Limnological Review 7, 2: 63-70

Thermal regime of Lake Ladoga as a typical dimictic lake

Mikhail Naumenko, Sergey Karetnikov, Vadim Guzivaty

Institute of Limnology of the Russian Academy of Sciences,
ul. Sevast'yanova 9, St. Petersburg, 196105 Russia; e-mail: m.naumenko@limno.org.ru

Abstract: Lake Ladoga, the largest dimictic lake in Europe, is situated at the periphery of the Baltic Crystalline Shield near St.-Petersburg is about 61°N, 31.5°E. A review of Lake Ladoga seasonal climatological cycles of water temperature and ice cover is the object of this article considering the features of typical dimictic lake. Quantitative analysis has been carried out using the vast thermal database. Depending on the morphometric regions we describe the time-depth variations of water temperature for Lake Ladoga from January to December. Owing to its large area and basin morphology, there is considerable horizontal and vertical heterogeneity in the temperature of Lake Ladoga in all seasons except the ice cover period.

Keywords: Lake Ladoga, mean seasonal temperature course, ice conditions, vernal thermal frontal zone, "biological summer".

Introduction

Recognition and understanding of the characteristics of the temperature regime of a lake are keys to successful interpretation of information on its physics, chemistry and biology. The rates of limnological processes usually temperature dependent, besides the spatial and temporal variation of that property strongly influence patterns of currents and density structure, and hence affect the rate of vertical mixing or of exchange between the nearshore zone and midlake, and influence the flushing characteristics of regions or the lake as a whole.

Lake Ladoga is an important public and industrial water supply and serves as a source of drinking water for more than 4.5 millions people. It is also important for fisheries and is used for commercial shipping and as a recipient for urban sewage and industrial effluent (mainly from paper and pulp mills).

The object of this paper is focused on review of Lake Ladoga seasonal climatological cycle of water temperature and ice cover. Quantitative analysis has been carried out using the vast thermal database. Depending on the morphometric regions we describe the time-depth variations of water temperature above parameters for Lake Ladoga during from January to December.

Study area and data

In the temperate climatic zone a large deep lake which overturns twice yearly, in spring and fall is classified as a dimictic lake (Ruttner 1966). Lake Ladoga, the largest dimictic lake in Europe, is situated at the periphery of the Baltic Crystalline Shield near St.-Petersburg. Lake Ladoga covers an area of 17800 km^2, with a mean depth of 46.9 m and maximum depth of 230 m. Depths of the northern part are from 60 up to 200 m, maximum depth is 230 m., while depths of the southern part are as a rule among 10-50 m.

The principal factor defining the temperature distributions in Lake Ladoga is the bathymetry, which partitions the lake into six distinct compartments. The limnological regions are delimited by isobaths and their morphometric features, as shown Fig. 1 (Naumenko1995, Naumenko et al. 2000b). The mean residence time of the lake is about 12 years.

Environmental temperature is one of the most important defining parameters in large lakes ecosystems. The mean Lake Ladoga thermal feature were determined by A. I. Tikhomirov on the base of data for 50-60 years of last century (Tikhomirov 1982).

The bank of Lake Ladoga limnological information, created in Institute of Limnology RAS (www.limno.org.ru), was used for investigation of

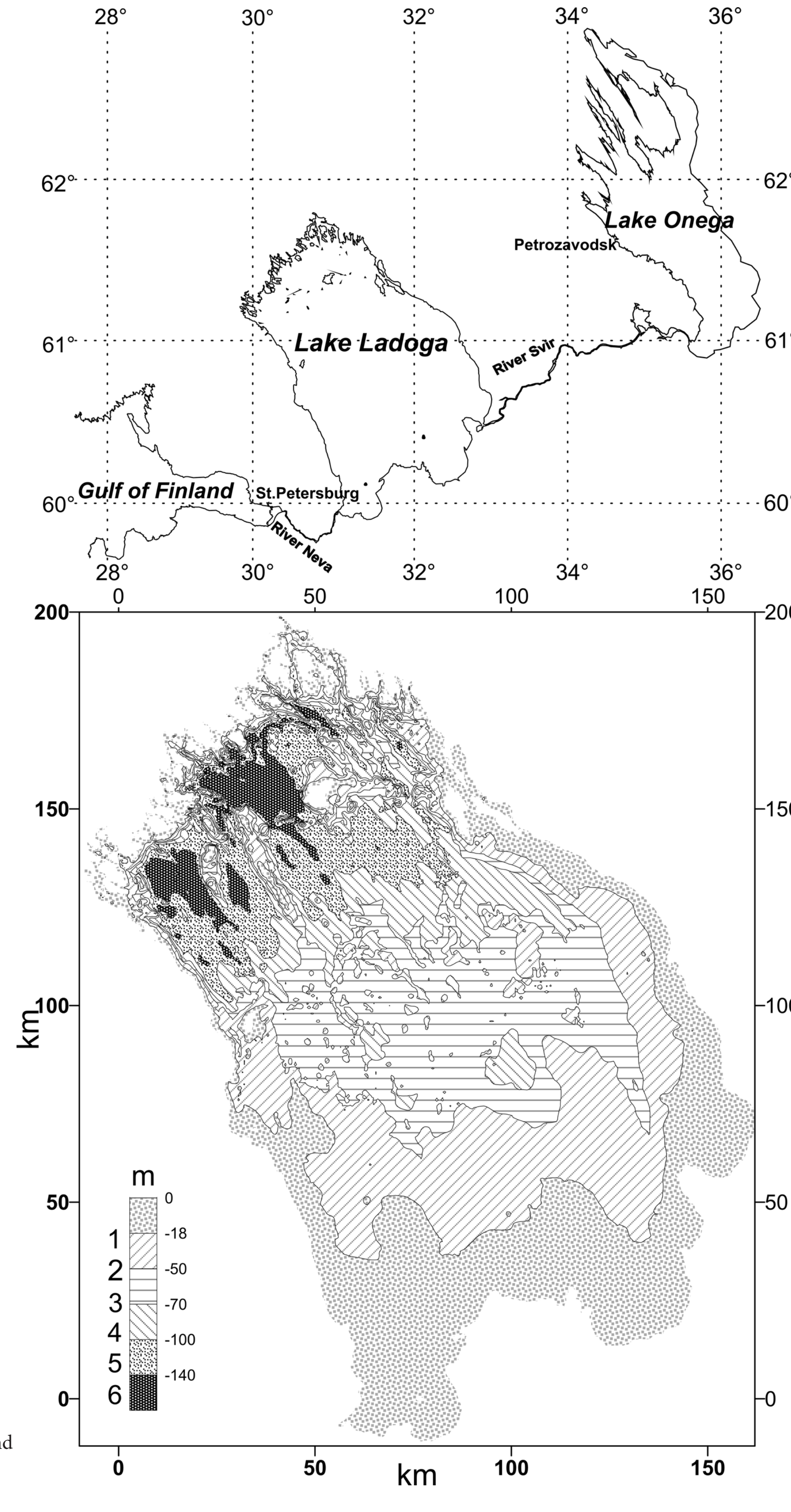

Fig. 1. Location of Lake Ladoga (a) and the lake's morphometric regions (b)

thermal region peculiarities. At present time the database capacity has reached 240,000 records, and covers the period from 1898 to 2006 (Naumenko et al. 2000a). The information density is more 285 measurements per km^3. Lake Ladoga computer thermal database has allowed to study the statistically significant changes in spatial thermal structure in the lake. Digital morphometric model is created to calculate the heart storage for whole lake and its parts (Naumenko 1995).

Ice cover

The important role for Lake Ladoga plays winter conditions. Freezing of the lake usually begins in November. Ice cover lasts from November to May (average 172 ± 3 days).

In the mid-February the lake is covered completely but it depends on weather conditions and severity of winter. Mean ice thickness on March is 50-60 cm, the minimum of whole water body temperature is reached at the beginning of April (about 0.6 °C). Ice break-up begins in the middle of March (Fig. 2).

The spatial distribution of ice over Lake Ladoga has been observed regularly since 1943. Aircraft and satellite information on Lake Ladoga ice cover conditions has been collected from 1943 through 2006. However, ice cover data for the period 1992-1996 are missing. On average, 15 surveys were carried out each winter; the maximum was 37 surveys in 2006.

In order to calculate the extent of lake ice cover, taking its concentration into account, the surface area of Lake Ladoga was split into 183 cells (10 km per side). Each ice chart, from either an aircraft or a satellite image, was converted into a geographic projection. The average percentage ice cover was estimated for each cell with 10% accuracy. The ice concentration was averaged over all grid cells to calculate the lake-averaged ice concentration on each composite chart for a given winter season. To date, about 1000 surveys have been processed for the 63-year period. We took account only of the spatial ice concentration, not its thickness.

We propose the Relative Ice Cover Index (RICI) to characterize each year in terms of a single dimensionless value. The RICI represents the area under the actual chronological ice concentration curve for a given year divided by the area under the mean seasonal curve. The RICI allows years to be compared with each other (Karetnikov and Naumenko 2007).

Data obtained throughout the continuous period of observation from 1943 to 2006 were used to estimate the main statistical characteristics of ice event dates and the durations of ice cover (Table 1).

The date of first/last ice was taken as the date of last/first remote survey without ice (i.e. open water) or as an extrapolated date of ice remote surveys to zero ice concentration. The total ice cover period was calculated as the number of days between first ice and last ice date. The complete ice cover was found to be unstable in some years, so the complete ice cover period was taken as 95% ice concentration. The date of 95% ice cover freeze-up represents the first date of complete ice cover, and the date of 95% ice cover breakup represents the last (Table 1).

Analysis of the inter-annual variation in ice phenomena dates and the duration of coverage shows very small but significant trends (1-6 days per 100 years). The trend is most marked for the freeze-up dates (14 days per 100 years), but the coefficient of determination is no more than 3%. The Relative Ice Cov-

Table 1. The statistical characteristics of dates and duration of ice cover stages in Lake Ladoga

Dates/durations	First ice date	95% ice cover when freeze-up	95% ice cover when break-up	Last ice date	95% ice cover duration	Total ice cover duration
Mean	Nov 24	Feb 13	Mar 24	May 13	34	172
Std. err., days	1.8	3.2	3.7	1.3	4.6	2.5
Median	Nov 24	Feb 11	Mar 22	May 12	27	172
Minimum	03/11/75	08/01/87	18/01/50	20/04/75	0 (1945,1961,1971,1975, 1989,1990,2000,2004)	118 (1973)
Maximum	26/12/72	28/03/57	09/05/85	29/05/74,79	117 (1987)	203 (1976)
Range, days	53	79	111	39	117	85
Total number of winter seasons used, N	50	38	39	59	55	53

er Index (RICI) shows a significant negative climatic trend. The decrease in ice cover was no more than 12% over the 63 winter periods, with a rather small coefficient of determination (Karetnikov and Naumenko 2007).

Annual temperature cycles

Lake temperature cycles are important for studies of most aquatic processes, especially for numerical models that are intended to simulate annual bio-geochemical cycles. Changes in lake temperatures, possibly resulting from changes in global climate, may have significant impacts on Lake Ladoga (Naumenko and Karetnikov 2002a). Seasonal cycle of the lake-wide averaged of water temperature, air and surface water temperature in Lake Ladoga are plotted in Fig. 2.

In late April when surface water temperature becomes equal to the water body temperature a vertical mixing due free convection occurs. During the period of stratification there is temporal lag between the time of maximum surface water temperature and the time of maximum whole lake temperature .

The semi-annual alternation between periods of stratification and extensive vertical mixing is typical of dimictic lakes. The heat content of Lake Ladoga varies from its annual minimum value in the first decade of April to the maximum value in the first decade of September. The difference between the maximum and minimum values, called the annual heat income, is 33,900 cal/cm^2. The spring heat income, which is the amount of heat required to raise the mean lake temperature from its minimum value at the end of winter to the temperature of maximum density, is 16,000 cal/cm^2. Therefore, approximately 53 percent of the annual heat income of Lake Ladoga is used for summer warming of water to its maximum.

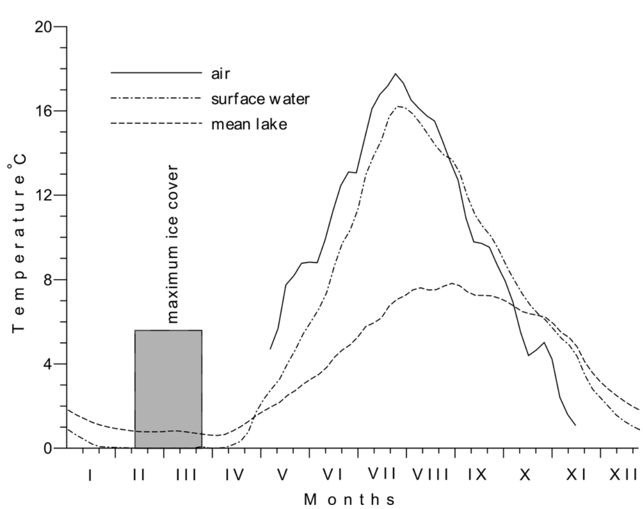

Fig. 2. Seasonal cycle of the lake-wide averaged of water temperature, air and surface water temperature in Lake Ladoga

The mean annual surface temperature cycle depend on the depth distribution. It relates with the thermal bar evolution. Morphometric differences in the limnic regions of Lake Ladoga determine the specific conditions for heat accumulation and loss during the annual cycle, the time of the beginning and end of hydrological seasons, and their duration (Naumenko et al. 2000e).

The water temperatures and its main statistical characteristics on 8 horizons (0, 5, 10, 20, 30, 40, 50 and 100 m) were calculated for each of Lake Ladoga limnological regions from January to December. The averaging period was 10 days with shifting on 5 days that has allowed to smooth high-frequency temperature fluctuations. The quantitative analysis of a seasonal course of water temperature for the regions in connection with their depths have been made (Naumenko and Karetnikov 2002b).

Figure 3 depicts the region-wide-averaged vertical distribution of temperature in Lake Ladoga. For every region free convection and stable stratification periods begin in the different dates and exist various duration. The dates when stratification of Lake Ladoga morphometric regions is complete ranges from mid-May to early July.

Owing to its large area and basin morphology, there is considerable horizontal and vertical heterogeneity in the temperature of Lake Ladoga in all seasons except the ice cover period.

For each region it was found that the variance (dispersion) of water temperature has regular change from month to month and on depths, that characterises the spatial – temporal irregularity of temperature fields on various horizons. The largest dispersions in surface temperature arise during the warming period, 20-30 days before the maximum temperature is reached, when a stable stratification begins to form. After this period the variation decreases and the maximum values shift to the deeper areas. Depending on the region the greatest depth at which a variance higher than 1 unit still exists in the annual cycle varies from 50 to 100 m. This depth defines the surface layer that is subjected to interannual thermal variation. Below the depth there is only a smooth temporal course of temperature without any fluctuations.

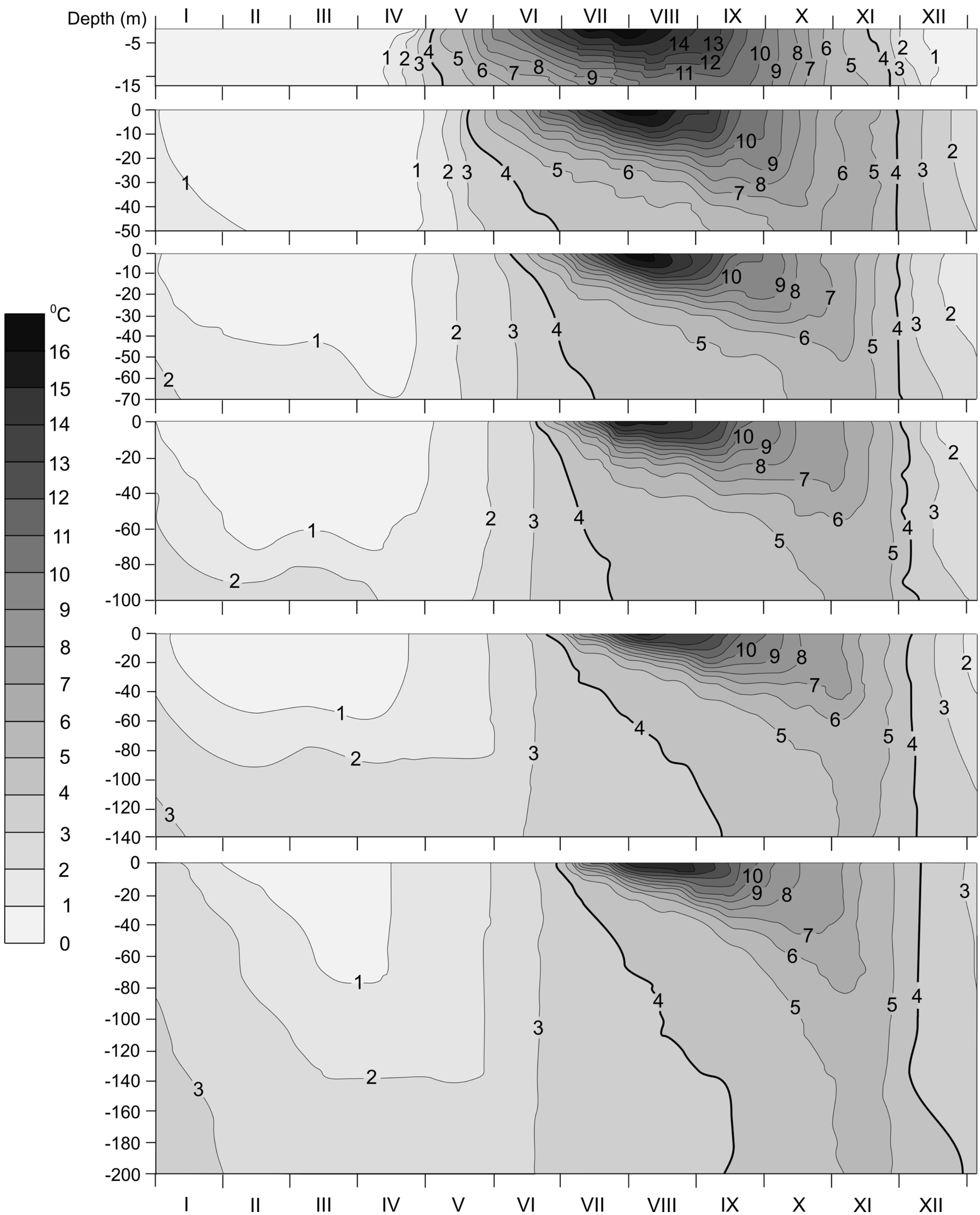

Fig. 3. Time – depth annual course of temperature for six limnetic regions of Lake Ladoga.

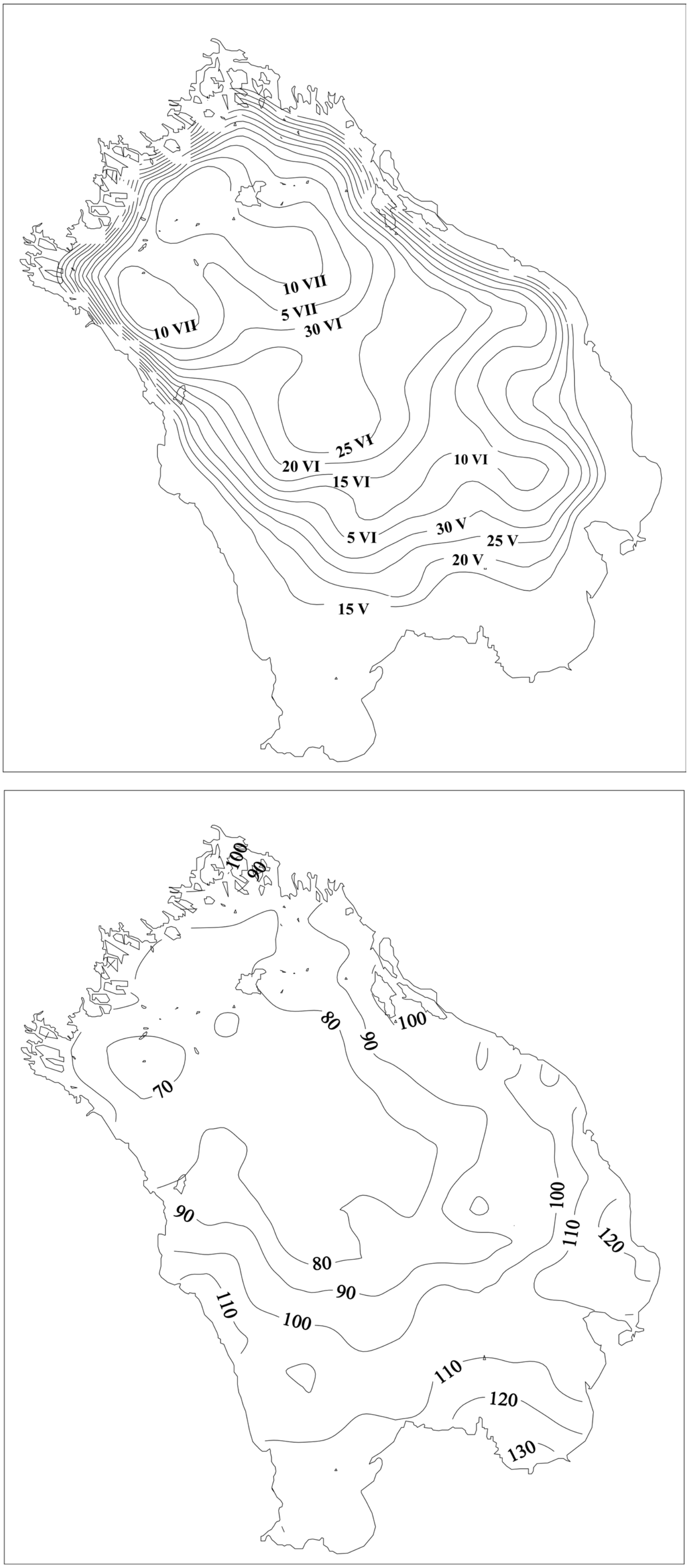

Fig. 4. Spatial and temporal evolution of position of thermal bar (a) and duration of "biological summer" (b).

The temporal variation of water surface temperature for different areas of the lake was discussed using in situ and aircraft measurements (Naumenko et al. 1996, Naumenko et al. 2000e).

The model of seasonal cycle of surface temperature as a functional representation was presented (Naumenko et al. 2000d). For the analysis of spatial daily water temperature distribution, the lake surface was divided up by means of a grid with area of about 10x10 km. Approximation functions were found for all 235 squares and the temporal limits of their applicability defined. The seasonal cycle of daily mean Lake Ladoga surface, 20 and 50 m water temperature were presented as a temporal functional representation ("typical" course) (Naumenko et al. 2000c). We have made the quantitative analysis of a seasonal course of water temperature for the limnetic regions in connection with their depths (Naumenko and Karetnikov 2002b).

Lake Ladoga seasonal climatological cycle of depth-distributed water temperature, density, their vertical gradients, stability, water temperature dispersions and vertical diffusivity have been discussed (Naumenko et al. 2003). The spatial daily mean surface, 20 and 50 m water temperature, air temperature and humidity over Lake Ladoga were plotted.

The thermal bar described by A. I. Tikhomirov is a consequence of the anomalous temperature-density relationship of water around 4°C (Naumenko et al. 1996). This is a very important phenomenon for biological and chemical processes in the lake. The thermal bar forms along the lake's perimeter at the near-shore shallow region on first decade of May. It exists for more than two months.

The thermal bar advances toward the centre of the lake as heating progresses and when the central portion reaches 4°C the thermal bar disappears. The dates when stratification of Lake Ladoga morphometric regions is complete ranges from mid-May to early July. The spatial daily mean surface 4°C isotherm positions (vernal thermal front) are presented in Fig. 4a.

For Lake Ladoga the "biological summer" can be determined as a period when the temperature of the surface water exceeds 10°C. This marks the time at which the summer plankton communities are actively developing. Mean scheme of "biological summer" duration have been obtain (Naumenko et al. 2000d) and is shown on Fig. 4b (Hvorov and Utin 2002). It varies from four months on Volkhov Bay to one month on northern deep areas.

Analysis of climatic surface water temperature trends in central part of Lake Ladoga was conducted for open water period. No significant trends in surface temperature were recorded for 80% of open water period. Surface temperature climatic trends of Lake Ladoga have been detected for very limited temporal scales comparable with synoptic periods (from 4 to 8 days). For these periods significant increasing trends of water temperature are 0.05-0.07°C/year. The maximum determination coefficient described 30-40% of the total variance (Naumenko et al. 2006).

Conclusion

As a typical large dimictic lake Lake Ladoga has common features with various dimictic lakes of the World. The main differences are related with depth distribution and influence of the latitude. Calculated seasonal cycles of thermal characteristics gives new possibilities at a solution of the diverse tasks on thermodynamic and its simulation and can serve as average background distributions at synoptic variability analysis and interannual variations.

References

Hvorov G. V., Utin G. N. (eds), 2002, Atlas of Lake Ladoga, Limnology Institute of the Russian Academy of Science, Saint-Petersburg (in Russian).

Karetnikov S. G., Naumenko M. A., 2007, Recent trends in Lake Ladoga ice cover, Hydrobiologia (in press).

Naumenko M. A., 1994, Some Aspects of Large Lakes Thermal Regime (Ladoga, Onega), Water Pollut. Res. J. Can. 29: 423-439.

Naumenko M. A., 1995, Novoe opredelenie morfometricheskikh khararteristik Ladozhskogo ozera. (New estimation of Lake Ladoga morphometrical characteristics), Doklady Akademii Nauk 345: 514-517 (in Russian).

Naumenko M., Karetnikov S., Tikhomirov A., 1996. Main features of the thermal regime of Lake Ladoga during ice-free period. Hydrobiologia, Proc. the First Int. Lake Ladoga Symp., V. 322, p. 69-73.

Naumenko M. A., Guzivaty V. V., Karetnikov S. G., 2000a. Lake Ladoga thermal database-Institute of Limnology (IL), [in:] Huttula T., Peltonen A., Filatov N. (eds), Hydrological monitoring and modelling of Lake Ladoga with recommendations for further research, University of Joensuu, Publ. of Karelian Institute,Working Parers M2: 11-21.

Naumenko M. A., Guzivaty V. V., Karetnikov S. G., 2000b, The thermal regions of Lake Ladoga, [in:] Peltonen A., Gronlund, Viljanen (eds), Proc. Third Int. Lake Ladoga Symp. 1999, University of Joensuu, Publ. of Karelian Institute No. 129: 437-441.

Naumenko M. A., Guzivaty V. V., Karetnikov S. G., 2000c, Spatial distribution of daily mean surface temperatures in Lake Ladoga from May to November, [in:] Peltonen A., Gronlund, Viljanen (eds), Proc. Third Int. Lake Ladoga Symp. 1999, University of Joensuu, Publ. of Karelian Institute No. 129: 442-447.

Naumenko M. A., Guzivaty V. V., Karetnikov S. G., 2006, O klimaticheskih trendah temperatury poverhnosti vody Ladozhskogo ozera v bezlednyi period (Climatic Trends of the Water Surface Temperature in Lake Ladoga during Ice-Free Periods), Doklady Akademii Nauk 408: 675-678 (in Russian).

Naumenko M. A., Karetnikov S. G., 2002a, Morfometriia i osobennosti gidrologicheskogo rezhima Ladozhskogo ozera (Lake Ladoga morphometry and hydrological regime features), [in:] Rumyantsev V. A., Drabkova V. G. (eds), Ladozhskoe ozero-proshloe, nastoyashee, budushee (Lake Ladoga: The Past, Present, Future), Nauka, St. Petersburg: 16-49 (in Russian).

Naumenko M. A., Karetnikov S.G., 2002b, Sezonnaya evolyutsiya prostranstvennogo raspredeleniya temperatury poverhnosti vody Ladozhskogo ozera v svyazi s ego morfometriei (Seasonal dynamics of spatial distribution of surface water temperature in Lake Ladoga in relation to the lake depth), Doklady Akademii Nauk, 386: 250-253 (in Russian).

Naumenko M. A., Karetnikov S. G., Guzivaty V. V., 2000d, Mean daily spatial surface temperature at Lake Ladoga: a new approach from thermal information-diagnostic system. Proc. 4th International Conference on Integrating Geographic Information Systems (GIS) and Environmental Modeling: Problems, Prospects and Needs for Research. (GIS/EM4), Sep. 2-8, 2000. (CD-ROM, ISBN: 0-9743307-0 -1) http://www.colorado.edu/research/cires/banff/pubpapers/246/

Naumenko M. A., Karetnikov S. G., Guzivaty V. V., 2000e, Prostranstvenno–vremennaya termicheskaya differenciaciya vod Ladozhskogo ozera (Spatial-temporal thermal differentiation of Lake Ladoga waters), Doklady Akademii Nauk 373: 247-250 (in Russian).

Naumenko M. A., Karetnikov S. G., Guzivaty V. V., 2003, 3-D thermal structure of Lake Ladoga: a new approach and results, Proc. 7thWorkshop on Physical processes in natural waters, 2-5 July 2003, Northern Water Problems Institute, Petrozavodsk: 45-49.

Naumenko M. A., Karetnikov S. G., Tikhomirov A. I., 1996, Main features of the thermal regime of Lake Ladoga during ice-free period, Hydrobiologia 322: 69-73.

Ruttner F., 1963, Fundamentals of Limnology: University of Toronto Press, Toronto, p. 295.

Tikhomirov A.I., 1982, Termika krupnykh ozer (Thermal regime of large lakes), Nauka, Leningrad, p. 232 (in Russian).