The response of Arctic Ocean methane hydrate to the climate change

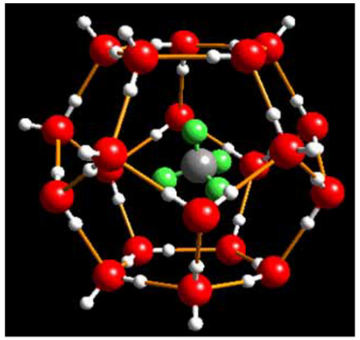
Malakhova V.V., Golubeva E.N.

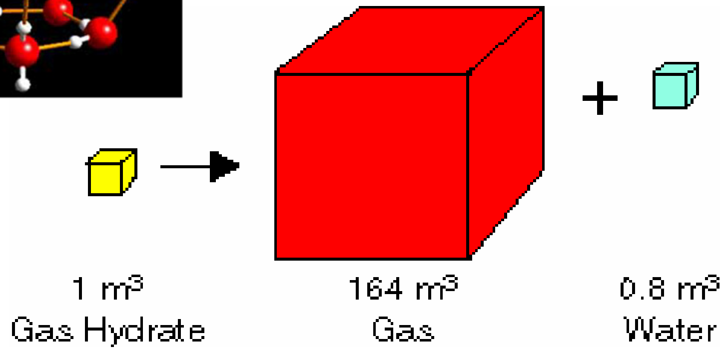
ICM&MG SB RAS, Novosibirsk

«CITES-2019»

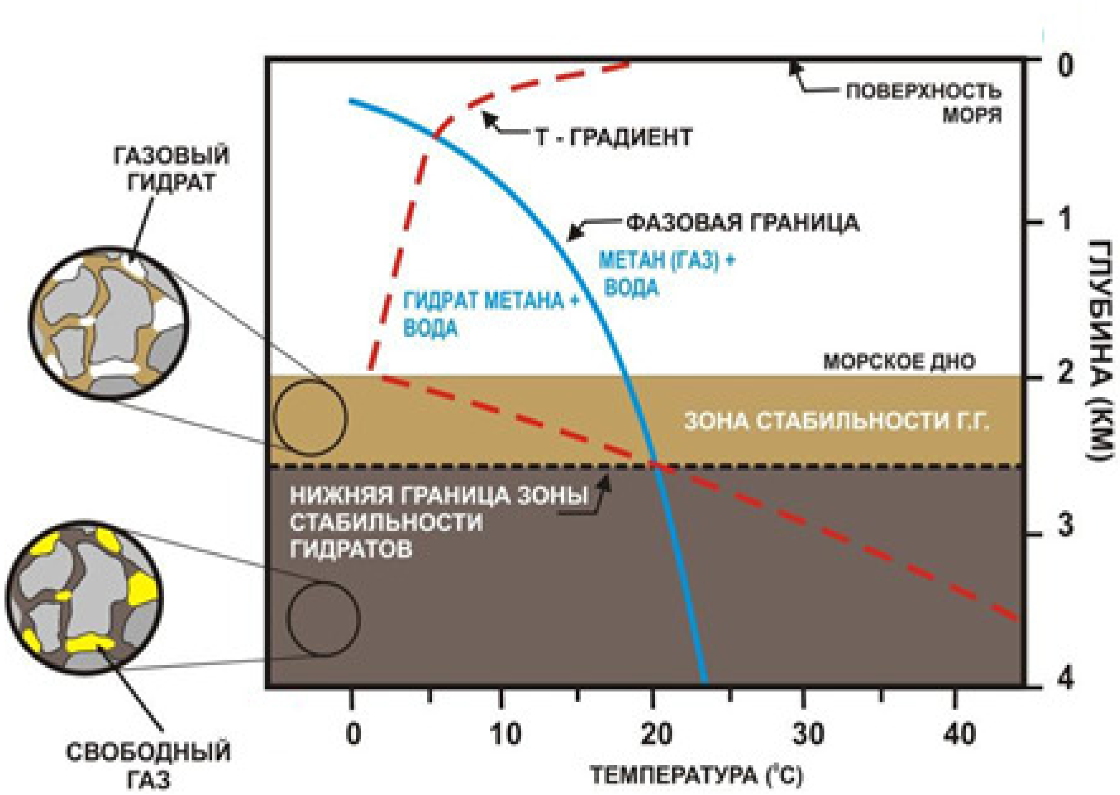
Methane Hydrate

- A gas hydrate is a crystalline solid. This it is similar to ice, except that the crystalline structure is stabilized by the guest gas molecule within the cage of water molecule
- Water molecules form the cage-like structure and methane molecules are contained in it





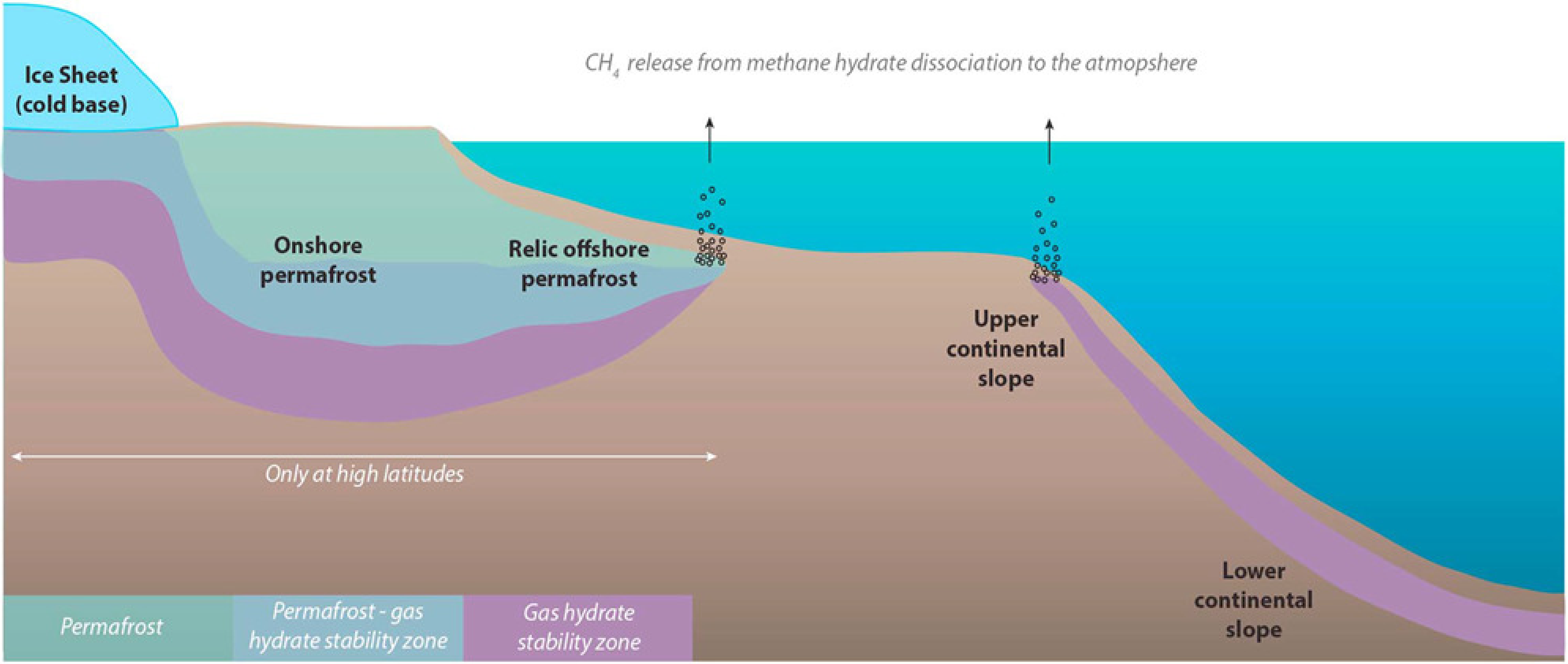
1 m³ of methane hydrate dissociates to approximately 160 – 170 m³ (at 0ºC and 1 atmosphere) of methane gas



Gas Hydrate Stability Curve

Pressure, temperature, and availability of sufficient quantities of water and methane are the primary factors controlling methane hydrate formation and stability.

Gas hydrate in the Arctic



Conceptual diagram of methane hydrate reservoir

Types of hydrate reservoirs are shown:

- subglacial hydrates,
- hydrates associated with onshore and offshore permafrost
- hydrates in upper and lower continental slopes
- deep-sea hydrates (is not shown because of its low climate sensitivity).

Upper continental slope and relic offshore permafrost associated hydrates are most vulnerable to climate change and may dissociate, but almost all CH4 liberated will be consumed in sediments and ocean before reaching the atmosphere. *(Ruppel and Kessler2017)*

Gas hydrate presence in the Arctic

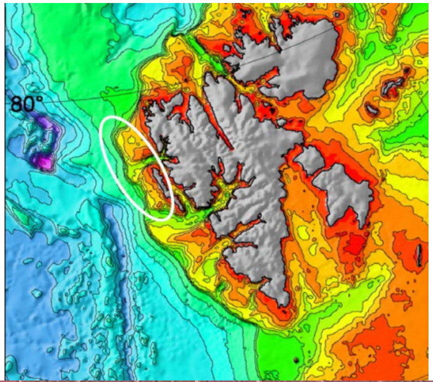
Map of gas hydrate–bearing areas in the Arctic
[Soloviev V.A., 1990]

Gas Hydrate Types	Volume CH4 , трлн. м3
Submarine gas hydrates	40 – 12600
Cryogenic gas hydrates	3 - 1960

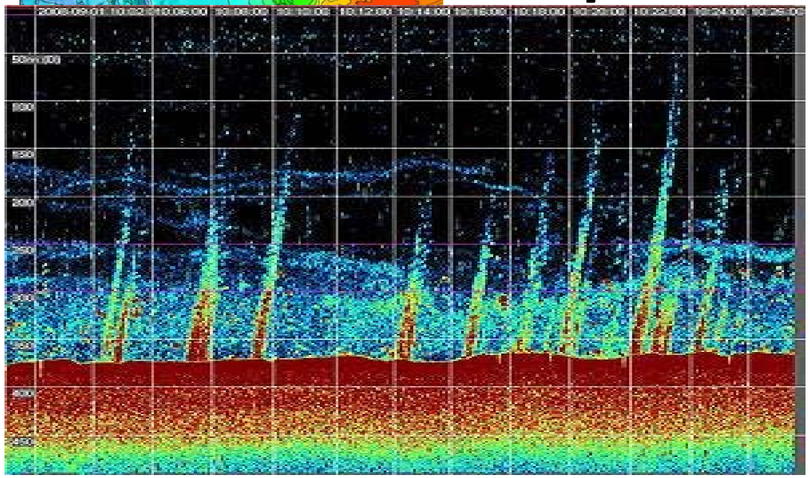
Gas resources in hydrates of the Arctic ocean sediment (James R.H., 2016)

Naturally occurring hydrates are known to exist in two different types of environments, arctic permafrost and deepwater oceanic sediments.

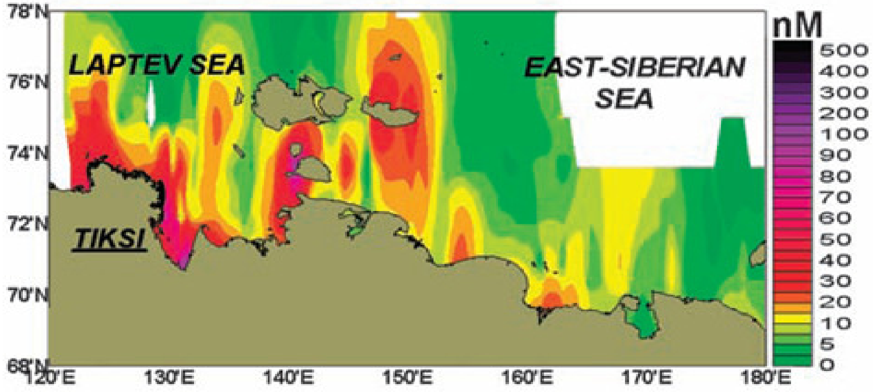
Methane plumes have been observed in the the Arctic

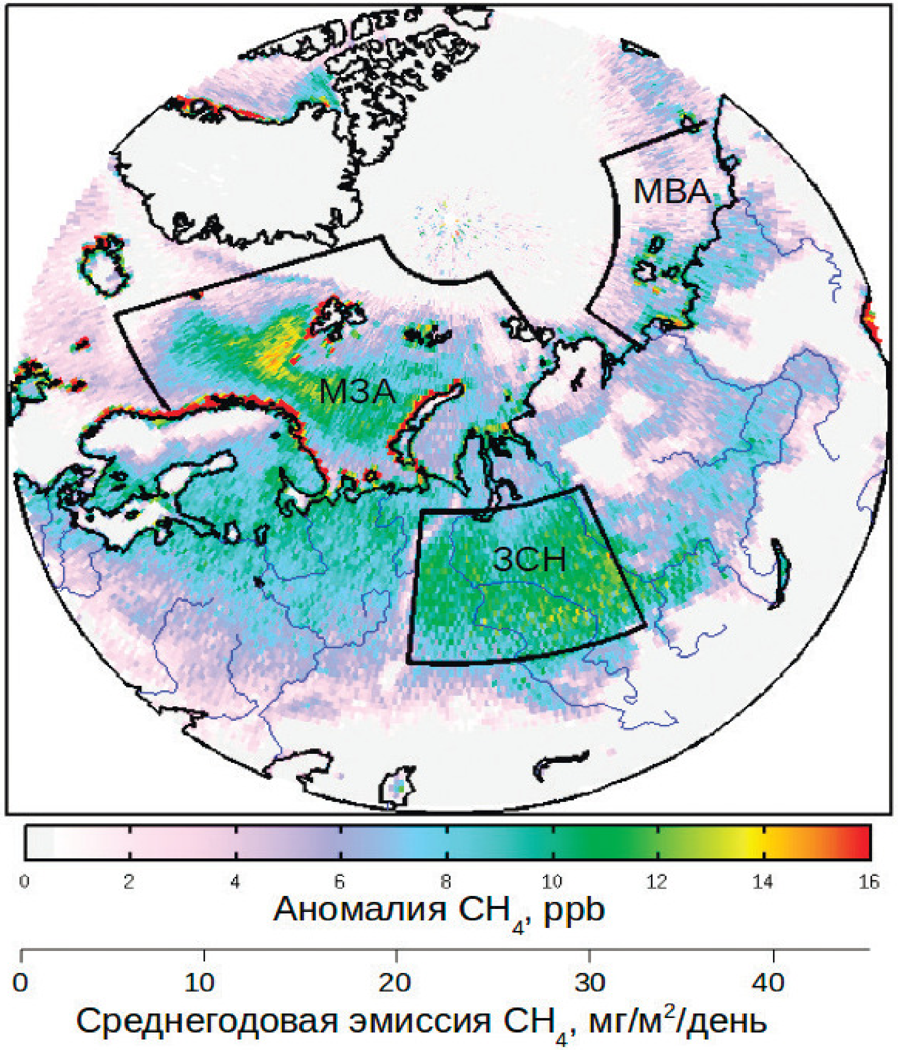


Sonar image of methane plumes rising from the Arctic Ocean floor near Svalbard in summer [Westbrook et al., 2009]



Bottom water methane concentration in the ESAS as reported by Shakhova et al. [2010a]





The distribution of the averaged anomalies of methane for 2010-2014 in the surface air (IASI data) [Юрганов и др. 2016]

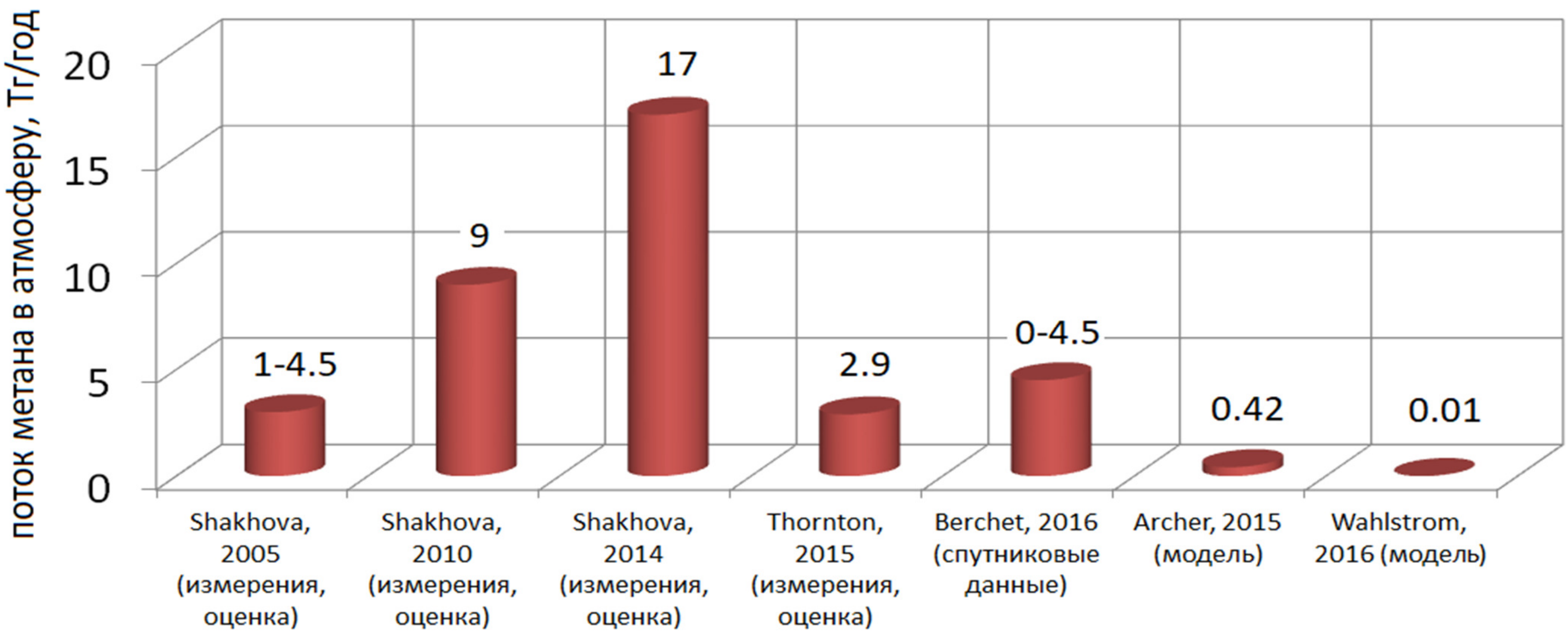
Methane flux from the water column into the atmosphere

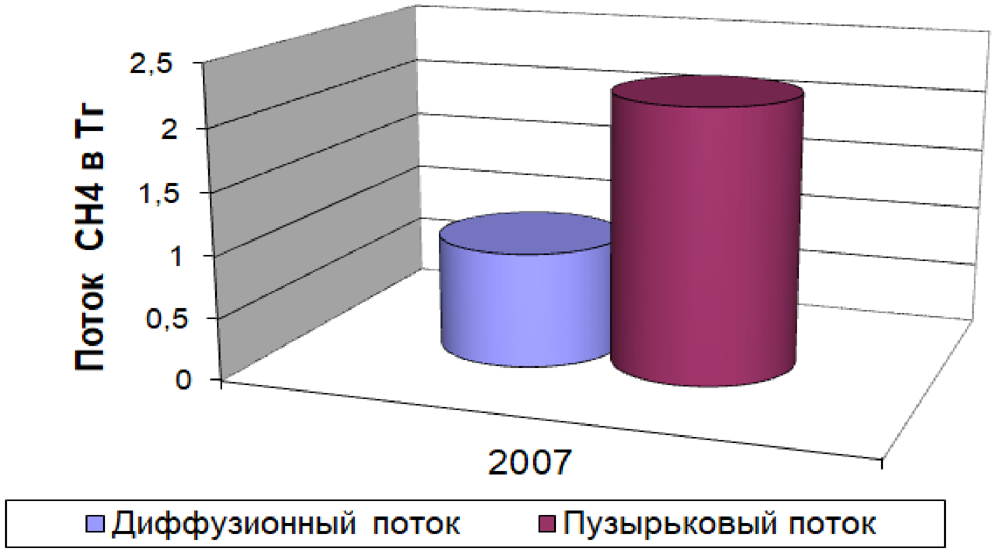
Authors	Area	Range	Median
Calculated from dissolved methane concentrations (bottom-up)			
Bussmann (2018)	Lena Delta	4–163	24
Bussmann (2013)	Buor-Khaya Bay	2–85	34
Shakhova and Semiletov (2007)	Northern parts of Buor-Khaya Bay	4–8	
Wahlström and Meier (2014)	Modelled flux for Laptev Sea	6±1	
Mau et al. (2015)	North Sea with stratified water column in summer	2–35	9
Mau et al. (2015)	North Sea in winter, including methane seepage	52–544	104
Borges et al. (2016)	Southern North Sea, 2010, near shore	426±231	
Steinle et al. (2017)	Eckernförde Bay, Baltic Sea	6-15	8
Myhre et al. (2016)	West off Svalbard with CH_4 seepage	Up to 69	3
Mau et al. (2017)	Coastal waters of Svalbard	-17–173	2
Graves et al. (2015)	Coastal waters of Svalbard	4–20	
Fenwick et al. (2017)	North American Arctic Ocean	-0.4–4.9	1.3
Calculated, modelled from atmospheric data (top-down)			
Thornton et al. (2016)	Ice-free Laptev Sea		94
Myhre et al. (2016)	West off Svalbard with CH_4 seepage	207–328	
Shakhova et al. (2014)	Ebullitive flux around Lena Delta	6250–39 375	

Table shows a comparison of diffusive methane flux from the water column into the atmosphere of this region from temperate and polar shelf seas (in μmol/m2 in day).
Within the polar environments, a broad range of emission occurs.

(Bussmann 2018).

Methane flux from the water column into the atmosphere in Tg





Диффузионный и пузырьковый потоки метана из шельфовых морей Восточной Арктики для летнего периода на основе данных измерений . (Shakhova et al., 2010)

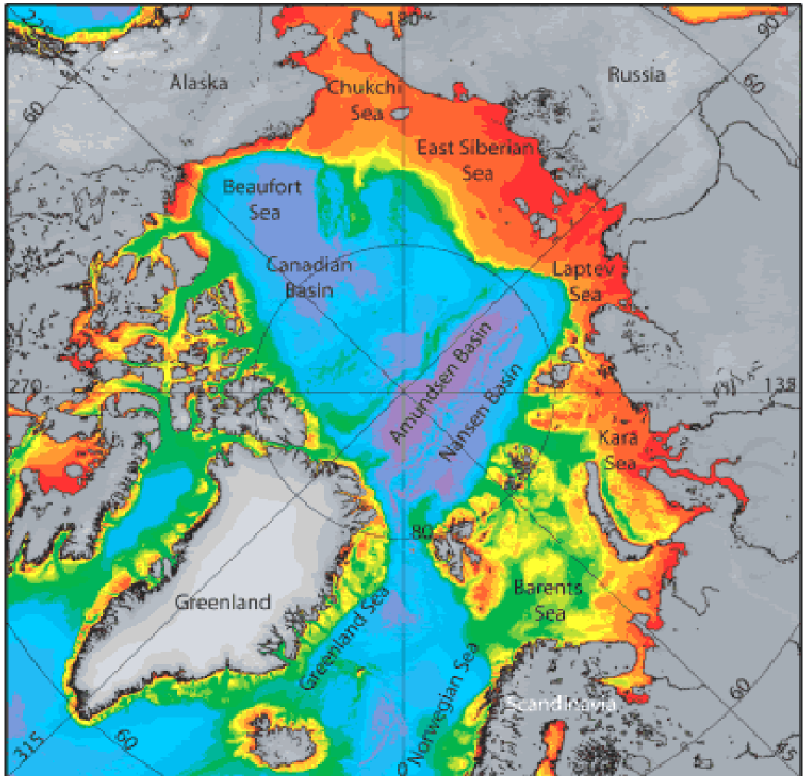
The Numerical Model configurations

- ***3D World Ocean Circulation Model of ICMMG based on z-level vertical coordinate approach*** *[Golubeva and Platov, 2007]*
- ***Ice model-CICE 3.0 (elastic-viscous-plastic)*** *[W.D.Hibler ,1979; E.C.Hunke, J.K.Dukowicz,1997; G.A.Maykut 1971 C.M.Bitz, W.H.Lipscomb 1999,J.K.Dukowicz, J.R.Baumgardner 2000, W.H.Lipscomb, E.C.Hunke 2004]*

- ***Atmospheric data from the NCEP/NCAR reanalysis (1948-2015)***

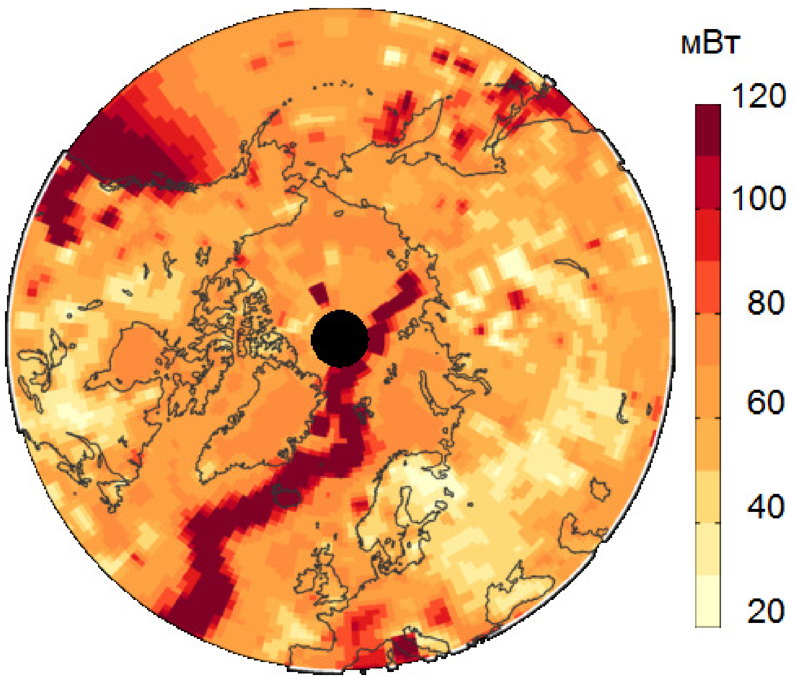
- ***The subsea permafrost model*** *[Malakhova, Eliseev 2017]*
- ***The Paleogeographic Scenario for subsea permafrost***
- ***P-T relationships hydrate stability*** **«HydrateResSim»** *[Reagan M. T., Moridis G. J., 2008]*

- ***Model of the dissolved methane transfer***
- ***Water column methane oxidation***
- ***The flux of CH_4 across the air-sea interface***
- ***Diffusive fluxes from the bottom reservoirs***

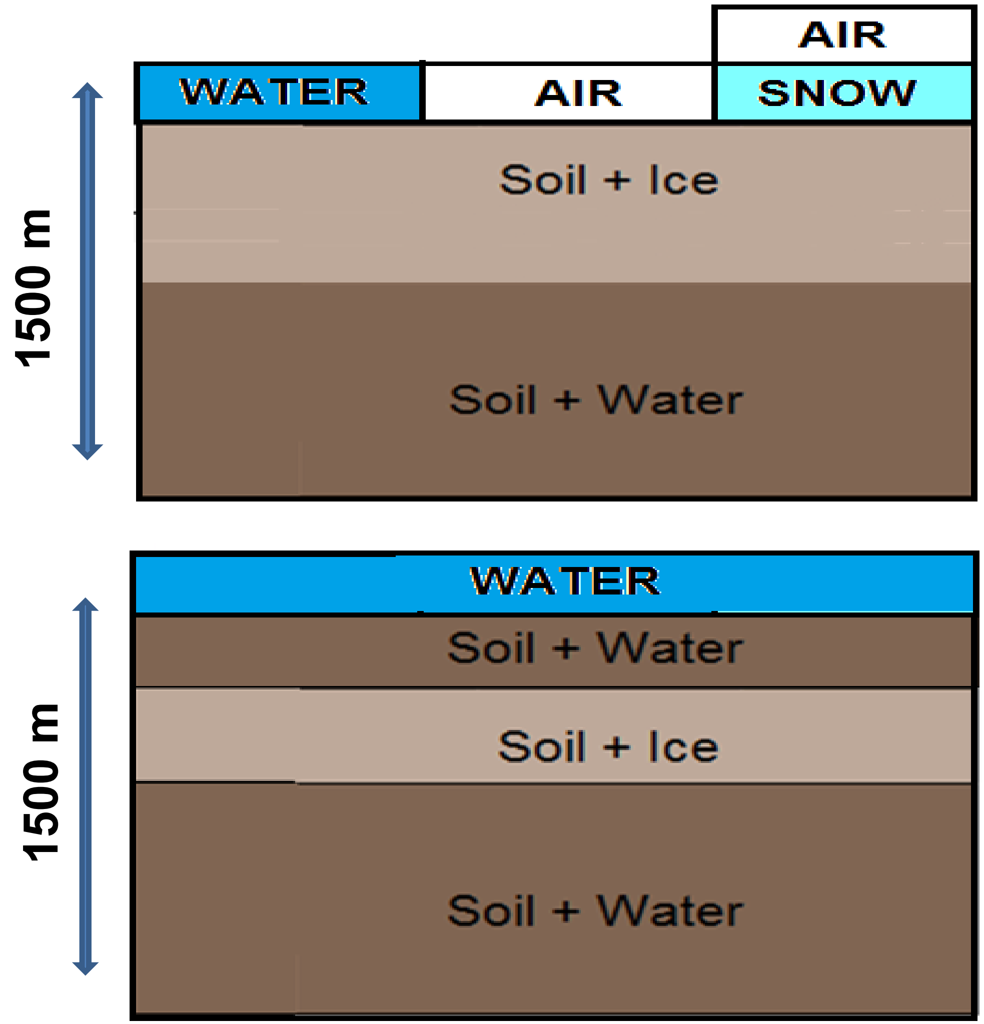


Permafrost modeling

$$T_B = \begin{cases} T_{BW} \\ T_A + \Delta T_{Pal} \end{cases}$$



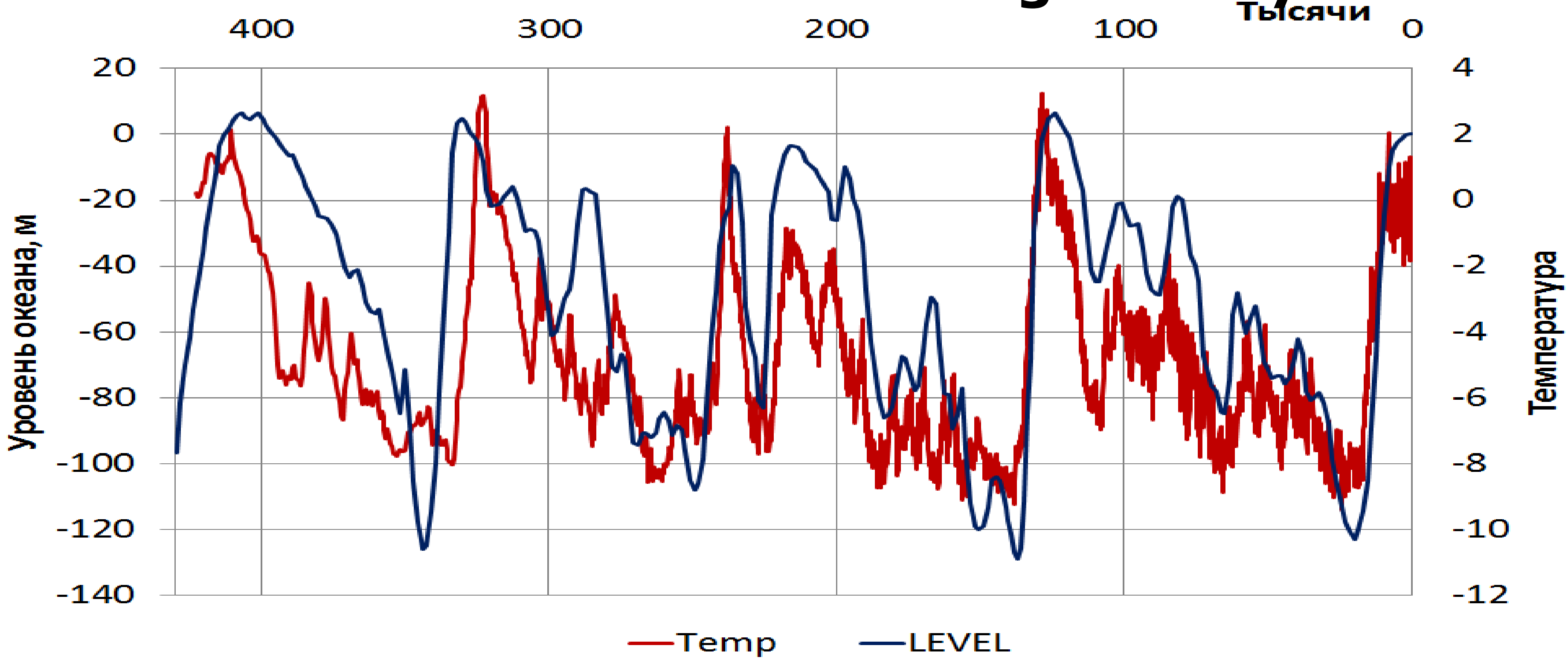
World Heat Flow Database (Davies, 2013)



«HydrateResSim» [Reagan M. T., Moridis G. J., 2008]

History of the surface forcing of the last 400Kyr

Mean annual air temperature and sea level reconstruction over the glacial cycles



$$T_B = \begin{cases} T_{BW} \\ T_A + \Delta T_{Pal} \end{cases}$$

Waelbroeck C., et al 2002 . Sea-level and deep water temperature changes derived from benthic foraminifera isotopic records

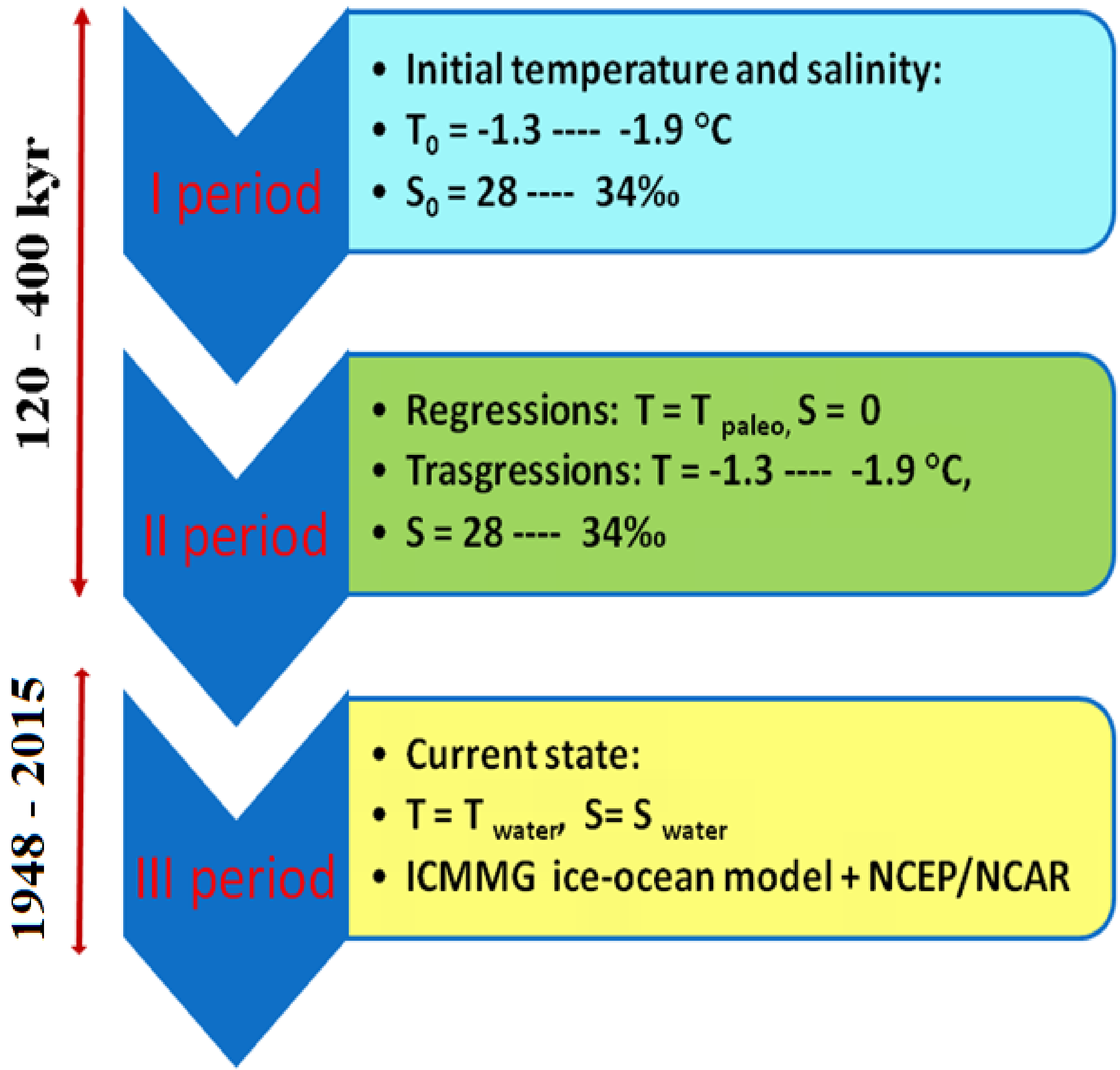
Petit J.R., et al 1999

Climate and atmospheric history of the past 420,000 years from the Vostok ice core, Antarctica

Bauch H. A., et al 2001 Chronology of the Holocene transgression at the North Siberian margin

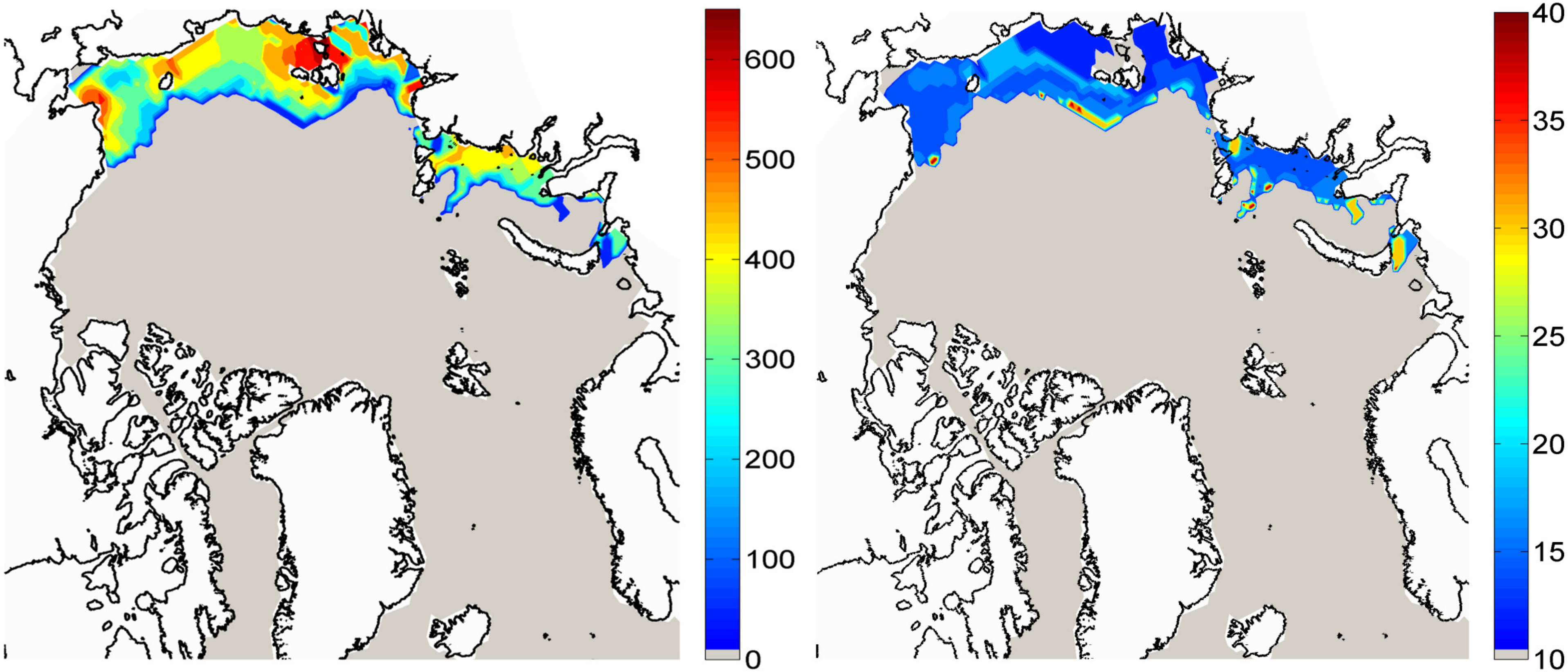
Model for thermal state of subsea sediment

- The one–dimensional single–point simulations with a model for thermal state of subsea sediments driven by the forcing constructed from the ice core data are performed.
- The timings of shelf exposure during oceanic regressions and flooding during transgressions are important for representation of sediment thermal state and hydrates stability zone (HSZ).



Sub-sea permafrost in the Arctic

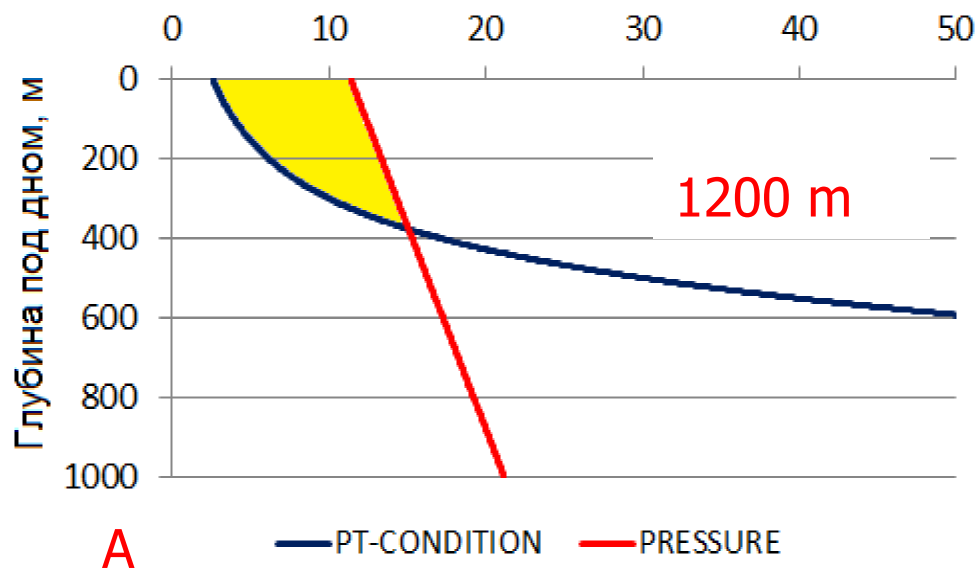
Cryolithozone - a regulator of methane emission in the ARCTIC

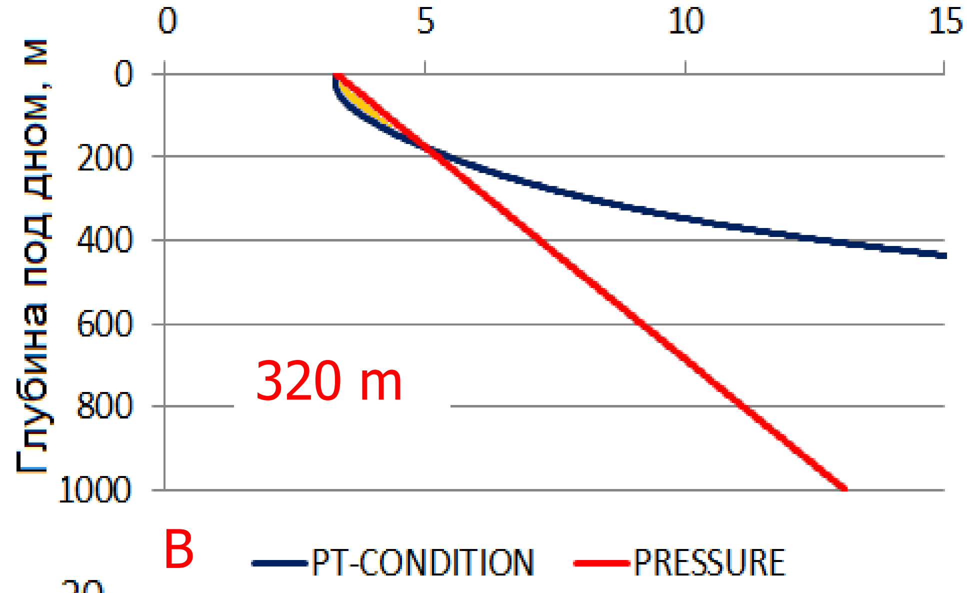


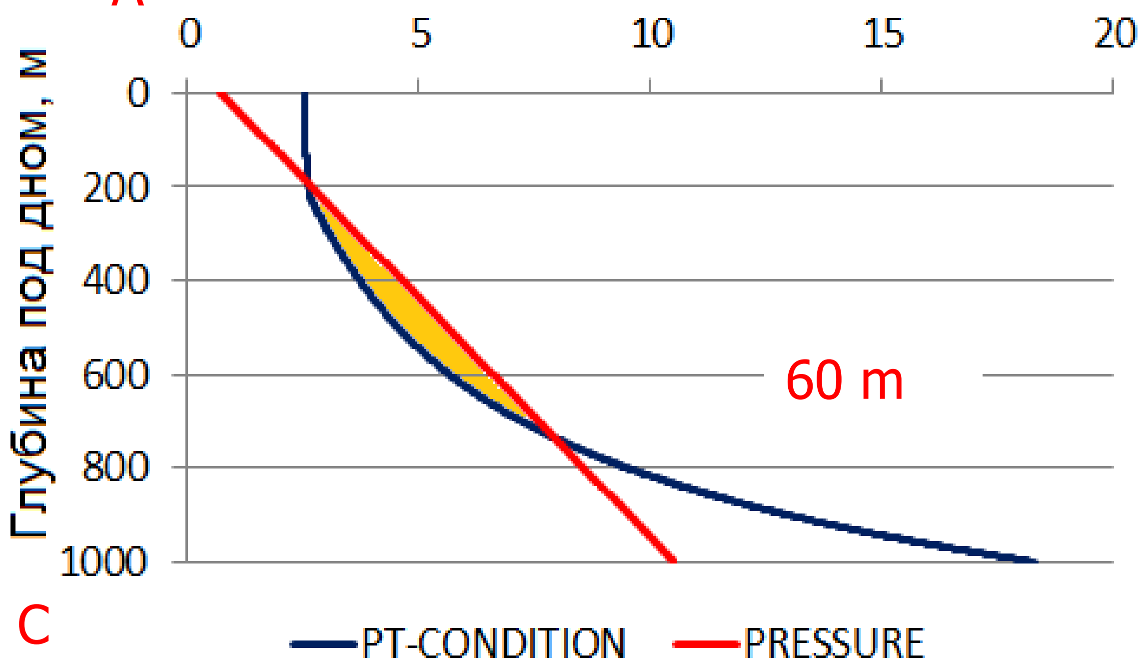
Simulated locations of the permafrost boundaries

Gas Hydrate Type Locales

Examples of gas hydrate stability assuming a water depth equal to 60m, 320m, 1200m



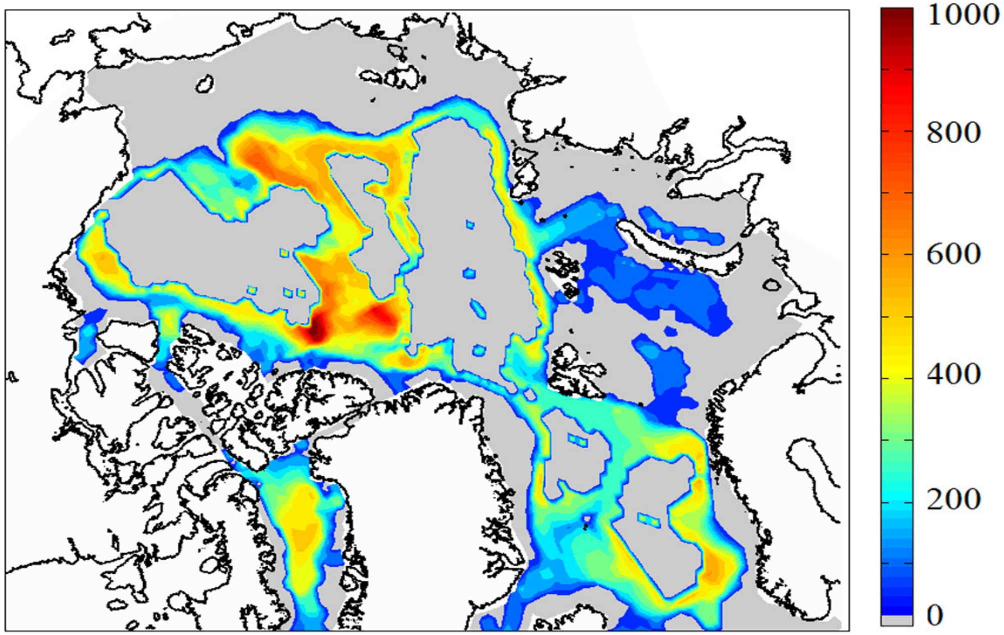


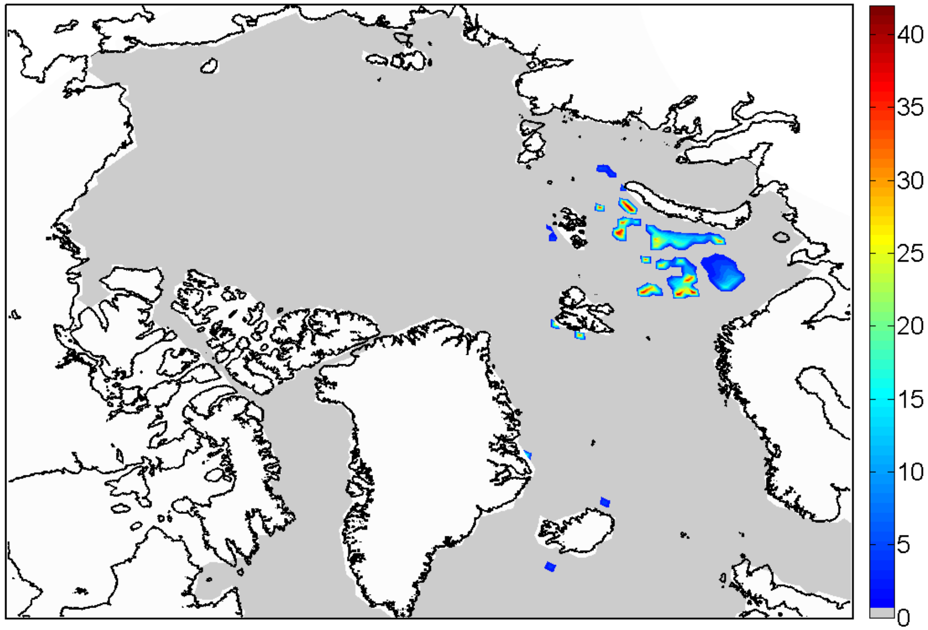


- **Deepwater hydrate (A)**
- **Continental shelves hydrate (B)**
- **Subsea permafrost hydrate (C)**

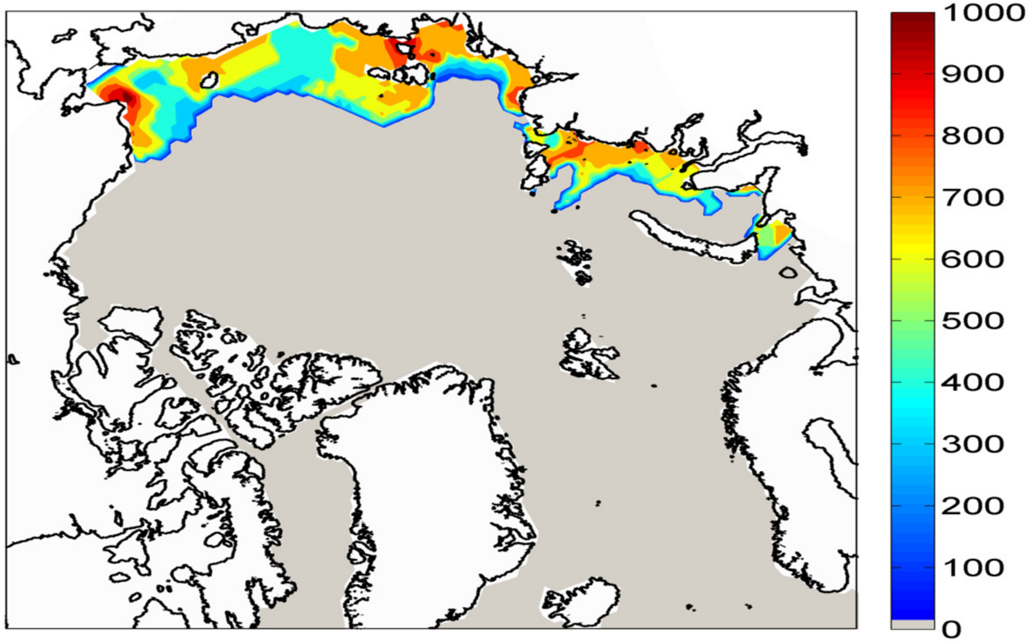
Model locations of methane hydrates by 2005

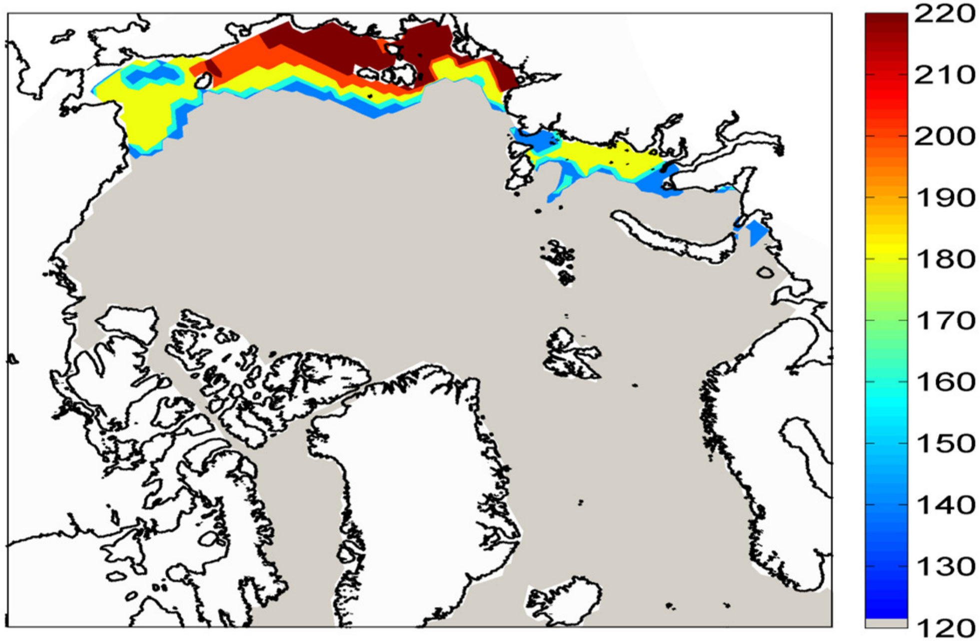
Map of the predicted thickness of the gas hydrate stability zone (GHSZ) and top of GHSZ



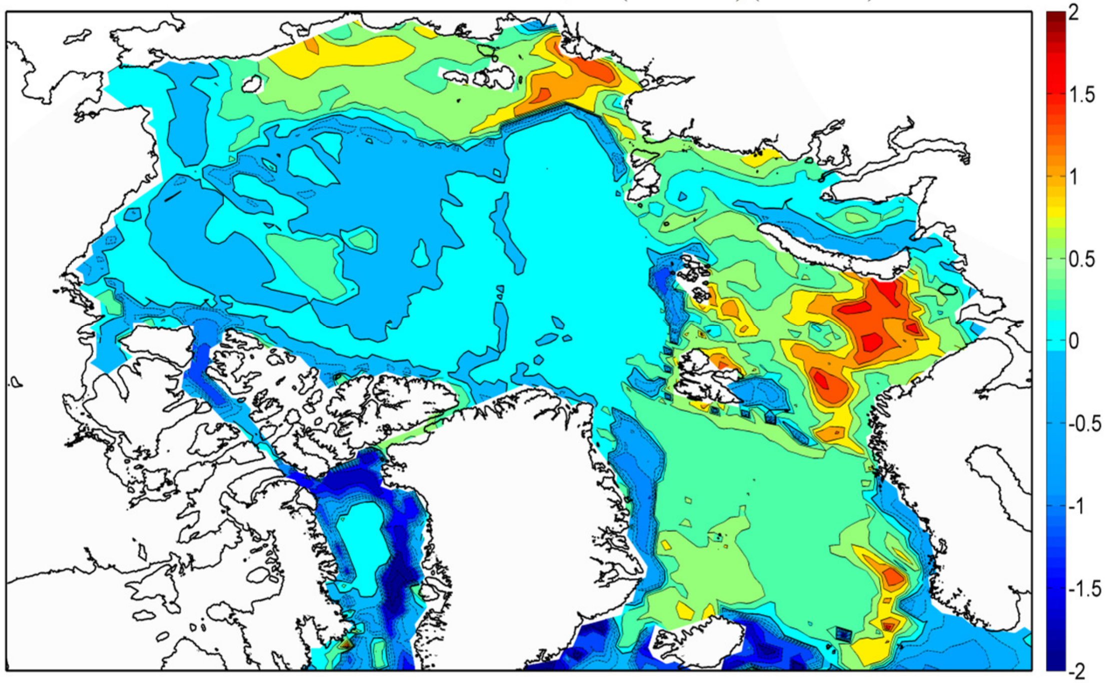


Stability zone of cryogenic gas hydrates and the top of the stability zone

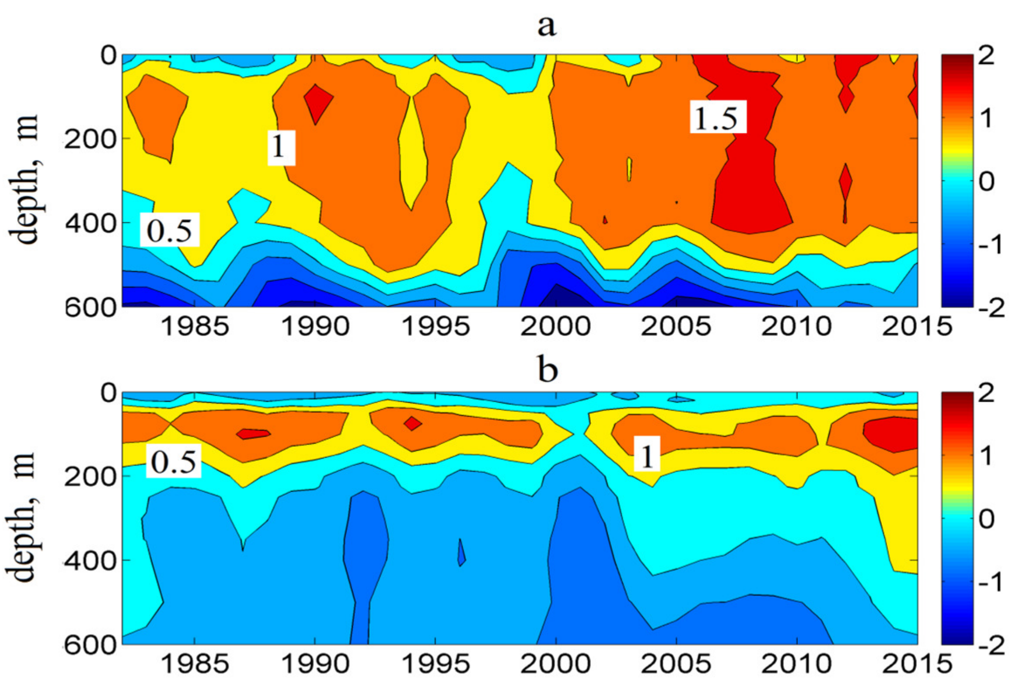




The simulated difference in the bottom temperature during the period of 1950-2015



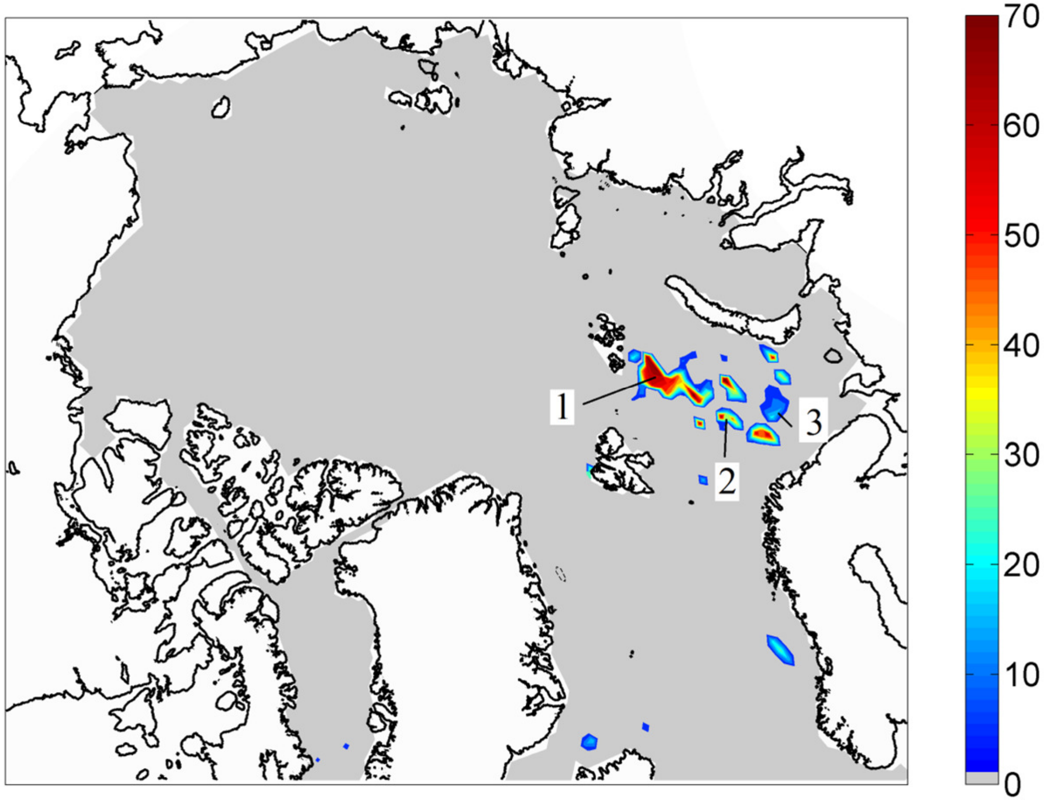
The two additional important sources of heat for the Arctic basin are: the waters of the Atlantic and the Pacific Oceans, entering the Arctic region through narrow straits.
The most important heat input to the Arctic comes from the Atlantic Water that has travelled through the Norwegian Sea and enters the Arctic Ocean through the Fram Strait and the Barents Sea.
Our numerical experiment simulates several warm impulses entering the Arctic Ocean through the Fram Strait and the Barents Sea.

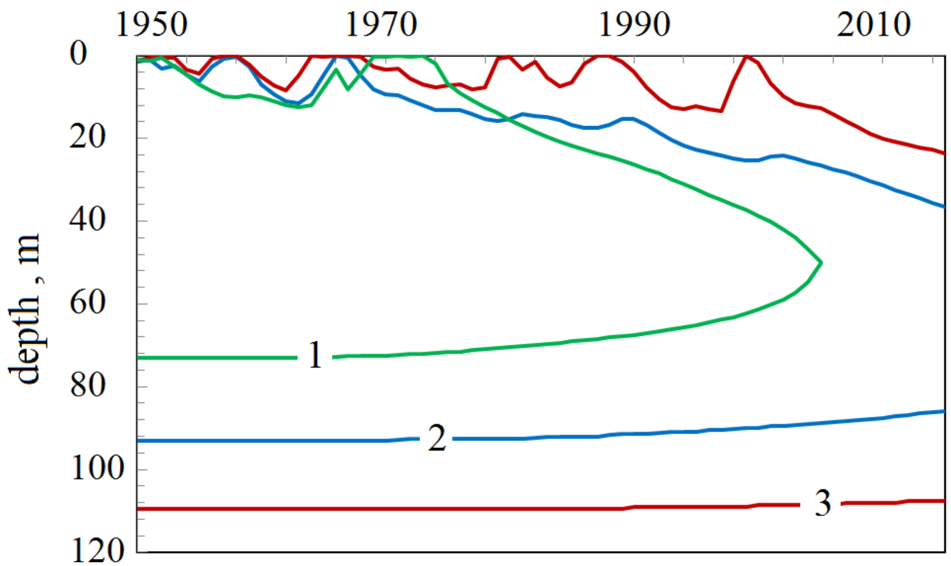


Temporal variability of the temperature difference (initial distribution is subtracted) averaged over

a) the Barents Sea region
b) the Fram Strait region

The modeling results show the changes of the GHSZ

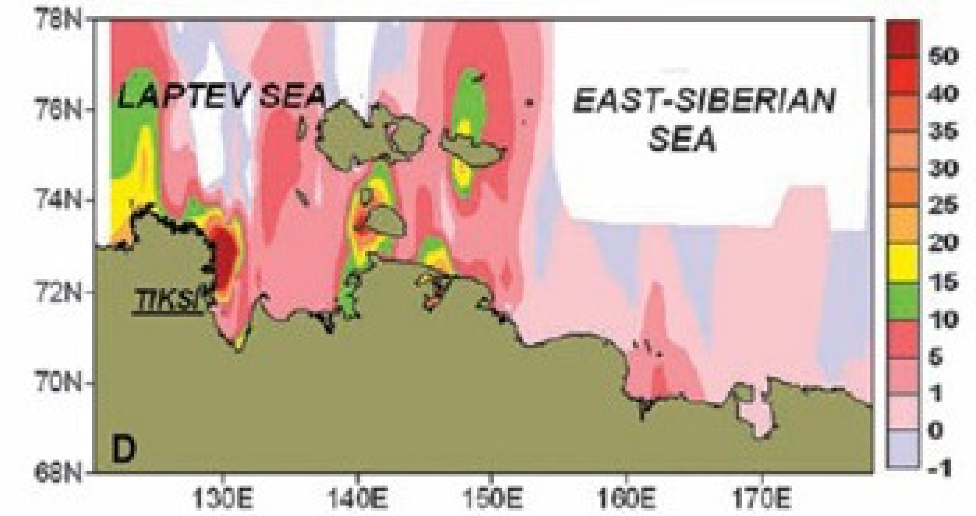


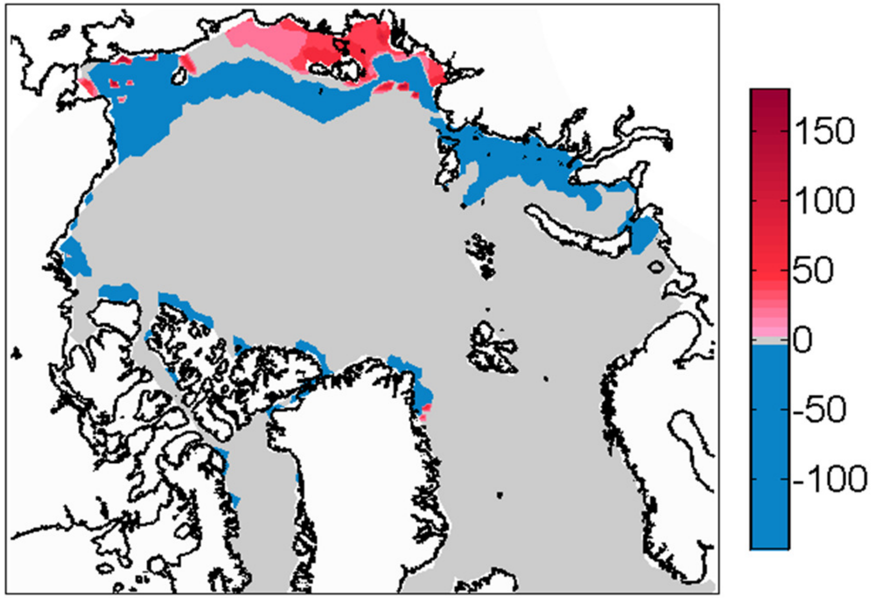


As water temperature rises, GHSZ moves down. The simulated changes in the gas HSZ thickness for the period from 1950 to 2015

Variability of the methane HSZ thickness (a) as compared to the evolution of the bottom water temperature above the HSZ at 250 -300 m water depth for regions 1,2,3 in the Barents Sea

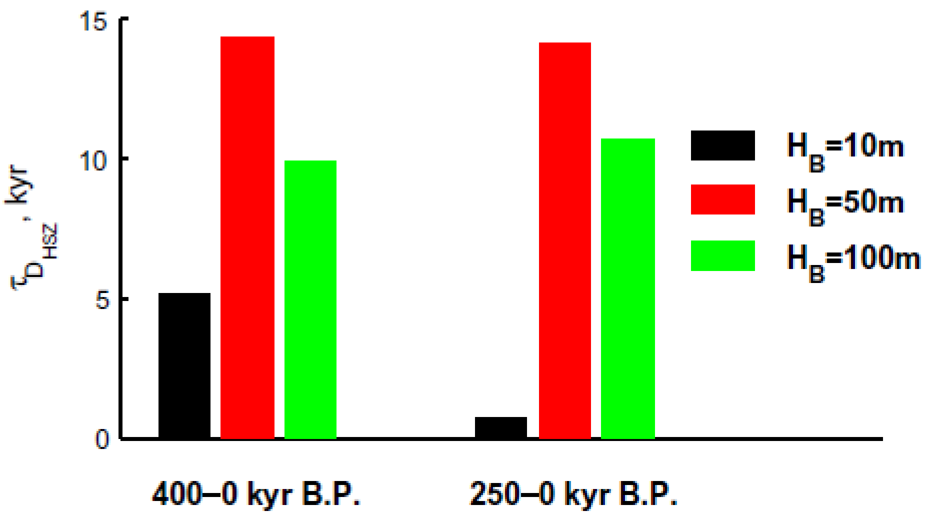
Why methane release from the East Siberian Arctic Shelf?



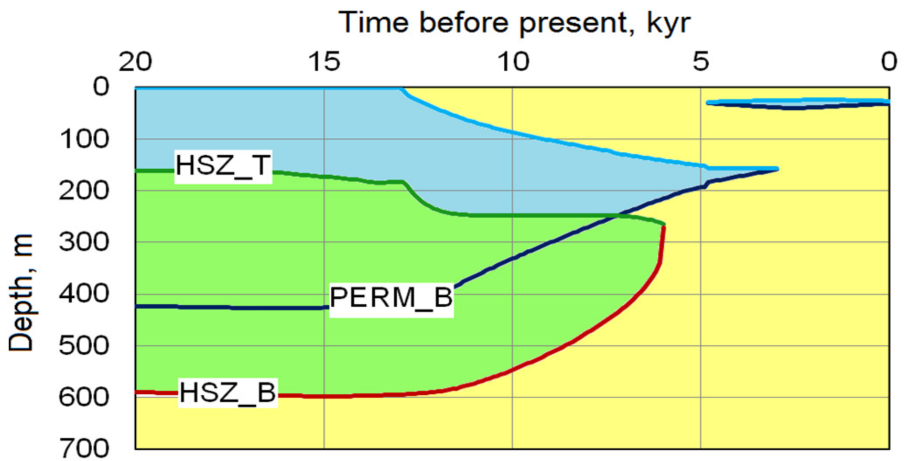


Shakhova et al. [2010a]

1) The deepening of the upper boundary of the HSZ after LGM



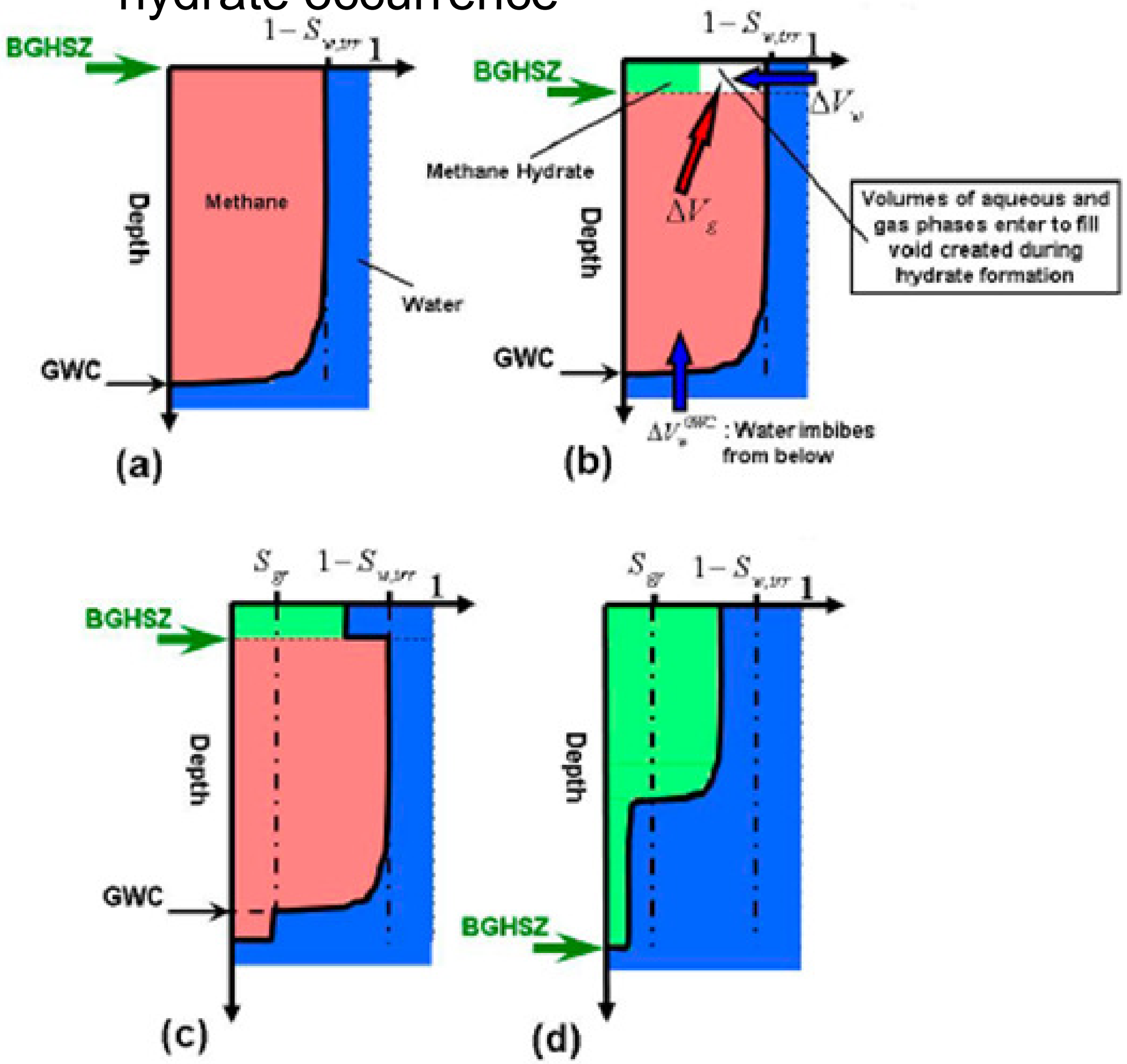
2) **Lags of HSZ thickness, with respect to temperature at the ocean–sediment interface for different time intervals of the simulations started at 400 kyr B.P.**



3) Intensification of degradation of the subsea permafrost is manifested in areas where thermokarst lakes arise.

Methane hydrate saturation profiles

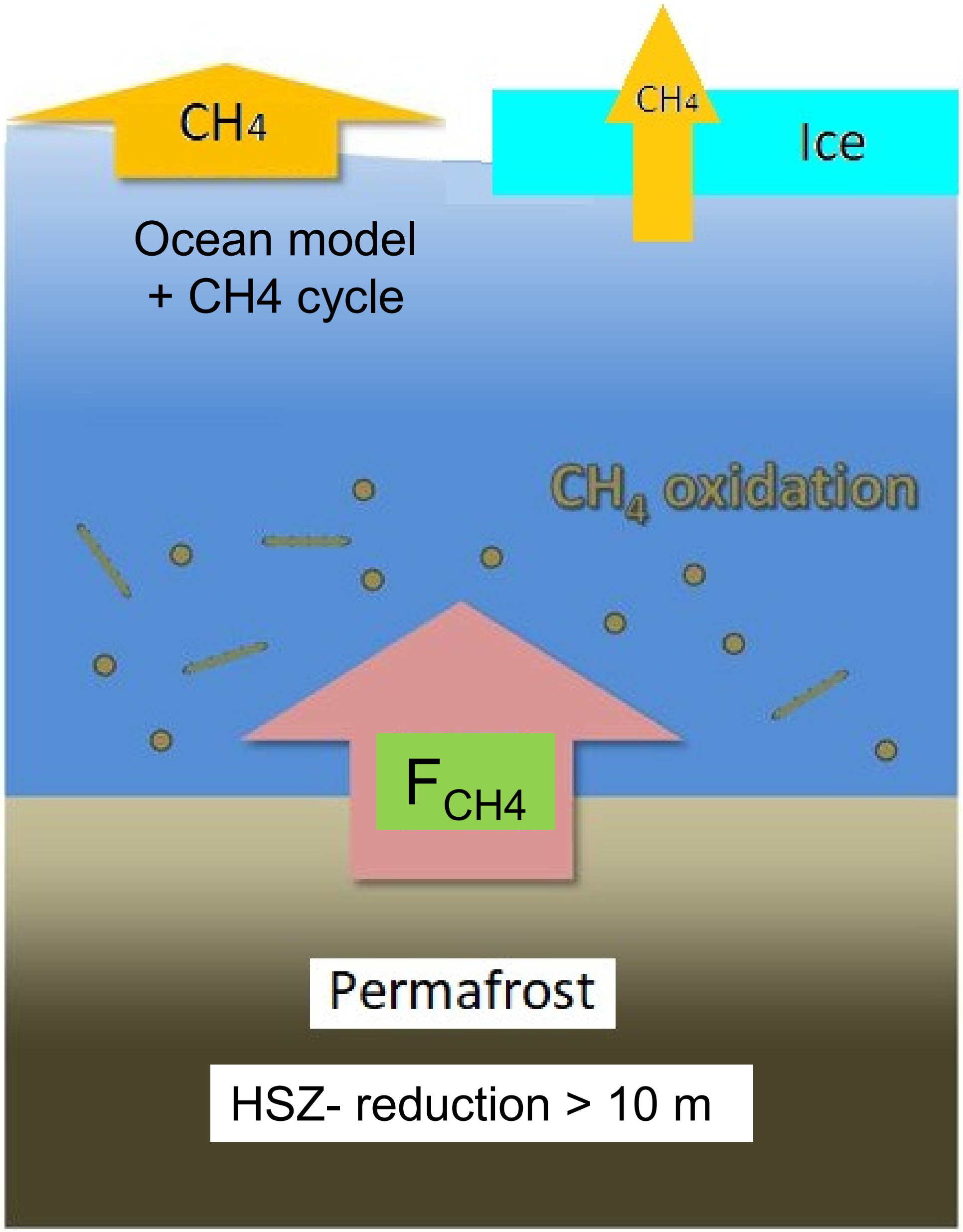
Note that the “gas hydrate stability zone” shows only potential methane hydrate occurrence



Methane hydrate saturation profiles for permafrost-related hydrate systems (Behseresht 2012).

- **Lags of HSZ thickness, with respect to temperature at the ocean–sediment interface**
- **Thawing subsea permafrost**
- **Thermokarst activity**
- **In the areas of oceanic rifts**
- **Effect of Salinity**

Coupled Ocean Modeling &CH_4 transport



- **Model of the dissolved methane transfer**
- **Diffusive fluxes from the bottom reservoirs:**

1) Subsea permafrost regions – 1 nmole/ м² in sec *(Shakhova2005, Wahstrom,2016)*

2) Hydrates in continental slopes. Deepening the upper boundary of the GHSZ > 10 m – 600-1000 nmole/ м² in sec *(Reagan M. T., Moridis G. J. 2008* «HydrateResSim»*)*

- **Methane oxidation in sea water** (Elliott,2011)
- ***The flux of CH_4 across the air-sea interface:***

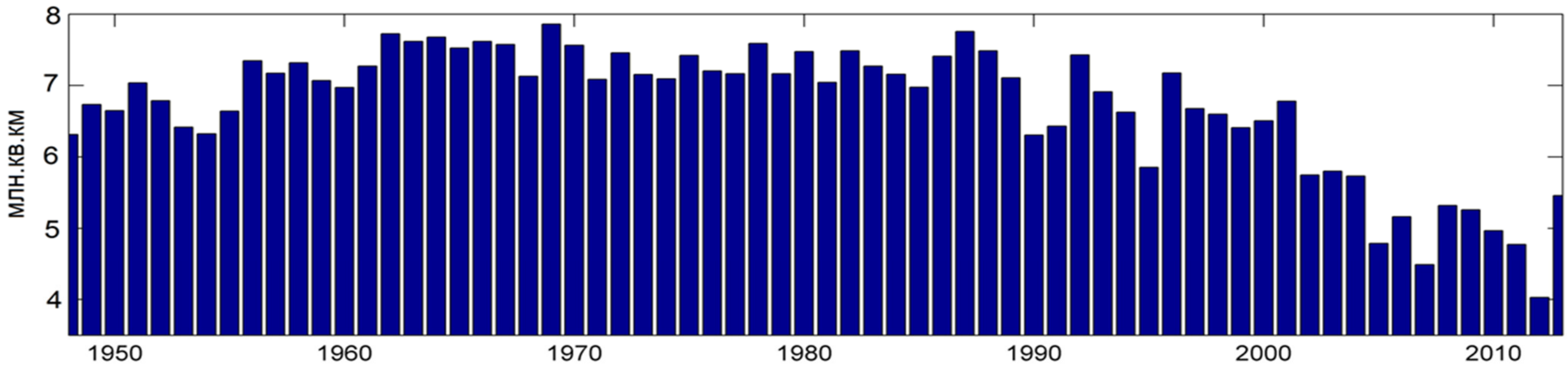
$$F = \kappa \left(\frac{Sc}{660} \right)^{-0.5} \Delta C \cdot (1 - Ice)$$

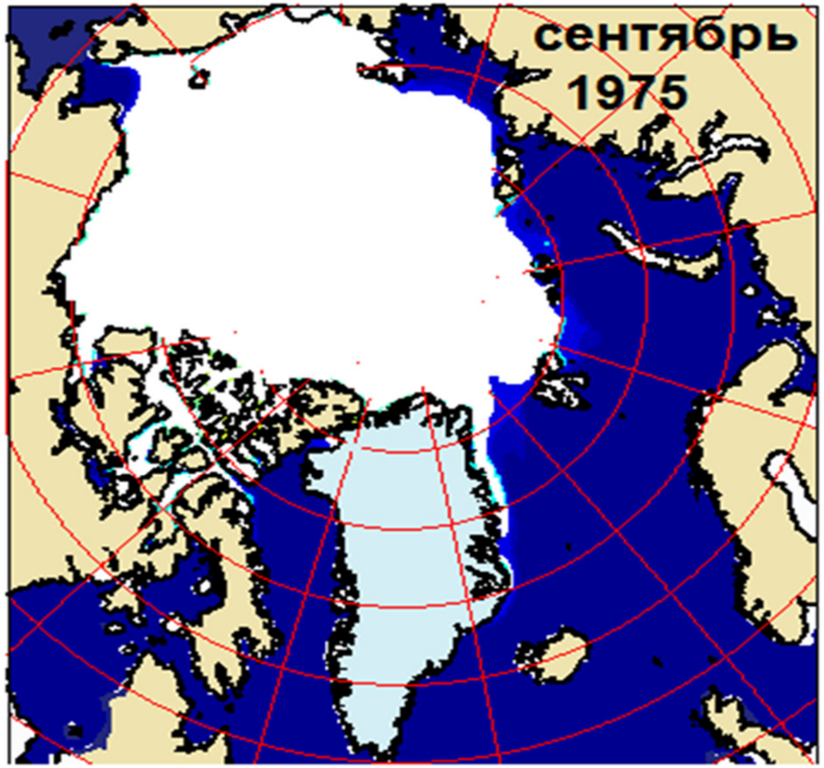
$$Sc = 2039.2 - 120.31T + 3.4209T^2 - 0.040437T^3$$

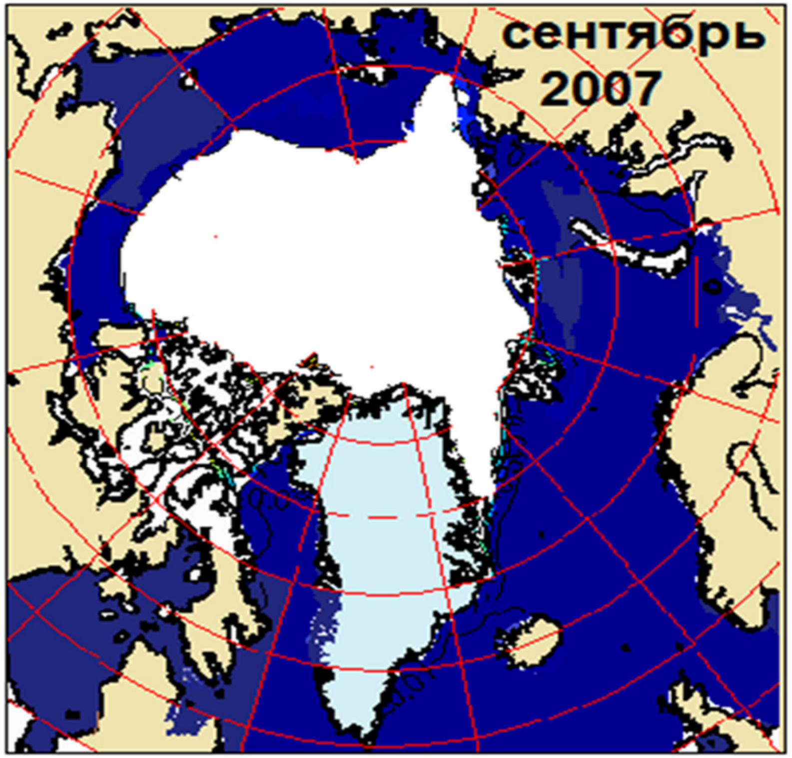
$$\kappa = F(\upsilon)$$

$$\Delta C = C - C_a(T,S)$$

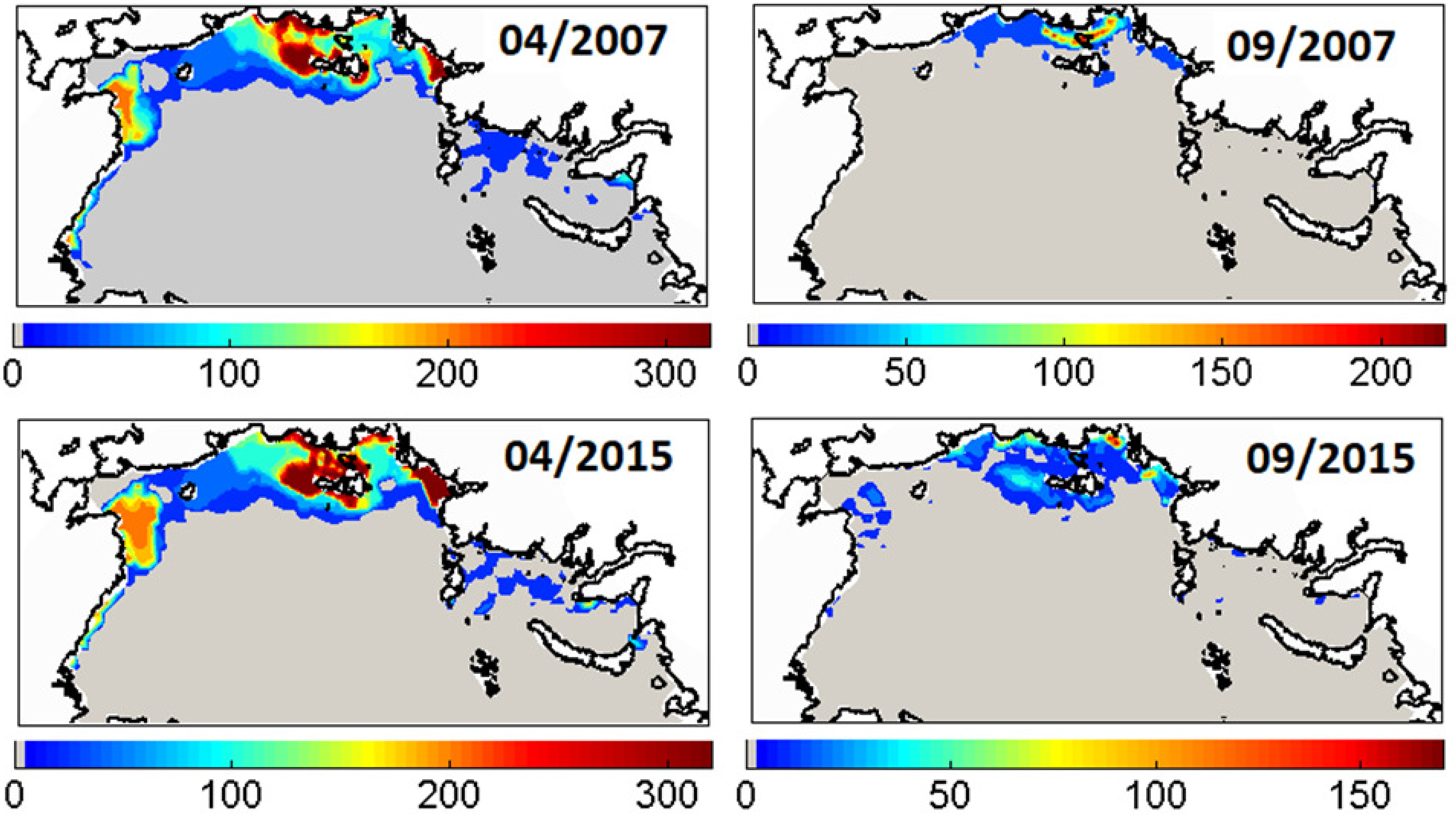
Arctic Sea ice extent. Numerical results



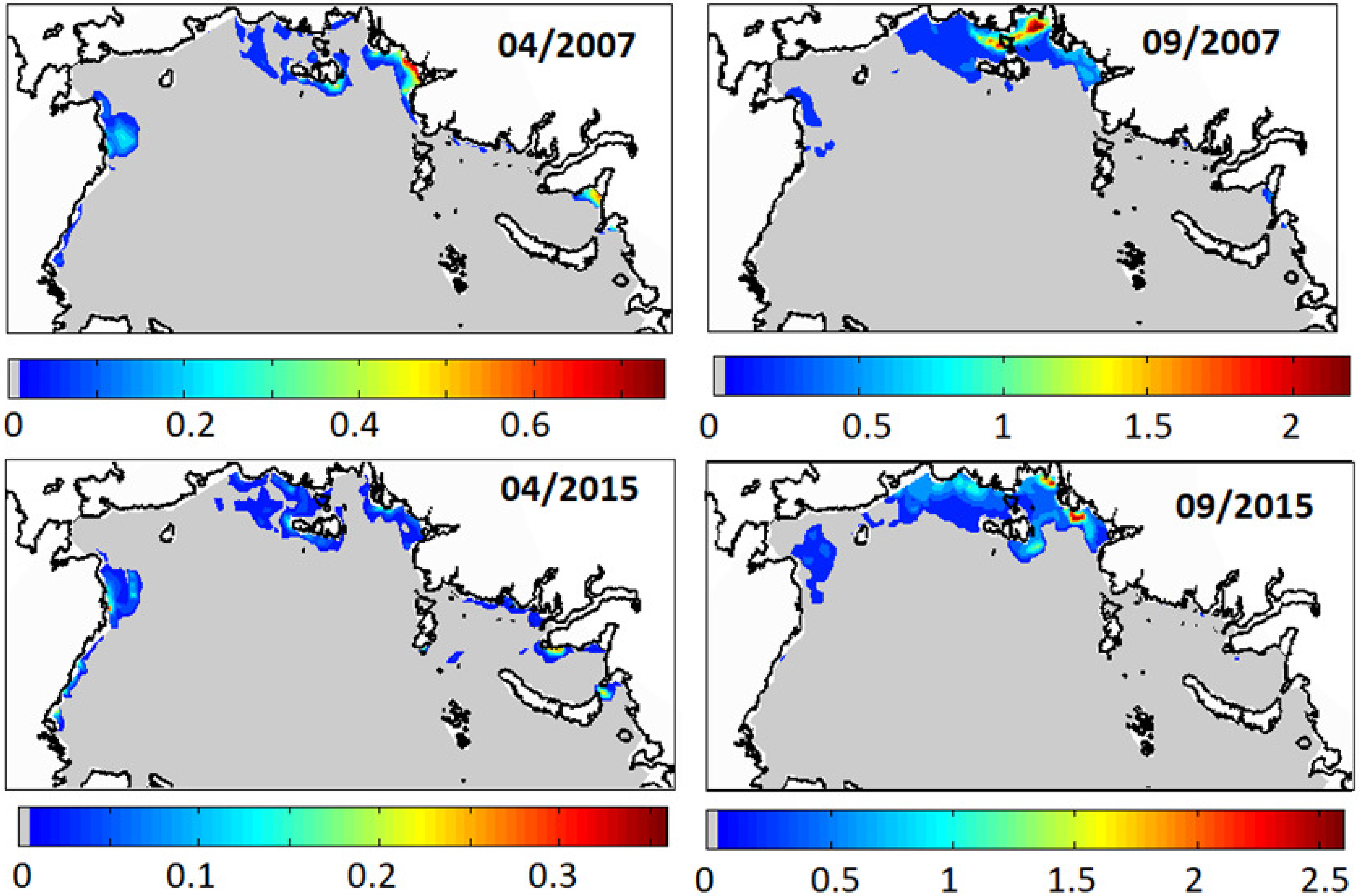




Numerical results:
CH4 in surface waters (в nM)

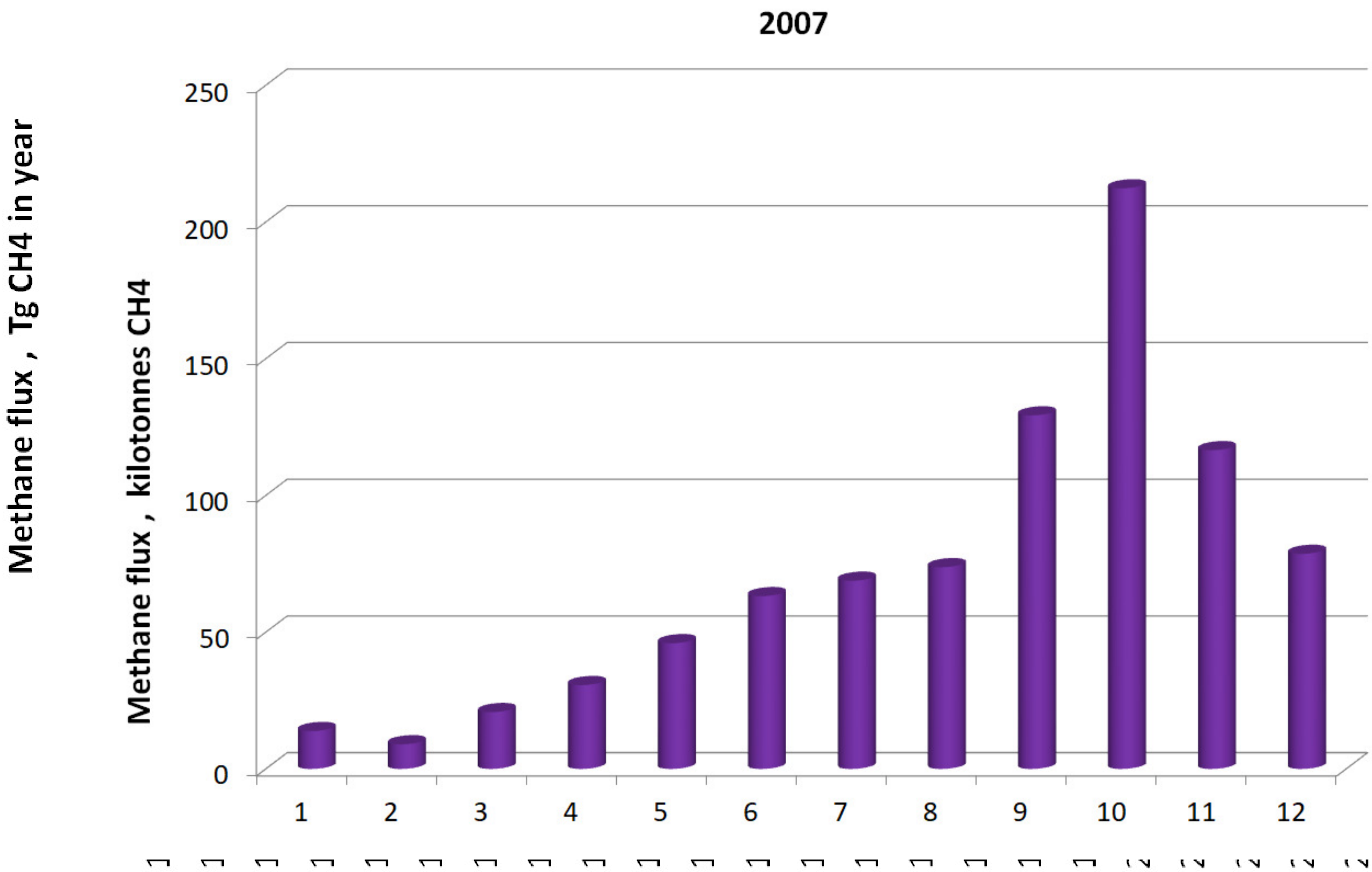


Sea-Air CH4 Fluxes (mg/m² in day)

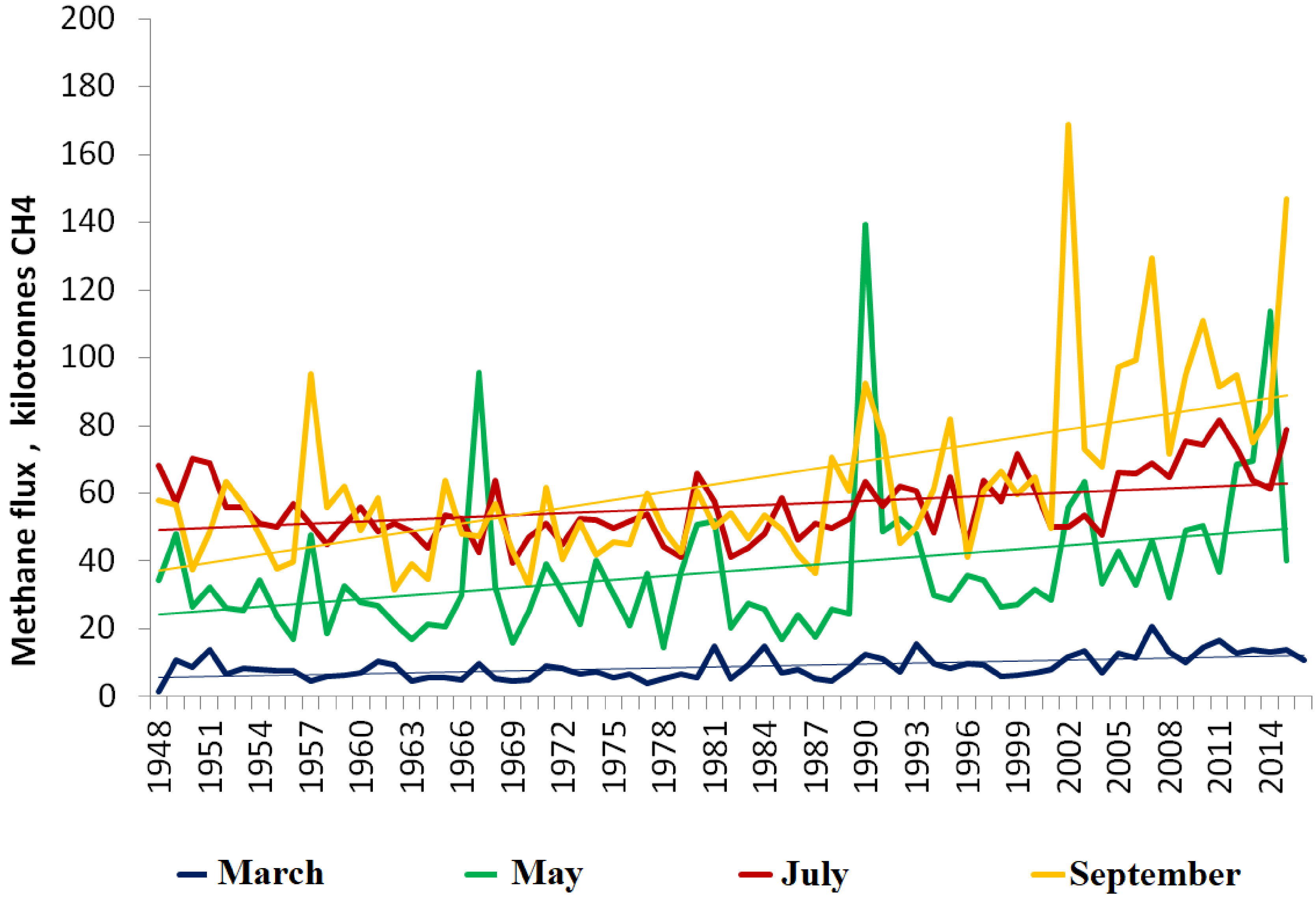


Measurements of CH4 in the atmosphere above, and surface waters of, the Laptev and East Siberian Seas, Thornton et al. (2016). Turbulence-driven sea-air fluxes along the ship's track were derived from these observations; an average diffusive flux of **3 mg/m2** in day was calculated for the Laptev Sea (for the ice-free period).

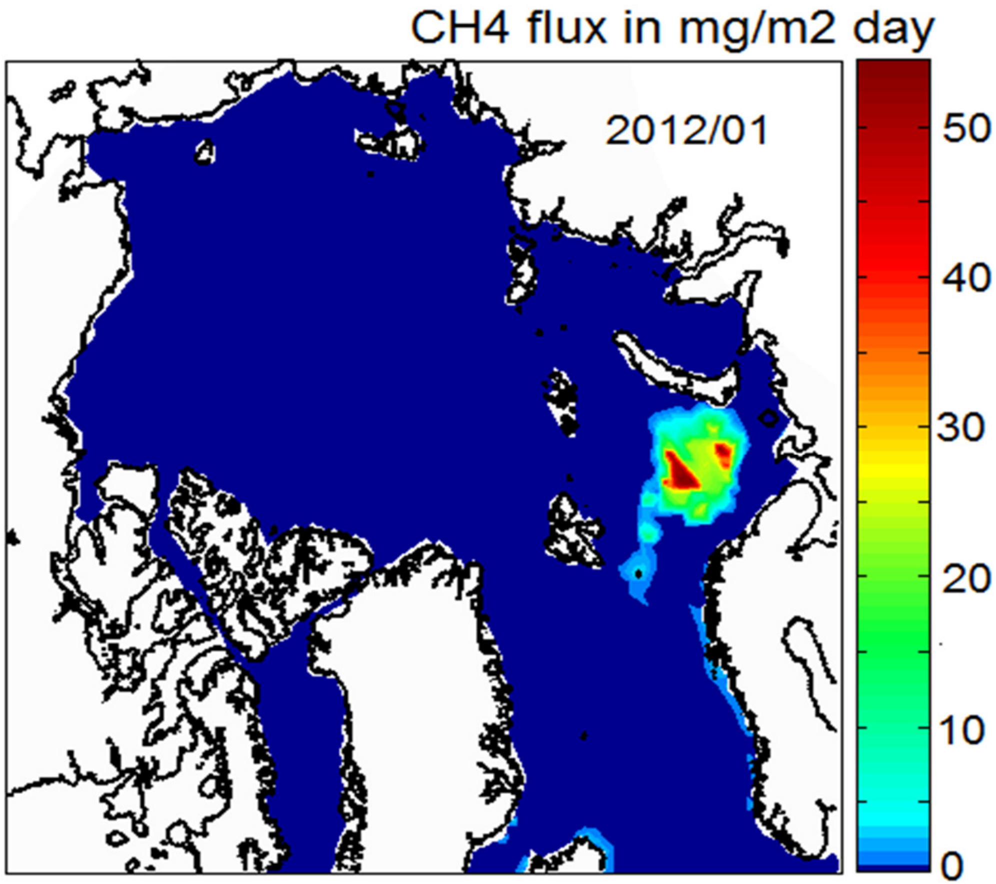
Coupled Ocean Modeling &CH_4 transport: methane flux from hydrates associated with subsea permafrost

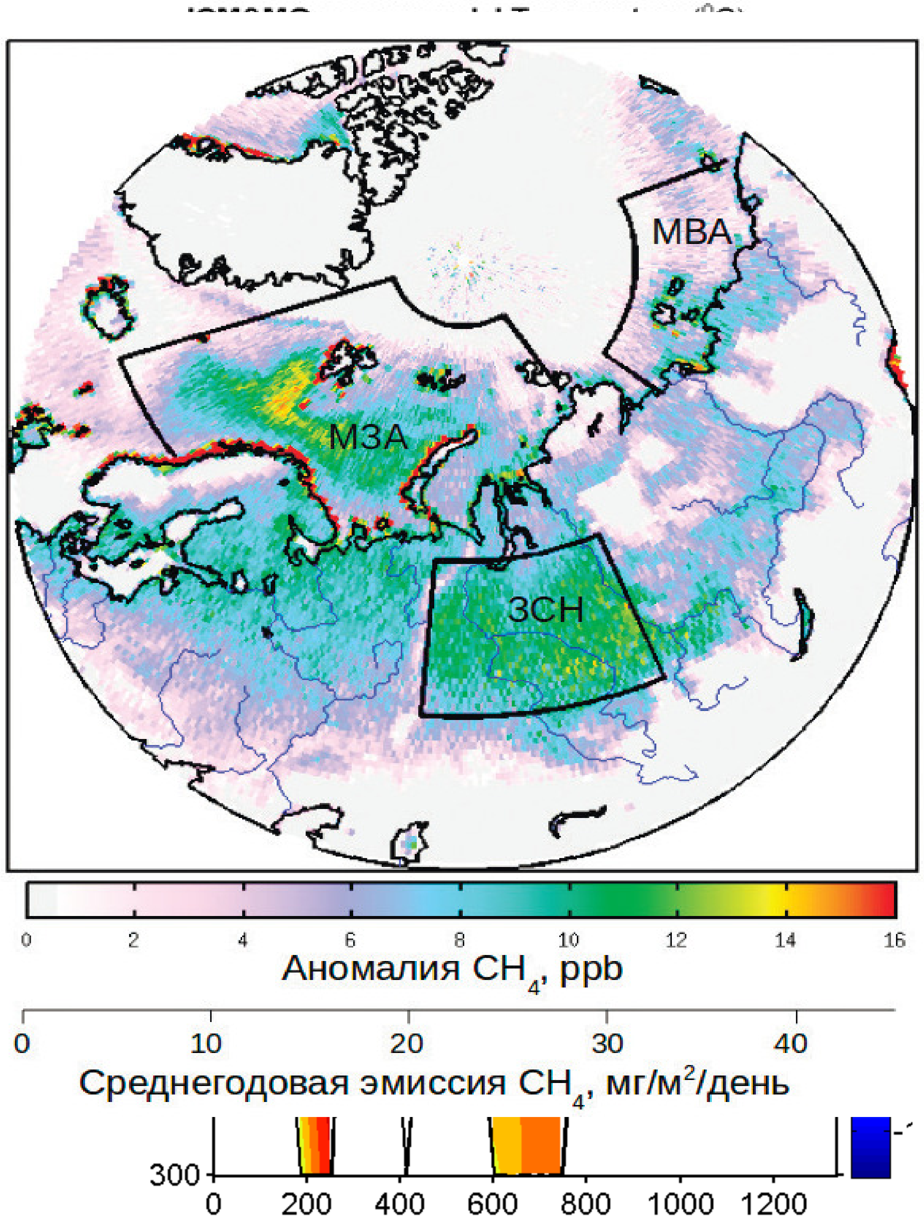


Methane flux from hydrates associated with subsea permafrost in month

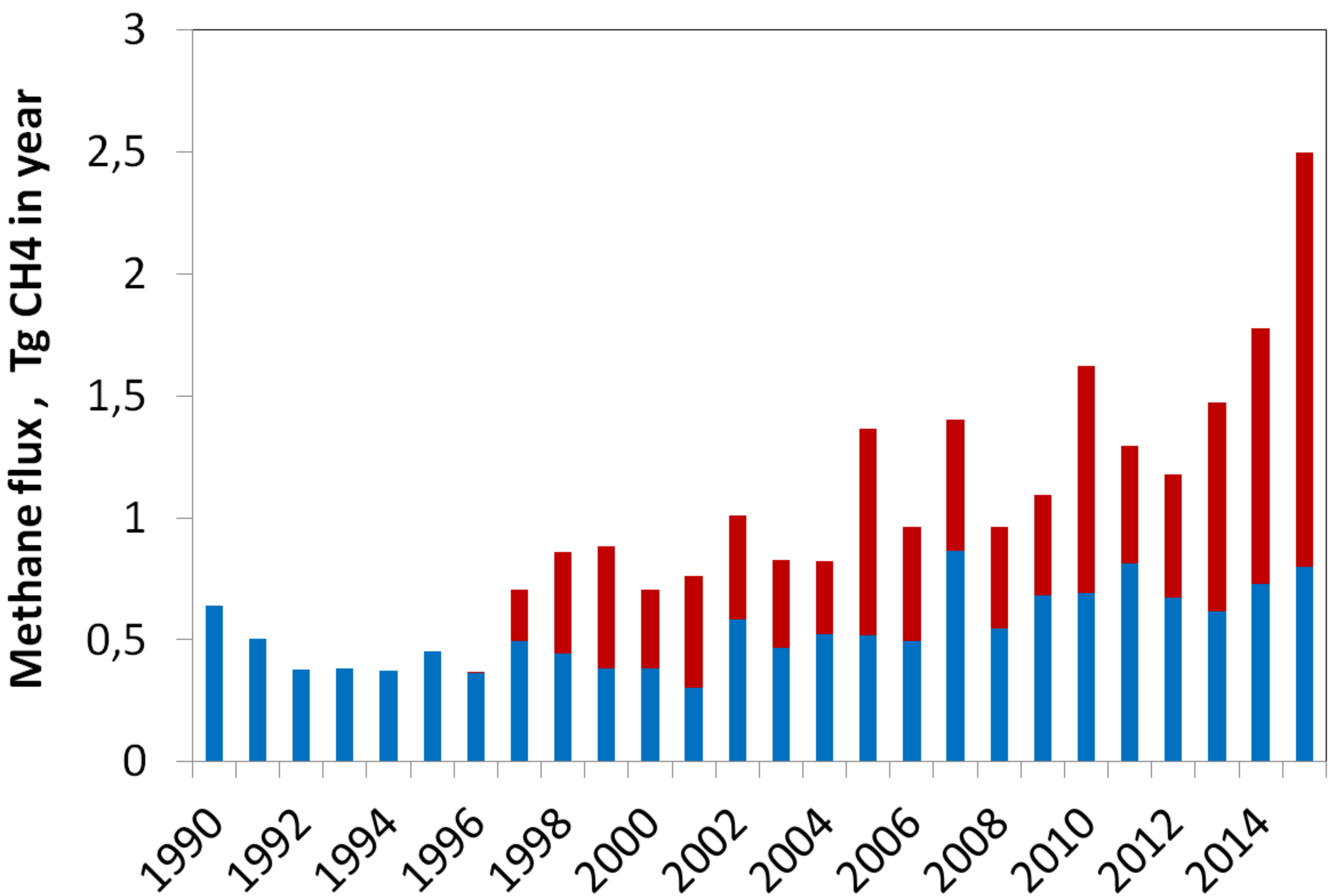


Coupled Ocean Modeling &CH_4 transport: methane flux from continental slopes hydrates





Methane flux



The total annual CH4 flux (in Tg) from Arctic to the atmosphere obtained in the experiments

Summary

- The results of the simulation of the dynamics methane hydrate stability zone in the Arctic Ocean sediment are presented.
- Our study shows that the gas hydrates in the upper continental slope sediments in the Arctic are the kind of the marine hydrates which are ready to dissolution during the ocean warming. We find that the reduction of the methane hydrate stability zone occurs in the Arctic Ocean between 250 and 400 m water depths in the Atlantic inflow area.
- The methane flux into the atmosphere from the bottom layers 250-400 m deep in the autumn-winter period can be explained by Intensification of seawater mixing in the ocean and the absence of ice cover in these areas.
- It has been shown that methane emission to the atmosphere (at constant CH4 fluxes from bottom sources) increases as a result of a decrease in the ice area in the shelf seas.
- Even when CH4 is released from gas hydrates, oxidative and physical processes may greatly reduce the amount that reaches the atmosphere as CH4
- The calculated CH4 diffusive flux into the atmosphere of the seas of the eastern Arctic exceed the fluxes for other shelf seas.
- However, they are about an order of magnitude lower than the estimates obtained in on the basis of measurement data.