Changes in hydrological regime of the large Russian freshwater lakes under global warming

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Abstract — Climate change is expected to affect lakes which are the important freshwater resource. Eight largest lakes contain about 96% of water resources of all lakes over Russia territory. Modern environmental and climate change, caused by natural and man-made factors, drives to important changes in hydrological regime of lakes. The response of the individual lakes to these changes depends on the magnitude of regional climate change.

Water balance, lake level, thermal characteristics, ice events and ice thickness have been studied for largest Russian Lakes Baikal, Ladoga, Onega, Ilmen, Chudsko-Pskovskoe, Chany, Taimyr and Khanka based on the data of observation.

The lakes' level is a reliable moisture integrator, reflecting water resource within a vast territory, and that is why it can be used as indicator of modern climate change. Three of studied lakes show negative water level trends (Ladoga, Onega and Chudsko-Pskovskoe) and Lake Chany manifests a positive one.

Important consequences for aquatic ecosystems and human activities on lakes have modern changes in lake ice with progress of warming. All studied lakes show the tendencies to earlier date of ice cover break-up and decrease in duration of ice cover on lakes. Maximal ice cover thickness had the most pronounced response to climate warming during the last decades.

Keywords — Climate change, response of lakes to global warming, water level, lake ice

1 INTRODUCTION

The lakes of Russia are an important source of fresh water and therefore there is no way to overestimate their significance for population and economy. There are 34 lakes with water surface exceeding 250 km^2 in Russia. There are only five saline and brackish lakes among them.

Anthropogenic influences on lakes environment, building dams and waterside structures and regulating river flows as well as current climate change have resulted in considerable changes of hydrological regime of lakes including water budget, lakes' level, water temperature and ice.

The issue of change of lakes hydrology under the impact of anthropogenic pressure and climate changes makes the subject of scientific researches and discussions for scientists of different fields of science including hydrologists, climatologists and hydrobiologists.

2 LAKES OF RUSSIA

Among 35163 lakes with water surface more than 1 km^2 over Russia there are 97 lakes with water surface more that 100 km^2 and 8 largest lakes with water surface larger than 1000 km^2 (Fig.1).

Total water surface of the large lakes makes up about 74 000 km^2 and it is comparable with total square of small lakes (from 1 to 10 km^2) [1]. About 96% of total fresh water of all lakes over Russia territory is contained in eight largest lakes with water surface more than 1000 km^2 and 23615 km^3 (95,2%) of fresh water of this volume gives Lake Baikal.

Fig. 1. Lakes with water surface larger than 1000 km^2

Characteristics of the largest Russian lakes are shown in Table 1. Lakes Ladoga, Onega, Chudsko-Pskovskoe and Ilmen are great fresh water lakes of European territory of Russia (ETR). The catchment area of Lake Ladoga includes catchments of two other Lakes – Onega and Ilmen (Fig. 2). The world's deepest and oldest Lake Baikal is among four large lakes of the Asian part of Russia and other lakes are Lakes Khanka, Taimyr and closed brackishwater Lake Chany.

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Table 1. The largest lakes of Russia [1] (* Total area; **Area belonging to Russia)

Lake	Area, km^2		Maximal depth, m	Volume km^3
	Watershed	Water surface		
Baikal	571000	31722	1642	23615
Ladoga	276000	17872	228	838
Onega	62800	9693	120	292
Taimyr	43920	4560	26	12.8
Khanka	20100* 18400**	4190* 3030**	10.6	18.5
Chudsko-Pskovskoe	47800* 27917**	3555* 1990**	15.3	25.07
Chany	23600	1294	8.5	2.58
Ilmen	67200	1100	4.25	2.85

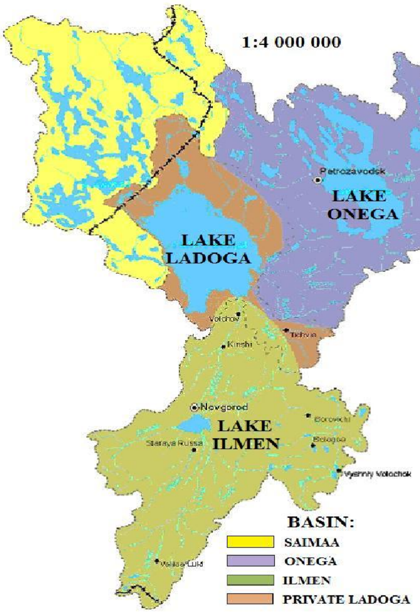


Fig. 2. Lake Ladoga drainage basin [2].

3 RESENT CLIMATE CHANGE ON THE TERRITORY OF RUSSIA

Climate change as a part of global environment changes becomes apparent on the different levels from global to local (landscape belts, countries, river's and lake's basins) during last decades. Lake' hydrological regime is determined by many interconnected factors including climatic ones.

Since the late 19th century the mean annual air temperature has increased by about 1.29°C for the Russian territory that surpasses the global annual air temperature increase [3].

The mean annual surface air temperature increased by 0.44°C in the period 1976-2010 [4]. 2007 has manifested to be the warmest year followed by 1995 and 2005 for Russia.

Anomalies of mean air temperatures in 2010 (against 1961-1990 normals) were positive for spring, summer and autumn. Summer in Russia was warmest for the period 1939-2010 with the temperature anomaly by 1.8°C. In winter cooling has taken place in Western and Central Siberia and in European part of Russia [4,5].

Warming was more evident in European territory of Russia including the basins of Lakes Ladoga, Onega, Ilmen and Chudsko-Pskovskoe and in Siberia with the highest growth of temperature. The annual warming trend for the Ladoga and Onega Lakes basins has been shown to be 0.5°C/decade, for the Lakes Ilmen and Chudsko-Pskovskoe basins by 0.6°C/decade in the period 1976-2010 (Fig.3). Warming was most intensive here in winter with trend up to 1.0°C/decade.

Trends about 0.2-0.4°C/decade were characteristic for Lake Baikal and Lake Khanka catchments during all seasons of the year. The larger trends was observed in Taimyr Lake basin in Arctic zone (from 0.4°C in winter till 0.8°C/decade in spring&autumn) [5,6,7].

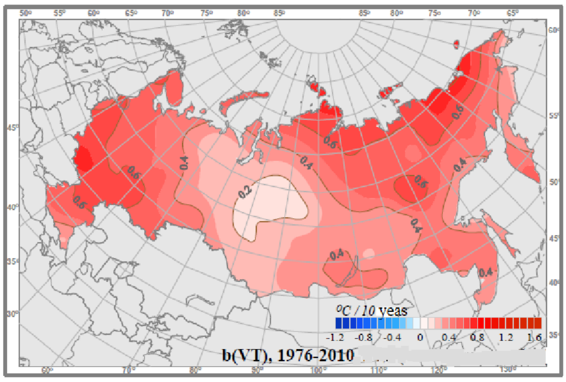


Fig. 3. Linear trend coefficients (°C/10 years) in annual temperature time-series (1- to 5-percent significance level). 1976-2010 [5].

The process of warming is evaluated in the growth of the period of air temperature higher than 0°C and 10°C in spring up to 10-12 days. An increase of air temperature also comes to earlier dates of a persistent transition of daily temperature through 0°C and 5°C in spring up to 10-12 days and to earlier melting of lake ice. An empirical data shows that the number of days with extremely low temperature decreased and the coldest month of year moves from January to February, December and even to November in the North-West and Central Russia Regions [7]. The minimum air temperature was increased by 0.8-1.4°C/10 years in the most part of Russia. The number of thaw days increased in cold period as a result of the growth of number of days (2 days per 10 years) with abnormally high air temperature in 1976-2006. Consequently the number of frosty days has been decreased of 4-5 days per 10 years for the same period [8].

Precipitation changes have more complicated spatial distribution than air temperature due to their variability. Changes in precipitation totals have not showed any clear tendency for last decades over the watersheds of study lakes. It was found that annual precipitation averaged over Lakes Ladoga, Onega and Ilmen drainage basin increased with trend 5%/decade for the period 1976–2010 against 1961-1990 normals. However, a decrease in annual, summer and autumn precipitation totals was observed in the basins of Lakes Baikal, Khanka, Taimyr and Chany [6,7,9].

4 HYDROLOGICAL REGIME OF LAKES UNDER THE IMPACT OF GLOBAL WARMING

The response of the individual lakes to climatic forcing depends on the magnitude and space-time structure of regional climate change and the specific geomorphologic characteristics of lakes [10].

The instrumental observations of lakes hydrological regime started in Russia in the middle of 19th century. The earliest data are dated to the 1859 for Lake Ladoga, which are the largest European Lake. Those largest Russian Lakes as Baikal, Onega, Ilmen, Chudsko-Pskovskoe and Khanka have less long period of observations: Lake Onega – since 1884; Lake Baikal - since 1901; Lake Chudsko-Pskovskoe – since 1907; Lake Ilmen – since 1916. Records of water level have been started in 1932 on Lake Khanka and since 1934 on Lake Chany, and the later, since 1960 on Lake Taimyr.

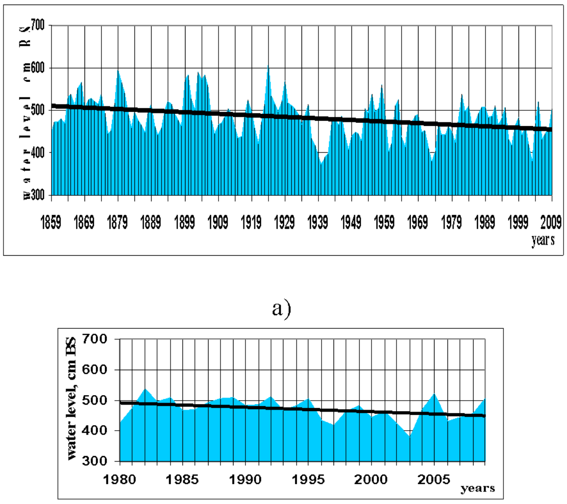
4.1 Water level

The analysis of lakes water level under climate changes during recent decades was carried out against the background of level variation during observation period [10,11].

The catchment area of Lake Ladoga includes catchments of two Lakes – Onega and Ilmen, but geomorphologic peculiarities of lakes and huge size of each of their basins (Table 1) need to make special research one by one.

The mean annual amplitude of water level of Lake Ladoga is 0.69 m. The highest annual level was observed in 1924 (6.2 m) and the lowest in 1940 (3.64 m) [11].

The analysis of fluctuations in mean annual water level of Lake Ladoga revealed statistically significant negative trend for 150 year observation period, and it accounts for 4 cm/decade. The rate in water level decrease has accelerated for the recent 30 years and it makes up 14 cm/decade for 1980-2009. Both trends are statistically significant at 95 % level. Fig. 4 shows the long-term changes of mean annual level of Ladoga Lake for the period of observation (a) and for the last 30 years (b).



a)

b)

Fig. 4. Water level of Lake Ladoga and linear trends for the period of observations (a) and for the 1980-2009 (b).

The second large lake of Europe is Lake Onega. Hydrological regime and water level of Lake Onega developed in natural conditions before Verhne-Svirskaya Hydropower Station startup in 1951. Water level variations of Lake Onega differ drastically from those of Lake Ladoga within interdecadal period. Negative water level trend of lake for the 1884-1951 changed into positive trend of 4 cm/decade from 1952 presenting background to negative tendency during last 30 years.

Lake Chudsko-Pskovskoe is ranked the third large lake in Europe in terms of surface. The water level within observation period manifested to have statistically significant negative trend of 5 cm/decade and makes up -12 cm/decade for 1980-2009.

The catchment of Lake Ladoga comprises Lake Ilmen. It differs considerably from other large lakes by its level regime. Lake Ilmen's uniqueness consists in considerable amplitude of water level variation. It is second to none in the country as its amplitude accounts for 7.5m.

The watershed area of Lake Ilmen is 60 times large as its water surface (Tables 1 and 2). The same index of Lake Ladoga makes up 15 times, the one of Lake Onega does 5 times. Lake Ilmen is shallow lake located in lowland and so, water level fluctuations during the seasons change its surface area more than by three times, and water volume by 12 times (Table 2).

Table 2. Morphometric characteristic of Lake Ilmen.

Level	Level, m BS	Volume km^3	Water surface m^2	Mean depth m	Maximal depth m
Low	16.00	1.01	660	1,55	2,25
Mean	18.00	2.85	1100	2,60	4,25
High	23.50	12.07	2230	5,40	9,75

Mean annual water level of Lake Ilmen demonstrated cyclical fluctuations. Duration of overall cycle of water level fluctuations makes 30-40 years. From 1994 there are observed short-term phases of low and high standing of water level by duration from 2 up to 5 years.

The behavior of water level of Lake Baikal differs from one of the other large Lakes Ladoga and Onega. Mean annual level of Lake Baikal have no statistically significant trends within natural regime (1901-1951) or within the last 30 years. The period 1959-1980 is marked by the Baikal water level decrease from its high in 1964 to its low level in 1980. Water level of 1964 was maximal for all time-series. The low water levels of 1980, 1981, 1997 and 2003 were 80 cm higher than minimums registered in 1920-s as water level is artificially regulated. Since 2001 water level is regulated in range of 1 m.

Lake Chany situated in semiarid zone (steppe area). Lake is closed and its water level exposes to considerable variations (up to 5 m). Total level increase equals to 2 m within the period from the early 1900 to 1914.

A decrease of 3 m was registered for 1914-1937 years. Then took place a sharp raise of the lake water level equals to 1.98 m within 1937-1950 which gave place to decrease of 1.84 m by 1972. Further decrease of water level was stopped by Yudinsky Stretch abjunction. A statistically significant positive trend equals to 30 cm/10years was observed within 1981-2000.

4.2 Water balance

The most complete study of mean annual water balance of the largest Russian lakes and its variations within the last decades was carried out by T.P. Gronskaya and published in monograph “Water resources of Russia and their use” [1,12].

The total income to 8 largest Russian lakes mainly consists of water inflow by rivers (205 km^3 /year) and precipitation to water surface (37.8 km^3/year). The outcome part includes river outflow and evaporation (32.6 km^3/year). For endorheic Lake Chany the income to lake is spent to evaporation only.

Patterns of water balance differ significantly for each specific lake. The inflow is the main part of income of Lake Ilmen (96.3%) but it gives smallest part of income for the Lake Chany. The most part of income to closed Lake Chany and Lake Khanka gives precipitation (60% and 55% respectively). The outflow makes up almost the entire outcome for the large lakes except closed Lake Chany with evaporation making up 100% of its balance outcome.

Assessment of climate change influence on water balance of the largest Russian lakes was made for 7 lakes (except Lake Taimyr) [12].

Comparison of mean values of water balance components for the period before 1980 and for the 1980-2005 showed it significant changes for Lakes Baikal, Ilmen, Chudsko-Pskovskoe.

Increase in inflow (14%), in precipitation (30%) and evaporation from water surface (up to 50%) was registered during the last 25-30 years for Lake Baikal as compared with the period before dam building in 1958. Higher water resources of rivers have come to increasing inflow to Lakes Ilmen and Chudsko-Pskovskoe for the recent years. Air temperature growth caused surface water temperature raise and increase in evaporation from water surface for Lake Ilmen and Lake Baikal more than 30% and 10-15% for Lakes Khanka, Ladoga and Onega.

4.3 Water temperature and lake ice

All observed characteristics of surface water temperature regime demonstrated the response to changes in air temperature over lakes basins. The water temperature change directly affected lake ice.

Study shows the largest increase of mean monthly water temperature in Lakes Chany and Baikal during June and July (0.5°C/decade) and about 0.3°C/decade in lakes of European Russia. Maximal water temperature did not change considerably for the Asian lakes (less than 0.3°C) and did not change in European lakes.

In average dates of transition of water temperature through 4°C and 10°C in spring move to earlier dates on 5-7 days. In autumn these dates move to later ones for Lakes Baikal, Chany and Khanka and move to earlier ones for Lakes Onega and Ladoga as some cooling was observed in autumn partly (in November) in the territory of European Russia.

Duration of complete ice cover period and maximal ice thickness vary in large ranges depending on lake location and it’s morphometric characteristics.

The duration of ice cover may last about 120 days (Lake Ladoga) to 145 days (Lakes Onega, Ilmen, Baikal, Khanka). The longest ice duration noted on Lake Taimyr up to 271 days [13].

Considerable influence of lakes’ morphometry is evident from comparison of Lakes Ladoga and Onega ice characteristics. Mean ice cover duration of shallower Lake Onega is near 20 days longer, and ice cover thickness is 5 cm more [14].

Temporal trends have been discovered towards changes in the duration of the complete ice cover and maximal ice thickness on the background of a long-term variability of the study characteristics.

All studied lakes show the tendencies to earlier date of ice cover break-up and decrease in duration of ice coverage in lakes. An analysis of lake ice events has shown that the duration of ice cover became 10-12 days shorter.

Maximal ice cover thickness had the most pronounced response to climate warming in winter time during the last decades. All studied lakes exhibited the tendency to decrease of maximal ice cover thickness after 1980 by 5-10 cm (Fig.5) [14, 15, 16].

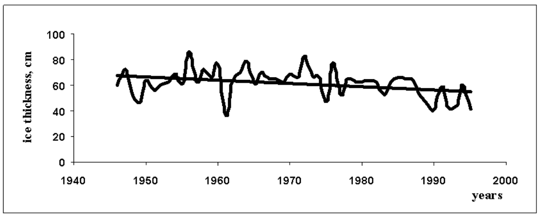


Fig. 5. Maximum thickness of the ice cover (cm) on Lake Ilmen.

5 CONCLUSIONS

Large lakes are very sensitive natural indicators reflecting both long-term and short-term climate changes.

The above mentioned tendencies of current climate change, to some extent, should explain the trends in mean annual lake level time series as integral index of water and climate resources fluctuations. Variations in air temperature, precipitation, and other meteorological parameters cause direct changes in water balance, lake level, thermal characteristics, ice events and ice thickness, as well as hydrochemical and hydrobiological regimes, and entire lakes ecosystem.

Changes of hydrological regime of lakes can have both positive and negative consequences for economic and social life. Decrease of lakes' level, as a rule, has negative after-effects. First of all it is connected with deterioration of water supply. High lakes' level can have both positive and negative consequences. Thus, it is favorable for water supply of the population, an agriculture, water-power engineering, etc. But it can result in flooding settlements and agricultural lands, to bogging and degradation of a soil cover [17,18].

Ice phenomena on lakes are very sensitive to the global warming. The most pronounced changes are characteristic for the maximal ice cover thickness.

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