Towards a lake greenhouse gases parameterization for the Earth System models

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Introduction

Lakes occupy a significant part of land in many northern regions, e.g. in Northern Siberia, Karelia, Finland and Canada. The importance of thermodynamic interaction between lakes and the atmosphere in these regions led to inclusion of lake parameterizations into climate models and numerical weather prediction systems. However, these lake parameterizations are still confined to heat and momentum exchange at the lake-atmosphere interface, whereas observational evidence *(see below)* is growing on the importance of greenhouse gases emissions from lakes. In order to extend our current knowledge on the dynamics of these emissions and gain a capability of making future projections of climate taking into account lake carbon fluxes, suitable modelling framework is to be developed. A lake model involving explicit treatment of both key biotic and abiotic controls of methane and carbon dioxide emissions is to be developed.

(Tranvik et al. 2009)

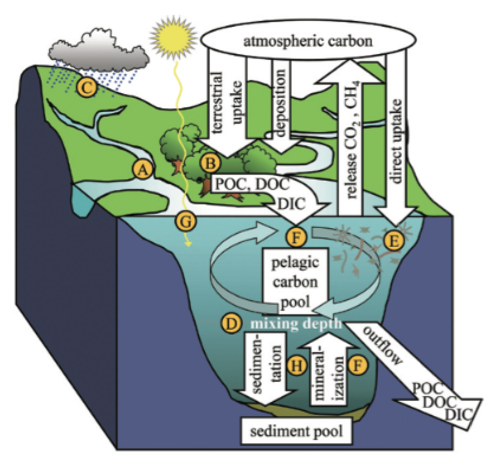


Fig. 2. Schematic diagram showing pathways of carbon cycling mediated by lakes and other continental waters. The letters correspond to rows in Table 1.

(Bastviken et al. 2011)

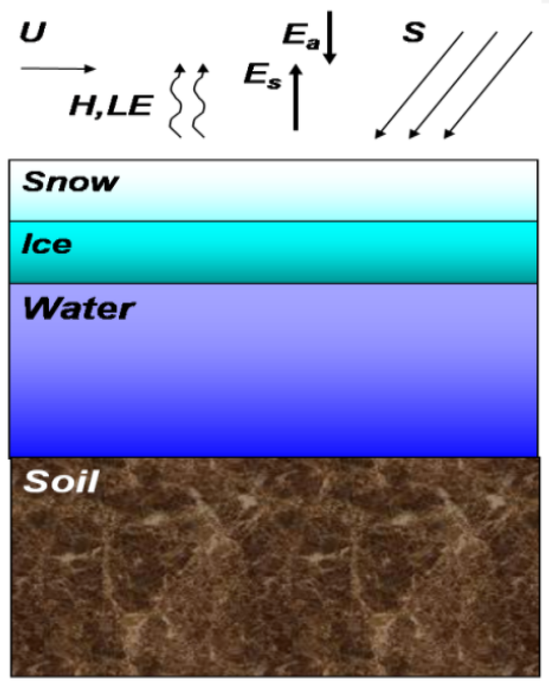
Latitude	Fluxes												Area (km²)
	Total open water			Ebullition			Diffusive			Stored			
	Emiss.	n	CV	Emiss.	n	CV	Emiss.	n	CV	Emiss.	n	CV	
Lakes													
>66°	6.8	17	72	6.4	17	74	0.7	60	37				288,318
>54°–66°	6.6	5	155	9.1	9	60	1.1	271	185	0.1	217	2649	1,533,084
25°–54°	31.6	15	127	15.8	15	177	4.8	33	277	3.7	36	125	1,330,264
<24°	26.6	29	51	22.2	28	54	3.1	29	97	21.3	1		585,536*
Reservoirs													
>66°	0.2†												35,289
>54°–66°	1.0	24	176	1.8	2	140	0.2	4	93				161,352
25°–54°	0.7‡												116,922
<24°	18.1	11	87										186,437
Rivers													
>66°	0.1	1											38,895
>54°–66°	0.2†												80,009
25°–54°	0.3	20	302										61,867
<24°	0.9‡												176,856
Sum open water	93.1	116		55.3	71		9.9	397		25.1	254		
Plant flux	10.2												
Sum all	103.3												

- Total freshwater methane emission is 104 Tg yr^{-1}, i.e. 50% of global wetland emission (177-284 Tg yr^{-1}, IPCC, 2013)
- greenhouse warming potentials from freshwater-originating CO_2 and CH_4 are roughly equal

Physics of 1D lake model

- 1D heat and momentum equations
- $k-\epsilon$ turbulence closure
- Monin-Obukhov similarity for surface fluxes
- Beer-Lambert law for shortwave radiation attenuation
- Momentum flux partitioning between wave development and currents (Stepanenko et al., 2014)
- Soil heat and moisture transfer including phase transitions
- Multilayer snow and ice models (not relevant in this study)

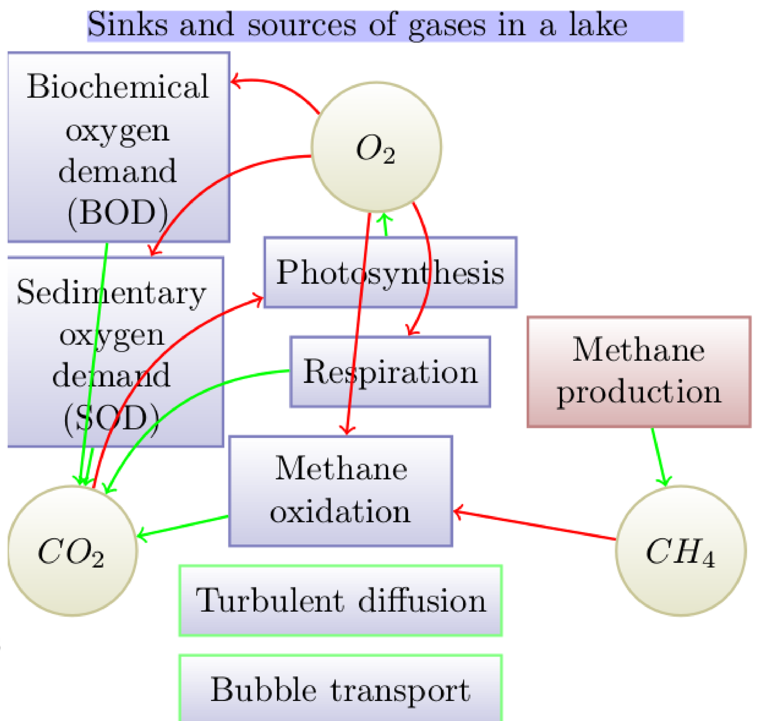
1D concept does not suffice the greenhouse gas modeling task, as it does not take into account differences between CH_4 & CO_2 emissions at deep and shallow sediments



Biogeochemistry of the model

- Photosynthesis, respiration and BOD are empirical functions of temperature and Chl-a (Stefan and Fang, 1994)
- Oxygen uptake by sediments (SOD) is controlled by O_2 concentration and temperature (Walker and Snodgrass, 1986)
- Methane production $\propto P_0 q_{10}^{T-T_0}$, P_0 is calibrated (Stepanenko et al., 2011)
- Methane oxidation follows Michaelis-Menthen equation

Sinks and sources of gases in a lake



Single bubble model

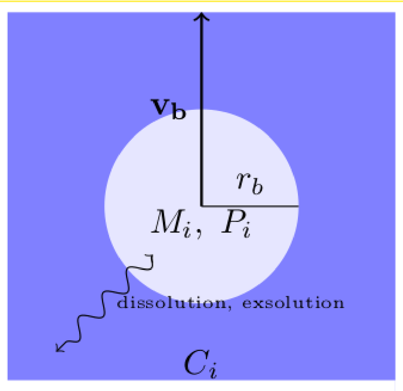
For shallow lakes (several meters), bubbles reach water surface not affected, for deeper lakes bubble dissolution has to be taken into account.

- Five gases are considered in a bubble: CH_4, CO_2, O_2, N_2, Ar
- Bubbles are composed of CH_4 and N_2 when they are emitted from sediments
- The velocity of bubble, v_b, is determined by balance between buoyancy and friction
- The molar quantity of i-th gas in a bubble, M_i, changes according to gas exchange equation (McGinnis et al.,

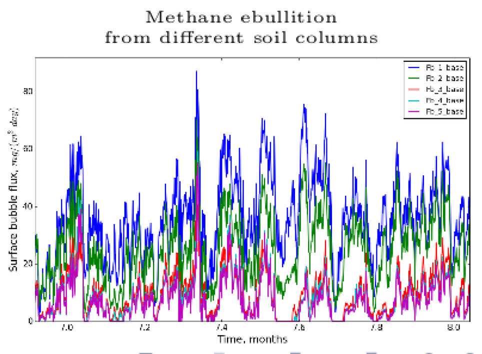
$$\frac{dM_i}{dt} = v_b \frac{\partial M_i}{\partial z} = -4\pi r_b^2 K_i (H_i(T)P_i - C_i).$$

- Gas exchange with solution is included in conservation equation for i-th gas :

$$\frac{\partial C_i}{\partial t} = \frac{1}{A}\frac{\partial}{\partial z} Ak \frac{\partial C_i}{\partial z} + \frac{1}{A}\frac{\partial AB_{C_i}}{\partial z} + F(z,t,C_i,A) + (H_{C_i} - B_{C_i,b})\frac{1}{A}\frac{dA}{dz}.$$

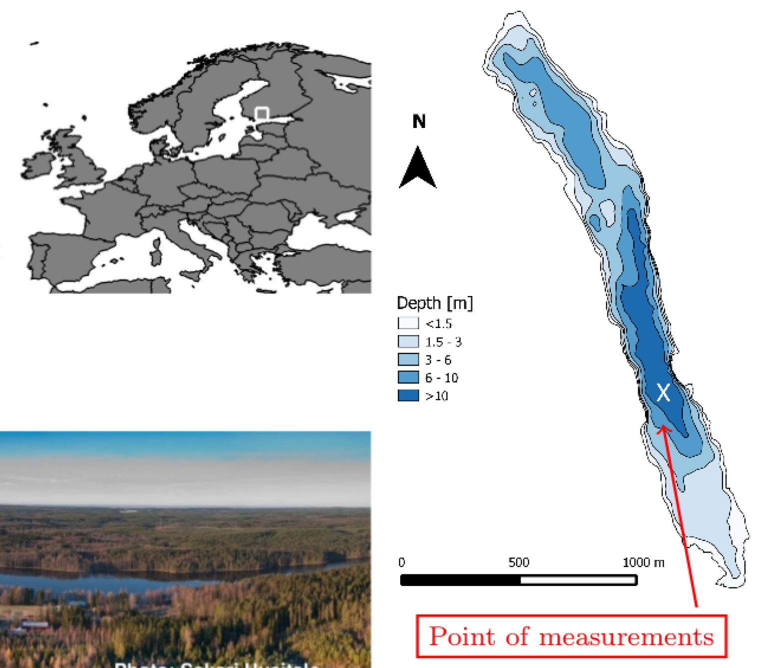


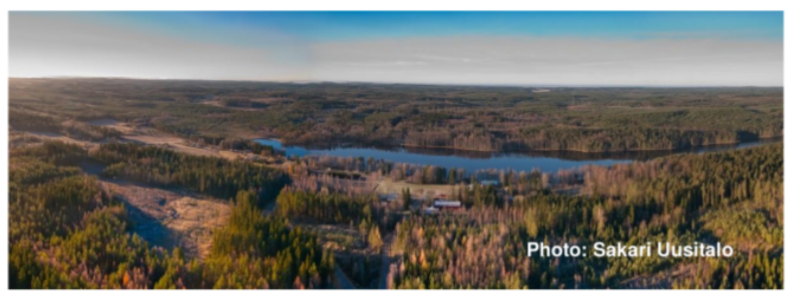
Methane ebullition from different soil columns



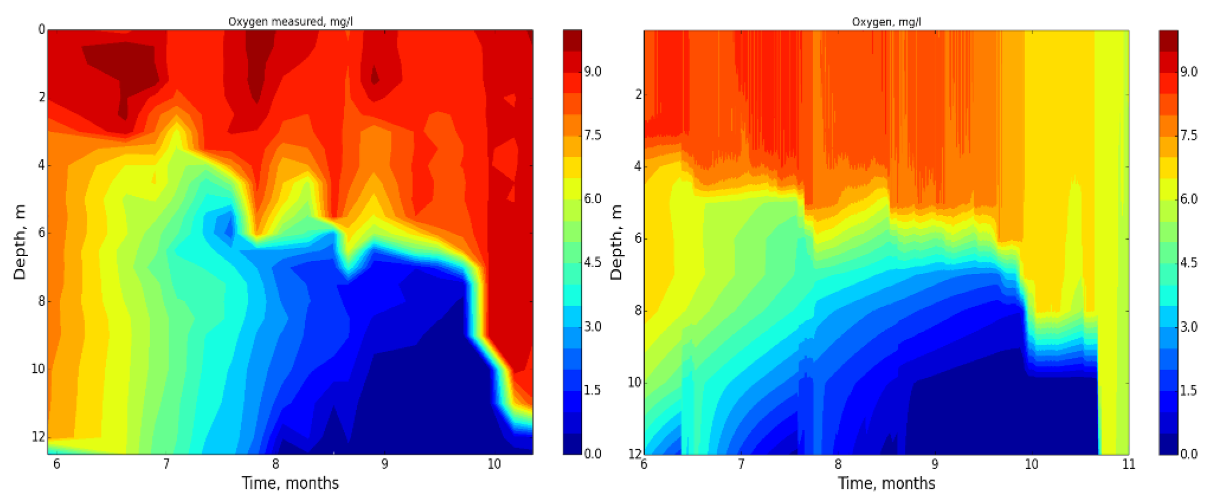
Validation Site 1: Kuivajarvi Lake (Finland)

- Mesotrophic, dimictic lake
- Area 0.62 km^2 (length 2.6 km, modal fetch 410 m)
- Altitude 142 m a.s.l.
- Maximal depth 13.2 m, average depth 6.4 m, depth at the point of measurements 12.5 m
- Catchment area 9.4 km^2



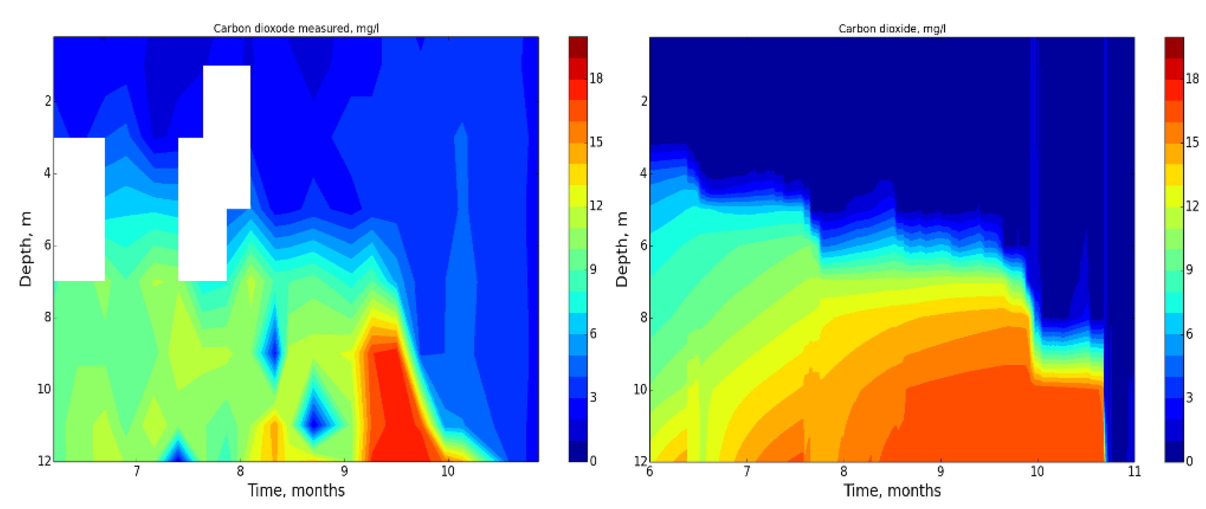


Kuivajärvi Lake: O_2



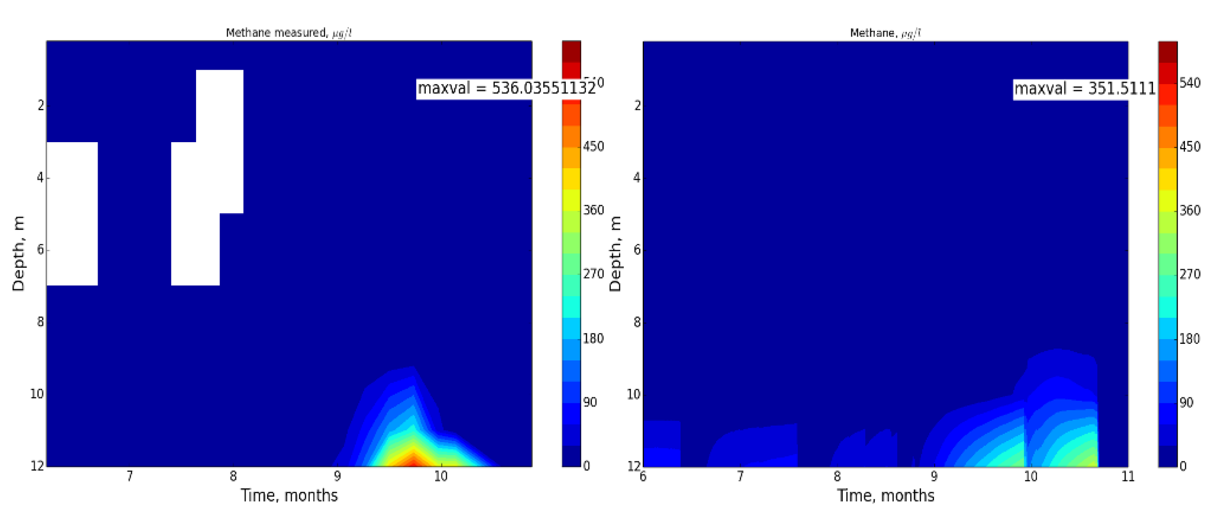
- Seasonal pattern is well captured: oxygen is produced in the mixed layer and consumed below
- Oxygen concentration in the mixed layer is underestimated by 1-1.5 mg/l, and more significantly during autumn overturn

Kuivajärvi Lake: CO_2



- Seasonal pattern is simulated realistically: carbon dioxide is consumed by photosynthesis in the mixed layer and produced in the thermocline and hypolimnion by aerobic organics decomposition
- Sudden CO_2 increase prior to autumn overturn is absent in the model

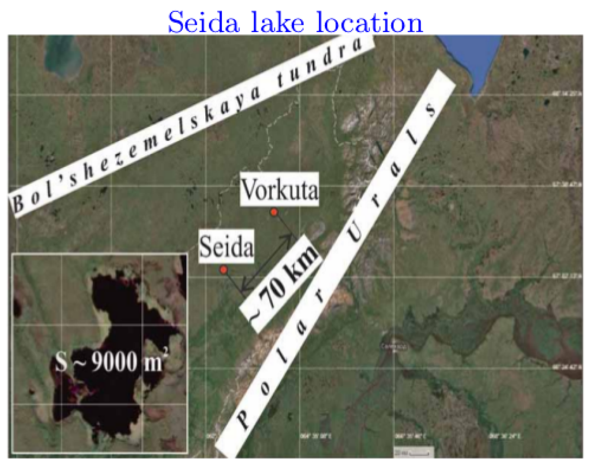
Kuivajärvi Lake: CH_4



- Methane starts to accumulate near bottom in the late summer when oxygen concentration drops to low values
- Surface methane concentration is very small leading to negligible diffusive flux to the atmosphere, consistent with measurements

Validation Site 2: Seida Lake (European Russia)

Seida lake location



Bubble flux (starting from 01.07.2007)

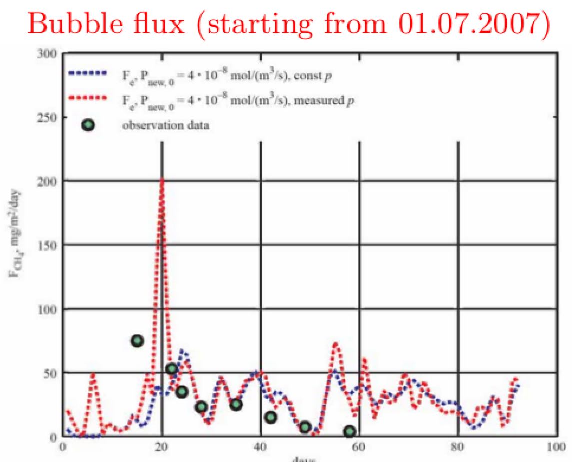
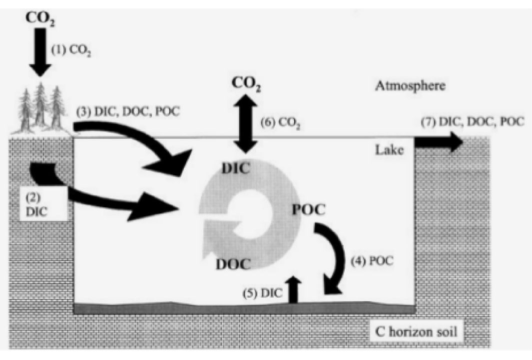


Table 3. Methane production rate constant $P_{new,0}$ in other studies

$P_{new,0}$ ($mol \cdot m^{-3} \cdot s^{-1}$)	Source
$3.0 \cdot 10^{-8}$	Lake Kuivajärvi, Finland [Stepanenko et al., 2016]
$2.55 \cdot 10^{-8}$	Shuchi Lake, North Eastern Siberia, Russia [Stepanenko et al., 2011]
$8.3 \cdot 10^{-8} - 1.6 \cdot 10^{-7}$	High latitude wetlands [Walter & Heimann, 2000]
$4.0 \cdot 10^{-8}$	Lake at the Seida site, current study

Further development of LAKE model biogeochemistry



Extended biogeochemical model

$$\frac{\partial C_{CH_4}}{\partial t} = Dif_A(C_{CH_4}) + B_{CH_4} - O_{CH_4}, \quad (1)$$

$$\frac{\partial C_{O_2}}{\partial t} = \mathrm{Dif}_A(C_{O_2}) + B_{O_2} + P_{O_2} - R_{O_2} - D_{O_2} - S_{O_2} - O_{O_2}, \quad (2)$$

$$\frac{\partial C_{DIC}}{\partial t} = \mathrm{Dif}_A(C_{DIC}) + B_{CO_2} - P_{CO_2} + R_{CO_2} + D_{CO_2} + S_{CO_2} + O_{CO_2}, \quad (3)$$

$$\frac{\partial \rho_{DOC}}{\partial t} = \mathrm{Dif}(\rho_{DOC}) + E_{POCL} - D_{DOC}, \quad (4)$$

$$\frac{\partial \rho_{POCL}}{\partial t} = \mathrm{Dif}(\rho_{POCL}) + P_{POCL} - R_{POCL} - E_{POCL} - D_{h,POCL}, \quad (5)$$

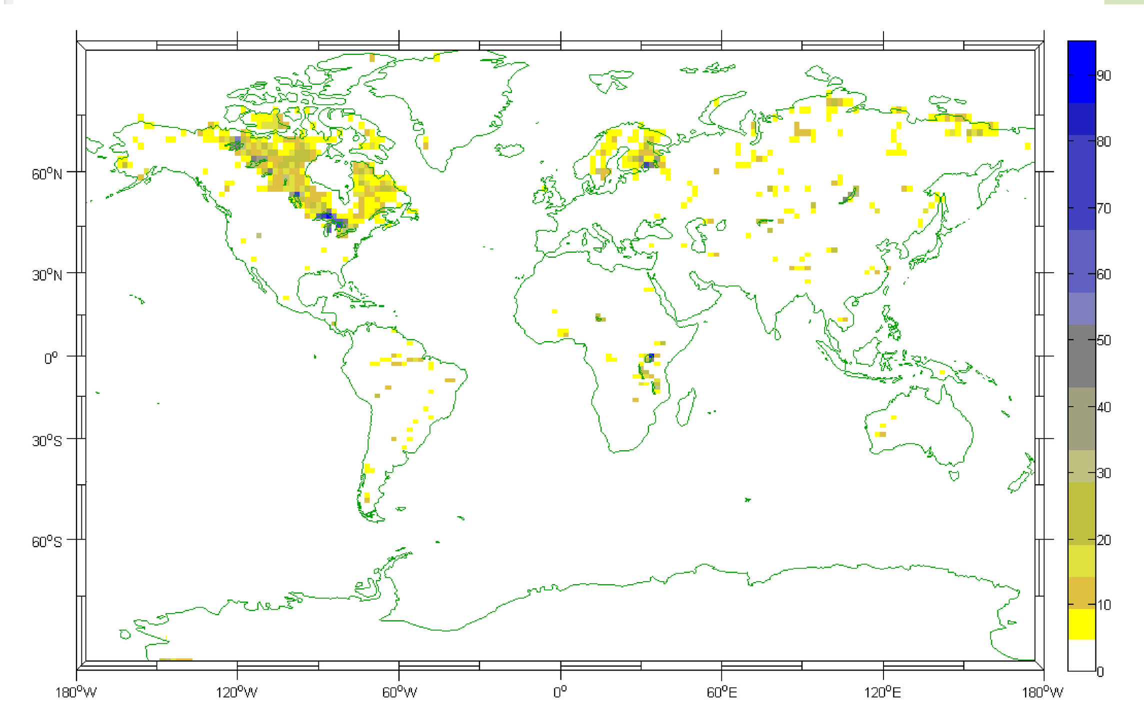
$$\frac{\partial \rho_{POCD}}{\partial t} = \mathrm{Dif}(\rho_{POCD}) - \frac{w_g}{h}\frac{\partial \rho_{POCD}}{\partial \xi} - D_{POCD} + D_{h,POCL}. \quad (6)$$

- The Hanson et al. model is reformulated to explicitly reproduce vertical distribution of DOC, POCL, POCD (instead of using mixed-layer and hypolimnion pools, as in original paper)
- The horizontal influx from catchment is to be included

Lake parameterization in INMCM ESM

- Previous lake have been presented in the model as soil with top layer without specific heat but with radiation and aerodynamic properties of water
- Turbulence closure in LAKE model has been changed to Hendersson-Sellers diffusivity for stable stratification
- Convective adjustment is added to LAKE for unstable stratification
- No lake morphometry
- Lake fraction and mean depth from GLDBv2 database (Choulga et al., 2014)
- Shortwave radiation extinction coefficient in lakes is taken 1 m^{-1} globally
- Lakes are added as a new tile to the surface layer
- Surface flux scheme for lakes taken the same as for other surfaces in INMCM, including Deardorff convective velocity scale (Beljaars, 1995)

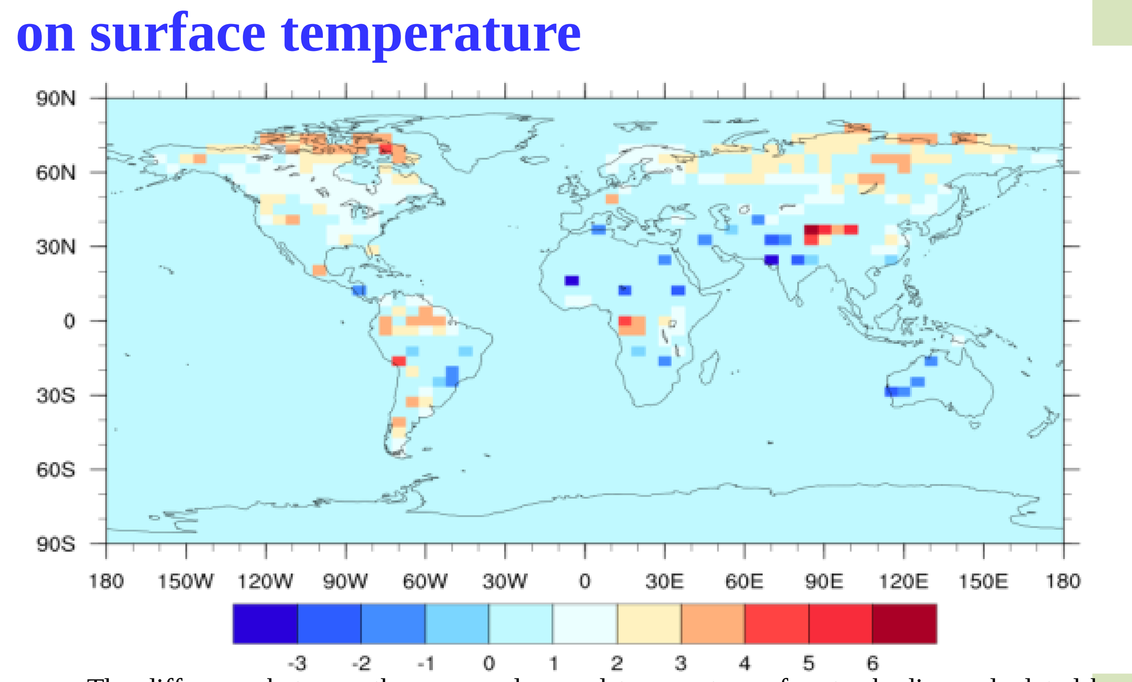
Lake fraction in INMCM Earth System Model



Lake surface temperature validation in a coupled model

The lake, country	The 5-year (1980-1985) averaged summer surface temperature, modelled, °C.	The 5-year (1980-1985) averaged summer surface temperature from observations, °C
Huron, Canada	19,2	17,9
Victoria, Tansania-Kenya-Uganda	25,25	23,6
Baikal, Russia	14,83	12,4
Ladoga, Russia	15,49	14,0

Lake parameterization effect on surface temperature



The difference between the averaged annual temperature of water bodies, calculated by the new lake parameterization and preceding lake representation as a wetland, 1981.

Conclusions

- 1D model LAKE simulates basic thermodynamic and dynamic processes in water, ice, snow and bottom sediments
- The model has been validated in terms of thermodynamic state variables on a number of lakes, including those studies in LakeMIP project
- Biogeochemical and physical processes controlling vertical distribution and dynamics of oxygen, methane and carbon dioxide in water column are taken into account
- Methane concentration and fluxes have been validated on lakes Shuchi (Siberia, not shown), Seida Lake (North European Russia) and Kuivajärvi Lake (Finland)
- Computationally cheap version of LAKE has been introduced to INMCM climate model where demonstrated reasonable performance in lake surface temperature

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Acknowledgements

The work is supported by grants RSF 17-17-01210 and RFBR 15-35-20958, 14-05-91752, 14-05-00510, 14-05-00038, 14-05-91754, 17-05-41095.