Journal of Great Lakes Research 40 (2014) 599–607

Contents lists available at ScienceDirect

Journal of Great Lakes Research

journal homepage: www.elsevier.com/locate/jglr

Ice–water heat exchange during ice growth in Lake Baikal

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ARTICLE INFO

Article history:
Received 27 November 2013
Accepted 7 May 2014
Available online 17 July 2014

Communicated by Leon Boegman

Index words:
Physical limnology
Lake Baikal
Ice cover
Lake hydrodynamics
Ice–water heat flux
Boundary layer

ABSTRACT

Using a custom-made thermistor chain frozen into the ice cover we obtained the first detailed information on distribution of temperature within ice and structure of the ice–water boundary layer during ice growth in Lake Baikal. A mathematical model of the heat transport in a multilayer ice–water system (Stefan problem) was developed and verified on results of in situ measurements. Effective coefficients of thermal diffusivity and ice–water heat fluxes were estimated from the inverse solution of the model and compared with direct flux estimates from the flux-gradient method. Both estimations agreed on flux values of 1–10 W m^{-2} and demonstrated strong synoptic variability in ice–water heat exchange. We estimated the thickness of viscous laminar sublayer under ice, as well as the thickness of the transitional layer on top of the turbulent water column. The thickness of the viscous sublayer of 1–1.5 cm in Lake Baikal was several times smaller than values reported previously from small lakes, suggesting high magnitudes of convective velocities and/or of the under-ice currents in Lake Baikal. Significant growth of the thermal diffusivity coefficient with increasing distance from the ice bottom was detected: its value at the top of the transition layer of under ice water was 10–40 times higher compared with its value in viscous laminar sublayer. This is also significantly higher than previous estimations in smaller freshwater lakes.

Introduction

The thickness of ice cover on lakes depends on the intensity and direction of the heat fluxes at the ice–atmosphere and ice–water boundaries. The variability of the ice–water heat flux within the ice season and among different lakes is poorly known because it is difficult to measure and depends on a number of physical processes including solar radiation absorption, temperature variability within the ice cover and in the under-ice water as well as currents and turbulence in the water column.

Lake Baikal—the most voluminous freshwater lake on Earth—is completely covered by ice for 3–5 months of the year. Consequently, ice regime plays a crucial role in hydrodynamics and ecosystem functioning of the lake. During an ice cover season, ice structure as well as ice and snow cover thicknesses vary significantly over the lake and that requires carrying out a wide range of ice-related field studies.

Systematic studies of the ice cover of Lake Baikal were started in 1869–1876 (Dybovskii and Godlevskii, 1897). First empirical relationships between the ice thickness and air temperature for Lake Baikal were developed by Treskov (1926) and Tsurikov (1939). Later studies were focused on ice structure and physical properties, as well as on the processes of ice growth and melting in winter and spring periods respectively (Boroday, 1939; Sokol'nikov, 1957; Verbolov et al., 1965; Vereshchagin, Kharkeevich, 1939).

Hydrological studies on physical properties of the under-ice water column (Menshutkin, 1964a) and under-ice turbulence (Speranskaya, 1959) yielded first quantitative estimations of the heat fluxes within the ice cover and below (Menshutkin, 1964b). Concurrently, an advance was achieved in research on the solar radiation regime in the ice cover and in the water column of Lake Baikal (Dovgiy, 1977; Sherstyankin, 1975; Sokol'nikov, 1959).

Using modern field techniques, the first detailed information was gained on the small-scale hydrodynamic processes of vertical mixing in the water column (Granin et al., 1999a,b, 2000) as well as on the large-scale current patterns under ice (Zhdanov et al., 2001; Zhdanov et al., 2002). Recently, the effects of ice and snow on the radiation regime in ice-covered Lake Baikal were studied in relation to the winter plankton development (Jewson et al., 2009).

Many publications have been devoted to field and modeling studies on ice cover formation in a wide range of freshwater environments, mainly focusing on the long-term variability of ice regimes associated with climate changes (Bengtsson et al., 1996; Duguay et al., 2003; Leppäranta and Uusikivi, 2002; Leppäranta and Wang, 2008; Leppäranta et al., 2010; Magnuson et al., 2000; Ménard et al., 2002a, 2002b). Both one-dimensional analytical (Onuki et al., 1974; Stefan, 1891) and semi-analytical (Ashton, 1986) models have been used for

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http://dx.doi.org/10.1016/j.jglr.2014.06.004
0380-1330/

qualitative description of thermal processes that occur during the formation and growth of ice. Various simplifications underlying the different modeling approaches and their drawbacks are discussed in reviews of analytical (Leppäranta, 1983, 1993) and numerical (Launiainen and Cheng, 1998) sea-ice growth models.

The vertical heat and mass transport across the water–ice boundary layer strongly affects growth and melting of the lake ice (Kirillin and Terzhevik, 2011; Mironov et al., 2002). Previous research on the dynamics of the boundary layer under ice was dedicated primarily to the radiatively-driven convection (Belolipetsky et al., 2004; Farmer, 1975; Forrest et al., 2008; Mironov et al., 2002; Pushistov and Ievlev, 2000) and, to a lesser degree, to convection driven by salt extraction during the ice growth (Granin et al., 1999b, 2000; Pieters and Lawrence, 2009). A large cluster of studies exist focused on the bulk estimations of the mean turbulent heat exchange and coefficients of vertical thermal diffusivity in ice-covered lakes (e.g. Ellis et al., 1991; Harleman, 1986; Likens and Ragotzki, 1965; Pivovarov, 1973) which can be used as indirect estimates of the heat flow at the ice–water boundary. Studies on large-scale currents under lake ice suggest a significant influence of quasi-stationary circulation patterns on the lateral distribution of the ice thickness and ice melting rates (Forrest et al., 2013; Granin, 2009; Rizk et al., 2014). However, their bulk effect on the lake-wide scales remains largely unknown.

The existing models of ice cover dynamics (Elo and Vavrus, 2000; Elo et al., 1998; Voevodin and Grankina, 2006) focus basically on the dependence of the ice thickness on the air temperature with implicit account of the effect of snow cover. The heat flux at the ice–water boundary, in turn, is usually neglected or parameterized in a very simplistic form (Liston and Hall, 1995). However, neglect of the basal ice melting due to heat flux at the ice–water interface produces appreciable errors in the modeled lake ice phenology (Bernhardt et al., 2012; Patterson and Hamblin, 1988). Recent studies on the coupled ice and circulation modeling of Laurentian Great Lakes (Fujisaki et al., 2013; Oveisy et al., 2012; Wang et al., 2010) demonstrated that adequate representation of the under-ice currents significantly improves model prediction of ice formation and melting.

Here, we present the first comprehensive analysis of the heat flux at the ice–water boundary of Lake Baikal based on detailed temperature data from the ice–water boundary layer. The coefficient of the effective turbulent exchange is estimated by solving the Stefan problem (see below) using data on ice cover thickness, temperature in the ice and in the water layer under the ice. Additionally, we deduce an independent estimation of heat fluxes directly from Stefan's condition at the ice–water interface.

Methods

Field measurement techniques

Temperature

Vertical temperature distribution in the air above the ice, within the ice and in the water under ice was continuously monitored at 3 km from the lake shore (51°50′14″N, 104°53′33″E) in February–March of 2009 using a custom-made chain of 16 digital thermistors DS18B20 (Maxim Integrated™) with resolution of 0.06 °C and initial factory accuracy of 0.5 °C. To reduce the systematic instrumental error, the sensors were additionally calibrated before deployment with adjustment of the calibration curve to the temperature range of interest from −5 to 10 °C. To reduce the random error, the sensor readings were internally averaged by the logging system over every 6 values; the resulting 1-min readings were additionally averaged over 15 min intervals before the analysis. The procedure ensured the final accuracy of the temperature measurements of ≤0.1 °C. One thermistor was placed 10 cm above the ice; one more was placed at the air–ice interface; ten sensors were distributed at 10 cm intervals below the ice surface; four remaining sensors were distributed across the underlying water column at 1 m intervals. Temperature measurements were recorded every 10 s. A self-contained unit was designed for collecting and storing temperature data on an SD memory card (Aslamov et al., 2010).

Ice thickness

Ice thickness was measured using a special-built echosounder (Aslamov et al., 2010). The device was submersed under the ice at a prescribed distance (about 2 m) from the ice surface and measured the distance to the lower surface of ice. A piezoelectric transducer with a resonant frequency of 550 kHz was used as the emitting and receiving element. The emitting circuit consists of push–pull amplifier and center-tapped transformer with 1:3 turn ratio coupled to the transducer. The echosounder generates short burst (ping) consisting of 4 periods of resonant frequency. The echosounder then switches into receiving mode and records amplified echo signal into the file. Digitization is performed with 10 Mega-samples per second conversion rate using 8-bit Analog-to-Digital Converter TLC5510 (Texas Instruments). Further post-processing of the received signal is carried out on a PC, using a specially developed detecting algorithm. The echosounder also measured water temperature with 0.01 °C accuracy for sound speed calculations (McDougall and Barker, 2011). Measurements were taken every 15 min. The relative precision of the distance measurement was 0.2 mm. The absolute precision of ice thickness measurements depended on the accuracy of the determination of span wire length and was approximately 5 mm.

Meteorological parameters, air temperature and humidity, incoming solar radiation, atmospheric pressure, wind speed and direction, were recorded by a remote weather station, Davis Vantage Pro2™, at the lake shore in Listvyanka (southern Lake Baikal).

Temperature and ice thickness model

A mathematical model of temperature distribution in a two-layer system with phase transition (the Stefan problem) was applied to interpret in situ measurements of the thermal regime within the ice of Lake Baikal. The model was implemented in two modes: First, direct solution of the Stefan problem with prescribed coefficients was used in order to estimate the effect of air temperature, solar radiation and heat transport within the ice–water column including latent and sensible heat fluxes at the ice–water interface, on temperature variability in the ice–water system. Second, an inverse solution of the Stefan problem based on the measured temperatures within the ice–water system was used to calculate the thermal diffusivity coefficients and to estimate vertical heat fluxes. The latter were identified and verified using experimental data.

Statement of the direct Stefan problem

The problem of growth and thawing of ice, and the phenomena associated with it, was formulated as a Stefan-type problem for the system of quasi-linear parabolic equations with free boundaries. The coordinate system was chosen with the origin at the ice surface and the vertical axis z directed downwards. Because the variations of potential temperature (which is indistinguishable from the in situ temperature in our case) $\Theta(x,y,z,t)|_{\substack{x=x_0\\ y=y_0}} \equiv T(z,t)$ along the vertical were much higher than horizontal variability, the heat transfer process was described as one-dimensional.

The Stefan problem for potential temperature $T(z,t)$ represents the ice–water system as a two-phase domain with the time-variable phase boundary $\xi(t)$ at the time interval $0 \le t \le t_{max}$. In one-dimensional case, the problem reduces to the solution of the heat equation with piecewise continuous coefficients (Gol'dman, 2002; Tikhonov and Samarsky, 1990; Vabishchevich, 1987):

$$c_j(T)\frac{dT}{dt} = \left(k_j(z,T)\frac{\partial T}{\partial z}\right) = f_j(z,t) \quad j = ice, wat \tag{1}$$