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Gas Exchange between Baikal and the Atmosphere During Under-Ice Period

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Abstract—In the under-ice period, gas exchange between Baikal and the atmosphere is taking place through a system of coastal and perennial fractures and airholes in the ice, as well as through the surface of the ice-free part of the lake at the Angara source [24]. The total area of the open water never exceeds 0.03% of lake water area. The emission of CO_2 in the course of ice sublimation over the entire period is ≤0.02 g CO_2 from 1 m^2. The transport of dissolved gases from under-ice water into the atmosphere is limited by molecular diffusion in microfractions of ice cover. The narrow daily variations of CO_2 in the air in lake coastal zone is due to the effect of populated localities on its coast and large coniferous forests, which serve as diffuse sources of CO_2, as well as diurnal variations of the direction and velocity of air mass transport by local winds.

Keywords: under-ice period, gas exchange, Baikal, coniferous forests, respiration, photosynthesis

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INTRODUCTION

Free gas exchange between the atmosphere and marine and continental water bodies in the moderate and high latitudes is taking place in open-water periods. After its formation, continuous ice cover blocks gas fluxes through the water–air interface [14, 24–26, 47]. Under ice cover, water exchange in the water body–air system is governed by ice permeability with respect to gas, rather than by the solubility of gases in water. The increase in CO_2 concentration over ice cover in arctic seas suggests the cessation of free gas exchange and absorption of atmospheric CO_2 by seawater in winter [14].

A question arises regarding the sources of CO_2 that cause small diurnal variations in its concentration in the atmospheric air at the contact with ice, as recorded in the coastal zone of northwestern Southern Baikal [29]. According to [29], this process is due to the gas exchange of the under-ice water layer with the atmosphere through the ice cover and thermal deformations (fracturing) of ice.

The objective of this study is to analyze the possible causes of diurnal variations of CO_2 concentration in the air above Baikal ice cover. With this in view, the structure of lake ice was described at the stage of its accretion and degradation before breakup; in addition, the permeability of freshwater ice was evaluated and compared with the gas-permeability of sea ice. The analysis included the coniferous forests on the slope of Baikal depression and the populated localities on its coast as possible sources of CO_2 in winter and early spring and the possible relationship between the daily variations of CO_2 concentration in the air and phytoplankton photosynthetic activity in under-ice water.

MATERIALS AND METHODS

The study uses the results of many-year studies of Baikal ice cover carried out by researchers of Baikal Limnological Station, USSR Academy of Sciences and Limnological Institute, Siberian Branch, Russian Academy of Sciences [3, 7, 8, 10, 13, 15, 35, 36]. Ice permeability was evaluated by the penetration of permanganate aqueous solution into it [8], and the concentrations of gases were determined by an eudiometer during ice melting in kerosene in a closed environment [8]. Salt concentrations in Baikal ice cover was evaluated by the specific conductivity of ice cakes [1] and its ionic composition [12, 13]. Gas fluxes through the free water–air interface was evaluated in accordance with [24–26].

The transfer of daily variations of a gas dissolved in under-ice water through a layer of degrading ice cover was described by a capillary model of water-saturated porous medium [42]. The issue of coniferous forests as a source of CO_2 was considered based on literary data [6, 16, 18, 20–22, 27, 43, 45, 48] on forest respiration and photosynthesis at air temperature below zero.

FORMATION CONDITIONS OF ATMOSPHERE–ICE GAS EXCHANGE

Daily Variations of CO_2 Concentration in the Air Over Ice Cover

Studies in late February–early March 2004 revealed daily variations in CO_2 concentrations in the air over ice cover in Baikal coastal zone [29]. The measurements were carried out with the use a camera mounted on ice near Bol'shie Koty Settl. (northwestern coast of the Southern Baikal). In the morning and evening, an increase in CO_2 concentration was recorded, which in [29] was attributed to gas exchange through ice cover and gas release at its thermal deformations. Notably, the measurements in the late March–early April in the same year showed no gas exchange. Nevertheless, weak daily variations were observed in CO_2 concentration in the air over ice.

Thus, we can conclude that the daily variations of CO_2 concentration in the air over ice cover are not due to gas exchange between the lake and the atmosphere in winter. The authors of [29] believe that there are anthropogenic CO_2 sources in the study area; however, in our opinion, the influence of a large populated locality on changes in the gas composition of atmospheric air near it cannot be ruled out. It should be taken into account that, in the populated localities like Bol'shie Koty Settl., stove heating with a more or less regular daily rhythm is used.

Gas Exchange Formation before Freezing and in Winter

Water temperature drop on Baikal surface in autumn contributes to an increase in the solubility of atmospheric gases in lake water. However, this does not imply that their partial pressures in water and the surface air layer become equal. The autumn and before-winter cooling of Baikal water masses is accompanied by an increase in the mean monthly wind velocities over the water area [4], which causes convective and dynamic water mixing in the lake active layer [44]. Deeper water layers, relatively poor in oxygen and enriched with dissolved free carbon dioxide, rise to the surface during autumn circulation. The degree of surface water saturation with oxygen decreases from 100 in September to 92% in December. Since the partial pressure of free carbon dioxide dissolved in water is higher than the pressure of atmospheric CO_2, it is not absorbed by the cooling water surface. November–December account for ~80% of the annual O_2 absorption by the lake and 40% of CO_2 emission from its surface [24].

The duration of the annual ice period in individual Baikal areas varies from 4 to 6 months. The elongation of the Baikal along the meridian causes a shift in the beginning of ice formation from the north to the south. In the early December, ice cover forms almost all over the northern part of the lake, while in its southern part, this process begins in the late December and early January. The process of ice formation lasts from several days to several weeks [7]. The ice cover forms first in the bays of the eastern coast, in the Selenga shallow, and in the northern part of the lake and next at the western shore in its central part. The breakup takes place in April–May, though some ice fields can be seen in early June.

The formation of ice cover on the water area and the decrease in free water surface reduces the total gas exchange between the lake and the atmosphere. The values of partial pressure of dissolved gases in under-ice water differ from those in equilibrium with the air above the lake (Table 1), implying that gas exchange in winter is possible. Such exchange partially takes place through the system of coastal and perennial fractures and airholes, as well as at a relatively small ice-free area in Listvennichnyi Bay near the Angara R. source (Table 2). The comparison of the course of the actual rate of winter gas exchange in this water area with the potential changes in gas fluxes through open lake surface (assuming no ice cover) shows them to agree [24]. Some difference between the compared absolute values are because the hydrological conditions near the Angara source is favorable for water from deeper horizons, richer in dissolved CO_2 [9, 32], to rise to the surface. In Angara source, at the passage from the lake to the Irkutsk Reservoir, the flow velocity and the vertical turbulent water exchange also increase.

The length of lake coastline, its indentation not take into account, is 1800 km [19]. We assume the length of the coastal fractures to equal to this value, while the length of perennial fractures, according to aerial observations [7] is 2000 km (Fig. 1). These fractures are assumed to be always open all along their length and to be up to 2 m in width. In total, this gives ~8 km^2 of open surface. The total area of all airholes and the ice-free lake area near the Angara source can be estimated at 2 km^2. Now the total area of open-water zones in the under-ice period, according to an oversized estimate is ≤10 km^2, or ~0.03% of the total Baikal area. This value is small enough to be neglected in the calculation of winter gas exchange between the lake and the atmosphere. Note that the fractures that open from time to time at a change in temperature can freeze again, and the actual width of an open fracture can be <2 m.

Baikal Ice Structure, Gas Permeability and Thermal Deformations

Depending on the hydrometeorological conditions (air and water temperatures, wind velocity, and snowfalls), the structure of ice in the early period of its formation can be different. Transparent ice will commonly form in the main, deep-water part of the lake, and along its western coast, while granulose ice with

Table 1. Many-year mean monthly partial pressures of CO_2 and O_2 in surface water of the open Southern Baikal; its saturation with gases relative to the atmosphere; the potential and actual gas exchange fluxes through water–air interface in autumn-prewinter and winter periods [25] (*F* is the flux at conventional calm, *FW* is the flux at mean wind speed; the positive flux is directed from the atmosphere into water; the values for potential flux for under-ice period are given in bold)

Month	P_{CO_2}, atm × 10^4	Saturation,%	Flux, mg CO_2 m^{-2} day^{-1}		P_{O_2}, atm × 10	Saturation, %	Flux, mg O_2 m^{-2} day^{-1}	
			F	*FW*			*F*	*FW*
Nov.	9.522	322	− 26	−249	1.871	94.25	+62	+520
Dec.	10.227	345	−25	−232	1.822	91.50	+85	+700
Jan.	8.509	286	**−15**	**−74**	1.876	94.00	**+52**	**+260**
Feb.	7.735	260	**−13**	**−52**	1.986	99.49	**+4.4**	**+28**
Mar.	7.122	240	**−11**	**−53**	1.989	99.98	**+0.2**	**+1**
Apr.	6.199	210	**−9**	**−48**	1.976	99.83	**+1.4**	**+6**
May	6.070	207	−9.4	−56	1.990	101	−9.1	−50

Table 2. Many-year mean monthly fluxes of CO_2 and O_2 through the water–atmosphere interface in the nonfreezing area of Lake Baikal near Angara sources in the autumn-prewinter and winter periods [25]

Gas fluxes	Months						
	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May
FW, mg CO_2 m^{-2} day^{-1}	−270	−300	−110	−100	−80	−75	−90
FW, mg O_2 m^{-2} day^{-1}	+500	+590	+270	+150	+50	−90	−90

poor transparency and inclusions of earlier formed ice of other types will form along the eastern coast of the lake [35, 36].

Outwardly structureless, crystal-clear light-blue ice, typical of the major portion of the lake forms at the freezing of clear water, containing no other types of ice. It consists of hexagonal columnar vertically elongated crystals and represents the primary form, i.e., suspended frazil ice, which forms on crystallization nuclei in the top layer of lake mixing zone. This ice belongs to type A2 (*Ih* by international classification), which is widespread in large open lakes; it forms after a long-time wind mixing and a considerable loss of water heat storage in the upper part of the active layer.

After ice formation, the light-blue ice in Baikal keeps outwardly structureless and absolutely transparent during February and the first half of March [10]. In the second half of March, first effects of insolation come into sight: vertically elongated gas bubbles appear in the top part of the surface layer up to 1.5 cm in thickness, and, several days later, the bottom layer (5–8 cm in thickness) starts getting cloudy because of fine gas bubbles forming in it. However, the ice keeps accreting, keeping almost transparent.

Studying the permeability of Baikal ice using a procedure developed by G.Yu. Vereshchagin [8] showed that structureless transparent ice is impermeable for an aqueous solution of potassium permanganate [10]. The porosity of dense transparent ice is rarely in excess of 1 cm^3 kg^{-1} [5]. This porosity is due to disconnected air bubbles frozen into ice. These bubbles do not form a single effective pore space like a system of interconnected pores or capillary canals, through which components of gaseous or aqueous solution could travel transported by molecular diffusion. The gas inclusions in Baikal ice amounted to 0.6–1.17 cm^3 kg^{-1} [10].

Salt concentrations in Baikal ice amounts to as little as 10–20% of the total principal ions in Baikal water [1, 13], which never exceeds 0.1 g L^{-1}. The concentration of salts as low as that has no effect on ice solidity and gas permeability. The freezing out of salts during ice cover accretion leads to their release in the under-ice water. The result is a salt (density) convection in the water layer in contact with ice under the conditions of inverse thermal stratification [15].

Unlike freshwater case, in the formation of sea ice begins with the formation of intergranular brine films containing frozen out salts, after which, the films transform into isolated cells. The sea ice is impermeable for volatile components. The coefficients of molecular diffusion of gases in sea ice are 5–8 orders of magnitude less than in water [14].

The Release of Gases during Ice Sublimation and Thermal Deformations

At the ice–water vapor phase transition, only small amount of gas is released into the air in contact with the ice. The mean annual evaporation (with conden-

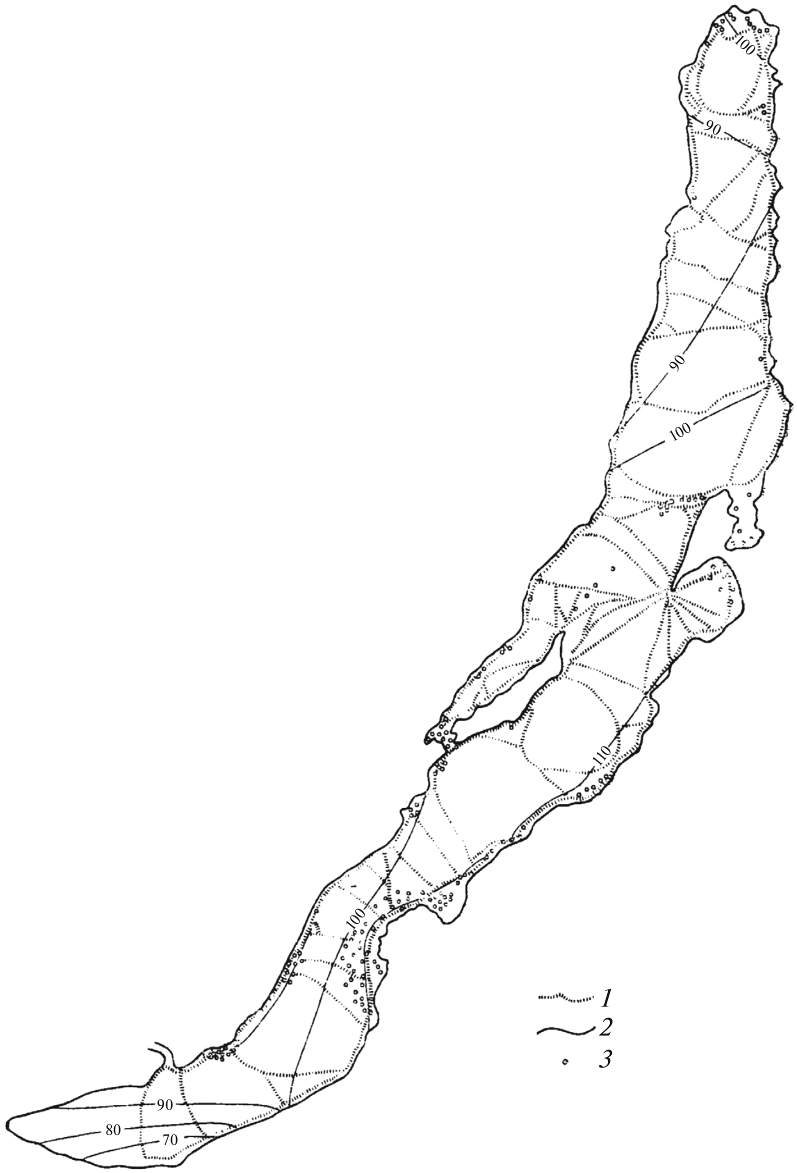

Fig. 1. Distribution of (*1*) perennial fractures against the background of (*2*) mean annual ice thickness and (*3*) airholes in Lake Baikal [7] by aerial observation data [7].

sation not taken into account) in Baikal is 334.6 mm/year, of which 309.8 mm is due to open-water period [7]. The evaporation of ice cover in January–April is estimated at 24.8 mm or ~0.21 mm day^{-1}, which, converted per ice mass under 1 m^2 of surface, corresponds to 0.193 kg m^{-2} day^{-1}. At the concentration of air in Baikal ice of 0.6–1.2 cm^3 kg^{-1} [8], its sublimation is accompanied by a gas flux never exceeding 0.1–0.2 cm^3 m^{-2} day^{-1}. Assuming the volumetric share of CO_2 in air inclusions to be 0.04%, we obtain its flux of 4×10^{-5}–8×10^{-5} cm^3 CO_2 m^{-2} day^{-1}.

Calculations show that in the second half or late March, during Baikal cracking of ice 0.6 m in thickness because of its thermal deformations, even simultaneous full release of all frozen air bubbles from a volume under 1 m^2 of ice cover surface under dead calm will lead to an increase in CO_2 concentration in 1 m^3 of near-ice air by as little as 0.2 cm^3. Note that, under normal conditions, 1 m^3 of dry air contains ~380 cm^3 CO_2. To identify the increase in CO_2 as small as that requires it measurement with an accuracy of up to hundredths of percent.

One should also take into account that the concentration of gases dissolved in ice is less than their concentration in water in equilibrium with the atmosphere under zero temperature and atmospheric pressure. For example, for dissolved CO_2, this value at –5°C amounts to only 5% of the concentration equilibrium for water at 0°C and ~1% at –20°C [31]. This means that the evasion of free CO_2 during ice evaporation over the whole winter is overestimated in [25], because in this calculation, CO_2 concentration in ice was taken equal to that in surface water at the moment of its freezing.

Changes in Ice Structure at the Stage of Its Spring Degradation

The estimation of the time when active gas exchange between the lake and the atmosphere resumes requires special consideration. In the spring, the crystalline structureless ice starts transforming with the formation of columnar crystals and through capillary channels filled with water [7]. This transformation of ice cover takes place in the Southern Baikal in the early or late April, depending on the meteorological conditions. Fine needle-shaped crystals form in the top 10-cm layer, the pore space between them is filled by water that formed due to melting of snow and ice on the surface. Permanganate solution freely penetrates through cleavage faces into the surface layer of the ice cover [8]. The ice is decaying from both its top and bottom. In this case, the middle, i.e., the main part of the ice cover keeps its monolith structure, remaining impermeable for permanganate solution. The growth of larger crystals on the bottom part of the ice cover is slower than in the top layer [7]. Before the breakup, when the ice is penetrated through its mass by capillary channels, water descend in them to its level in ice-holes, and the upper part of the capillaries becomes filled with air.

Gas Exchange through Ice Cover after Its Columnar Crystallization

Before lake breakup, its ice is a water-saturated porous medium. The concentrations and partial pressures of the gases dissolved in under-ice water differ from those in equilibrium with atmospheric air, thus creating the conditions for molecular-diffusion transport of dissolved gas in the ice cover.

The daily variations of the rate of photosynthetic activity of cold-loving planktonic algae in under-ice water cause variations in the absolute concentrations and partial pressures of dissolved free CO_2 and O_2 in lake trophogenic zone [12]. These variations at the bottom boundary of the ice cover can be expected to cause similar variations in the water-saturated ice and, seemingly, in the surface air layer, provided that there is gas exchange through the ice.

In April, after the separation of ice into individual crystals [7, 10], the ice cover is an anisotropic medium with effective pore space, consisting of a series of vertical channels. The process of ice columnar crystallization can be interrupted by temperature drops, which cause refreezing of the top layers of the ice cover.

In the general case, the daily variations of air temperature over ice surface causes temperature waves in the ice mass, and the shape of the ice crystals that form in the course of columnar crystallization differs from ideal: their cross-section is greater in the upper than in the lower part. This causes changes in the shape of pore channels in ice layer and determines the conditions of molecular-diffusion transport of dissolved components.

The exact quantitative description of the structure of real porous medium and diffusion transport process in it is very difficult; therefore, a macroscopic approach is commonly used with this medium assumed homogeneous, i.e., a continuum [42]. The effective parameters of this continuum are chosen such as to equalize the diffusion fluxes in it and in the real porous medium.

In the capillary model of porous medium, the effective pore space is represented by a number of sinuous non-intersecting capillaries. The capillaries may have some distribution over their radiuses, but the cross-section area of each channel is assumed constant [38, 42].

The expression for diffusion flux F in a porous medium can be written as [38]:

$$F = -D_{\mathrm{ef}}\frac{\partial C}{\partial z}, \quad D_{\mathrm{ef}} = D_0\frac{p}{\gamma^2}, \tag{1}$$

where D_{ef} is the effective molecular-diffusion coefficient for the given dissolved component, D_0 is its molecular-diffusion coefficient in a diluted aqueous electrolyte solution, C is its concentration in the porous medium, z is coordinate, p is porosity, γ is capillary-pore sinuosity.

A. Lerman [46] recommends Archie formula $D_{\mathrm{ef}} = D_0p^2$ for use to calculate the effective diffusion coefficient for a medium with porosity p. The value of D_0 for diluted molecular solutions of electrolytes can be adequately described by Wilk formula [17, 37]. As only a small portion (~1%) of dissolved free CO_2 interacts with water [2], this interaction can be neglected in this case and CO_2 in the aqueous solution can be regarded as represented by molecules alone.

Consider a layer of water-saturated porous ice penetrated by capillary channels (pores) throughout its thickness. We place the origin of coordinates at the ice bottom boundary (water–ice surface) and direct the positive z axis upward. Under the effect of photosynthetic activity and planktonic algae respiration, the concentrations of dissolved free CO_2 and O_2 in the under-ice water show diurnal variations. In the Fourier expansion of real concentration variations, we chose the harmonic component with a period of 1 day. According to the third Fourier law, the harmonics with larger frequencies attenuate faster than the least-frequency harmonic. We assume that molecular-diffusion gas exchange with adjacent air $z \geq z^*$ can take place through ice surface with coordinate z^*.

The propagation in a layer of porous water-saturated ice of variations in dissolved-gas concentrations, governed by the diurnal variations of its concentration in the under-ice water can be described by a one-dimensional diffusion problem:

$$\frac{\partial C}{\partial t} = \frac{\partial}{\partial z}\left[D_{ef}(z)\frac{\partial C}{\partial z}\right], \quad t > 0, \quad 0 \leq z \leq z^*, \qquad (2)$$

$$C(0,t) = \phi(t) = A\cos(\omega t), \quad \omega = \frac{2\pi}{T^*}, \qquad (3)$$

$$D_{ef}\frac{\partial C}{\partial z} = \alpha(C - C_{eq}), \quad z = z^*, \qquad (4)$$

$$D_{ef}(z) = D_0[p(z)]^2, \quad 0 \leq z \leq z^*, \qquad (5)$$

where C is the concentration of dissolved gas in the porous medium, z^* is ice thickness, A is the amplitude, ω is the cyclic frequency, T^* is oscillation period, T is the temperature, α is gas-exchange coefficient, C_{eq} is gas concentration in equilibrium with the air.

The system of equations (2)–(5) was solved numerically with the use of an explicit central four-point scheme [23, 28]. This scheme is stable when

$$\frac{2D_{ef}\Delta t}{(\Delta z)^2} \leq 1,$$

where Δt is time step, and Δz is coordinate step. The comparison of the numerical solutions with available analytical solutions of steady-state and transient equation of solute transport showed them to be in agreement.

We assume that the temperature T of water-saturated ice is 0°C. Molecular diffusion coefficients are of the same order and amount to 3.4×10^{-6} for CO_2, 4×10^{-6} for O_2, and 2.9×10^{-6} $m^2 h^{-1}$ for CH_4. The effective porosity p is assumed constant at $0 \leq z \leq z^*$. Under such conditions, the coefficient D_{ef} is also constant. The gas-exchange flux at the ice surface is proportional to the difference between dissolved-gas concentration and its value in equilibrium with air. Molecular diffusion coefficients in porous ice were take equal to D_{ef} ($0 \leq z \leq z^*$).

Taking into account that the upper portions of pore capillaries are filled with air, the degrading ice can be regarded as a two-layer porous medium. In this case, the main water-saturated part of the ice is limited to the interval $0 \leq z \leq z'$ ($z' < z^*$), and air fills the pores only in the upper layer with coordinates z' and z^*. Here the transport is taking place in a pore medium composed of a solid body and a gas with appropriate values of molecular-diffusion coefficients.

Model calculations show that the forced diurnal variations of dissolved gas concentration in the pore medium of water-saturated ice attenuate within the first two centimeters from the water–ice interface, even with the assumption that $p = 0.5$ (Fig. 2). It is reasonable to suppose that, with the total thickness of the degrading ice cover of 20–60 cm, the effect of the ice–air interface can be neglected and the diurnal variations of concentrations can be considered in a semi-infinite space.

The limited solution of the problem without initial conditions for the half-space

$0 \leq z < \infty$ and time $t > 0$ [41]

$$\frac{\partial C}{\partial t} = D_{ef}\frac{\partial^2 C}{\partial z^2}, \qquad (6)$$

$$C(0,t) = \varphi(t) = A\cos \omega t, \qquad (7)$$

$$C(z,t)|_{z\to\infty} < B < \infty, \qquad (8)$$

and Fourier laws imply that the amplitude $A(z)$ will decrease exponentially with increasing horizon coordinate and the variations will show a phase shift δ:

$$\frac{A(z)}{A(0)} = \exp\left(-\sqrt{\frac{\omega}{2D_{ef}}}z\right), \quad \delta = \frac{z}{\sqrt{2\omega D_{ef}}}, \qquad (9)$$

The solution of problem (2)–(5) for ice layer of the given thickness at $\Delta z = 1$ mm and $\Delta t = 0.144$ s is in quantitative agreement with the appropriate solution of the problem (6)–(8) for a half-space. Diurnal harmonic variations of dissolved-gas concentrations attenuate completely in water-saturated ice ($p = 0.5$) within 2 cm from the water–ice interface. As near as within the first centimeter from the interface, the variation amplitude of dissolved CO_2 decreases 50 times; O_2, about 40; and CH_4, 70 times. At the same time, the phase lag of variations reaches 14–16 h. This implies that the daily variations of gas concentrations in under-ice water at its interface with ice cannot be the cause of the appropriate synchronous variations of their concentration in the near-ice air layer.

Note that the flux density of the gas dissolved in under-ice water through the layer of degrading water-saturated ice into the adjacent air is small. The point is that the rate of gas exchange in the open-water–air system is governed by the thickness of the boundary surface water layer, in which mass transport is taking place through molecular diffusion.

According to the theory of regenerating free water surface [33], water exchange under direct temperature stratification takes place within a time interval between two successive collapses of thermals. Under calm weather and weak wind, this interval ranges from several tens to several hundreds of seconds, and the thickness of the boundary microzone varies from 0.5 to 1 mm [34].

In Baikal under-ice water, the thickness of the laminar boundary microzone at the contact with ice under inverse thermal stratification and small flow velocities never exceeds 10–15 mm [3]. It decreases to 1–5 mm when the flow velocity under ice increases. In the ice

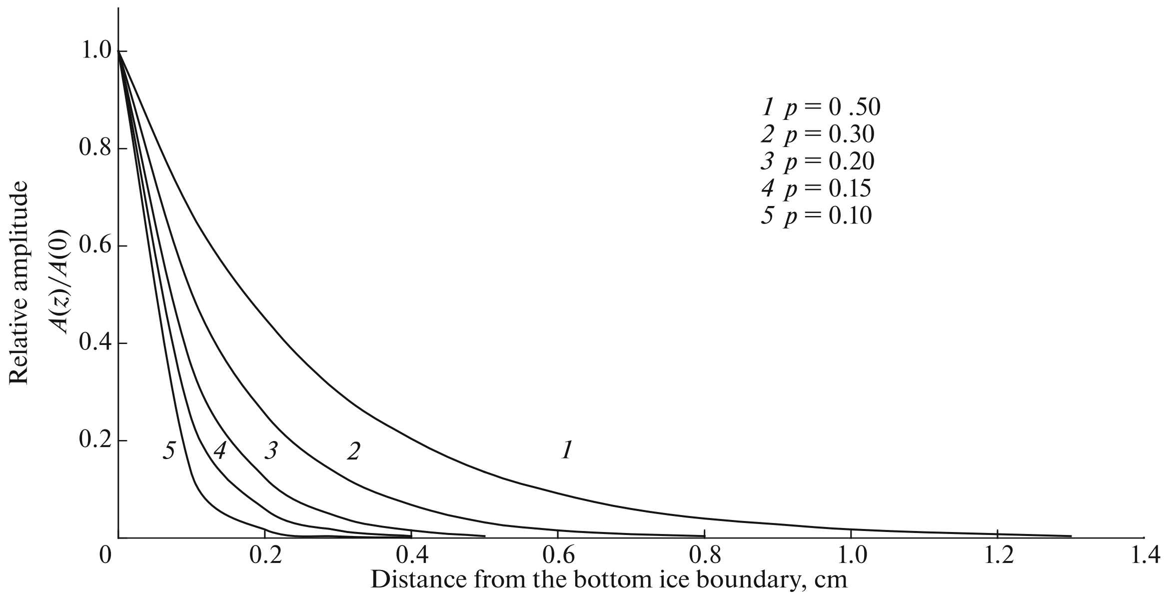

Fig. 2. Variation of the relative amplitude of daily variations of CO_2 concentration in water-saturated ice of different porosity *p* with distance from the water–ice interface.

cover with columnar crystallization, the length of capillary channels through which dissolved gas diffuses is ~30–40 cm, implying that the molecular-diffusion transport from under-ice water through ice cover, other conditions being the same, is several orders of magnitude less than the rate of direct gas exchange between the free water surface and air.

Forest Massifs as an Occasional Source of CO_2

There is reason to believe that small variations of CO_2 concentration in the air over the lake and in the under-ice water have a common cause and can be governed by the daily variations in the temperature and light intensity, which have their effect on both the vital activity of phytoplankton and the nocturnal respiration and photorespiration of coniferous trees and their photosynthesis process.

On the slopes of the northern and northwester coasts of the Southern Baikal and in the nearby parts of Baikal region, coniferous forests are widespread, represented mostly by common pine (Pinus silvestris L.). In some areas, it forms associations with the cedar (Pinus sibirica) and larch (Larix sibirica Ledeb.). On the northern slopes of the Khamar-Daban Ridge, which face the lake, Siberian cedar (Pinus sibirica), fir (Picea abies L.) (in some places), and silver fir (Abies sibirica Ledeb.). Overall, the forest-land percentage in Southern Baikal watershed varies from 90 to 100% [16]. Pine forests also occur on the eastern coast of the Middle Baikal, and cedar occurs in a considerable portion of the western coast of the northern lake depression.

The ability of coniferous trees to perform photosynthesis even in winter is due to the wide interval of air temperature favorable for the functioning of the enzymatic systems of these trees and cofactors of the photosynthetic process [45]. The rate of plant photosynthesis depends on the light, water, and temperature conditions. The integral response of the photosynthetic apparatus to changes in air temperature in the interval 20–25°C can be described by a unimodal curve with an optimum for the plants of moderate zone. The temperature optimum of photosynthesis is not a species feature, as it is determined by the adaptation of a plant to certain temperature conditions and can vary within a season. The lower limit of air temperature at which photosynthesis takes place in coniferous trees (pine, cedar, and fir) is –15°C [27]. Thus, in a mountain valley near Innsbruck (Austria), the photosynthesis of Norway spruce extended to winter. The onset of frosts (from –10 to –15°C) caused the cessation of photosynthesis [20]. Note also that the minimums of respiration in verwintering coniferous trees lie between –10 and –25°C [6].

The joint studies of the carbon balance and gas exchange for a pine forest in the southern subzone of the middle taiga (Turukhansk raion, Krasnodar krai), carried out in 1999–2000 by the Sukachev Institute of Forest, Siberian Branch, Russian Academy of Sciences, and Max Planck Institute of Biochemistry

Table 3. Many-year mean monthly air temperatures in January–April on the northern coast of the Southern Baikal and in the test area in Krasnoyarsk krai [43]

Weather station	Months			
	Jan.	Feb.	Mar.	Apr.
L. Baikal coast [37]				
Listvyanka	−16.7	−16.2	−9.5	−0.6
Babushkin	−16.8	−16.5	−9.7	−0.7
Turukhansk raion, Krasnoyarsk krai [38]				
Sym (trading station)	−23.3	−20.6	−12.8	−2.5
Yartsevo	−23.3	−19.9	−12.6	−3

(Germany) showed that the photosynthetic activity is low in October and November; however, the forest is still a weak source of CO_2 all over the cold season [43]. The net gas exchange of pine-forest ecosystem and the respiration of all its elements (tree trunks and crowns and the soil) do not cease completely even at air temperature of –20 to –40°C and at soil temperature at a depth of 5 cm lying within 0 to –3°C. The light conditions in this case are also favorable: the photosynthetically active radiation (PAR) increased to 10–15 μmol m^{-2} day^{-1} as early as the late February; while in mid-March, it reached 20 μmol m^{-2} day^{-1}, which amounts to ~2/3 of its mean intensity in the warm season.

The study [43] was carried out in an area with coordinates 60°45′ N and 89°23′ E, which is almost 9° (~1000 km) north of the northern and northwestern coast of the Southern Baikal (~52° N). Naturally, the area at the latitude of the Southern Baikal shows earlier spring and higher winter–spring air temperature on the lake (Table 3). It should also be taken into account that Baikal water mass has a warming effect on its coast in the cold season. In addition, in January–March, under cloudless sky, the daily input of direct solar radiation onto the slopes of the lake depression of southern and southeastern aspect with a slope of 10°–30° is 1.2–2.7 times greater than that onto lake surface at the same latitude. At a steepness of 45°, this difference reaches 1.6–4.4 times [30]. Taken together, these factors determine milder winters in the lake depression, earlier increase in PAR intensity in February–March, as well as an increase in the intensity of respiration and photosynthetic activity of coniferous forests.

Of key role for physiological processes is the temperature of the plant, and plant microclimate and ambient microclimate are to be distinguished [22]. The trunks and needles of coniferous plants can be warmed considerably by direct solar radiation, especially, in winter [6], thus creating favorable conditions for winter photosynthesis [48]. Studying heat exchange in conifers in a high-mountain zone in the Alps showed that in winter, when air temperature is below zero, the temperature of plants can be 9–12°C higher than that of the air [48].

Experiments in the Mountain Altai on test areas at an elevation of 1570–2100 m above sea level have shown that yellow pigments, which accumulate in the needles of Siberian cedar (Pinus sibirica Du Tour) in the course of photosynthesis, are in metabolically active state in all seasons of the year [18]. The high concentration of carotinoids (violaxanthin cycle pigments) in winter is caused by a more active photoprotection of cedar photosynthetic apparatus under high insolation.

The Siberian Institute of Plant Physiology and Biochemistry, Siberian Branch, Russian Academy of Sciences (SIPPB SB RAS) carried out systematic seasonal measurements of the electric conductance of the near-cambium layer of fir, spruce, and cedar on the Khamar-Daban Ridge (southern coast of the Southern Baikal [21]. A specific feature of the current climate situation in the southern Baikal region, is positive temperature anomalies within the cold season. In this case, even under short-time thaws, the activity of plants is found to reach its spring level, thus suggesting an increase in the intensity of the daytime respiration of the conifers and leading to an increase in CO_2 release into the atmosphere. An example is the diurnal variation of conifers respiration in early February 2007 [21]. The northern ecotypes of the examined tree species show an explosive change in both their seasonal activity and the rate of physiological processes at daytime increases in the temperature of the environment and the plant in winter.

The effect of forests on the magnitude and diurnal variations of CO_2 in the air in Baikal coastal zone is superimposed on the local circulation of air masses, i.e., breezes and mountain-valley winds. Pilot-balloon observations in the spring (March–April) in the bottom atmosphere layer (~0.2 km) identified air flows shoreward from the lake in the daytime and in the opposite direction in the night. The daytime circulation begins in 9–10 a.m. and disappears in 18–19 p.m. [11].

CONCLUSIONS

In the under-ice period, the gas exchange between Lake Baikal and the atmosphere takes place through a system of coastal and perennial fractures and airholes in the ice, as well as through the surface of the ice-free part of Listvennichnyi Bay at the Angara source (Southern Baikal). In this case, the total open-water area accounts for as little as a few hundredths percent of the water area. The lake ice is impermeable for gases: their molecular diffusion coefficients in a monolith ice cover are several orders of magnitude less than the appropriate values for aqueous solutions.

Ice evaporation and cracking under the effect of thermal deformations do not determine the daily variations of CO_2 content of air over lake ice cover. Note that the noise caused by ice cover deformation is commonly loudest about the midday and midnight, while an increase in CO_2 concentration in the atmospheric air is recorded in the morning and evening [29].

The largest diurnal variations of CO_2 concentrations in Baikal coastal zone are due to the effect of the coastal populated localities rather than gas exchange between the lake and the atmosphere through the ice cover. Coniferous forests on Baikal coast and nearby areas are also distributed CO_2 sources of variable intensity, determined by a combination of nocturnal respiration, photosynthesis, and photorespiration, which also take place and air temperature below zero, though with weaker intensity. In the zone of influence of local winds, the offshore transport of air masses in the night-time and its onshore transport in the daytime determine the daily variations of CO_2 concentration in the bottom atmospheric layer above the lake.

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