Multi-source method for analysing ice cover phenology of high-altitude (High Tatra Mts.) lakes

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Abstract

This paper presents a multi-source analysis for studying lake ice cover phenology in the high mountain environment. For the study, two lakes located in the High Tatra Mts. (southern side belonging to Slovakia), were selected. The combination of optical satellite imagery (Sentinel-2) and webcam images from meteorological stations (Avalanche Prevention Centre, MRS of the SR) with a direct view of these lakes was used. Such approach compensates for the technological limitations of separate methods and the limitations of this specific environment. It allowed for the first time to determine in detail the individual phenological phases of freezing, thawing/breaking and duration of lake ice cover on the Slovak side of this mountain range. The method might be generally applicable in high-altitude lakes which are difficult to access, small in size, and located in an area of high cloud cover, but represent a significant part of the high mountain cryosphere.

Key words: lake ice phenomena, high mountain conditions, optical satellite images, Sentinel-2, webcam images

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Introduction

Ice cover plays an important role in the seasonal dynamics of lakes at high latitudes and altitudes (Livingstone et al. 2009, Duguay et al. 2015). The periodic cycle of their freezing, thawing, and duration (ice cover phenology) is an important indicator of changes in global climate (Latifovic and Pouliot 2007, Adrian et al. 2009, Benson et al. 2012). Changes in the duration and, more generally, the presence of lake ice cover have broad implications for climate, the ecology of the ecosystems themselves,

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water balance and water quality, as well as the many ecosystem services they provide to society (Weyhenmeyer et al. 2008, Preston et al. 2016, Hampton et al. 2017, Woolway and Merchant 2017, Knoll et al. 2019, Caldwell et al. 2020). There are currently 14,800 lakes in the Northern Hemisphere, with intermittent ice cover affecting the lives of 394 million people (Sharma et al. 2019).

The reasons for monitoring ice cover phenology have changed with times. Historical phenological observations were primarily driven by practical needs, with the challenges of living in colder climates and using frozen lakes for the benefit of human activities (transport and trade, power engineering, fisheries, food storage, recreation, and sport, but also cultural and religious purposes). Subsequently the monitoring also took on ecological significance, *i.e.* that focused on monitoring climate change effects (Sharma et al. 2016, 2019, 2022; Knoll et al. 2019). Historical records represent some of the longest climate observations and are a valuable source of information on past climate trends and variability and the basis for long-term studies (Magnuson et al. 2000, Benson et al. 2012, Qi et al. 2020, Newton and Mullan 2021, Su et al. 2021).

Such field (*in situ*) observations are considered to be highly temporally accurate, but have a large number of limitations, *e.g.* terrain and weather inaccessibility (incomplete view of the lake, change of observation site, fog), human factors (multiple observers and their subjectivity, different definitions of ice cover phases, financial difficulties), poor temporal continuity and consistency of data (changing calendars, missing observations - nights, weekends and holidays, war conflicts) (Benson et al 2012, Kropáček et al. 2013, Sharma et al. 2019, Qi et al. 2019, Heinilä et al. 2021, Liu et al. 2021, Zhang et al. 2021a, Huo et al. 2022). Since the 1980s, therefore, this type of observation has been in decline (Shiklomanov et al. 2002) and is being replaced by several alternative monitoring methods.

Terrestrial observation can now also make use of recordings/images from (web)cameras placed at lakes (at weather stations, restaurants, mountain huts, and sports clubs), which is a sought-after alternative for this type of monitoring (L'Abée-Lund et al. 2021, Sharma et al. 2022). Thermistors have also started to be used to measure lake water temperature profiles directly in the field (Zhang et al. 2021, Sun et al. 2023), from which it is also possible to determine the presence of ice cover (but not in detail the different phases) (Pierson et al. 2011).

Since the late 1990s, satellite remote sensing of the Earth has revolutionised the monitoring of ice cover dynamics on water bodies. Satellite monitoring can be divided based on wavelengths and physical properties and used for automatic (or semi-automatic) feature extraction of lake ice cover phenology (Qi et al. 2019).

Optical remote sensing satellite sensors (MODIS, Landsat, Sentinel-2, AVHRR, VIIRS) (Kropáček et al. 2013, Zhang et al. 2016, Cai et al. 2020, Zhang et al. 2021a) have relatively good temporal (some even diurnal) and spatial (10 to 1000 m) resolution, but are limited by local climate factors, such as *e.g.* frequent cloud cover formation (Sun et al. 2023), daylight duration (Arctic regions) (Duguay et al. 2003, Zhang et al. 2016, 2021a), as well as the presence of aquatic plants (Ritchie et al. 2003). For automatic extractions, complex algorithms are required to remove these errors (their correction), which are particularly useful for lakes of larger sizes (Gafurov and Bárdossy 2009, Gao et al. 2010, López-Burgos et al. 2013, Li et al. 2019).

Microwave methods (Du et al. 2017, Murfitt and Duquay 2020, Su et al. 2021) are less limited by weather conditions than optical remote sensing, and are also useful in high cloud cover and polar night (Che et al. 2009, Zhang and Gao 2016, Su et al.

2021). Passive microwave remote sensing satellite sensors (SSM/I, AMSR-E and AMSR-2, SMMR, SSM/R) have high temporal resolution (two or more times per day) but low spatial resolution (2 to 25 km) and are, therefore, applicable to large bodies of water, especially those with regular shapes. Active microwave remote sensing satellites (Sentinel-1, ASAR and SAR, RADARSAT, ALOS PALSAR) provide high spatial resolution (20 to 100 m) but have limited global coverage and low temporal resolution (5-6 days) (Du et al. 2017, Su et al. 2021), which can lead to many errors for lakes with short freeze-thaw periods (Geldsetzer et al. 2010). In addition, radar signals can be affected by wind, accumulated wet snow that does not allow radar signal to penetrate below such layer (Surdu et al. 2015), and deformation of the ice cover (Murfitt and Duquay 2020).

Although it is generally argued that satellite data provide a better, more objective (top view), more economical, and more up-to-date view of ice cover phenology (Qi et al. 2019, Yang et al. 2019, Heinilä et al. 2021), each method has its unique aspects and limitations, and its use depends on the specificity of the water body under study, and it is therefore recommended to use a combination of multiple methods (Liu et al. 2021, Su et al. 2021, Huo et al. 2022).

The phenology of lake ice cover in high mountain areas has been significantly less studied that lowland and anthropogenic water bodies (Livingstone 1997, Ohlendorf et al. 2000, Hendricks and Scherrer 2008), precisely because of the limitations of these environments (remoteness and accessibility – difficult terrain and harsher conditions during winter and rapid weather change) (Choiński et al. 2013, 2016; Pawłowski 2018, Gądek et al. 2020), even though these are significant areas of the high-altitude cryosphere (long-standing ice cover, large elevation gradient in a small geographic area, isolated environment and natural state, and rapid response to climate change) (Thompson et al. 2005, Choiński et al. 2013, Pepin et al. 2015, Pawłowski 2018, Qi et al. 2019).

Regionally focused ice cover studies are scarce in the Tatra Mountains (Mts.) and research has been carried out mainly in the Polish part of this mountain range by direct observation of lakes near tourist shelters and huts (Choiński et al. 2013, Choiński 2016, 2017; Pawłowski 2018, Solarski and Rzetala 2022). The temperature regime of the Slovak Tatra Mts. lakes has been discussed in detail by Gregor and Pacl (2005); for some lakes, they also give the average period of freezing and thawing (month) and the approximate length of ice coverage of these lakes. Gądek et al. (2020) attempted to classify the Tatra Mts. lakes (also on the Slovak side) in terms of the duration of a complete ice cover, and the authors Šporka et al. (2006) and Novikmec et al. (2013) made one-year measurements of water temperature profiles in the Tatra Mts. lakes using thermistors, from which the presence of an ice cover was inferred.

The paper tests a combination of two methods, aiming to monitor the phenology of the ice cover of lakes on the Slovak side of the High Tatra Mts. for the first time in detail, despite the specificities and limitations of this area. The analysis of the ice phenomena of the two high-altitude lakes under study evaluates the strengths and weaknesses of each method on the example of one hydrological year, to obtain relevant data from available sources that will form the basis for further research in this area.

Material and Methods

Study area – glacial origin lakes

The High Tatra Mts. (341 sq.km) is the highest cross-border range of the Western Carpathians, situated between Slovakia (260 sq.km) and Poland (81 sq.km) (*see* Fig. 1). It is the smallest mountain range in the world, with a typical alpine climate and character formed by glacial activity. The last glaciers melted about 8000 years ago. The youngest natural features created by their activity are glacial lakes, known as "pleso" (an expression in Slovak) (Linder et al. 2003, Makos et al. 2014, Zasadni and Kłapyta 2014). These lakes represent more than 90% of all lakes in Slovakia (Štefková and Šporka 2001). Most of the Tatra lakes are located in the High Tatra Mts. Currently, there are 170-230 lakes on the Slovak side (Gregor and Pacl 2005, Kapusta et al. 2018). The vast majority of them (>85%) are located above the tree line and only about 70 High Tatra Mts. lakes have a surface area above 0.15 ha, the remaining lakes are even smaller in size and most of them are periodic (Gregor and Pacl 2005). The data on the number of lakes vary, because of their periodicity and their gradual disappearance (Hreško et al. 2013, Kapusta et al. 2018). The High Tatra Mts. is part of the Tatra National Park (TANAP), and a large part of the area is inaccessible to tourists - only about 40 lakes are accessible. In this study, we investigate two lakes located above the forest zone (Fig. 1), the lake Ľadové pleso (2 057 m a.s.l., 1.7 ha) in the alpine zone of the valley Veľká Studená dolina, which is inaccessible to tourists, and the lake Velické pleso (1 665 m a.s.l., 2.2 ha) in the subalpine zone of the valley Velická dolina, on the shore of which is the tourist-attractive Mountain hotel Sliezsky dom (Gregor and Pacl 2005).

Observation of ice phenomena - multisource analysis

The two lakes studied were selected based on the possibility of combining the two methods to compensate for their individual limitations in the observation of ice phenomena and the limitations of the specific high mountain environment. Two sources of lake ice observation were proposed. The first source was optical satellite imagery from Sentinel-2 (European Space Agency – Copernicus program). The Sentinel-2 data are accessible via the EO Browser platform[2], which provides access to multi-sensor data access – from multiple satellite missions. The Sentinel-2 L1C images are from June 2015 and the Sentinel-2 L2A images are from March 2017, with atmospheric correction and global coverage.

Only two meteorological stations with webcams of the Avalanche Prevention Centre, MRS of the SR, located near the lakes of the study area, provide a direct view of their water surface, which allows the use of this method as a second source in the analysis. Therefore, the first study lake is Ľadové pleso, with the meteorological station Ľadové pleso (MS1 – Fig. 1) located about 70 m south (49.1829400N, 20.1612600E) of its shore (in operation since spring 2015). The second study lake that can be monitored is Velické pleso, near Mountain hotel Sliezsky dom, where the meteorological station Sliezsky dom (MS2 – Fig. 1) is located (49.1561200N, 20.1559719E) (in operation since autumn 2016).

The webcams have an hourly frame rate. Data from the meteorological stations are available on the meteoportal[3] with an online archive for up to 7 days. All data are processed and archived at the Avalanche Prevention Centre of the Mountain Rescue Service of the Slovak Republic.

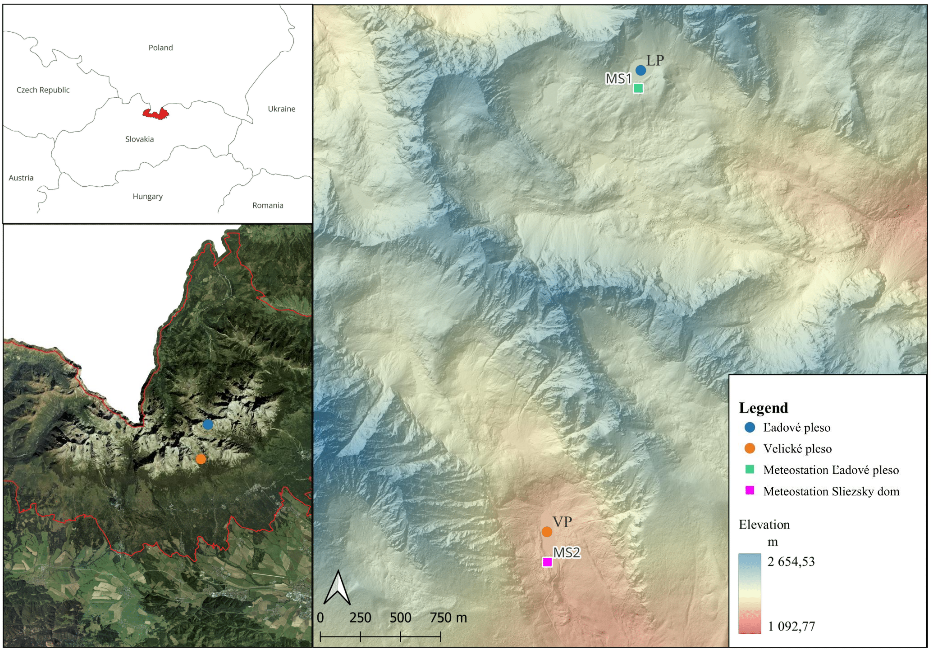


Fig. 1. Map of the location of the studied area of the High Tatra Mts., the studied lakes (ĽP – 49.1840039N, 20.1614250E and VP – 49.1576808N, 20.1558811E) and the meteorological stations of the Avalanche Prevention Centre, MRS of the SR, from which the webcam images were provided. (Hrivnáková 2024 – map base:[1]).

Extraction of individual phases of lake ice phenology

The following well-established classification (Kropáček et al. 2013, Cai et al. 2020, Qi et al. 2020) of the different characteristics/phases (Table 1) of lake ice development was used to analyse ice cover of the studied lakes.

Due to climate change, the lakes are currently experiencing so-called "extreme" events, where lakes can freeze and thaw several times during different phases, due to fluctuations in climatic factors. Therefore, it may be more difficult to determine a certain date for individual ice characteristics for some years (Yang et al. 2019). However, we still consider the first freeze up onset date (FUS) to be the day when the first ice formation appears on the lake, which may still melt completely, and the lake begins to freeze over again. Similarly, for thawing, we consider the beginning of breaking (BUS) to be the day when a free body of water first appears, even though it may still refreeze. These events thus prolong the duration of some phenological phases.

Phases		Calculation
FUS (Freeze up start)	The day on which detectable ice / ice phenomenon or formation first appears on a water surface.	specific day/date
FUE (Freeze up end)	The first day when the water body is completely covered with ice.	specific day/date
FUD (Freeze up duration)	The period from when detectable ice first appears on a water surface until it is completely covered with ice.	FUS-FUE (Days)
BUS (Break up start)	The day on which a detectable part of open water free of ice first appears.	specific day/date
BUE (Break up end)	The first day when the entire water surface is ice-free.	specific day/date
BUD (Break up duration)	The period from when a detectable portion of ice-free open water first appears to when the water surface is completely clear.	BUS-BUE (Days)
IceD / **IP** / FD (Ice cover duration Ice phenomena Frozen duration)	A period when an ice phenomenon or formation occurs on a water surface but does not have to cover the entire body of water.	FUS-BUE (Days) first day of freezing to last day of thawing
CID / CFD (Complete ice cover duration Complete frozen duration)	A period when the water body is completely covered with ice, there is no detectable open water surface.	FUE-BUS (Days) last day of freezing to first day of thawing

Table 1. Definition of the different phases of lake ice dynamics.

Results and Discussion

To the best of our knowledge from the literature and available information, there is no comprehensive dataset of lake ice phenology on the Slovak side of the High Tatra Mts., which would include more detailed multi-year observations of individual phenological phases. It is a pity that phenological observations of lake ice in this area were not been initiated in the past for the benefit of human activities – *e.g.* boating on Štrbské pleso, use of water from the lakes for the operation of mountain chalets – Popradské pleso near the Mountain Hotel Popradské pleso and Majláthova Chalet, the studied Velické pleso near the Mountain Hotel Sliezsky dom, Nižné sesterské pleso near Zbojnícka Chalet, Prostredné Spišské pleso near the Téry Hut or Zelené pleso kežmarské at The Cottage at Zelené pleso (Bohuš 2007), observations due to the safety of movement on these frozen areas – by the national park administration or by hydrological and meteorological institutes. In many regions, such (also historical) records are a valuable source of information on long-term trends in ice cover phenology (Sharma et al. 2016, 2022).

The lack of historical records in this area is mainly due to limitations of the environment, such as inaccessibility (including seasonal closure) and the difficulty and danger of the terrain (especially in winter – avalanche prone areas) (Choiński 2016, 2017) and frequent changes in climatic conditions (Novikmec et al. 2013), but also, for example, the need to train local observers (a challenge with frequently changing hut staff) to maintain the consistency and accuracy of the records (Sharma et al. 2020, 2022).

In this paper, we outline a suitable research method with options for obtaining relevant data from available sources.

Thanks to the availability of data from both sources since 2016, we had the opportunity to analyse almost a decade of data on the two studied lakes of the High Tatra Mts. We present examples of the hydrological year 2020 – the period starting from the 1st of October and ending on the 30th of September, of the following calendar year, a period with a typical seasonal pattern that captures the phenological phases of lake ice cover (Yang et al. 2019).

Regarding the most globally used method of satellite remote sensing of the Earth, the use of optical satellite sensors is most appropriate for this type of small-sized lakes with relatively rapid changes in ice phenomena. Landsat 8-9 has a suitable spatial resolution (30 m) but a very sparse temporal resolution (16 days) (Zhang et al. 2021b), which, together with the large influence of cloud cover, is not sufficient to study this area. Sentinel-2 sensors have high a spatial resolution (10 to 60 m) and a more suitable 5-day coverage and show good agreement with the real field situation (Liu et al. 2021). However, the influence of atmospheric conditions still needs to be considered (Huo et al. 2022). In the hydrological year 2020, there were only 27 days with cloud cover below 30% and 38 days with cloud cover below 50% in the area of the High Tatra Mts. from the beginning of the ice events until the complete melting of the studied lakes (beginning of November – beginning of August = 9 months) (EO Browser platform). Frequent high cloud cover in high mountain areas (Fig. 2) and thus only a few usable images (Fig. 4A) can cause a significant error in the determination of the different phases, up to several days (Latifovic and Pouliot 2007, Yang et al. 2019, Zhang et al. 2021). The authors Gądek et al. (2020) used only satellite imagery (of which there were only a few) in their analysis of the complete ice cover in the hydrological year 2017 at lake Ľadové pleso, while at lake Velické pleso web-camera imagery was also used (a few accessible via [4]), which refined the determination – a check by our detailed multi-source analysis. Due to the small size of the lakes, complex cloud correction algorithms cannot be applied (Gafurov and Bárdossy 2009, Gao et al. 2010, López-Burgos et al. 2013, Li et al. 2019).

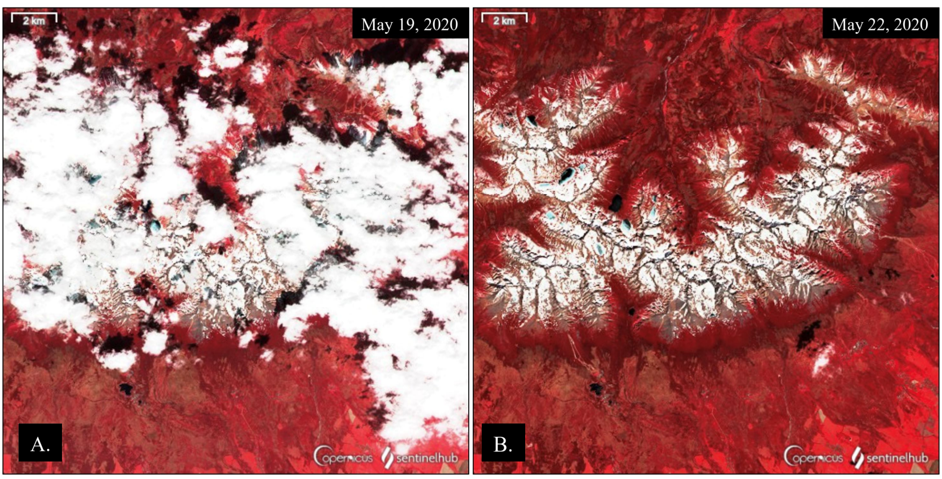


Fig. 2. Area of the High Tatra Mts. (Slovak and Polish part) covered with clouds (A) and without clouds (B) shown on satellite images (Sentinel-2 L2A, European Space Agency) (Data downloaded: February 2024).

To observe changes in the ice cover, the most suitable method is to use a popular combination of spectral bands – the false colour composite, which uses near-infrared, red, and green bands (B08, B04, B03) to highlight certain features – improving the visualization of changes in the ice cover (*e.g.*, the contrast between ice and water) and making them more resolvable for the human eye (Sun et al. 2023) (Figs. 3, 4). White or pale blue indicates lake ice/snow and black usually represents open water. However, it is not always possible to determine the phenological phase from satellite imagery, even in good visibility. Thin ice is optically dark and may also have a layer of water on top of it, its reflectivity is similar to that of open water, and optical methods cannot distinguish this difference (Fig. 3A – 14th of November 2019) (Heinilä et al. 2021, Zhang et al. 2021, Huo et al. 2022).

Using only one method is not sufficient for this type of lake and the error in such a determination can be significant up to several days (Yang et al. 2019, Zhang et al. 2021).

By suitably positioning two meteorological stations with the webcams of the Avalanche Prevention Centre of the MRS of the SR facing the studied lakes (Figs. 3, 4), it is possible to use this alternative method (L'Abée-Lund et al. 2021), as a second source for the analysis of ice cover changes, thus filling in the gaps caused by cloud cover and the limitations of optical satellite imagery. Hourly webcam imagery allows us to capture in detail the different processes that occurred during the night – for example, the lake still has a first icing – thin ice in the early morning hours, which is melted during the day, but the start of the freezing process has already occurred. However, this method also has its technical limitations, such as missing data during the exchange of the system or the displacement of the webcam (incomplete view of the lake). The operation of meteorological stations in the high mountain environments is also challenging due to the extreme climatic conditions. Snowfall, fog, or ice frost have made the images unusable on some days (Fig. 3A – 28th of November 2019).

HY 2020 Study lake	**FUS** [DOY]	**FUE** [DOY]	**FUD** FUS-FUE [Days]	**BUS** [DOY]	**BUE** [DOY]	**BUD** BUS-BUE [Days]	**IP** FUS-BUE [Days]	**CID** FUE-BUS [Days]
Ľadové pleso	Nov. 8 **312**	Nov. 28 **332**	**20**	Jun. 15 **167**	Aug. 4 **217**	**50**	**270**	**200**
Velické pleso	Nov. 25 **329**	Dec. 2 **336**	**7**	Apr. 12 **103**	May 16 **137**	**34**	**173**	**132**

Table 2. Ice cover phenology - results of the analysis of the study lakes (ĽP and VP) during hydrological years 2020.

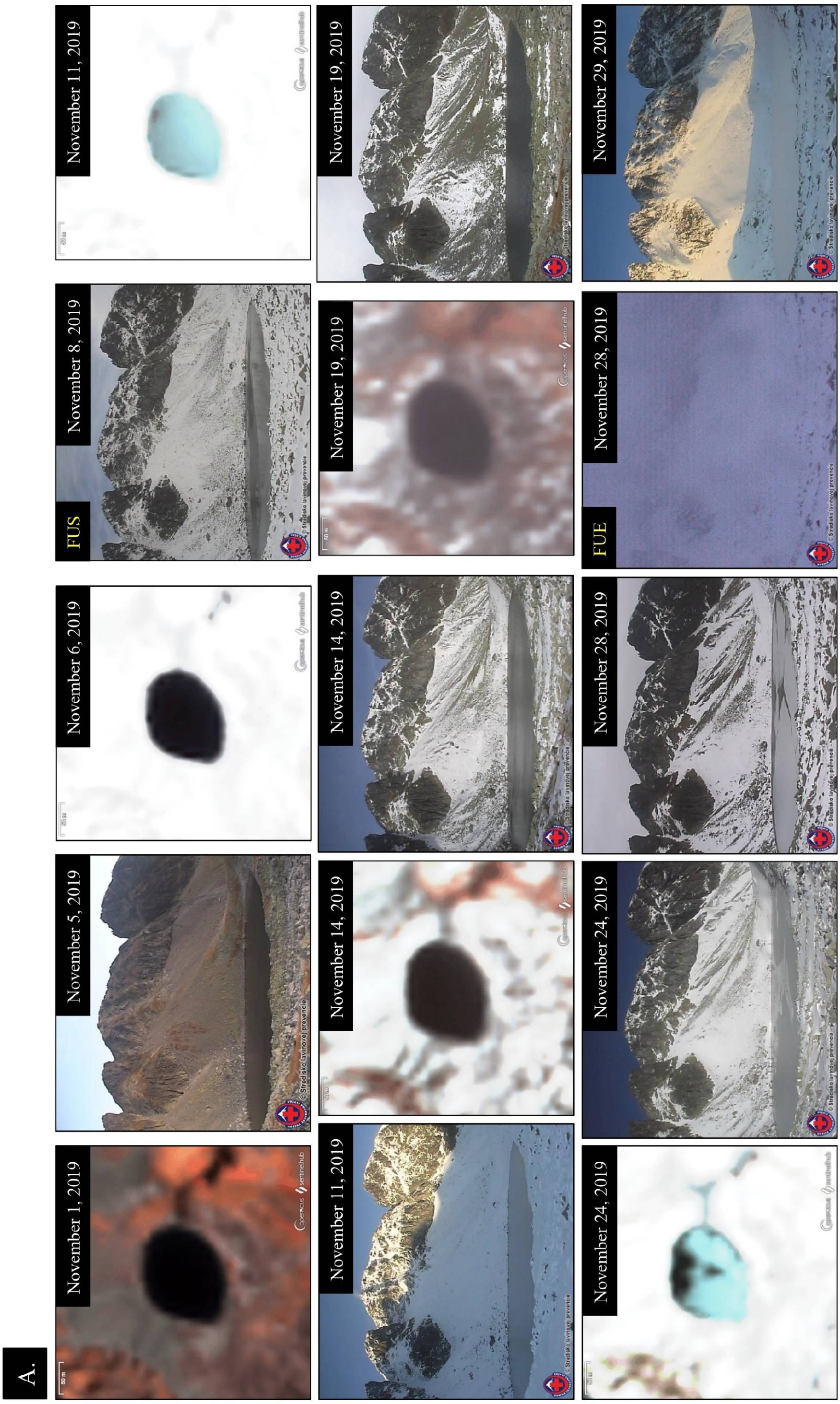
In Fig. 3A, we can see that the higher elevation lake Ľadové pleso starts to freeze up (FUS) in hydrological year (HY) 2020 on the 312th day of the year - 8 November, with the first snowfall. According to satellite and camera images, the water surface was almost completely ice-covered after only three days. Since 14 November, however, the thin ice cover has begun to thaw. On 24 November, the ice re-formed on the lake, combined with further snowfall, and completely covered the lake by 28 November. After this 332nd day of the year, there is no more break-up of the complete ice cover (FUE), and the freeze up period of the lake Ľadové pleso after thaw-freezing events, was thus 20 days (FUD). The images in Figure 4A, from our multi-source analysis, show that the 392 m lower situated lake Velické pleso begins to freeze up (FUS) in HY 2020, 17 days later, on the 329th day of the year – 25 November. The formation of a complete ice cover takes only seven days (FUD). The water surface of the lake was completely covered with ice (FUE) on the 336th day of the year – 2 December. The complete ice cover duration (CID) of lake Velické pleso lasted 132 days in HY 2020, when a detectable ice-free part of the water surface (BUS) was observed on satellite imagery at the inflow point (Fig. 4B) on the 103rd day of the year – 12 April. The lake thawed for 34 days (BUD) until 16 May – the 137th day of the year – when the last ice formations (BUE) left the water surface via the lake outflow. Ice phenomena (IP) on this lake thus lasted 173 days – almost half a year. In Fig. 3B, from the thawing of lake Ľadové pleso in HY 2020, located in the alpine zone, we observe that the lake thaws much later and the opening of the water surface (BUS), after the thawing of the thick snow layers occurs only about two months later, on the 167th day of the year – 15 June. The layers of snow and ice remain on the lake for up to 50 days (BUD), and complete melting (BUE) does not occur until midsummer in HY 2020, on the 217th day of the year – 4 August. Later and longer thaws higher up the lake significantly extend the duration of the complete ice cover (CID) to 200 days, and ice events (IP) on this lake last for almost three-quarters of the year – 270 days.

The results of our analysis (shown in the example of HY 2020 – Figs. 3,4) confirm that the use of multi-source analysis compensates for the limitations and that the proposed method allows us to determine in detail the different phases of the ice cover phenology on the studied lakes of the High Tatra Mts. (Table 2).

The capabilities of the methods used will improve as technology advances. In the future, it will be possible to use satellites in a lower Earth orbit, which are less affected by clouds (Cooley et al. 2017, 2019, Liu et al. 2021), or to place additional meteorological stations with webcams near other lakes in the Tatra Mts. Alternatively, the existing ones could be directed to the lakes (using the APC, MRS of the SR network of meteorological stations[3]).

Ice formation (freezing) and thawing (breaking) on high-mountain water bodies is a complex interaction of several climatic (extreme, rapidly changing weather – low temperatures, strong winds, high precipitation) and non-climatic parameters (altitude, lake morphometry, topography and catchment characteristics, presence of inflow and outflow), and the dominant factors may be different for lakes (Livingstone et al. 2009, Brown and Duguay 2010, L'Abée-Lund et al. 2021).

Signs of climate warming are clearly visible in mountainous areas with ongoing glacial processes (Adler et al. 2022), and in unglaciated mountains, lake ice cover, especially its dynamics, can serve as an indicator of climate change trends (Latifovic and Pouliot 2007, Adrian et al. 2009, Benson et al. 2012).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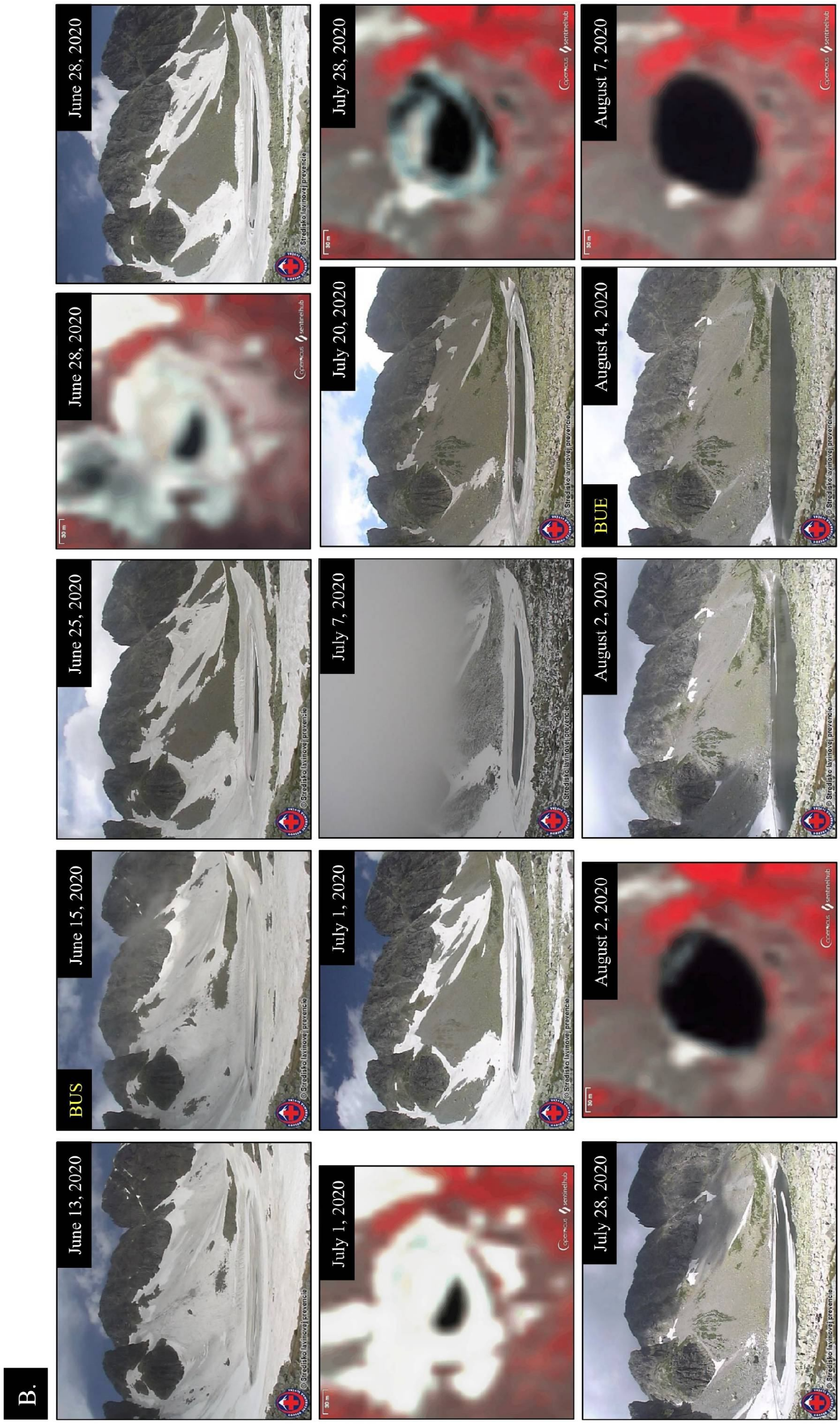


Fig. 3. The process of freezing (**A.▲**) and thawing (**B.**) of the lake Ľadové pleso during HY 2020 shown on webcam images from the meteorological station MS1 (APC, MRS of the SR) and satellite images (Sentinel-2 L2A, European Space Agency). (Data downloaded: February 2024).

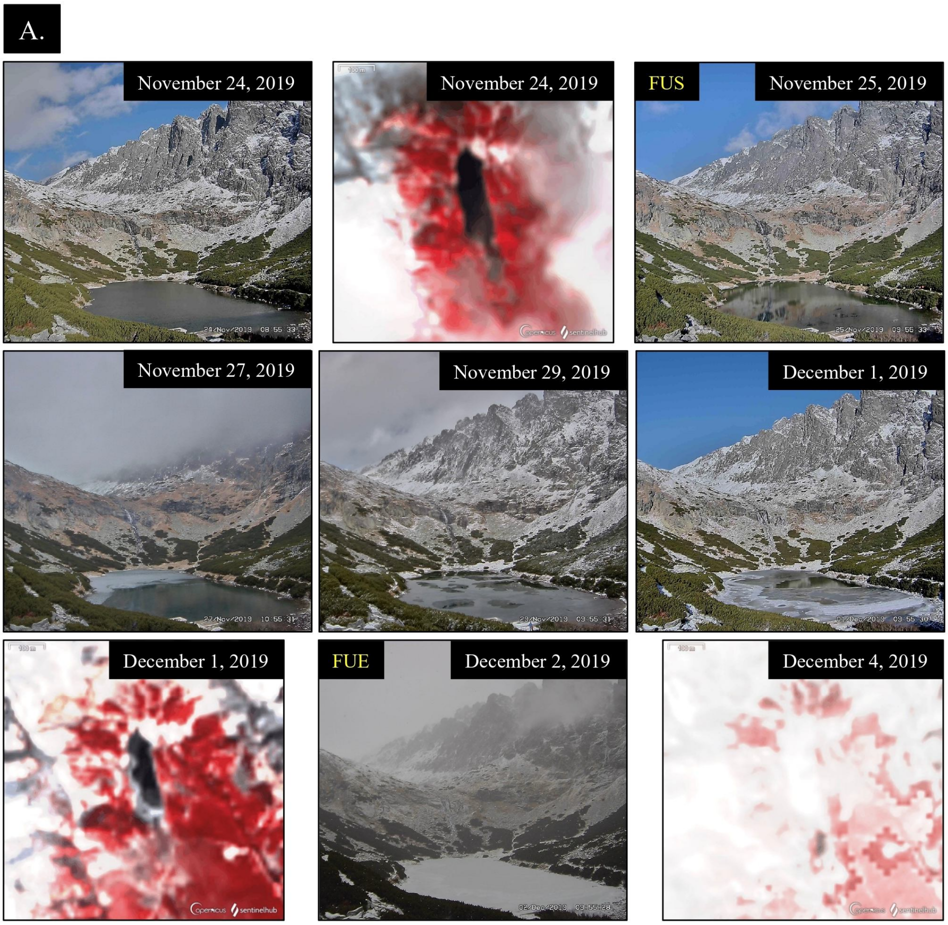
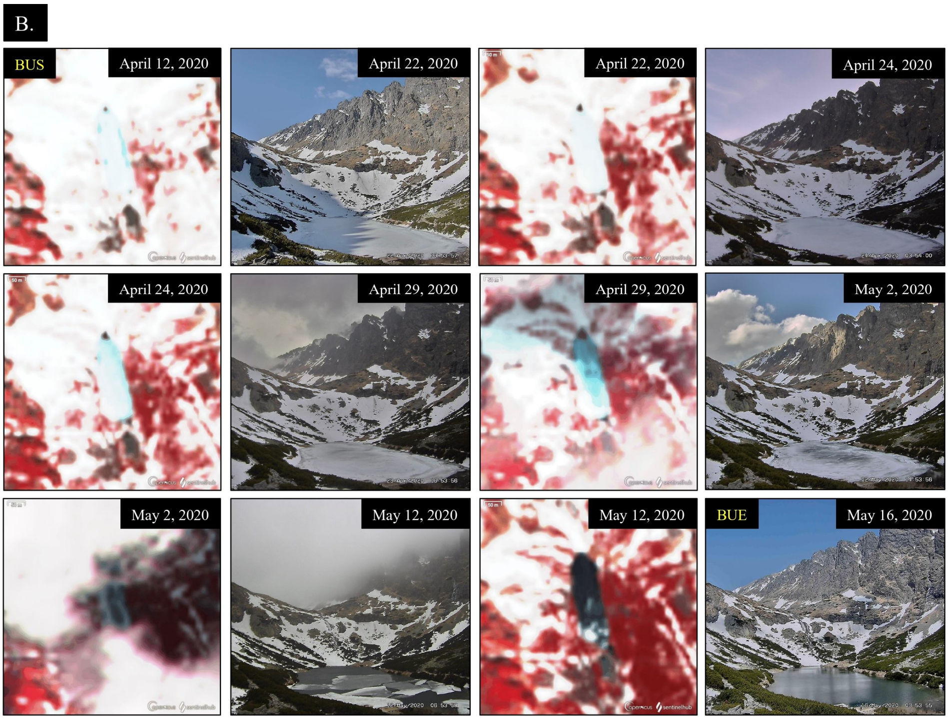


Fig. 4. The process of freezing (**A.**) and thawing (**B. ►**) of the lake Velické pleso during HY 2020 shown on webcam images from the meteorological station MS2 (APC MRS of the SR) and satellite images (Sentinel-2 L2A, European Space Agency). (Data downloaded: February 2024).



Conclusions

The difficulty of the high mountain terrain, especially during the winter season, the frequent cloud cover, and the small size of the lakes in the High Tatra Mts. are the reasons for the lack of detailed multi-year studies of their ice cover phenology (on the Slovak side). In this study, we present the applicability and suitability of a combination of multi-source observations, optical satellite imagery (Sentinel-2), and webcam records from meteorological stations for this type of lake, which compensates for the individual technological limitations and constraints of the high mountain environment. Thanks to this method, it is possible for the first time to analyse in detail the individual phases of the ice cover phenology on selected lakes on the Slovak side of the High Tatra Mts. for the last decade (2016-2024). Our data would provide a basis for long-term studies and analysis of long-term trends. Furthermore, the method will help to identify and assess the effects of climatic factors (also using climatic variables from meteorological stations) on the lakes. Moreover, follow-up studies allow to identify specific local factors of this environment that may significantly influence the spatio-temporal dynamics of ice cover, an important indicator of climate change.

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