Estimation of the possible climate change impact on the methane hydrate state in the Arctic Ocean

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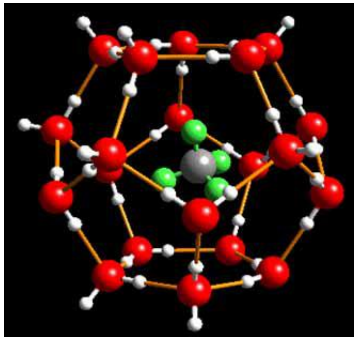
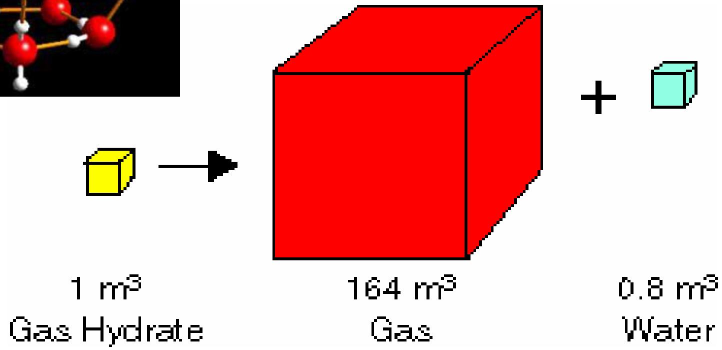
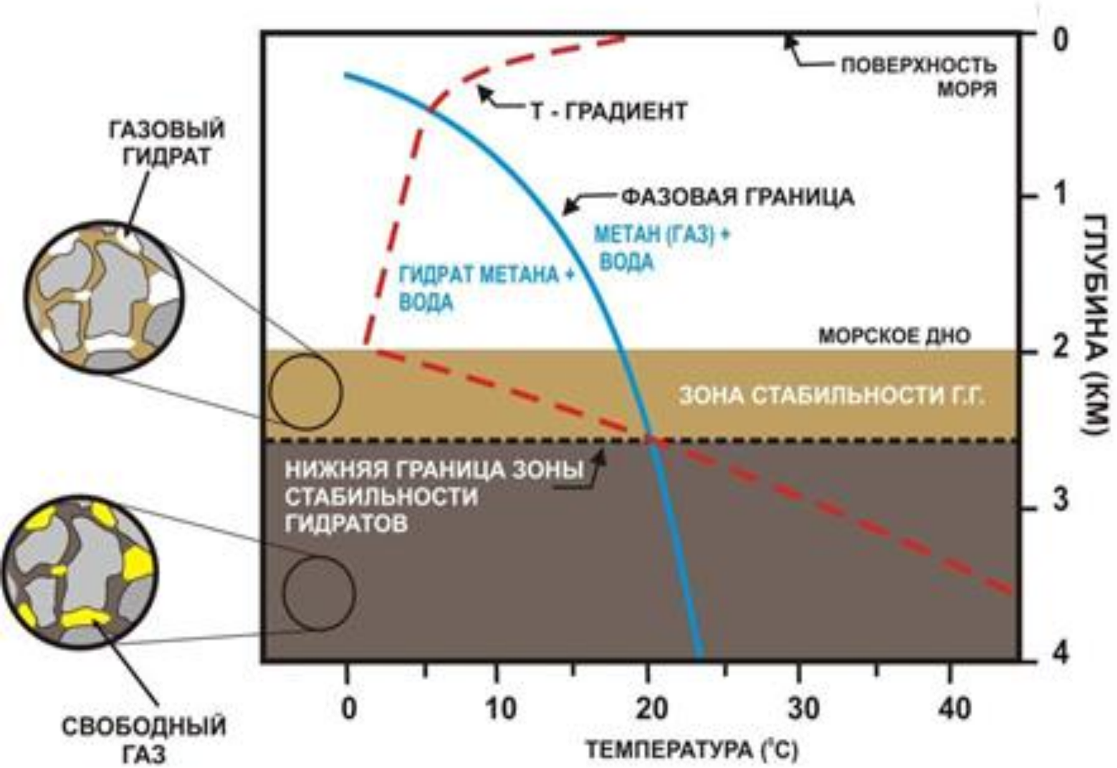
Methane Hydrate

- 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



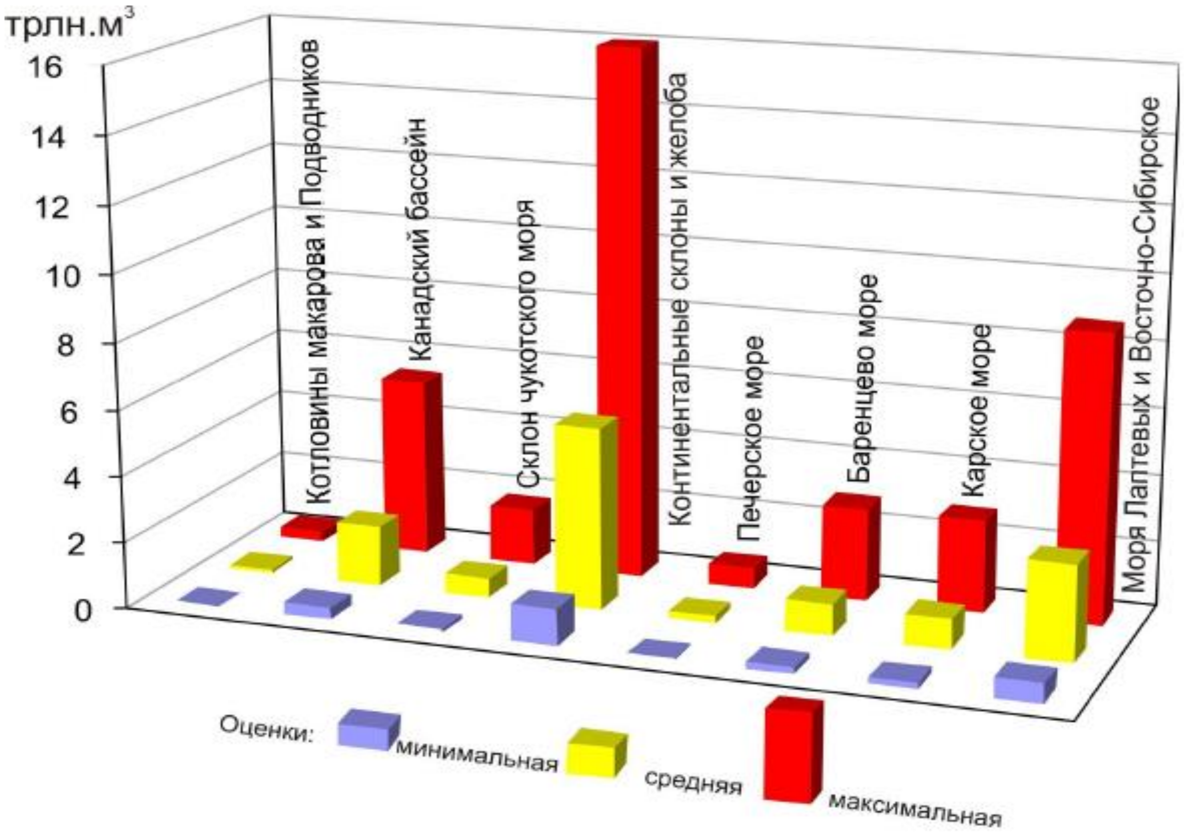
Gas Hydrate Stability Curve

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

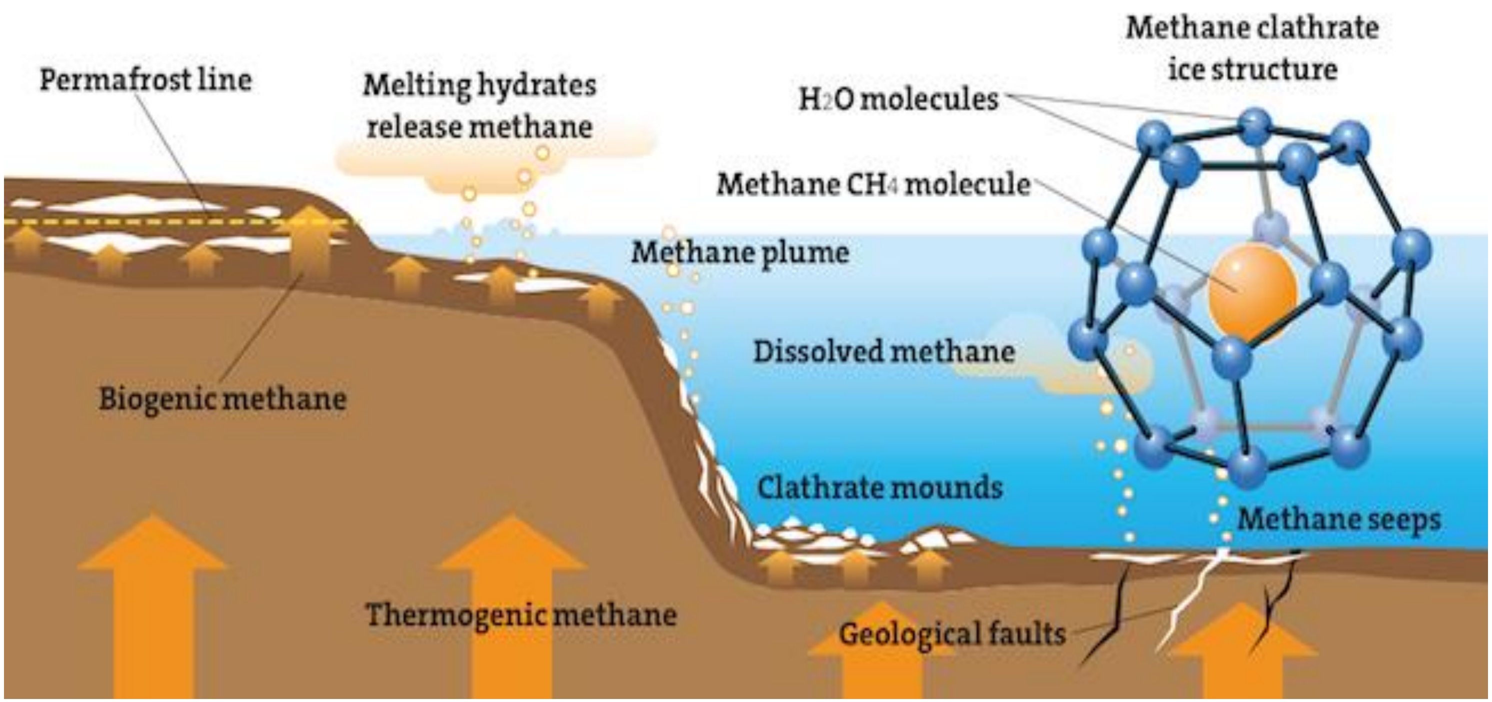
Gas hydrate presence in the Arctic

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

Gas hydrate resources in the Arctic Basins [Matveeva T.V., 2011]



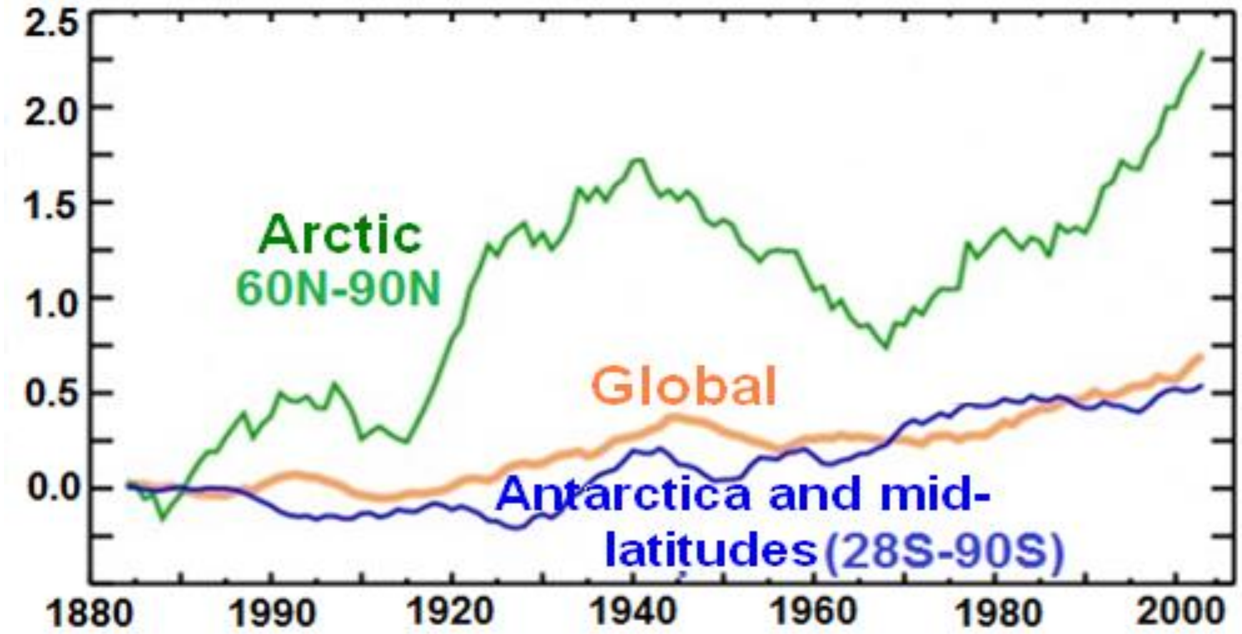
Gas hydrate in the Arctic



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)

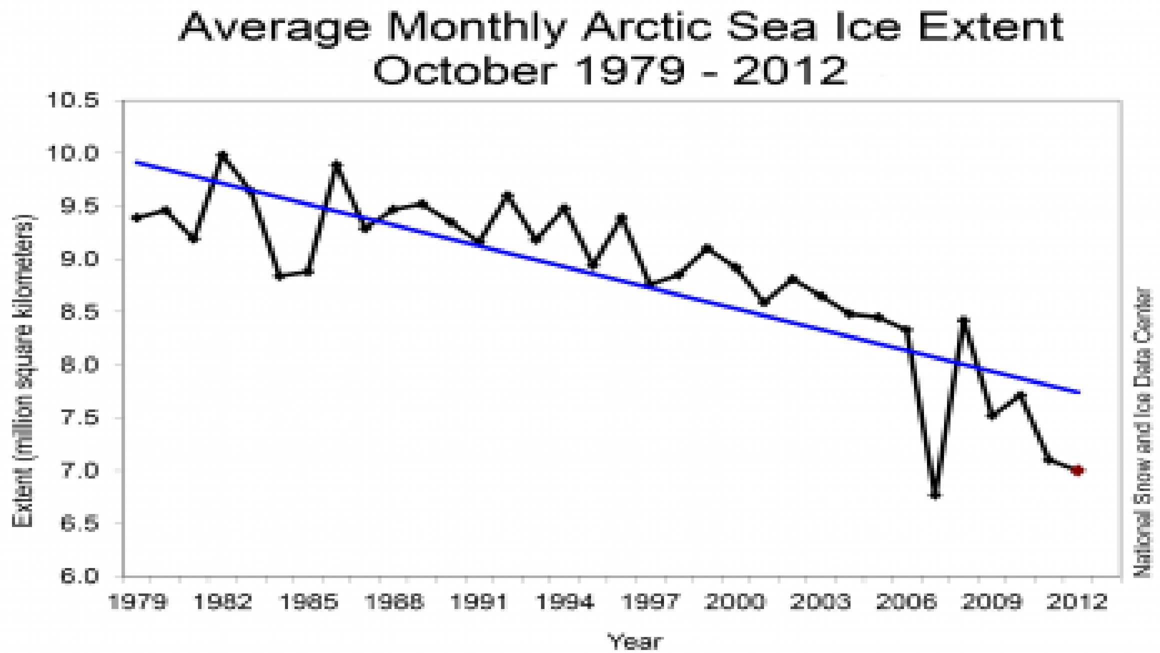
Motivation



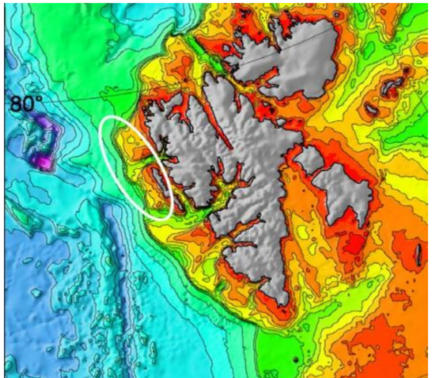
The temperature rise in the Arctic, compared to temperatures at lower latitudes (surface air temperatures as nine-year running means relative to the 1880–1890 mean)

http://www.nature.com/ngeo/journal/v2/n4/abs/ngeo473.html

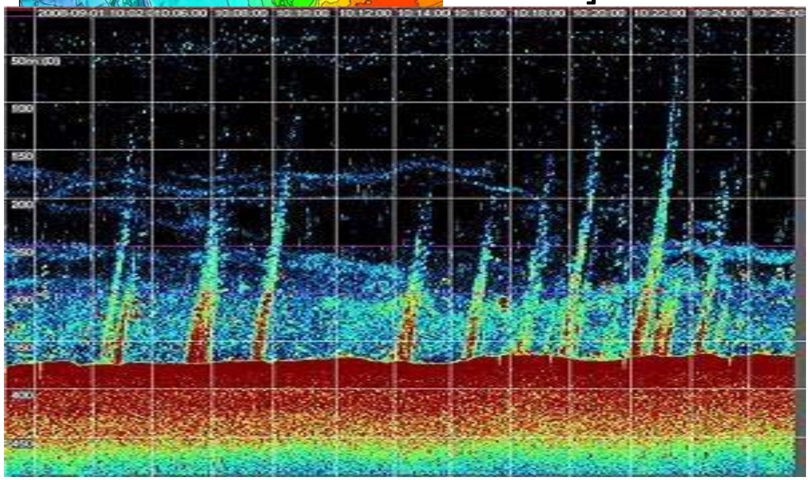
Yearly Minimum Arctic Ice Volume Data from the Pan-Arctic Ice Ocean Modeling and Assimilation System



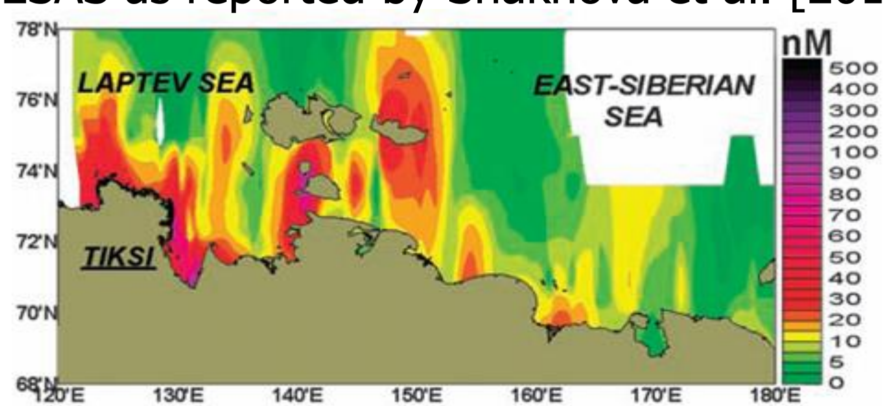
Methane plumes have been observed in the the Arctic

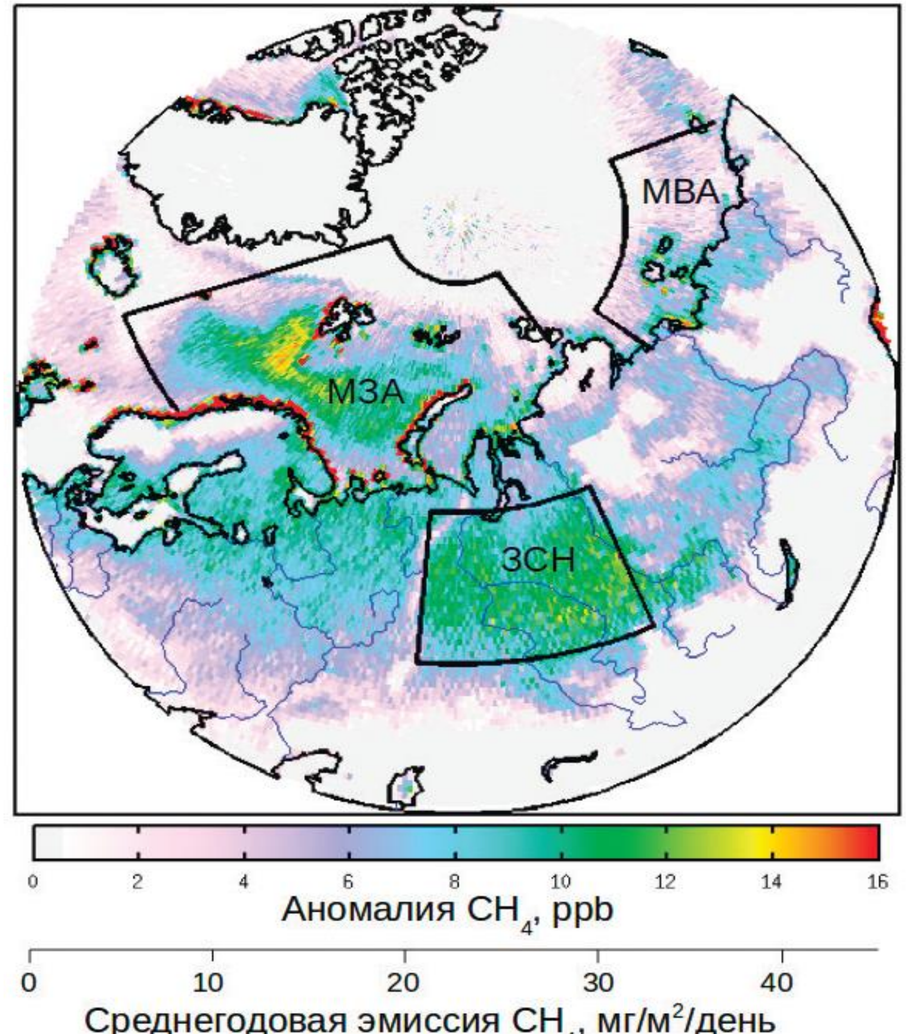


Sonar image of methane plumes rising from the Arctic Ocean floor near Svalbard in summer [Westbrook et al., 2009]



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



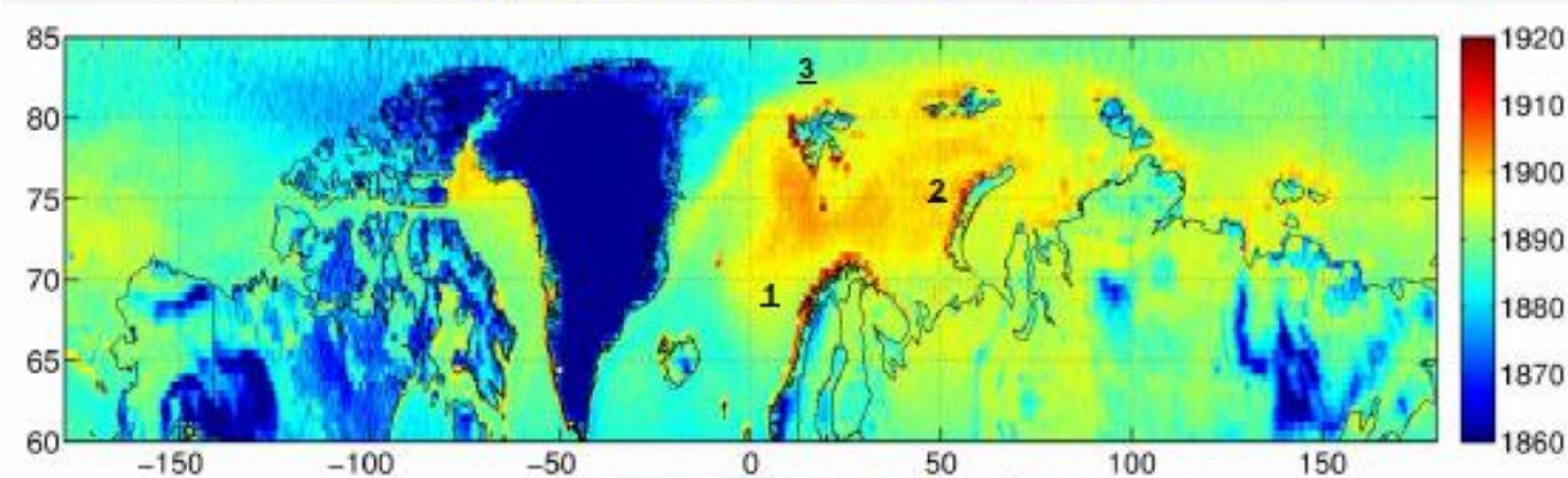


The distribution of the averaged anomalies of methane for 2010-2014 in the surface air (IASI data) [Юрганов и др. 2016]

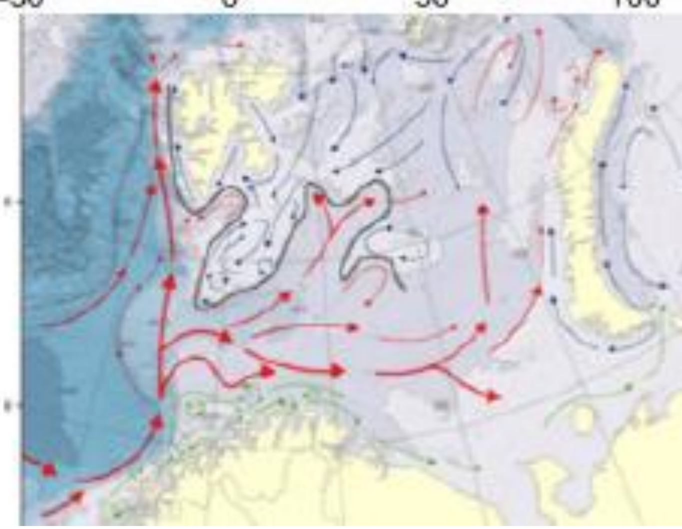
Locations of methane sources

IASI CH4 was averaged over all data of 2010-2014
At least 3 main emission areas were found:

1) North of Norway, 2) West of Novaya Zemlya 3) West of Svalbard.



Let's compare with the path of the warm Atlantic water



Ocean currents: red are warm

According to IASI data, the Arctic Ocean, mostly along the coasts of Norway, Novaya Zemlya and Spitsbergen, contributes ~2/3 of methane emitted from the terrestrial Arctic.

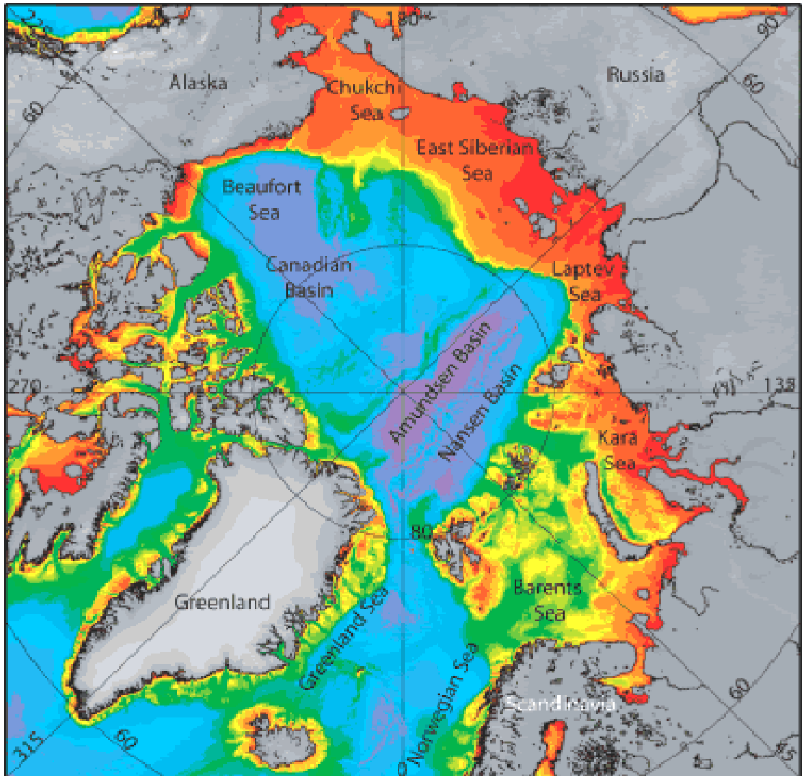
Yurganov L.N., 2017

The Numerical Model configurations

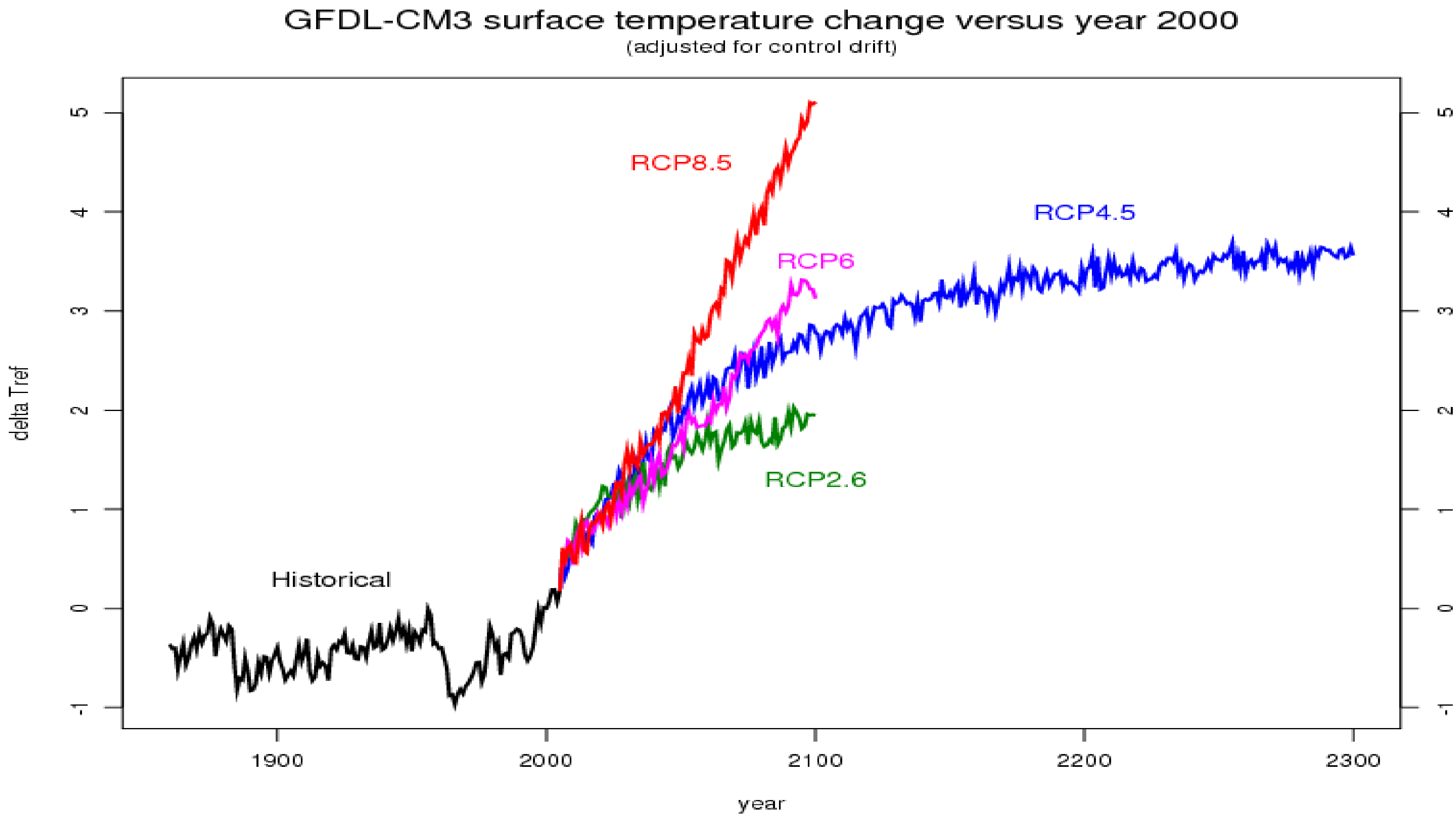
- ***3D World Ocean Circulation Model of ICMMG based on z-level vertical coordinate approach*** *[Golubeva and Platov, 2007]*
- ***Ice model-CICE 3.0 (elastic-viscous-plastic)*** *[W.D.Hibler ,1979; E.C.Hunke, J.K.Dukowicz,1997; G.A.Maykut 1971 C.M.Bitz, W.H.Lipscomb 1999,J.K.Dukowicz, J.R.Baumgardner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

- ***Atmospheric data from the NCEP/NCAR reanalysis (1948-2005)***
- ***For future climate change (2006-2100), model simulations forced by the RCP 8.5 scenario***

- ***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]*



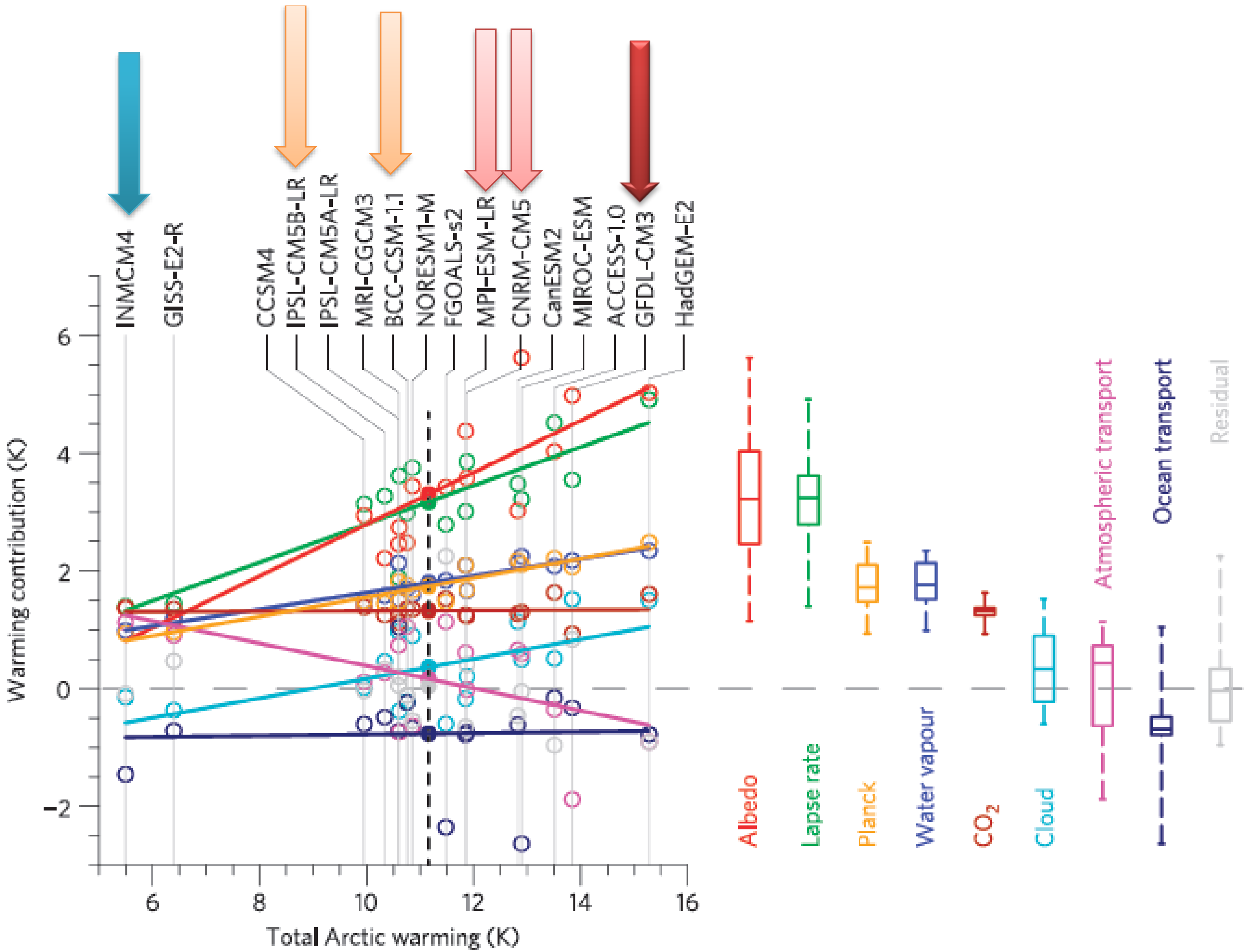
RCP scenario



Under the RCP 8.5 scenario (Stocker, 2013) the Arctic temperature could rise as much as 10-12 degrees by 2100 in certain areas.

Arctic amplification dominated by temperature feedbacks in contemporary climate models

Felix Pithan* and Thorsten Mauritsen



INMCM4

IPSL-CM5B-LR

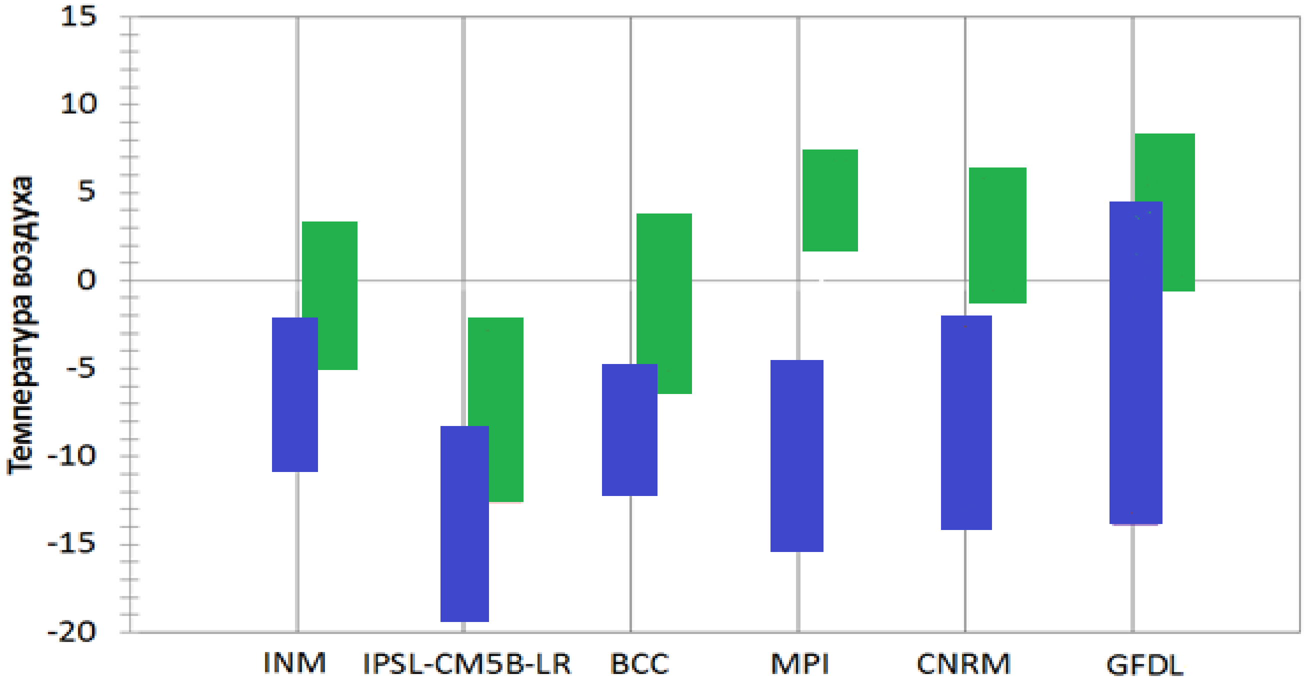
BCC-ESM

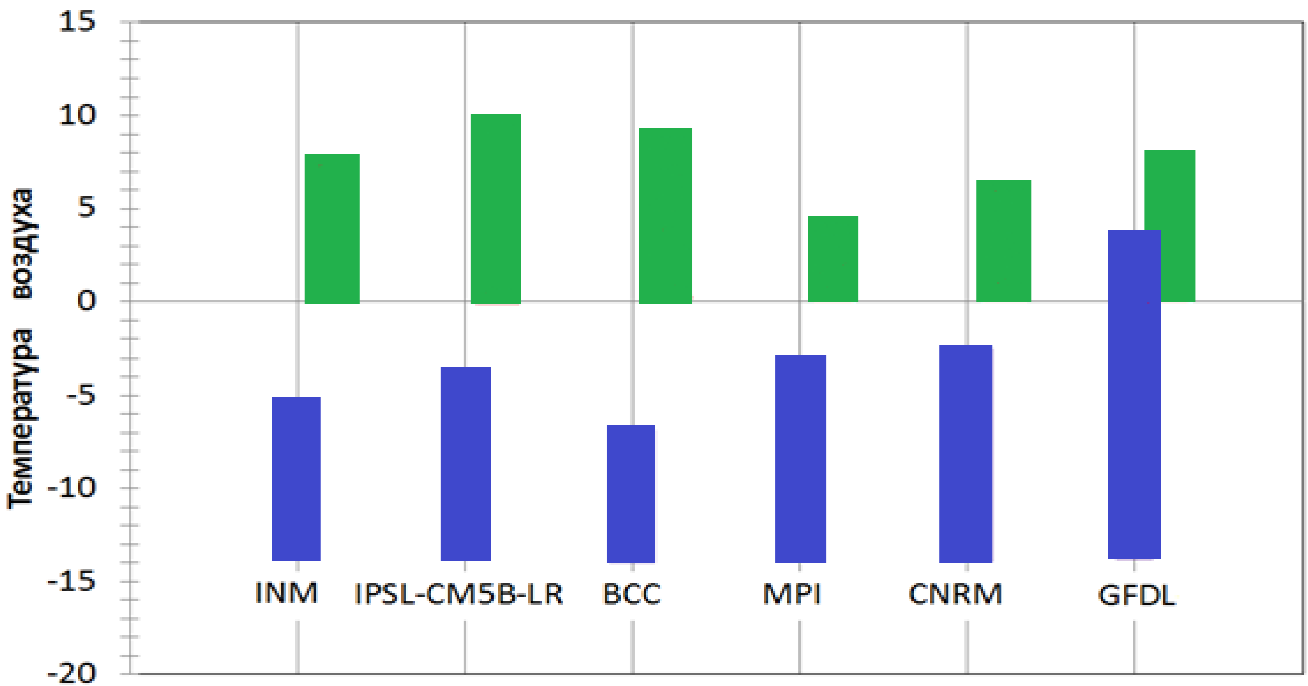
MPI-ESM-LR

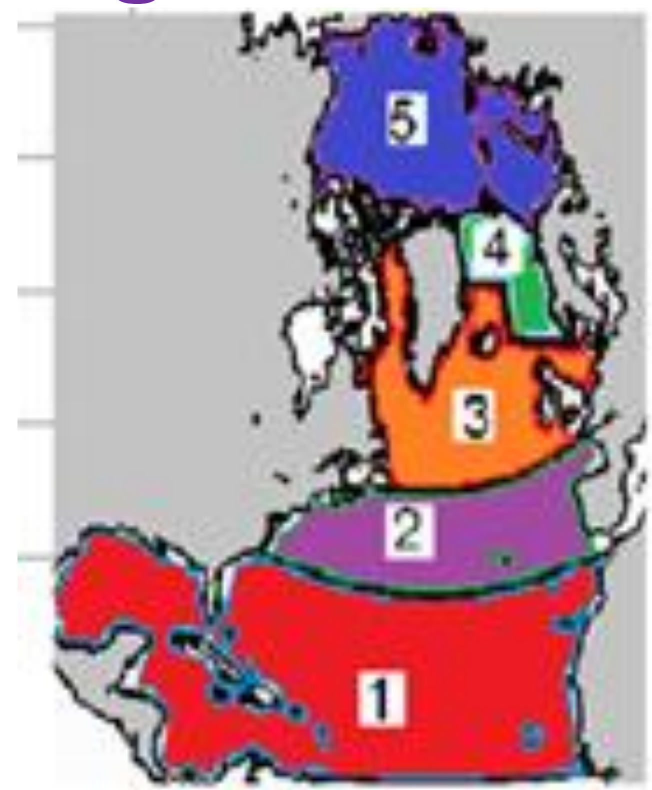
CNRM-CM5

GFDL-CM3

Arctic temperature change



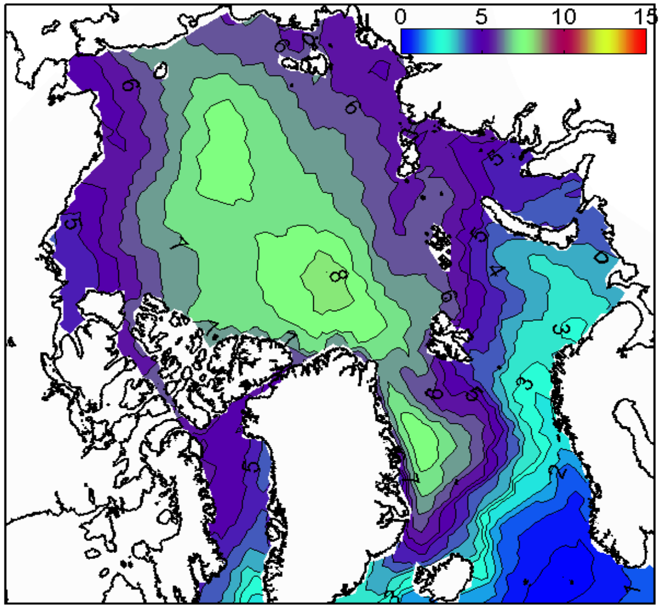




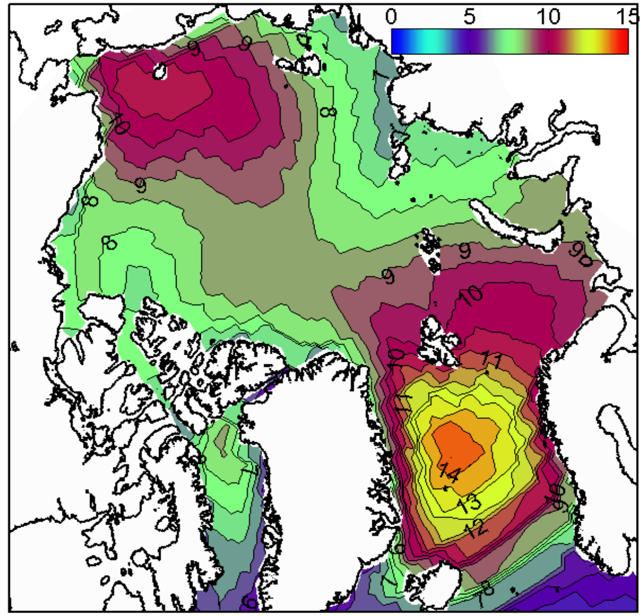
The approach utilizes an ensemble of six CMIP5 climate predictions to the *Ocean Circulation Model of ICMMG and to the transient evolution of hydrate stability*

Warming in the Arctic (2015-2006)/(2100-2091)

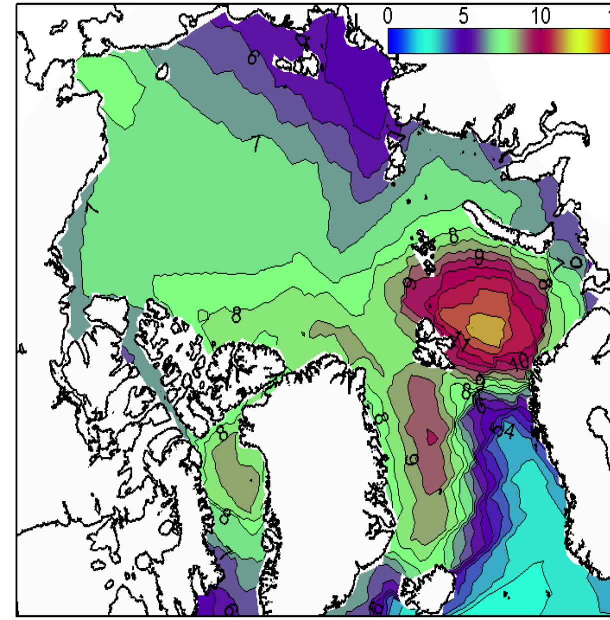
INMCM4



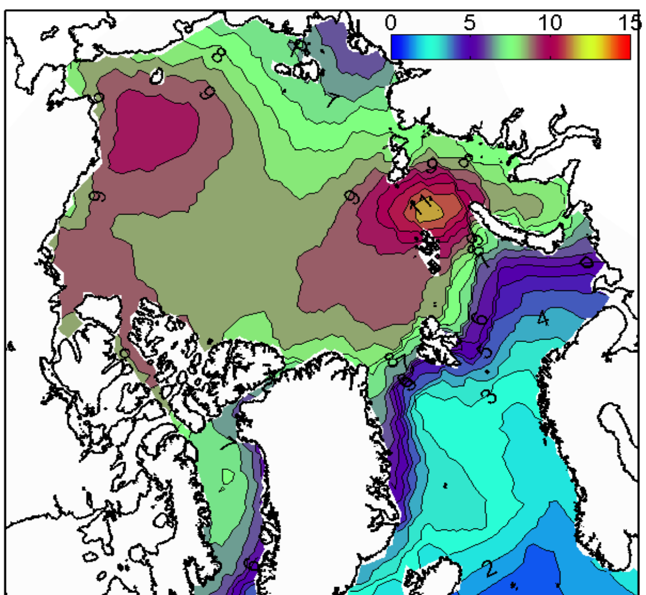
IPSL-CM5B-LR



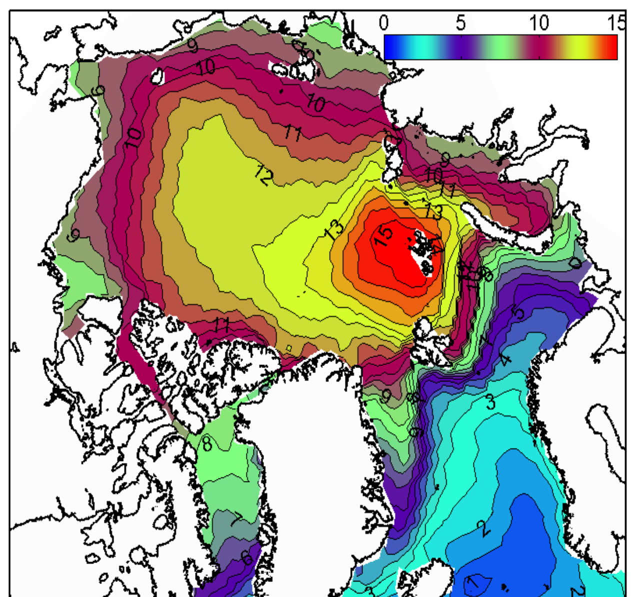
BCC-ECM



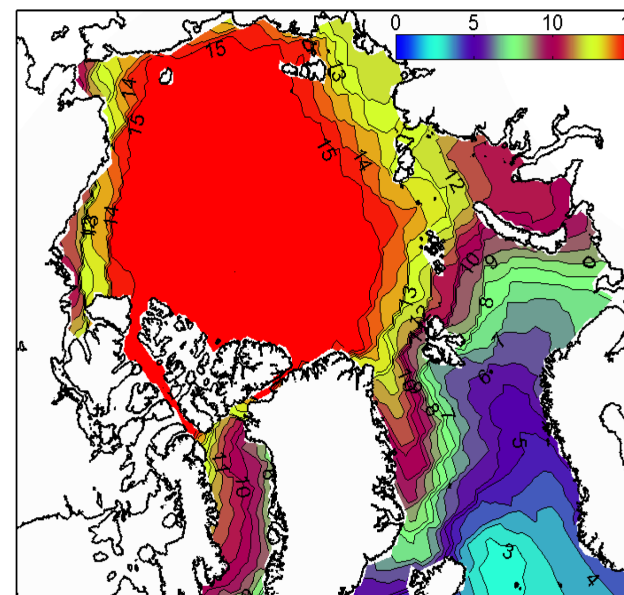
MPI-ESM-LR



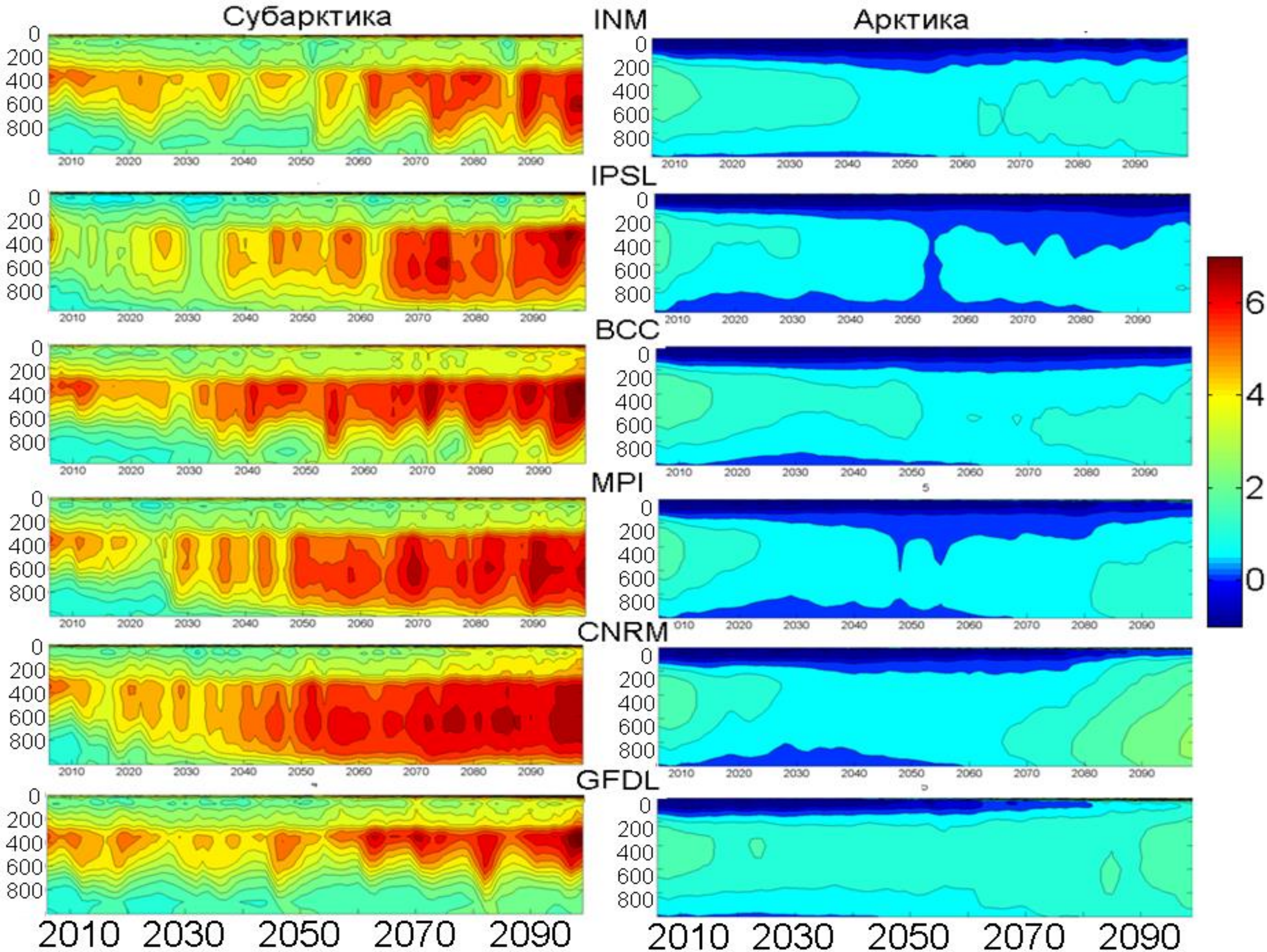
CNRM-CM5



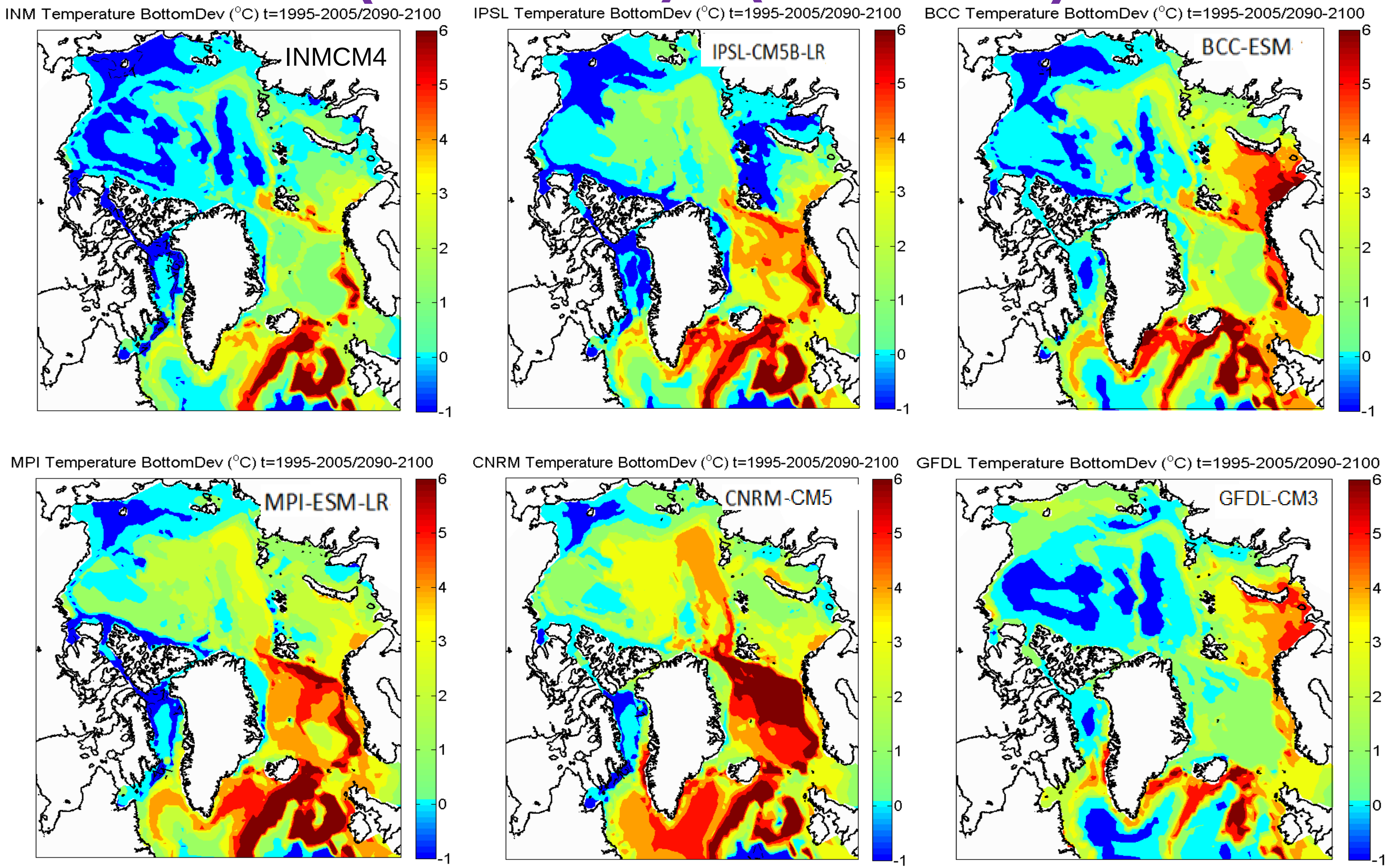
GFDL-CM3



The temperature variability predictions in the 1000-m ocean layer



Near-bottom water warming in the Arctic (2095-2100) - (1995-2005)



Governing equations of Permafrost model

$$C_{SN}\frac{\partial T_{SN}}{\partial t}=\frac{\partial}{\partial z}\left(\lambda_{SN}\frac{\partial T_{SN}}{\partial z}\right)$$

$$C_{T}\frac{\partial T_{S}}{\partial t}=\frac{\partial}{\partial z}\left(\lambda_{T}\frac{\partial T_{S}}{\partial z}\right)$$

$$C_{M}\frac{\partial T_{S}}{\partial t}=\frac{\partial}{\partial z}\left(\lambda_{M}\frac{\partial T_{S}}{\partial z}\right)$$

$$\frac{\partial (W_N S)}{\partial t}=\frac{\partial}{\partial z}\left(D_{S}\frac{\partial S}{\partial z}\right)$$

Фазовый переход на границе между мерзлой и талой зоной:

$$T_S=T_F(S)$$

$$\left(\lambda_T\frac{\partial T_{ST}}{\partial z}-\lambda_M\frac{\partial T_{SM}}{\partial z}\right)=L(W_S(z)-W_N)\frac{\partial X}{\partial t}$$

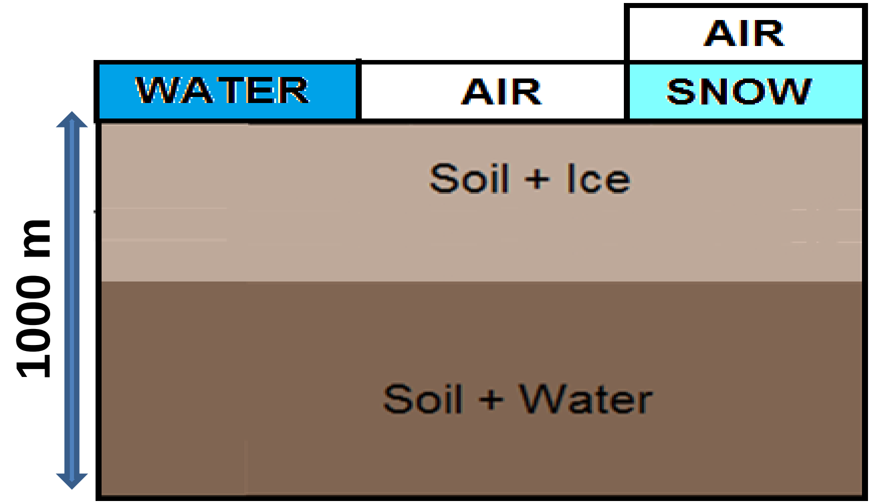
Граничные условия

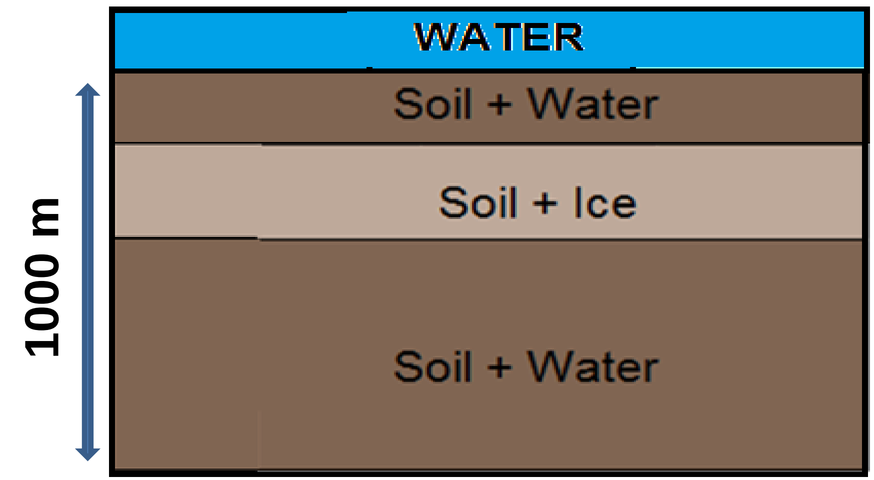
$$z=0: T_S=T_B(t)$$

$$z=H_S:\lambda_T\frac{\partial T_S}{\partial z}=Q_T$$

$$T_B(t)=T_{SN}(t)$$

$$T_B(t)=T_A+T_{PAL}(t)$$



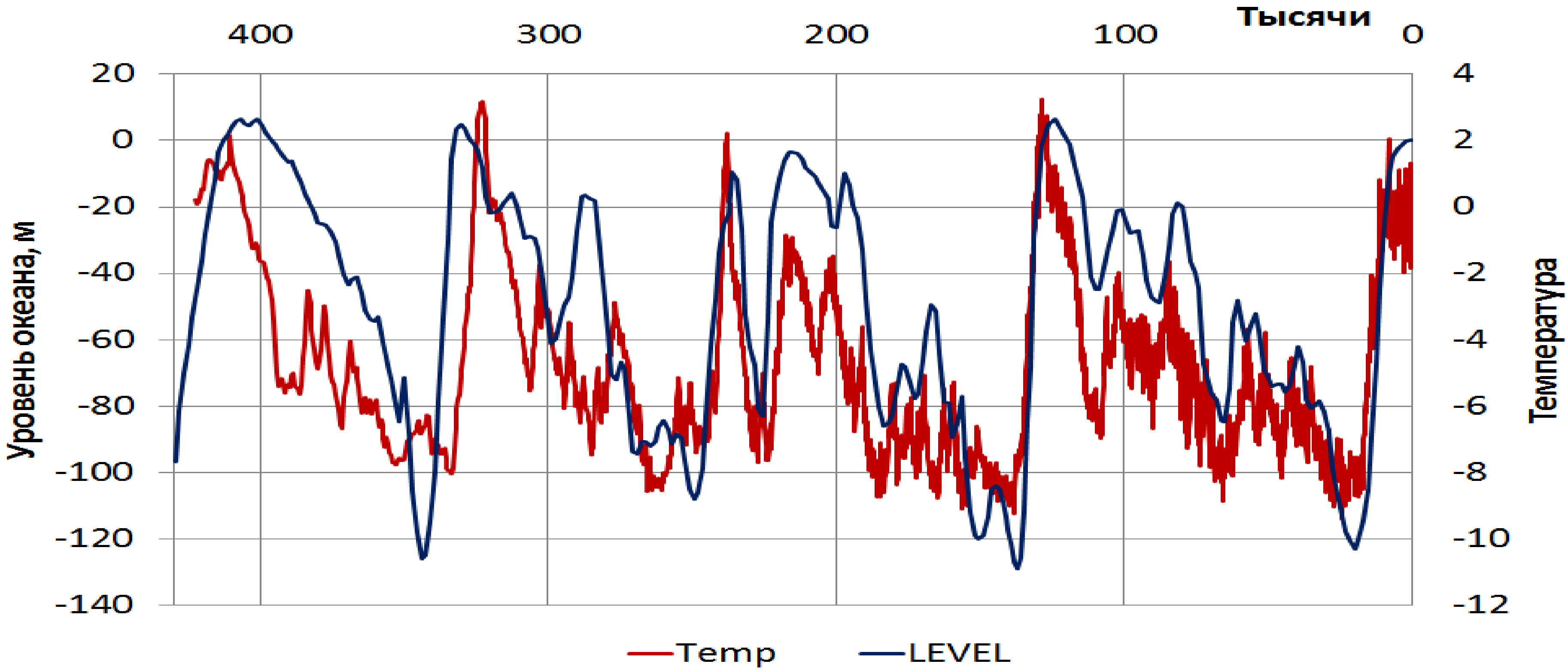


$$T_F(z)=-0.064\cdot S(z)-0.073\cdot P(z)$$

«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

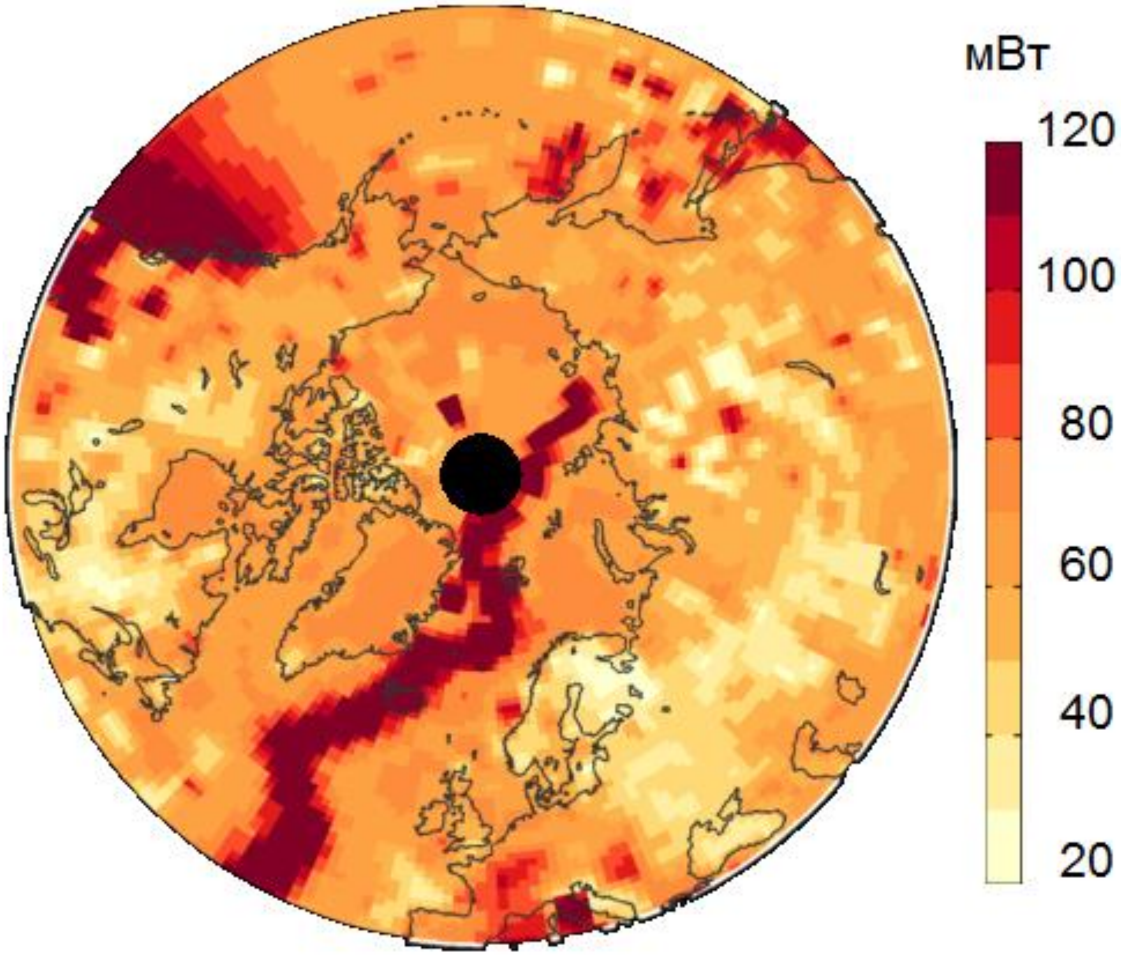


$$T_B = \begin{cases} T_{BW} \\ T_A + \Delta T_{Pal} \end{cases}$$

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

Petit J.R., 1999
Climate and atmospheric history of the past 420,000 years from the Vostok ice core, Antarctica

Heat Flow

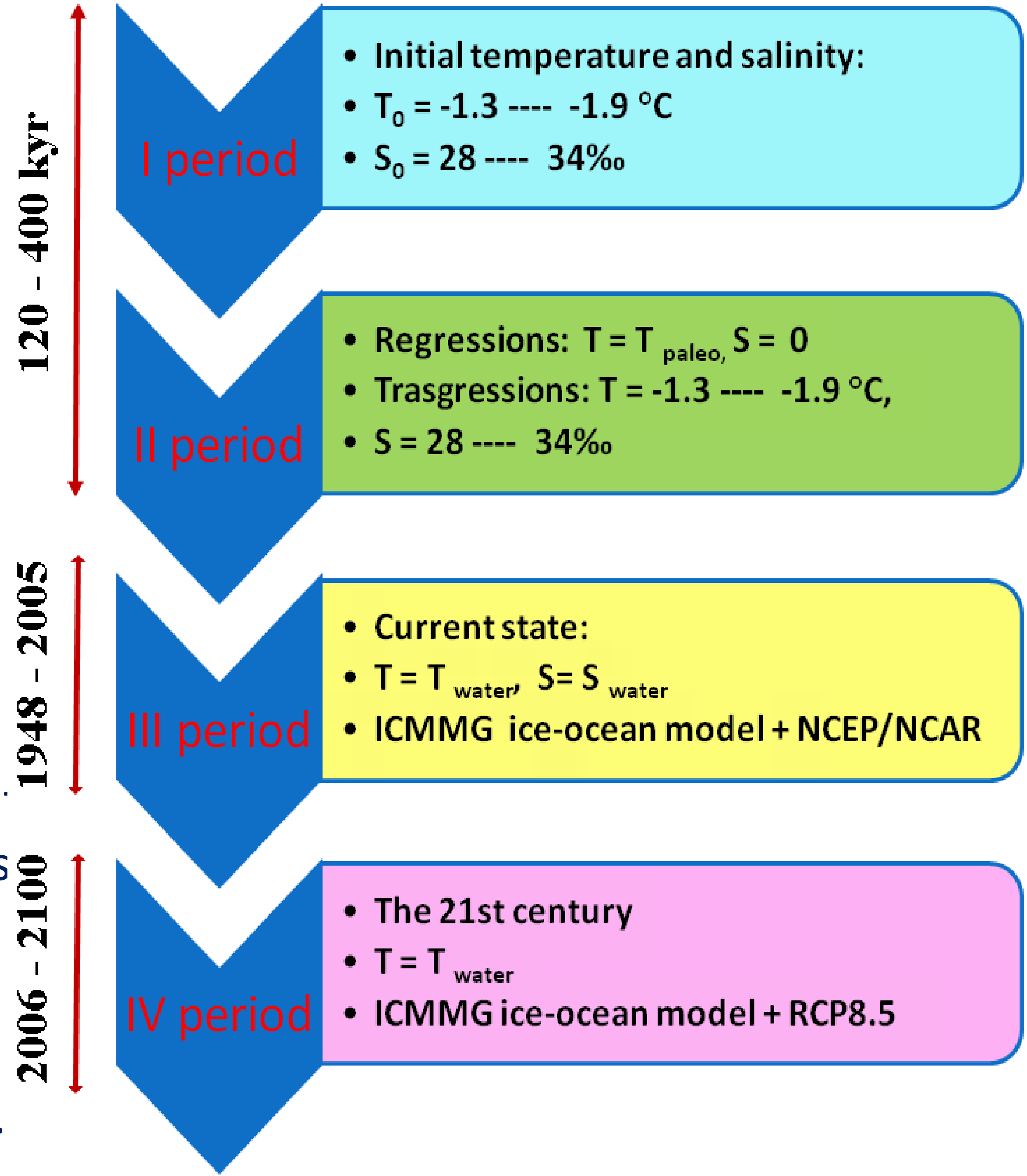


World Heat Flow Database

(Davies J. H. Global map of Solid Earth surface heat flow, 2013)

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).
- These timings should depend on the contemporary shelf depth.



P-T relationships

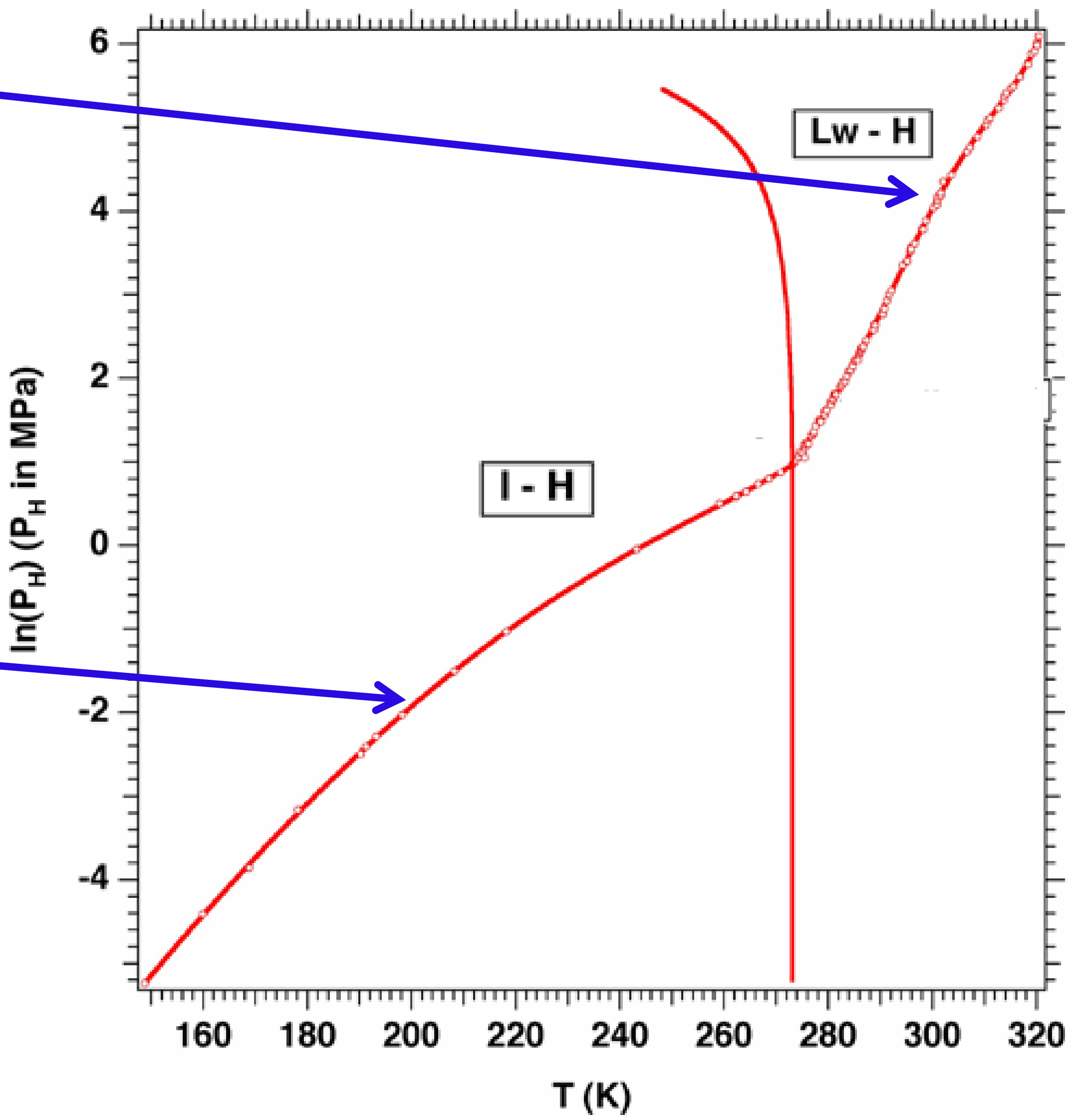
«HydrateResSim» [Reagan M. T., Moridis G. J., 2008]

For T>273.2 ^{0}K:

$$\ln(P_e) = -1.94138504464560\times10^{5} +3.31018213397926\times10^{3}\,T -2.25540264493806\times10^{1}\,T^{2} +7.67559117787059\times10^{-2}\,T^{3} -1.30465829788791\times10^{-4}\,T^{4} +8.86065316687571\times10^{-8}\,T^{5}$$

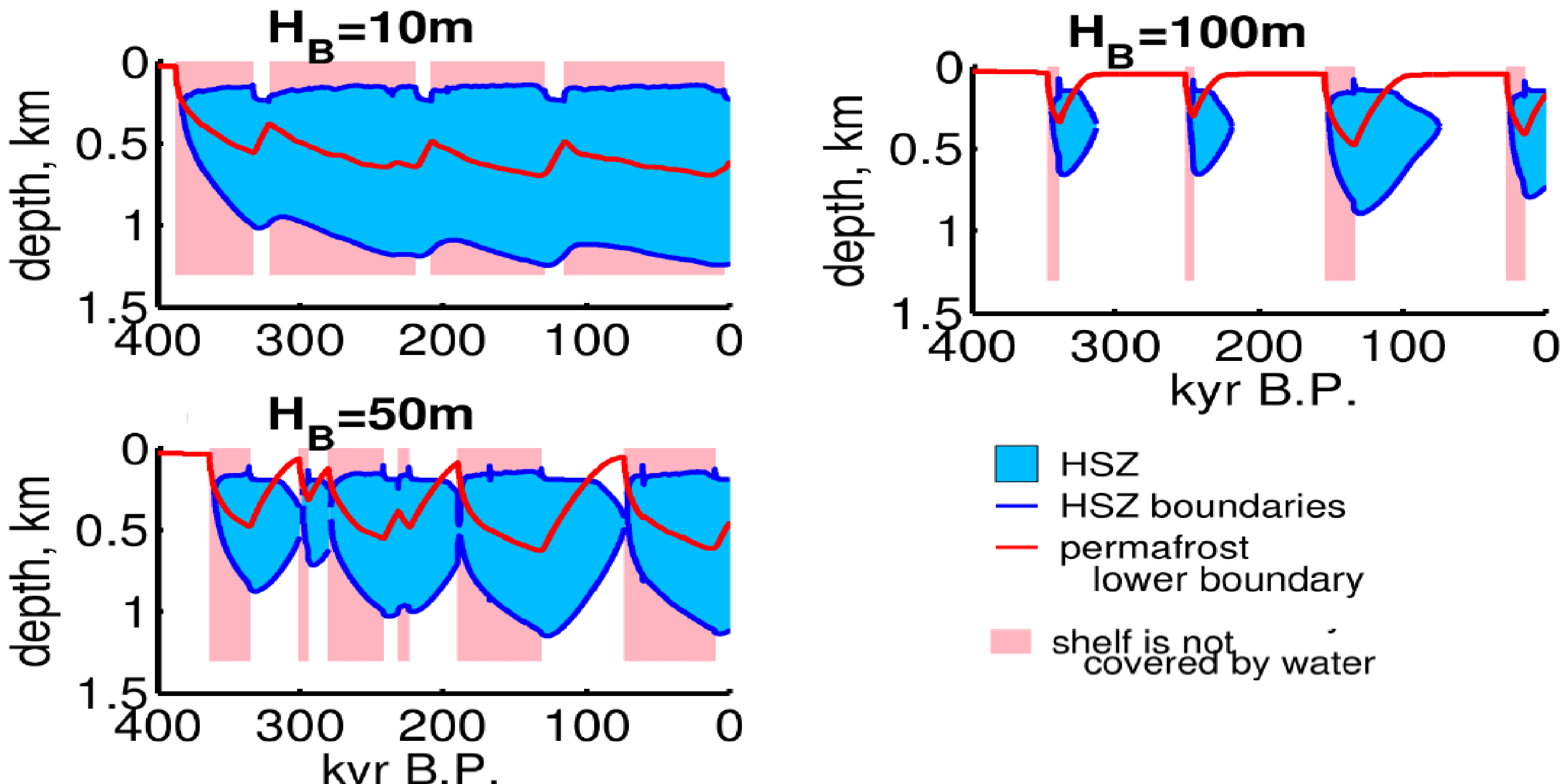
For T<273.2 ^{0}K:

$$\ln(P_e) = -4.38921173434628\times10^{1} +7.76302133739303\times10^{-1}\,T -7.27291427030502\times10^{-3}\,T^{2} +3.85413985900724\times10^{-5}\,T^{3} -1.03669656828834\times10^{-7}\,T^{4} +1.09882180475307\times10^{-10}\,T^{5}$$



The subsea permafrost and HSZ dynamics during glacial cycles

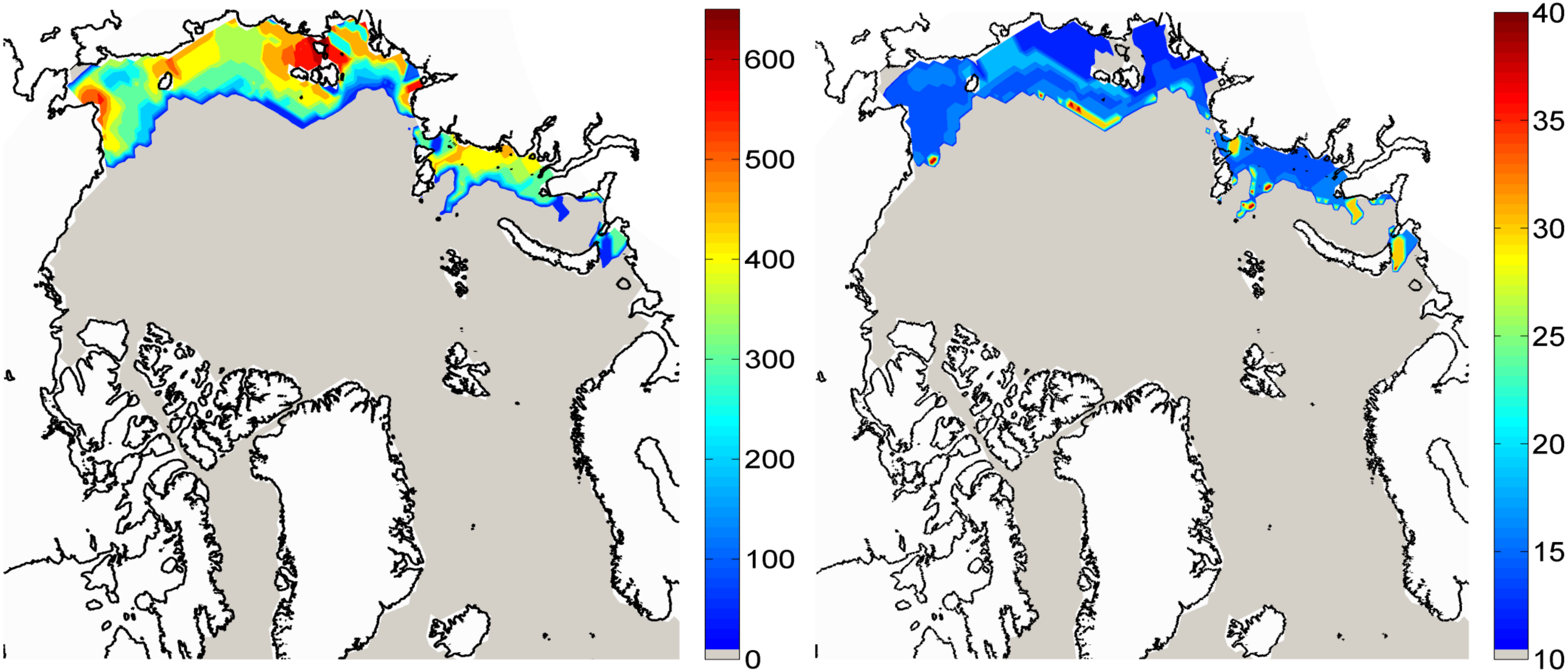
Depths (below the sediment top) of HSZ boundaries and permafrost bottom in simulation group S400.



The subsea permafrost and HSZ survive during interglacials for $H_B \leq 30$ m but disappear during these interglacials for larger H_B.

Sub-sea permafrost in the Arctic

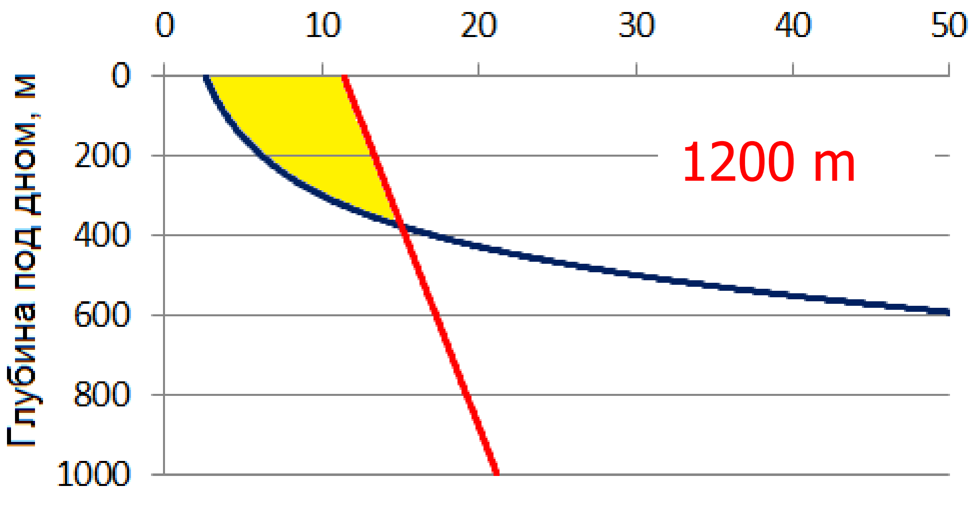
Cryolithozone - a regulator of methane emission in the ARCTIC



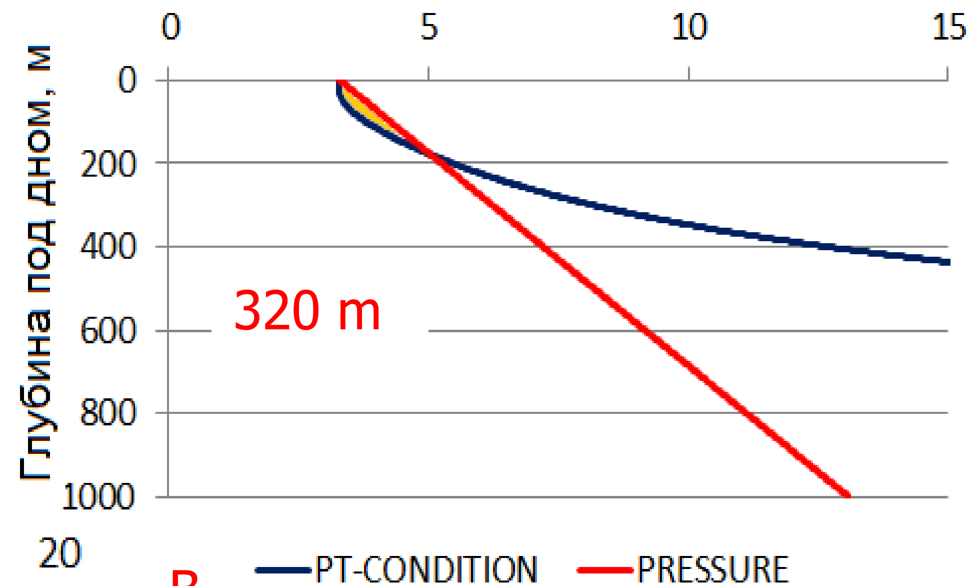
Simulated locations of the permafrost boundaries for 2006

Gas Hydrate Type Locales

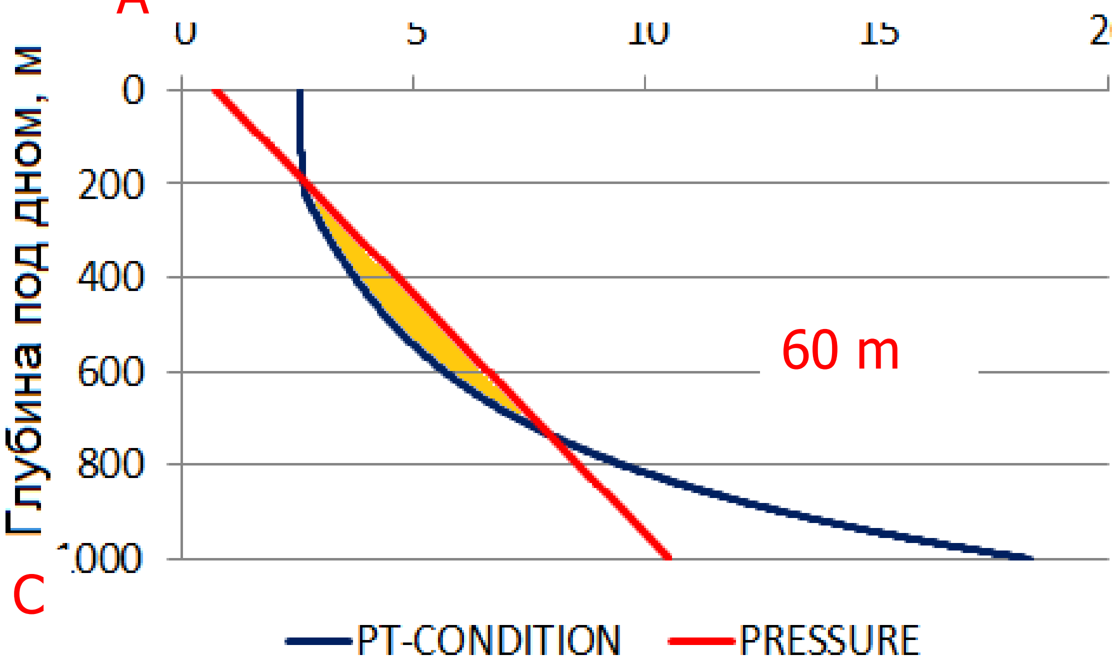
Examples of gas hydrate stability assuming a water depth equal to 60m, 320m, 1200m



A



B

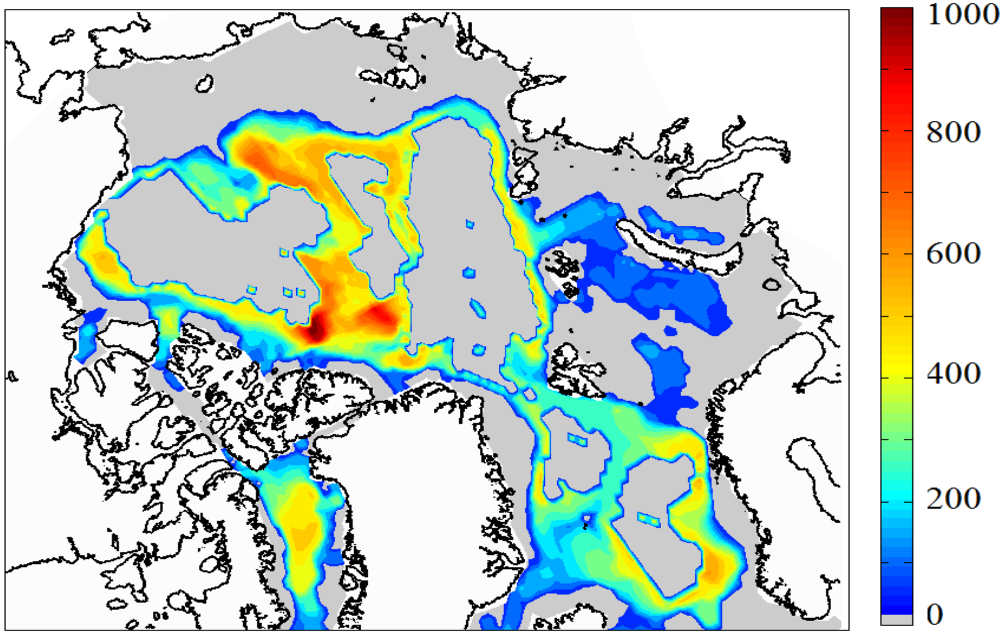


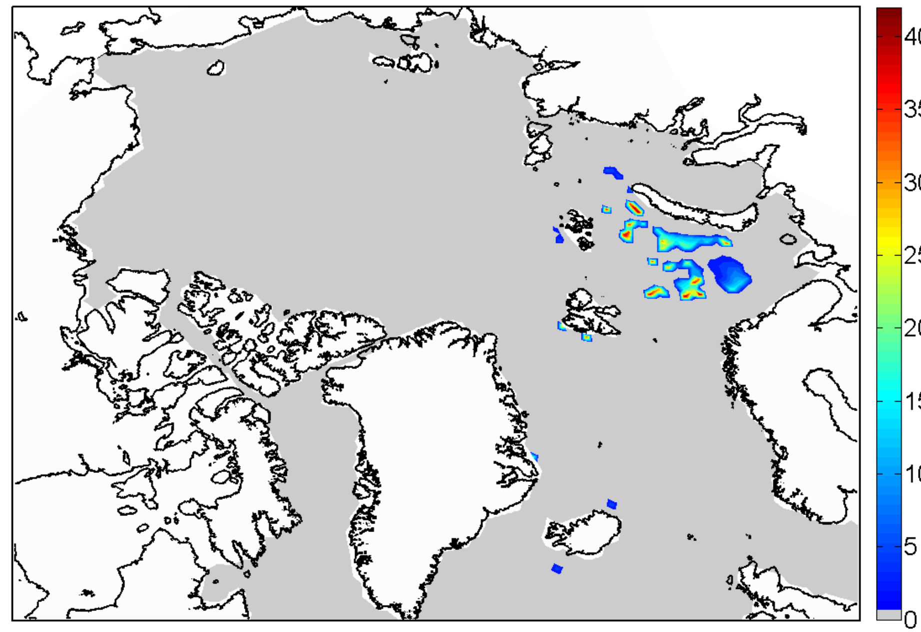
C

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

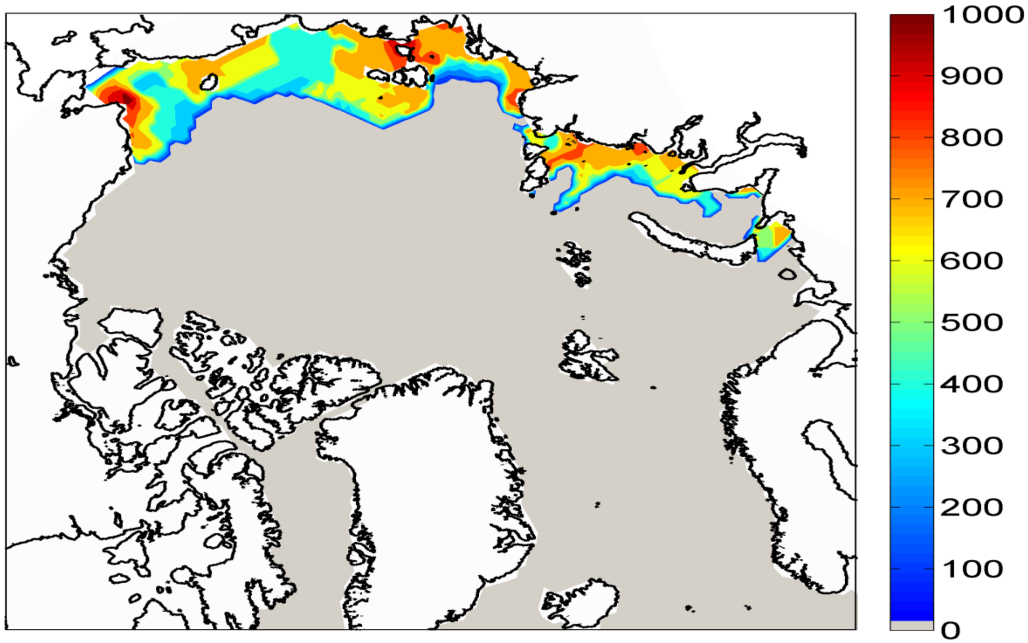
Model locations of methane hydrates by 2005

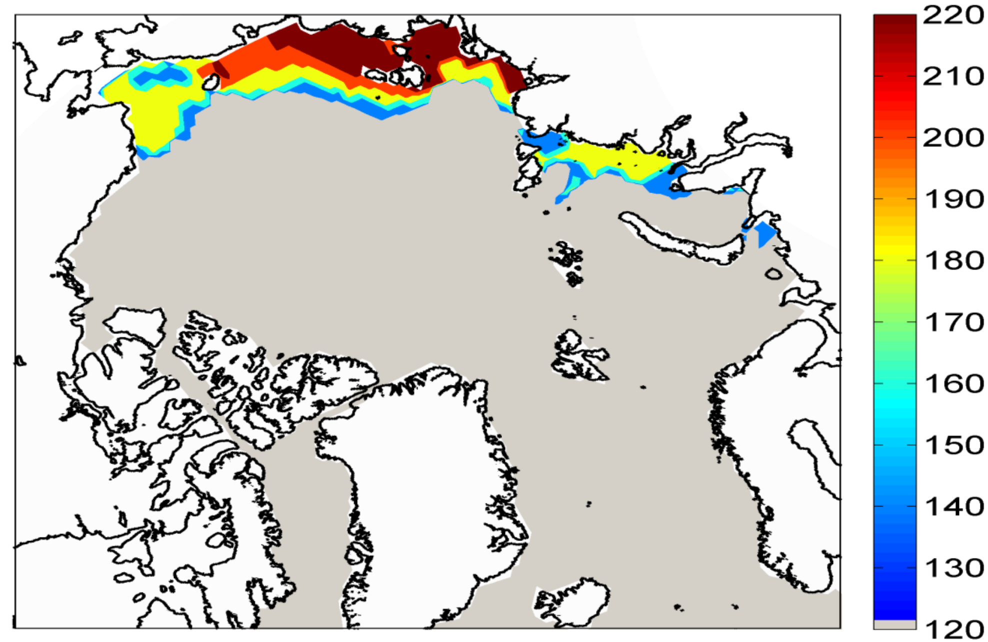
Map of the predicted thickness of the gas hydrate stability zone (GHSZ) and top of GHSZ



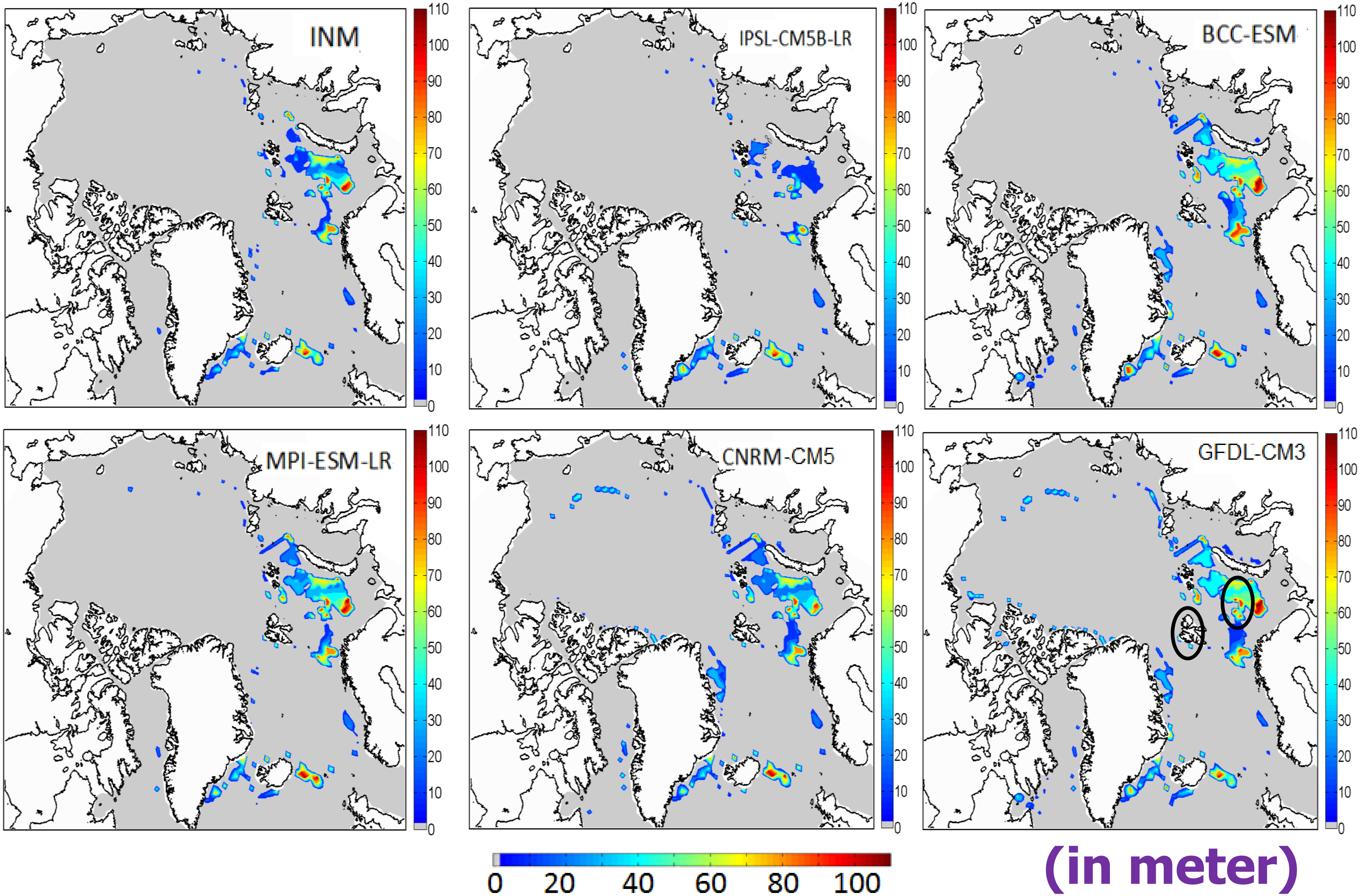


Stability zone of cryogenic gas hydrates and the top of the stability zone

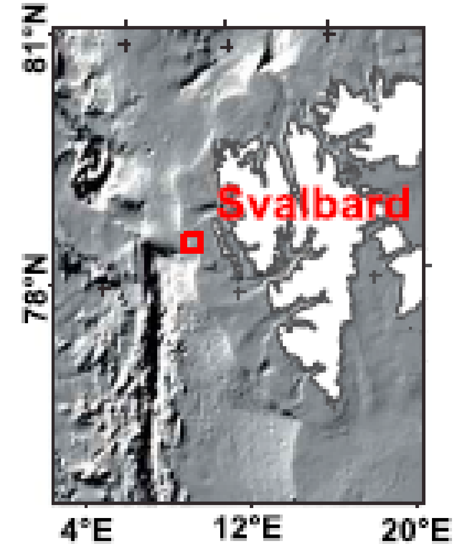


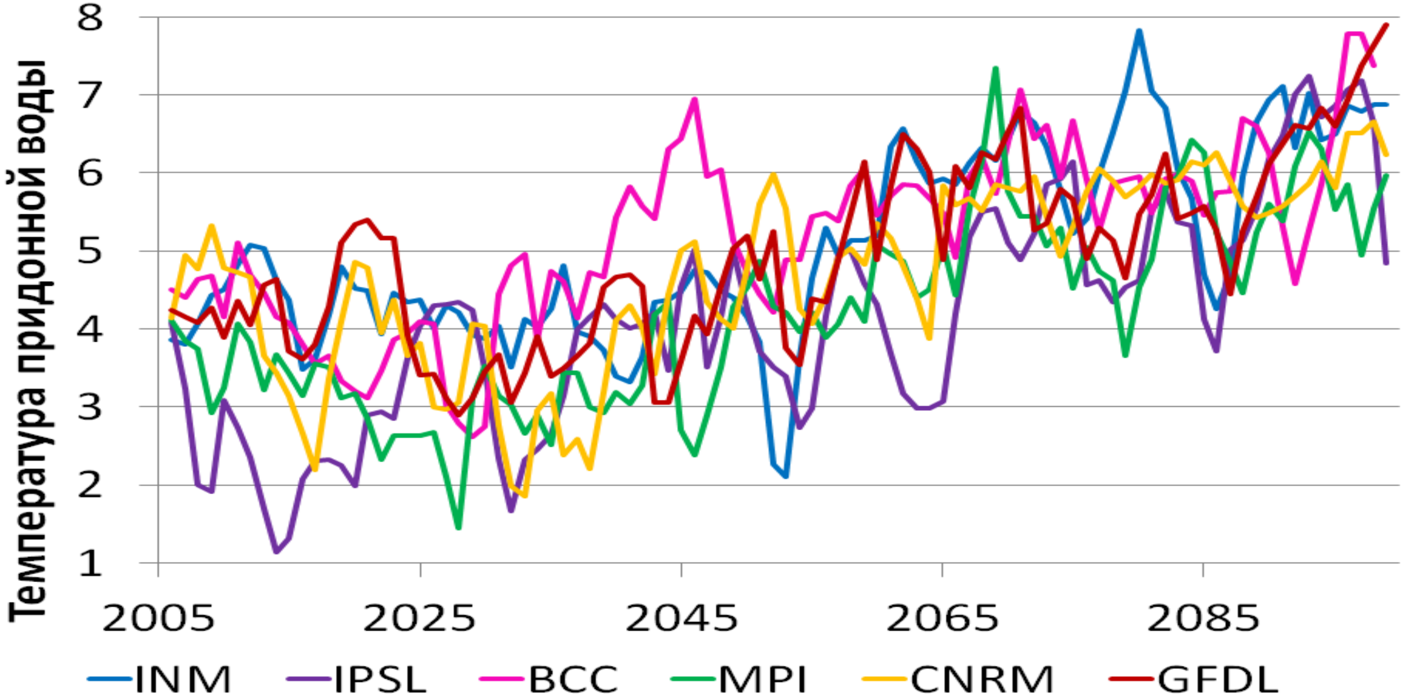


The modeling results show the changes of the GHSZ predicted to 2100

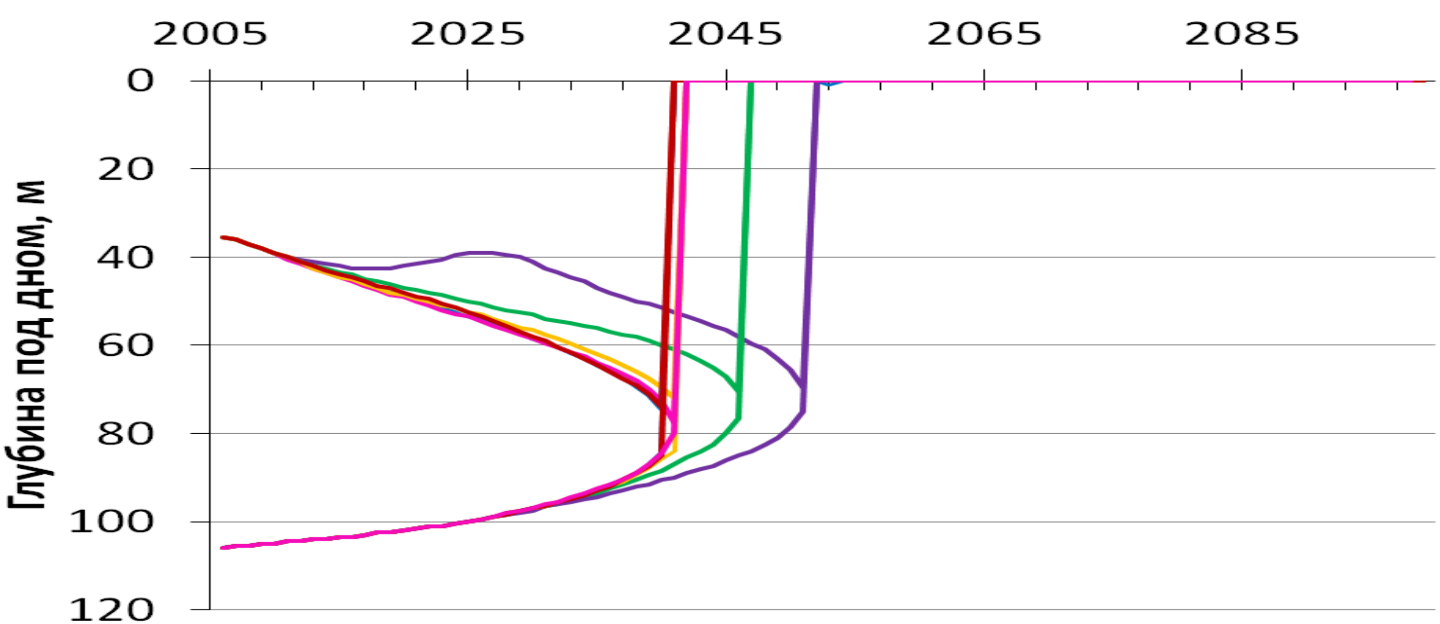


The predicted change for continental margin west Svalbard: Temperature and the GHSZ



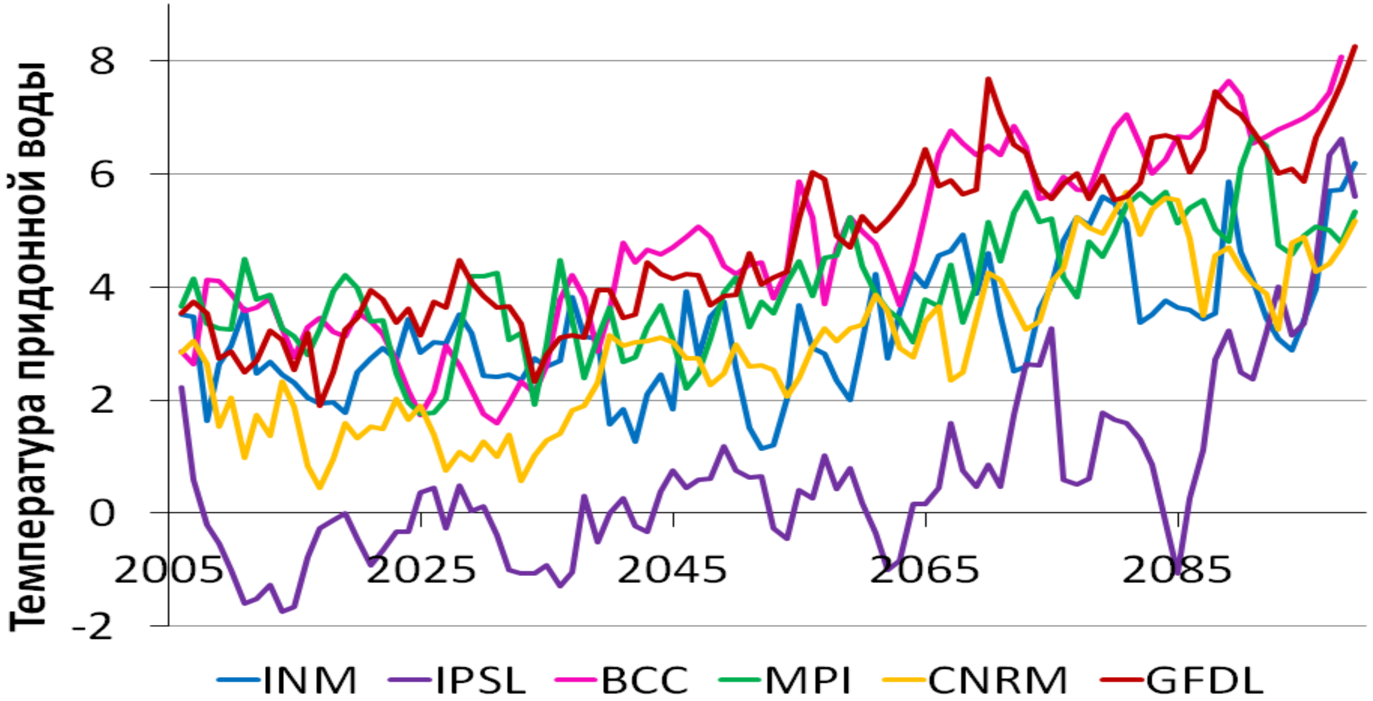


The predicted change in the bottom water temperature for future climate change, on the 300 m isobath

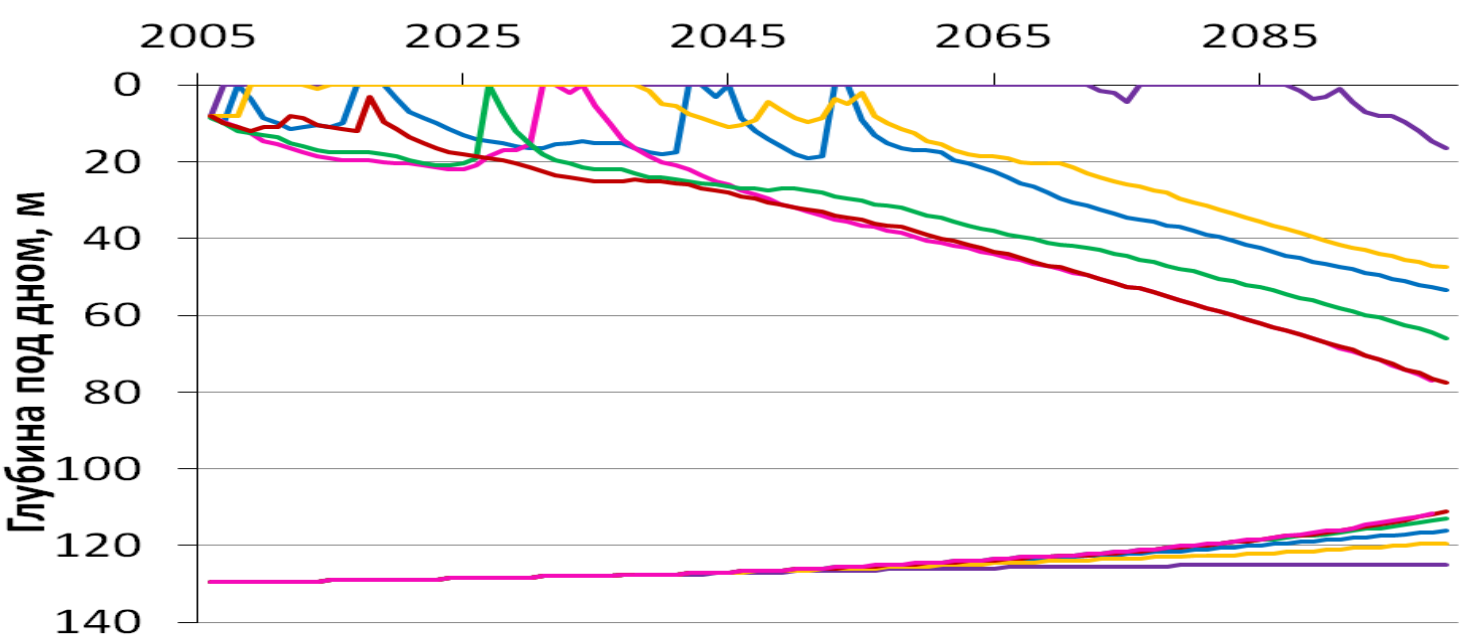


The predicted change in the thickness of the GHSZ for ensemble trends

The predicted change for the Barents Sea at 300-m water depth: Temperature and the GHSZ



The predicted change in the bottom water temperature for future climate change, on the 300 m isobath



The predicted change in the thickness of the GHSZ for ensemble trends

Summary

- The distribution of gas hydrate stability zone is obtained based on available data on pressure, temperature, permafrost and geothermal conditions in the Arctic Ocean
- Shallow hydrates can release significant methane rapidly. Contemporary and future gas hydrate degradation will occur primarily on the Arctic Ocean continental shelves.
- We find that the reduction of the methane hydrate stability zone occurs in the Arctic Ocean between 250 and 500 m water depths within the upper 100 m of sediment in the Atlantic inflow area.
- We have identified the areas of the Arctic Ocean where an increase in methane release is probable to occur at the present time.

Acknowledgement

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17-05-00396 “Отклик газогидратов донных отложений океана на естественные и антропогенные изменения климата”
17-05-00382 “Анализ прошлых и прогноз возможных изменений циркуляции Арктических морей России в условиях глобального потепления”
18-05-60111-Арктика “Изменения криосферных процессов в Российской Арктике и связанные с ними опасные явления и последствия”