Effect of climate and morphometry on thermal regime of lakes

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ABSTRACT
Generalized from long-term (1945-1989) observational data on water temperature at stations of the Hydrometeorological Service network that describe reservoirs of different types in northwestern Russia, empirical relationships of the thermal regime on various geographical factors are established (lake morphometry, geographical latitude and altitude above sea level, residence time). We have demonstrated that for stable thermal stratification to emerge, a lake must have a certain combination of geometric parameters. Regional boundaries between epi-, meta- and hypothermal types of lakes have been quantified depending on the area and maximal depth of the lakes. Analysis of the results has shown that the temperature in the upper 5 m layer of water mainly depends on the latitude, whereas at a depth of more than 10 m it is more significantly affected by the lake morphometry, inflow and outflow of rivers. Modeled curves describing average annual daily surface temperature values for lakes of different size and depth were received with use of the 6-parameter regression function. All parameters are dimensional and have a clear physical interpretation. This feature favorably distinguishes the function from previously published regression models.

KEYWORDS
Vertical thermal structure, regression model, stratification, epilimnion depth, “biological summer”, geographical factors

1. INTRODUCTION

The water temperature is one of the main factors that govern the rate of biological processes in reservoirs. The relationships between fetch and depth at which a lake would be stratified have earlier been quantified by Lathrop & Lillie (1980), Patalas (1984), Gorham & Boyce (1989). Birge and colleagues made the first description of the water temperature in a lake by means of the continuous function (Birge et al., 1927). Strashkraba (Strashkraba and Gnauk, 1989) has used a harmonic function for the description of the annual cycle of surface temperature and bottom layer in ice-free lakes and rivers in accordance to geographical zoning. The functional description of the average daily cycle of water surface temperature was carried out for Great American Lakes (Lesht and Brandner, 1992) and lakes in Europe (Efremova and Petrov, 1992; Naumenko et al., 2000). The purpose of this investigation was to quantify the effect of climate and morphometry on the thermal regime of lakes.

2. MATERIALS AND METHODS

Analysis of the average annual vertical temperature distribution was based on data received in fifty eight lakes located in North-Western Russia, 55-70°N, (1958-1989), and in eight Finnish lakes (1961-1975) (Kuusisto, 1981). Seasonal variability of average annual water surface temperature was studied using data on 52 lakes of North-Western Russia collected during a period of 1945-1980 at stations of the Russian Hydrometeorological Service network, and data on two Finnish lakes summarized by the Finnish Hydrometeorological Service network (1961-1991) (Figure 1).

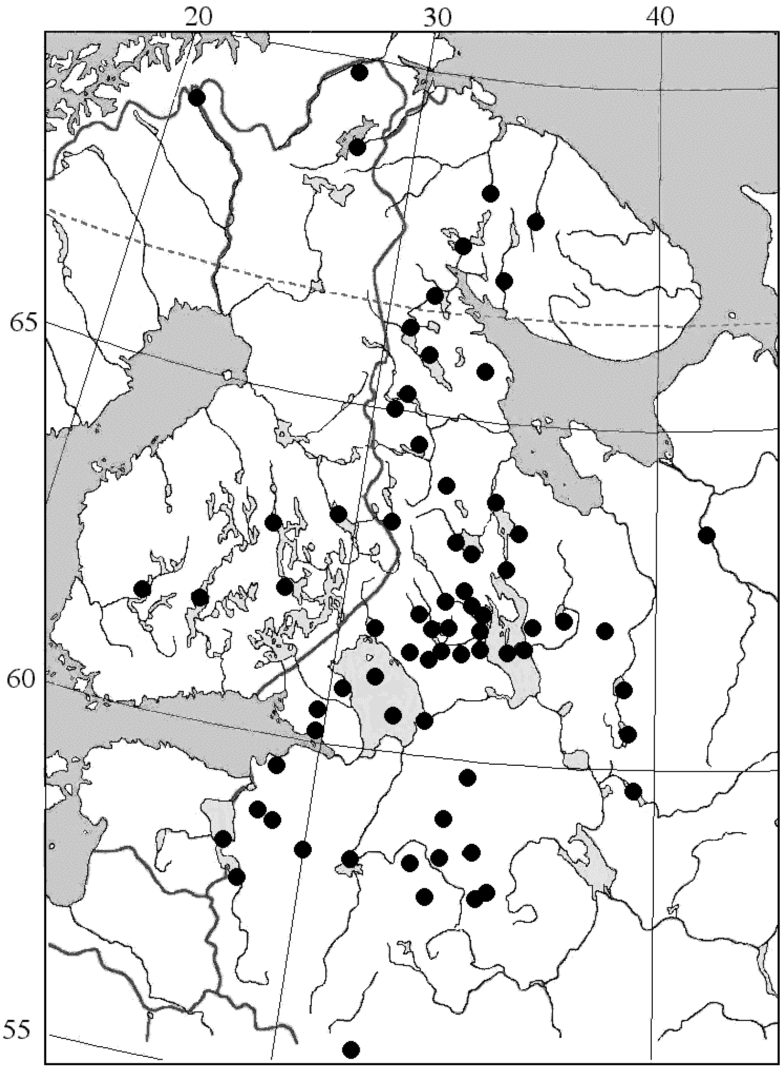

Figure 1. Map of study area and the investigated lakes.

Morphometric features of lakes vary in a wide range: from the largest lakes of Europe – Ladoga and Onego – to the small lakes with area less than 1 km^2. The range of some characteristics of the lakes studied is shown in Table 1. Preliminary statistical analysis shows that there is no correlation between geometric sizes of lakes and latitude, altitude, residence time (R< 0.25). Correlations between the area size and average or maximum depth of research lakes are not high (R < 0.5).

Table 1 Characteristics of the lakes studied

Parameter	Range
Latitude, deg.	55º37` - 69º46` N
Longitude, deg.	20º30` - 41º32` E
Altitude, m asl	4.5 - 463
Area, km^2	0.65 - 17,872
Mean depth, m	1.6 - 46.9
Max depth, m	5 - 230
Volume, km^3	0.002 - 837.9
Residence time, year	0.01-16.7

Registrations of water temperature in these lakes have a different length from 10 to 35 years. This causes some heterogeneity of data, however, general trends of dependency of water temperature from zonal climatic effects and morphometric characteristic are retained. The data were statistically treated using the Newton nonlinear estimation method and multiple regression analysis. We made up the equation and selected the main geographical factors (latitude, altitude, area of lakes, average of the lake depth, depth at the sampling point, inflow and outflow of rivers), exerting influence on water temperature in the lakes. Verification of the stochastic models has been performed with observational data which were excluded from the process of definition of regression relationships.

3. RESULTS

3.1. Types of thermal structure in lakes

The relationship between the stratification type and maximum depth (H_{max}, m) and the area (S, km^2) of the lakes was determined. Location of the lakes in different climatic areas (55-70ºN) causes certain difficulties with their clustering. Therefore, boundaries between hypo-, epi- and metathermal types of lakes (Figure 2) were drawn by the dimensionless temperature Θ,

$$\Theta = \frac{\overline{T}_H - T_{md}}{\overline{T}_0 - T_{md}},$$

where $\overline{T}_0$ and $\overline{T}_H$ are average annual temperatures of the surface and near-bottom layers in late July – early August; T_{md} – temperature of max density.

Empirical formulae for (h_1, h_2) boundaries between different types of lakes have been obtained,

$$h_1 = 6{,}43 + 3{,}51 \lg S \qquad \text{when } \Theta = 0{,}7; \qquad (1)$$

$$h_2 = 17{,}78 + 8{,}55 \lg S \qquad \text{when } \Theta = 0{,}3, \qquad (2)$$

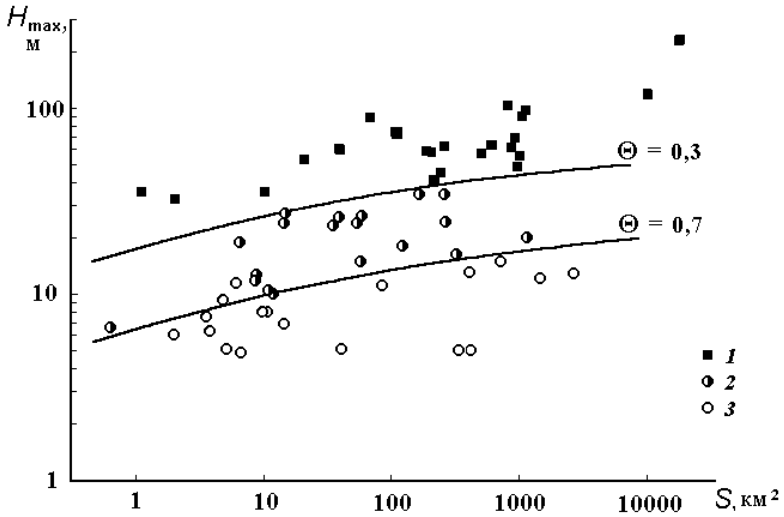

Figure 2. Relationship between stratification of lakes and their area and max depth. *1-3* are hypo-, meta- and epithermal lakes, respectively.

Deeper lakes (hypothermal, $\Theta < 0.3$) are typical representatives of the dimictic lake class with three vertical strata: epi-, meta- and hypolimnion. The water mass in shallow lakes (epithermal, $\Theta > 0.7$) shows transient thermal stratification in summer and occasionally gets overturned down to the bottom due to the wind action or because of water cooling. Medium-depth lakes (metathermal, $0.3 \le \Theta \le 0.7$) normally have two strata that are the upper quasihomogeneous and the lower stratified.

Contrary to the three-class grouping suggested above, Lathrop & Lillie, Gorham & Boyce have grouped the lakes into two classes: stratified and unstratified, wherefore the differentiation limits are different (Table 2). Patalas has clustered the lakes into three classes relying on the depth of epilimnion in relatively deep-water lakes (h_e/H_{max} ~1.0 – homothermal lakes; 0.5 < h_e/H_{max} < 0.9 – lakes with two strata – epilimnion and thermocline; h_e/H_{max} < 0.5 – a three-layer system with epilimnion, thermocline and hypolimnion). For lakes of northwestern Russia, the ratio of epilimnion depth to h_1 and h_2 calculated by formulae (1) and (2) are 0.8-0.9 and 0.3-0.4.

Table 2 Epilimnion depth (h_e), thermocline depth (h_t) and depth needed for stratification to emerge (h_s, h_1, h_2)

L, km	h_e, m		h_t, m		h_s, m		h_1, m	h_2, m
	Patalas	Formula (3)	Araj	Gorham, Boyce	Lathrop, Lillie	Gorham, Boyce	Formula (1)	Formula (2)
1	4.6	4.8	6.2	6.4	7.3	10.8	6.4	17.8
2	6.1	7.1	7.7	8.4	10.3	15.2	8.5	22.9
3	7.2	8.4	8.7	10.4	12.6	18.6	9.8	25.9
4	8.1	9.3	9.5	12.4	14.5	21.5	10.7	28.1
5	8.9	10.0	10.1	14.4	16.3	24.0	11.3	29.7
6	9.6	10.6	10.7				11.9	31.1
7	10.2	11.1	11.2				12.4	32.2
8	10.8	11.5	11.7				12.8	33.2
9	11.3	11.9	12.1				13.1	34.1
10	11.8	12.2	12.5				13.5	34.9

Using data collected by Patalas (1984) from lakes situated in different climatic zones (170 lakes of North America, Poland and Japan) a new formula (3) has been suggested for calculating the epilimnion depth (h_e), which takes not only the fetch (L), but also the geographic latitude (φ) into account.

$$h_e = 4{,}83 + 0{,}119\,\varphi\,\lg L \quad (r = 0{,}88;\ \text{rms} \pm 1{,}56). \tag{3}$$

Corrections to h_e from φ proved to be not very high but significant. The prevalent wind mixing mechanisms are different in lakes of different geometric sizes. To estimate how this factor related to the fetch tells on the epilimnion depth we divided the sample into three groups (for small lakes L < 5.5 km, for small and medium-size lakes L < 15 km, for all 170 lakes, including largest ones with $L \leq 33$ km) and found empirical relationship for them.

Close values of regression coefficients and absolute terms in the formulae evidence the stability of the relationships. Estimates of h_e by the above formulae within the L ranges under consideration show a <0.2 m divergence of the calculated values. Thus, the common formula can be employed to calculate h_e for both small and large lakes with areas up to 1000 km^2 situated between 45º and 66º N.

3.2 Vertical thermal structure

The vertical thermal structure of lakes was evaluated on data of measured water temperature on standard horizons 0.1, 2, 5, 10, 15, 20, 25, 30, 40 m. For the analysis we choose the period with the direct thermal stratification under the maximum heat content in lakes (20 July –10 August). We found that an average annual water temperature on different depths in lakes can be represented by following regression equation:

$$T(z) = a_0 + a_1(72 - \varphi) + a_2 Z + a_3 \lg S + a_4 \left(\lg \overline{H}\right)^2 + a_5 h + a_6 \lg K + a_7 E\,, \tag{4}$$

where φ is latitude of a sampling station (deg); Z altitude (m); S area of lake (km^2); $\overline{H}$ its mean depth (m); h the depth at the point of measurement (m); K residence time (year); $E = S/\overline{H}$ is an openness factor. Parameters $a_0 - a_7$ for different depths are shown in the Table 3, the coefficients of multiple-regression correlations and standard deviations are also computed.

Table 3 Coefficients of multiple-regression correlations *(R)*, standard deviations of water temperature (ε) and parameters $a_0 - a_7$ for different depths (*z*) equation (4).

z, *m*	***R***	ε	Parameters							
			a_0	a_1	a_2	a_3	a_4	a_5	a_6	a_7
0	0,94	0,78	14,16	0,564	-0,0048	-0,12	-0,31	-0,004	0,095	-0,0058
2	0,93	0,78	13,52	0,554	-0,0048	-0,04	-0,31	-0,004	0,103	-0,0059
5	0,86	1,09	11,69	0,553	-0,0033	0,52	-0,66	-0,012	0,364	-0,0054
10	0,83	1,36	8,22	0,391	0,0025	2,14	-1,25	-0,035	1,663	-0,0049
15	0,86	1,09	5,70	0,227	0,0085	2,45	-1,45	-0,029	2,253	-0,0039
20	0,89	0,86	4,94	0,214	0,0097	2,25	-1,50	-0,020	2,141	-0,0049
25	0,92	0,70	2,78	0,261	0,0112	2,00	-1,39	-0,006	1,992	-0,0058
30	0,95	0,63	2,22	0,282	0,0115	1,72	-1,32	-0,000	1,934	-0,0059
40	0,97	0,53	1,73	0,280	0,0115	1,52	-1,11	-0,001	1,754	-0,0058

Change of parameters $a_0 - a_7$ with depth proves a successfully selected regression model. Their vertical distribution shows that zonal effects mostly influence the water temperature in upper layer of lakes. Correlation coefficients (*r*) between the water temperature on depths 0-5 m and latitude are 0.77 - 0.84. Notice that with increasing depth dependency of water temperature on φ drops down, but it increases on morphometric effects and water flowage. Increase of lake areas leads to the slight reduction of water temperature on depths 0 - 2 m (parameter a_3) and to essential rise of temperature at depths of 10 m and more in hypolimnion. If a mean depth in lakes increases, the water temperature on standard horizons (parameter a_4) decreases. Depth at the point of measurement (a_5) was used for taking into account heterogeneity of the average field of temperature in large deep lakes. For through-flow lakes, small increase of water temperature in the upper layer (0 – 2m) and considerable increase in the thermocline and hypolimnion is typical (parameter a_6). Vertically averaged profiles of the temperature distribution in some lakes, measured and calculated with use of the Eq. (4), are shown in Figure 3.

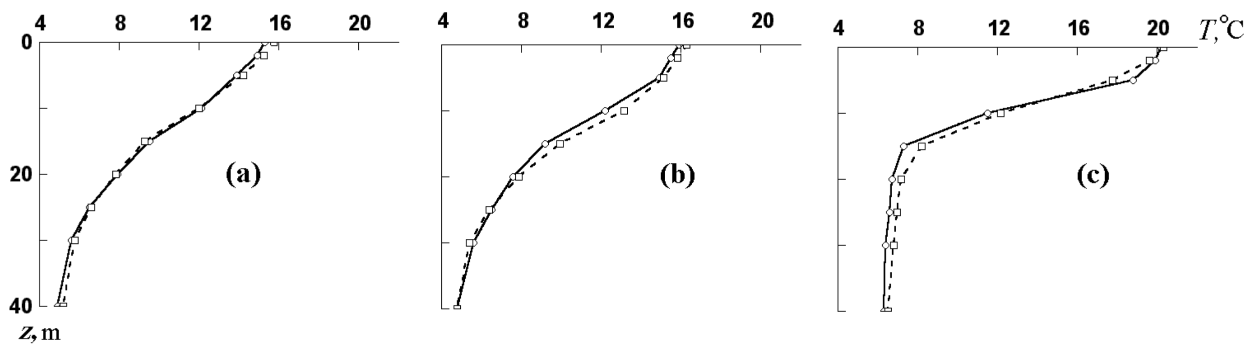

Figure 3. Comparison of the computed (dotted curve) and observed (solid curve) average temperature profiles for a) – Topozero, b) – Onego c) – Valdaiskoye lakes

Obviously, a simple regression model can not take into account all effects related to the seasonal development of the thermal structure in lakes. The main advantage of this model is it's ability to reconstruct a vertical distribution of the water temperature in lakes that is very important in certain application.

3.3. Annual cycle of the surface temperature in lakes

On the first stage, our purpose was to fit a specific function for each lake to describe the climatology of the surface temperature cycle with use of data observed. Function, which we use, is written as follows:

$$T(t,z) = b_0 + b_1 \left\{ 1 - \frac{1-\exp\left[(t-b_2)b_3\right]}{1+\exp\left[(t-b_2)b_3\right]} \right\} \cdot \left\{ 1 + \frac{1-\exp\left[(t-b_4)b_5\right]}{1+\exp\left[(t-b_4)b_5\right]} \right\}, \tag{5}$$

where *T(d)* is surface temperature (˚C); d time counted from 1st January (days); $b_0 - b_5$ are empirical parameters.

In our model, we consider the open-water period as time from ice melting in spring till ice formation in late autumn. To find parameters of the model for each lake that results in the lowest mean-squared error between the function and observed data, we used the Newton method. In Eq. (5) two parameters (b_0 and b_1) are related to the min and max function, two non-dimensional parameters (b_3 and b_5) are related to the shape of distribution (asymmetry and kurtosis), and two parameters are related to the dates of maximum growth in spring (b_4) and decrease in autumn (b_2) of surface water temperatures.

On the following stage, we investigated dependencies of model parameters simultaneously from zonal climatic effects, geometrical sizes of lakes, and water exchange. To solve this problem, we used values b_i for all lakes to get a simple expression, common for all parameters, with limited numbers of predictors. We found that the best regression equation is as follows,

$$b_i = a_0 + a_1(72-\varphi) + a_2 Z + a_3 \lg S + a_4 \left(\lg \overline{H}\right)^2 + a_5 \lg K + a_6 P, \tag{6}$$

where $P = \overline{H}/H_{max}$ is a capacity factor. Parameters $a_0 - a_6$ for calculating different model parameters b_i are shown in Table 4, where also multiple-correlation coefficients are placed.

We have established that latitude, area of lakes, and their mean depth mostly influence model parameters b_i and the average annual cycle of water surface temperature. Influence of altitude on the water surface temperature for the given sample of lakes is small, as all lakes are situated within a range 0-200 m. Notice that all model parameters b_i are connected to each other and changing one of them leads to the change of others. The minimal temperatures (parameter b_0) depends on the area of lakes mainly, and maximum temperatures (parameter b_1) from latitude. At the same time, velocity of temperature reduction during the autumn period (parameter b_3) is dependent mainly from the depth of lakes.

Table 4 Parameters a_0 - a_6 for Eq. 6 and multiple-correlation coefficients.

b_i	R	Parameters (Eq. 6)						
		a_0	a_1	a_2	a_3	a_4	a_5	a_6
b_0	0,958	-4,5963	-0,0311	-0,00144	0,984	-0,507	-0,242	-1,17
b_1	0,986	5,3717	0,134	-0,00149	-0,347	0,647	0,129	0,112
b_2	0,838	271,68	0,842	-0,0287	-3,863	0,138	-1,130	-5,09
b_3	0,941	-0,0429	0,00071	-0,00002	-0,00191	0,00922	0,00119	-0,0007
b_4	0,953	148,54	-1,718	-0,0000	2,662	11,02	1,607	-1,282
b_5	0,865	-0,0588	0,00139	-0,00003	-0,0026	0,00683	-0,00008	-0,0128

Curves for average daily surface temperatures (bold lines) resulting from the best fits to Eq. (5) along with 10-day-average observed data for these two lakes and parameters $b_0 - b_5$ calculated with Eq. (6) are shown in Fig. 4 (solid lines). Evidently, coincidence of calculated and observed profiles is remarkably good. Typical differences between observed and simulated water temperatures are about 0.27˚C. Such accuracy makes the equation (1) very useful for modelling a "typical" annual cycle.

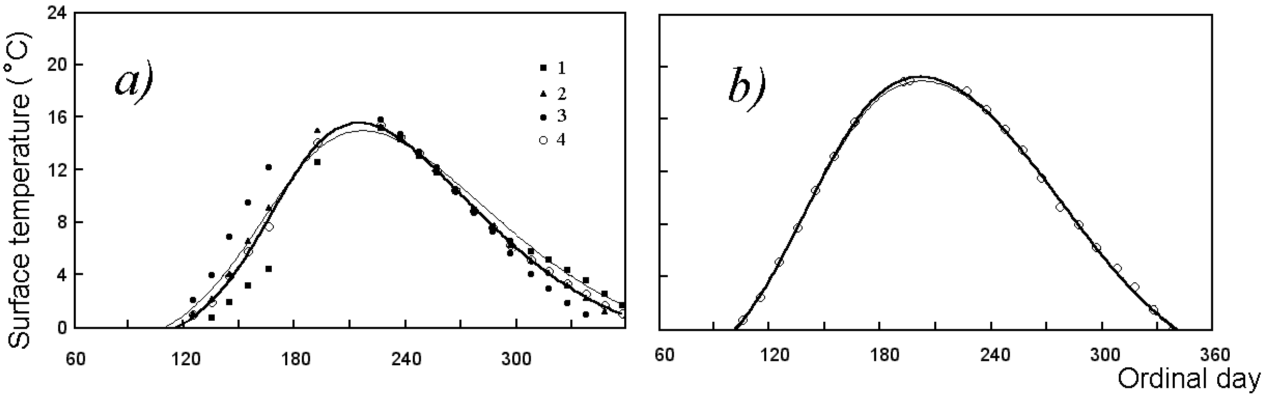

Figure 4. Model curves with best fits to equation 5 (bold lines) and calculation of parameters b_i on Eq. 6 (thin lines) for a) – lake Ladoga, b) – lake Glubokoye. Average 10 days surface temperature (1 – deep-water region, 2 – intermediate region, 3 – littoral region, 4 – all lake).

Figure 5 shows discrepancies between observed values of water temperature and those calculated with use of Eq. 5. The correlation coefficient is rather high (0.99), and a rms value is 0.70˚C. Such accuracy of our method makes it useful for modeling a typical annual temperature cycle for lakes where measurement data is short or completely absent. The method allows defining a surface water temperature for any date, using a limited number of initial parameters. It is effective compared with use of complicated numerical models that need long-term series of meteorological data (air temperature, humidity, wind velocity, cloudiness, solar radiation, etc.).

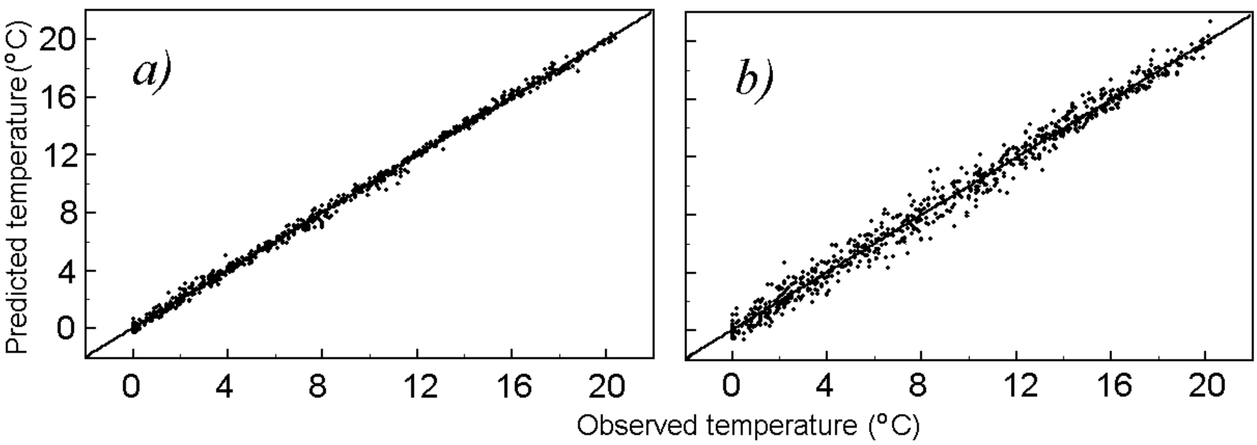

Figure 5. Scattering graph average surface temperature in 47 lakes a) – calculated values with best to Eq. 5 and b) – at calculation parameters b_i on Eq. 6.

3.4. «Biological summer»

The "biological summer" is defined here as a period when the temperature of the upper-layer water in lakes is above 10ºC. Relationships between characteristics of the "biological summer" and various geographic factors were estimated using annual 10-day averaged daily data on the water surface temperature in the lakes. The first step was to smooth them and calculate the daily temperature in accordance with the approximating function (5).

Step-wise regression analysis was performed to find out the weightiest predictors of the "biological summer" characteristics among geographical factors:

$$t_1 = -35 + 2{,}75\ \varphi + 11{,}2\ \lg \overline{H} + 1{,}3\ \lg S + 0{,}014\ Z, \quad (\text{rms} = \pm 3{,}4;\ \ R = 0{,}96) \tag{7}$$

$$t_2 = 395 - 2{,}15\ \varphi + 9{,}1\ \lg \overline{H} - 0{,}039\ Z - 0{,}89\ \lg S, \quad (\text{rms} = \pm 2{,}6;\ \ R = 0{,}95) \tag{8}$$

$$t_2 - t_1 = 432 - 4{,}95\ \varphi - 0{,}05\ Z - 2{,}2\ \lg S, \quad (\text{rms} = \pm 4{,}3;\ \ R = 0{,}97) \tag{9}$$

$$\int_{t_1}^{t_2} T(t,0)dt = 8485 - 103\ \varphi - 57\ \lg S - 1{,}1\ Z - 120\ \lg \overline{H}, \quad (\text{rms} = \pm 97;\ \ R = 0{,}97) \tag{10}$$

where t_1, t_2, $t_2 - t_1$ are the dates when the water temperature rises above/falls beyond 10ºC in spring, autumn and duration of the “biological summer”, respectively; $\int_{t_1}^{t_2} T(t,0)dt$ – total degree days with water temperature above 10ºC; R and rms are shown in brackets.

In equations (7-10), predictors are given in the order of decreasing weight. The factor most strongly influencing all characteristics of the “biological summer” is the geographic latitude, which is directly related to the solar radiation flux onto the water surface. According to determination coefficients (R^2), the proportion of variance of various parameters of the “biological summer” explained by the geographic latitude only is 0.65 to 0.84. For medium-sized lakes of Northwest Russia, the date at which the water temperature transgresses 10ºC grows by 2.8 days with each degree of latitude growth in spring, and decreases by 2.1 day in autumn. Total degree days throughout the “biological summer” fall by 103ºC with each latitudinal degree.

3.5. Response of the vertical thermal structure on climate variations

In stochastic models the water temperature is mainly related to the air temperature (Rogers, 1987; Blumberg, Di Toro, 1990; McCormic, 1990; Robertson, Ragotzkie, 1990). Dependence of the hypolimnetic temperature on the monthly-average wind velocity becomes apparent only in spring, and on the maximal daily wind velocity during the period of summer stratification. The air temperature is a key weather parameter, and its monthly average values are well simulated by the global climate change models compared to other meteorological parameters. Relation between the air temperature and that of water at different depths (0, 5, 10, 15, 20, and 25 m) was studied by the example of the Petrozavodsk Bay, Lake Onego.

The following freely available observational data collected by the Russian (USSR) Hydrometeorological Service were taken into analysis: the air temperature from the Petrozavodsk station and long-term water temperature measured along the raid vertical in the central part of the Petrozavodsk Bay (1958–1989). Exponentional smoothing of data on air and water temperatures was performed with Eq. 5. Determined empirical relationships allow calculating the water temperature in the Petrozavodsk Bay provided data on the air temperature annual course is available. This is essential in estimating seasonal variations of the vertical thermal structure of the bay under different scenarios of the regional climate change or in recovering missing data. The developed model was approved against data on the seasonal variations of the vertical bay thermal structure in 2004-2006.

The observational data analysis reveals that deviations of the monthly average air temperature of 3-5°C during the period of the maximal heating lead to analogous changes of the water temperature in the upper 5-m layer. Within the thermocline, dependence of the water temperature on the air temperature basically decreases. At the 10-m depth these changes comprise of 1-2°C, and at 15-m depth and deeper are close to zero. In the bottom (20-25 m) layer weak reverse dependence (changes in fractions of °C) can be noticed. In the thermocline and hypolimnion, relation between dates and rates of changes of the air and water temperatures during spring warming and autumnal cooling can be traced. This is in a good accordance with results of studies performed in the Great American Lakes: Ontario, Erie, and Michigan (Rogers, 1987; Blumberg, Di Toro, 1990; McCormic, 1990).

4. CONCLUSIONS

Based on the analysis of long-term data obtained in different-type reservoirs of North-Western Russia and Finland, the stochastic models to simulate the thermal structure of poorly studied or newly constructed water reservoirs are developed. They allow efficiently calculate the annual course of the surface water temperature and the vertical thermal structure during maximal warming for any lake on the basis of existing geographical information (latitude, altitude above sea level, object geometry, residence time). By virtue of their simplicity, the models can be used as a tool not only for hydrophysists but for a wider circle of experts (chemists, biologists, ecologists) in solving basic and applied problems.

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