Spatial variability of characteristics of the ice cover of the Rybinsky reservoir in winter 2022

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Abstract. The paper presents the results and a brief analysis of in-situ measurements of thickness and other characteristics of the ice cover of the Rybinsky reservoir, which took place during two expeditions in February and April 2022. In expeditions, 49 ice cores were taken, which provide enough information to evaluate the heterogeneity of the ice cover. The most accurate data were obtained for two profiles, which cross the reservoir from the north to the south and from the southwest to the northeast and coincide with two tracks of the satellite altimeter Jason-3. In 2022 ice cover of the Rybinsky reservoir was heterogeneous and made up several different ice layers. Combination and thickness of these layers were distributed unevenly over the surface of the reservoir and were changing over time. The most uneven distribution was observed in the winter: near the shore and in the southwest part of the reservoir ice cover consisted of black ice, central part of the reservoir was made of black ice and frazil ice and east part of the reservoir was made up black ice and white ice. In the spring, ice cover became much more homogeneous and consisted of thick layers of white ice and black ice.

1 Introduction

Climate changes affect the cryosphere. Since the ice cover of lakes and reservoirs is a part of the cryosphere it is under the influence of climate changes too. The Rybinsky reservoir is one of the most suitable objects for studying and monitoring changes in special features and characteristics of the ice cover in Russia for various reasons. Firstly, the Rybinsky reservoir has been deeply explored comparing with other Russian reservoirs so far. Secondly, hydrometeorological conditions over the surface of the Rybinsky reservoir are uneven due to the big size of its surface (4.58 sq km). In the long-term, this feature gives an opportunity to emerge special variability of the ice cover characteristics in response to the ongoing climate changes.

Despite the availability of a great amount of data, ground-based measurements of the ice cover characteristic of the Rybinsky reservoir are still relevant. It is caused by the significant size of the reservoir, limitation of the standard hydrometeorological observation and demand for the development of new satellite remote sensing methods. Therefore, the goal of the research is to evaluate the variability of the ice cover based on ground-based measurements and remote sensing data.

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2 Methods

Ground-based measurements of the ice cover of the Rybinsky reservoir took place in February (25 January – 5 February) and April (1-2 April) 2022 as part of two expeditions organized by the Department of Land Hydrology, Moscow State University. During the winter and the spring expedition, forty and nine virtual stations were made respectively. Thirty of the winter virtual station formed two profiles (I profile crossed the reservoir from SW to NE; II profile crossed the reservoir from N to S, figure 1, figure 2). Their location coincided with the tracks of the satellite altimeter Jason-3. So, a comparison between the data received from the altimeter and the results of the ground-based measurement gives an opportunity to use remote sensing not only to determine ice phenology but also to study some properties of the ice cover. Observations on each station included ice and snow thickness measurements (with an ice stake and a snow stake) and snow density measurements (with a snow-density gauge). On several stations ice cores (figure 3) were described too [1-6].

The analysis of the received data and definition of possible ice cover formation types were based on the images in visible band from Moderate Resolution Imaging Spectroradiometer (MODIS), weather data from four weather stations (for Rybinsk, Cherepovets, Breitovo and Poshekhonie), and ice thickness and ice phenomena data from five gauging stations located on the shore of Rybinsky reservoir.

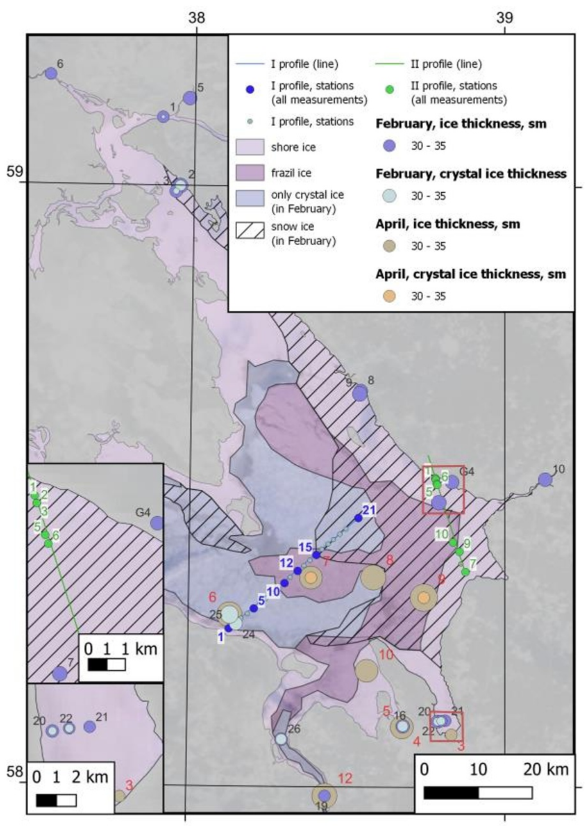
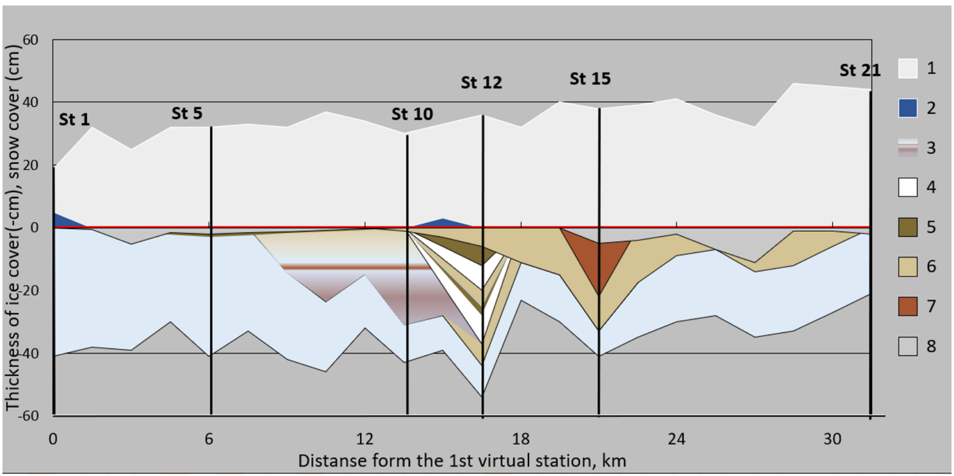


Fig. 1. The location of the virtual station.

Thickness of white (snow) and black (crystal) ice is being represented by the size of the marker. Stations made in February have black, blue and green labels, and stations made in April have red labels. Distribution of different ice layers in February is shown by colour and hatching. The base of the map is the image from Moderate Resolution Imaging Spectroradiometer (MODIS) for 05\12\21 (source: worldview.earthdata.nasa.gov).

A



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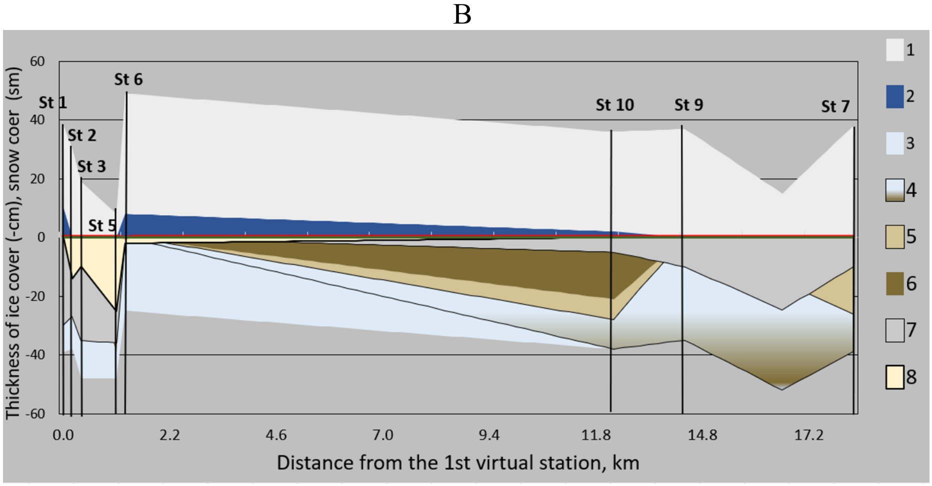


Fig. 2. The structure of the ice and snow cover of the Rybinsky reservoir along the I and the II profiles: a – I profile: 1 – snow, 2 – water, 3 – combination of brown frazil ice and transparent black ice, 4 – black ice (transparent), 5 – black ice (brownish), 6 – whitish frazil ice, 7 – brown frazil ice, 8 – white ice; b – II profile: 1 – snow; 2 – water, 3 – black ice (transparent), 4 – black ice (transparent with brown inclusions), 5 – frazil ice, 6 – black ice (brown), 7 – white ice, 8 – deep frozen snow.

The size of the fields on the graph is representing thickness of the ice cover (for negative values) and thickness of the snow cover (for positive values). Inner structure of the fields is representing thickness of the different layers of the ice cover. Colours of the fields were chosen so as to reflect natural colours of the ice layers.

3 Results

Results of ground-based measurements are shown in figure 1 and figure 2.

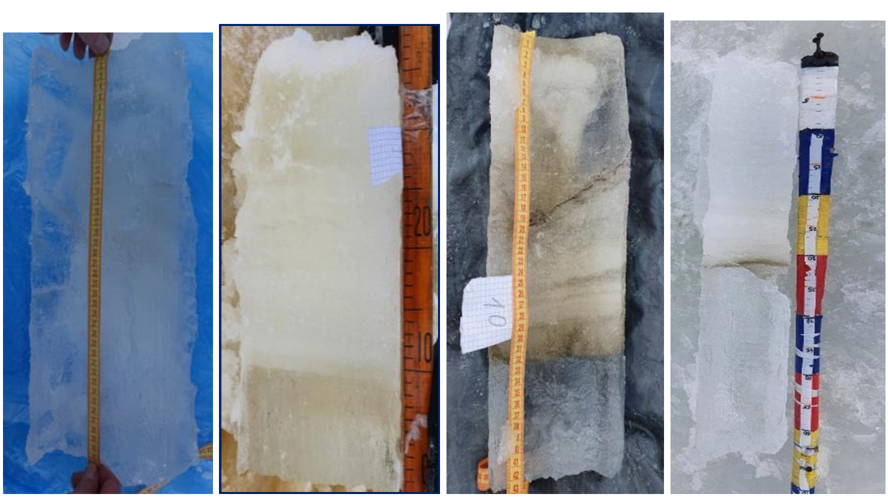
Locations of all virtual stations are shown in figure 1. Except the stations of the I and II profiles, the figure 1 shows thickness of the ice on the stations. For some station the figure 1 shows thickness of black ice layer, too.

Figure 2 illustrates the structure and thickness of the ice and snow cover. The graphs were plotted based on measurements of the ice cover thickness and snow cover thickness in 21 and 10 virtual stations which form I and II profile respectively. Structure of the ice cover was described on six of the I profile stations (stations 1,5,10,12,15,21) and on eight of the II profile stations (stations 1,2,3,5,6,7,9,10). It allowed to plot changes of thickness of different ice cover layers along the profiles (for stations where only thickness of ice and snow cover were measured estimated data were plotted).

4 Discussion

In situ measurements emerged, that the ice cover of the Rybinsky reservoir is heterogeneous and made of several different ice layers. The feature is typical for most of the lakes and reservoirs. The specific feature of the Rybinky reservoir is the spatiotemporal heterogeneity of combination and thickness of different ice layers. It is caused by unevenness of hydrometeorological conditions, which lead to uneven process of ice cover formation and development.

Three ice types are typical for the Rybinsky reservoir: black ice (transparent; consists of columnar vertically oriented crystals, figure 3a), white ice (whitish, has crumble structure, is composed of snow saturated by water and frozen, figure 3b), frazil ice (appears when water surface is exposed to wind and nearly all water layers are supercooled due to turbulent mixing; it is composed of ice particles frozen together; usually contains many air bubbles and transported particles; therefore it's brownish and has unregular structure, figure 3c).



a b c d

Fig. 3. Ice cores from different parts of the Rybinsky reservoir: a – station 1, I profile; b – station 1, II profile; c – station 10, profile I; d – station 7, April

The ice cover of the Rybinky reservoir was the most uneven in winter on account of specific features of the ice cover formation process (figure 1). In 2022 initial formation of the ice cover of the Rybinky reservoir started right after air temperatures stably dropped under 0℃ (1st December 2021): shore ice (thin fixed layer of ice on the surface) formed along the whole shoreline (mostly in the east). The process was preceded by supercooling of a thin top layer of water because it was not being mixing by wind (wind velocity was less than 2 m/s). At the same time in the central part of the reservoir high wind velocity (up to 20 m/s) and intensive turbulent mixing occurred (due to the big width of the reservoir it was enough space for wind to accelerate and due to relatively small depth of the reservoir potential height of waves increased). Therefore, nearly all water layers were supercooled and ice particles formed. After steed decrease of air temperatures (up to –20℃, 5-9 December) these ice particles transformed into frazil ice. Simultaneously as a result of heat loss shore ice started to develop intensively: crystals started to grow into the water below the increasing thickness of the black ice layer. Then the process spread over the whole reservoir. However, in the areas where frazil ice occurred the processes were less intensive because this ice layer blocked the exchange of the energy between the air and water and thus decreased the rate of heat loss.

Together with the frazil ice formation, the process of ice particles eastward drifting took place (apparently due to westerlies). As the result the western part of the reservoir was free of ice and ice particles during the first period of ice cover formation. So, the ice cover of this part of the reservoir did not include a layer of the frazil ice. Drifting of the ice particles also led to its deposition under the bottom surface of the ice cover eastwards (in the central part of the reservoir). For instance, in station 12 of the I profile there were several layers of the frazil ice in the same ice core, which alternated with black ice layers. Moreover, in 2022 the process of slash and floats eastward drifting occurred too. This is confirmed by the presence of the pressure ridges and cracks in ice cover along the boundary between shore ice and the area of the frazil ice extension. To sum up, in February ice core taken from the southeast part of the Rybinsky reservoir were distinctly composed of two ice layers. Upper layers consisted of frazil ice: porous layered whitish with brown inclusion and rough borders between layers. The bottom layers consisted of black ice (Fig.3, C). Ice cores taken from the western part of the reservoir consisted of only one thick layer of black ice.

As the ice cover of the Rybinsly reservoir developed, it became significantly thicker and more homogeneous. In April, almost all ice cover of the reservoir consisted of two main layers: the white ice layer (upper layer) and the black ice layer (bottom ice). In the central part of the reservoir, a thin layer of compressed and modified frazil ice emerged between the main layers. The process of the ice cover differentiation decreasing appeared due to the formation of white ice. This layer of ice forms of frozen and compressed snow which had benn saturated by water. In February 2022 the saturation was caused by overcoming the buoyancy of the ice by overlaying snow cover, submergence of the ice cover and rising of water through cracks under the pressure. Thus, in February the layer of white ice formed only in the eastern part of the reservoir, where the density of the cracks in the ice cover reached its maximum. In April, the thin even layer of white ice covered all the reservoir. It was formed due to a thaw that lasted from 17 to 20 February. The thaw led to the saturation of all snow cover of the reservoir and to its complete transformation into the white ice. At the same time the phenomenon of “water above the ice cover” disappeared, because the water level in the reservoir dropped and thus the additional pressure of the snow cover was compensated.

Uneven and intensive (brown) colour of the black and the frazil ice was specific feature of the ice cover of the Rybinsky reservoir (stations 10-15 of the I profile and stations 7-10 of the II profile). The feature is apparently caused by the extra concentration of transported particles (mostly of organic origin) in some parts of the reservoir caused by deposition and washout (erosion) of 800 km2 of bogs flooded after the appearance of the reservoir.

5 Conclusion

One of the main features of the ice cover of the Rybinsky reservoir is a spacetime heterogeneity of the thickness and the structure. Owing to the big size of the reservoir, the process of freezing was multi-stage and uneven, which led to the formation of different ice layers. Presence of the weather data for the period of ice cover formation allowed to estimate the combination and the thickness of different layers of ice for each point of the reservoir. In the central and the western parts of the reservoir, owing to high wind velocity, frazil ice formed. Areas of white ice distribution coincided with the areas of cracks formation in the winter. In 2022 the highest density of cracks was observed in the eastern part of the reservoir, along the boundary between the shore ice and the area of the frazil ice extension. So, in the winter presence of white ice was observed in this part of the reservoir. In the spring white ice precented in every part of the reservoir because snow cover overlaying the ice cover transformed into the white ice due to the thaw. The intensity of the black ice formation was determined by the rate of energy flow from the water mass to the air through the ice cover. The rate decreased with the rising of the thickness of the overlaying ice layers. Thus, the development of the reservoir ice cover structure is characterized by the tendency to the homogeneity.

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