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Numerical modelling of methane emissions from thermokarst lakes

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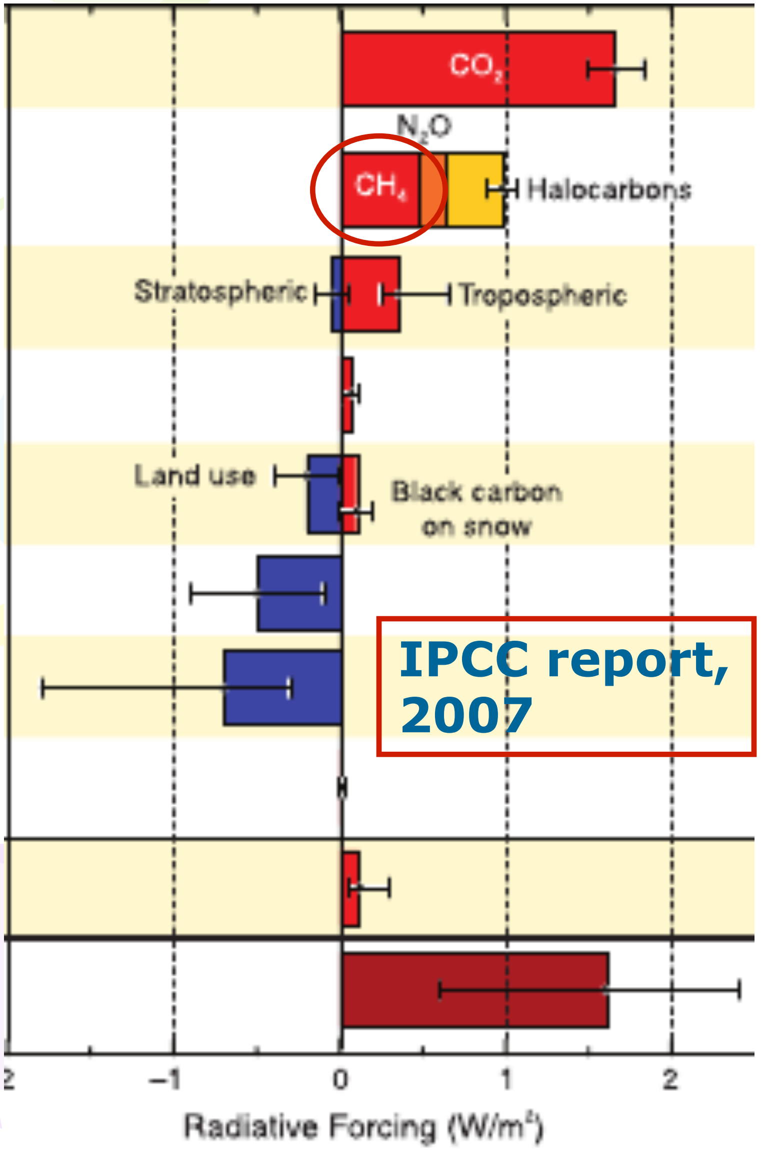
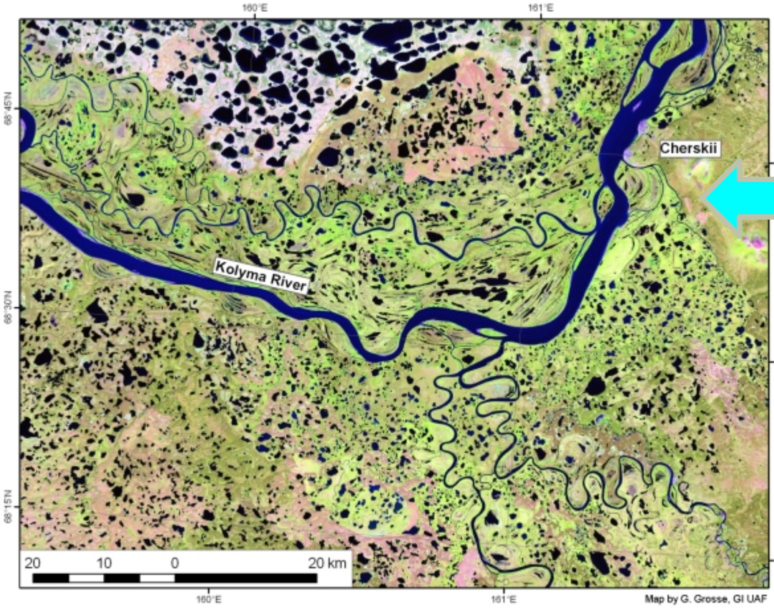
Atmospheric methane and its sources

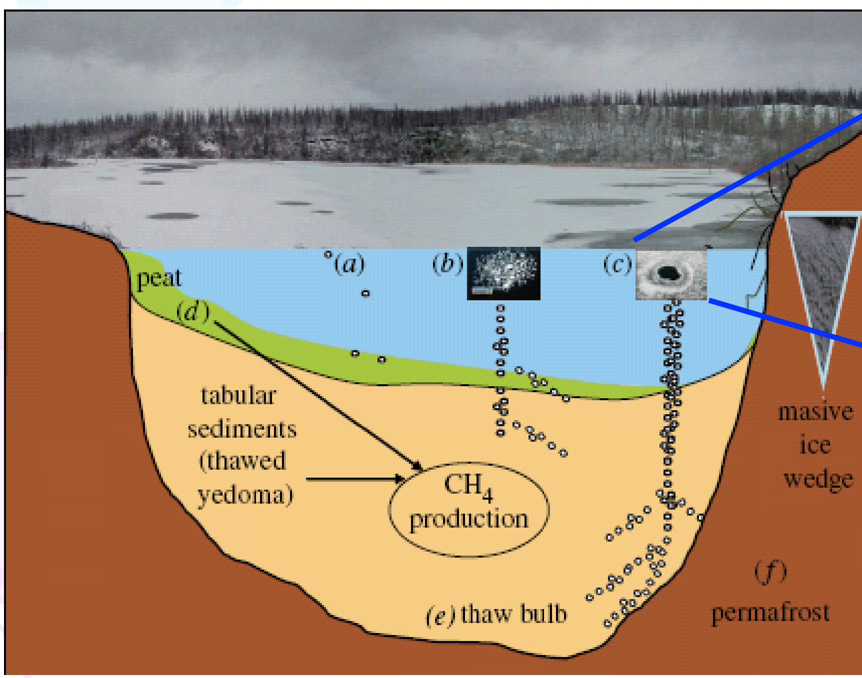


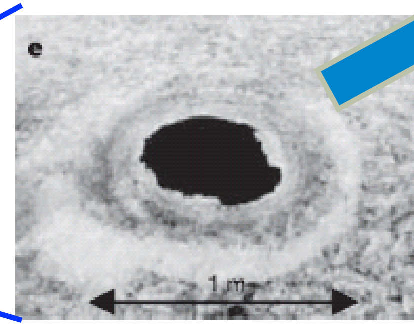
Sources of methane in a climate system	Mtones CH_4/yr
Animals (mostly ruminants), without termites	106
Termites	23
Rice paddies	69
Natural wetlands, excluding tundra	**113**
Tundra	**19**
Oceans	14
Lakes	**5**
Methane hydrates	4
Volcanoes	1
Other natural sources	6
Burials of solid waste products	33
Coal industry	46
Gas industry	54
Biomass burning	40
Automobiles	1
TOTAL	**~530**

Emission of methane by thermokarst lakes



- thermokarst lakes in Northern Siberia occupy 22-48% of the area
- satellite images indicate expanding of thermokarst lakes area



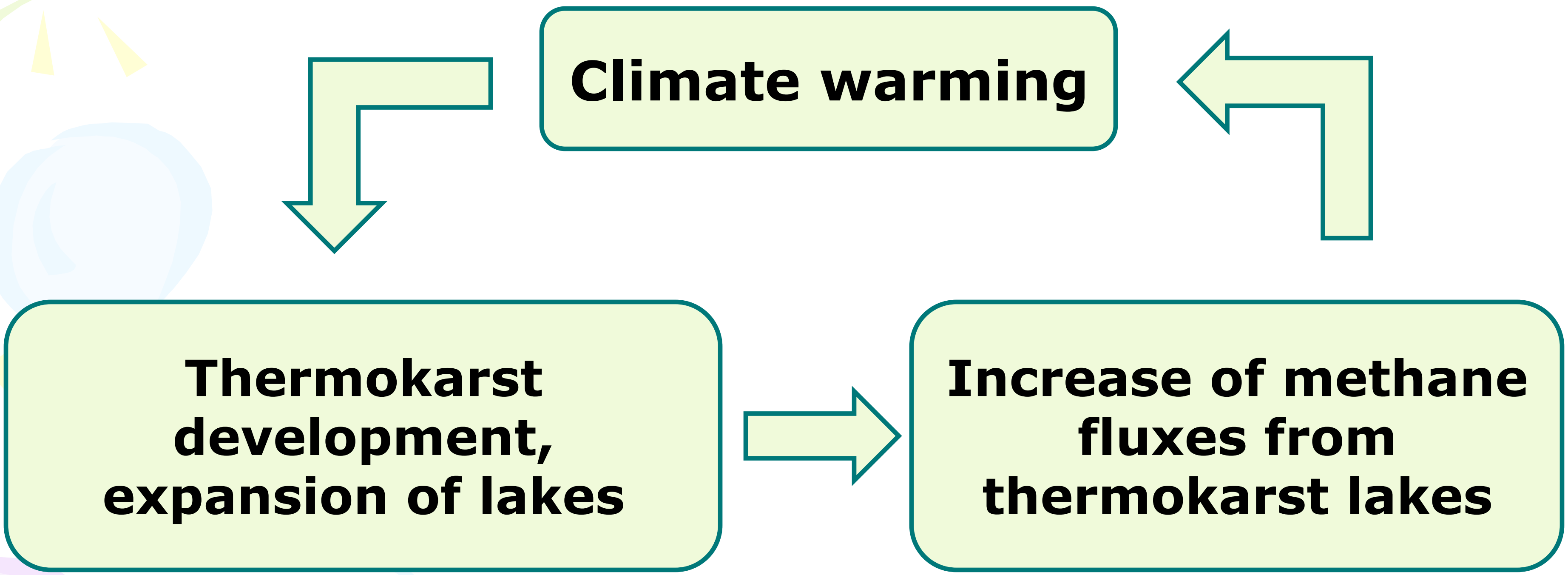


Unfreezing “hotspot” – the source of methane during wintertime

- 8 - 50% of anthropogenic emissions in XXI century depending on IPCC scenario (K. Walter et al., 2006, *Nature*)

Implication to climate change and climate modeling

- Positive feedback:



We need a modeling tool, a parameterization of thermokarst lakes' emissions in climate models

Methane emission: bogs and lakes

Mechanism of methane production

- On **bogs** the substrate for methane production comes from surface NPP -> modeling approaches are well developed
- In **lakes** methane is produced (i) from lake bottom NPP and (ii) from the old organics, that has been sequestered in permafrost and comes to positive temperature region while talik is deepening -> the need for new parameterization

Implication to annual cycle

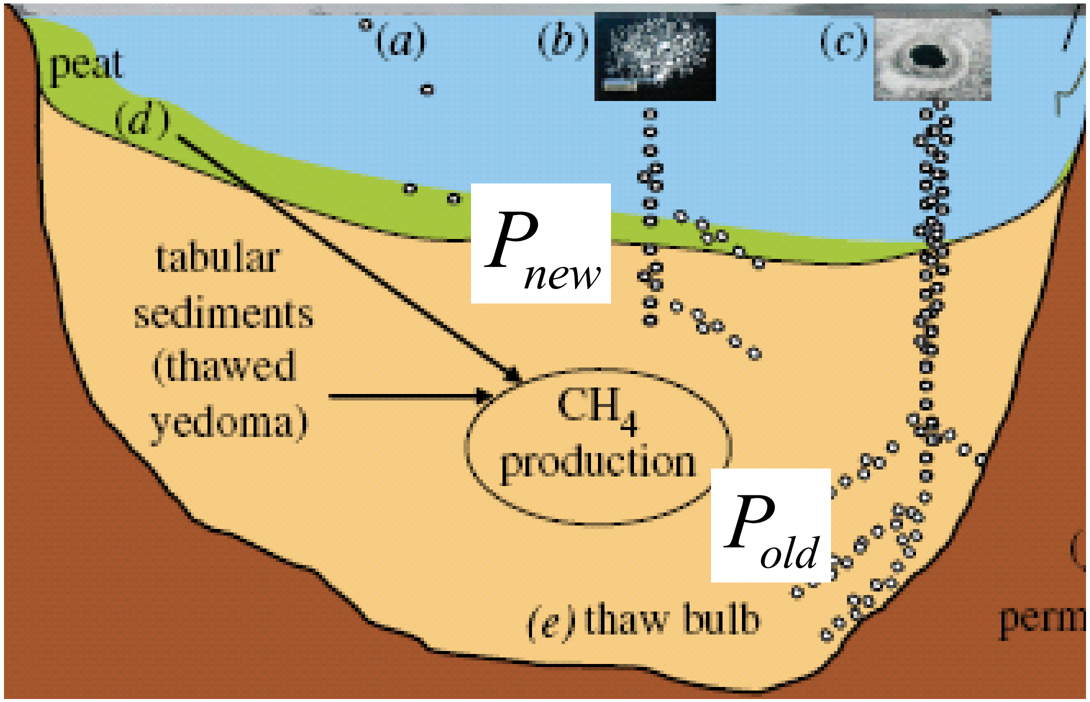
- On **bogs** cold season emission is very low;
- In **lakes** methane is produced in talik, that is under positive temperatures all year round (40-50% of annual emission happen in cold period)

Methane concentration in lake talik

$$\frac{\partial [CH_4]}{\partial t} = \frac{\partial}{\partial z} k_{CH_4,m} \frac{\partial [CH_4]}{\partial z} + P - E - F$$

(B. Walter & Heimann, 1996, 2001)

Neglected:
vegetation transport F



Ebullition:

$$E = k_e f_{step}\left(\Delta[CH_4]\right)\Delta[CH_4],$$

$$\Delta[CH_4] = [CH_4] - [CH_4]_{max}$$

Production:

$$P = P_{new} + P_{old}$$

$$P_{new} = P_{new,0} \exp\left(-\alpha_{new} z\right) f_{step}\left(T\right) q_{00}^{T/10}$$

$P_{new,0}$ **- calibrated parameter**

Methane production from old organics decomposition

- happens only under positive temperatures
- is exponentially dependent on temperature
- is proportional to decomposable organics content

$$P_{old} = P^*_{old,0} C_{old} f_{step}(T) q_{00}^{T/10}$$

$P^*_{old,0}$ - calibrated parameter

Michaelis-Menthen equation for decomposition (1)

$$\frac{\partial C_{old}}{\partial t} = -\frac{V_{C,\max} C_{old}}{\alpha_C + C_{old}},$$

$$C_{old} = f(t, t_0, \alpha_C, V_{C,\max})$$

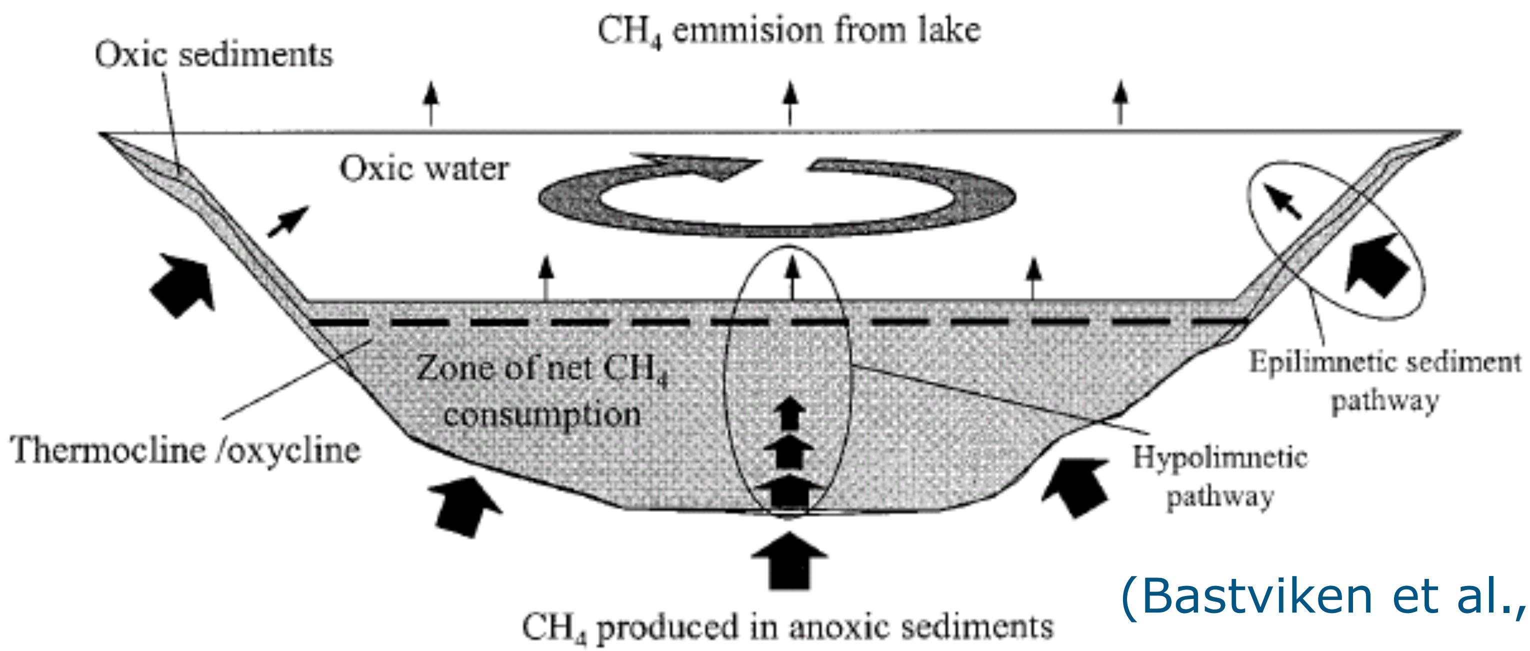
Analytical law for talik deepening (2)

$$z = C_t \sqrt{t_0},\ h_t = C_t \sqrt{t}$$

Combining (1) and (2) yields

$$C = C_{old,0}\left(2 + \lambda_C - \sqrt{(1 + \lambda_C)^2 + 2\gamma_C C_t^{-2}\left(h_t^2 - z^2\right)}\right)$$

Methane transfer in the water body



(Bastviken et al., 2002)

- **dissolved gases**:
  - methane
  - oxygen
  - carbon dioxide
- **processes:**
  - turbulent diffusion
  - methane oxidation

$CH_4 + O_2 = CO_2 + 2H_2O$

$$\frac{\partial[CH_4]}{\partial t} = \frac{\partial}{\partial z} k_{CH_4} \frac{\partial[CH_4]}{\partial z} - V_{oxid},$$

$$\frac{\partial[O_2]}{\partial t} = \frac{\partial}{\partial z} k_{O_2} \frac{\partial[O_2]}{\partial z} - 2V_{oxid},$$

$$\frac{\partial[CO_2]}{\partial t} = \frac{\partial}{\partial z} k_{CO_2} \frac{\partial[CO_2]}{\partial z} + 2V_{oxid}$$

One-dimensional k-ε model (LAKE)

Heat equation

$$\frac{\partial T}{\partial t}=\frac{\partial}{\partial z}\left(k_T\frac{\partial T}{\partial z}\right)-\frac{1}{c_p\rho}\frac{\partial S}{\partial z}+\frac{1}{A}\int_{\Gamma_A}(\vec{u}\cdot\vec{n})T\,dl$$

Momentum equations

$$\frac{\partial u}{\partial t}=\frac{\partial}{\partial z}k_M\frac{\partial u}{\partial z}+fv-g\cdot\mathrm{tg}\,\alpha_x-C_{veg}u\sqrt{u^2+v^2},$$

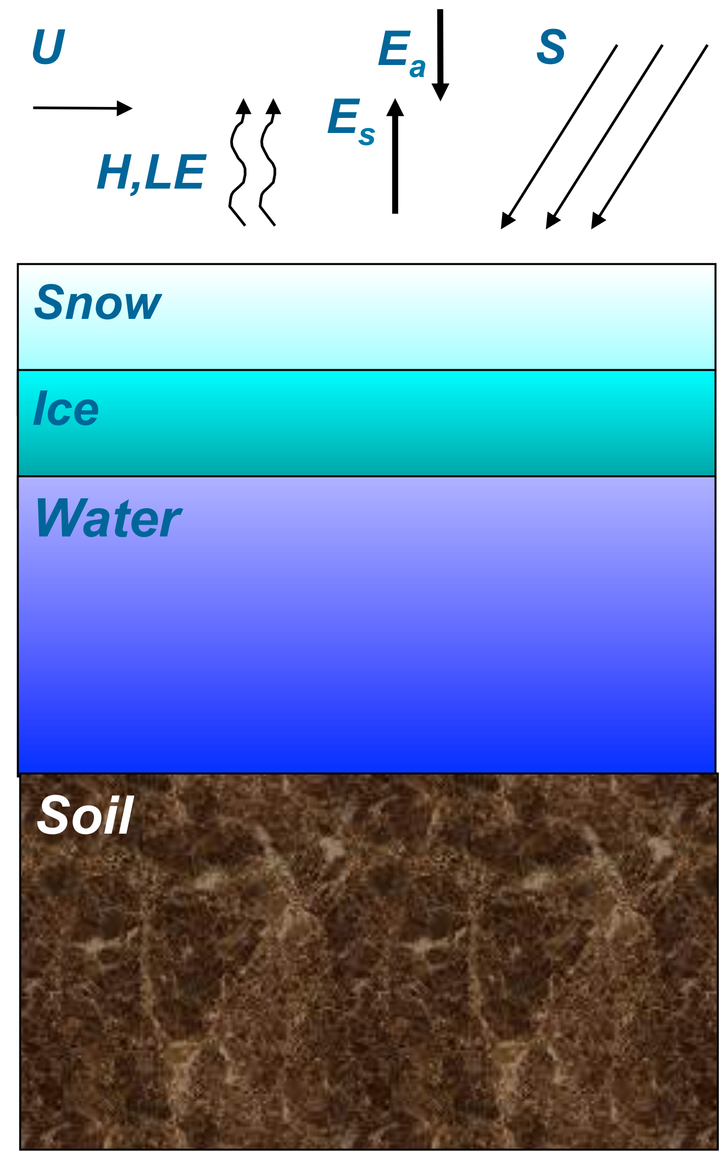
$$\frac{\partial v}{\partial t}=\frac{\partial}{\partial z}k_M\frac{\partial v}{\partial z}-fu-g\cdot\mathrm{tg}\,\alpha_y-C_{veg}v\sqrt{u^2+v^2}$$

K-ε turbulence closure

$$k_M=C_e\frac{E^2}{\varepsilon},$$

$$\frac{\partial E}{\partial t}=\frac{\partial}{\partial z}\left(\nu+\frac{k_M}{\sigma_E}\right)\frac{\partial E}{\partial z}+P+B-\varepsilon,$$

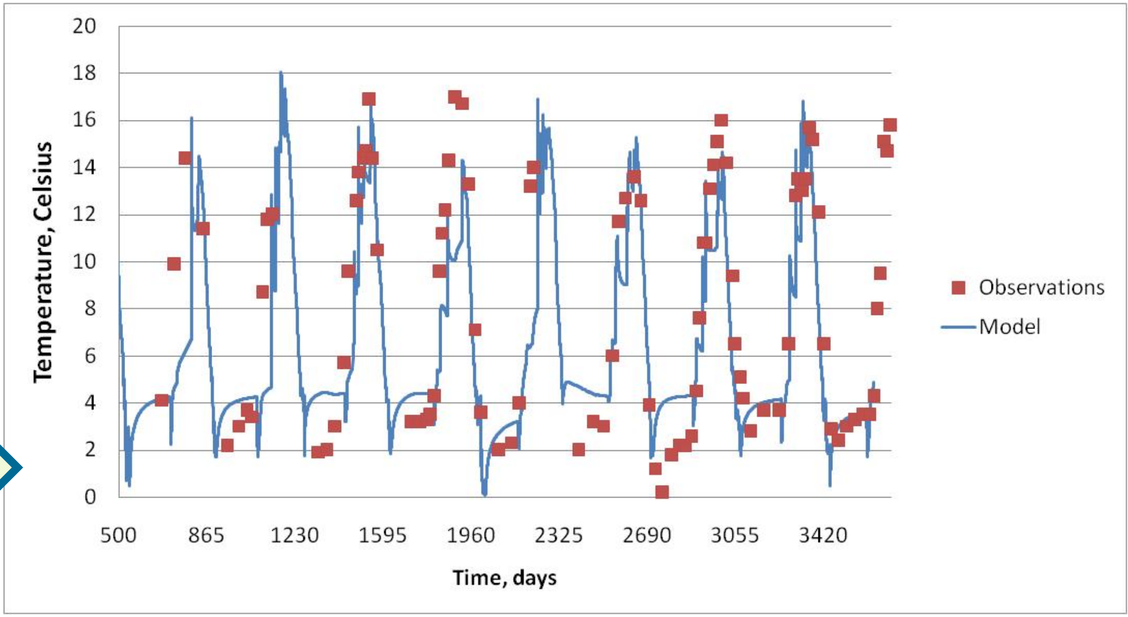
$$\frac{\partial \varepsilon}{\partial t}=\frac{\partial}{\partial z}\left(\nu+\frac{k_M}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial z}+\frac{\varepsilon}{E}\left(c_{1\varepsilon}P+c_{3\varepsilon}B-c_{2\varepsilon}\varepsilon\right)$$



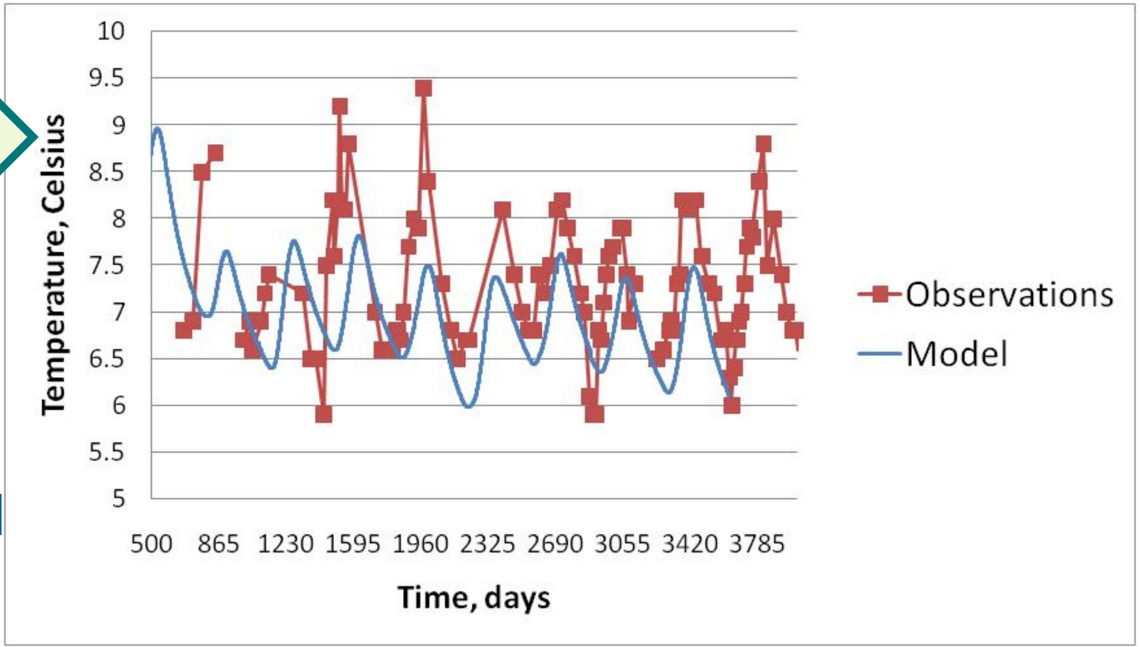
Validation: sediments temperature

- **Krasnoe Lake, (near S.-Petersburg)**
- **1969 – 1979**
- **Sortavala station forcing**

Bottom temperature



Bottom sediments temperature (3 m depth)

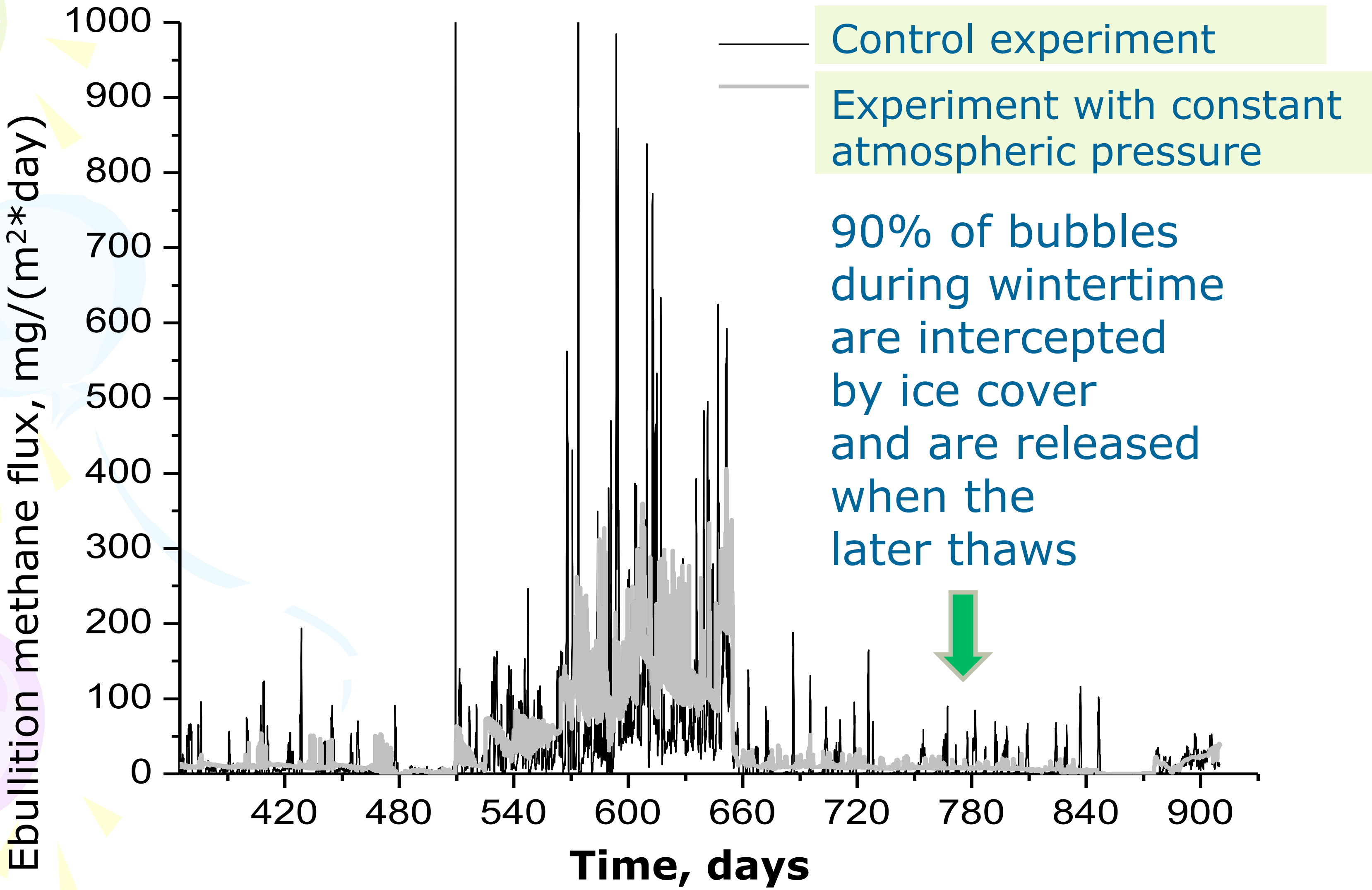


Observations: Kusmenko, 1976.

Soil heat conductance: Cote and Konrad model (Sen Lu et al., 2007)

Case study: Lake Shuchi

- Time series of atmospheric variables as input to lake model are extracted from ERA-Interim reanalysis



90% of bubbles during wintertime are intercepted by ice cover and are released when the later thaws

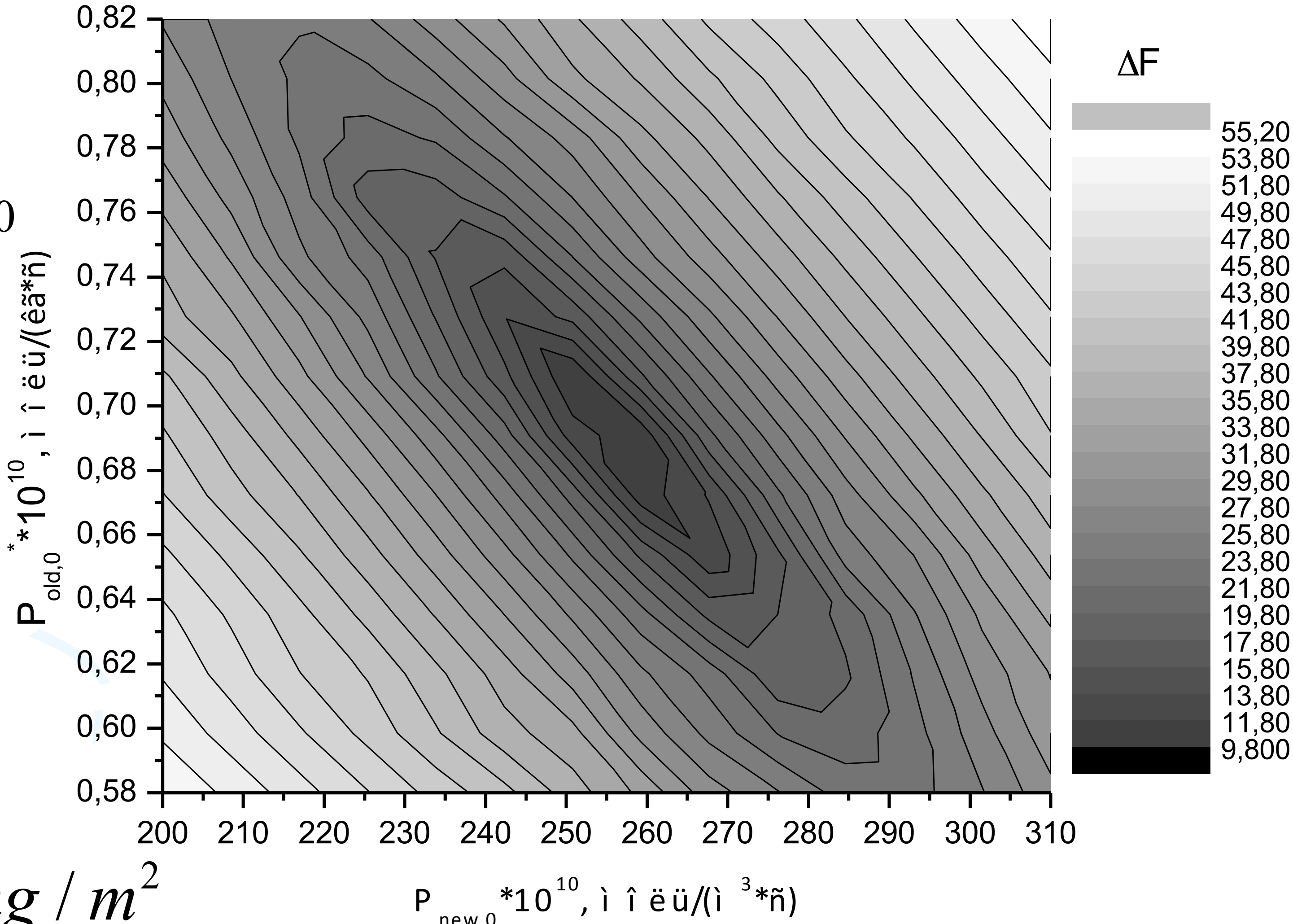
Model calibration: Lake Shuchi

The measure of model error $$\Delta F^2 \equiv \left(F_a^w - F_{a,m}^w\right)^2 + \left(F_a^s - F_{a,m}^s\right)^2$$

- Calibrated parameters

$$P_{old,0}^*, P_{new,0}$$

- ΔF has single minimum



$$\Delta F_{\min} \cong 10\, mg / m^2$$

Model validation

Observations: **Lake Shuchi** (K. Walter et al., 2006) hourly observations of ebullition and diffusion methane fluxes in different lake sections for 2003 – 2004

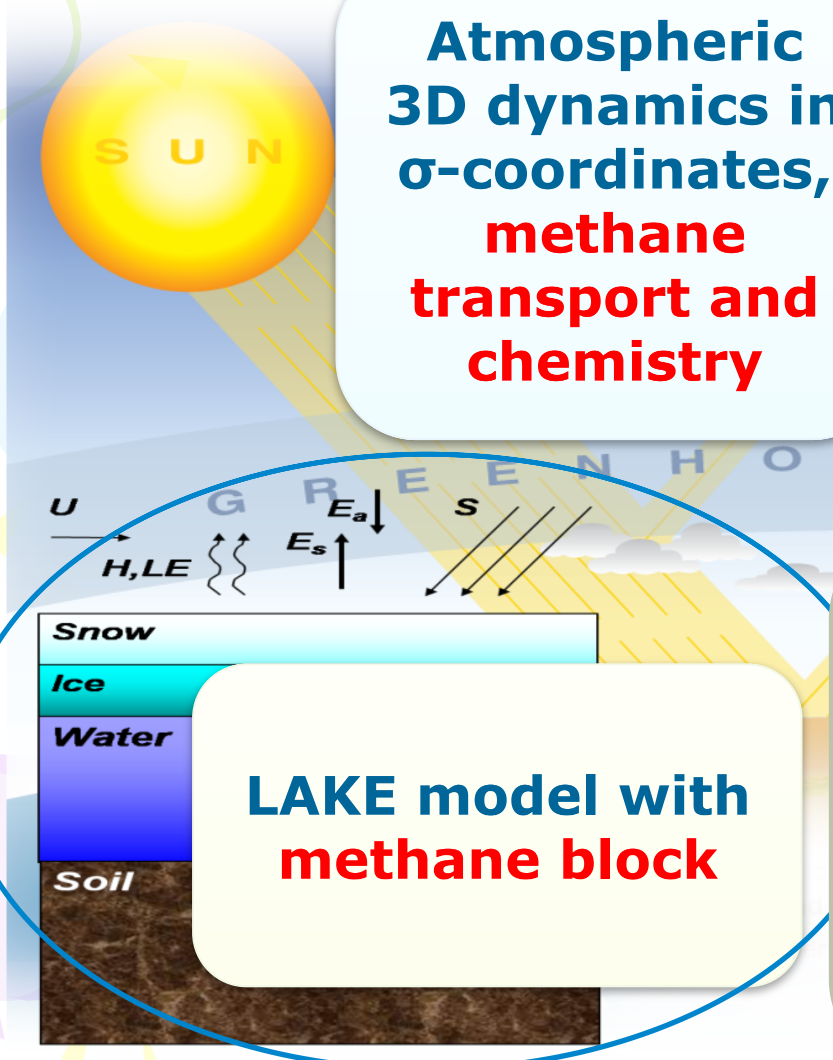
	Annual methane emission, **mg/(m²*yr)**	A part of open-water period emission , **%**	A part of ice-covered period emission, **%**
Observations	**22658**	**54**	**46**
Model	**22588**	**54**	**46**

	Open water period	Ice-covered period
A part of young methane in emissions (observations) , **%**	**47**	**6**
A part of young methane in net generation (model) , **%**	**61**	**32**

Remarks on lake methane model

- The values of calibrated parameters depend on errors (lack of observations!) of input parameters: lake depth, water turbidity, atmospheric forcing, etc.
- The model should be verified on a significant number of thermokarst lakes
- The model does not consider thermokarst lake development (deepening, drainage, etc.)

Regional atmospheric model NH3D_MPI



Atmospheric 3D dynamics in σ-coordinates, methane transport and chemistry

LAKE model with methane block

Land surface model of INM:

1. **Soil (including permafrost)**
2. **Vegetation**
3. **Snow cover**
4. **Walter and Heimann methane model for bogs**
5. **A set of models for oxic soils carbon cycling**

- horizontal spacing 1-10 km
- 30 levels in vertical
- time step 5-10 s
- **parallel implementation using MPI**

Research perspectives

- Inverse modeling of atmospheric methane transport on a regional scale to (i) identify sources (ii) validate and calibrate land surface methane models (bogs and lakes) using measurements of atmospheric methane concentration
- Incorporation of lake methane model in regional and global climate models to assess regional feedback between climate change and thermokarst lakes and its global significance