Modeling of subsea permafrost related methane emissions in the East Siberian Arctic Shelf

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Valentina Malakhova (malax@sscc.ru) and Elena Golubeva (elen@ommfao.sscc.ru)

Institute of Computational Mathematics and Mathematical Geophysics SB RAS, Novosibirsk

The Arctic climate variability

Records of increasing temperatures, melting glaciers, reductions in extent and thickness of the sea ice, thawing permafrost, and a rising sea level all these factors provide strong evidence of recent warming in the Arctic. Evaluation of the linear trend mean air temperature of the Arctic Ocean for the period of 1936-2007 has revealed a statistically significant positive linear trend [1]. The thermal processes occurring in the Arctic Ocean and in the Arctic Seas have formed a unique thermal state of the surface layer of the ocean in the summer. The uniqueness of the formed thermal field of the surface layer in the Arctic Ocean in the summer of 2007 is especially well distinct when comparing it with the average climate field water temperatures derived from observations for 1950-1989 (Fig. 1). Over the past 30 years, the annual average sea-ice extent has decreased by about 8%, or nearly one million square kilometers, and the melting trend is accelerating.

MOTIVATION

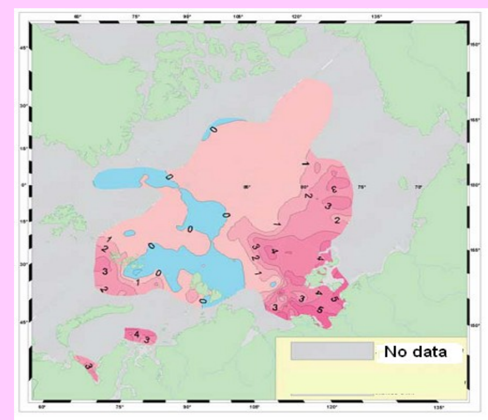


Fig.1 The average water temperature anomalies in the layer of 5-10 m in 2007 as related to the averaged the temperature for 1950-1989 years, [1]

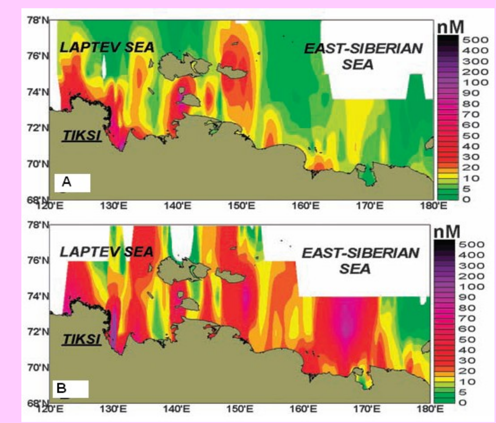


Fig.2. Dissolved methane concentrations in surface (A) and bottom (B) water

Methane in the Arctic

The extensive Arctic Shelf can play an important role in methane cycling because of a huge storage of organic matter buried in permafrost, which can be involved in the modern biogeochemical cycles subject to warming. The eastern Siberian shelf is underlain by the relic off-shore submarine permafrost in an environment that is favorable for the stability of gas hydrates [2, 3]. During the last glacial maximum, the global sea levels fell by over a hundred meters, with a result that the shallow seas of the ESAS became a dry land, which allowed the permafrost to develop there.

The dissolved methane concentrations in the East Siberian Arctic Shelf (ESAS) water during the summers of 2003 to 2008 show a widespread supersaturation over large spatial scales [4,5] (Fig.2). The horizontal and vertical methane distributions in the observational data indicate to a sedimentary source which is likely to be associated with thawing of the underwater permafrost and release of gas from the shallow Arctic gas hydrate.

STUDY AREA

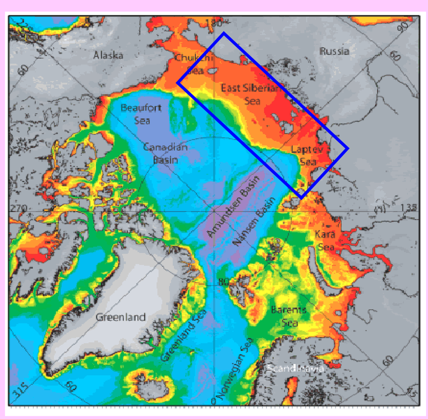


Fig.3. Study area—ESAS

The eastern Siberian shelf, consisting of the Laptev and the East Siberian Seas, represents the shallowest and broadest shelf region (Fig. 3). The ESAS is 2.1×10^6 km^2 area (~25% of the Arctic Shelf, ~ 8% of the total area of the World Ocean's continental shelf), 80% of the total area of the subsea permafrost is in the ESAS.

OUR OBJECTIVES:

- Simulate the variability of the Arctic Ocean water masses state for the period from 1948 to 2011 in order to examine modern trends of the bottom layer hydrography associated with climatic changes
- Examine the stability of the ESAS submarine permafrost
- Simulate the dissolved methane transport from the bottom reservoirs in the shelf water
- Estimate the total methane emission to the atmosphere in the area under study

METHODS

Coupled Ice-Ocean Model
3D World Ocean Circulation Model of ICM MG based on z-level vertical coordinate approach [6]

Conservation laws for heat, salt and momentum with Boussinesq, hydrostatic and 'rigid lid' approximations
Separation of external and internal modes in the momentum equations
Barotropic momentum equations are expressed in term of stream function
QUICKEST is used in the latest model version for T-S advection.
Two versions of mixed layer parameterization:
- Vertical adjustment based on the Richardson number
- Vertical diffusion coefficient based on the stable solution of turbulent energy equation

Ice model-CICE 3.0 (elastic-viscous-plastic)

The Los Alamos Sea Ice Model, http://oceans11.lanl/gov/trac/CICE

The model grid

The model grid has 1x1 degree resolution in the North Atlantic. At 65N, the North Atlantic spherical coordinate grid is merged with the polar grid, resulting from the spherical coordinate rotation and reprojection of its hemisphere onto the area above 65N. The horizontal spacing in the polar grid varies from 50 to 34 km. Maximum model resolution is in the vicinity of the North Pole. Vertically, the grid has 33 constant layers, with a higher resolution near to the surface.

Thermal model of the bottom sedimentary layer IAP RAS, [7]

Mathematical modeling was applied in order to study the distribution and thickness of the relic offshore permafrost. The core of the permafrost dynamical model used in this study is based on [7]. The geothermal heat flux at the low boundary of frozen sediments was set as 60-100 mW/m^2 [2, 3, 8, 9].

Model of the dissolved methane transfer

By analogy with all other biogeochemical tracers, the evolution of methane concentration is simulated as advection-diffusion supplemented with local sources and sinks

$$\frac{\partial C}{\partial t} + u\cdot\nabla C = Diffusion + C_{ox}$$

We simulate the lifetime and removal C_{ox} as [10].

Methane is also interchanged between the ocean and atmosphere at the surface interface, using the molecule specific transfer coefficient from [12] .

$$F = 0.31\upsilon^2\left(\frac{Sc}{660}\right)^{-0.5}(C_w - C_a)\cdot(1 - Ice)$$

$$Sc = 2039.2 - 120.31T + 3.4209T^2 - 0.040437T^3$$

Numerical modeling

Assuming an increase in gas permeability of perennial frozen sediments caused by climate changes, the numerical simulation of the dissolved methane transport from the bottom reservoirs in the shelf water was carried out. An upward fluid flow from the seabed was set and the simulation has been continued for 9 years (2002-2011).

- **Experiment C1:** assumes an increase in gas permeability of frozen sediments at water depths up to 100 m and a flow of dissolved methane from sediments in the form of diffusive fluxes of order of 3 nmole/m^{2}s [10].
- **Experiment C2:** diffusive fluxes from the bottom reservoirs in certain areas assuming gas hydrate degradation. Fluxes from the bottom reservoirs were set in modeled locations of open taliks in the Laptev Sea Shelf (the Lena River delta. Reagan and Moridis [11] were the first to simulate fully coupled flow, transport and decomposition for the marine hydrates subject to the ocean warming. The total methane fluxes were of order 1000 nmole/m^{2}s for a cold shallow case which is Arctic specific. Since the objective here is to estimate an extreme potential response, 1000 nmole/m^{2}s was chosen as the value for a superimposed, hydrate-driven input.

MODEL RESULTS

Variability of the water masses state

Based on the regional model the Arctic Ocean–North Atlantic, the variability of the Arctic Ocean water masses state was simulated for the period from 1948 to 2011. The model was driven by atmospheric data from the NCEP/NCAR reanalysis. The analysis of the thermohaline characteristics of the ESAS water in the model run (Fig.4) showed the positive trend in the bottom temperature, which is in agreement with the observational data. Temperature increase of the bottom waters can lead to the thawing of the frozen bottom sediments and the release of additional amount of methane from gas hydrates.

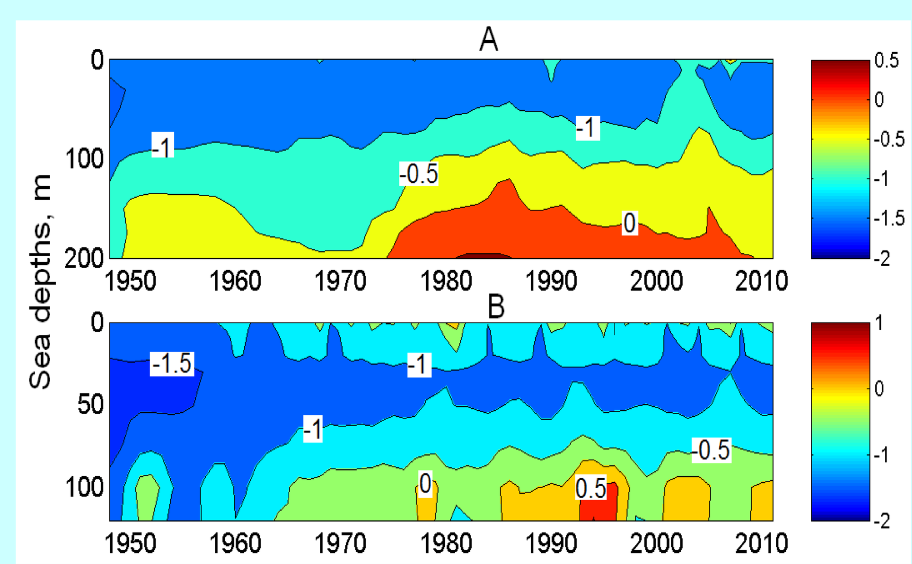


Fig. 4. Vertical temperature distribution in the East Siberian Sea (A) and in the Laptev Sea (B)

The Subsea Permafrost

The initial temperature profile (8000 years ago) across the upper 1000 m layer of sediments represents a linear temperature distribution from −13.5°C at the surface up to 15.4°C at 1000 m. Approximately 8000 years ago, the terrestrial permafrost started its inundation, and the temperature at its upper boundary was increased by 12°C, from −13.5°C up to −1.5°C, [8]. The initial vertical temperature profile for 1947 is set from the output of a paleosimulation starting 8000 years ago until 1947. From 1948 to 2011, we have simulated the temperature in the sediment based on the bottom water temperature with the Arctic Ocean regional model (Fig. 5).

The results of this study have revealed that the rate of permafrost thawing is proportional to the geothermal heat flux value (Fig. 6). As a result, by the end of transgression stages, sediment blocks with different Q_t values have different thickness of the preserved permafrost. The modeling has shown that the offshore permafrost has been continuously preserved within part of the shelf with Q_t values 60-70mW/m^2. In the rift zones with Q_t values above 100mW/m^2, open taliks can exist. They may serve for the emission of CH_4 from the layers under the permafrost.

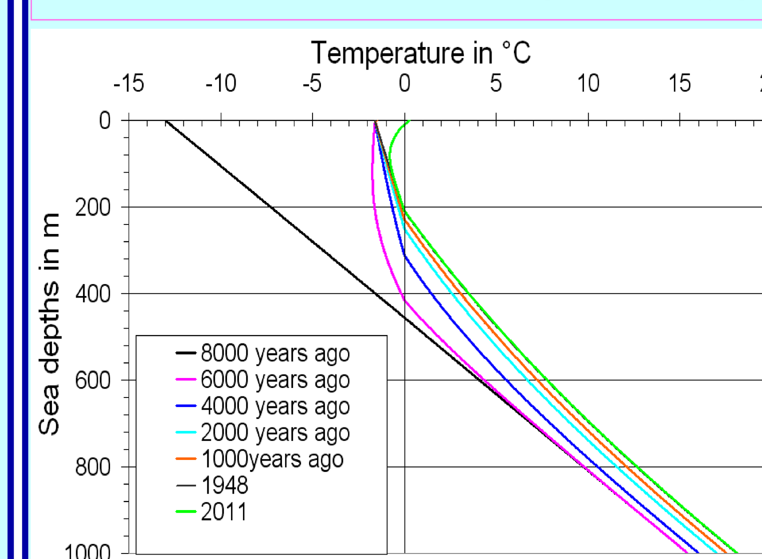


Fig. 5. Permafrost and sediments temperature 8'000, 6'000, 4'000, 2'000, 1'000 years ago and in 1948, 2011

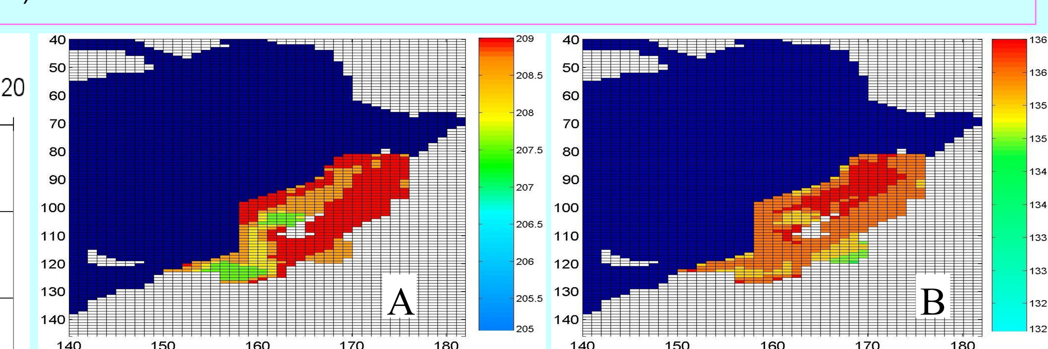
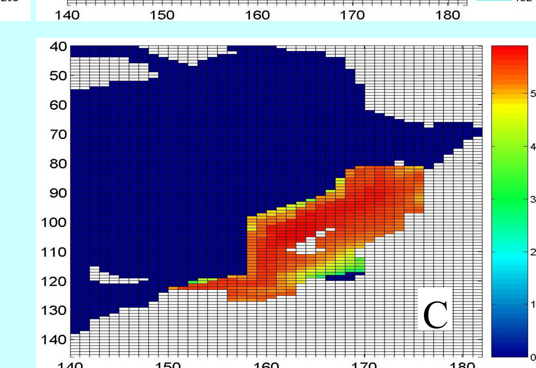


Fig. 6. Distribution subsea permafrost thickness. Results of modeling:

(A) - for Q_t= 60mW/m^2
(B) - for Q_t= 70mW/m^2
(C) - for Q_t= 100mW/m^2



Dissolved Methane transport

Assuming an increase in the gas permeability of the perennial frozen sediment caused by climate change, the numerical simulation of the dissolved methane transport from the bottom reservoirs in the shelf water was performed. The dissolved methane is transported in the Arctic Seas according to the system of currents and depends on the considered period. In this case, the water along the coast is moving usually to the east. This current originates in the Laptev Sea, where a freshened abundant flow of the Lena River water through the Straits is penetrating into the western part of the East Siberian Sea.

In C1, a fluid flow of methane from the shelf seafloor is set uniformly, but the accumulation of methane occurs in terms of circulation of a region, where the plumes are formed. High concentrations of methane are stored in the entire water column from the bottom to the surface (Fig. 7-8). The results of C2 showed that abnormal concentrations of methane (up to 6000 nM) are stored in the bottom layer of water in both areas setting diffusion fluxes (Fig. 9). However, high methane concentrations occur in the surface part of the water column only in the delta of the Lena River. In this case, according to the dynamics of water masses of the circulation formed, the diffusion transport of methane takes place throughout the water column. Later on, methane is spreading over the whole water surface of the Laptev Sea.

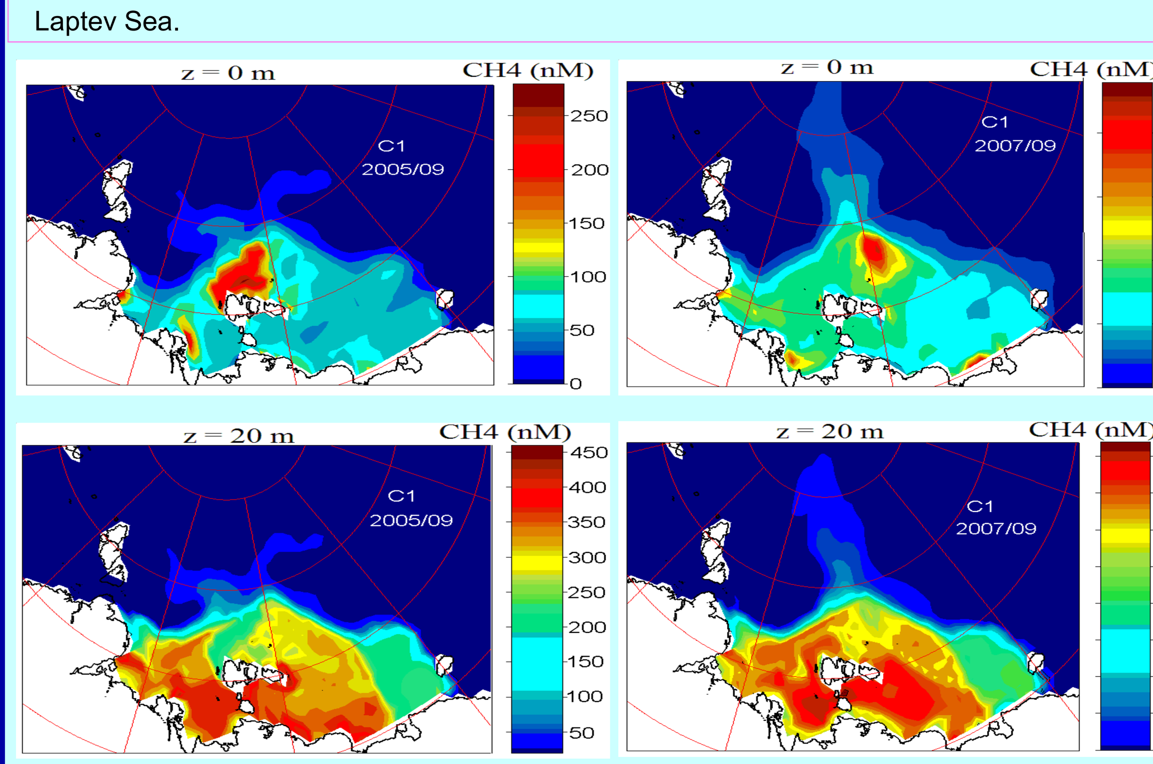


Fig. 7. The dissolved CH_4 distribution for the sea water in study areas (nM) for September , 2005, 2007 obtained in the experiment C1: (top) – in surface water, (bottom) – in bottom water

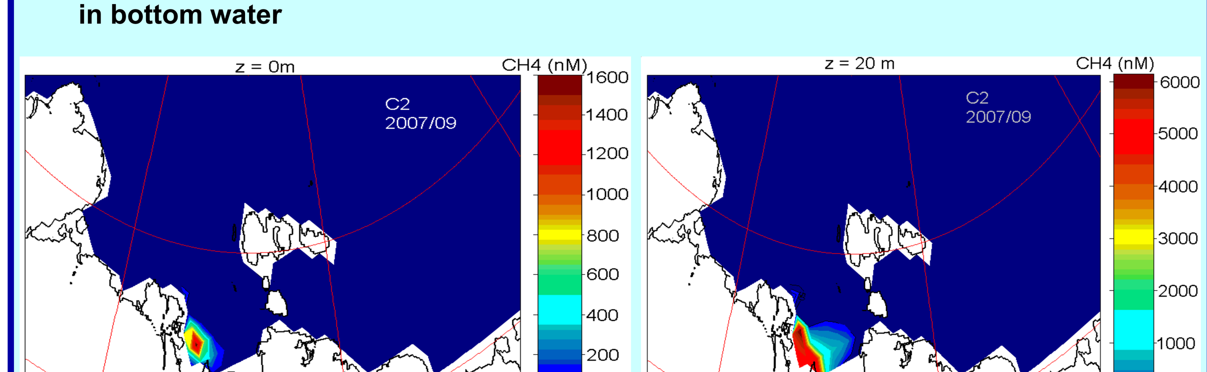


Fig. 8. The dissolved CH_4 distribution for the sea water in (nM) for September 2007, obtained in the C2: (top) – in surface water, (bottom) – in bottom water

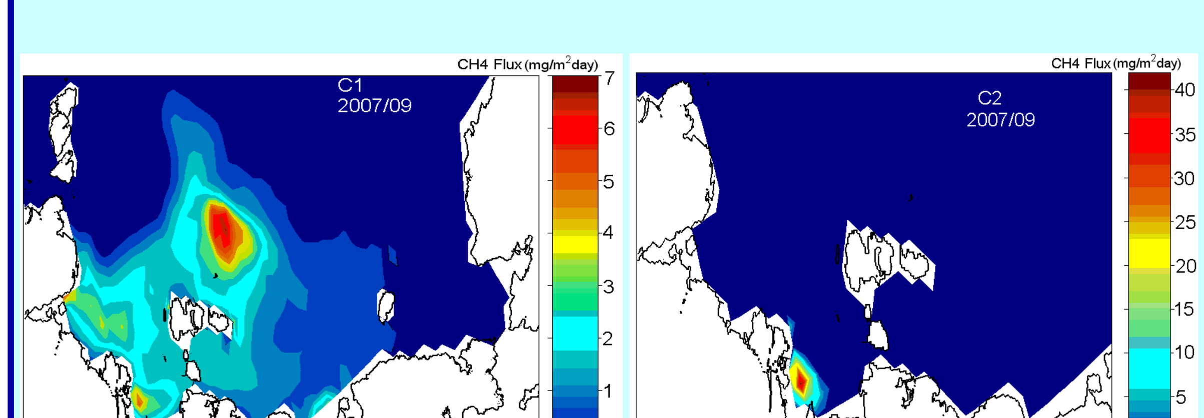


Fig. 9. Fluxes of CH_4 (in mg/m^{2}day) venting to the atmosphere over the Arctic Seas obtained for September 2005, in the experiment C1 (left figure) and C2 (right figure)

Methane flux

A large concentration of the dissolved methane in the surface water can bring about methane fluxes to the atmosphere. The larger part of the East Siberian shelf territory is a source of methane in summer, keeping the emission to the region's atmosphere in the range from 1 to 3 mg of CH_4/m^{2}day (C1), Fig.10. During the whole period of open water, the emission of methane may reach 20-80 kilotons CH_4 per year for C1 and 5-38 kilotons CH_4 per year for C2 (Fig.11).

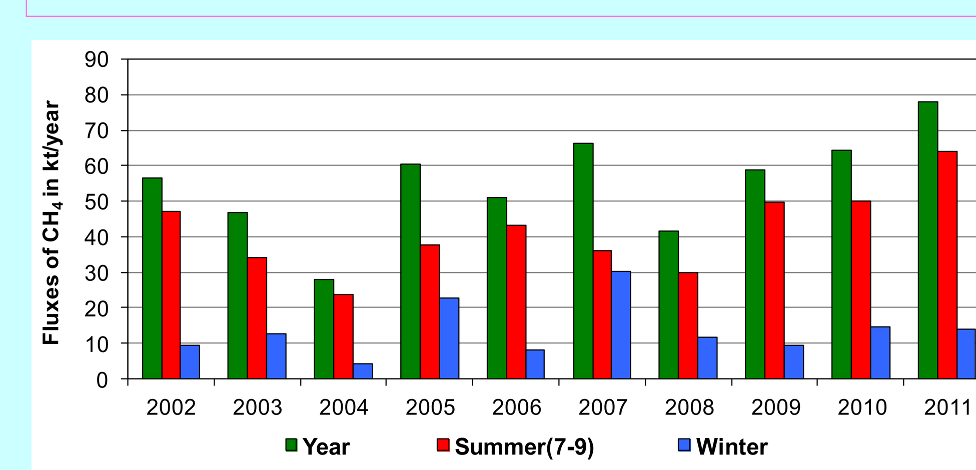


Fig. 10. The total annual CH_4 flux (in kilotons) from ESAS to the atmosphere obtained in the experiments C1

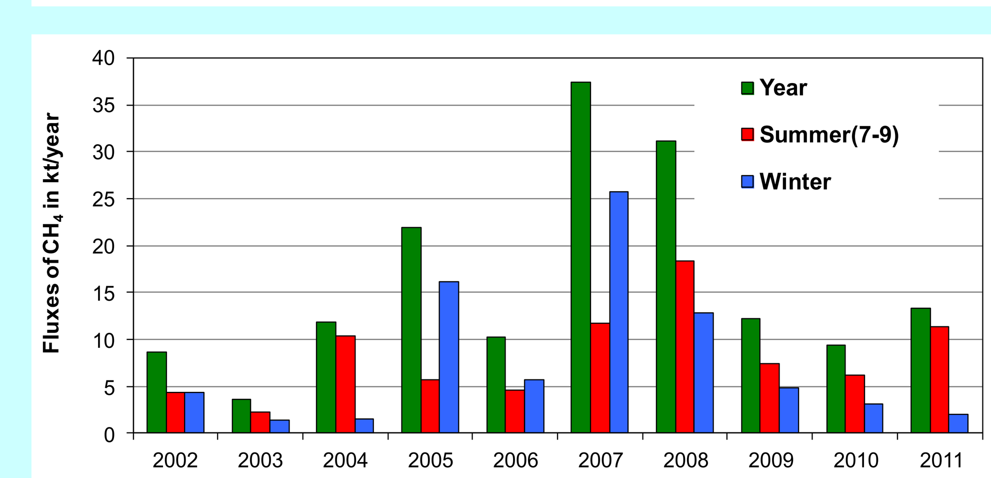


Fig. 11. Fluxes of CH_4 vented to the atmosphere in summer and in winter (through wintertime polynyas) obtained in C2

CONCLUSIONS

- Based on the regional model of the Arctic Ocean–North Atlantic the variability of the Arctic Ocean water masses state was simulated for the period from 1948 to 2011. The analysis of the thermohaline characteristics of the East Siberia Shelf water in the model run has shown a positive trend in the bottom temperature, which is in agreement with the observational data.
- Increasing temperature of the bottom waters can result in the thawing of the frozen bottom sediments and to the release of additional amount of methane from gas hydrates. The permafrost failure uncorks a huge gas reservoir, leading to large-scale releases of methane from the seabed.
- It is shown that accumulation of the dissolved methane is formed according to a system of currents in the region, but is not localized in the places of setting sources.
- Estimates of the diffusive methane flux from the water to the ESAS atmosphere have been obtained. The total annual venting methane emission to the ESAS atmosphere may attain to 100 kilotons per year for the period of open water. Calculation of methane fluxes in the study area for the years of 2002-2011 has shown that a maximum emission is typical of 2005 and 2007. Increasing ice-free period in the Arctic seas may have contributed to the increased emission of methane to the atmosphere in 2005 and 2007.

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