Climatogenic Dynamics of Lakes in the Russian Part of Daur Steppe According to Earth's Remote Sensing Data

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***Abstract* – The use of Earth's remote sensing methods is one of the effective methods of monitoring. It allows estimating the areas of the water line of lakes and their quantity over vast and inaccessible territories. An analysis of the dynamics of basinal lakes in the Daurian steppe Russian part from 1989 to 2016, performed using a modified normalized differential water index MNDWI, showed that the maximum number of lakes was observed in 1992 (1245 pcs.) with a total area of water surfaces amounted to 1088 km^2. Both indicators reached the lowest point in 2016, while the total area of lakes decreased by more than 70% towards the maximum and amounted to 319.4 km^2, and their number had fallen by 10 times. The revealed changes resulted from the climatic factors influence. This proves by significant correlations between the characteristics of lakes and meteorological parameters.**

Keywords* – *basinal lakes; Dauria; moisture content; spectral water index; identification; monitoring.

I. INTRODUCTION

Intergovernmental Expert Group on Climate Change estimates that the average global temperature of the earth over the period from 1906 to 2005 has increased by 0.74 °C [1]. Since the 1970s, climate warming has noticeably accelerated. According to the survey, the average rate of the globe and the land warming for the period from 1976 to 2012 in the Northern Hemisphere is 0.166 and 0.328 °C/10 year, respectively, while during the period 1901-2012 – 0.075 and 0.105 °C / 10 year [2]. The beginning of the XXI century remains the warmest 12-year cycle in the instrumental observation period [3]. According to observations and model calculations, the climate of Russian territory is more sensitive to global warming than the climate of many other regions of the globe. The temperature in Russia is growing much faster than global: 0.45 °C / 10 year, and it is especially fast in the polar region, where the growth rate reaches 0.80 °C / 10 year [4]. In Russia, the annual precipitation for the period during 1976-2012 is positive. On average, in Russia it is 0.8 mm / month for 10 year [2].

An increase in temperature is accompanied by an increase in evaporation and a decrease in runoff, which leads to a decrease in humidity. That primarily affects the ecological state of the intracontinental areas; in particular, the lakes undergo significant changes. Consequently, basinal lakes that do not have surface discharge or underground drainage to adjacent catchments, whose water flow comes from evaporation, are sensitive indicators reflecting climate variations [5–13].

Since the basinal lakes are confined mainly to arid steppe and forest-steppe territories, their monitoring allows analyzing current climatic tendencies, in particular, the overall territory humidity, which in arid zones determines the regional natural and economic systems functioning.

The Earth's remote sensing (ERS) data usage is effective and often the only source of objective and relevant information for analyzing the dynamics of changes in the water content of basinal lakes in vast and inaccessible areas. Mathematical methods for processing multispectral images of the Earth's surface from satellites provide information on the spatiotemporal parameters of various objects, including water [14-18, etc.].

The objects of the study are the lakes located on the Daur steppe in Russian part. Geographically, this territory occupies the Onon-Torei high plain [19]. The average height of the relief of the study area is 600-800 m. [20]. Zun-Torey and Barun-Torey are the largest lakes located on the studied territory. In high-water periods, their areas reach respectively 300 and 580 km^2 at depths of up to 7 and 5 m.

Eastern monsoon and dry southern air masses have paramount importance, since the location of the ridges bordering the Onon-Torei plain protects its territory from the

Atlantic and Arctic air transfers. The climate is sharply continental with negative average annual air temperatures (-0.1 - -2.0 ºC), with small average annual precipitation (300-370 mm), a short freeze-free period and high sunshine duration.

The territory is characterized by a pronounced cyclical alternation of wet and dry periods. Moisture cycles determine the dynamics of changes in the water bodies' area, up to and including the complete disappearance during dry periods. The most significant is the intrasecular cycle lasting about 30 years [21].

II. METHODS AND MATERIALS

The analysis of the dynamics of the water line area and the number of lakes was made on an area of 22,161.1 km^2 in a transboundary area located within the Russian part of the Daur steppes (Fig. 1)

Fig. 1. Research area and location of meteorological observing stations used

Multispectral images of Landsat TM, ETM + and OLI spacecraft (http://earthexplorer.usgs.gov/) [16] for the period from 1989 to 2016 were used to identify water surfaces from May to September. The spatial resolution of images is 30 meters; the frequency of shooting is 16 days. For each year, the best picture was selected with a minimum cloud cover. The method of working with multispectral images included the following processing steps: preliminary processing of space data (radiometric calibration and atmospheric correction), obtaining spectral index images, highlighting the water bodies under study. The water line extent and the number of lakes was determined using a modified normalized difference water index [17-18], as it was proved before that, compared to other spectral indices, MNDWI has greater accuracy in decoding water surfaces in the studied region. The mean root square error is less than 0.08 km [15]. When calculating the MNDWI, the combination of channels of the green visible channel Green (0.525-0.600 μm) and the near-short-wave infrared channel SWIR (1.560-1.660 μm) is used, MNDWI is calculated using the formula [22]:

$$MNDWI = (Green – SWIR) / (Green + SWIR).$$

Processing of images and calculation of water indices were performed using the tools of Image Classification and Spatial Analyst ArcGIS 10.

The perennial changes in the number of lakes and the their water line extent are mainly determined by the weaher and climatic conditions of the warm period of the year (May-September), therefore the average monthly data on air temperature and precipitation for May-September were analyzed according to observations of 4 Transbaikal Hydrometeorology and Environmental Monitoring Department meteorological stations (Aksha, Borzya, Nizhny Tsasuchey, Solovyevsk) (Fig. 1), which located near the study area for 60 years (1957-2016). In order to estimate the parameters of aridity and humidity for the same period, the hydrothermal G.T. Selyaninova coefficient (HSC) and the D.A. Pedya index (SI) were calculated.

The climatic norm is calculated for a 30-year base period (1981-2010), which is recommended by the World Meteorological Organization [23].

Climate change tendencies were identified by calculating and analyzing linear trends. Trends in time series were calculated using the least squares method. The evaluation of their statistical significance was performed using Student's criterion at a significance level of α = 5%

III. RESULTS

The dynamics analysis of the lakes characteristics, performed using the water index MNDWI for the period from 1989 to 2016, revealed that the maximum number of lakes was observed in 1992 (1245 pcs.) with a total area of their water surfaces of 1088 km^2 (Fig. 2). There has been a significant decrease in the studied parameters since 1993; their dynamics is expressed by a negative trend at a 5% significance level. Both indicators reached the minimum values in 2016, while the total lakes extension decreased by more than 70% relative to the maximum and amounted to 319.4 km^2, and their number – in 10 times.

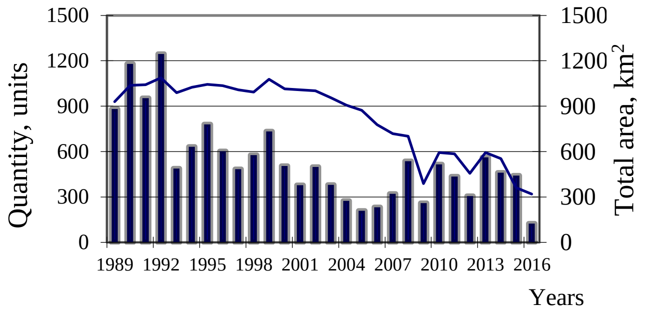

Fig. 2. The change in the number and total area of basinal lakes of the studied territory for the period from 1989 to 2016.

According to the water surface of the lakes extension [24], ponds (0.001-0.01 km^2) p total area [illegible] y area – 67% of total amount, and very small lakes (0.1-1.0 km^2) - 27%. A minor, up to 5%, number are small (1.0-10 km^2) lakes. The average (10.1-100 km^2) and large (100.1-1000 km^2) categories are divided into two lakes: Khara-Nor and Nozhii and Barun-Torey and Zun-Torey, respectively.

During the study period in different years, there were from 77 (2016) to 965 (1992) ponds. The number of very small lakes ranged from 34 (2016) to 258 (1990). Small lakes ranged from 11 (2016) to 38 (1990). The two lakes were included in the medium category, but in 2009 and 2012, due to the reduction in area, the Barun-Torey Lake fell into this category.

Analyzing the changes in the number of lakes it appears that for the period from 1989 to 2016 their dynamics is characterized by a negative trend. A marked decline in the number occurred in 1993 due to the ponds, when their number dropped from 965 to 285 pieces. The number of very small lakes had been decreasing since 1992, and the number of small lakes had only halved since 2002 (from 33 to 18).

According to the lakes total water line area, the distribution was as follows: large lakes - 80%, small - 9%, very small - 6%, medium - 4% and lakes occupy 1% of the total area of lakes.

Among the lakes under the study, the greatest interest is Barun-Torey, which is the largest and one of the most examined lakes in the studied territory and in Transbaikal. Historical and modern data confirm the periodic high water and drying up of the Barun-Torey Lake with different duration of cycles [25]. Studies on the change in water level for the period from 1965 to 2009, performed in the work of V.A. Obyazov [12] indicated that in 1965 the lake level was the highest since the beginning of the century. In subsequent years, the level of Barun-Toreya decreased and reached a minimum in 1982 and 1983; in 1984 it began to increase again. The maximum level, which became the highest level of the twentieth century, was noted in 1998. The subsequent decrease in the level was completed by 2009 with an almost complete drying of the Barun-Torey Lake.

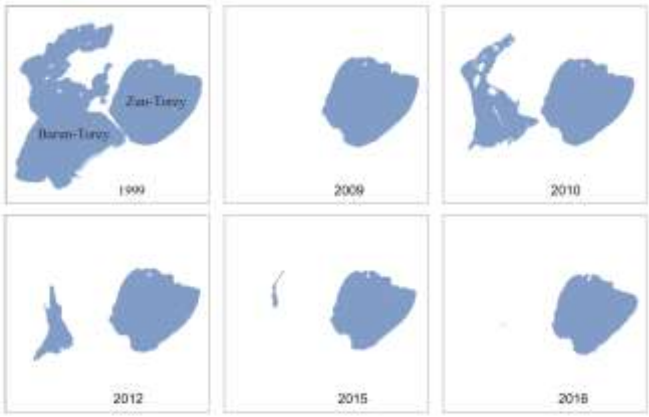

Fig. 3. The change in the area of the water line of Barun-Torey Lake and Zun-Torey Lake according to the results of Landsat satellite imagery decoding using MNDWI water index.

The dynamics of the water lane depicted in satellite imagery, performed for the period from 1989 to 2016, is consistent with the data on the level change. The maximum value of the area - 557.8 km^2 - was in 1999 (Fig. 3), then, with the beginning of the new arid phase, the size of the lake decreased and in 2009 it dried out completely. In 2010, the area of the Barun-Torey Lake recovered to 180 km^2, which is 2 times less than its average area over the study period. The next decrease in the water surface of the lake to critical values – to 5.5 and 0.1 km^2– was observed in 2015 and 2016, respectively.

IV. DISCUSSION

According to the climatic analysis, based on an averaged data from 4 meteorological stations, for the period from 1957 to 2016, the temperature of the air during the warm period (May-September) is characterized by a reliable positive linear trend at a 5% significance level, which was 0.4 °C / 10 year. The average temperature variations were from 13.2 (1987) to 17.2 °C (2007) (Fig. 4). Furthermore, since 1999, there has been a significant increase in temperatures. Throughout this period (up to 2016 inclusively) there was an excess of the climatic norm (14.8 °C) calculated for the period 1981-2010, the exception was only 2003, when the average temperature of the warm period was 14.1 °C. At the same time, the precipitation sum of the warm period during 1999-2016 years is characterized by negative anomalies (Fig. 5). During this period, precipitation did not exceed the climatic norm of 281 mm, and in 2004 and 2007 decreased to 151 and 165 mm, respectively. The exceptions were 2010, 2008, 2012 and 2013.

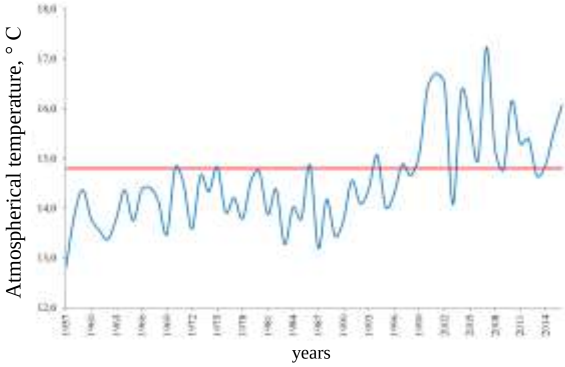

Fig. 4. Perennial changes in the average air temperature of the warm period (May-September) according to an averaged data from 4 meteorological stations. The red line shows the perennial climatic norm.

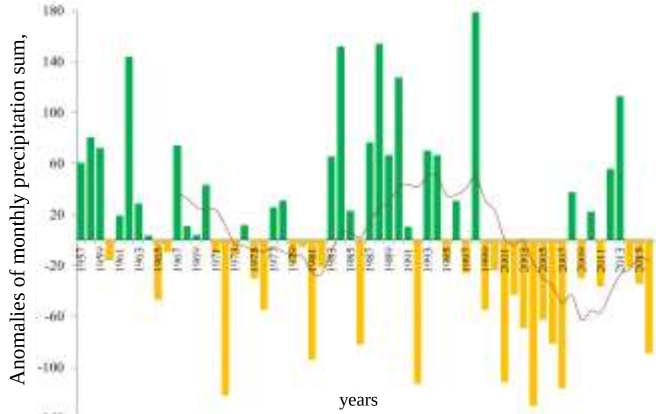

Fig. 5. Perennial changes in the amount of precipitation of the warm period (May-September), according to an averaged data from 4 meteorological stations.

Following the subtractive cumulative curves of the amounts of precipitation, 2 quasi-thirty-year cycles are clearly distinguished in the territorial humidity regime, where the period from 1955 to 1963 is characterized by precipitation above normal, then from 1964 to 1982 the dry phase follows, and from 1983 the wet period begins again, which lasted until

1998, and from 1999 a new arid phase begins [21]. The same conclusion is confirmed by the calculations made in terms of the study. According to our data, the beginning of the wet period of the new climate cycle began in 2011.

Using the correlation analysis, at a significance level of α = 5%, a positive reliable relationship was established between the number of lakes in the study area and precipitation (r = 0.37) and the hydrothermal G.T. Selyaninova coefficient (r = 0,43) and negative with temperatures (r = -0,60) and the aridity D.A. Pedya index (r = -0.58). Cross-correlation analysis revealed that significant relationships with the studied climatic characteristics are noted not only for the current year, but also for 1-5 previous years. The relationship between the total water surface extension and meteorological parameters is noted only after 4-6 years, which is also confirmed by reliable correlation values.

The calculations results confirmed that the dynamics of the amount and total water line area of basinal lakes on the Russian part of the Daur steppe, detected using the modified normalized differential water index MNDWI, is due to the climatic factors influence. The last arid phase of the climatic cycle coincided with an increase in temperatures of the warm period, which led to increased evaporation and a significant reduction in the number and total lakes extension.

The number of lakes is a more dynamic indicator. First of all, the lakes with the smallest area runs dry – ponds and very small lakes, given that they make up 97%, their drying leads to a reduction in the quantitative indicator, but due to their small size, this almost does not affect the change in the total area of the water surface in the study area. The total area changes later; it is more associated with the drying out of large lakes. For basinal lakes, the size of the current year is a consequence of the liquid water content nature over the past years, a decrease in size may occur in the high-water year if this was preceded by a series of low-water years, and an increase in low-water if this low-water year is observed within the high-water period.

As the dry phase in the climate cycle in 2011 ends and the reaction of the lakes lags, the recovery of the lakes should be expected in the coming years.

V. Conclusion

The results of this study indicate that the use of remote sensing methods allows obtaining information on the spatial and temporal parameters of lakes and their morphometric characteristics in vast and inaccessible territories with great accuracy and in a short time. Analysis of the basinal lakes dynamics, which are sensitive indicators of climate change, plays an important role in solving fundamental and applied problems of hydrology and climatology.

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