

# **Large-eddy simulation of the coupled plankton-convection ecosystem in the ice-covered deep lake: maintenance of non-motile heavy diatoms in the photic zone\***

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The first results of the construction of complex numerical models for physical and biological systems of a deep ice-covered lake in early biological spring period are presented. This complex includes an eddy-resolving model of the convective mixing in the under-ice water layer and a model for the dynamics of the nutrients-phytoplankton-zooplankton system. Effects on heavy phytoplankton (diatom) cells suspension in the photic zone are discussed in detail.

## **1. Introduction**

The processes of initiation and development of turbulent penetrative convection in the under-ice water layer at sufficient intensity of solar radiation penetrating through the ice layer are usually observed in deep lakes [1–3] and reservoirs [4] in spring. The duration of this phenomenon is several weeks (March–April, usually). In depth, it propagates to several tens of meters. It has been established experimentally that the essentially nonstationary and nonlinear processes of penetrative convection are hydrophysically dominant in the formation of the detailed thermal and dynamic structure of the under-ice mixing layer. They also provide the biophysical optimum which is necessary for total phytoplankton spring bloom. Lake Baikal provides a good example of these events [5]. The winter-spring under-ice phytoplankton bloom (mostly diatoms) is typical for Baikal. According to [6] planktonic diatoms play a central role in studies of Lake Baikal. Not only they are dominant producers in the lake food chain, but exceptionally long lake sediment records are diatom rich, and many of the taxa are endemic, which makes them of interest for evolution studies. The under-ice bloom intensity of diatoms shows a strong interannual variability. The causes of these changes are unclear yet [2, 7]. But it is known that diatom population

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sizes are controlled by the physical and biotic environment of Baikal, e.g., temperature, ice formation and mixing and grazing, rather than by nutrient availability; population successions are controlled by complex interactions with zooplankton; diatom sinking rates can be extremely rapid, cover a wide range from a few meters up to several tens meters per day [6]. *Aulacoseira Baikalensis* diatom is a dominant pelagic endemic species of Lake Baikal [5, 7] during spring. The diatoms begin to multiply in February–March under ice at 0.1–0.2°C; its concentration reaches a maximum (up to 10 mg m<sup>-3</sup>) in April–May at 1–3°C. The cells of *A. Baikalensis* have no physiological mechanism that could provide them a positive buoyancy. Since they have heavy siliceous shells, they sink into the underlying water layers at average rate of gravitational sinking of about 3–4 m per day [2]. Therefore, the following two factors are of critical importance for total bloom of *A. Baikalensis* in the water adjacent to ice. These are: the cell fission rate which depends on photosynthetic active irradiance transmission, and the intensity of turbulent convection, which maintains the diatom cells in the photic zone [2, 8].

For the first time, the Large Eddy Simulation (LES) methodology was used to describe the under-ice convective boundary layer (UICBL) of the freshwater deep lake in [9]. The possibility of representing the flow in the UICBL in the form of the following decomposition: mean state, coherent structures ("large eddies"), and small-scale quasi-isotropic turbulence was justified in [10]. It was shown in [11, 12] that the space-time evolution of the UICBL directly depends on the thermodynamic and optical properties of the atmosphere and the snow and the ice layers that cover the lake.

The growing importance of the studies of lake ecosystems continually calls for development of more and more precise models describing both physical and biological components of environment. A recent comprehensive overview of the state-of-the-art mathematical modeling for the Baikal water ecosystems with regard to phytoplankton annual variability has been made [13]. An attempt of simulation of the dynamics of the three-component plankton population with the use of a numerical model of spring thermal bar adapted to the conditions of the lake Baikal Central Basin was described in [14]. Note that sinking losses of phytoplankton and vertical migration by zooplankton have been neglected in the proposed model. This hypothesis has a major negative consequence on the quality of the predictions, that is emphasized in [14].

In this paper, we briefly describe an ecosystem complex of models for primary production in the UICBL of a deep lake in the early biological spring period. We want to pay special attention to the hypothesized fundamental relationship between turbulent convection and spring under-ice diatom bloom. In support of this hypothesis, a coupled plankton (three-component approach) convection (LES) model was developed. We argue that turbulent

convection is a process which maintains the diatom cells in the photic zone by some results of numerical experiments.

## 2. A model of the ecosystem of a deep ice-covered lake

The vertical structure of the model is shown in Figure 1. The original equations for the hydrodynamic part of the model have the following form:

- atmosphere:

$$Q_C = c_p \rho_a C_H u_a (T_a - T_{hs}), \quad Q_E = \rho_a C_E u_a (q_a - q_{hs}); \quad (1)$$

- snow:

$$\frac{\partial T_s}{\partial t} = \frac{\partial}{\partial z} K_s \frac{\partial T_s}{\partial z} + \frac{\partial R_s}{\partial z}; \quad (2)$$

- ice:

$$\frac{\partial T_i}{\partial t} = \frac{\partial}{\partial z} K_i \frac{\partial T_i}{\partial z} + \frac{\partial R_i}{\partial z}; \quad (3)$$

- water: mean state

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z} \nu \frac{\partial \theta}{\partial z} - \frac{\partial}{\partial z} \overline{w\vartheta} + \frac{\partial R_w}{\partial z}, \quad (4)$$

penetrative turbulent convection

$$\begin{aligned} \frac{du}{dt} &= -\frac{1}{\rho_0} \frac{\partial p}{\partial x} + \frac{\partial}{\partial z} \nu \frac{\partial u}{\partial z} + \mu \Delta u, \\ \frac{dv}{dt} &= -\frac{1}{\rho_0} \frac{\partial p}{\partial y} + \frac{\partial}{\partial z} \nu \frac{\partial v}{\partial z} + \mu \Delta v, \\ \frac{dw}{dt} &= -\frac{1}{\rho_0} \frac{\partial p}{\partial z} + \lambda \theta + \frac{\partial}{\partial z} \nu \frac{\partial w}{\partial z} + \mu \Delta w, \\ \frac{d\vartheta}{dt} &= -w \frac{\partial \theta}{\partial z} + \frac{\partial}{\partial z} \nu \frac{\partial \vartheta}{\partial z} + \mu \Delta \vartheta + \frac{\partial}{\partial z} \overline{w\vartheta}, \\ \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} &= 0. \end{aligned} \quad (5)$$

Here

$$\begin{aligned} \frac{d}{dt} &= \frac{\partial}{\partial t} + u \frac{\partial}{\partial x} + v \frac{\partial}{\partial y} + w \frac{\partial}{\partial z}, \quad \Delta = \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2}, \\ \overline{w\vartheta} &= \frac{1}{L_x} \frac{1}{L_y} \int_0^{L_x} \int_0^{L_y} w\vartheta \, dx \, dy. \end{aligned}$$

The following notations are used here:  $R_{LI}$  is the intensity of the incoming solar radiation for the snow surface ( $z = h_s$ ),  $R_{LO}$  is the effective radiation,

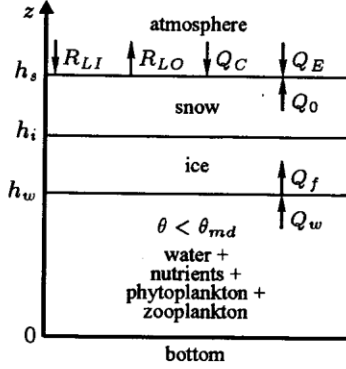


Figure 1. Vertical structure of the ecosystem model

$Q_C$  and  $Q_E$  are the available and latent heat fluxes at the lower atmospheric boundary,  $Q_0$ ,  $Q_f$ , and  $Q_w$  are the heat fluxes at the interfaces  $h_s$  and  $h_w$ , respectively,  $c_p$  and  $\rho_a$  are the specific heat capacity and density of the air,  $C_H$  and  $C_E$  are the heat transfer and evaporation coefficients,  $u_a$ ,  $T_a$ , and  $q_a$  are the velocity, temperature, and specific humidity of air,  $T_s$  and  $T_i$  are the sought-for temperatures of ice and snow,  $K_s$  and  $K_i$  are the coefficients of temperature conductivity of snow and ice,  $\theta$  and  $\vartheta$  are the mean and convective components of the water temperature,  $\nu$  and  $\mu$  are the vertical

and horizontal coefficients of small-scale turbulent exchange in the water layer,  $u$ ,  $v$ , and  $w$  are the convective velocity components,  $p$  is the pressure deviation,  $\theta_{md}$  is the temperature of maximum density,  $R_s$ ,  $R_i$ , and  $R_w$  are the fluxes of short-wave solar radiation which are partially absorbed by the snow and the ice layers and completely absorbed by the water layer. Models to describe these flows acceptable from the practical point of view are presented in [11]. The questions of formulation of initial and boundary conditions for problem (1)–(3) are discussed in detail in [11], and for (4), (5) in [9].

The  $b$ - $\epsilon$ -model, which is quite traditional for hydrophysical problems, is used to calculate  $\nu(z, t)$ . Also here  $t$  is the time,  $x$ ,  $y$ ,  $z$  are the Cartesian coordinates,  $L_x$ ,  $L_y$  are the sizes of averaging domain in the UICBL.

The fields of velocity, temperature, and irradiance calculated by using the LES-model and the characteristics of small-scale turbulence in a grid domain of high spatial and temporal resolution form a "hydrophysical space", which is necessary and sufficient for the construction of a biophysical  $N$ - $P$ - $Z$  model of plankton as a part of the ecosystem complex. The equations of the model have the following form:

$$\begin{aligned} \frac{dN}{dt} &= \frac{\partial}{\partial z} \nu \frac{\partial N}{\partial z} + \mu \Delta N + (J + m_p)P - (\gamma I + m_z)Z, \\ \frac{dP}{dt} &= \frac{\partial}{\partial z} \nu \frac{\partial P}{\partial z} + \mu \Delta P - G - (J + m_p)P - IZ, \\ \frac{dZ}{dt} &= \frac{\partial}{\partial z} \nu \frac{\partial Z}{\partial z} + \mu \Delta Z + [(1 - \gamma)I - m_z]Z, \end{aligned} \quad (6)$$

where  $N$ ,  $P$ ,  $Z$  are the concentration of nutrients, phytoplankton and zooplankton, respectively,  $I$  is the zooplankton grazing rate:

$$I = R_m \Lambda P (1 - e^{-\Lambda P}), \quad J = -V_m e^{-\eta(h_w - z)} N (N + k_s)^{-1},$$

$G = w_g \frac{\partial P}{\partial z}$ ,  $R_m$  is the maximum ingestion rate of zooplankton,  $\Lambda$  is the Ivlev constant for zooplankton,  $V_m$  is the maximum growth rate of phytoplankton,  $\eta = \eta(P, Z)$  is the light extinction coefficient,  $k_s$  is the nutrient uptake half saturation constant,  $w_g$  is the sinking velocity of diatom cells,  $m_p$ ,  $m_z$  are the phyto- and zooplankton death rates, respectively,  $\gamma$  is the unassimilated fraction of zooplankton grazing fraction. The problems of statement of initial and boundary conditions for (6) and specification of biological parameter values of this model are discussed in detail in [14].

Computational realization and verification of the complex ecosystem models deep ice-snow-covered lake during the spring solar heating are required for the solution of numerous interdisciplinary problems to support hypothesized relationship between convection and phytoplankton succession and its important contribution to the success of a spring bloom.

Some of them will be mentioned below in Section 4. Here we discussed only one.

### 3. Effects on algal suspension: numerical study

The first part of the title of this section coincides with the second part of that in [8], exactly. It is not accidentally, since namely Kelley has formulated the question, the answer on which we have to get by numerical experiments with our coupled convective-plankton model. In [8, p. 1861], he wrote: "As in the case with most diatoms, *A. Baicalensis* cells are heavier than water, so they can be expected to sink out of the mixed layer in a few days ... The fact that high concentrations are observed throughout the mixed layer for periods exceeding this time scale, with much lower concentrations in deeper water, implies the presence of a mechanism of active suspension of the cells. How might this suspension be achieved?" Our  $N-P-Z$  plankton LES model of the UICBL describes three mechanisms of the vertical transport of the diatoms: (A) gravity sinking of the cells; (B) eddy-viscosity transport by small-scale turbulence and (C) large-eddy convective turbulence, when migration into  $N-P-Z$  system is driven by a ensemble of nonlinear and nonsteady coherent structures ("thermals" and/or "plumes"). Although the convective mechanism has been invoked previously to explain suspension of algal in freshwater lakes [8], the details have not been worked out fully. Several researchers expect that an ad hoc modeling of sinking should be devised, for example, by introducing an additional "suspending velocity", that is proportional to the vertical eddy-viscosity coefficient or simply by reducing the sinking rate in unstable regions [14]. However, the problem of the sinking parameterization is not solved fully, too. Taking into account the complexity of the simulated phenomenon, at the first stage of calculation we gave up the applying models of dynamics and optics of snow and ice. We

made use of a simple approximation  $R_W(z, t) = -\alpha F e^{-\eta z} / (c_p \rho_0)$ ,  $F$  is the solar radiation flux at  $z = h_w$ ,  $\alpha$  is the coefficient allowing us to take into account the increase of the radiation intensity from day to day. For studying the action of (A), (B), and (C) mechanisms, three numerical experiments were made. The results of these experiments have sequentially described the action of the mechanism (A) only (Experiment I), the joint action of (A) and (B) (Experiment II) and action of (A), (B), and (C), simultaneously (Experiment III).

In all the experiments, pure biological effects (gross primary production, mortality, and grazing) were omitted. This approach rely on the assumption that a small background concentration of plankton is always available to initiate a spring bloom. Observations appear to justify this assumption [5], but the actual mechanism, which accounts for the presence of plankton in the photic layer in spring, is still unknown [8]. The results of the LES-modeling of the initial stage (5 days) of generation of the UICBL with the following values of parameters of the numerical model:  $L = 120$  m ( $\Delta x = 0.5$  m),  $H = 40$  m ( $\Delta z = 0.5$  m), the time step is 5 s,  $\nu = \mu = 10^{-4}$  m<sup>2</sup>/s,  $\eta = 0.5$  m<sup>-1</sup> are described in details in [9, 15]. For the numerical solution of the  $P$ -equation in (6), we used the following boundary conditions:  $\nu \frac{\partial P}{\partial z} + w_g P = 0$  at  $z = h_w$ ;  $\frac{\partial P}{\partial t} = w_g \frac{\partial P}{\partial z}$  at the bottom [16]. The sinking velocity  $w_g$  was set to a constant rate of 3 md<sup>-1</sup> in all the experiments [2]. The initial distribution of  $P(z)$  at  $t = 0$  was the same in all the experiments and was given in the following manner:  $P = 0$  at  $z = h_w$ , at the depth 10 m and below, local maximum is  $P = 1$  at the depth 5 m with the linear interpolation between the values  $P = 0$  and  $P = 1$ . This distribution is certainly artificial, but it may be useful for comparison with the conceptual model from [2]. The temporal evolution of the vertical distribution of horizontally averaged concentration  $\bar{P}$  (in conditional units) during 3 days obtained in Experiments I–III are represented in Figure 2.

For the full LES-model (Experiment III), we introduced of the initialization period (48 h) to obtain more realistic initial conditions at  $t = 0$  for equations (4), (5). In Experiment III, solar heating was included on intervals of  $t$ : 0–12 h, 24–36 h, 48–60 h with max  $R_w$  in mid daytime. In other hours,  $R_w$  was equal to 0 (“nighttime”). The thickness of mixing layer was about 5 m at the time of the maximum convective development ( $\sim 9$  h in Figure 2c) for the 1st day with mean deepening rate of the base mixed layer about 1.5–2 m per day from one to next daytime. Convective disturbances were enough rapidly diffused during few (3–5) hours after sunset.

The physical interpretation of the result of Experiment I (Figure 2a) is not required essentially. Figure 2b illustrates that small temporal changes of the vertical distribution  $\bar{P}$  occur in areas of large values of  $\frac{\partial \bar{P}}{\partial z}$ . However, at given parameters of the model, we watch general sinking of plankton tracers (non-vegetal diatom cells) through the water column. The condition of local

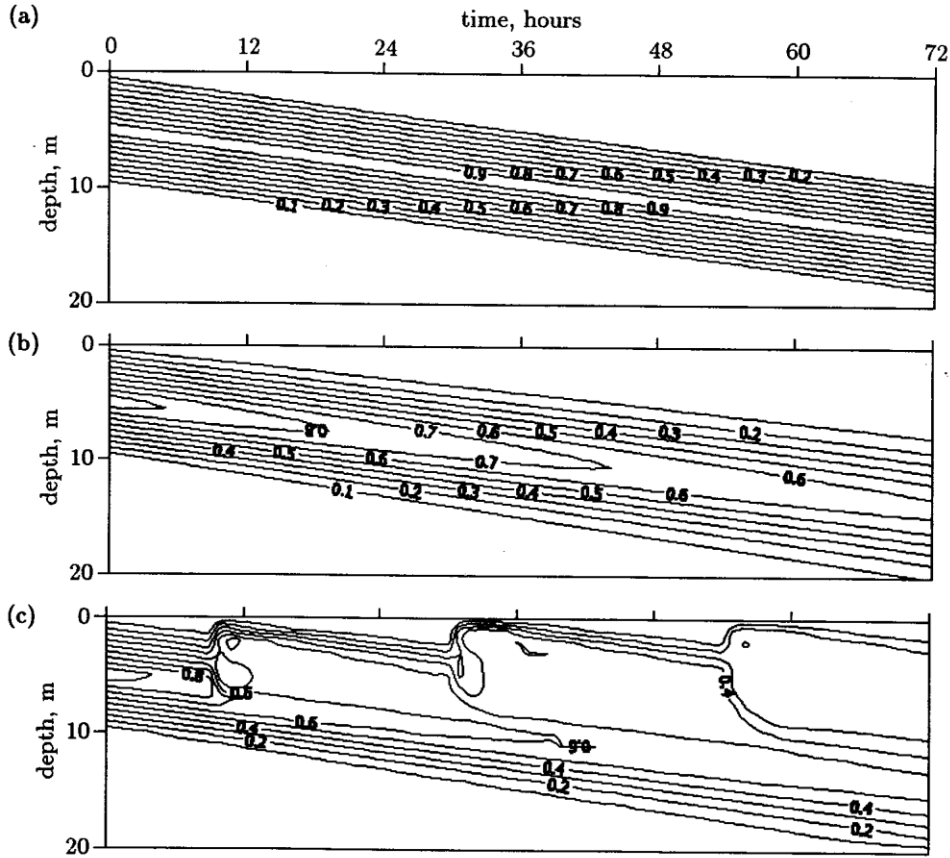
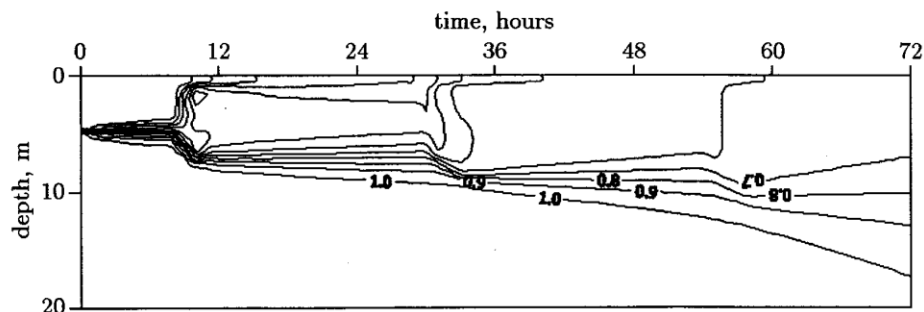


Figure 2. Temporal evolution of  $\bar{P}$ : (a) in Experiment I, (b) in II, and (c) in III

steady of  $\bar{P}$  in the area with  $\frac{\partial \bar{P}}{\partial z} < 0$  (Experiment II) have the following form:  $w_g \bar{P} = \nu \frac{\partial \bar{P}}{\partial z}$ . It allows the local conservation of initial  $P$  at the depth 2.5 m when  $w_g = 0.17 \text{ md}^{-1}$ . So, small value  $w_g$  is not typical for real tracers, but it is more important that vertical distribution  $\bar{P}$  in layer 0–5 m is not in keeping with observations. According to [8, 5], the algal cells are distributed with approximately uniform concentration in a surface mixed layer during initial period of spring bloom. Namely, this kind of the vertical distribution of  $\bar{P}$  was predicted by coupled model in the Experiment III (Figure 2c) as a result of the convective activity in the periods of maximally developed convection. We also fixed the local maximum of  $\bar{P}$  in a thin layer just under the ice on curves of the vertical profile of  $\bar{P}$  (not shown). From comparison of Figures 2b and 2c one can come to a conclusion about exclusive role of the large-eddy convective turbulence in the upper zone of under-ice layer of water, where they are provided by solar radiation, necessary for a blooming at spring time.

Figure 3. Temporal evolution  $\bar{N}$ 

In the context of primary production, according to our notions, upward component of convection has to play very important role, as the mechanism which brings nutrients from deep layers toward into photic zone. For verification of that, a special numerical experiment was carried out. In this experiment, we included the equation for  $N$  from (6) without biological source terms to model for Experiment III with the following initial conditions:  $N = 0$  in the layer 0–5 m and  $N = 1$  from the depth 5 m to the bottom. Vertical boundary conditions were taken the same as for  $P$  at  $w_g = 0$ . The results of the  $N$  calculation are shown in Figure 3. Apparently, that the large-eddy convective turbulence is a very effective mechanism for vertical transport of nutrients from the basis of mixing layer into a thin diatoms aggregation layer just under the ice.

#### 4. Conclusions

A three-component plankton model has been included in the LES-model of the UICBL and has been used to predict convective effects on algal suspension and the transport of nutrients into photic zone. They are very important for simulation of spring time blooms of the diatoms in Lake Baikal and in similar ice-covered deep lakes, bearing in mind the possible importance of physical/biological coupling. In this paper, we argue that the large-eddy convective turbulence has a very high potential of the keeping of heavy non-motile diatoms, providing cells with enough nutrients for growth during spring ice-covered period. We hope that the subsequent improvement of the plankton-convection coupled model permits us to understand better many fundamental problems of the functioning of ecosystems of ice-covered lakes, including the mechanisms of vegetative cells physiological regulation of their buoyancy, the sources of small background concentration of diatoms to initiate spring bloom, the bio-optical effects of the very high concentration of plankton during the period of bloom.

The authors encourage the collaboration aimed at the development of such models.



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