Spatial inhomogeneity of thermal interaction of Lake Ladoga surface with air boundary layer

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Abstract. The article is devoted to describe the features of seasonal inhomogeneity of heat transfer between the surface of Lake Ladoga and the atmosphere, taking into account the limnic zoning of the lake. We present a climatological approach of surface water-air interaction for the lake during ice-free period. Our findings have implications for understanding the role of temperature-dependent processes in large lakes.

1. Introduction

Sensible and latent heat fluxes at the lake surface play an integral part in determining the energy budget and thermal structure in lakes, including regulating how lakes respond to climate change [3]. Lake surface heating/cooling determines the physical environment of the lake ecosystem.

The purpose of this article is to analyze spatially inhomogeneous processes of heat exchange on the surface of Lake Ladoga with the air boundary layer for ice-free period. The main idea was to estimate the direction of two heat fluxes at the lake surface: sensible \( P = f(t_w - t_a) \) and latent \( LE = f(e_w - e_a) \) fluxes which dependent on difference of the water \( t_w \) and the air temperature \( t_a \) and difference of the saturation vapor pressure at the water temperature \( e_w \) and the vapor pressure of the air temperature \( e_a \) respectively. Clearly, wind speed affects the magnitude of heat flux, but does not change its direction. Therefore, the investigation has been without discussion of wind velocity [12].

Lake Ladoga is the largest northern lake among the great lakes in Europe. It covers an area of 18,329 km², of which 457 km² falls on islands. The volume of water mass of the lake is 848 km³ on 5.1 m height above sea level. Maximum bottom depth (230 m) is located in the northern part of the lake. Mean depth is 48 m. The length of the coastline, excluding the length of the coastline of the islands, is 1570 km. The lake is dimictic. The ice cover lasts for 171 ± 3 days on average from the end of November to the mid-May. The basin of Lake Ladoga is of great importance for life and economic activity in the zones [4].

The study of the regularities of the space-time change of evaporation and turbulent heat exchange of the lake surface with the atmosphere was carried out in the 1970s by A.F. Izotova on the basis of materials of more than 20-year comprehensive field research of Limnology Institute of Russian Academy of Sciences, hydrometeorological observatories on lakes and hydrometeorological network. Generalization of materials of ship observations, temporary posts and identification of regularities in
the distribution of meteorological elements in the water area of Lake Ladoga led to the need to divide its area by physical and geographical features into areas that are homogeneous in the first approximation by hydrometeorological regime [5, 6].

More than 35 years ago in 1982, the monograph of A.F. Izotova "Turbulent heat and humidity exchange of large lakes", which summarizes the results of studies of the exchange of heat and humidity of the surface of large lakes with the atmosphere, in particular Lake Ladoga [7]. However, there was no similar targeted research about Lake Ladoga before present.

It is known that an accurate quantitative description of the morphometric characteristics of Lake Ladoga, the shape of its depressions and depth distribution are of paramount importance for studying the thermal regime, wave processes, etc. A digital bathymetric model of Lake Ladoga was first created at the Limnology Institute of RAS. Lake Ladoga was divided into six regions (zones) (figure 1) with the specific depth distributions, assuming that for each of these regions the rate of heating and cooling, biological communities will have only their inherent values [8].

![Figure 1. Limnic zoning of the depths of Lake Ladoga.](image)

Area numbers correspond to numbers in the text.

2. Materials and methods
To describe the climatological cycle of required parameters, a new study was carried out of thermal interaction of the surface of Lake Ladoga with the atmosphere. Large database of thermal data and limnic zoning of Lake Ladoga created at the Limnology Institute of RAS was used. The database, which has more than 300,000 measurements of hydrometeorological parameters from 1897 to 2012, served as the basis for further study of the thermal state of the water and the boundary layer of the lake’s air. Air and water surface temperatures were used as initial data, as well as the absolute humidity values for the open water period. These turbulent heat exchangers, proportional to the difference between water temperature and air temperature, as well as the loss of heat for evaporation
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(condensation) [9], are proportional to the difference between the vapor pressure and the humidity of the boundary layer of air [7].

All the available variables for May to November were included in the analysis regardless of the year of observation. Currently, the calculation for all long-term seasonal course are based on the characteristics of all selected areas of Lake Ladoga from May 5 to November 25 to study statistically reasonable changes in the spatial thermal structure during the open water period. Averaging was carried out in the synoptic period (10 days) with an overlap of 5 days, which allows for spatial and temporal variations in each region.

3. Results and discussion
Seasonal courses of air and water temperature were calculated for every limnic zone. Figure 2 shows the temporary changes in the parameters for sharply contrast areas: the lake shallow water with a depth of less than 18 m and the deepest region with a depth of more than 140 m. The variables analyzed varied throughout the lake, especially during the lake-heating phase after ice breakup [2].

The heating of the boundary layer of air (at a height of 2 m) in the shallow water zone (1) is faster than in the deep water (6). The maximum in both zones are simultaneous in mid-August, after which the air temperature throughout the entire water area of Lake Ladoga drops at the same speed, up to reaching negative temperatures, with the autumn cooling rates being lower than the spring heating rates.

The temperature of the surface of the water rises much faster at temperatures above 4 °C, when the free convection process ends in the surface layer. The temperature difference in the heating process between the first and sixth zones reaches 11 °C in mid-June. In the deep-water zone, the maximum surface temperature is late compared to the shallow coastal zone by 15–20 days. After the occurrence of the maximum, which is particularly well expressed in the deep-water zone, the process of cooling the water surface begins. Cooling in all zones occurs uniformly, without marked differences and more smoothly than heating. However, the coastal zone cools faster than deep water.

The obtained values of the water temperature dispersion from May to July vary intensively and irregularly, especially in the deep-water zone, which characterizes the spatial-temporal heterogeneity of the temperature distribution in all zones in the seasonal aspect. Noteworthy that the variability of the surface temperature of the water increases dramatically after the transition temperature at 4°C in the occurrence of stable stratification.

For the first time, an average long-term course of air humidity was obtained for six limnic zones of the lake. During the period of spring heating from May to July, there are noticeable differences of magnitudes, almost twice between the zones under consideration, which is similar to the differences observed when comparing air temperatures.

In the intra-annual distribution of heat loss for evaporation and turbulent heat exchange with the atmosphere, various features of the meteorological conditions of the boundary layer of air the open part of the lake and the inshore areas appear under the assumption that the wind effect is constant. The heat fluxes are proportional to the gradients of temperature and humidity in the driving layer of air and depend on the season, the distribution of depths and distance from the coast [7]. To consider the features of the exchange of heat and moisture, it is necessary to know the patterns of distribution of hydrometeorological elements in the boundary layer. Depending on thermal stratification, on the transformation of the air flow under certain conditions in time and in space, the exchange processes can be directed from or to the water surface and flow at different intensities [10]. The direction of the processes of heat and moisture exchange can be judged by the vertical gradients of temperature and humidity in the boundary layer [7, 11]. Figure 3 shows the seasonal variation of the difference between the surface water temperature and the air temperature (t_w – t_a) and the humidity difference, e_w – e_a, which influences evaporative heat transfer at the air–water interface, was calculated as the difference between the specific humidity of saturated air at the water surface temperature and difference between the vapor pressure (humidity deficit) [1, 12].
Figure 2. Seasonal course of air temperature, water surface temperature and humidity of the boundary layer of air and their variances for 1st and 6th limnic zones.

Obviously (figure 3) that the greatest fluctuations in the intensity of heat fluxes are observed in the deep water zone (6) during the heating period, which is confirmed by the previous results on average values of water and air temperature (figure 2), which also points out of the intensely turbulent heat exchange process between the surface of Lake Ladoga and the atmosphere. The temperature gradient
in the deep-water zone varies from -1 to -5°C, which means that the air is warmer than water during the heating period, which is also confirmed by the gradients in the coastal zone, but less intensely. The coastal zone is characterized by insignificant changes, which is explained by small depths (small thermal inertia), and, accordingly, the smallest temperature gradients due to relation with shore. The change in the direction of the heat flow due to turbulent heat exchange in the coastal zone occurs earlier than in the deep-water zone. After the onset of the maximum (mid-July) and further in the process of cooling, fluctuations in the temperature gradient between the limnic zones become insignificant, which means that all zones are cooled at the same rate, approximately until the beginning of November.

Figure 3. The seasonal cycle of water-air temperature’s difference and the air humidity deficit.

Similar conclusions were drawn from the seasonal variation of the saturation vapor pressure and air humidity (figure 3). The humidity gradient in the deep-water zone varies from 0 to -2 mbar during the heating period, and between the coastal and deep-water zones - from -2 to 3.5 mbar, which indicates the intensity of heat flow during evaporation from the surface of Lake Ladoga. The cooling process in all zones proceeds evenly, the humidity gradient varies from 2 to 4 mbar. Figure 3 shows an important feature of the spatio-temporal variability of the coastal and deep-water zones humidity deficit. For almost the entire period of open water in the coastal zone, the evaporation process prevails with a maximum in August. Opposite in the deep-water zone until August condensation exists, and later it is replaced by evaporation, reaching a maximum in September. In mid-September, the heat flux from evaporation and the heat flux due to turbulent exchange are the same ones across the entire surface of Lake Ladoga.

The obtained results give a quantitative assessment of the existing spatial and temporal heterogeneity of the thermal interaction of the surface of Lake Ladoga with the air boundary layer.

4. Conclusion

More comprehensive research investigation of direction of heat exchange has been on basis of 10-days-averaged air, water temperature as well air humidity which has extended the initial research of A.F. Izotova for Lake Ladoga. The results obtained have a climatic value for the study of Lake Ladoga, allow us to characterize the thermal differentiation of its regions.

As a result of the research, it can be concluded that all the studied characteristics: water temperature, air temperature, air humidity, there are significant differences in all limnic zones during
the heating period. The cooling process, on the contrary, takes place evenly, without marked differences in all areas. These conclusions confirm the spatial-temporal heterogeneity of the thermal interaction of the surface of Lake Ladoga with the driving layer of air. This feature is extremely important when calculating the components of the thermal balance of the water surface, which are necessary when simulating thermo-hydrodynamics and heat propagation deep into Lake Ladoga. The future investigation will continue for estimation of spatial inhomogeneity of wind distribution over Lake Ladoga.

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References
[1] Laird N F, Kristovich D A 2002 Variations of Sensible and Latent Heat Fluxes from a Great Lakes Buoy and Associated Synoptic Weather Patterns (Journal of Hydrometeorology) 3 pp 3-12
[2] Schertzer W, Rouse W, Blanken P, Walker A. 2003 Over-Lake Meteorology and Estimated Bulk Heat Exchange of Great Slave Lake in 1998 and 1999 (Journal of Hydrometeorology) 4 pp 649-659
[3] Woolway R I, Verburg P, Lenters J D, Merchant Ch J, Hamilton D P, Brookes J, Eyo E, Kelly S, Healey N C, Hook S, Laas A, Pierson D, Rusak J A, Kuha J, Karjalainen J, Kallio K, Lepistö A, Jones I D 2018 Geographic and temporal variations in turbulent heat loss from lakes: A global analysis across 45 lakes (Limnology and Oceanography) 63 6 pp 2305-2889
[4] Ladozhskoe ozero i dostoprimechatel'nosti ego poberezh'ya [Lake Ladoga and the sights of its coast]. Atlas / ed. by Rumyantsev V A 2015 (SPb.: Nestor-History Publ.) pp 200
[5] Smirnova N P 1968 Radiacionnyj balans Ladozhskogo ozero [Radiation balance of Ladoga Lake] Teplovoj rezhim Ladozhskogo ozero: kniga [Thermal regime of Ladoga Lake: book] / ed. by Kalesnik S V (L.: LSU Publ.) pp 5-73
[6] Naumenko M A 2013 Analiz morfometricheskikh karakteristik podvodnogo rel'efa Ladozhskogo ozero na osnove cifrovoj modeli [Analysis of morphometric characteristics of the underwater relief of Ladoga Lake on the basis of a digital model] Izvestiya RAN. Seriya geograficheskaya [News of RAS. Series geographical] 1 pp 62-72
[7] Izotova A F 1982 Turbulentnyj teplo- i vlagoobmen bol'shikh ozer [Turbulent heat and moisture exchange of the great lakes] (L.: Science Publ.) pp 144
[8] Naumenko M A, Karetnikov S G 2002 Morfometriya i osobennosti gidrologicheskogo rezhima Ladozhskogo ozero [Morphometry and characteristics of the hydrological regime of Ladoga Lake] Ladozhskoe ozero: proshloe, nastoyashchee, budushchee: kniga [Lake Ladoga: past, present, future: book] / ed. by Rumyantsev V A and Drabkova V G (SPb.: Science Publ.) pp 16-49
[9] Ukazaniya po raschytov ispareniya s poverhnosti vodoyomov [Instructions for the calculation of evaporation from the surface of reservoirs] 1969 (L.: Gidrometeoizdat Publ.) p 84
[10] Ivanova E V, Panin G N, Pozdynakov SH R, Rumyantsev V A 2013 Osobennosti rezhima ispareniya s akvatorii Ladozhskogo ozero [Features of the evaporation regime from the water area of Ladoga Lake] Meteorologiya i gidrologiya [Meteorology and hydrology] 11 pp 87-93
[11] Lappo S S, Gulev S K, Rozhdestvensky A E 1990 Krupnomasshtabnoe teplovoe vzaimodejstvie v sisteme okean – atmosfera i ehnergoaktivnye oblasti Mirovogo okeana [Large thermal interaction in the ocean – atmosphere system and energy-active regions of the World ocean] (L.: Gidrometeoizdat Publ.) p 335
[12] Matveev L T 1984 *Kurs obshchej meteorologii. Fizika atmosfery* [The course of general meteorology. Physics of the atmosphere] (L.: Gidrometeoizdat Publ.) p 752