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Numerical simulation of generation, transport and oxidation of methane on the shelf of the Arctic Ocean

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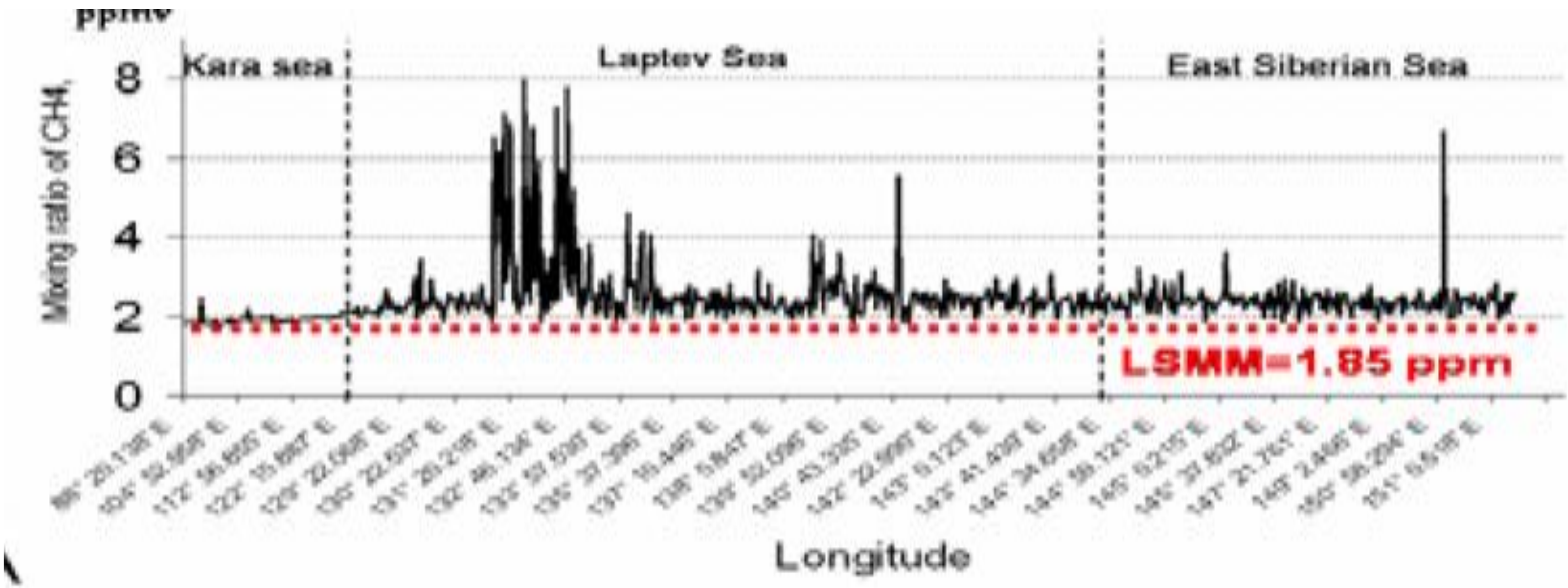
Outline

- Atmospheric methane in high latitudes: observational evidences and known sources
- Methane hydrates and other methane sources in Arctic Ocean
- 1D methane transport model formulation for Arctic shelf and results
- FEMAO-1 ocean model results and development
- Outlook

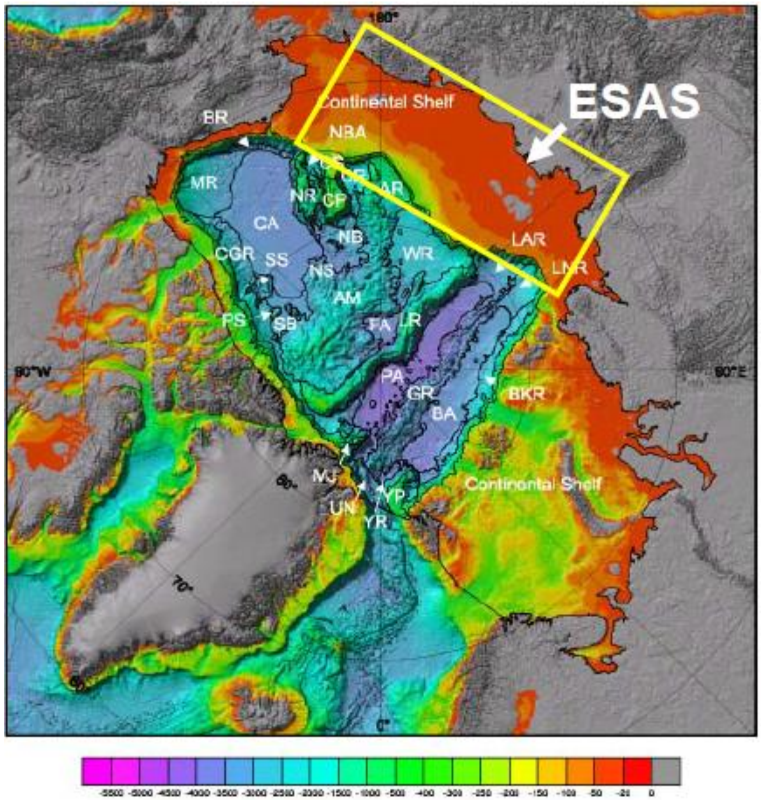
Atmospheric methane over Arctic Ocean

Sea ship (Shakhova and Semiletov 2010) and airborne (Kort et al. 2012) measurements over leads and polynyas indicate enhanced methane concentrations over open water at the Arctic Ocean, indicating an ocean as a source of CH_4.



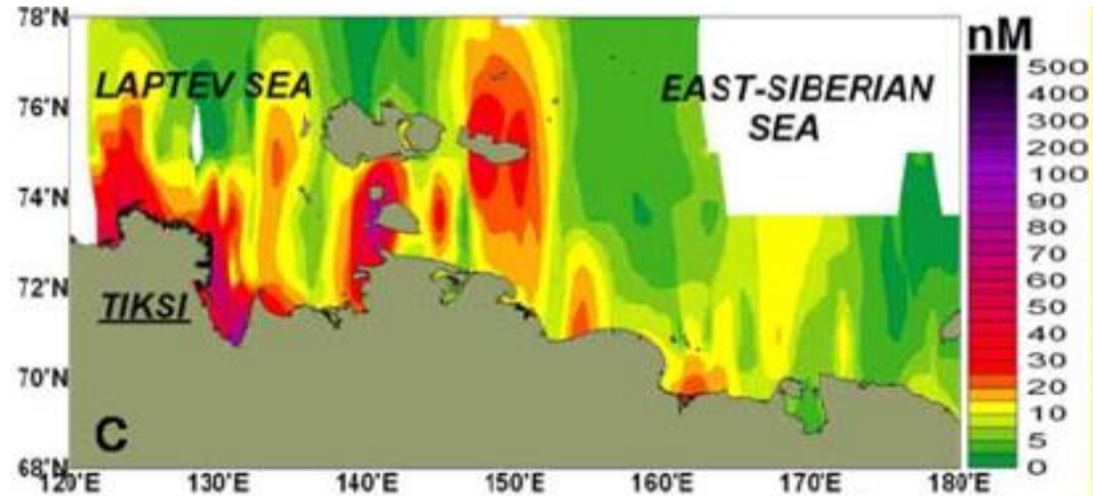
Shakhova and Semiletov 2010

Dissolved methane in East Siberian Arctic Shelf (Shakhova et al. 2010)



East Siberian Arctic Shelf is ~8% of World Ocean's shelf containing **high organics content** as a consequence of abundant terrestrial life here during last Ocean regression.

Surface water methane concentration



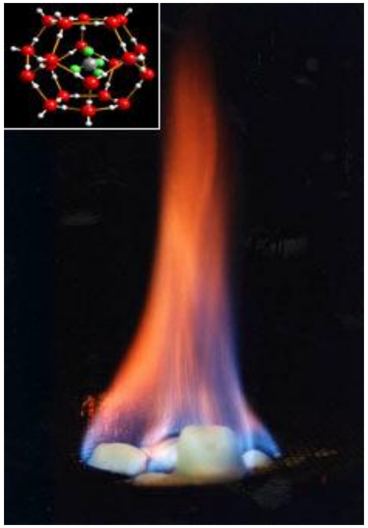
- Surface waters of East Siberian Arctic shelf are supersaturated up to 800% in respect to present atmospheric concentration of methane 1.85 ppm
- Bottom concentrations are typically higher by <=30% than surface ones
- Winter concentrations are 5-10 times greater;

Methane sources in Arctic Ocean

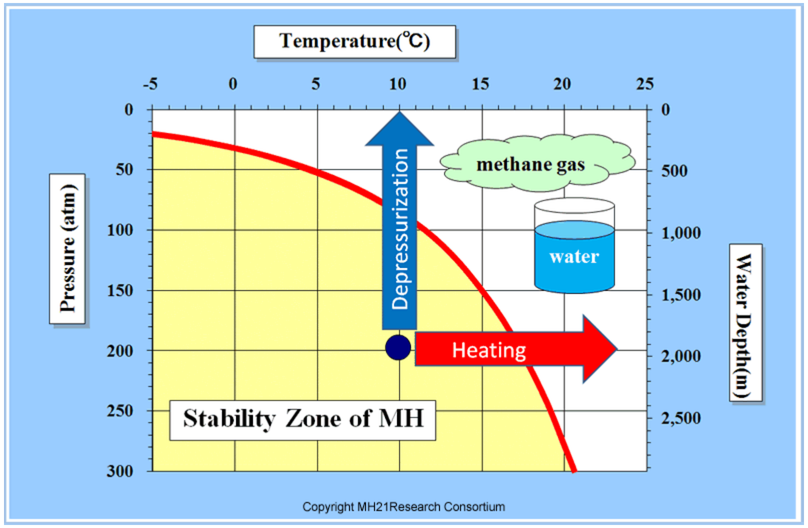
- **Methane transport by Siberian rivers**
- **Thermogenic methane from tectonic faults**
- **Destabilization of methane hydrates below the bottom**
- Biogenic production of methane in bottom sediments
- Methane generation in oxic waters (Damm et al. 2011)

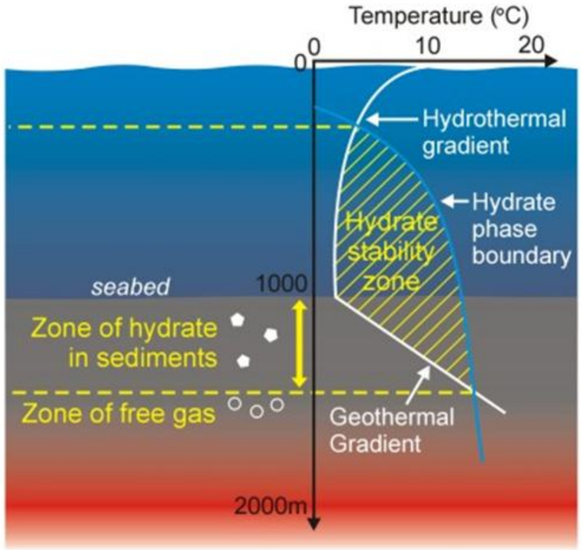
Usually considered as the largest contributors

Methane clathrate ($CH_4 \cdot 5.75H_2O$), also called **methane hydrate**, is a solid clathrate compound (more specifically, a clathrate hydrate) in which a large amount of methane is trapped within a crystal structure of water, forming a solid similar to ice (*Wikipedia*).



Methane hydrate stability diagram





Modeling studies

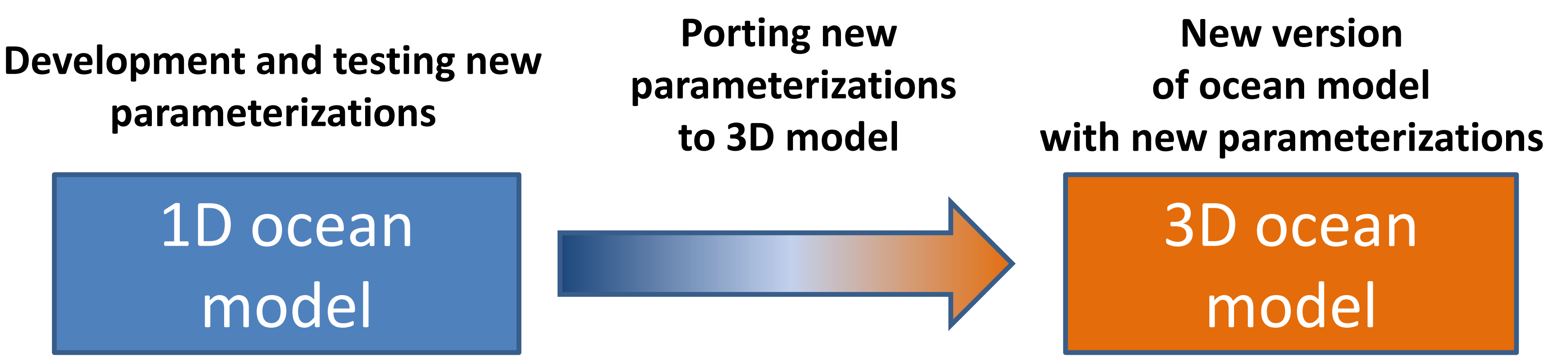
- Modeling of subsea permafrost (Delisle 1998, Nicolsky and Shakhova 2010, Dmitrenko et al. 2011)
- Sophisticated models of methane hydrate dynamics in porous soil (Sun et al. 2005, Esmaeilzadeh et al. 2008, Garg et al. 2008)
- Studies of methane hydrate response to climate change (Hatzikiriakos and Englezos 1994, Dmitrenko et al. 2011, Denisov et al. 2011)
- Single bubble models (McGinnis et al. 2006, Yamamoto et al. 2009)
- Dissolved methane diffusion, advection and oxidation in ocean (Malakhova et al. 2012)

To the best of our knowledge no 3D ocean models exist that take into account the "complete" set of processes:

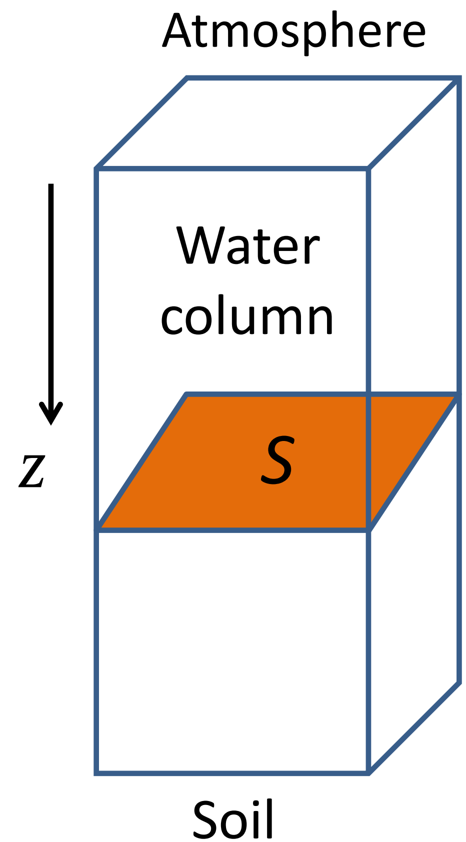
✓ **dissolved methane diffusion and advection in ocean**
✓ **bubble transport of methane and other gases**
✓ methane generation in soil beneath the ocean – the processes are unclear
✓ methane production in oceanic water
✓ **inflow of methane by rivers**

Our model study setup

- **Goal**: development of an ocean model explicitly reproducing the most important methane transport processes and the most likely climate feedback mechanisms given the modern knowledge of methane sources
- This needs the development and testing the new 1D parameterizations: (i) bubble model, (ii) methane production and transport in sediments
- Testing new parameterizations implies multiple runs that are expensive in 3D model
- 3D model has sparse resolution at shelves that does not allow to accurately reproduce the vertical turbulent transport



Mathematical development of 1D ocean column model



Consider 3D heat balance equation

$$\frac{\partial T}{\partial t}+\frac{\partial uT}{\partial x}+\frac{\partial vT}{\partial y}+\frac{\partial wT}{\partial z}=-\frac{\partial F_{Tx}}{\partial x}-\frac{\partial F_{Ty}}{\partial y}-\frac{\partial F_{Tz}}{\partial z}-\frac{1}{\rho_{w0}c_w}\frac{\partial S}{\partial z}$$

applying averaging over horizontal cross-section *S*

$$\tilde{f}=\frac{1}{S}\iint\limits_{S'} f\,dx\,dy$$

yields (after simplifications):

horizontal advection

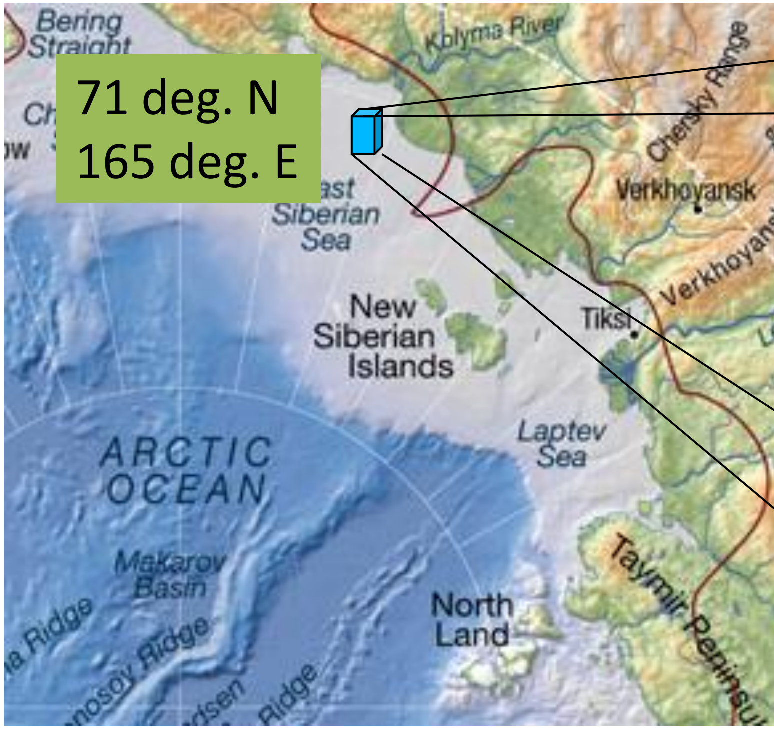
$$\frac{\partial \tilde{T}}{\partial t}=\frac{\partial}{\partial z}k_T\frac{\partial \tilde{T}}{\partial z}-\frac{1}{S}\oint\limits_{\Gamma_{S'}}(\vec{u}\cdot\vec{n})T\,dl-\frac{1}{\rho_0 c_p}\frac{\partial \tilde{S}}{\partial z}$$

Analogous derivation brings equations for salinity and horizontal velocity components.

The 1D model or water reservoir LAKE (Stepanenko et al. 2011) was generalized to account for this case.

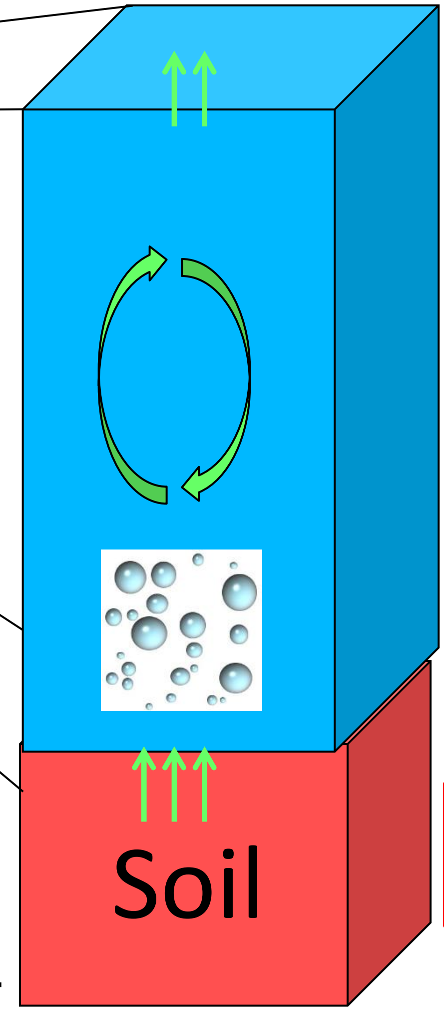
ONE-WAY COUPLING TO 3D OCEAN MODEL FEMAO-1

(Iakovlev 2009, 2012)



$u_{3D}, v_{3D}, T_{3D}, s_{3D}$

Vertical profiles from FEMAO-1 model are advected at inflow boundaries



$u_{1D}, v_{1D}, T_{1D}, s_{1D}$

Current profiles from 1D model are advected at outflow boundaries

$$\frac{\partial T_{1D}}{\partial t} = 1D\,diffusion + 1D\,radiation + \boxed{\frac{1}{l} u_{3D}\left(T_{3D} - T_{1D}\right)}$$

Heat advection at boundaries

Numerical experiment with 1D model:

- Depth 25 m (20 layers), soil depth 400 m (40 layers)
- Atmospheric forcing: reanalysis NCEP 1948-2011 yrs
- Initial vertical dissolved gas profiles – equilibrium with atmosphere

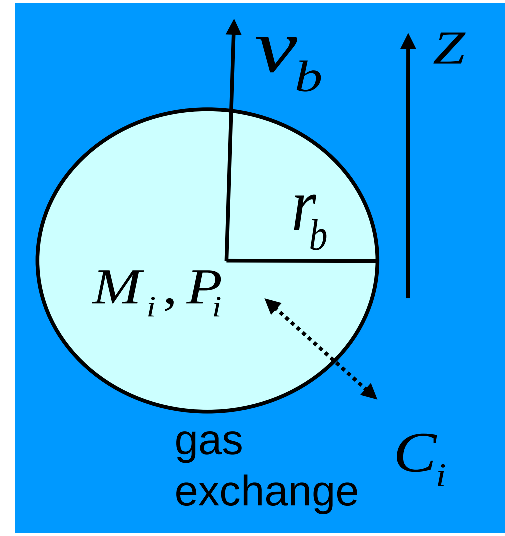
Processes:

- ❑ Generation of biogenic methane in soil
- ❑ Turbulent (diffusive) and bubble vertical transport of CH4, O2 и CO2
- ❑ Methane oxidation

THE MODEL FOR BUBBLE AND DIFFUSIVE VERTICAL TRANSPORT OF METHANE

- The 1D model of bubble with a mixture of gases

$$\frac{dM_i}{dt} = v_b \frac{\partial M_i}{\partial Z} = -4\pi r_b^2 K_i \left(H_i(T) P_i - C_i \right),\ i = 1,\dots,n_g$$



$$M_0 = \frac{\left(p_a + \rho_{w0} g h\right) \frac{4}{3}\pi r_{b0}^2}{RT},$$

$$M_{i0} = \alpha_i M_0,\ i = 1,\dots,n_g$$

Initial condition at the bottom:
Initial radius and initial gas molar fractions

- Coupling of bubble model with a 1D model of diffusion-reaction of dissolved gases

$$\frac{\partial C_i}{\partial t} = \frac{1}{h^2}\frac{\partial}{\partial \xi} k \frac{\partial C_i}{\partial \xi} + \frac{1}{h}\frac{\partial C_i}{\partial \xi}\left(\xi \frac{dh}{dt} - B_w\right) + R_i + \boxed{B_i}$$

The bubble-water gas exchange

If all bubbles are of the same size then

$$B_i = \frac{n_b v_b}{h}\frac{\partial M_i}{\partial \xi} = \frac{F_{B0,i}}{h}\frac{\partial (N m_i)}{\partial \xi}$$ where $m_i = M_i / M_{i0}$ and $N = (n_b v_b)/(n_{b0} v_{b0})$

$$F_{B0,i} = \boxed{F_{B0,1}}\frac{\alpha_i}{\alpha_1},\ i = 2,\dots,n_g$$

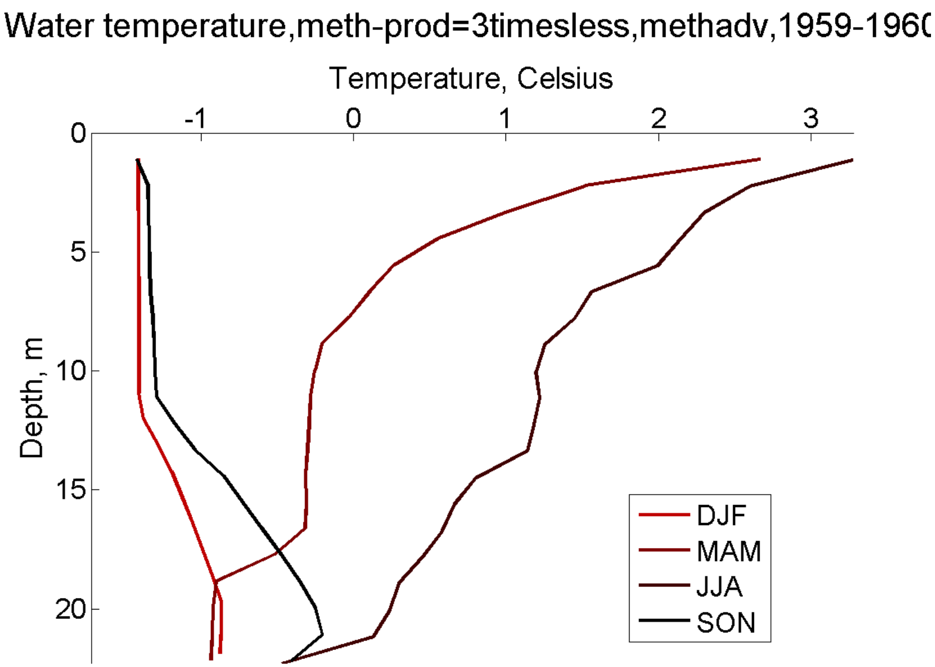
Bubble flux of methane at the bottom

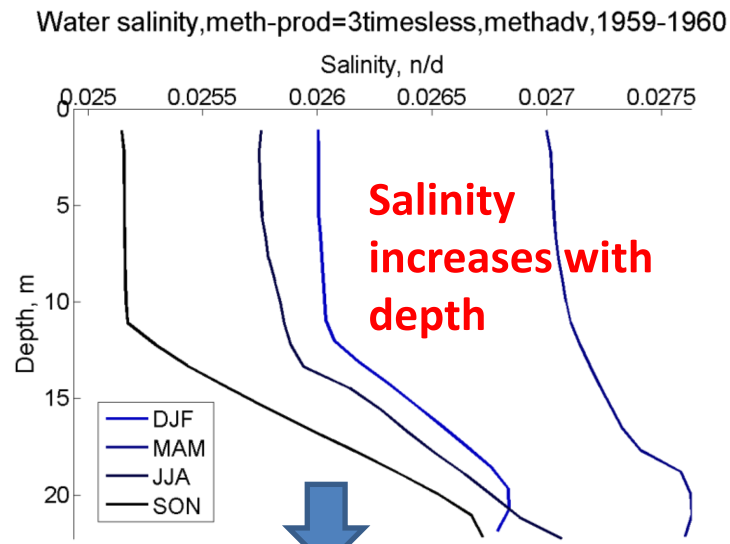
The model is incorporated in
1D k-ε water reservoir model LAKE
(Stepanenko et al. 2011) which includes the model
of generation and transport of methane in soil

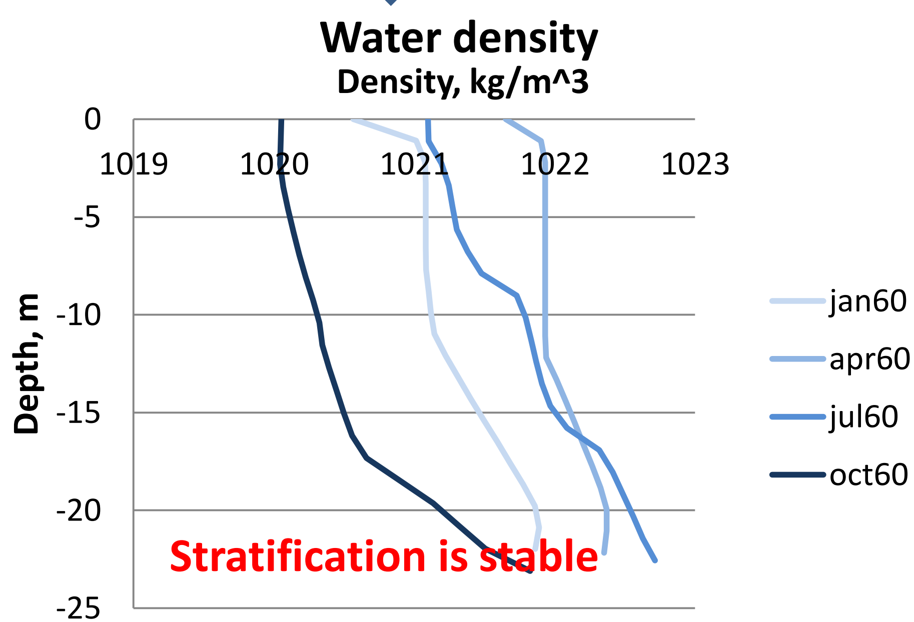
Baseline experiment

- Production of methane in soil **is zero**
- Initial methane concentration in soil is set to be slightly unsaturated in respect to bubbles **(no bubbles form!)**

Temperature, salinity and density







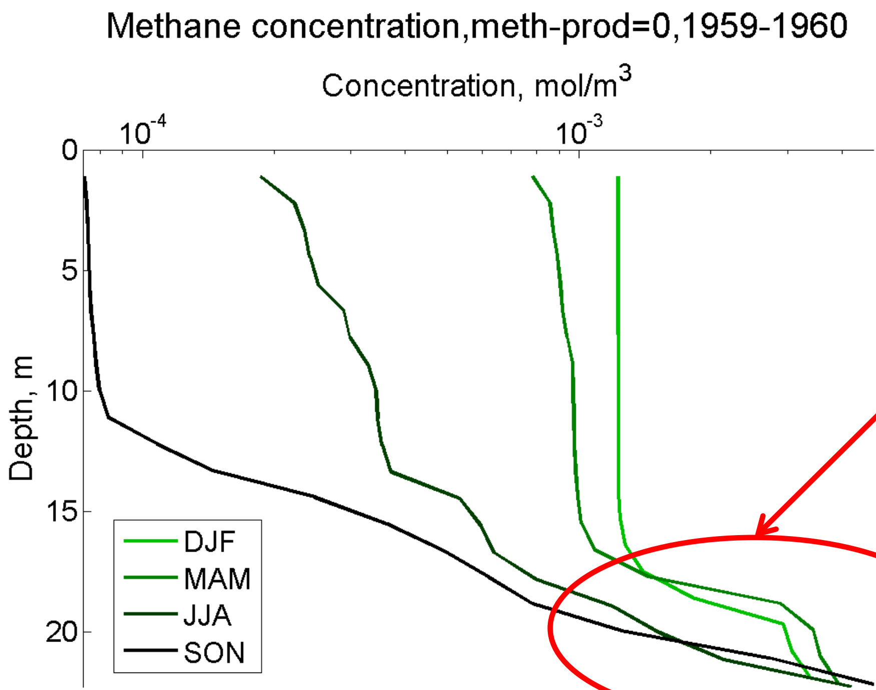
Surface temperature for 1951-2011:

Mean summer value 4.6 C

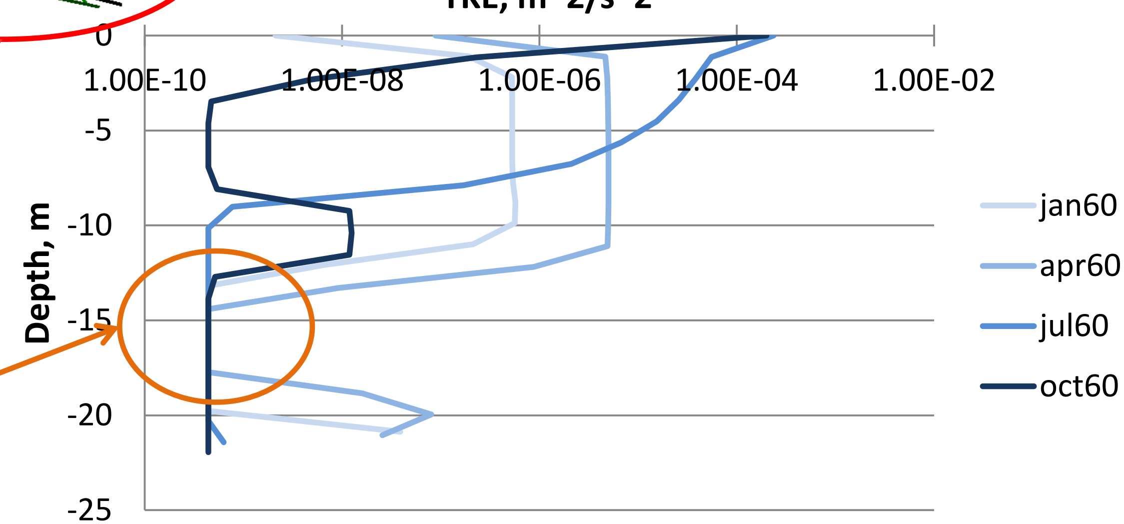
Mean winter value -1.2 C

Corresponds well to in situ measurements by research vessels Akademik Korolev, HX 139 and others (NODC data)

Dissolved methane profile

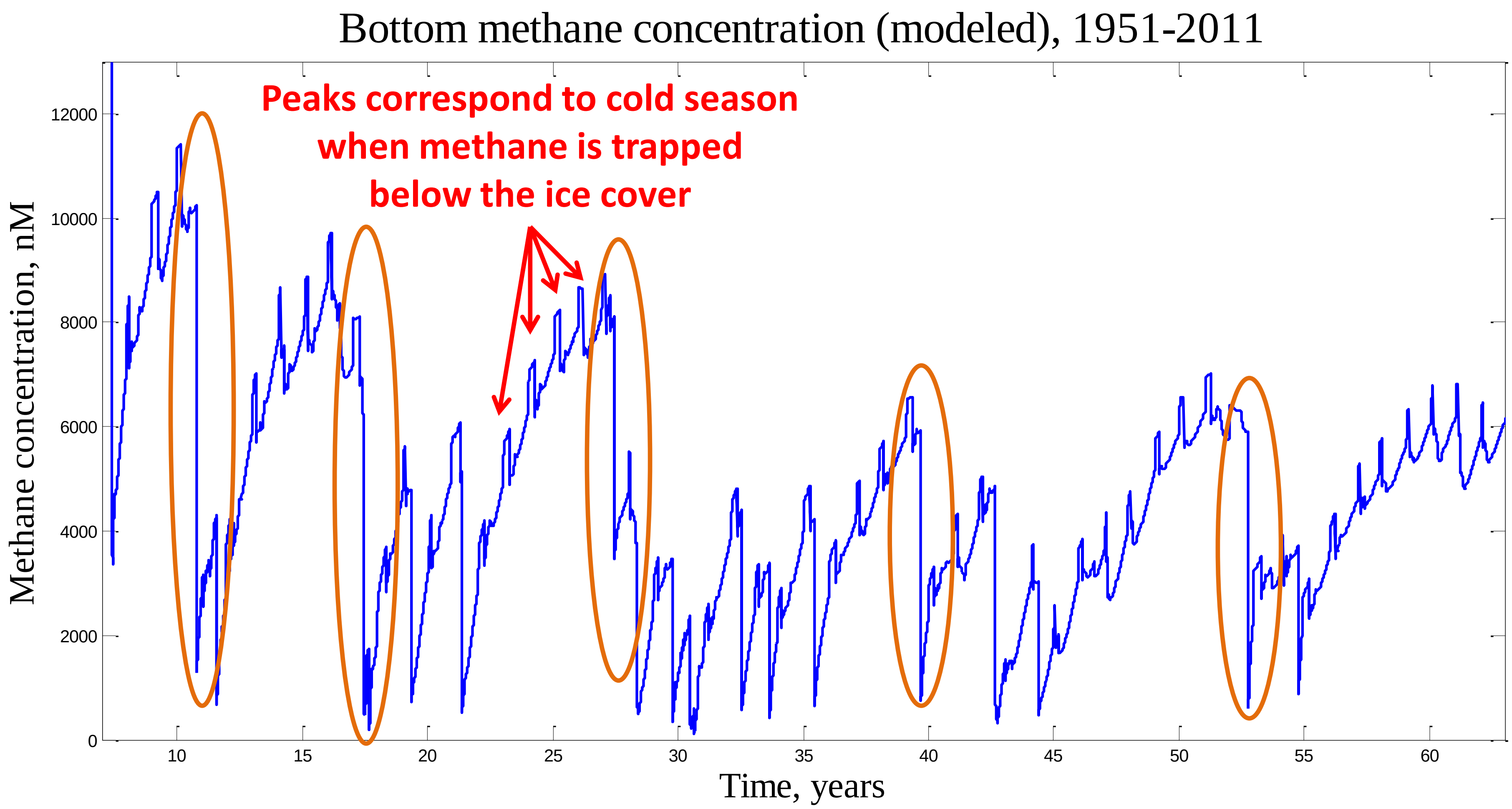


Bottom concentrations are **an order of magnitude** larger than surface concentrations. Observations (Shakhova et al. 2010), however, demonstrate **<=30%** difference.



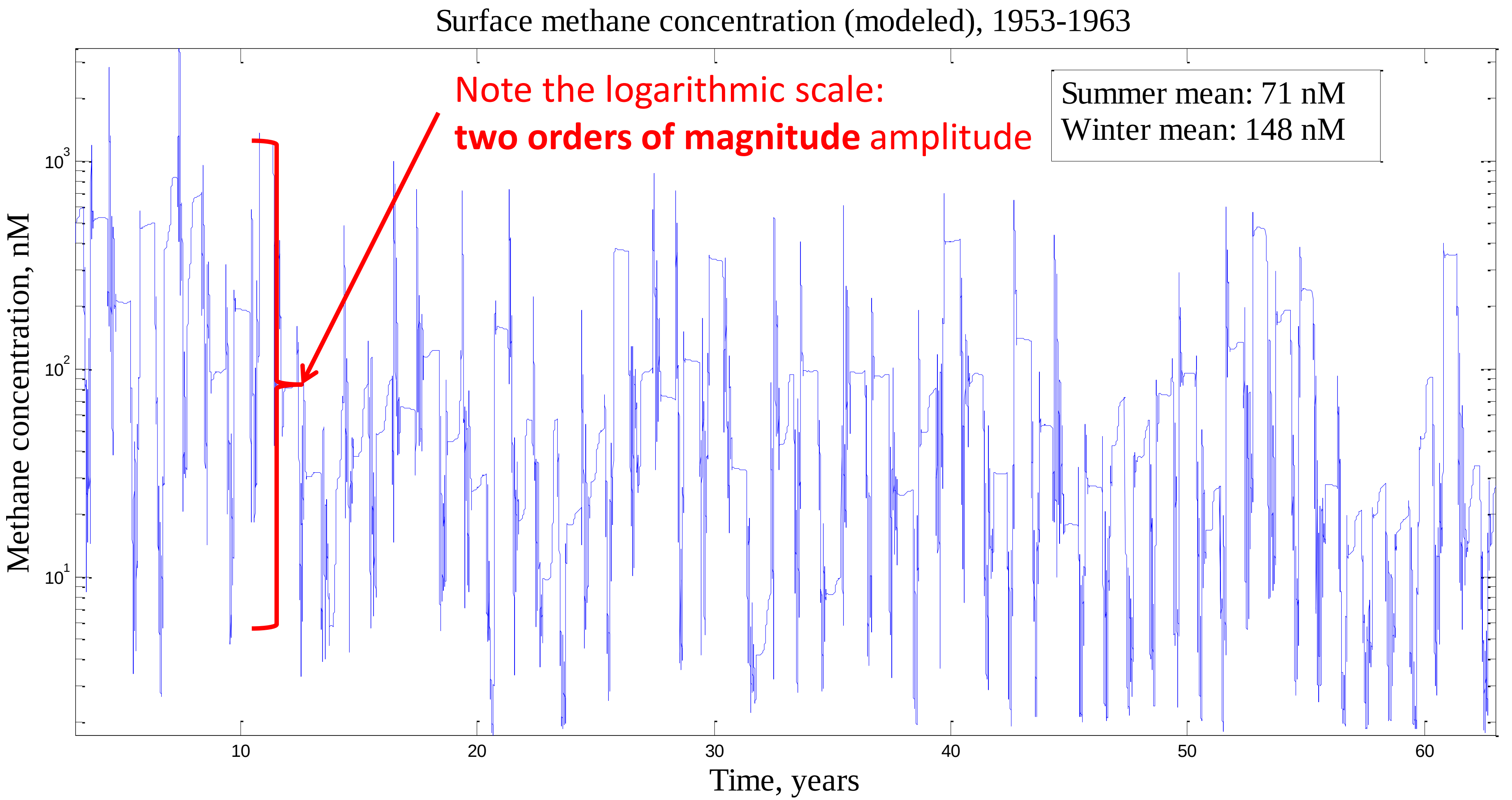
High concentration gradients near the bottom are due to low turbulence level.

Near bottom methane concentration, 1953-1963



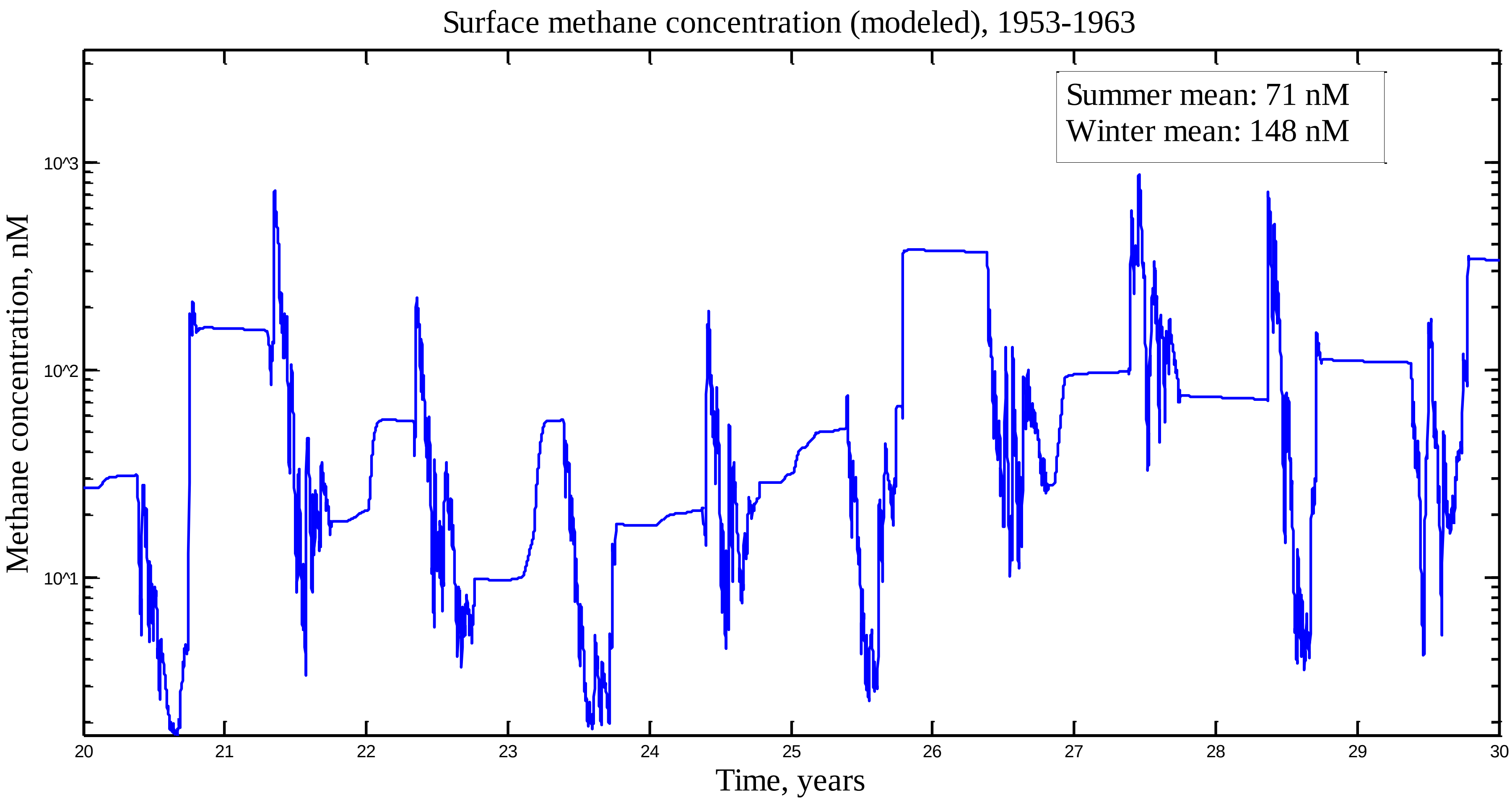
Methane concentration drops down during intensive mixing events repeating every ~10 years

Surface methane concentration, 1953-1963



- **High methane abundance variability** is due to turbulent mixing variability bringing high amounts of methane from near bottom layer (bottom concentrations demonstrate much smoother behavior)
- Observed surface methane concentration in East Siberian Sea 1-100 nM (Shakhova et al. 2010)

Surface methane concentration, 1968-1978

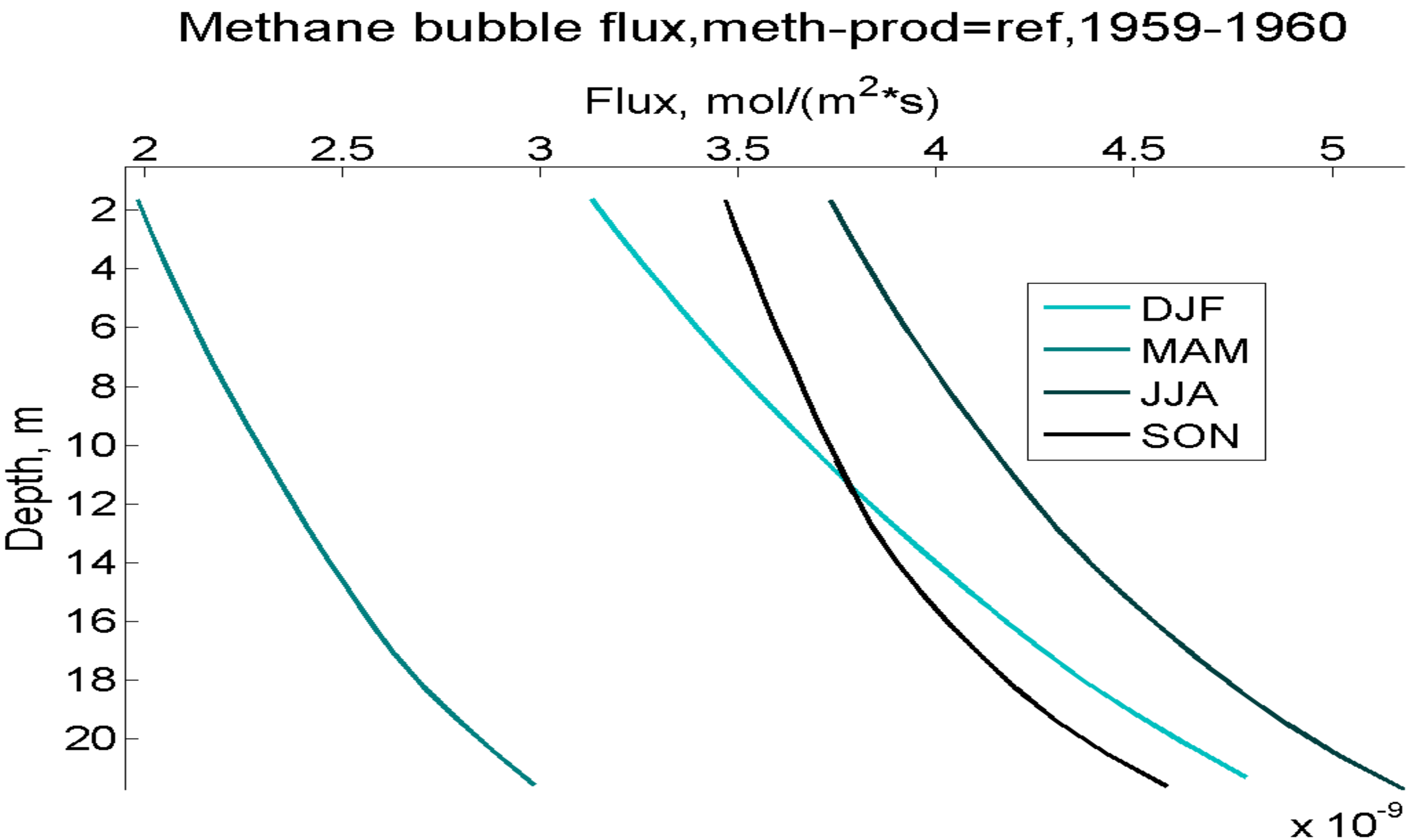


- **Smooth temporal curve during winters** as opposed to high variability during summers due to absence of wind stress and heat balance effect on turbulence
- On average winter concentrations are **2 times** higher than summer ones (in observations (Shakhova et al. 2010) **5-10 times**)

Experiment with bubble flux

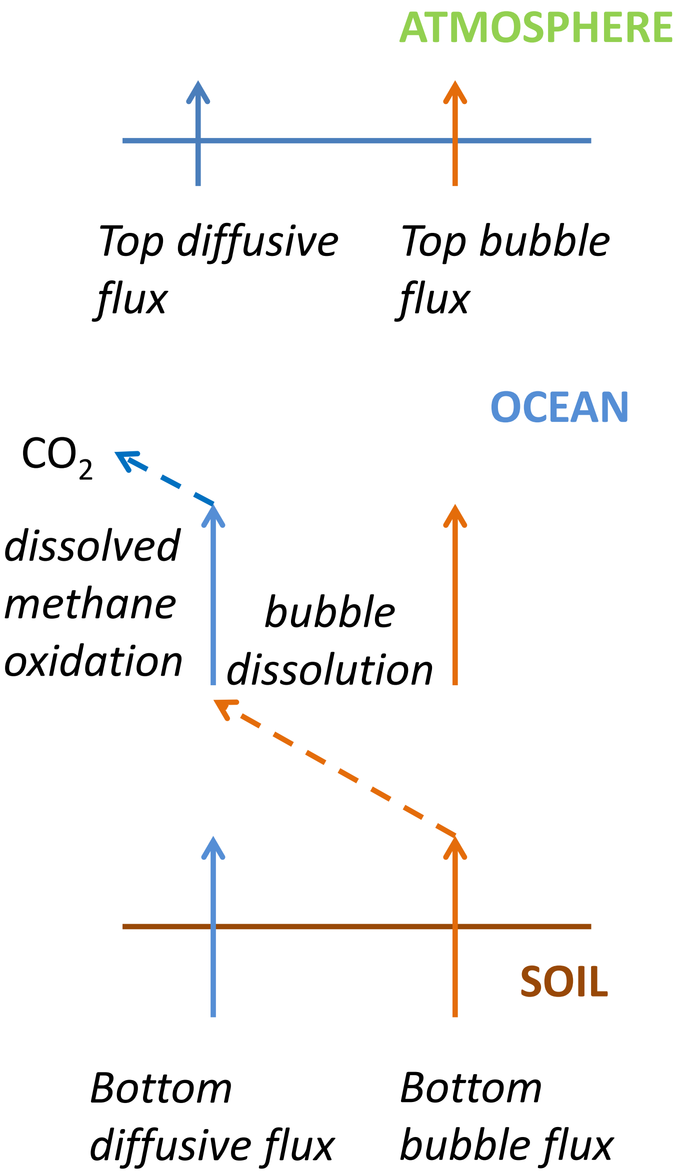
- Production of methane in soil **is switched ON**
- The intensity of production is chosen so that the methane bubble flux at the bottom ~ the diffusive flux

Methane bubble flux



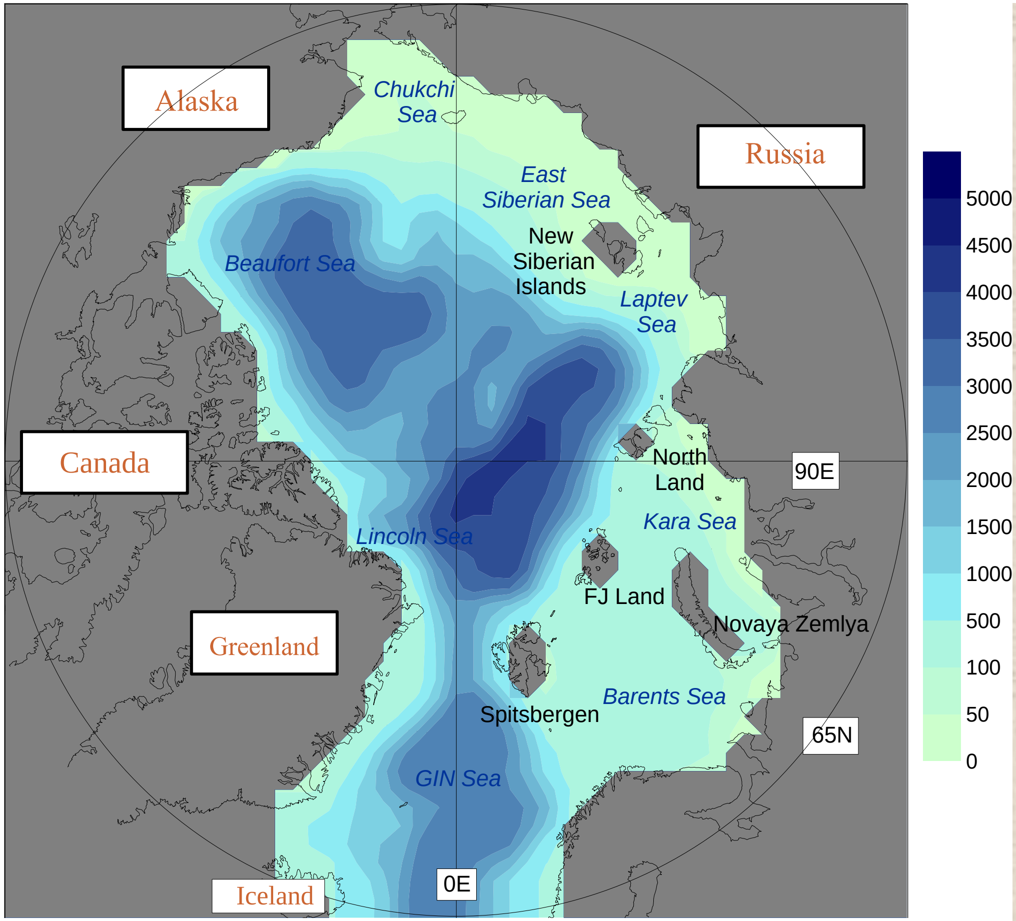
25-35% of bubble methane is dissolved in water column that **is consistent with measurements of Semiletov et al. 1996** demonstrating 15% methane loss when bubble rises from 10 m depth

Methane budget in a water column



Methane flux, g/(m^2 yr)	Baseline	Including production in soil
Bottom diffusive flux of methane	0.18	2.14
Top diffusive flux of methane	0.17	2.29
Bottom bubble flux of methane	0	2.21
Top bubble flux of methane	0	1.2
Total oxidation in water column	0.04	0.72
The fraction of bottom methane flux reaching the atmosphere	94%	80%

The finite-element model of coupled 3D dynamics of ocean and sea ice FEMAO-1

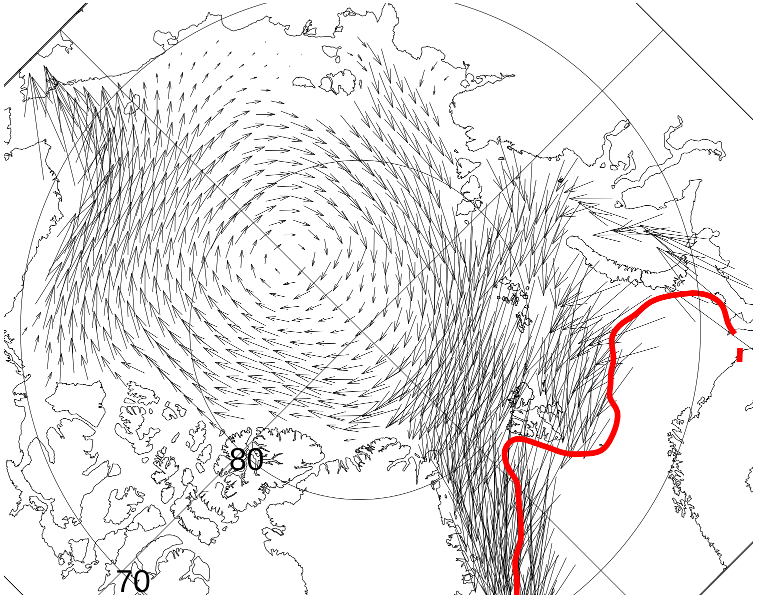


- Area of the Arctic Ocean north to 65N.
- North Pole shifted to the point 0N, 180E.
- 1 degree (~111.2 km) spatial resolution in the new coordinate frames.
- Z-coordinate vertical approximation, 16 levels.
- 5 islands.
- 6 passages with the specified mass transports.
- 8 main rivers (freshwater fluxes).
- AOMIP Forcing (Daily Ta, Pa, monthly mean climatology for cloudiness, humidity, precipitation, river run-off, PHC 3.0)

An example of sea ice extent and its dynamics

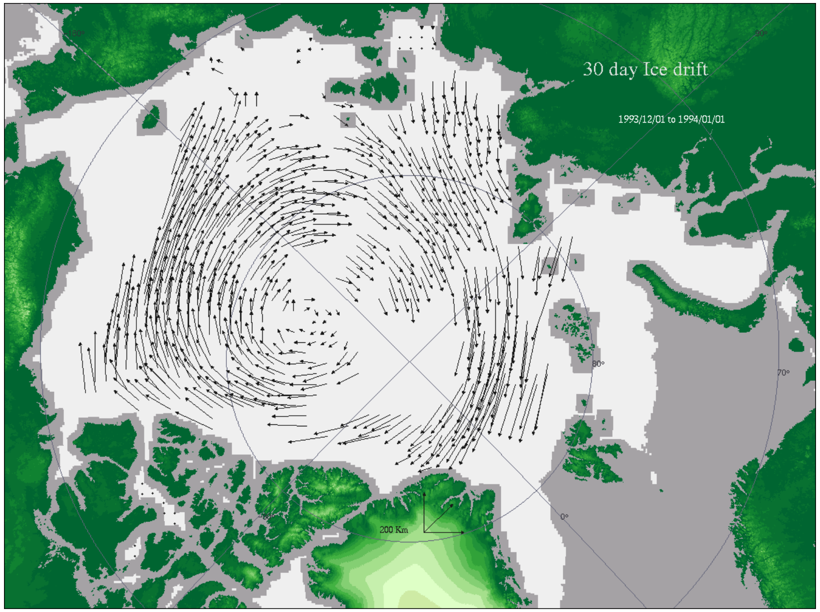
Model, December 1993

7.22 см/s



Satellite Data, December 1993

~ 8см/s



Red curve – sea ice edge in the model

Satellite Data From: ftp://ftp.ifremer.fr/ifremer/cersat/products/gridded/psi-drift/data/arctic/)

New version of the ocean model for methane dynamics calculation

- Fine vertical resolution, 40 levels: **0, 2.5, 5, 7.5, 10, 15, 20, 27.5, 37.5, 50, 65, 82.5, 100 (shelf levels)**, 125, 150, 175, 200, 225, 250, 275, 300, 325, 350, 375, 410, 450, 500, 600, 700, 850, 1050, 1250, 1500, 1750, 2100, 2500, 3000, 3500, 4000, 4500 m;
- New dynamic boundary condition at open boundaries, allowing for time varying in/outflow and volume conservation in the model domain;
- FE-FCT (Finite Element Flux Correction Scheme) for tracers is implemented in test mode;

Outlook

- Parameterization of heterogeneity of bottom methane saturation (bubble flares versus unsaturated background) in 1D column model
- Estimation of bottom diffusive and bubble fluxes of methane by fitting observed methane concentrations in 1D model
- Embedding dissolved methane transport (including bubble flux), diffusion and oxidation in Arctic Ocean
- Ocean simulations for historical period assessing the role of different ocean processes in methane dynamics, e.g. the ice cover variability


Thank you for your attention!