Numerical modeling of internal mixing and greenhouse gas dynamics in boreal lakes

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Outline

- The role of lakes in a global carbon cycle
- LAKE model: basic 1D version
- Extended 1D lake modeling framework, surface seiche parameterization
- Biochemistry model for $O_2,\ CO_2,\ CH_4$
- Kuiväjärvi Lake: site description
- Testing applicability of 1D model approach for the lake
- Model performance in lake temperature and gases concentrations
- Estimates of possible contribution of basin-scale seiches to the vertical gas transport
- Outlook

Freshwaters in global carbon cycle

(Tranvik et al. 2009)

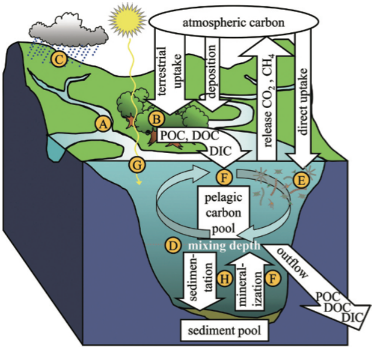
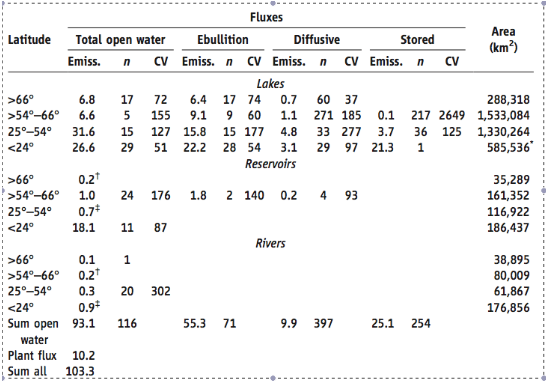


Fig. 2. Schematic diagram showing pathways of carbon cycling mediated by lakes and other continental waters. The letters correspond to rows in Table 1.

(Bastviken et al. 2011)



Latitude	Fluxes												Area (km^2)
	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°	$0.2^{\dagger}$												35,289
>54°–66°	1.0	24	176	1.8	2	140	0.2	4	93				161,352
25°–54°	$0.7^{\ddagger}$												116,922
<24°	18.1	11	87										186,437
						Rivers							
>66°	0.1	1											38,895
>54°–66°	$0.2^{\dagger}$												80,009
25°–54°	0.3	20	302										61,867
<24°	$0.9^{\ddagger}$												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												

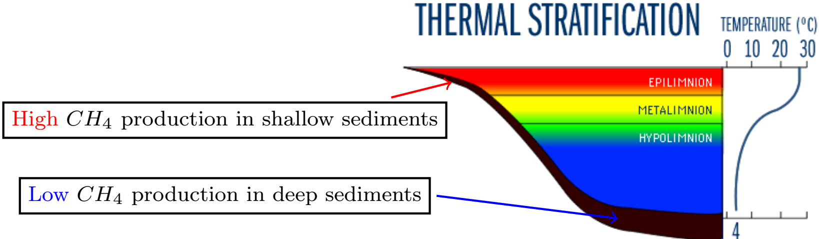
- Total freshwater methane emission is 104 Tg yr^{-1}, i.e. 50% of global wetland emission (177-284 Tg yr^{-1}, IPCC, 2013)
- greenhouse warming potentials from freshwater-originating CO_2 and CH_4 are roughly equal

CH_4 and CO_2 production and vertical transport in a lake

Vertical gas transport mechanisms:

- Ebullition
- Surface mixed-layer turbulence → driven by wind forcing and surface heat balance
- Thermocline → very strong stratification with intermittent turbulence. Possible mixing mechanisms are K-H instability, nonlinear wave breaking, and marginal shear induced by seiches.
- Hypolimnion → governed by gravity currents and seiche-induced turbulence

Typical summer stratification in a temperate lake



High CH_4 production in shallow sediments

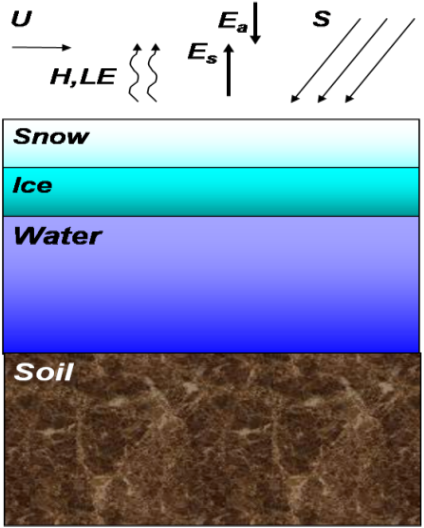
Low CH_4 production in deep sediments

Thermodynamics and hydrodynamics of LAKE model

1D version

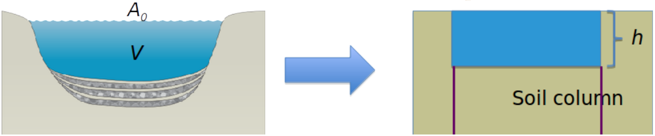
- 1D heat and momentum equations
- $k - \epsilon$ turbulence closure
- Monin-Obukhov similarity for surface fluxes
- Beer-Lambert law for shortwave radiation attenuation
- Momentum flux partitioning between wave development and currents (Stepanenko et al., 2014)
- Soil heat and moisture transfer including 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



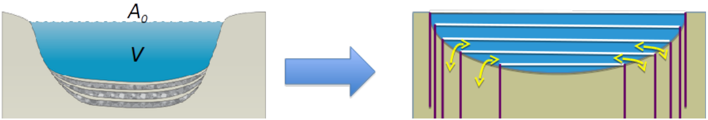
Extended ($1D^+$) modeling framework

Traditional 1D model concept



$1D^+$ model concept

- $1D^+$ model includes friction, heat and mass exchange at the lateral boundaries
- Heat, moisture and gas transfer are solved for each soil column independently



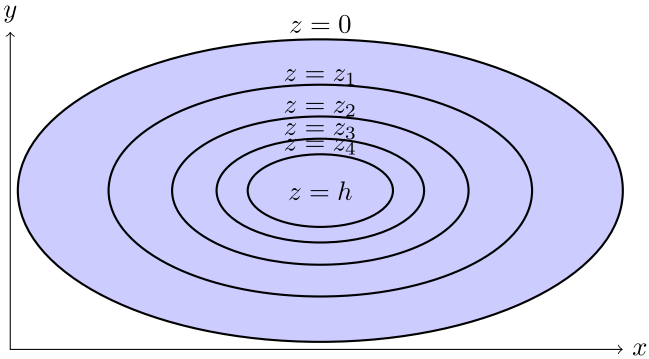
In $1D^+$ model horizontally averaged quantity f obeys the equation:

$$\frac{\partial f}{\partial t} = \frac{1}{A}\frac{\partial}{\partial z} A k_f \frac{\partial f}{\partial z} + F(z, t, f, A) + H_f \frac{1}{A}\frac{dA}{dz}.$$

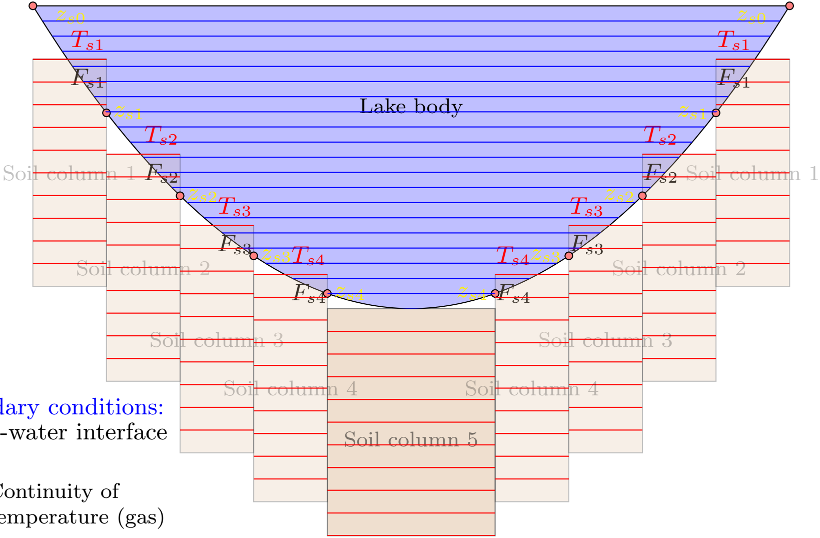
Soil columns in the model

Horizontal projection

Soil columns are geometric figures of the same vertical dimension confined by adjacent isobaths in horizontal:



Coupling $1D^+$ lake model to soil columns

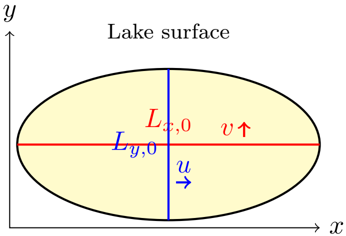


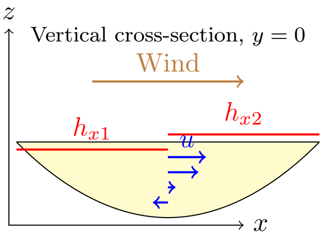
Boundary conditions:
at soil-water interface

- Continuity of temperature (gas)
- Continuity of flux

Parameterization of barotropic seiches

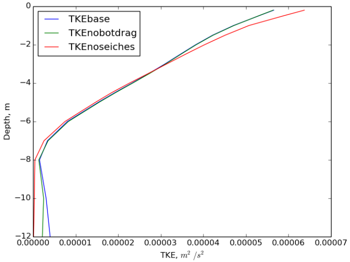
Barotropic (surface) seiches are lake surface and related velocity oscillations after strong wind events.





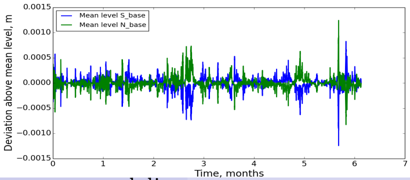
Turbulent kinetic energy profile (modeled), June 2013, Kuivajarvi Lake, seiches produce TKE near bottom

Mass conservation
$$\begin{cases} \frac{dh_N}{dt}A_0(t) = -\frac{dh_S}{dt}A_0(t) = 2\int_0^1 vL_{W-E}hd\xi, \\ \frac{dh_E}{dt}A_0(t) = -\frac{dh_W}{dt}A_0(t) = 2\int_0^1 uL_{S-N}hd\xi, \end{cases}$$



Barotropic pressure gradient force
$$\begin{cases} g\overline{\frac{\partial h_s}{\partial x}} \approx \frac{g\pi^2}{4}\frac{h_E - h_W}{L_{W-E,0}}, \\ g\overline{\frac{\partial h_s}{\partial y}} \approx \frac{g\pi^2}{4}\frac{h_N - h_S}{L_{S-N,0}}. \end{cases}$$

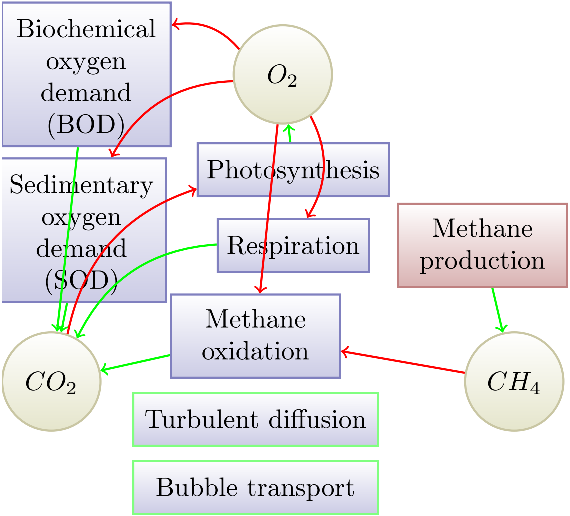
Surface oscillations in the model



Biochemistry 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 Snodrgass, 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



Biochemical oxygen demand (BOD)

O_2

Sedimentary oxygen demand (SOD)

Photosynthesis

Respiration

Methane production

Methane oxidation

CO_2

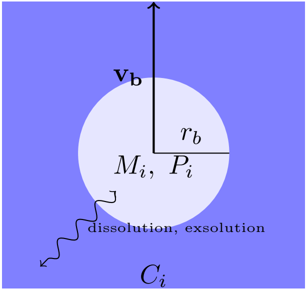
CH_4

Turbulent diffusion

Bubble transport

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.,

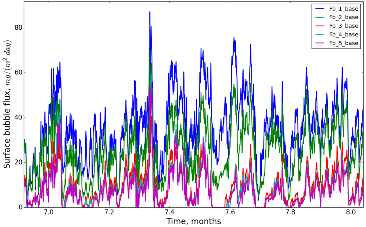
$$\frac{dM_i}{dt} = v_b \frac{\partial M_i}{\partial z} = -4\pi r_b^2 K_i (H_i(T)P_i - C_i).$$

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

$$\frac{\partial C_i}{\partial t} = \frac{1}{A}\frac{\partial}{\partial z} Ak \frac{\partial C_i}{\partial z} + \boxed{\frac{1}{A}\frac{\partial AB_{C_i}}{\partial z}} +$$

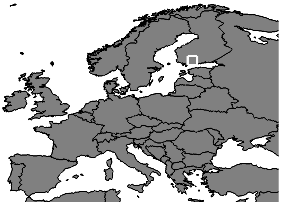
$$F(z,t,C_i,A) + (H_{C_i} - \boxed{B_{C_i,b}})\frac{1}{A}\frac{dA}{dz}.$$

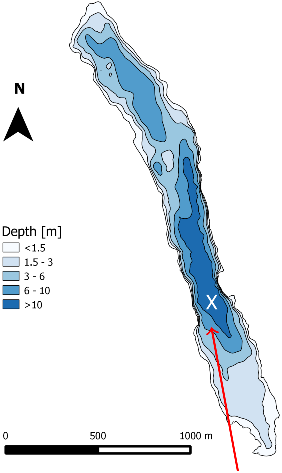
Methane ebullition
from different soil columns



Kuiväjärvi 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 the point of measurements 12.5 m
- Catchment area 9.4 km^2





Point of measurements

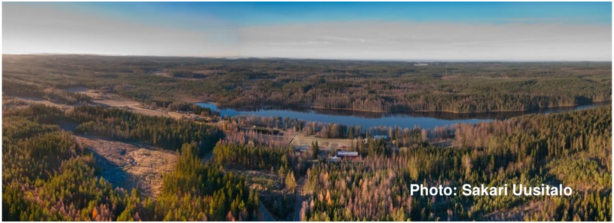


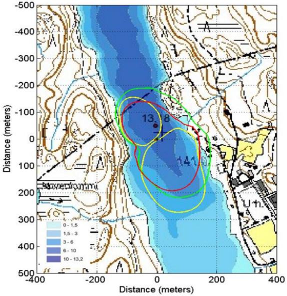
Photo: Sakari Uusitalo

Observations

- Conducted since 2009 by University of Helsinki
- Ultrasonic anemometer USA-1, Metek GmbH
- Enclosed-path infrared gas analyzers, LI-7200, LI-COR Inc.
- Four-way net radiometer (CNR-1)
- relative humidity at the height of 1.5 m (MP102H-530300, Rotronic AG)
- thermistor string of 16 Pt100 resistance thermometers (depths 0.2, 0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 3.5, 4.0, 4.5, 5.0, 6.0, 7.0, 8.0, 10.0 and 12.0 m)
- Turbulent fluxes were calculated from 10 Hz raw data by EddyUH software

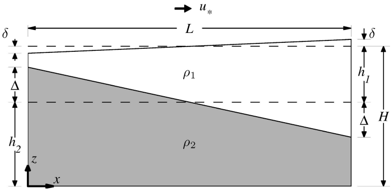
Measurement raft

Footprint of the raft measurements



Validity of 1D approximation for Kuiväjärvi Lake

Wedderburn and Lake numbers



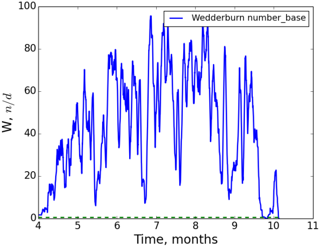
Shintani et al., 2010

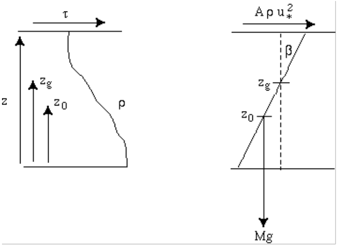
Wedderburn number

$$W = \frac{g \Delta \rho h_1^2}{\rho_0 u_*^2 L}$$

$$W_{cr} \approx \frac{1}{2}$$

Running means





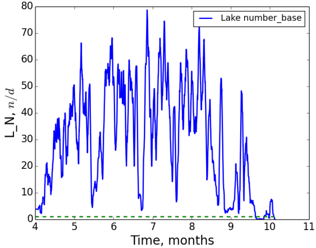
Imerito, 2015

Lake number

$$L_N = \frac{2(z_m - z_v) V \rho_0 g h_1}{z_v \tau A_0 L}$$

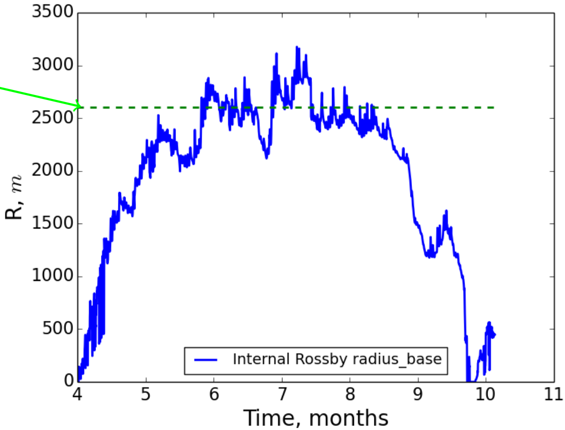
$$L_{N,cr} \approx 1$$

Thermocline displacement is negligible compared to mixed-layer depth



Significance of Coriolis force for Kuiväjärvi Lake

Rossby deformation radius, $\lambda = \frac{NH}{f} \approx \frac{\sqrt{g\rho_0^{-1}\Delta\rho\ h_{ML}}}{f}$

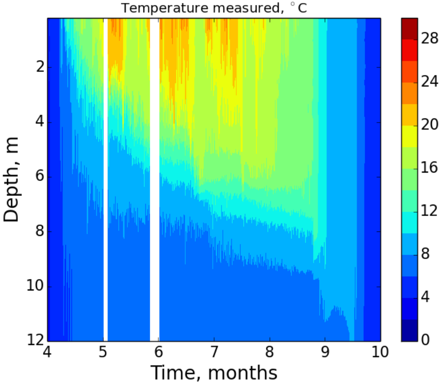


The lake's length

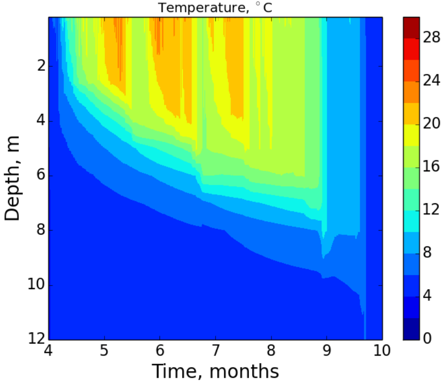
Rotational effects are comparable with those of stratification.

Water temperature

Measurements



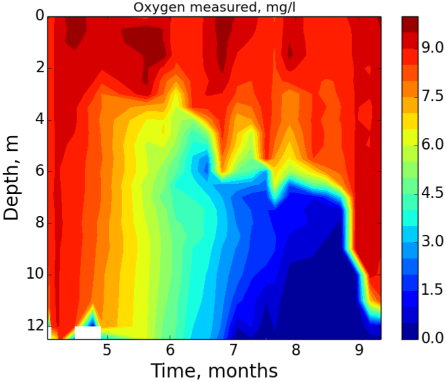
Model



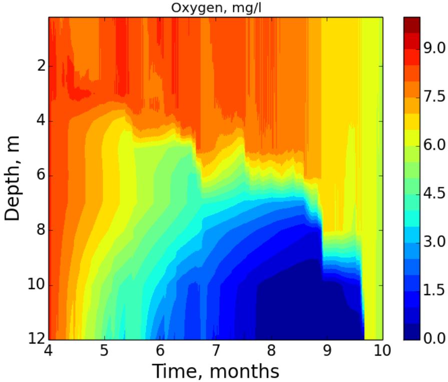
- Mixed layer depth and surface temperature are well reproduced
- Stratification strength in the thermocline is overestimated
- Model results lack frequent temperature oscillations in the thermocline

Oxygen

Measurements



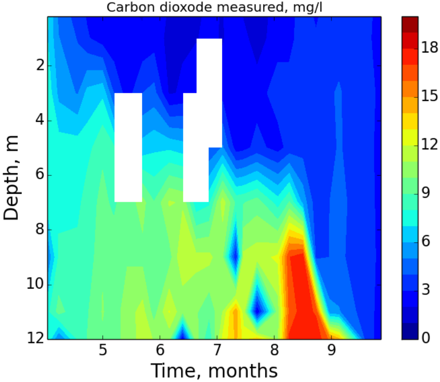
Model



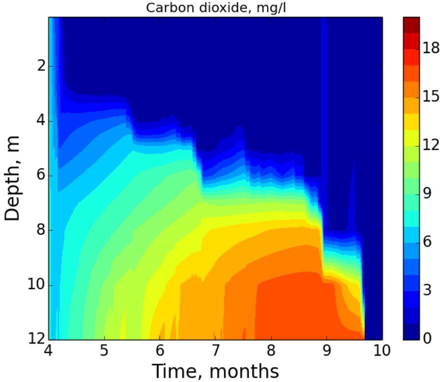
- Seasonal pattern is well captured: oxygen is produced in the mixed layer and consumed below
- Oxygen concentration in the mixed layer is underestimated by 1-1.5 mg/l, and more significantly during autumn overturn

Carbon dioxide

Measurements



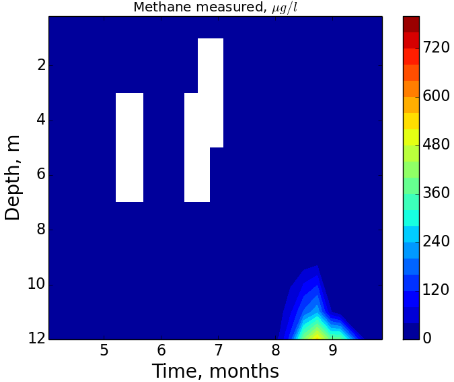
Model



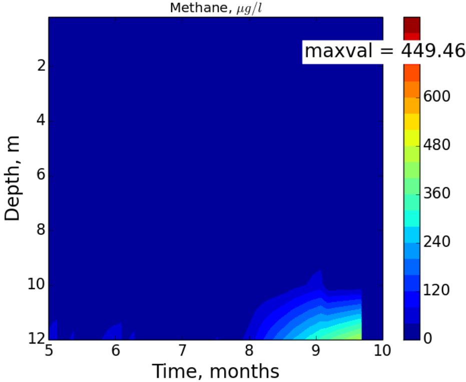
- Seasonal pattern is simulated realistically: carbon dioxide is consumed by photosynthesis in the mixed layer and produced in the thermocline and hypolimnion
- Sudden CO_2 increase prior to autumn overturn is absent in the model

Methane

Measurements

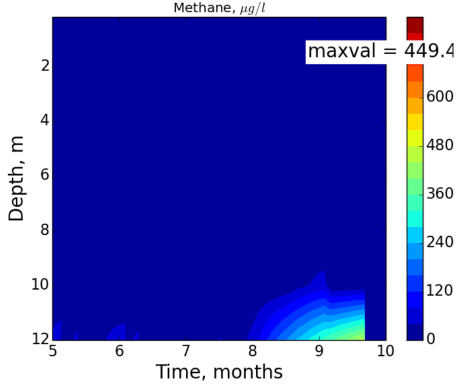


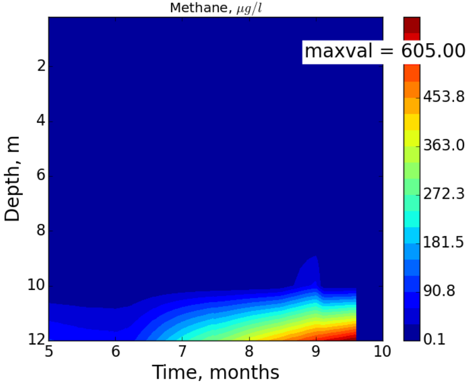
Model



- 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

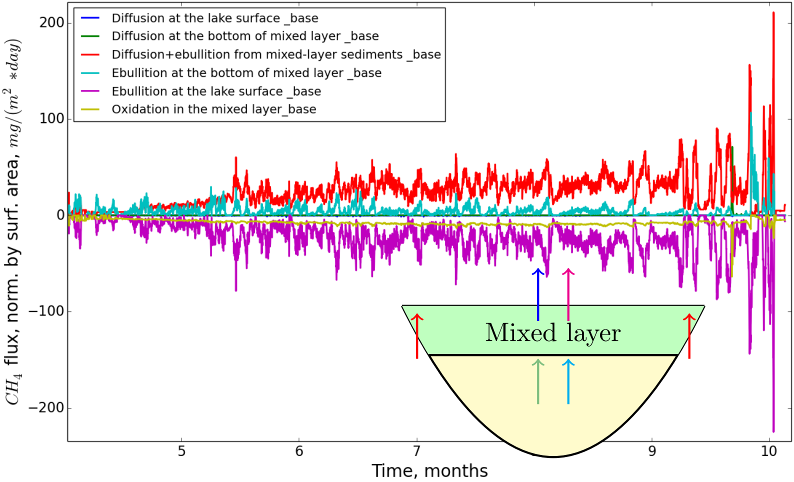
The effect of barotropic seiches on methane concentration


Control simulation


Seiches <u>excluded</u>

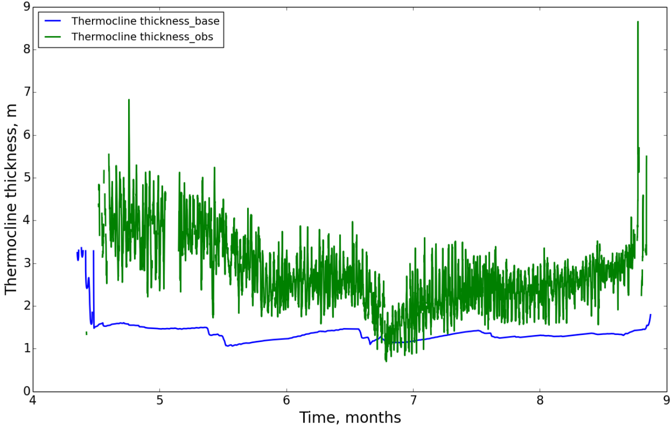
Neglecting barotropic seiches leads to $TKE \approx 0$ below thermocline, less oxygen flux from above and earlier accumulation of methane near bottom

Methane budget in the surface mixed layer



The diffusive flux through thermocline is negligible compared to other terms

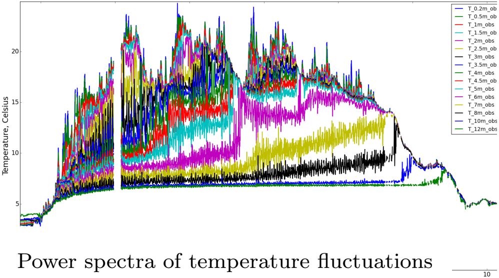
Thermocline thickness



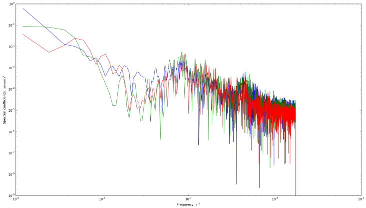
Thermocline thickness is defined as a depth difference between 8 °C and 14 °C isotherms

Internal seiches in Kuiväjärvi

Temperature series at different depths

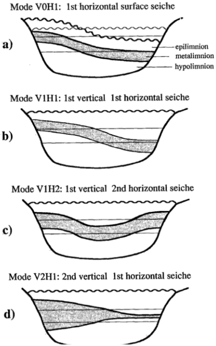


Power spectra of temperature fluctuations at three depths in the thermocline, maxima at $T \approx 5h$ and $T \approx 22h$



- Internal seiches are oscillations of thermocline after strong wind events.
- The periods of internal seiches may be calculated by linear theory (Münnich et al., 1992)

Seiche modes



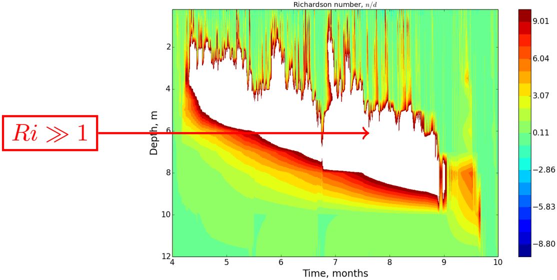
$$\frac{d^2W}{dz^2} + \left(\frac{N^2}{\omega^2} - 1\right) k^2 W = 0, \; W|_{z=0,H} = 0.$$

The Kuivajarvi stratification in June 2013 (N^2) and depth (12.5 m) yields $T \approx 7h$ for V1H1 mode and $T \approx 21h$ for V2H1.

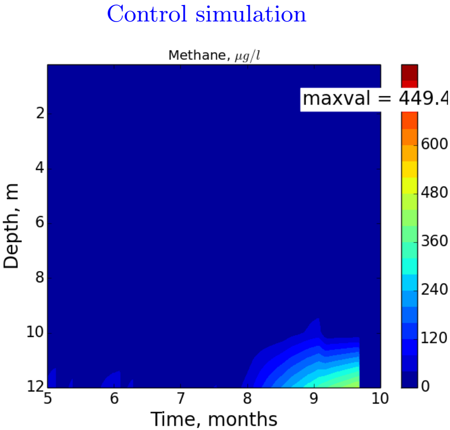
Internal seiche mixing parameterization in $k-\epsilon$ model

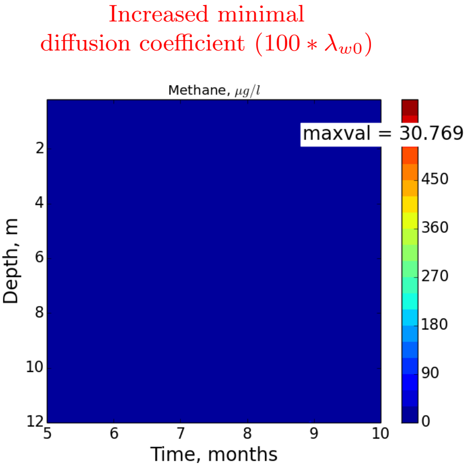
Goudsmit et al. 2002

- Shear production is generalized to include seiches $P = \nu_t M^2 + P_s$;
- TKE production by seiche-induced shear at lake's margins $P_s = -\frac{1-C_{diss}\sqrt{C_{d,bot}}}{\rho_{w0} c A_b}\gamma\frac{1}{A}\frac{dA}{dz}N^2 E_s^{3/2}$, E_s - seiche energy;
- Seiche energy is derived from wind forcing: $\frac{dE_s}{dt} = \alpha A_0 \rho_a C_d (u^2+v^2)^{3/2} - \gamma E_s^{3/2}$
- Stationary Richardson number (Burchard, 2002) may be derived for this case as $Ri_{st} = \frac{Pr\Delta c_{\epsilon 21}}{\Delta c_{\epsilon 23} - \nu_0^{-1} Pr C_s \Delta c_{\epsilon 21}(u^2+v^2)^{3/2}} \approx 0.30$ for typical wind speed



The effect of additional mixing in the thermocline


Control simulation


Increased minimal diffusion coefficient ($100 * \lambda_{w0}$)

Increasing minimal diffusivity 100 times improves thermocline thickness (in terms of temperature) but strongly deteriorates oxygen and methane concentrations

Conclusions and Outlook

- -> The model constructed shows reasonable agreement with measurements in temperature and gas dynamics, with the only unconstrained calibration parameter (in methane production formula);
- -> Some peculiarities of gas dynamics are not captured suggesting the significance of factors missing in the model, e.g. advection from the lake's catchment;
- -> We show that in terms of gases concentrations the basin is comprised of mixed layer and a hypolimnion with almost molecular diffusive exchange between;
- -> Our results suggest no solid evidence for wave-induced mixing in the thermocline at the whole-lake scale, however...
- -> ... the lake is characterized by strong seiches, hinting at possibility of significant role of internal wave breaking at its margins (Heiskanen et al., 2013).

A more rigorous approach to estimate transport mechanisms through thermocline would involve 3D hydrodynamic code.

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