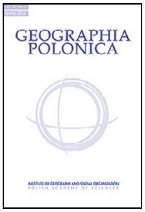

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ICE COVER PHENOLOGY OF TWO HIGH-ALTITUDE LAKES ON THE SLOVAK SIDE OF THE TATRA MTS. (2016-2024)

Kristína Hrivnáková • Silvia Čajková • Juraj Hreško

Department of Ecology and Environmental Sciences, Faculty of Natural Sciences and Informatics
Constantine the Philosopher University in Nitra
Tr. A. Hlinku 1, 949 01 Nitra: Slovak Republic
e-mail: kristina.hrivnakova@ukf.sk (corresponding author)

Abstract

The first multi-year examination of the phenological phases of lake ice cover in this area utilized a two-source method to address the constraints of this environment. Higher air temperatures impacted the reduction in ice cover duration, while its fluctuation and windiness influenced the occurrence of repeated freeze-thaw events, ultimately extending these periods. The extended duration of ice cover at higher elevation lake (CID +56 days, IP +75 days) can be attributed to later and prolonged break-ups (BUS +48 days, BUE +64 days, BUD +16 days). Studying these factors' interaction with the lake's characteristics (such as their morphology and the presence of flow) and their surroundings (including topography) has enhanced our understanding of the dynamics of this crucial component of the high mountain cryosphere.

Keywords

high mountain cryosphere • lake ice phenomena • optical satellite images • Sentinel-2 • webcam images • climatic and local factors

Introduction

The presence of ice cover on lakes is a crucial seasonal aspect of the cryosphere (Duguay et al., 2015), serving as a direct indicator of climate change (Latifovic & Pouliot, 2007; Adrian et al., 2009; Benson et al., 2012) through its variability and trends in freezing, thawing, and duration (ice cover phenology) (Kropáček et al., 2013; Qi et al., 2020). Interest in research on this topic has grown in recent years, with long-term studies of lakes in the Northern Hemisphere being among the most frequently cited (Magnuson et al., 2000; Benson et al., 2012; Newton & Mullan, 2021; Su et al., 2021). The ongoing global warming and increasing climate extremes result in later freezing and earlier thawing, reducing ice cover duration and maximum thickness. This issue is projected to worsen (Fountain et al., 2012; Sharma et al., 2019; Filazzola et al., 2020).

The impact of large-scale climatic factors such as air temperature, solar radiation, wind, precipitation, and atmospheric oscillations on ice phenomena is influenced by a complex interaction with the local environment, including latitude, altitude, and topographic features, as well as the individual characteristics of lakes – their volume, depth, and shoreline ruggedness (Livingstone et al., 2009; Brown & Duguay, 2010; L'Abée-Lund et al., 2021; Leppäranta & Wen, 2022). When a lake's surface is completely covered with ice, it becomes isolated from external conditions for extended periods, leading to alterations in the physical, chemical, and biological processes within the lake ecosystem, such as evaporation, vertical stratification, oxygen content, and water quality (Weyhenmeyer et al., 2008; Kirillin et al., 2012; Woolway & Merchant, 2017; Caldwell et al., 2020). Changes in the timing of ice cover formation and melt can significantly impact lake ecology and the practical use of lake ice for human activities, affecting stability and regional water resources (Preston et al., 2016; Weyhenmeyer et al., 2022).

The historical records of ice cover conditions because of human activities serve as the foundation for long-term studies (Sharma et al., 2016; 2019; 2022; Knoll et al., 2019). While most available studies focus on lowland lakes and human-made water bodies, far fewer papers address ice phenomena in montane and alpine lakes (Livingstone, 1997; Ohlendorf et al., 2000; Hendricks & Scherrer, 2008). The limited research in these areas can be attributed to their remote locations, difficult accessibility, and the challenging conditions for field measurements during the winter season (Choiński, 2017). Additionally, modern methods like remote sensing of the Earth have limitations in this environment, including issues with cloud cover for optical methods (Kropáček et al., 2013; Cai et al., 2020; Zhang et al., 2021), lower temporal resolution for active microwave, and spatial resolution suitable for detecting large lakes for passive microwave methods (Du et al., 2017; Su et al., 2021).

It is believed that the lack of focused studies on the lakes on the Slovak side of the Tatra Mountains may be attributed to the absence of historical and direct observations in this area. Additionally, satellite imagery can challenge studying small high-altitude lakes with frequent cloud cover. However, research on ice phenomena, particularly lake ice thickness, has been carried out on the Polish side of the mountain range, especially on lakes near tourist huts that are more easily accessible. This research has been documented in works by Pociask-Karteczka and Choiński (2012), Choiński et al. (2013, 2017), Solarski and Szumny (2020), and Solarski and Rzetala (2022).

These lakes are considered susceptible indicators of climate change due to their isolated locations, extreme climate, and prolonged ice cover (Adrian et al., 2009; Adler et al., 2022). Warming trends and shorter, milder winters have also been observed in the Tatra Mountains (Żmudzka, 2011; Gądek, 2014). Long-term studies conducted on the Polish side of the accessible Morskie Oko lake reveal similar trends of decreasing ice cover duration and changing thickness (Pociask-Karteczka & Choiński, 2012; Choiński et al., 2010; Pawłowski, 2018). Additionally, studies from the Slovak side on water column temperature properties, which are used to infer the presence of ice cover, indicate the significant influence of local factors on these processes (Šporka et al., 2006; Novikmec et al., 2013; Gądek et al., 2020).

The paper aims to examine the spatio-temporal dynamics of high-altitude lake ice cover on the Slovak side of the Tatra Mountains. This involves conducting the first multiyear investigation into the various phases of lake ice formation and melt and identifying the factors influencing these processes. The study utilizes available data sources to overcome the challenges of this unique environment. Understanding the phenology of ice cover serves as an indicator of ongoing climate change in high mountain areas.

Material and methods

Local data – study area

We studied the geomorphological part of the Tatra Mountains (Western Carpathians), focusing on the transboundary range (Slovak/Polish) High Tatra Mts. With an area of 341 km^2, this mountain range is the world’s most miniature with typical alpine characteristics, shaped by glacial activity and subject to sudden and often extreme weather changes of an alpine climate. The youngest natural formations resulting from Pleistocene glacial activity are glacial lakes, referred to as “pleso” in Slovakia and “staw” in Poland. These lakes began to take on their current form approximately 20,000 years ago, while bodies of liquid water began forming around 8,800 years ago, following the melting of the last glaciers. Currently, the water in these lakes is no longer of glacial origin; instead, it comes from precipitation (Lindner et al., 2003; Makos et al., 2014; Zasadni & Kłapyta, 2014). The number of these lakes on the Slovak side of the High Tatra Mts. ranges from 170 to 230 due to their periodicity and gradual disappearance. In the Tatra region, the term “pleso” / “staw” is also used to describe several bodies of water that are not glacially formed but were created through human activities, stream damming, or during snowmelt in depressions, etc. Nevertheless, as in this study, limnological research in the Tatra region primarily focuses on lakes with an area exceeding 1.5 hectares with glacial origin (Gregor & Pacl, 2005; Kapusta et al., 2018).

The forest zone is a critical ecological area, above which is over 85% of the lakes. Lakes in the alpine zone typically have simple shapes, with shallow, undeveloped shorelines and steeply sloping walls. These lakes are characterized by steep scree-debris catchments, lack of vegetation and soil cover, and usually no inflow and surface outflow. The first lake studied, Ľadové pleso (2057 m a.s.l., surface area 1.7 ha, max. depth 18.0 m), is located in the Veľká Studená dolina valley

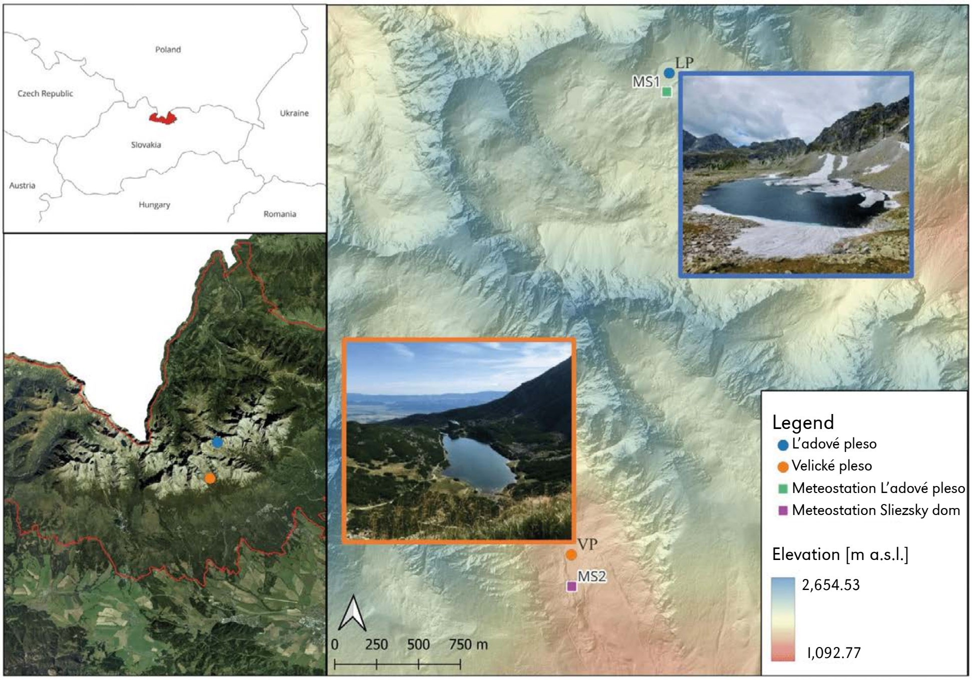

Figure 1. Map depicting the location of the Tatra Mountains study area and the lakes under study (ĽP: 49.1840039N, 20.1614250E and VP: 49.1576808N, 20.1558811E) and the meteorological stations of the Avalanche Prevention Centre of the MRS of the SR, which provided the data
Note: ĽP (Ľadové pleso), VP (Velické pleso), MRS of the SR (Mountain Rescue Service of the Slovak Republic).

Map source: www.zbgis.sk

(Fig. 1) and is inaccessible to tourists. The second lake, Velické pleso (1665 m a.s.l., surface area 2.2 ha, max. depth 4.6 m), is situated in the subalpine zone of the Velická dolina valley, near the popular Mountain hotel Sliezsky dom (Fig. 1). Lakes in this zone are generally larger, with shallower and more rugged shorelines. Their catchment areas are often covered with grassland and dwarf mountain pine – *Pinus mugo* (although they still belong to oligotrophic lakes), and they typically have surface inflow and outflow (Gregor & Pacl, 2005; Novikmec et al., 2013).

Ice cover data

The study lakes were chosen based on their potential to utilize a combination of two methods to overcome the individual technological limitations of each technique and the challenges posed by the high mountain environment. The first method, multi-source analysis, involved using Sentinel-2 optical satellite imagery with a spatial resolution of 10-60 m and a 5-day temporal resolution during low cloud days (Fig. 2), which is accessible through the EO viewer platform (https://services.sentinel-hub.com) as part of the European Space Agency's Copernicus program. The Sentinel-2 L1C images are from June 2015, while the Sentinel-2 L2A images are from March 2017 and include atmospheric correction and global coverage.

The optimal placement of two meteorological stations from the Avalanche Prevention Centre of the Mountain Rescue Service of the Slovak Republic provides a direct view of the designated lakes (Figs. 1 and 2), enabling this method as a secondary resource in the analysis. The first lake under study is Ľadové pleso, with the meteorological station Ľadové pleso (MS1 – Fig. 1) positioned approximately 70 meters to the south (49.1829400N, 20.1612600E) of its shoreline (operational since spring 2015). The second lake available for monitoring is Velické pleso, located near the Mountain hotel Sliezsky dom, where the meteorological station Sliezsky dom (MS2 – Fig. 1) is situated (49.1561200N, 20.1559719E) (operational since autumn 2016). The webcams capture images at hourly intervals.

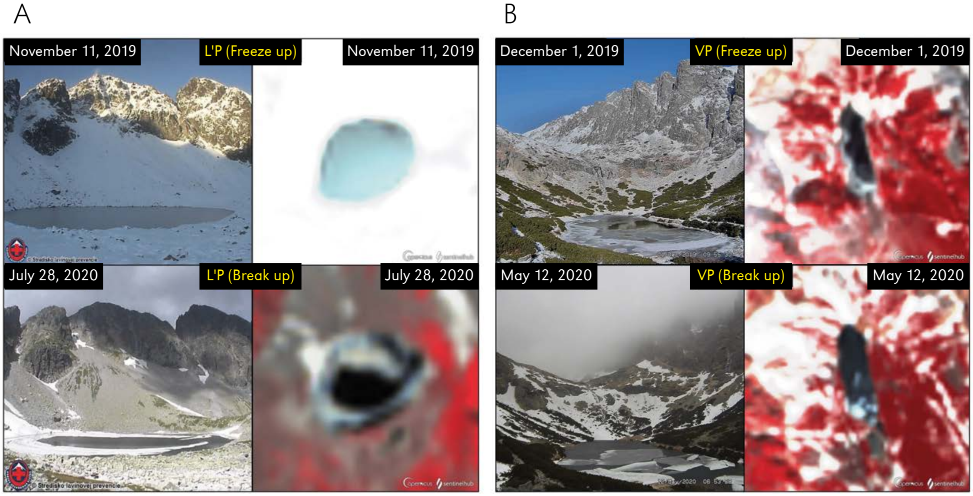

Figure 2. Freezing and thawing process of lake Ľadové pleso (A) and Velické pleso (B) during the year 2020, as captured in webcam images from the meteorological stations (APC, MRS of the SR) and satellite images (Sentinel-2 L2A, European Space Agency). (Data downloaded: March 2024)
Note: ĽP (Ľadové pleso), VP (Velické pleso), APC (Avalanche Prevention Centre), MRS of the SR (Mountain Rescue Service of the Slovak Republic). Satellite images are in False colour (combination of bands 8,4,3) with 10 m resolution. White or pale blue indicates lake ice/snow and black *usually* represents open water.

Data from these stations can be accessed on the meteoportal (https://meteo.hzs.sk/), with an online archive available for up to 7 days. All data are processed and stored at the Avalanche Prevention Centre of the Mountain Rescue Service of the Slovak Republic.

Combining these two methods enabled data analysis from the hydrological years 2016-2024 (spring 2016-autumn 2023). A hydrological year is the period from the 1st of October to the 30th of September of the following calendar year (Yang et al., 2019), aligning with the typical seasonal pattern encompassing ice phenomena. For freezing, the analysis covered the period of hydrological years 2017-2024, while thawing was studied for hydrological years 2016-2023, along with the duration of the ice cover during hydrological years 2017-2023.

During the study period, 102 satellite images and 170 camera images were utilized for lake Ľadové pleso, and 97 satellite images and 150 camera images were used for lake Velické pleso to analyse the ice cover. Additionally, six satellite images were employed for part of the valley Veľká Studená dolina. The freezing and thawing dates of the lake ice, obtained through multisource analysis, were used to create a database. Various established definitions of ice cover (Kropáček et al., 2013; Cai et al., 2020; Qi et al., 2020) were defined based on this data, as shown in Figure 3.

Climatic data

During the study period (hydrological years 2016-2023), we utilized consistent climatic data from the aforementioned meteorological stations, including air temperature [°C] and wind strength and gusts [m/s], to analyse climate sensitivity. In examining the impact of air temperature on ice cover phenology, we computed mean values for periods based on similar studies (Latifovic and Pouliot, 2007; Kropáček et al., 2013; Choiński, 2017) and the seasonality in the Tatra Mountains under study (Tab. 2).

Statistics

We utilized descriptive statistics, time series plots, and bar charts to analyse trends in individual ice cover phenological phases and present them visually using MS Excel. We evaluated the correlation between ice cover parameters at different sites and their relationship with climatic and non-climatic factors through observation, comparison with climatic plots, and Pearson correlation analysis, using a t-test to determine the significance of the correlation coefficient (r) in Past 4.15 Statistical Software.

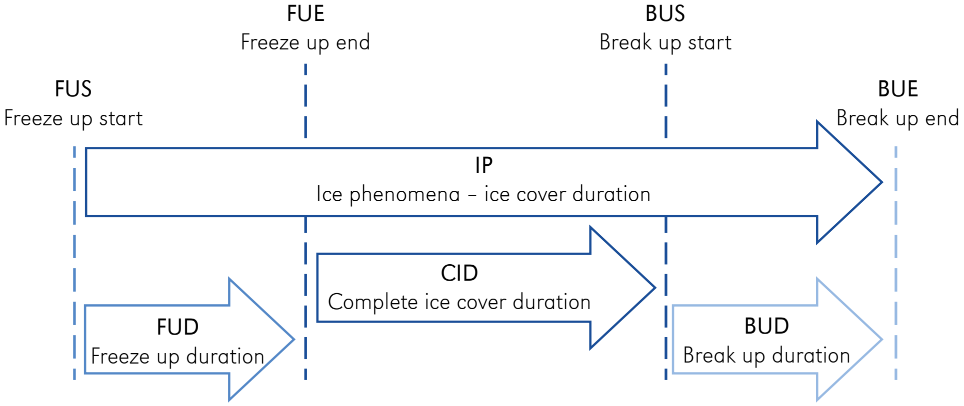

Figure 3. Graphical representation of the temporal evolution of the lake ice cover according to Yang et al. (2019) (ed. Hrivnáková, 2024)

Table 1. Summary of ice cover records for study lakes (ĽP and VP) during hydrological years 2016-2024

Phenological phases	HY	n	Ľadové pleso		Velické pleso		ĽP-VP	ĽP:VP
			Avg ± SD	(min – max)	Avg ± SD	(min – max)	Difference	r
FUS (Freeze up start)	2017-24	8	306 ± 13	(278 – 317)	315 ± 9	(298 – 329)	-9	0.44
FUE (Freeze up end)			318 ± 18	(282 – 333)	328 ± 10	(305 – 336)	-10	0.33
FUD (Freeze up duration)			12 ± 7	(4 – 21)	13 ± 6	(6 – 21)	+1	0.13
BUS (Break up start)	2016-23	8	158 ±15	(125 – 174)	110 ± 12	(93 – 125)	+48	0.43
BUE (Break up end)			201 ±13	(178 – 217)	137 ± 11	(116 – 149)	+64	**0.83**
BUD (Break up duration)			43 ± 9	(27 – 53)	27 ± 8	(17 – 37)	+16	-0.18
IP (Ice cover duration / Ice phenomena)	2017-23	7	263 ± 12	(245 – 284)	188 ± 8	(173 – 197)	+75	0.00
CID (Complete ice cover duration)			205 ± 13	(188 – 232)	149 ± 8	(132 – 157)	+56	-0.05

Note: ĽP (Ľadové pleso), VP (Velické pleso), HY (hydrological year), n (number of records), SD – standard deviation. Avg. indicates the average day/number of days (min – minimum and max – maximum values in parentheses) for the period under study (HY). FUS, FUE, BUS, and BUE are the specific day of the year (Julian day number). FUD, BUD, IP, CID, and difference (ĽP-VP) are the number of days. The bold number in the last column represents statistical significance at the 95% confidence level ($p < 0.05$) (t-test). r is the correlation coefficient.

Results

The analysis results of the individual characteristics of the ice cover phenology of lakes Ľadové pleso and Velické pleso during the hydrological years 2014-2016 are presented in Table 1 and Figures 4 and 5.

Based on the data presented in Table 1 and Figures 4 and 5, it is evident that there are no significant differences in the freezing processes. The study indicates that the lakes typically begin to freeze over (FUS) in the first half of November, with a relatively short freeze-up period (FUD). Full ice coverage of the water surface (FUE) usually occurs in the second half of November. Lake Ľadové pleso exhibits continuous freezing, with a thin layer of ice forming over the entire surface and gradually thickening, eventually becoming covered with snow (Fig. 2A). In contrast, lake Velické pleso freezes gradually, starting from the shores and forming ice sheets. Various ice deformations are occasionally observed during the freezing period (FUD) on this lake (Fig. 2B).

Lake Velické pleso typically begins to thaw (BUS) in the second half of April, while lake Ľadové pleso did not thaw until the beginning of June. The duration of complete ice cover at lake Velické pleso ranges from 132 to 157 days during recorded full seasons. In contrast, at lake Ľadové pleso, the ice cover lasts an average of 56 days longer, ranging from 188 to 232 days. The thawing process for the investigated lakes (BUD) takes longer, with lake Velické pleso being completely ice-free on average by mid-May. In contrast, ice formation on lake Ľadové pleso lasts on average until the second half of July, which is statistically significantly later ($p = 0.01$). Satellite imagery with good visibility shows that the thawing and freezing of the lake Ľadové pleso is delayed against six other closely spaced lakes at approximately the same elevation. Lake Ľadové pleso thaws (in circles/ellipses) from the centre, with a more pronounced southwest direction towards the shores. The ice remains at the shores of the lake, resembling firn fields from the steep surrounding slopes. On the other hand, lake Velické pleso thaws in the direction of the currents, starting from the inflow to the outflow locations, followed by the lake shores, until ice chunks are left floating on the surface and are carried by the current to the outflow. The ice phenomena (IP) lasted 173 to 197 days on lake Velické pleso, which is on average 75 days longer than the 245 to 284 days on lake Ľadové pleso.

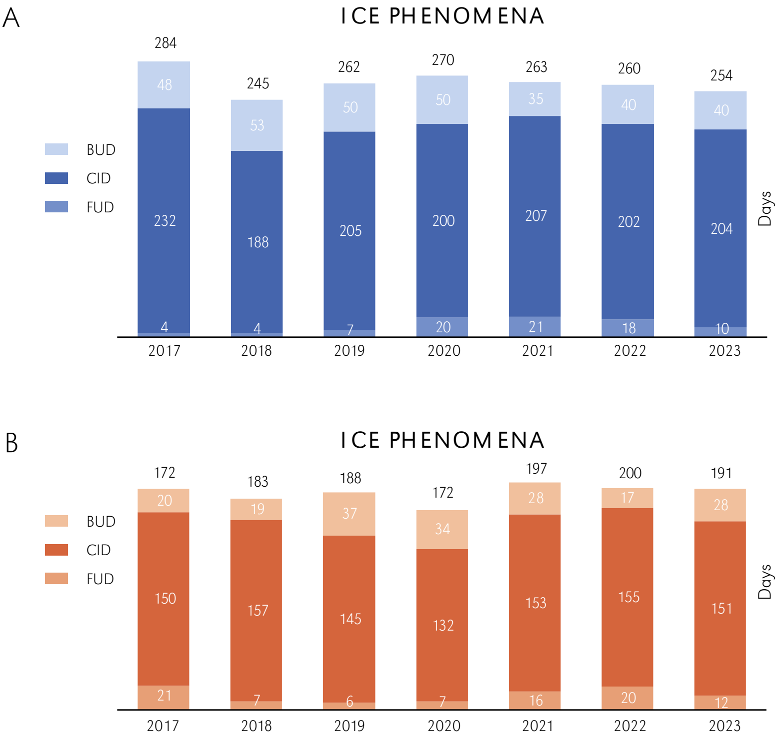

Figure 4. Duration of individual phases FUD + CID + BUD = IP of ice cover for study lakes (A) Ľadové pleso and (B) Velické pleso in individual hydrological years 2017-2023
Note: The names of the different phases of ice phenology are explained in Table 1 or Figure 3. The bar graphs show the total duration of IP (Ice phenomena) = FUD (FUS-FUE) + CID + BUD (FUS-BUS).

The results of the correlation analysis of the individual characteristics of the ice cover phenology of the lakes Ľadové pleso and Velické pleso with the average air temperature are presented in Table 2 and the correlation map (Fig. 6).

We approach the interpretation of the correlation analysis results between the phenological phases and the average air temperature with caution due to the relatively short period studied. Nevertheless, the correlation analysis reveals certain connections. The correlation map (Fig. 6) illustrates that the processes of freezing and thawing, as well as the duration of ice cover in the studied lakes, are influenced by changes in air temperatures during different seasons, with some relationships being significant (Tab. 2 – $p < 0.05$). The duration of ice phenomena (IP) and complete ice cover (CID) decrease with rising average temperatures. The characteristics of lake ice formation exhibit the most substantial correlation coefficients with average air temperature for both lakes. In years when both annual average and seasonal (except spring) air temperatures increase, we observe a shift in the onset of freezing (FUS) and the formation of total ice cover (FUE) towards later dates. At lake Ľadové pleso, the freeze-up duration (FUD) is also prolonged.

Interestingly, lower spring temperatures are recorded, especially at lake Velické pleso, in hydrological years when the lake freezes later in autumn. This indicates a shift in the winter; warmer autumn leads to colder spring and prolonged ice events. A similar trend is observed for thawing processes, with warmer average temperatures during

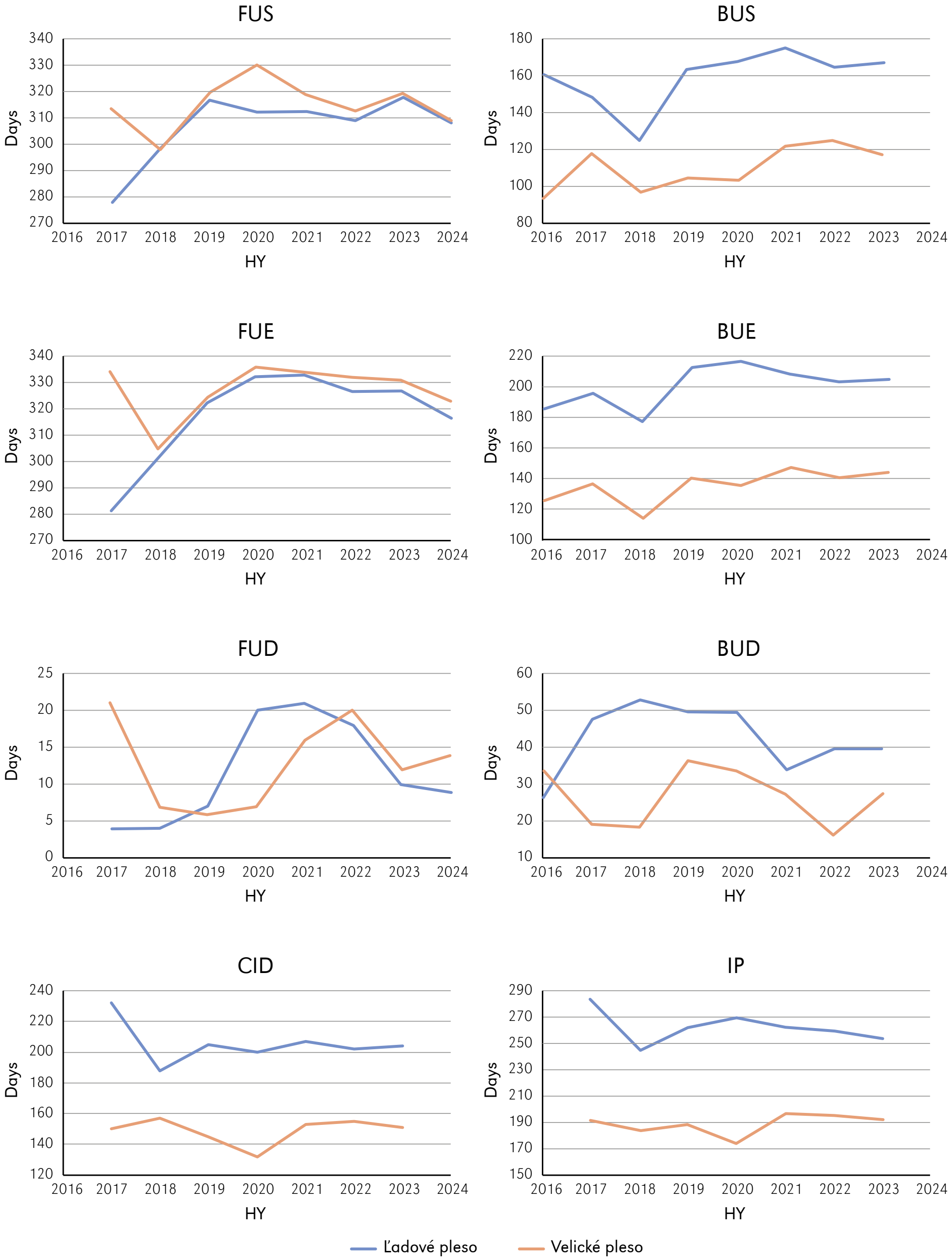

Figure 5. Temporal changes in lake ice phenology at study lakes (ĽP and VP) from HY 2015 to 2024 in freezing (FUS, FUE, FUD), breaking (BUS, BUE, BUD), and ice cover duration (IP, CID)
Note: ĽP (Ľadové pleso), VP (Velické pleso), HY (hydrological year), DOY (day of the year). The names of the individual phases of ice phenology are explained in Table 1 or Figure 3.

Table 2. Correlation coefficients between lake ice phenology parameters and annual/seasonal average air temperatures T_A [°C] (HY 2016-2023) for the two studied lakes (ĽP and VP)

Correlation coefficient	FUS		FUE		FUD		BUS		BUE		BUD		IP		CID	
	ĽP	VP	ĽP	VP	ĽP	VP	ĽP	VP	ĽP	VP	ĽP	VP	ĽP	VP	ĽP	VP
T_A (annual) Oct. 1.-Sep. 30	0.84	0.51	**0.88**	0.49	0.69	-0.02	0.32	-0.13	0.32	-0.01	-0.14	0.11	-0.62	-0.87	-0.82	-0.72
T_A (winter) Nov. 1-Apr. 30	0.60	0.59	0.79	0.54	**0.99**	-0.13	0.75	-0.16	0.78	0.04	-0.25	0.24	0.13	-0.90	-0.21	-0.81
T_A (summer) May 1-Oct. 31	**0.97**	0.61	**0.95**	0.64	0.59	0.27	0.73	0.73	0.75	0.93	-0.25	0.77	-0.31	0.53	-0.45	-0.25
T_A (autumn) Sep 1.-Nov. 30	0.72	0.86	0.80	0.75	0.71	-0.41	0.71	-0.00	0.84	0.54	0.12	0.90	0.07	-0.52	-0.26	**0.95**
T_A (spring) Mar./Apr. 1-May 31/ Jun 30	-0.31	**-0.96**	-0.44	**-0.99**	-0.61	-0.34	**-0.90**	-0.69	-0.79	-0.93	0.73	-0.80	-0.49	0.05	-0.42	0.71

Note: Bold numbers represent statistical significance at the 95% confidence level ($p < 0.05$) (t-test). T_A is the average air temperature during the (hydrological) annual/winter/summer/autumn/spring period. The time periods were determined based on similar studies (Latifovic & Pouliot, 2007; Kropáček et al., 2013; Choiński, 2017). ĽP (Ľadové pleso), VP (Velické pleso). The names of the individual phases of ice phenology are explained in Table 1 or Figure 3.

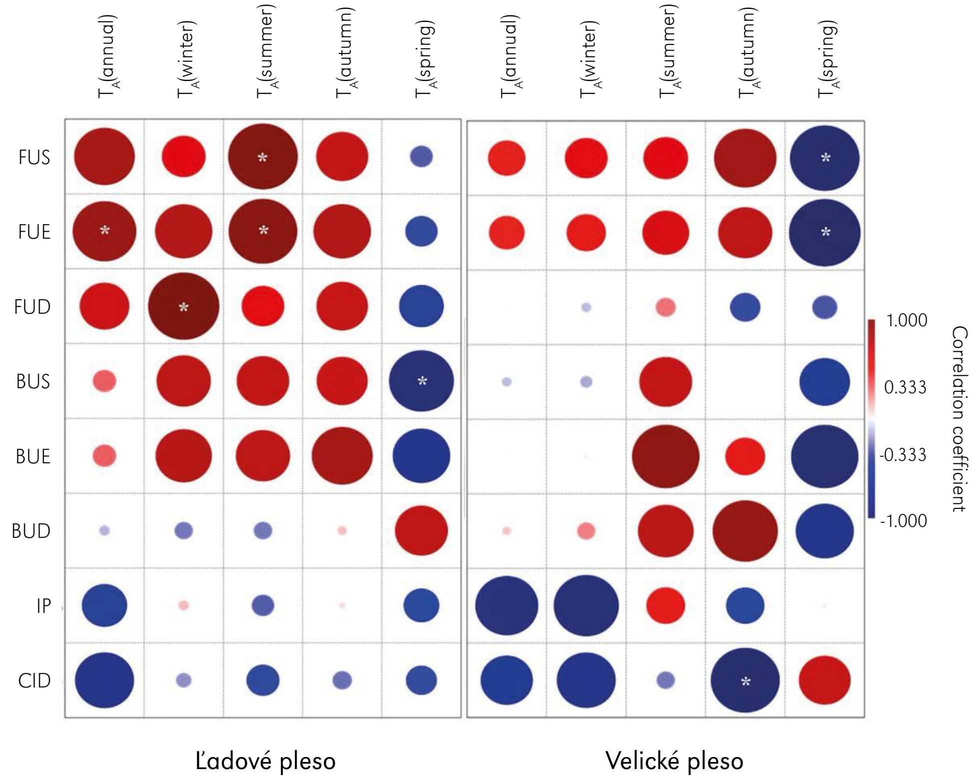

Figure 6. Correlation map showing relationship between ice cover phenology variables and annual/seasonal average air temperatures T_A (°C) (HY 2016-2023) for the two studied lakes (ĽP and VP)
Note: Red induces a positive correlation, blue induces a negative correlation. The size of the circle represents the absolute value of the correlation coefficient. * represents significance at 95% confidence level ($p < 0.05$).

winter and autumn causing the thawing phases (BUS, BUE, BUD) to occur later, and lower spring temperatures are recorded during this period.

However, gaining a more comprehensive understanding of these relationships necessitates long-term phenological data on lake ice cover and climatic conditions in the area.

Discussion

Trends of the last decade

A lasting ice cover forms annually in the high mountain lakes under study (Šporka et al., 2006; Novikmec et al., 2013). These lakes typically start freezing from early October to early December, resulting in complete ice cover. The thawing period ranges from the beginning of April to the end of July. The duration of complete ice cover varies from 132 to 232 days, while the duration of ice events ranges from 173 to 284 days (see Tab. 1, Figs. 4 and 5). Similar trends have been observed by Novikmec et al. (2013).

Despite the relatively short observation period, data availability since 2016 justifies the analysis of the obtained data. These hydrological areas are significant and have been understudied regarding ice cover (Thompson et al., 2005; Adrian et al., 2009). Our findings can help identify and describe the ice cover phenology in this area, providing valuable data for future studies and facilitating the analysis of long-term trends. Several factors influence the characteristics of the ice cover.

Influences of air temperature and wind

In our short-term study, we observed a relationship between higher average air temperatures (annual/seasonal) and a shift in the freezing and thawing of the study lakes to later and earlier dates, along with a reduction in the duration of the ice cover (Tab. 2, Fig. 6).

It's important to note that a decade of data is insufficient to reliably detect significant trends and fully evaluate the impact of climate change (Hodgkins, 2013), unlike long-term studies (Magnuson et al., 2000; Benson et al., 2012; Newton and Mullan, 2021; Su et al., 2021). There have also been observations of lower air temperature increases and milder winters in the Tatra Mountains (Żmudzka, 2011; Gądek, 2014). Studies from the Polish side of the Tatra Mountains have demonstrated that the duration of ice events on the Tatra lakes is significantly decreasing, and the maximum thickness of the ice cover is changing, primarily due to climate change and gradual warming (Choiński et al., 2010; Pociask-Karteczka & Choiński 2012; Pawłowski, 2018).

The duration of freezing and thawing periods at lake Ľadové pleso and the winter season in the Tatra Mountains appear to be extending. In years with notably warm and prolonged autumns, the onset of freezing is delayed, leading to more extended winter conditions in spring. This results in a shift of thawing processes to later dates and *vice versa* (see Fig. 6). Additionally, we have observed more frequent occurrences of "refreezing" and "rethawing" events of the lakes during different phases (FUD, BUD), a phenomenon that has been observed more frequently in recent decades (since 2000) and attributed to climate change (Guo et al., 2017; Sharma et al., 2021).

The events also led to significant variations in the individual phenological phases of ice cover in some years (Fig. 5). For instance, during the study period, both lakes froze roughly simultaneously. Still, in the hydrological year 2017, lake Ľadové pleso started freezing as early as 278 day of the year (October 4th, 2016), with the freezing period lasting only four days. In contrast, the lower lake Velické pleso didn't show detectable ice until more than a month later, on the 313th day of the year (November 8th, 2016), and even experienced a complete thaw on November 22nd, only to refreeze on November 27th, leading to a complete and permanent ice cover on November 29th. Due to the frequent and significant variability of climatic conditions that autumn, lake Velické pleso repeatedly froze and thawed for up to 21 days – a maximum recorded period. This difference was likely due to the influx of Arctic air that began on October 4th and lasted for a week (Siman & Šinger, 2016). The temperatures at higher elevations were low enough to freeze lake Ľadové pleso, and the ice cover remained intact during the subsequent warming period. Meanwhile, the lakes at lower elevations did not freeze during this period or began to freeze only in early November, about a month later.

During the research period, we noted that sudden fluctuations in climatic factors such as air temperature and wind intensity significantly impacted ice cover dynamics. For instance, as the studied lakes (Ľadové pleso: HY 2018 and 2019; Velické pleso: HY 2019) were thawing, the gradual warming and melting process was interrupted by a sharp drop in temperature combined with strong winds, causing the water surface to cool and the lakes to refreeze (Lei et al., 2011). Nevertheless, the same strong winds also hastened the thawing process by breaking up and dispersing floating ice objects during the final thawing stages in the studied lakes (Leppäranta, 2009; Kirillin et al., 2012). High-altitude environments are known for unstable and rapid weather changes (Novikmec et al., 2013). The sudden and often extreme variations in climatic factors significantly impact the delicate phenology of lake ice (Adrian et al., 2009; Leppäranta, 2009; Livingstone et al., 2009; Adler et al., 2022).

Effects of local factors

In addition to comparing the extracted ice cover phenology data of the study lakes with climatic variables, we also concentrated on local factors to pinpoint the primary drivers of ice cover dynamics over the past decade. Connecting ice phenology to environmental influences is a complex undertaking (Livingstone et al., 2009), and the intricate nature of these factors can result in atypical characteristics of lake ice phenology in certain lakes (Kouraev et al., 2007).

Elevation

Elevation is a crucial local factor that is also impacted by climatic conditions. The difference in elevation between lake Ľadové pleso in the alpine zone and Velické pleso in the subalpine zone significantly influences the duration of ice cover. As elevation increases, the duration of ice cover is primarily influenced by thawing processes (BUS, BUE), leading to notable differences. Lake Ľadové pleso thawed much later (BUS +48 days, BUE +64 days – statistically significant) and remained frozen for a longer duration (BUD +16 days) compared to lake Velické pleso in the subalpine zone (Tab. 1, Fig. 5) (Novikmec et al., 2013). Our analysis confirms that lake freezing is not dependent on elevation (Šporka et al., 2006) and that the freezing phases (FUS, FUE) of the lower-lying lake Velické pleso lag slightly behind those of lake Ľadové pleso in the alpine zone (Tab. 1, Fig. 5). The thawing of lakes is primarily controlled by external meteorological forces, which mainly act through height-dependent air temperature, with a decrease of 0.6 °C per 100 m in the Tatras (Konček & Orlicz, 1974). On the other hand, the freezing of lakes is more dependent on individual lake characteristics (Duquay et al., 2006). Additionally, warm autumn inversions at higher altitudes may play a minor role (Šporka et al., 2006; Livingstone et al., 2009).

The variability of lakes at the same altitude is also influenced by individual lake characteristics and their surroundings (Williams et al., 2004; Šporka et al., 2006; Choiński et al., 2013). Lakes in the Tatras Mountains, located at approximately the same altitude, exhibit diverse morphometric characteristics and are challenging to classify (Gądek et al., 2020).

Morphometry

The valley Veľká Studená dolina is known for having the highest number of lakes (Gregor & Pacl, 2005). Satellite images of the valley, with good visibility, have revealed the presence of lakes near lake Ľadové pleso.

Although we lack accurate phenological records of these lakes, as there are no webcams nearby, clear satellite images during the hydrological years 2016-2024 indicated that lake Ľadové pleso freezes and thaws later and for a notably longer duration than the surrounding lakes. We posit that this delayed freezing is due to its substantial depth and area, making it the largest and deepest lake in the valley. Consequently, it stores more heat, requiring lower temperatures and greater energy to initiate the freezing process. The depth of the lake can significantly influence the amount of heat it stores, leading to the delayed onset of ice formation as thermal inertia mitigates the impact of external conditions (Williams et al., 2004; Brown & Duguay, 2010; Yang et al., 2019). Initial ice cover, known as primary ice, forms on the surface of a lake, followed by downward thickening into the water column (Fig. 2A) (Kirillin et al., 2012; Zhang et al., 2021).

Topography

In high-altitude environments, the accumulation of snow layers is crucial (Solarski & Szumny, 2020) and significantly impacts the thawing processes. Initially, a substantial layer of snow must melt before the actual ice melting can occur, with solar radiation levels playing an important role (Livingstone, 1997; Duguay et al., 2003; Novikmec et al., 2013). The orientation of the ice cover on both lakes is not expected to be significantly affected by topographic shading, which is particularly important in high mountain environments (Šporka et al., 2006; Choiński et al., 2013; Novikmec et al., 2013).

The topographic features of the area, as documented by Šporka et al. (2006), Choiński et al. (2013), and Novikmec et al. (2013), play a significant role in the ice processes of lake Ľadové pleso. The steep terrain and susceptibility to avalanches can lead to the accumulation of snow, as observed in the Tatra Mountains (Žiak & Dlugosz, 2015; Solarski & Szumny, 2020; Solarski & Rzetala, 2022). Notably, the ice on lake Ľadové pleso melts fastest in the central area, resulting in a thinner ice cover that gradually thickens towards the shore in a circular pattern (Solarski & Szumny, 2020).

The firn fields on the steep surrounding slopes that feed into the lake were the final remnants of ice before the complete thawing of the lake (Figs. 1 and 2A). These fields are crucial in lowering the lake surface water temperature (LSWT) and consequently slowing down the melting process (Thompson et al., 2005). Notably, lake Ľadové pleso is one of the last lakes to thaw, and even during hot summer months (see Figs. 1 and 2A), ice persists (the latest recorded date of complete thaw being 217 days into the year – August 4th, 2020), hence its name (Bohuš, 1996).

Flow

The characteristics of the ice cover processes in lake Velické pleso highlight its unique nature. Unlike lake Ľadové pleso, which lacks inflow and surface outflow, lake Velické pleso is influenced by sub-ice cover circulation. The inflow and outflow temperature and flow rate affect the lake's water retention time, impacting the freezing and thawing processes. As a result, some of the Tatra Mts. lakes do not have complete ice cover in winter (Choiński et al., 2013; Sharma et al., 2020; Solarski & Szumny, 2020).

At lake Velické pleso, the tributary froze last at the inflow and outflow points, with the freezing starting at the shallow shores and thawing first (Fig. 2B) (Sun et al., 2023). If the tributary had not opened the water surface earlier, considering the thaw's beginning (BUS), the onset of thaw at this lake would have been dated somewhat later. A similar impact of the flow on the ice cover and the transport of melting ice to the outflow was observed at the long-studied Tatra lake Morskie Oko on the Polish side of the Tatra Mountains (Choiński et al., 2010). At lake Velické pleso, ice melting at the inflow and outflow was followed by ice on shallow shores (Fig. 2B) (Šmejkalová et al., 2016). This is attributed to the morphometry of subalpine lakes, which have a shallower and more rugged shoreline zone compared to alpine lakes, where the basin slopes steeply downwards. The ice on the lake shores is thicker and melts later (Fig. 2A) (Solarski & Szumny, 2020).

Anthropogenic activity?

Lakes in remote, isolated mountainous areas with minimal human influence are considered to be the most indicative of regional climate change (Kropáček et al., 2013; Qi et al., 2019). While anthropogenic activities do not directly impact most lakes in the Tatra Mountains (Pawłowski, 2018), lake Velické pleso is situated near the popular Mountain hotel Sliezsky dom (Fig. 1), which utilizes water from the lake through its regulated outflow. Further research would be necessary to determine whether this activity affects the lake's ice cover changes. It is important to note that wastewater discharges (Solarski et al., 2011; Choiński et al., 2013; Pawłowski, 2018; Qi et al., 2019) are not expected to impact the lake and its ice cover.

Various interconnected factors influence the timing of lake ice formation and melting (Kirillin et al., 2012; Yao et al., 2013; Cai et al., 2020). Unravelling the connection between ice phenology and the local and climatic parameters mentioned above is complex but essential for forecasting the potential impacts of their alterations (L'Abée-Lund et al., 2021).

Conclusion

Utilizing a two-source analysis, we identified the individual phases of the lake ice cover phenology on the Slovak side of the Tatra Mountains for the first time, allowing for the examination of multi-year time trends. Following this, we observed the impact of environmental factors and emphasized the critical interplay of these variables in lake ice dynamics. Thorough and precise monitoring of this segment of the high mountain cryosphere is crucial for comprehending this evolving environment, and further investigation in this area is necessary. Through the monitoring and comprehension of the phenology of the lake ice cover in the Tatra Mountains, we can gain an understanding of its response to climate change and next explore its effects on ecosystems and water resources, as well as the potential consequences for human activities.

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Editors' note:
Unless otherwise stated, the sources of tables and figures are the authors', on the basis of their own research.

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