7th LAKES 2024 Workshop on Parameterization of Lakes
in Numerical Weather Prediction and Climate Modelling

The influence of the water transparency on the development of radiatively driven convection in lakes under ice

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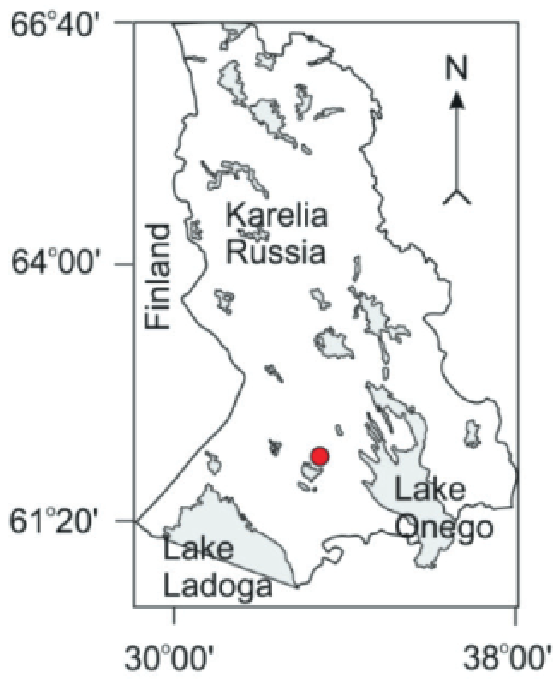
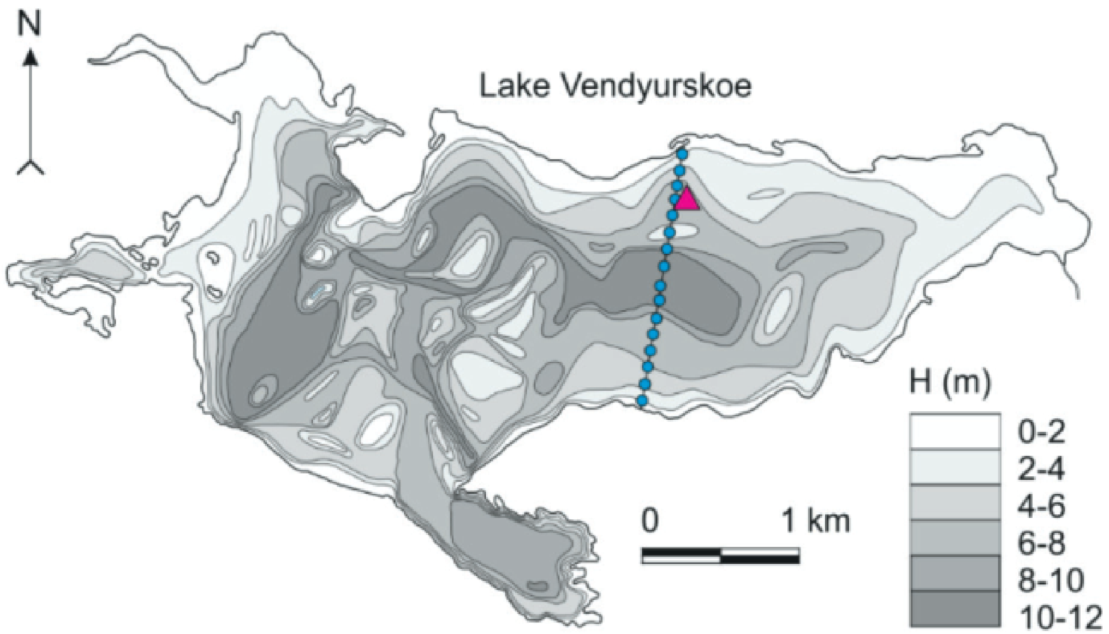
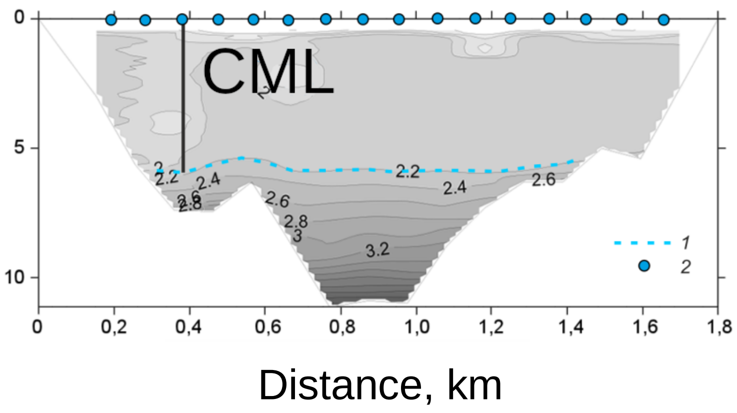
Introduction

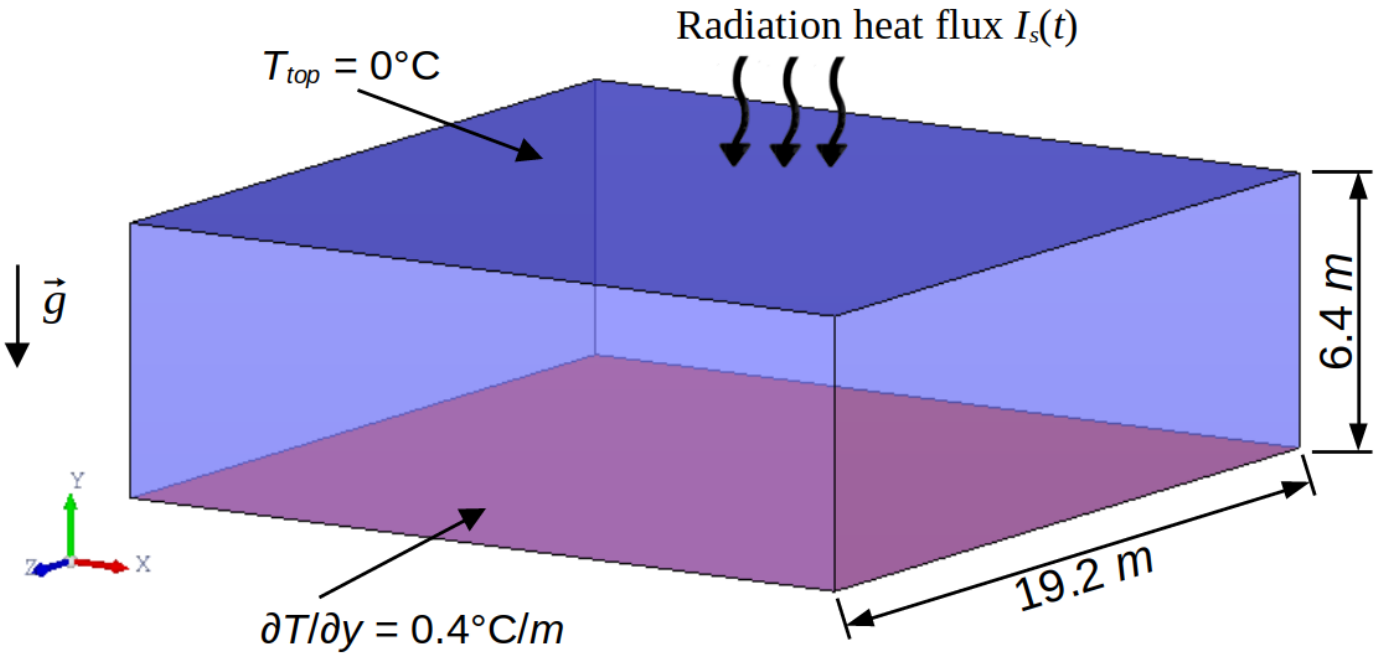






- The peculiarities of turbulent heat and mass transfer in a stratified fluid exposed by periodical inhomogeneous volume heating is of great practical and fundamental interest.
- Such phenomena take place in geophysical flows, for example, in the ice-covered boreal lakes in spring time, where the mechanisms and efficiency of mixing of water masses has a great effect on the chemical and biological processes in lakes.
- 3D numerical simulation of such phenomena is of great theoretical and practical interest. One of the first numerical investigation in this area was performed by D. Mironov et al in 2002. Our research group has been carrying out similar studies for the past several years.

Problem definition



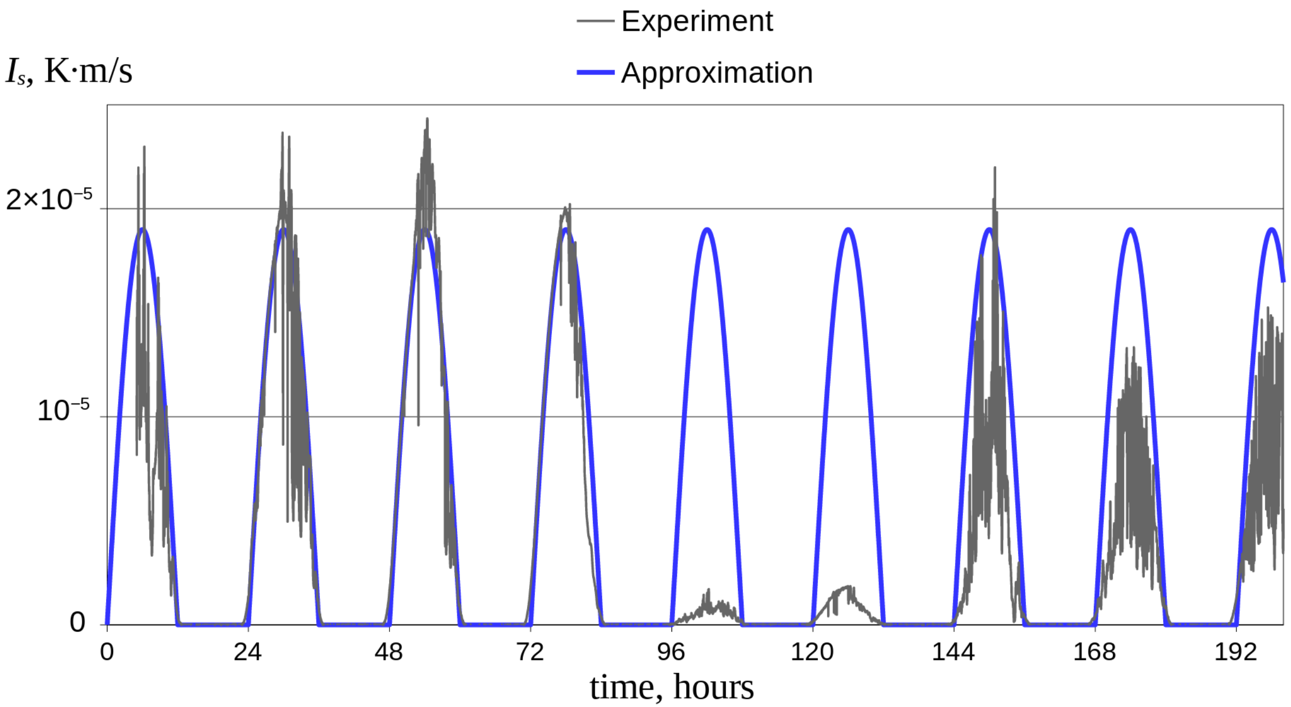
- Navier-Stokes equations for incompressible fluid with Boussinesq approach for the buoyancy force.
- Thermal expansion coefficient is the linear function of temperature; other thermophysical parameters of the fluid are taken for the pure water at 2°C.
- Initial fields were set corresponding to the equilibrium state: velocity is zero, linear profile from top to bottom is specified for the temperature (according to the boundary conditions on the bottom surface).

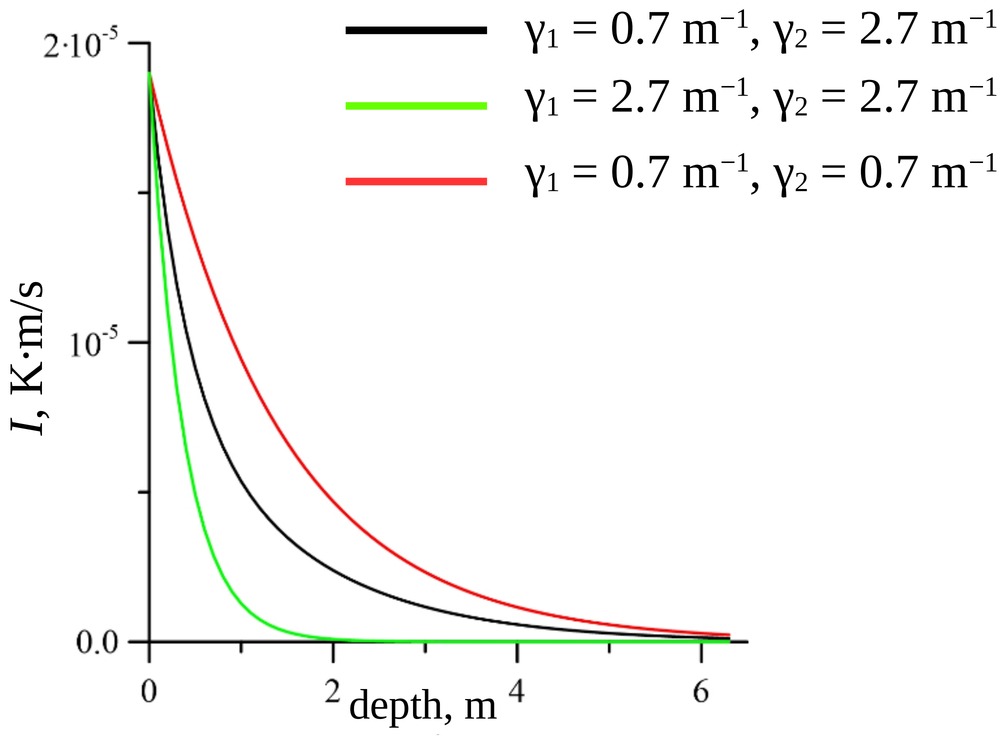
Problem definition

Two-band approximation of the decay law for radiative heating under ice:

$$I(z, t) = I_s(t)[a_1\exp(-\gamma_1 z) + a_2\exp(-\gamma_2 z)] \qquad a_1 = a_2 = 0.5$$

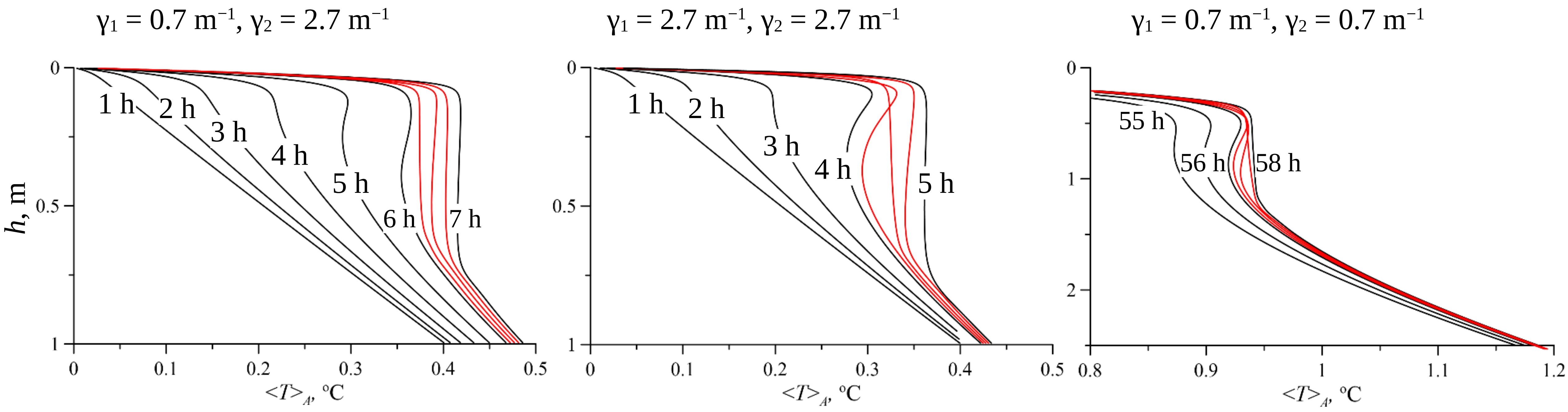
$$I_s(t) = I_0\max(\sin(2\pi t/T), 0)$$





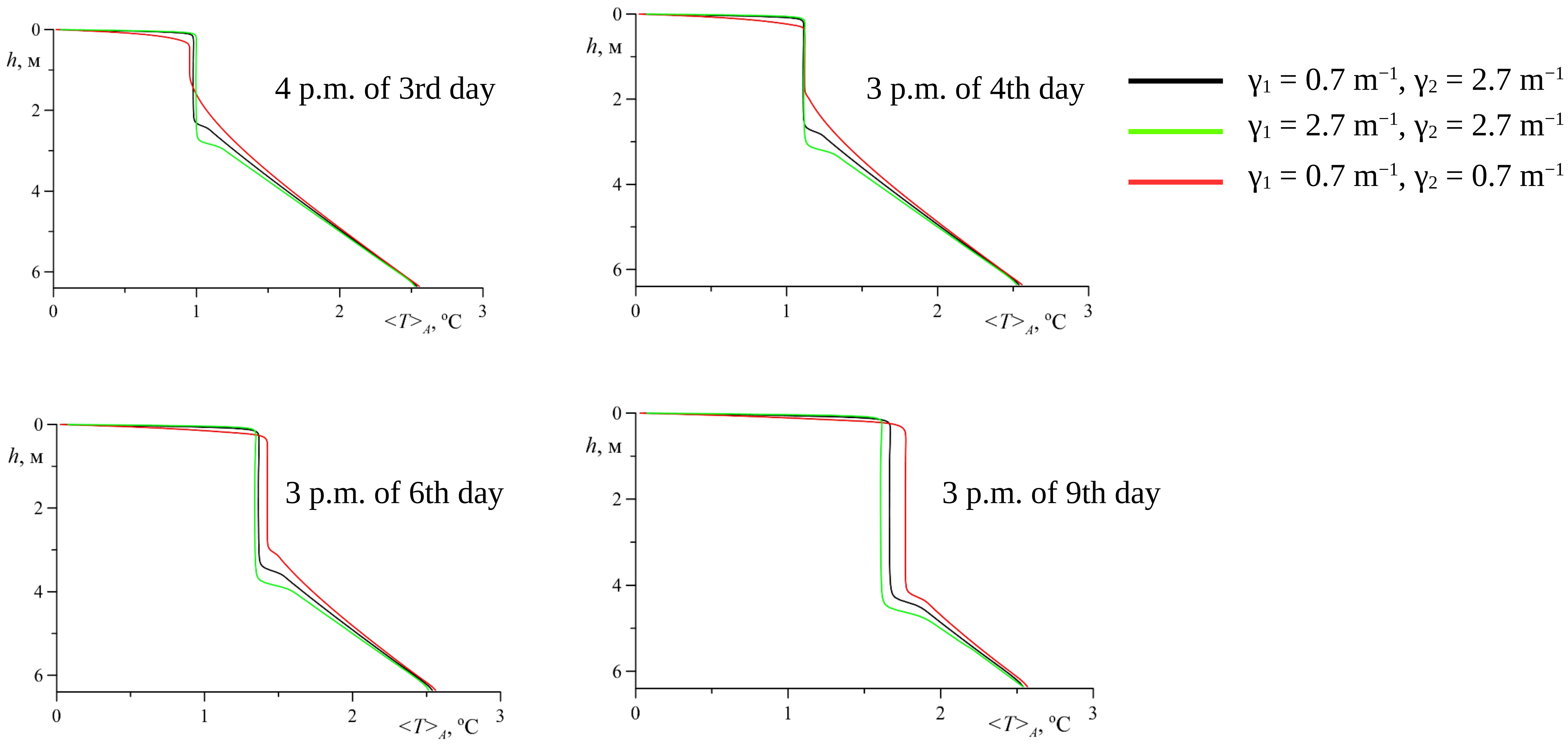
The objectives of the study: numerical simulation of the initial stages of the CML evolution in a model problem of the development of the RDC in a small ice-covered lake using Implicit LES approach for the different values of the extinction coefficients γ_1 and γ_2 characterizing the water transparency.

Averaged temperature profiles at the initial stages

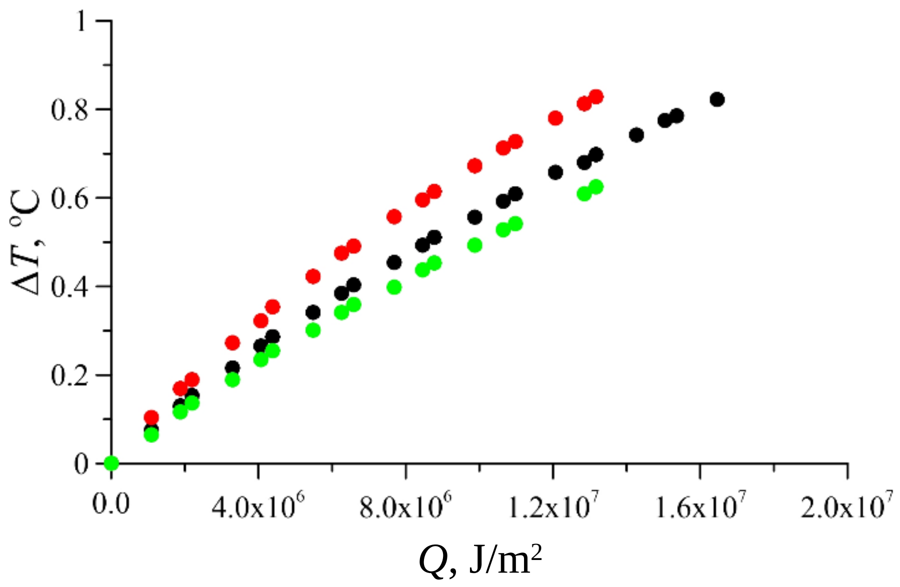


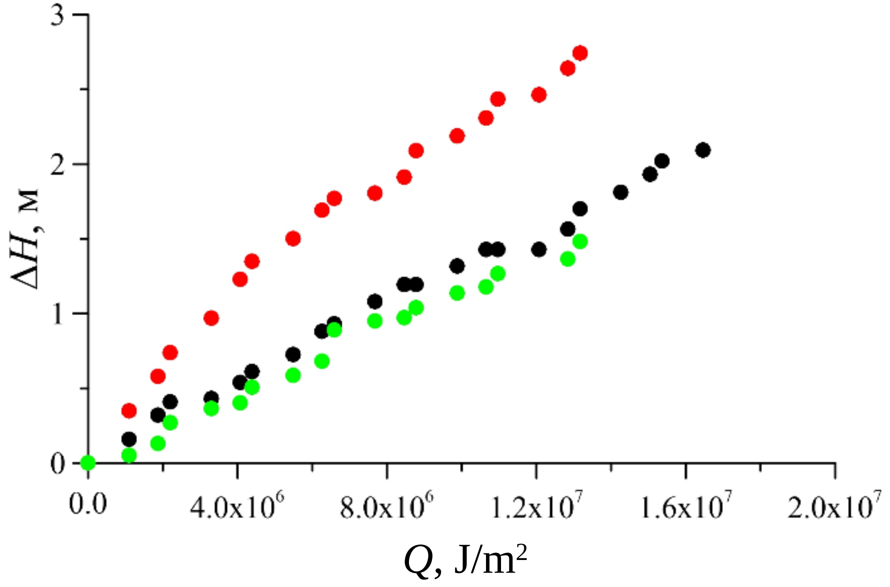
- Black lines – temperature profiles at one-hour intervals; red lines – temperature profiles at 15-minute intervals.
- In the initial variant and the variant with the lowest water transparency, the CML is formed relatively quickly, 5-6 hours after the start of the simulation.
- In the case of the most transparent water, the CML is formed only on the 3rd day.

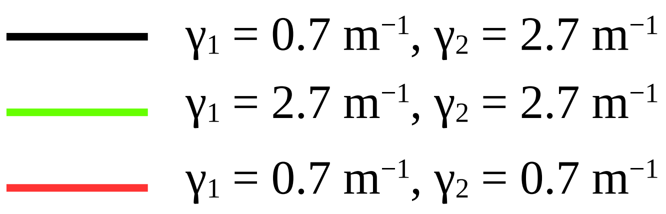
Time evolution of temperature profiles

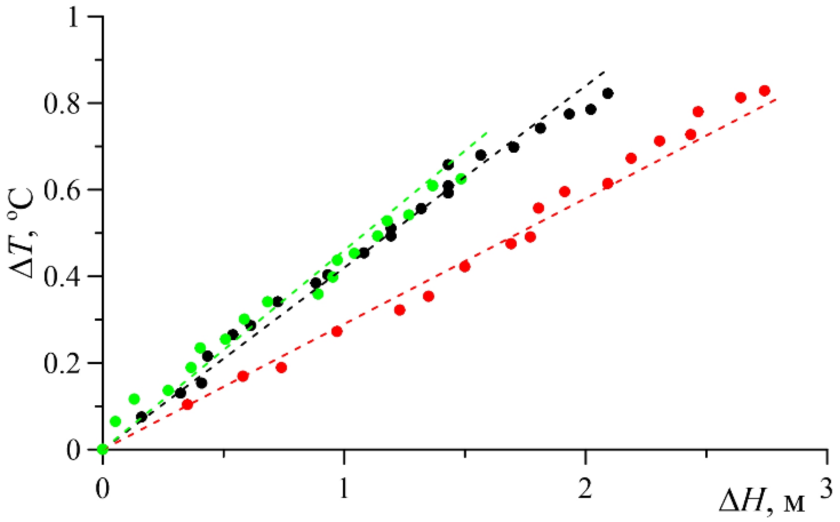


Dependence of CML temperature Δ*T* and depth Δ*H* increments on cumulative heating *Q*





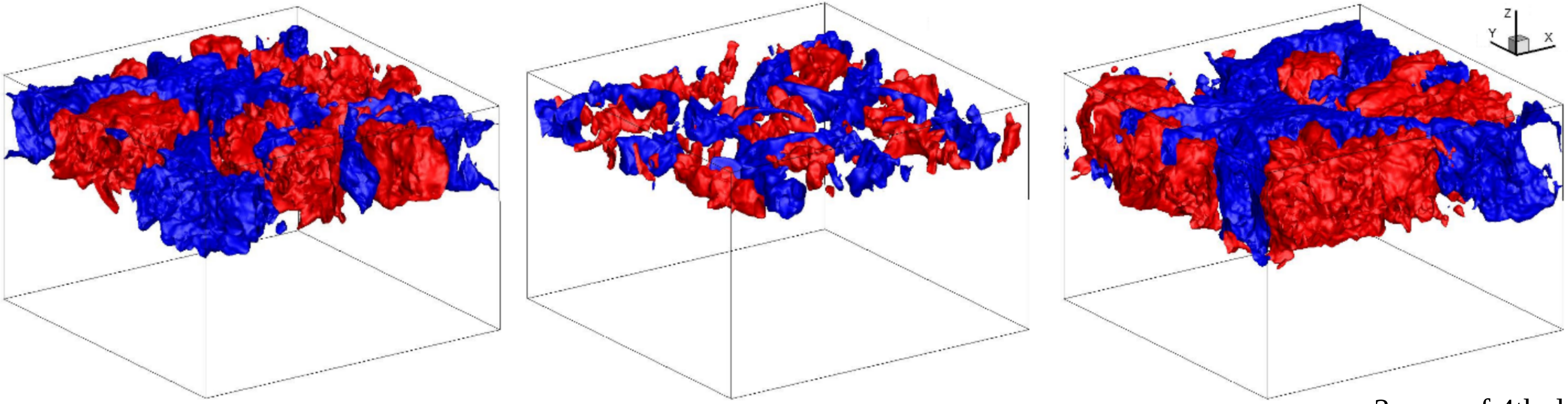




- The highest rate of temperature growth and deepening of the lower boundary of the CML is observed for variant with the most transparent water.
- Thus, a more uniform absorption of energy leads to a higher rate of change of the integral parameters of the RDC.
- The data obtained in numerical simulation are in good agreement with field observations.

Large-scale convective cells visualization: isosurfaces of the time-averaged vertical velocity component

$\gamma_1 = 0.7\ m^{-1}, \gamma_2 = 2.7\ m^{-1}$ $\gamma_1 = 0.7\ m^{-1}, \gamma_2 = 0.7\ m^{-1}$ $\gamma_1 = 2.7\ m^{-1}, \gamma_2 = 2.7\ m^{-1}$

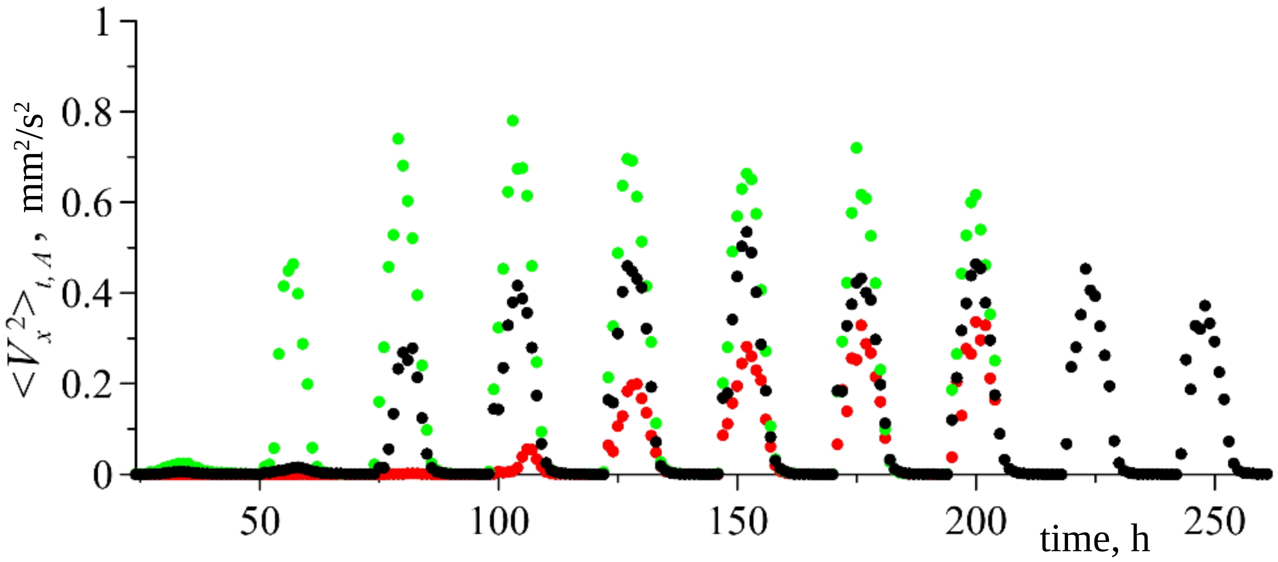


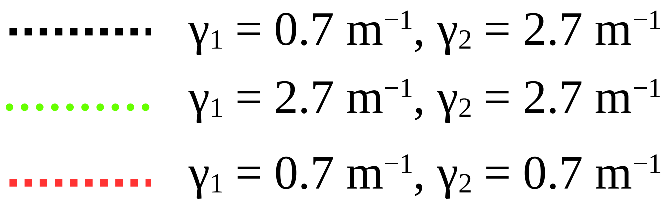
3 p.m. of 4th day

- As noted in many papers (e.g. Mironov et al, 2002), large-scale convective cells fill the entire CML. With increasing depth of the CML, these cells also increase in size.
- The evolution of convective cells is similar in all the variants considered.

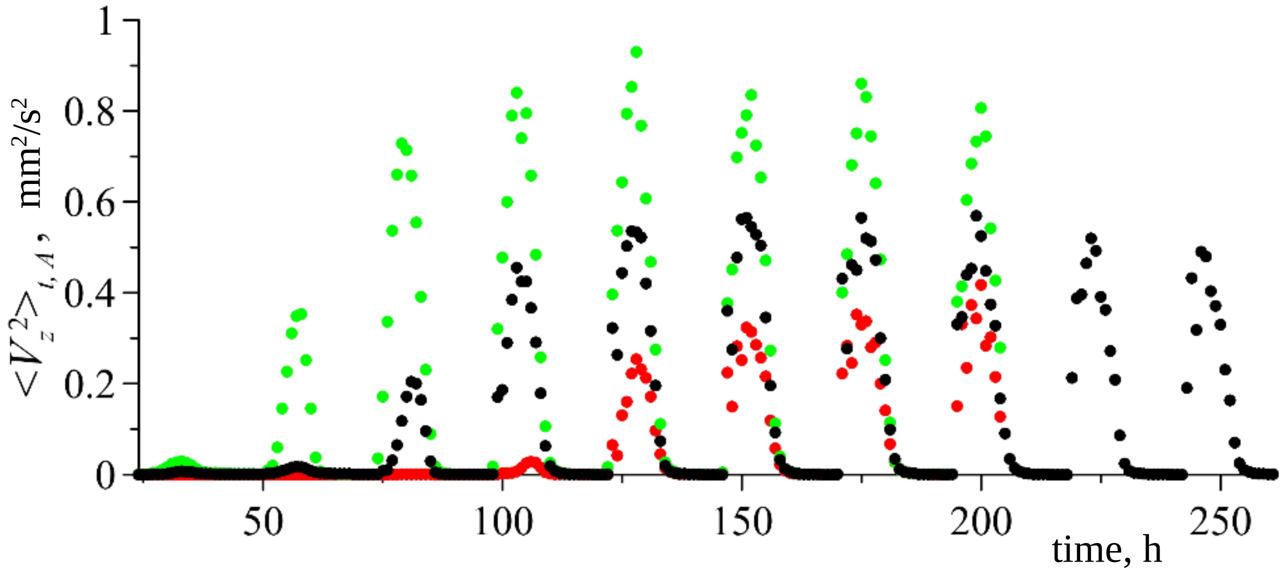
Velocity fluctuations

Horizontal





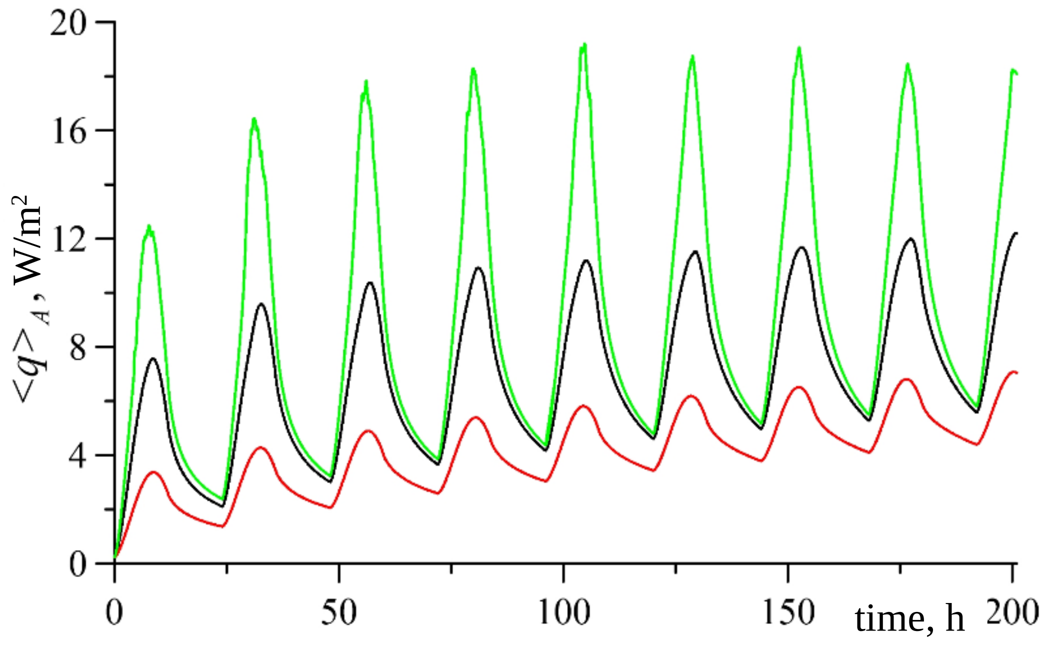
Vertical

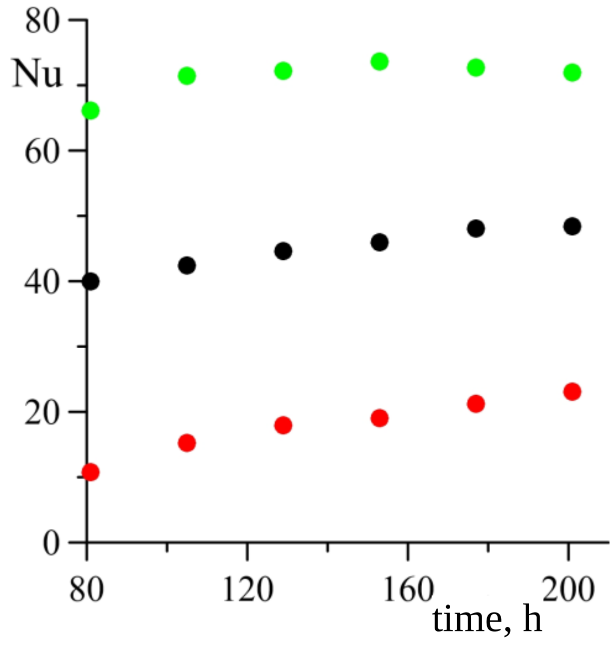


The more transparent the water, the less intense the fluctuations observed within the CML.

This is probably due to the fact that in more transparent water the process of "thermals" falling is less intense.

Evolution of heat flux and averaged Nusselt number at ice-water boundary





$$Nu = \frac{\langle q \rangle_A h_{CML}}{\lambda T_{CML}}$$

Obtained values of bottom temperature gradient *Γ* and entrainment coefficient *A*

Variant	Γ, °C/m	Entrainment coefficient A
$\gamma_1 = 0.7\ \text{м}^{-1}$, $\gamma_2 = 2.7\ \text{м}^{-1}$	0.42	0.17
$\gamma_1 = 2.7\ \text{м}^{-1}$, $\gamma_2 = 2.7\ \text{м}^{-1}$	0.46	0.13
$\gamma_1 = 0.7\ \text{м}^{-1}$, $\gamma_2 = 0.7\ \text{м}^{-1}$	0.29	0.24

$$h^2_{CML} - h^2_0 = 2\frac{(1+2A)}{\Gamma}\frac{\Delta Q}{\rho c_p}$$

Summary

- The CML is formed most rapidly (about 5 hours) in the variant with the lowest degree of water transparency, in the intermediate (initial) variant the CML is formed a little later (about 6 hours), and in the variant with the highest degree of transparency the fully formed CML is observed only on the third day. At the same time, the rate of increase in temperature and depth of the CML (from the moment of its occurrence) is the highest for the most transparent water.
- In general, the dynamics of the increase in temperature and depth of the CML corresponds to theoretical concepts and field observations. In the variant with the highest degree of water transparency, the entrainment coefficient is higher than in other considered variants.
- Maximum heat fluxes during one day, as well as the average Nusselt numbers, first increase day by day and then reach an almost constant value. A strong sensitivity of heat fluxes to the degree of water transparency is observed: the less transparent the water, the greater the heat flux into ice.
- Simulation show that the greater the degree of water transparency, the lower the values of velocity fluctuations. This is due to the less intense process of collapse of local "thermals" inside the CML. Thus, the conducted study allowed us to obtain new information about the influence of water transparency on the formation and development of the CML during radiation heating of ice-covered lakes.

Thank you for attention

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http://www.spbstu.ru/