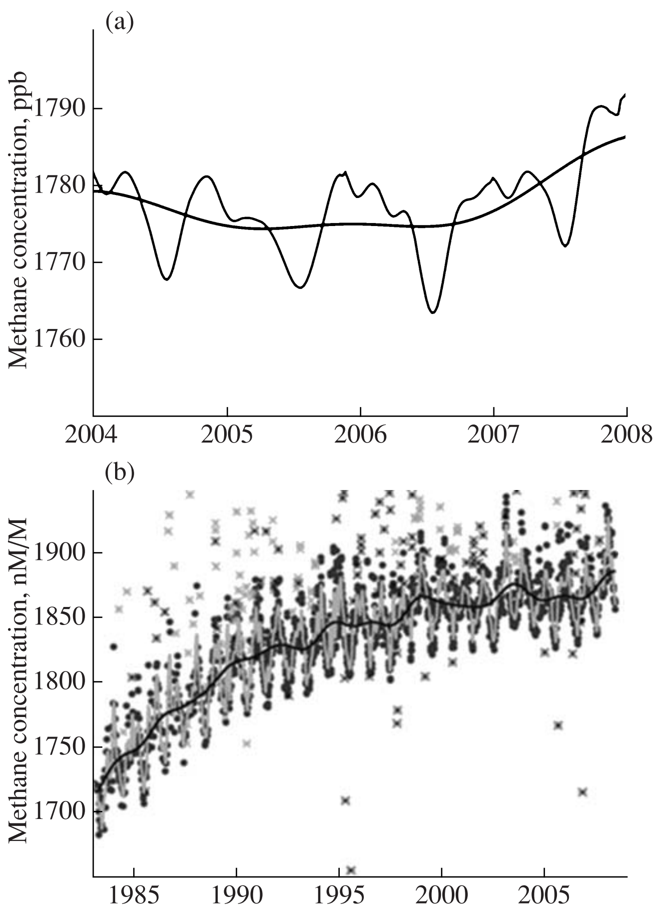

Fig. 9. Five-year dynamics of averaged concentrations of methane in the earth's atmosphere (a) and the long-standing dynamics of atmospheric methane in Arctic regions (from the example of the Barrow station in the United States) (b). Over the past several years, a tendency toward a significant growth of the average concentration of atmospheric methane, which was 1. 786 ppm in 2008, has been observed. In the Arctic regions of the world, the average concentration of atmospheric methane has also been tending to grow, the values of the average concentrations exceeding global ones and approximating 1.9 ppm.

possible. Most likely, a similar phenomenon was recorded near Bennett Island in the 1980s [34]. It is also possible that similar phenomena may repeat regularly and become catastrophic.

The history of our planet has known many climate changes. This led to catastrophic consequences for all flesh on the earth. Although the world scientific community has not come to a common opinion concerning the nature of such sudden climate changes, one of the existing hypotheses associates them with a possible salvo emission of methane from oceanic gas hydrates [35]. Until today, only one thesis of this hypothesis was open to criticism: oceanic gas hydrates form primarily at depths of 700–1300 m, and if methane is released under their destruction, its larger part dissolves in the water column and oxidizes before it reaches the water surface and, respectively, the atmosphere.

Shallow Arctic shelf gas hydrates have never been viewed as a possible alternative reservoir of disintegrating gas hydrates. Finding themselves in nonstationary thermobaric conditions after the flooding of the East Siberian shelf, they inevitably undergo destabilization and disintegrate, which leads to the accumulation of free gas under the underwater permafrost. The emission of gas to the upper layers of the geosphere is controlled by the state of the permafrost, which plays the role of a shutoff valve. Under normal development of climate cycles, the underwater permafrost, most likely, reaches the quasi-stationary state, remaining largely impermeable for ascendant gas. In this case, the contribution of the East Siberia shelf to the modern biogeochemical cycle will be minimal, while deep reservoirs of methane, including gas hydrates, remain practically isolated.

Our data show that, under modern conditions, the underwater permafrost of the shallow part (from 0 to 50 m) of the East Siberian shelf is likely to have stopped playing the role of a shutoff valve. To all appearances, this is due to the global climate changes and the breakdown of the climate cycle [36]. Taking into account that the amount of methane accumulated on the shelf in the form of gas hydrates alone is hundreds of times higher than the critical amount (10 Gt) that, according to [37], may initiate a catastrophic climate change on the planet, we should view further studies in this region as not only one of the most important scientific priorities but also as an element of national safety.

ACKNOWLEDGMENTS

We thank Academician G.S. Golitsyn for useful discussions and valuable recommendations.

This paper was supported by the Presidium of the RAS Far Eastern Division, the Russian Foundation for Basic Research (grants nos. 07-05-00050a and 08-05-00191a), the US National Scientific Foundation (OPP-0230455), and the US National Ocean and Atmosphere Administration (Cooperative Agreement NA17RJ1224).

REFERENCES

1. I. P. Semiletov, I. I. Pipko, N. Y. Pivovarov, et al., "Atmospheric Carbon Emission from North Asian Lakes: A Factor of Global Significance," Atmos. Environ. **30**, 1657–1671 (1996).
2. S. A. Zimov, Yu. V. Voropaev, I. P. Semiletov, et al., "North Siberian Lakes: A Methane Source Fueled by Pleistocene Carbon," Science **277**, 800–802 (1997).
3. I. P. Semiletov, "On Aquatic Sources and Sinks of CO2 and CH4 in the Polar Regions," J. Atm. Sci. **56** (2), 286–306 (1999).
4. E. M. Rivkina, G. N. Kraev, K. V. Krivushin, et al., "Methane in Permafrost of Northeastern Arctic," Cryosphere Earth **10**, 23–41 (2006).

5. I. Semiletov, N. Shakhova, V. Romanovsky, and I. I. Pipko, "Methane Climate Forcing and Methane Observations in the Siberian Arctic Land–Shelf System," World Resource Rev. **16**, 503–542 (2004).
6. N. N. Romanovskii and H.-W. Hubberten, "Results of Permafrost Modeling of the Lowlands and Shelf of the Laptev Sea Region, Russia," Permafrost Periglac. Processes **12**, 191–202 (2001).
7. N. N. Romanovskii, H.-W. Hubberten, A. V. Gavrilov, et al., "Offshore Permafrost and Gas Hydrate Stability Zone on the Shelf of East Siberian Seas," Geo–Mar. Lett. **25**, 167–182 (2005).
8. *Cryothermia and Natural Gas Hydrates in the Arctic Ocean*, Ed. by V. A. Solov'ev (Sevmorgeologiya, Leningrad, 1987) [in Russian].
9. N. E. Shakhova, I. P. Semiletov, A. N. Salyuk, et al., "Methane Anomalies in the Near-Water Atmospheric Layer above the East Siberian Arctic Shelf," Dokl. Akad. Nauk **414**, 819–823 (2007) [Dokl. Earth Sci. **415** (5), 764 (2007)].
10. N. E. Shakhova, I. P. Semiletov, and N. N. Bel'cheva, "Dissolved Methane in Shelf Waters of Arctic Seas," Dokl. Akad. Nauk **402**, 529–533 (2005).
11. N. E. Shakhova, I. P. Semiletov, and N. A. Bel'cheva, "The Great Siberian Rivers as a Source of Methane on the Russian Arctic Shelf," Dokl. Akad. Nauk **414**, 683–685 (2007) [Dokl. Earth Sci. **415** (5), 734 (2007)].
12. A. Obzhirov, R. Shakirov, A. Salyuk, et al., "Relations between Methane Venting, Geological Structure, and Seismo-Tectonics in the Okhotsk Sea," Geo–Mar. Lett. **24**, 135–139 (2004).
13. W. S. Reeburg, "Oceanic Methane Biogeochemistry," Chem. Rev. **107**, 486–513 (2007).
14. http://www.cmdl.noaa.gov/ccgg/insitu.html.
15. T. Schwenk, V. Spiess, H. Kassens, et al., AGU (2005) Abstract C31A–1112.
16. J. P. Chanton, C. S. Martens, and C. A. Kelley, "Gas Transport from Methane-Saturated Tidal Freshwater and Wetland Sediments," Limnol. Oceanogr. **34**, 807–819 (1989).
17. *IPCC, 2001: Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change* (Cambridge Univ. Press, Cambridge (UK), 2001).
18. A. V. Gavrilov, N. N. Romanovskii, H.-W. Hubberten, and V. E. Tumskoy, "Reconstruction of Ice Complex Remnants on the Eastern Siberian Arctic," Permafrost Periglac. Processes **14**, 187–198 (2003).
19. A. N. Khimenkov and A. V. Brushkov, *Introduction to Structural Cryology* (Nauka, Moscow, 2006) [in Russian].
20. L. U. Arenson and D. C. Sego, "The Effect of Salinity on the Freezing of Coarse-Grained Sands," Can. Geotech. J. **43**, 325–337 (2006).
21. K. McCarthy, L. Walker, and L. Vigoren, "Subsurface Fate of Spilled Petroleum Hydrocarbons in Continuous Permafrost," Cold Regions Sci. Technol. **38**, 43–54 (2004).
22. K. W. Biggar, S. Haidar, M. Nahir, and P. M. Jarrett, "Site Investigation of Fuel Spill Migration into Permafrost," ASCE J. Cold Regions Eng. **2**, 84–104 (1998).
23. Y. F. Makogon, S. A. Holditch, and T. Y. Makogon, "Natural Gas Hydrates: A Potential Energy Source for the 21st Century," J. Petroleum Sci. Engineering **56**, 14–31 (2007).
24. N. N. Romanovskii, H.-W. Hubberten, A. V. Gavrilov, et al., "Thermokarst and Land-Ocean Interaction, Laptev Sea Region, Russia," Permafrost Periglac. Processes **11**, 137–152 (2000).
25. G. Delisle, "Temporal Variability of Sub-Sea Permafrost and Gas Hydrate Occurrences as Function of Climate Change in the Laptev Sea, Siberia," Polarforchung **68**, 221–225 (2000).
26. L. Naudts, J. Greinert, and Yu. Artemov, et al., "Geological and Morphological Settings of 2778 Methane Seeps in the Dnepr Paleo-Delta, Northwestern Black Sea," Marine Geol. **227**, 177–199 (2006).
27. H. Kassens, S. Priamikov, V. Rachold, et al., http://www.arcus.org/annual_meetings/2006/downloads/presentations/af_friday/case_study_4_Heidmarie_ Kassdens.pdf.
28. B. Cramer and D. Franke, "Indications for an Active Petroleum System in the Laptev Sea, NE Siberia," J. Petroleum Geol. **28**, 369–384 (2005).
29. T. E. Osterkamp and W. D. Harrison, *Sub-Sea Permafrost: Probing, Thermal Regime, and Data Analyses, 1975–1981. Summary Report* (Geophys. Inst., Univ. of Alaska Fairbanks, 1985).
30. C. K. Paull, W. Ussler III, S. R. Dallimore, et al., "Origin of Pingo-Like Features on the Beaufort Sea Shelf and Their Possible Relationship to Decomposing Methane Gas Hydrates," Geophys. Res. Lett. **34**, 1–5 (2007).
31. V. P. Mel'nikov, V. I. Spesivtsev, and V. I. Kulikov, "On Jet Degassing of Hydrocarbons as a Source of New Ice Formation on the Shelf of the Pechora Sea," in *Results of Fundamental Studies of the Earth's Cryosphere in the Arctic and Subarctic Regions* (Nauka, Novosibirsk, 1997), pp. 259–269.
32. V. Rachold, D. Y. Bolshiyanov, M. N. Grigoriev, et al., "Nearshore Arctic Subsea Permafrost in Transition," Eos **88**, 149–156 (2007).
33. G. D. Ginsburg and V. A. Solov'ev, *Submarine Gas Hydrates* (VNIIOkeangeologiya, St. Petersburg, 1994) [in Russian].
34. J. W. Clarke, P. St. Amand, and M. Matson, "Possible Cause of Plumes from Bennett Islands, Soviet Far Arctic," AAPG Bull., No. 70, 574 (1986).
35. J. P. Kennett, K. G. Cannariato, I. L. Hendy, and R. J. Behl, *Methane Hydrates in Quaternary Climate Change* (AGU, Washington, 2003).
36. R. B. Alley, J. Marotzke, W. D. Nordhaus, et al., "Abrupt Climate Change," Science **299**, 2005–2010 (2003).
37. D. E. Archer and B. Buffett, "Time-Dependent Response of the Global Ocean Clathrate Reservoir to Climatic and Anthropogenic Forcing," Geochem., Geophys., Geosys. **6** (3) (2005).