Monitoring long-term variation in level of lakes Issyk-Kul and Chatyr-Kul based on measurements with altimetry instruments and optical images of satellites.

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Monitoring level of Lake Issyk-Kul

Observations of changes in the level of Issyk-Kul have a long history and are represented by the results of instrumental measurements since 1927. Currently, these observations are carried out by the Kyrgyz Hydrometeorological Service (KHM) by directly measuring the lake's water level. However, since 1993, with the advent of altimetry satellites, it became possible to determine the lake level based on the results of their measurements. Figure 1 shows the results of measurements of the long-term variation of the level of Lake Issyk-Kul, both according to KHM data, in the Baltic height system (BSH), and satellite altimetry with height systems: EGM 2008 (USDA), EIGEN-6C-static (GFZ) .

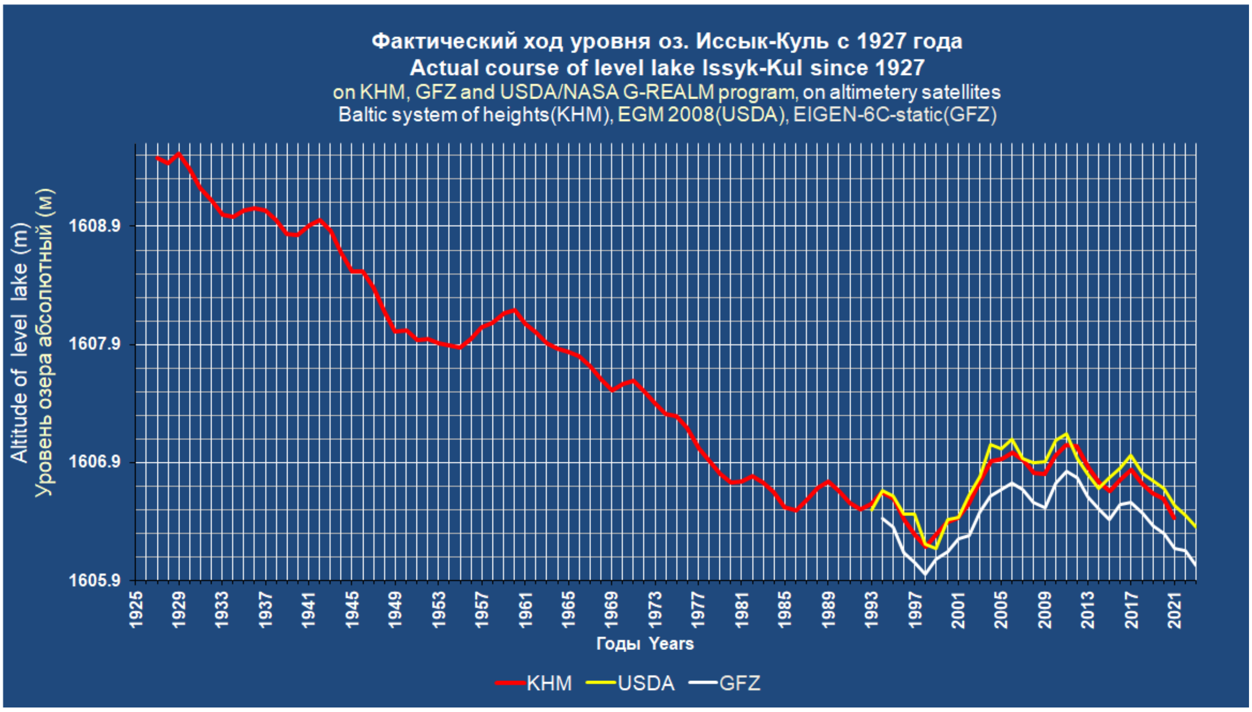

Fig. 1 Changes in the level of Lake Issyk-Kul according to instrumental measurements of the KHM and satellite altimetry for the period 1927-2023.

In this case, to analyze changes in the level of Lake Issyk-Kul using satellite data, the results of processing primary radar altimetry satellite information obtained by the USDA (U.S. Department of Agriculture) /NASA/SGT/UMD group, based on data from the AVISO data center at CNES and the NASA Physical Oceanography DAAC (Lake USDA/NASA G-REALM program at https://ipad.fas.usda.gov/cropexplorer/global_reservoir/). As well as the results of processing satellite information obtained by GFZ (Deutsche GeoForschungs Zentrum, Tilo Schöne, tschoene@gfz-potsdam.de) from the CAIAG Sensor Data Storage System (SDSS, http://sdss.caiag.kg/sdss/index.php?&page=measure_page). In both cases, In both cases, were used measurements from the “Topex/Poseidon” (Nasa/Cnes 1992-2002), “Jason 1, 2, 3” (Cnes/Nasa/Eumetsat/Noaa, 2002-2008; 2008-16, 2016 – present), “Sentinel 6” (ESA/ Eumetsat/EU/ Cnes/ Noaa/Nasa/JPL, 2016-present). Since the beginning of 2021, lake levels have been measured by the “Sentinel 6” satellite, and until March 2022, data from the “Jason 3” satellite was also used. The time range for using data from different radar satellites to measure the level of Lake Issyk-Kul is shown in Figure 2. Satellite tracks or trajectories on the earth's surface, along which absolute altitude is measured, cross the lake in the submeridian direction, as can be seen in Figure 3, for the case of the “Sentinel 6A” satellite (https://www.altimetry-hydro.eu/oltc).

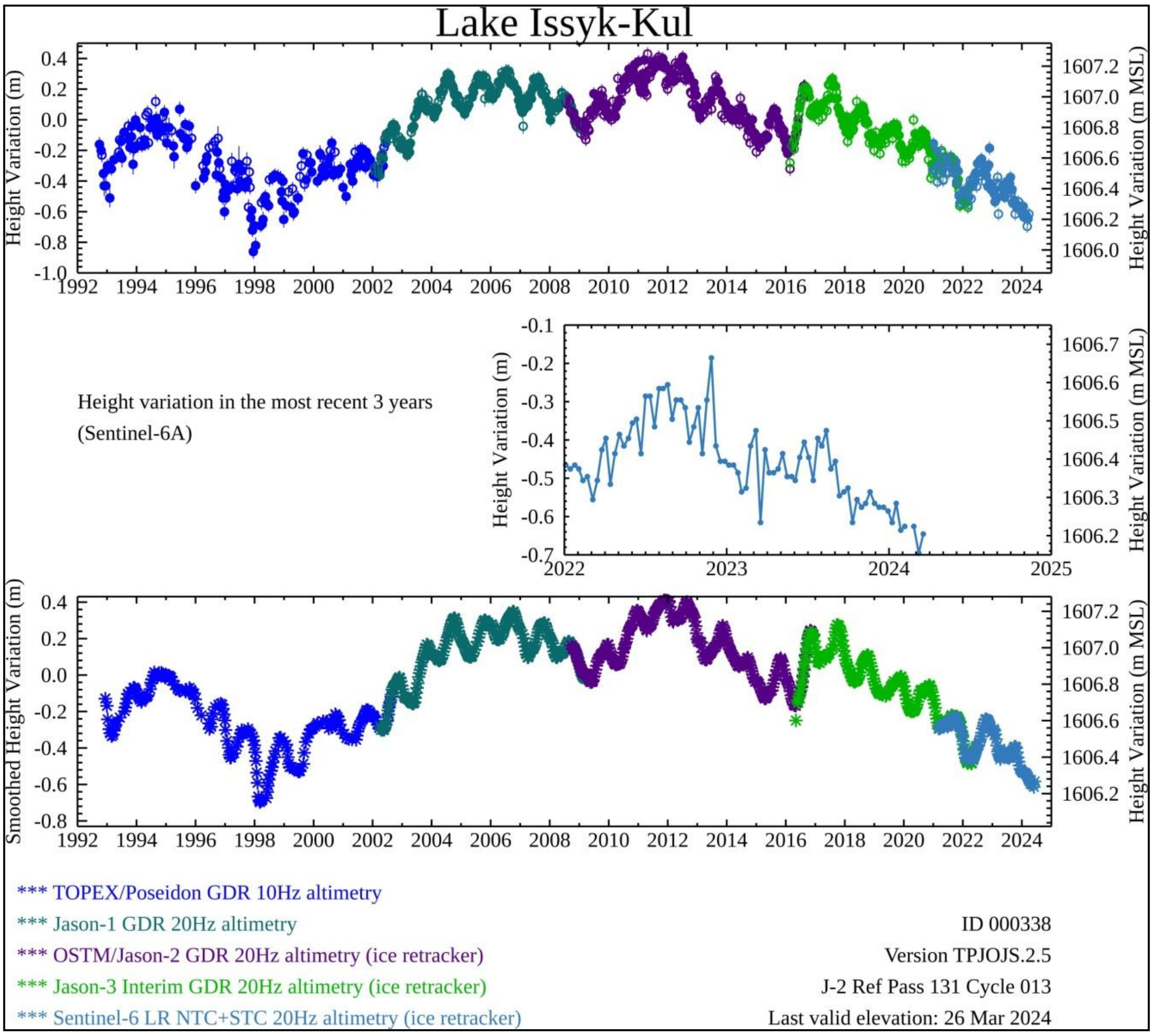

Fig. 2 Changes in the level of Lake Issyk-Kul according to altimetry satellites from 1993 to 2024 (source: USDA and others)

The frequency of flights over the same point on the earth's surface by the mentioned satellites is 10 days. The instrumental accuracy of measuring the absolute altitude of the satellites under consideration with altimeters is in the range of 3-5 cm, however, the accuracy of direct measurements depends on many factors that must be taken into account in order to make corrections to the final result. The accuracy of measurements is affected by atmospheric parameters, the nature of the topography of the earth's surface, variations in the diameter of the radar beam on the earth's surface, and others. For this reason, standard deviations of the measured values can vary from 10 cm for large open lakes, to 20 cm for small, windproof lakes and up to many tens of centimeters for reservoirs located in narrow, deep valleys. Lake Issyk-Kul, which has a large area and gently sloping sides of the lake basin, is characterized by a variant with minimal values of the standard deviation of the measured absolute height [1,2].

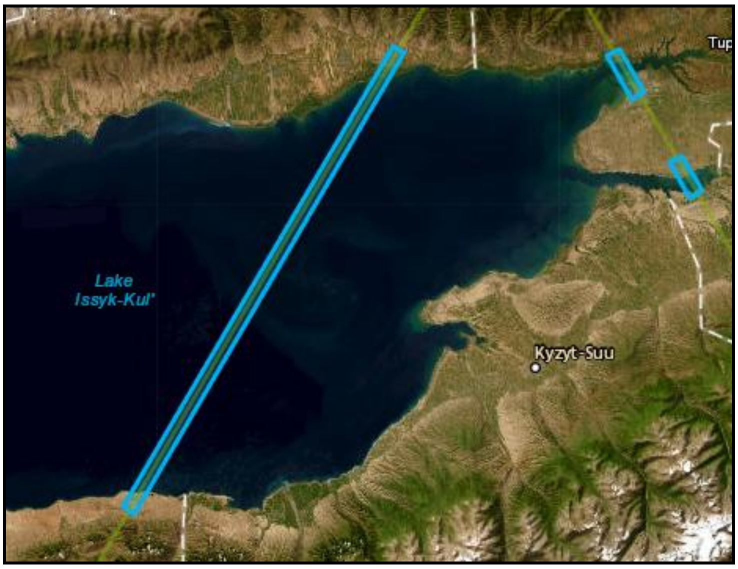

Fig. 3 Location of “Sentinel 6A” satellite tracks in the water area of Lake Issyk-Kul (https://www.altimetry-hydro.eu/oltc).

The general character of the scatter in the measured altitude values of Lake Issyk-Kul is visible in the upper graph of Figure 2, in contrast to the lower smoothed graph. The values of standard deviations of altitudes measured by satellites for Lake Issyk-Kul according to GFZ data are shown in Figure 4. In this case, data from the same satellites was used that was used by USDA et al.

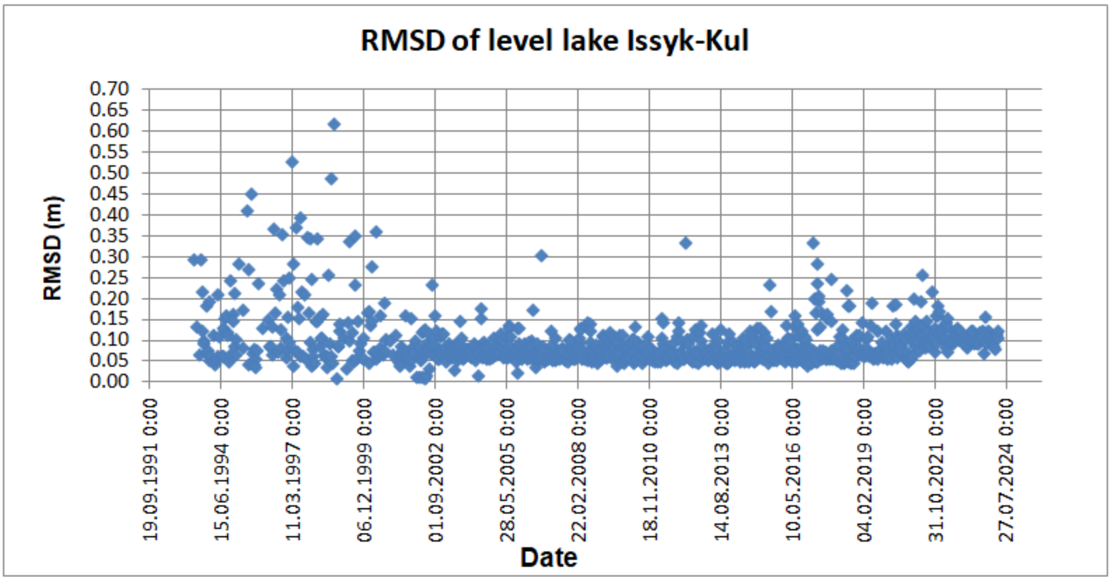

Fig. 4 Standard deviations of satellite-measured altitudes of Lake Issyk-Kul, according to GFZ data

Figure 4 shows that the accuracy of altitude measurements has improved since approximately 2000. The largest number of standard deviation values is in the range of 0.05-0.15 m. The median RMSD value shown in Figure 4, is 0.08 m.

Comparison of the level altitudes of Lake Issyk-Kul obtained by Kyrgyzhydromet, USDA and GFZ is shown in Figure 5. As can be seen in this figure, the difference in the magnitude of altitudes is mainly of a systematic character, associated with different zero points of absolute height: BSH (KHM) , EGM2008 (USDA), EIGEN-6C-static (GFZ). Average difference in lake level altitudes obtained by KHM and GFZ in the period 1994-2021. is 0.24 m, with a constant excess of the altitude values obtained by the KHM. The character of the difference in altitudes obtained by KHM and USDA is more complex. In this case, the role played by the smaller difference in altitude values from different sources and the presence of errors in direct level measurements and processing of satellite data. As can be seen in Figure 5, there is mainly an excess of the altitude value obtained by the USDA over the value obtained by the KHM, however, in 1993, 1999, 2012, 2013, 2014 this ratio was the opposite, with a maximum difference in 1999 equal to 0.12 m .   From 2015 to 2021, the nature of the ratio of lake level altitudes, according to the USDA and KHM, is stable, with a stable systematic excess of the level of the first over the second by an average of 0.1 m, which is associated with the use of more advanced satellite altimetry technology and methods correction of primary data, as well as with correct direct instrumental measurement of lake level. Figure 6 shows the considered stable ratio of the values of average monthly lake level altitudes according to Kyrgyzhydromet and USDA data.

Thus, the values of the absolute lake levels obtained by different methods have a good agreement in the nature of changes in the lake level, and the resulting value of their mutual deviation is relatively constant, which allows, starting from 2015, their mutual correction and monitoring of objectivity.

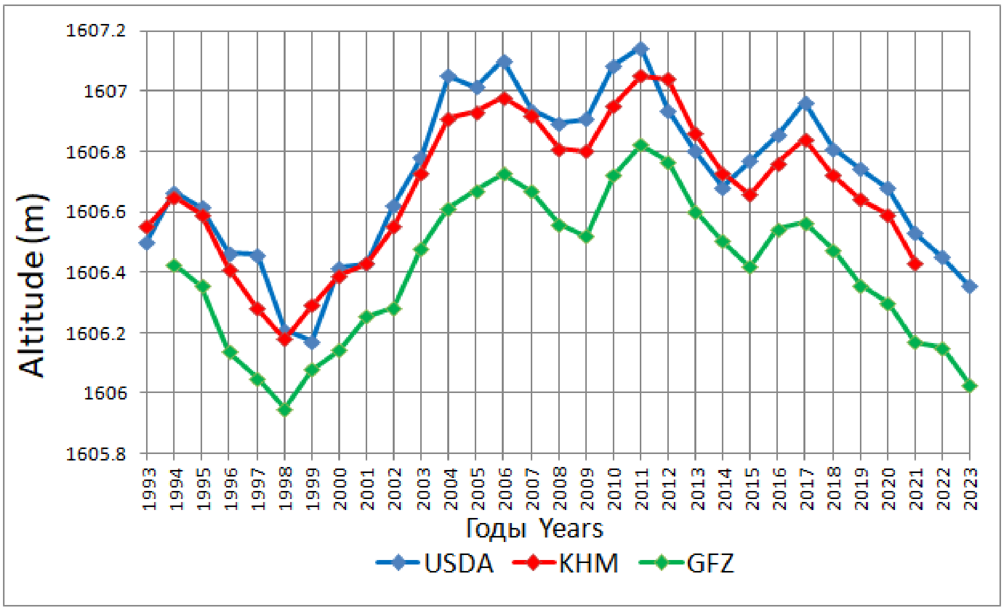

Fig.5 Comparison of level altitudes of Lake Issyk-Kul obtained by Kyrgyzhydromet, USDA, GFZ.

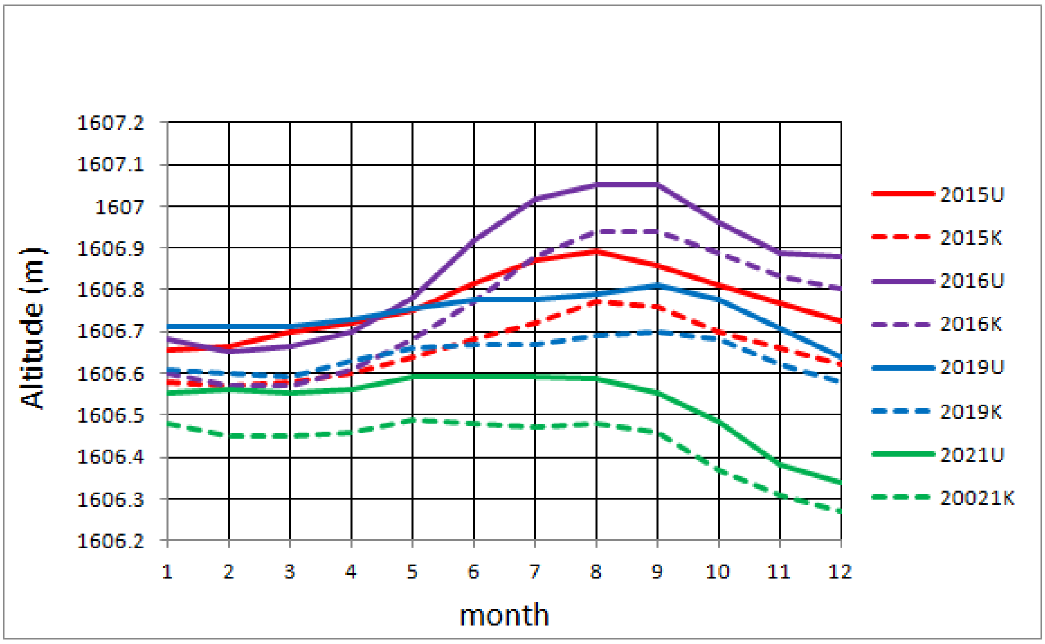

Fig.6 Ratio of average monthly level altitudes of Lake Issyk-Kul, according to Kyrgyzhydromet (K) and USDA (U), in the period 2015-2021.

Analysis of changes in the average long-term variation in the level of Lake Issyk-Kul for the entire period of instrumental measurements since 1927 showed (Fig. 1) that the decrease in lake level from 1927 to 2023 was 3.22 m (1609.48 m (KGM) - 1606.26 m (USDA-0.1 m)). Against the background of this general downward trend in level, from 1998 to 2004, the largest rise in the level of Lake Issyk-Kul with an amplitude of 0.8 m occurred over the entire observation period, against the background observed long-term downward trend in levels. In previous years, short-term small rises in level were also observed, the largest of which, with an amplitude of 0.32 m, was recorded in the period from 1955 to 1960. From 2004 to 2017, for 14 years, the trend of level rise changed to relative stabilization, during which short-period, about 3-4 years, multidirectional level fluctuations with an amplitude of about 0.4 m were observed. From 2017 to 2023, the lake level tends to decrease, approaching the position in 1998. This fact , possibly marking the beginning of a new cycle of steady decline in lake levels after relative stabilization between 2004 and 2017. Thus, the water balance of the lake in the period from 2017 to 2023 is negative, reflecting the excess of the discharge item in the form of, mainly, evaporation over the income item in the form of inflow of river and groundwater. Considering the ongoing long-term increase in air temperature in the Issyk-Kul Lake basin, in accordance with global warming, it seems most likely that the trend of lake level decline will continue in subsequent years. This means that in future economic activities it is necessary to take into account the retreat of the lake's shoreline and the shallowing of individual coastal areas of the water area.

In addition to the results discussed above, satellite altimetry measurements also made it possible to identify such a feature of the level topography of Lake Issyk-Kul as a level depression in its central sublatitudinal part. This phenomenon is observed according to data from all altimetry satellites in different years and seasons. In particular, it was determined from the tracks of the altimetry satellite "CryoSat 2" (https://visioterra.net/VtCryoSat/). This radar satellite, launched in 2010 and still in operation, has a measurement cycle repetition period of 369 days. The results of its measurements indicate the stability of the lowered position of the level in the central part of the lake by an amount of about 1.3 m (Fig. 7, 8). The lower position of the average lake level in 2019 relative to the level in 2017 and 2018, as can be seen in Figure 7, is due to a more negative water balance of the lake in 2019 compared to previous years.

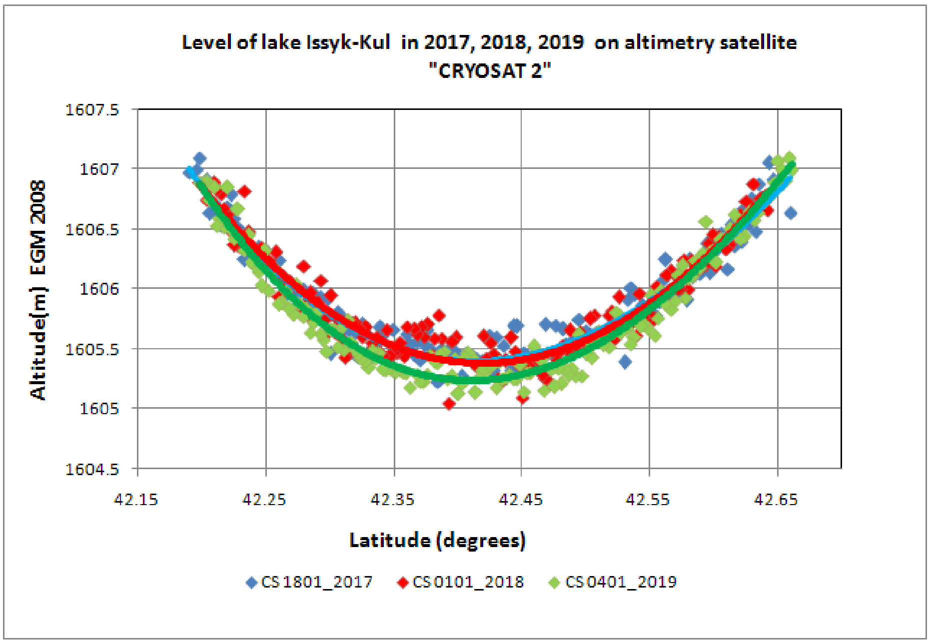

Fig. 7 Level of Lake Issyk-Kul according to the altimetry satellite "CryoSat 2" along submeridional profiles A (01/01/2018; 01/04/2019) and B (01/18/2017) (see Fig. 8)

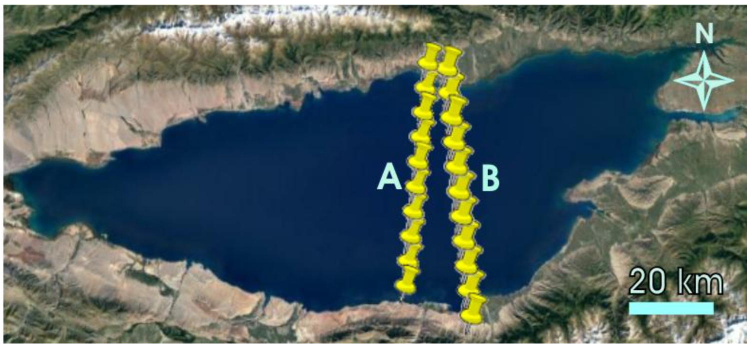

Fig. 8 Altimetry profiles based on the tracks of the satellite "CryoSat 2" on Lake Issyk-Kul.

Similar result was obtained from measurements of the "IceSat 2" altimetry satellite, which has a laser range finder with a horizontal position accuracy of 3.6 m, and a vertical accuracy of better than 0.1 m. Its measurement repeat period is from 91 days, with variations, (https://openaltimetry.earthdatacloud.nasa.gov/data/icesat2/. NASA National Snow and Ice Data Center Distributed Active Archive Center). This satellite provides highly accurate measurements of the altitude of the earth's surface, but the results depend on the presence of clouds. Figures 9 and 10 show the results of measuring the altitude of Lake Issyk-Kul by this satellite along one of the tracks No.66, with three pairs of measurement beams, namely, a pair of beams gt3r and gt3l. On the graph in Figure 9, with the altitude of the lake level at the southern and northern edges of the shore equal to 1606.2 m, the maximum level depression is 0.58 m, at a point with an altitude of 1605.62 m. At the same time, the median value The standard deviation of the altitude measurement, along two rays, is respectively equal to: gt3l=0.024m, gt3r=0.027m. This value of the lake level depression, obtained by the "IceSat 2" satellite, according to the corresponding track positions, is the most correct, due to the greater accuracy of the laser rangefinder measurements compared to the radar. According to satellite measurement tracks of lake level altitude located in the eastern and western parts of the lake, the depression value is less, from several centimeters to 0.10-0.12 m. That is, the maximum level depression occurs in the central part of Lake Issyk-Kul.

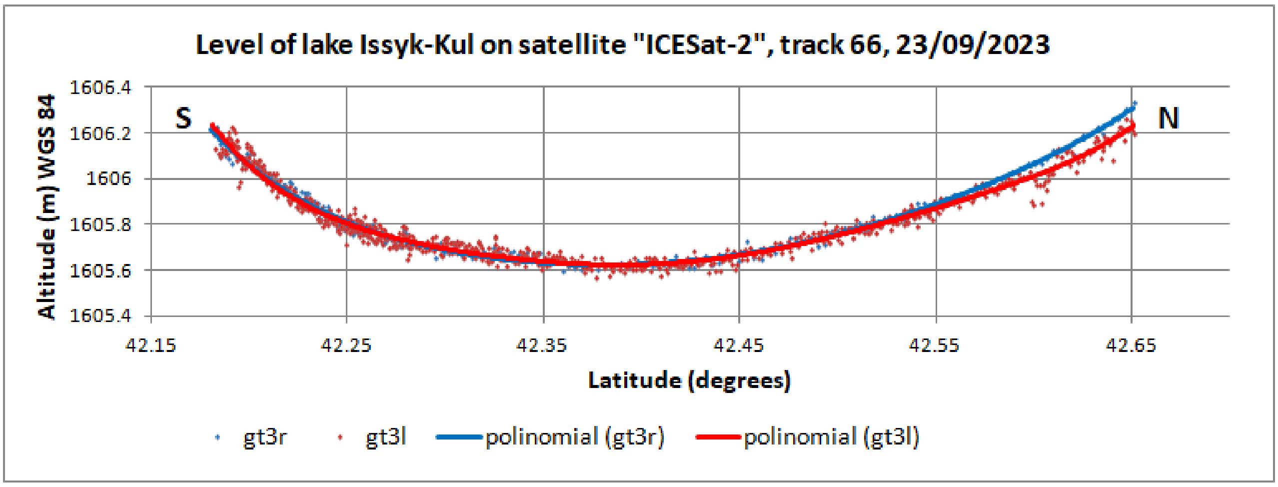

Fig. 9 Results of measurements by the "IceSat 2" satellite of the altitude of Lake Issyk-Kul along track No.66, using a pair of beams gt3r and gt3l.

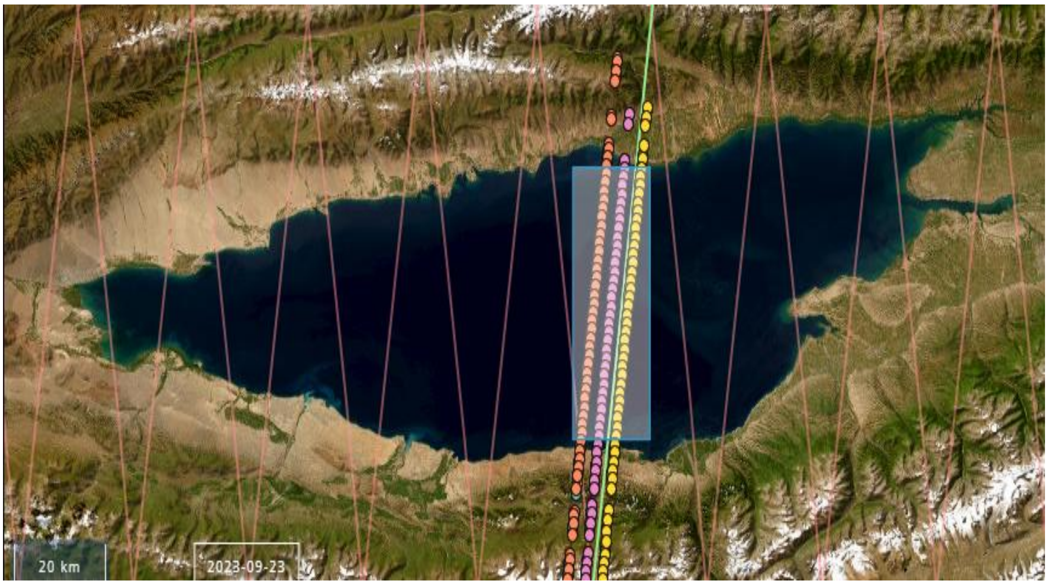

Fig. 10 Location of altitude measurement points of track No. 66 (the left trace of the ray corresponds to the pair of rays gt3r and gt3l).

The phenomenon of the level depression of Lake Issyk-Kul, in our opinion, is due to the gravitational attraction of two sublatitudinal ridges: Teskey and Kungey. Some influence may also be due to the anticyclonic flow of lake waters and differences in water density due to temperature and salinity in the coastal and central parts of the lake.

Monitoring level of Lake Chatyr-Kul

In 2023, satellite monitoring of the level of the closed lake Chatyr-Kul, located in the Central Tien Shan at an absolute altitude of 3530 m, began. Monitoring of the lake level is carried out according to satellite data: laser “IceSat 2” and radar “Sentinel 3”, launched in 2016, with a measurement repeatability of 27 days and an instrumental measurement error of 0.03 m (Copernicus Data Space Ecosystem). The location of the Sentinel 3 and “IceSat 2” satellite tracks in the waters of Lake Chatyr-Kul is shown in Figure 11.

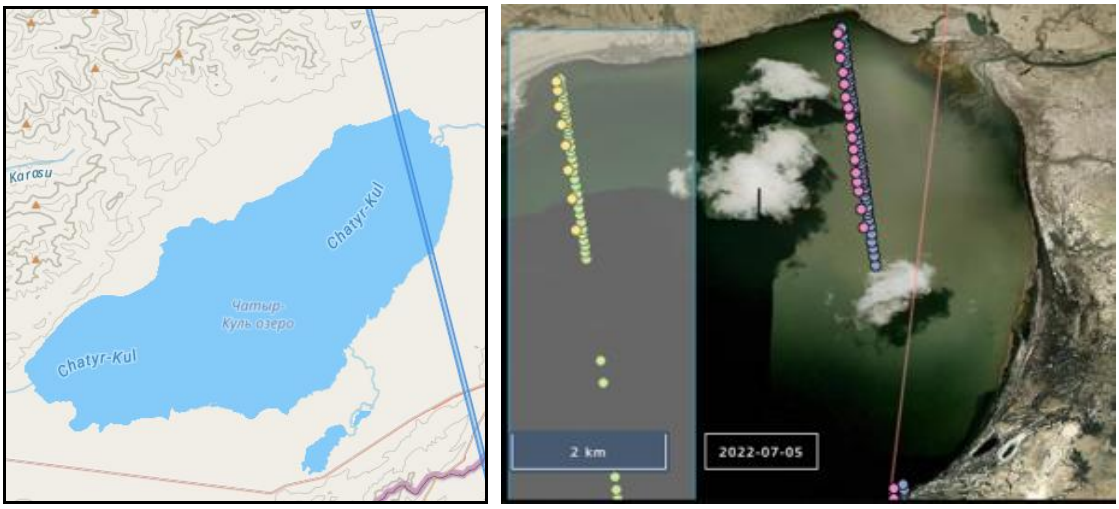

Fig. 11 Track of the “Sentinel 3” satellite (left) and track No. 211 of the “IceSat 2” satellite (right) in the waters area of Lake Chatyr-Kul.

Lake Chatyr-Kul level monitoring was carried out from 2016 to 2024. by processing in CAIAG the primary measurement data of the “Sentinel 3” satellites, using the Level -2

LAN_HY product, (https://browser.dataspace.copernicus.eu/) and “IceSat 2”, (https://openaltimetry.earthdatacloud. nasa.gov/data/icesat2/). In addition, in the analysis of changes in lake level, the results of processing measurements from the “Sentinel 3” satellite, carried out by GFZ (Deutsche GeoForschungs Zentrum) from the CAIAG Sensor Data Storage System (SDSS, http://sdss.caiag.kg/sdss/index.php? &page=measure_page).

From the observation results presented in Figure 12 it follows that for the period from 2016 to 2024 there is a slight linear trend towards a decrease in the level (gradient = - 0.00007 m/year) of Lake Chatyr-Kul. The nonlinear trend shows the presence of periodic fluctuations in level, with a period of about 5 years. In general, the regime of Lake Chatyr-Kul during the period under review is relatively stable. A feature of Lake Chatyr-Kul is freezing, mainly from October to April, which should be taken into account when interpreting the level in winter, when the level is affected by ice deformation, accumulation and wind transfer of snow. The difference in the absolute heights of the lake level, according to different sources, observed in Figure 12 is due to the difference in the algorithms for introducing corrections into satellite data and different geoid models that determine the zero mark of the absolute height. The accuracy of determining lake level altitude using the “Sentinel 3” radar satellite is shown in Figure 13, where the median RMSD value presented on the graph is 0.13 m.

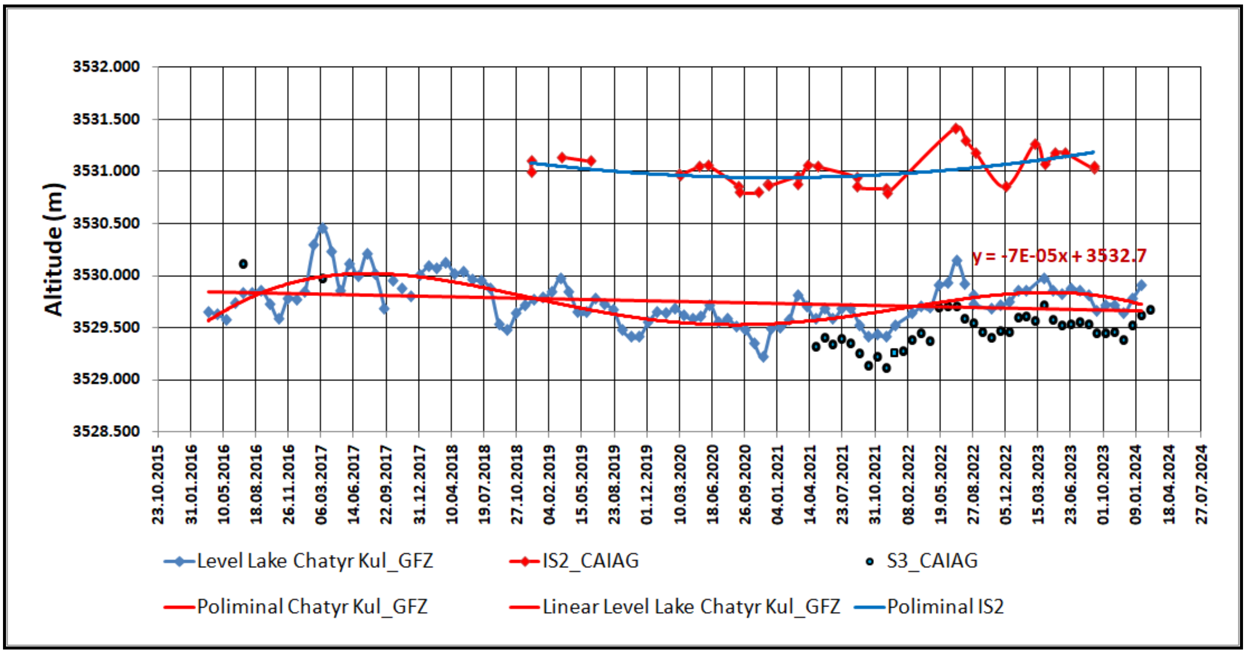

Fig. 12 Long-term change in the level of Lake Chatyr-Kul according to data from the “Sentinel 3”, “IceSat 2” satellites, based on the results of processing by CAIAG and GFZ.

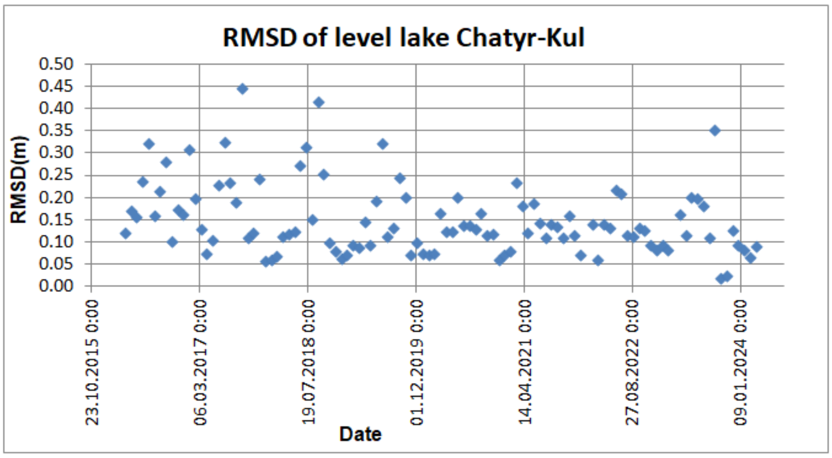

Fig. 13 Standard deviation of the measured altitude values of Lake Chatyr-Kul according to GFZ data on “Sentinel 3”

According to previous studies [3,4], from the beginning of the 20th century to the 80s, the level of Lake Chatyr-Kul dropped by several meters and the water balance was mostly negative. However, systematic observations and measurements have not been carried out on the lake. In order to clarify the state of the lake level in the past and to the present, an analysis of optical satellite images was performed.

To analyze changes in the level of Lake Chatyr-Kul, optical images of Hexagon KH9 satellites from 08/04/1973 were used. with a resolution of 6 – 9 m/p, “Landsat 1-5” from 1984, 1988, 57 m/p, “Landsat 4-5” from 1993, - 30 m/p (USGS EROS Archive) and “Sentinel 2” from 2023, -10m/p. (ESA, Copernicus Data Space Ecosystem). Analysis of available satellite images showed, as can be seen from Figure 14 and Table 1, that in 1973 the area of Lake Chatyr-Kul was close to that in 2023 and, accordingly, the absolute water level of the lake is currently close to that in the past . According to a topographic map at a scale of 1:100000, showing the state of the area in 1977, the water edge of Lake Chatyr-Kul had an absolute elevation of 3530 m in the Baltic elevation system. At the same time, the average value of the range of absolute heights of the lake level, according to various sources, according to the graph in Figure 12, is 3530.25 m. The contour of the lake on this map practically coincides with the contour obtained from the Hexagon KH9 satellite image from 08/04/1973.

Thus, the state of the lake’s water balance at these points in time was similar. However, a satellite image from 1984 shows a significant reduction in the area of Lake Chatyr-Kul. That is, after 1973-77. There was a change in the balance of the lake towards the predominance of the expenditure part and such conditions continued until 1992-93, after which began a steady rise in the level to its present position in 2023.. This rise was accompanied by periodic slight decreases in the level in 1995-97, 2008, 2013-15, which can be seen in satellite images of “Landsat 5.7, 8” on changes in the contour of the lake's shoreline during these years. The amplitude of these declines was approximately up to 0.5 m, and was likely close to that observed in Figure 12 in 2020-21.

Changes in the area of Lake Chatyr-Kul Table 1

Years	1973	1984	1993	2023
Area (km^2)	164	130,5	143,6	158,4

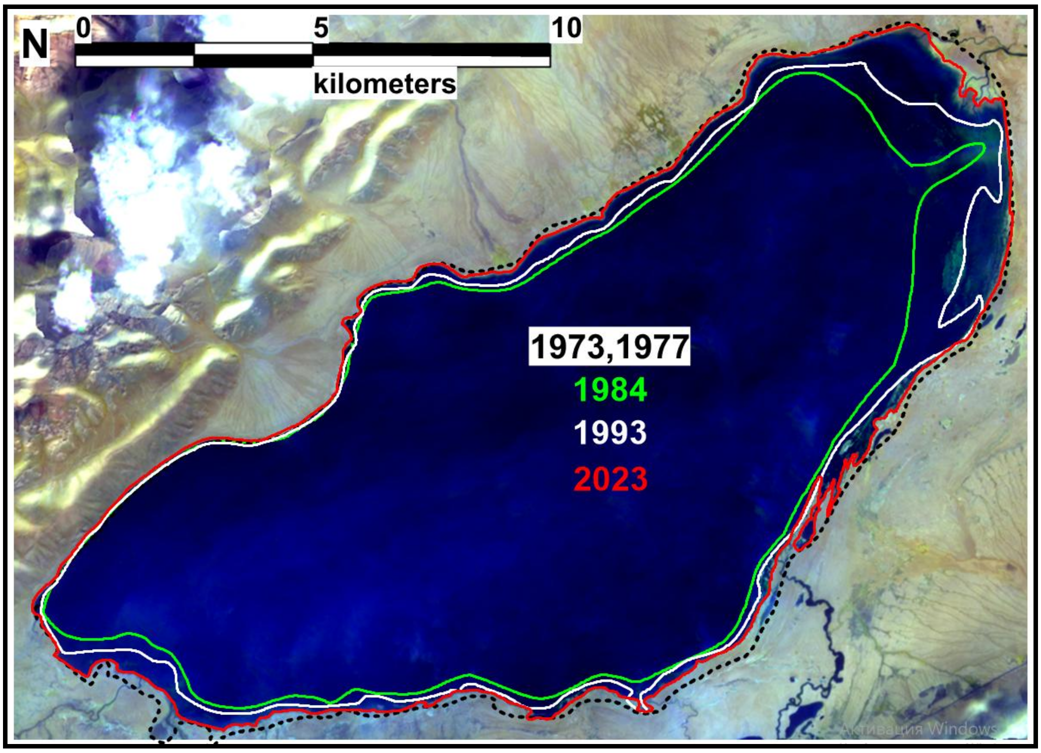

Fig. 14 Boundaries of Lake Chatyr-Kul in different years, according to satellite images

The total amplitude of the increase in the level of Lake Chatyr-Kul from 1984 to 2023 can be approximately estimated from the bathygraphic curve of the lake presented in [3] and shown in Figure 15; it is of the order of 1 m.

The results obtained for the level regime of Lake Chatyr-Kul indicate an insignificant impact of global warming on the water balance of the lake, located at high absolute altitudes.

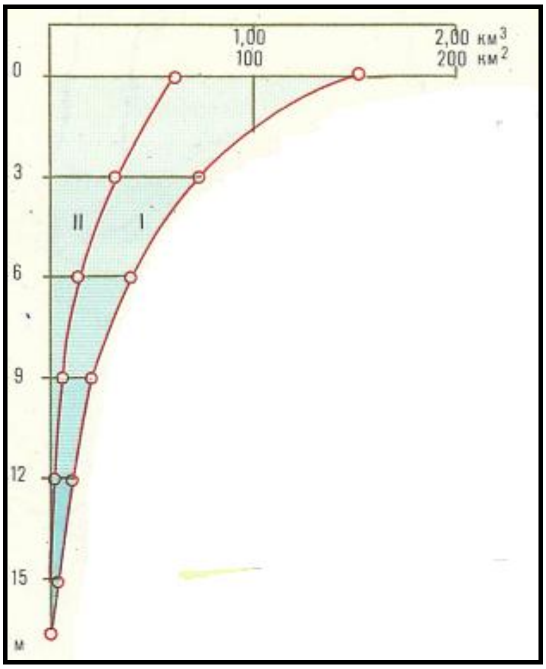

Fig. 15 Graphs: I - bathygraphic and II - volumetric of Lake Chatyr-Kul.

Thus, the use of satellite information makes it possible to accurately monitor lake levels over many years, study the patterns of their development, and the dependence of the water balance in the high mountain regions of Kyrgyzstan on climate change.

Literature

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