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Icings in the Selenge River basin as an indicator of climate change

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ABSTRACT

The Selenga River basin, with approximately two-thirds of its area located in Mongolia and the remaining third in Russia, hosts over 29,000 icings of diverse genetic types that form annually. In this study we analyzed the interannual variability of icings in the Selenga River basin. Using multi-temporal Landsat imagery, data from meteorological stations, hydrometric stations and expedition observations, the main trends in the change of icings formation intensity were established. Over the period from 1990 to 2024, a 3.5% decrease in the area of giant icings in the Mongolian part of the basin over 10 years was revealed. In the Russian part of the catchment basin, besides the reduction in the total area of icings by 6,7% over 10 years, an increase in the number of medium, small and very small ones is observed against the background of a decrease in the number of very large icings. The established trend is related to climate change. A significant increase in air temperature in April (on average in the basin by 0.75° over 10 years) may be one of the reasons for the overall reduction in the area of icings. As a result of the observed warming, the thickness of seasonal freezing of rocks decreases, which leads to an increase in the transition of icing-forming groundwater outside the icing fields. Also, melting of permafrost is recorded. Thus, icings are a kind of indicator of changes in permafrost-hydrogeological conditions under the influence of global climatic processes.

KEYWORDS

Selenga river basin, Icings, Climate change, Permafrost, Landsat

1. INTRODUCTION

Icings are layered ice masses or crusts on land surfaces, ice cover, or man-made in frastructuresformed by the freezing of periodically pouring natural or anthropogenic water [1]. In the Selenga River basin, there are more than 29,000 icings of different genetic types formed annually [2]. Since icings are the object of the cryosphere, their study makes it possible to assess changes in the state of the cryolithozone under the influence of climatic processes.

Icings play a crucial role in river flow regulation. They accumulate a significant portion of winter surface and groundwater runoff. The meltwater from icings in spring feeds rivers and streams, maintains favorable conditions for floodplain ecosystems and serves as a water source for irrigation and livestock watering. The reduction in icings coverage (and water volume) alters river regimes and decreases spring discharge, with consequent negative impacts on local landscapes.

The present study focuses on assessing multi-year variability of the icings' areas in the Selenga River basin to identify the influence of air temperature increase on icings formation processes, which are directly related to the state of the cryolithozone. The topic is of interest because the study area lies on the southern boundary of permafrost distribution, making natural systems here particularly sensitive to climate change. In the 20th century, the average annual air temperature in the Selenga River basin increased by 1.8 - 2.3 °C [3;4;5], which inevitably affected cryogenic processes.

2. RESEARCH METHODS

This study focuses on the Selenga River basin as the research area (Fig. 1).

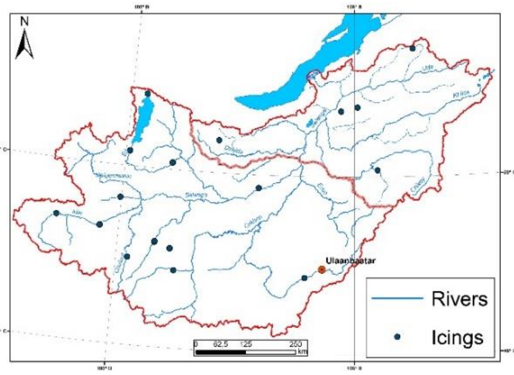

Figure 1. Study area

The study utilized a cartographic database of icings in the Selenga River basin, generated from Landsat-8 and Sentinel-2 satellite imagery for 2021 [2]. This database comprises over 29,000 icings covering a total area of 1,154.2 km² (0.25% of the basin's total area).

Interannual variability of giant icings was analyzed specifically in the Mongolian part of the Selenga River basin. The assessment the multi-year changes in icings surface area was conducted using satellite imagery acquired immediately after snowmelt. For the period 1986–1998, Landsat-5 (TM sensor) imagery was used; for 1999–2012, Landsat-5 and Landsat-7 (ETM+ sensor) imagery; from 2013 onward, Landsat-8 (OLI sensor) imagery; and for 2018–2024, most icings were delineated using Sentinel-2 (MSI sensor) imagery.

All datasets were processed consistently using the Normalized Difference Snow Index (NDSI) (Hall et al., 1995). A threshold NDSI value of 0.4 was applied to identify snow and ice features.

The consistency of interannual changes in icings surface area was assessed using Pearson's and Spearman's correlation coefficients. Long-term trends in icings surface area were evaluated using the non-parametric Theil-Sen estimator, which is robust against outliers. A significance level (α) of 0.05 was applied for both correlation coefficients and trend slope coefficients.

In the Russian part of the Selenga River basin, where giant icings observed in Mongolia are absent, we examined groups of icings in individual small catchment basins within the Selenga mid-mountain region. Using the technology described above, we analyzed the dynamics of icing areas at key study sites from 1990 to 2024, as well as interannual variability in the total icing area of the Selenga mid-mountains for specific years (1990, 2000, 2018, and 2022).

Meteorological data on temperature and precipitation were obtained from weather stations located in Russia and Mongolia.

3. RESULT AND DISCUSSION

The studied icings belong to different genetic types, including riverine icings, groundwater icings, and spring-fed icings [6; 7]. The giant icings in the Mongolian part of the Selenga River basin likely have a mixed origin. They form on medium-sized rivers such as the Ider, Delgermurun, and Eg when water flow freezes in the river channels [8; 9]. These icings flood the floodplains, and their growth continues until the end of the cold season, sustained not by river water but by water influx from subchannel taliks, alluvial deposits of river valleys (groundwater), and deep aquifer springs.

In the Russian part of the basin, groundwater icings predominate, accounting for up to 70% of all the icings in the area [10].

The interannual variability of all the mentioned icing types is most significantly influenced by the amount of warm-season precipitation preceding icing formation, the air temperature that determines seasonal freezing conditions [11], and the state of permafrost.

On average, for all the studied icings in the Mongolian part of the Selenga River basin, a statistically significant surface area reduction of 3.5% per decade was identified. These findings are consistent with previously published data for specific sections of this territory [8]. The minimum average icings surface areas were recorded in 2008, 2012, and 2016, while the maximum values occurred in 1995-1996, 2002, and 2004.

Figure 2 shows the dynamics of the giant icing surface area on the Eg River. A clear decreasing trend in the surface area is evident. The same pattern is observed for other giant icings in the Mongolian part of the Selenga River basin.

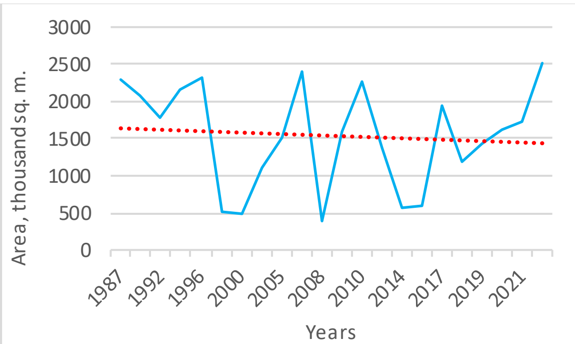

Figure 2. Long-term variability of the giant icing surface area in the Eg River valley

Despite differences in icing formation conditions, a similar pattern is observed in the Russian part of the basin (Fig. 3).

Icings surface areas are decreasing both in individual studied basins and across the entire territory as a whole. In 1990, the total icings' area in the Russian part of the Selenga middle mountains was 269.3 km², while currently (as of 2022), this value has decreased to 206.4 km², that is by 6,7% over a decade. At the same time, against the background of decreasing icings sizes, their number is increasing. A fragmentation of very large icings into smaller ones is observed, forming further downstream [10]. Thus, the average rate of icing reduction across the entire basin exceeds 5% per decade.

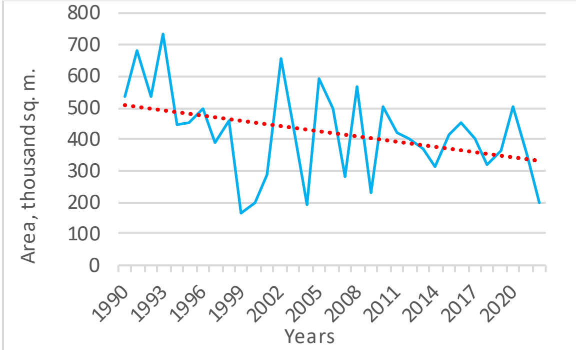

Figure 3. Long-term variability of the giant icing surface area in the Kuitunka river basin

In our view, these processes result from changes in permafrost-hydrogeological conditions due to climate warming. Rising air temperatures in the region have reduced the seasonal freezing depth. In permafrost-affected areas, active layer thawing has increased aquifer thickness, allowing groundwater to circulate more freely during cold seasons. Consequently, water increasingly bypasses icing formation zones, either draining away or contributing to streamflow, which leads to reduced icing extent and volume, icings fragmentation and displacement of their locations.

The basin-wide consistency of these changes suggests they reflect regional-scale impacts, aligning with observations from northern permafrost zones [12]. Notably, forest cover degradation may further alter groundwater storage patterns, though this requires dedicated study.

4. CONCLUSION

Based on the conducted research, the following main conclusions can be drawn:

1. During the study period (1986-2022), the areas of giant icings in the Mongolian part of the Selenga River basin have decreased by an average of 3.5% per decade.
2. In the Russian part of the basin, where permafrost is predominantly sporadic, the total area of icings decreased by more than 20% between 1990 and 2022 (by 6,7% over a decade). At the same time, an increase in their total number has been observed.
3. The reduction in the icings surface areas, their redistribution across the landscape, and fragmentation are associated with global climate change. Rising near-surface air temperatures affect

both seasonal and permafrost. There is a decrease in seasonal freezing depth and thawing of the permafrost table. This leads to more intensive circulation of icing-forming waters, which affects the size of icings.

Thus, the icings in the Selenga River basin serve as a reliable indicator of cryolithozone transformation under the influence of climate change.

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