Conditions of spatiotemporal variability of the thickness of the ice cover on lakes in the Tatra Mountains

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Abstract: This research aimed to identify the impact of local climatic and topographic conditions on the formation and development of the ice cover in high-mountain lakes and the representativeness assessment of periodic point measurements of the ice cover thickness by taking into consideration the role of the avalanches on the icing of the lakes. Field works included measurement of the ice and snow cover thickness of seven lakes situated in the Tatra Mountains (UNESCO biosphere reserve) at the beginning and the end of the 2017/2018 winter season. In addition, morphometric, topographic and daily meteorological data of lakes from local IMGW (Polish Institute of Meteorology and Water Management) stations and satellite images were used. The obtained results enabled us to quantify the impact of the winter eolian snow accumulation on the variation in ice thickness. This variation was ranging from several centimetres up to about 2 meters and had a tendency to increase during the winter season. The thickest ice covers occurred in the most shaded places in the direct vicinity of rock walls. The obtained results confirm a dominating role of the snow cover in the variation of the ice thickness within individual lakes.

Keywords: Mountain lakes; Ice cover; Tatra Mountains; Climate change; Ice phenology

Introduction

In recent years, there has been a steady increase in research on the ice phenology of lakes and reservoirs in the temperate climatic zone (Magnuson et al. 2000; SolarSKI et al. 2011; Choiński et al. 2015a; Ariano and Brown 2019; Lopez et al. 2019; Sharma et al. 2019). The studies mainly focused on linking ice regimen patterns with contemporary climate change (Magnuson et al. 2000; Duguay et al. 2003; Marszelewski and Skowron 2006; Salonen et al. 2009; Brown and Duguay 2010; Karetnikov and Naumenko 2011; Pociask-Karteczka and Choiński 2012; Choiński et al. 2015a; Leppäranta 2015; Wrzesiński et al. 2016; Hewitt et al. 2018; Likens 2019; Lopez et al. 2019). The occurrence of ice, and especially of ice cover, has been demonstrated to have a number of impacts on limnic processes, such as: the dynamics of the water mass and its thermal and oxygen conditions (Gao and Stefan 1999; Leppäranta et al. 2003; Šporka et al. 2006; Granados et al. 2020), the available light (Prowse and Stephenson 1986; Leppäranta et al. 2003; Kiili et al. 2009; Lei et al. 2011), gas concentrations (Prowse and Stephenson 1986; Terzhevik et al. 2009; Terzhevik et al. 2010), and chemical and biochemical processes (Shuter et al. 2012). Lake ice in general and that on large lakes in particular is a factor in the development of littoral geomorphology and plant and wildlife

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species (Bryan and Marcus 1972; Cox 1984). Indeed, ice and its cover may be a significant factor in the development of lacustrine biotopes and biocenoses (Greenbank 1945; Fang and Stefan 1998; McCord et al. 2000; Shuter et al. 2012; Santibáñez et al. 2019; Wüest et al. 2019). Ice phenology and changes to the lake ice regimen also influence local communities living near lakes throughout the temperate zone (Knoll et al. 2019). The overwhelming majority of available studies focus on low-altitude lakes, primarily in lowlands and uplands (SolarSKI et al. 2011; Choiński et al. 2015a). Much less is available with regards to the patterns of development of ice cover and the ice phenology of mountain and high-mountain lakes (Livingstone 1997; Ohlendorf et al. 2000). This is primarily explained by their combination of remoteness and difficult access that makes the collection of data physically challenging and, in avalanche-prone areas, also risky.

The issue of the spatial variability of ice thickness has been widely addressed in the limnological literature in relation to lowland lakes and anthropogenic water bodies located in different parts of the world (Andrews 1962; Adams and Shaw 1967; Sokolnikov 1969 after Choiński 2007a; Adams and Roulet 1980, 1984; Adams 1981, 1982, 1984; Bengtsson 1986; Choiński et al. 2006; Choiński 2007a, 2007b; Jankowski et al. 2009; Machowski and Ruman 2009; Choiński et al. 2010; Piątek et al. 2010; SolarSKI and Pradela 2010; Rzętała and SolarSKI 2011; SolarSKI et al. 2011; Choiński and Ptak 2012, 2013; Choiński et al. 2013). However, few studies have addressed the problem of surface variation in the thickness of ice on mountain lakes (Choiński 2007a, 2007b, 2016; Choiński et al. 2013). Existing research on the surface variability of the thickness of ice on lowland lakes and highland water reservoirs demonstrates that the surface variability of the thickness of the ice cover on lakes is influenced by several factors, with the compaction of the ice cover by the layer of snow accumulated on it in winter and the build-up of white snow on top of the ice cover coming to the fore (Bengtsson 1986; SolarSKI et al. 2011). In the initial stages of lake ice formation, the variation in ice thickness is small (several centimetres) which increases considerably in snowy winters (SolarSKI et al. 2011). Research by Adams and Roulet (1980, 1984) shows that the

redistribution of the snow layer by wind gives rise to local differences in the thickness of white and crystalline ice and the thickness of the snow layer accumulated thereon. The researchers have found that a thicker layer of snow (brought in by wind) accumulates near the shores, forming snowdrifts (Adams and Roulet 1980, 1984). Initially, this hinders the formation of crystalline ice due to the insulating properties of the snow, but this then triggers ice cover compaction processes, which lead to the formation of snow ice (Leppäranta 1983, 2009, 2015). Consequently, researchers have found a thicker layer of crystalline ice in the central areas of the lake, and a greater proportion of snow ice near the shores (Adams and Roulet 1980, 1984).

The history of measurements of the winter water temperature and ice thickness on the lakes included in the study dates back to 1804 when the renowned Polish scientific pioneer Stanisław Staszic explored the Morskie Oko lake (Borucki 2005; Kielkowski 2018). It was not until 1963, however, that measurements and observations of ice phenomena on this particular lake took on a more regular format (Pawłowski 2018). Additionally, nearly a decade's worth of measurements is also available from Wielki Staw Polski (1971-1979) (Choiński 2017). The earliest information about the thickness of the ice cover on the Tatra lakes and its layered structure appeared in the late 19th century (Wierzejski 1881; Birkenmajer 1901) (Table 1). The information was confirmed by Lityński (1914, 1917), who observed and described the layered structure of lake ice and found that the thickness of the lower layer is inversely proportional to the thickness of the two upper layers. Following this, Olszewski provided information on the formation of layered lake ice (Olszewski 1948a, 1948b, 1949a, 1949b, 1950, 1955), confirming Lityński's earlier observations (1914, 1917) (Table 1). Ice of considerable thickness (often in excess of 1 metre) develops as a result of the accumulation of layers of snow on the original ice, which are then saturated with water flowing out through crevices in the snow-loaded ice cover. At very low temperatures, the layer of wet snow freezes. The process repeats many times and leads to the build-up of several layers of ice separated by layers of wet, partly frozen snow or slush. Based on long-term research into the maximum thickness of the Morskie Oko ice cover (Choiński et al. 2006;

Choiński 2010; Choiński et al. 2010, 2013, 2014, 2015b), a declining trend in the annual maximum thicknesses of the ice has been identified. Researchers have also found a relationship between the thickness of the ice cover and the

depth of the lake at individual locations and the reach of the shadow cast by the southern faces of the postglacial cirque (Choiński et al. 2006; Choiński 2007a, b). The high variability in the thickness of the ice cover in the Tatras has mainly been attributed to internal factors: circulation of the waters under the ice, the supply of the basin with groundwater, and the release of heat from bottom sediments with the shading of some areas of the lake basin by mountain peaks identified as the only external factor (Choiński 2007a, 2007b; Choiński et al. 2013). This means that research has disregarded the factor that seems crucial, namely non-uniform growth of white ice from the top.

The Tatra lakes begin to freeze over near the shores, where, according to some researchers, ice reaches the greatest thickness (Birkenmajer 1901; Pacl and Wit-Jóźwik 1974; Łajczak 1980, 1982). By contrast, the ice melts the fastest in the central part of the lake, where it is thinnest (Birkenmajer 1901; Pacl and Wit-Jóźwik 1974; Łajczak 1980, 1982; Choiński et al. 2014). According to some authors, these dependencies affect the manner and rate of formation and disappearance of the ice cover on the lake (Szaflarski 1948; Łajczak 1980, 1982; Choiński 2007a, 2007b; Pociask-Karteczka and Choiński 2012, Choiński et al. 2013, Pociask-Karteczka et al. 2014; Choiński et al. 2014) (Table 1).

The objective of this research is to determine the thickness of the snow and ice covers, their spatial and temporal variability and the factors driving this variability on the seven Tatra lakes selected for the study (Figure 1; Table 2). In this way the authors expect to elucidate the following questions:

- 1) What is the impact of the local topoclimatic and geomorphological conditions on the ice phenomena on the largest lakes in the Polish Tatra Mountains?
- 2) How useful are ice thickness measurements taken in a single spot for general research on the influence of the climate on lake ice?

Table 1 Examples of the thickness of ice on lakes in the Tatra Mountains.

Lake name	Max. ice thickness (cm)	Date	Measurement taken by
Zadni Staw Polski	130	18-26.05.1932	Szaflarski 1936a,b
	175	24.03.1938	Olszewski 1948a
	260	15.05.1938	Olszewski 1948b
	267	22.04.2018	Solarski and Szumny
Czarny Staw Polski	140	25.03.1938	Olszewski 1948a
	170	14.04.1938	Olszewski 1948b
	190	14.05.1938	Olszewski 1948b
Przedni Staw Polski	115	26.03.1938	Olszewski 1948a
	155	11.05.1938	Olszewski 1948b
	220	20.03.2018	Solarski and Szumny
Wielki Staw Polski	110	27.03.1938	Olszewski 1948a
	135	28.03.1938	Olszewski 1948a
	165	29.03.1938	Olszewski 1948b
	97	1978	Choiński 2017
	100	1979	Choiński 2017
	105	20.03.2018	Solarski and Szumny
Czarny Staw Gąsienicowy	≈ 200	1892/1893	Birkenmajer 1901
	100	1911	Lityński 1917
	40-60	1911	Lityński 1917
	10	12.11.1936	Olszewski 1948a
	25	11.12.1937	Olszewski 1948b
	40	15.12.1937	Olszewski 1948a
	60	09.03.1938	Olszewski 1948b
	110	28.04.1938	Olszewski 1948a
	85	18.05.1938	Olszewski 1948b
	350	1937/1938	Olszewski 1948a
	110	11.02.2018	Solarski and Szumny
Czarny Staw pod Rysami	40-60	03.05.1911	Lityński 1917
	120	15.03.1938	Olszewski 1948a
	90	06.05.1938	Olszewski 1948b
	77*	24.03.2010	Choiński 2016
	52-95	18.02.2015	Choiński 2016
	106	08.04.2018	Solarski and Szumny
Morskie Oko	80	28.02.1891	Birkenmajer 1901
	115-120	25.03.1891	Birkenmajer 1901
	80	01.03.1892	Świerż 1893
	75	12.18.01.1893	Birkenmajer 1901
	150	12.04.1893	Świerż 1894
	100 centre	17.03.1938	Olszewski 1948a
	100 SW	17.03.1938	Olszewski 1948b
	100	05.05.1938	Olszewski 1948a
	130	08.05.1939	Szaflarski 1936a,b
	72*	1971-1980	Choiński 2017
	84	1978	Choiński 2017
	74	1979	Choiński 2017
	80	04.03.1994	Mościcki 1996
	70-100	11.04.2007	Choiński et al. 2013
	34-60	18.02.2015	Choiński 2016
	85	31.03.2018	IMGW data 2018

Note: * means long-term average.

Table 2 Selected elements of the morphometry of the lakes examined (Source: [Gregor and Pacl 2005](#); [IMGW 2007](#))

1 Study Area

central part of Europe (49°10'N, 20°10'E). Their area is about 790 km² (Balon et al. 2015), about 22% of which lies in Poland, and the rest in Slovakia (Figure 1). The present-day climate of the Tatras is Alpine, with a transitional character between

Table 3 Field works on the study lakes in the 2017/2018 winter season

Lake name	Measurement date (Start of the season)	Number of drill holes	Measurement date (End of the season)	Number of drill holes
Czarny Staw pod Rysami	10 February 2018	18	8 April 2018	12
Morskie Oko	16 December 2017	27	8 April 2018	26
Przedni Staw Polski	18 December 2017	12	20 March 2018	12
Wielki Staw Polski	12 January 2018	18	20 March 2018	19
Zadni Staw Polski	19 December 2017	13	22 April 2018	13
Czarny Staw Gąsienicowy	11 February 2018	18	15 April 2018	22
Smreczyński Staw	17 December 2017	11	No data	No data

maritime and continental. This is attributable to the geographical location, land relief and altitude (Hess 1965). The mean annual air temperature (MAAT) decreases with altitude and is 6°C in the northern foreland (approx. 850 m a.s.l.) and <-2°C on the highest peaks (Łupikasza and Szypuła 2019). At the turn of the 20th century, an increase in air temperature was observed in the Tatra Mountains, mainly in winter, with a simultaneous decrease in annual snowfall totals (Żmudzka 2011; Gądek 2014). The maximum thickness and durability of the snow covers (Falarz 2002) and ice of lakes (Pociask-Karteczka and Choiński 2012) also decreased.

The ice on the Tatra lakes usually lasts from 6 to 10 months. Overall, there are 262 lakes in the Tatras (Kopáček et al. 2004), most of which are located in the High Tatras (81%). All the lakes in question are of postglacial origin and most are located above the upper line of the spruce forest, with the exception of Smreczyński Staw (1226 m a.s.l.), which lies within the forest zone in the Western Tatras. In terms of area and volume, the Tatra lakes selected for study are also very deep, except for Smreczyński Staw (Table 2). All the lakes examined lie on the northern slope of the Tatra Mountains and are shaded for a large part of the year (Radwańska-Paryska and Paryski 1995) (Figure 1). The morphometric features and location of the study lakes translate into differences in the heating conditions of the lake waters and in the water capacity of the catchment (Łajczak 1980). However, despite the large variations in the altitude at which they lie (from 1220 to 1890 m a.s.l.), the morphometry of the lake basin, the size and exposure of the topographic catchment, and the screening of the horizon, the lakes have many common features (Table 2) (Łajczak 1996). The total volume of all the lakes in the Tatras is 53×10^6 m³, of which 42×10^6 m³ lie on the northern slope (Łajczak 1996). The volume of the lakes examined in this study is 39.32×10^6 m³, which is 74.19% of all

lakes in the Tatras (93.37% of the lakes located on the northern slope of the mountains).

2 Methods

The observation of changes in the thickness of the snow-ice cover on the selected lakes in the winter season 2017/2018 was carried out from the time when a solid and continuous ice sheet formed on the lake (December) until the early phase of its disappearance (April). The thickness of the ice cover was measured at several to several dozen points distributed evenly on the lake's surface (Table 3). The positioning of the points was determined by means of a portable Garmin Montana 600 GPS receiver with an accuracy of 1-2 m. Drill holes at the points were made with an 8" MORA ICE Pro 120 ice drill. The total thickness of the ice cover (as well as of its individual layers) was determined using a measure with an accuracy of 0.5 cm, which was also used to measure the thickness of the snow cover. The results obtained were compiled in Microsoft Excel. On basis of these, maps of surface variations in the thickness of the ice, snow and slush layer, and snow-ice cover were prepared. In parallel, the data was used to calculate the Pearson correlation coefficient between the thickness of the lake ice layer and the thickness of the layer of snow and slush lying on the ice cover at the points studied (Tables 4, 5). The study data had a normal distribution, which was tested using the nonparametric Kolmogorov-Smirnov test. Meanwhile, the level of statistical significance of the existing relationships was tested using Student's t-test. In addition, the maximum and minimum values were determined, and the arithmetic means of the ice cover and the snow layer accumulated thereon were calculated for each lake in the individual measurement series. Based on the isopach maps prepared, the volumes of the

Table 4 Volume of the snow-ice cover on the study lakes in the 2017/2018 winter season.

Item	Lake name	Start of season													
		Min _{IT}	Max _{IT}	AV _{IT}	Min _{S&ST}	Max _{S&ST}	AV _{S&ST}	Min _{SICT}	Max _{SICT}	AV _{SICT}	IC _c	SS _c	SIC _c	C _{ic}	C _{SIC}
1	Morskie Oko	15.0	31.0	25.1	15.0	46.0	27.1	34.0	63.0	52.2	87.5	83.9	171.4	0.9	1.7
2	Czarny Staw pod Rysami	51.0	64.0	56.2	34.0	74.0	52.0	88.0	134.0	108.2	114.4	110.6	225.0	1.5	2.9
3	Czarny Staw Gąsienicowy	50.0	110.0	80.8	25.0	78.0	45.7	78.0	164.0	126.5	135.6	73.1	208.7	3.6	5.5
4	Smreczyński Staw	16.0	30.0	22.9	10.0	26.0	20.5	40.0	47.0	43.4	1.4	1.5	2.9	10.3	21.4
5	Przedni Staw Polski	37.0	60.0	44.1	11.2	16.0	7.0	44.0	76.0	55.3	35.3	9.1	44.4	3.1	3.9
6	Wielki Staw Polski	36.0	80	47.3	2.0	13.0	4.6	40.0	93.0	51.9	162.1	18.5	181.9	1.3	1.4
7	Zadni Staw Polski	36.0	97.0	73.7	7.0	18.0	11.5	45.0	110.0	85.2	52.0	7.9	59.9	5.7	6.5
Item	Lake name	End of season													
		Min _{IT}	Max _{IT}	AV _{IT}	Min _{S&ST}	Max _{S&ST}	AV _{S&ST}	Min _{SICT}	Max _{SICT}	AV _{SICT}	IC _c	SS _c	SIC _c	C _{ic}	C _{SIC}
1	Morskie Oko	36.0	62.0	50.7	0.0	13.0	3.5	43.0	62.0	54.2	169.3	8.6	177.9	1.7	1.8
2	Czarny Staw pod Rysami	90.0	106.0	98.0	24.0	36.0	30.6	119.0	135.0	128.6	196.1	62.0	258.1	2.5	3.3
3	Czarny Staw Gąsienicowy	31.0	84.0	43.0	0.0	0.0	0.0	31.0	84.0	43.0	70.4	0.0	70.4	1.9	1.9
4	Smreczyński Staw	nd.	nd.	nd.	nd.	nd.	nd.	nd.	nd.	nd.	nd.	nd.	nd.	nd.	nd.
5	Przedni Staw Polski	72.0	220.0	111.6	18.0	35.0	25.9	90.0	249.0	137.5	90.7	20.7	111.4	8.0	9.9
6	Wielki Staw Polski	60.0	105.0	75.2	19.0	44.0	25.0	81.0	129.0	100.2	259.4	88.4	347.8	2.0	2.7
7	Zadni Staw Polski	46.0	267.0	114.6	2.0	2.0	2.0	48.0	116.6	269.0	86.9	1.4	88.3	9.5	9.6

Notes: nd.–No data; Min_{IT} – Minimum ice thickness (cm); Max_{IT} – Maximum ice thickness (cm); AV_{IT} – Average ice thickness (cm); Min_{S&ST} – Minimum snow and slush thickness (cm); Max_{S&ST} – Maximum snow and slush thickness (cm); AV_{S&ST} – Average snow and slush thickness (cm); Min_{SICT} – Minimum snow-ice cover thickness (cm); Max_{SICT} – Maximum snow-ice cover thickness (cm); AV_{SICT} – Average snow-ice cover thickness (cm); IC_c – Ice cover volume (1·10³ m³); SS_c – Snow/slush cover volume (1×10³ m³); SIC_c – Snow-ice cover volume (1×10³ m³); C_{ic} – Percentage of lake volume occupied by ice cover (%); C_{SIC} (%) – Percentage of lake volume occupied by snow-ice cover (%).

Table 5 Values of the Pearson correlation coefficient between the snow and ice thicknesses at the measuring points

Lake name	Correlation coefficient	
	Start of the season	End of the season
Czarny Staw Gąsienicowy	0.453 ($p = 0.090$)	No snow cover
Czarny Staw Pod Rysami	0.540 ($p = 0.038$)	0.289 ($p = 0.636$)
Morskie Oko	-0.749 ($p = 0.000$)	No snow cover
Smreczyński Staw	-0.867 ($p = 0.001$)	No data
Przedni Staw Polski	0.830 ($p = 0.003$)	0.476 ($p = 0.165$)
Wielki Staw Polski	0.948 ($p = 0.000$)	0.449 ($p = 0.193$)
Zadni Staw Polski	0.219 ($p = 0.544$)	No snow cover

Notes: 0.830 - correlations statistically significant; 0.476 - correlations not statistically significant.

ice and snow-ice covers were calculated, and their percentage shares relative to the total volume of the lake were determined (Table 4). All the statistical calculations were made using Statistica10PL software.

The duration of the ice phenomena on the lakes studied in the 2017/2018 season was determined from the analysis of the results of Landsat-8 and

Sentinel-2 images from October 2017 to May 2018 and of field observations. The compositions of Naturalcolour and NDWI spectral channels with resolutions of 30 m (Landsat) and 20 m (Sentinel-2) used in the paper were sourced from: <https://apps.sentinel-hub.com>. Under the expression ice cover author means the situation, when 100% of the lake surface has been covered by ice. The

situation, when ice is present in the water of the lake but does not cover entire surface of the lake is called ice phenomena. Accuracy of determining the appearance and disappearance of the ice phenomena and ice cover is: 1 day for Morskie Oko and Przedni Staw Polski, 3-4 days for other lakes.

To illustrate the weather conditions in the study area a matrix of air temperature, precipitation, snow cover and wind speed and direction was compiled covering the period from 1 October 2017 to 31 May 2018. The data came from three weather stations located in the same valleys as the study lakes (except Smreczyński Staw) and one at the summit of Kasprowy Wierch. The three valley stations include: i) Hala Gąsienicowa at ca. 1530 m a.s.l., 1.5 km north of Czarny Staw Gąsienicowy (1620 m a.s.l.); ii) Dolina Pięciu Stawów (1671 m a.s.l.) just 0.1 km from Przedni Staw (1668 m a.s.l.), 0.5 km from Wielki Staw (1665 m a.s.l.) and 2.5 km from Zadni Staw (1890 m a.s.l.); and finally iii) Dolina Rybiego Potoku (1400 m a.s.l.) located at a straight-line distance of 0.1 km to the north of Morskie Oko (1393 m a.s.l.) and 1.1 km from Czarny Staw Pod Rysami (1580 m a.s.l.). To better understand the weather around Zadni Staw the authors used records from the Kasprowy Wierch weather station (1987 m a.s.l.) located 3.0 km to the north of the lake and just short of 100 metres above. The Pearson correlation coefficient was used to correlate the weather data which was first checked for distribution using the Kolmogorov-Smirnov test. The level of statistical significance of the existing relationships was tested using Student's t-test.

3 Results

3.1 Meteorological features

The weather station matrix suggests that all parts of the study area followed a very similar temperature profile (Figure 2).

This is corroborated by the Pearson correlation coefficient values that ranged from $r=0.95$ ($p=0.000$) for temperature comparisons between the Morskie Oko and Kasprowy Wierch stations, to $r=0.99$ ($p=0.000$) for temperatures between those from the Hala Gąsienicowa and Dolina Pięciu Stawów stations. The air temperature

dropped with altitude. During the ice build-up period, i.e. from 1 November to 31 March, it ranged from -4.2°C (Morskie Oko), to -4.4°C (Hala Gąsienicowa), to -5.4°C (Dolina Pięciu Stawów) and -7.0°C (Kasprowy Wierch). The values followed a similar pattern during the period from 1 October to 31 May, when the average air temperatures were: 0.0°C (Morskie Oko), -0.2°C (Hala Gąsienicowa), -1.1°C (Pięć Stawów) and -3.0°C (Kasprowy Wierch).

Precipitation values also revealed significant relationships between the weather stations. They ranged from $r=0.75$ ($p=0.001$) (Morskie Oko-Kasprowy Wierch) to $r=0.90$ ($p=0.001$) (Hala Gąsienicowa - Kasprowy). During the ice build-up period, precipitation totals were recorded as follows: 400.4 mm (Hala Gąsienicowa), 450 mm (Morskie Oko), 460 mm (Dolina Pięciu Stawów) and 470 mm (Kasprowy Wierch), which was reflected in the values of the snow cover thickness (Figure 2). The maximum snow cover thickness ranged from 121 cm at Hala Gąsienicowa to 280 cm on Kasprowy Wierch (Figure 2).

During the research season, the prevailing winds in the valleys were coming from the southern sectors. Southwestern and southern winds were the most frequent, followed by southeastern winds (Figure 2). The average wind speeds of the ice build-up period ranged from 2.5 m s^{-1} (Morskie Oko), to 3.6 m s^{-1} (Hala Gąsienicowa), 4.5 m s^{-1} (Dolina Pięciu Stawów) and 6.8 m s^{-1} (Kasprowy Wierch).

3.2 Variability of the thickness of snow-ice cover

Based on the network of drill holes made with a hand drill, it was found that the maximum (267.0 cm) and minimum (46.0 cm) thicknesses of the ice may occur in different sections of the lake surface during one winter season, and that the difference in the thickness for the lakes examined may be as high as 221.0 cm (Figures 3, 4, 5). Variations in the ice thickness do not only pertain to the location on the lake surface, but also to the time when ice develops on the individual lakes. The results of measurements based on two series of observations, spanning a period of several months, were used to conduct a comparative analysis and an assessment of the dynamics of ice cover changes.

Figure 2 Weather conditions during the research season: 1 – Hala Gąsienicowa, 2- Morskie Oko, 3 – Kasprowy Wierch, 4 – Dolina Pięciu Stawów Polskich, 5 – Kasprowy Wierch (precipitation), 6 – fieldwork dates.

3.2.1 Smreczyński Staw

In December 2017, the average ice thickness was 22.9 cm with substantial differences between the minimum and maximum values (Figure 3). The winter (snow-ice) cover did not demonstrate such pronounced differences (7 cm) (Figure 5). The

highest value of maximum ice thickness was recorded near the north, northeast and southwest shores of the lake, while the lowest was found in its central and western areas (Figure 3). The ice thickness was greatest where the thickness of the snow cover was the smallest (Table 5). The volume of the ice cover lying on the lake at the beginning of

1 – Czarny Staw Pod Rysami, 2 – Morskie Oko, 3 – Przedni Staw Polski, 4 – Wielki Staw Polski, 5 – Czarny Staw Gąsienicowy, 6 – Zadni Staw Polski, 7 – Smreczyński Staw, 8 – isopachytes of ice (cm), 9 – drilling points; B – Beginning of the winter season, E – End of the winter season.

Figure 3 Spatial differentiation of ice cover thickness in the winter season 2017/2018.

the season was $1.4 \times 10^3 \text{ m}^3$, which represented nearly half the volume of the snow-ice cover and 10.3% of the volume of the lake waters (Table 4).

3.2.2 Morskie Oko

In the winter season 2017/2018, the lake's ice cover was characterised by significant variations (15.0–31.0) cm. The greatest maximum ice thickness, which was recorded in April, was 62.0

cm (Figure 3), i.e. twice the size of the cover observed at the beginning of the winter season. In the period from December to April the variations in ice thickness changed on the lake's surface. The maximum ice cover thickness in December was found off the north and southwest shores of the lake, while in April it was found on the north and south areas of the lake (Figure 3). In general, there was an observable increase in the thickness of the

1 – Czarny Staw Pod Rysami, 2 – Morskie Oko, 3 – Przedni Staw Polski, 4 – Wielki Staw Polski, 5 – Czarny Staw Gąsienicowy, 6 – Zadni Staw Polski, 7 – Smreczyński Staw, 8 – isopachytes of snow (cm), 9 – drilling points, B – Beginning of the winter season, E – End of the winter season.

Figure 4 Spatial differentiation of snow cover thickness in the winter season 2017/2018.

winter (snow-ice) cover from the north to the south (with the exception of the northern shore area) (Figure 5). In December, the average thickness of the snow cover was almost the same as that of the ice cover. In April, it was only 3.5 cm thick and was characterised by greater variations, and its thickness was 14.5 times smaller than the thickness of the ice (Figure 4). At the beginning of the season, the volume of the lake's ice cover was $87.5 \times 10^3 \text{ m}^3$,

which accounted for 0.9% of the volume of the lake waters, while towards the end of the season, it was $169.3 \times 10^3 \text{ m}^3$, i.e. 1.7% of the lake's volume (Table 4).

3.2.3 Czarny Staw pod Rysami

In February, the spatial variability in the ice cover on the lake was inconsiderable (from 51.0 cm to 64.0 cm) in contrast to the differences in the snow cover (from 34.0 cm to 74.0 cm). Incidentally,

the areas of variation in the ice and snow covers nearly overlapped (Figures 3, 4, 5). The minimum thickness of the ice cover was found in the northeastern part of the lake, while the maximum thickness in the western section of the lake (Figure 3). In April, the ice thickness continued to display low variability, and it averaged 98.0 cm and was about twice as large as the cover measured in February. In April, the average thickness of the

snow cover and its variability decreased significantly. In the winter season 2017/2018, there was a clear increase in the thickness of the snow-ice cover from the northeast to the southwest, with little variation (Figure 5). At the the beginning of the season, the volume of the lake's ice cover was $114.4 \times 10^3 \text{ m}^3$, which accounted for 1.5% of the volume of water in the lake, while towards the end of the season it was $196.1 \times 10^3 \text{ m}^3$, i.e. 2.5% of the

1 – Czarny Staw Pod Rysami, 2 – Morskie Oko, 3 – Przedni Staw Polski, 4 – Wielki Staw Polski, 5 – Czarny Staw Gąsienicowy, 6 – Zadni Staw Polski, 7 – Smreczyński Staw, 8 – isopachytes of snow-ice cover (cm), 9 – drilling points, B – Beginning of the winter season, E – End of the winter season.

Figure 5 Spatial differentiation of snow-ice cover thickness in the winter season 2017/2018.

lake's water volume (Table 4).

3.2.4 Czarny Staw Gąsienicowy

In February, the average thickness of the ice cover was 80.8 cm and was almost twice as large as the snow cover. Its spatial variability was considerable (from 50.0 cm to 110 cm), and similar to that of the snow cover (from 25.0 cm to 78.0 cm), and this persisted throughout the winter season (Figures 3, 4, 5). In April, the thickness of the ice decreased by half, with a complete absence of snow on the lake surface (Figures 3, 4, 5). In the winter of 2017/2018, the thickness of the winter cover increased from the northeast to the south-west (Figure 5). In the first part of the season, the volume of the ice cover on the lake was $135.6 \times 10^3 \text{ m}^3$, which accounted for 3.6% of the volume of the lake waters, while towards the end of the season it was $70.4 \times 10^3 \text{ m}^3$, i.e. 1.9% of the volume of the lake waters (Table 4).

3.2.5 Zadni Staw Polski

In December 2017, the average thickness of the ice cover was 73.7 cm, but its spatial variability was very high (Figure 3). In the same period, the average snow thickness was 11.5 cm with little variation in the snow cover (Figure 4). In April, the snow cover disappeared nearly completely, shrinking to 2 cm, and there was an increase in the spatial variability in the thickness of the ice cover (221.0 cm) on the lake (Figures 3, 4, 5). At that time, the highest value of maximum ice thickness on the lakes examined was recorded in the winter season 2017/2018 (267 cm) off the south-west shore (slope of Walentkowy Wierch). The ice thickness increased from the east westwards (Figure 5). In the first part of the season, the volume of the lake's ice cover was $52.0 \times 10^3 \text{ m}^3$, which accounted for 5.7% of the water volume of the lake, while towards the end of the season it was $86.9 \times 10^3 \text{ m}^3$, i.e. 9.5% of the lake's water volume (Table 4).

3.2.6 Przedni Staw Polski

In December 2017, the average ice thickness was 44.1 cm and displayed moderate spatial variability (Figure 3). The snow cover was characterised by low thickness (7.0 cm on average) and very small variations (4.8 cm) (Figure 4). On 20 March 2018, the maximum thickness of the ice was 220.0 cm (Figure 3). There was also a large

increase in the spatial variability of the ice thickness on the lake on that day (148 cm). The average thickness of snow (25.9 cm) and spatial differentiation of its thickness (17.0 cm) increased (Figure 4). The thickness of the snow-ice cover increased from west to north-east and reached its maximum in March in the northern section of the lake (249.0 cm) (Figure 5). In the first part of the season, the volume of the lake's ice cover was $35.3 \times 10^3 \text{ m}^3$, which accounted for 3.1% of the water volume of the lake, while towards the end of the season it was $90.7 \times 10^3 \text{ m}^3$, i.e. 8.0% of the lake's water volume (Table 4).

3.2.7 Wielki Staw Polski

Overall, throughout the winter season 2017/2018, the thickness of the ice cover varied greatly and increased from northwest to southeast (Figure 3). In January, the average ice thickness was 47.3 cm, with considerable spatial variation (Figure 3). The snow cover was not thick (4.6 cm on average) and did not show major spatial variations (11.0 cm) (Figure 4). March saw an increase in the thickness of the ice and snow covers and in the spatial variability in their thickness (Figures 3, 4). The trend of spatial increase in the thickness of ice and snow from north-west to south-east persisted (Figure 5). The greatest maximum ice thickness in the winter season 2017/2018 was recorded along the eastern shores of the lake (slopes of Miedziany Szczyt) (Figure 3). In the first part of the season, the volume of the lake's ice cover was $162.1 \times 10^3 \text{ m}^3$, which accounted for 1.3% of the water volume of the lake, while towards the end of the season it was $259.4 \times 10^3 \text{ m}^3$, i.e. 2.0% of the lake's water volume (Table 4).

3.3 Correlations

The data obtained were used as the basis for determining the relationship between the thickness of the ice cover and the thickness of the snow layer. In terms of the size and directions of the dependencies, the correlation coefficients were varied and statistically significant only for the measurements of snow and ice taken at the beginning of the 2017/2018 winter season (Table 5). In the case of the Morskie Oko and Smreczyński Staw lakes, the dependencies were strong and inverse, which means that a thick layer of snow covered relatively thin ice. Measurements on these

reservoirs were made at the very beginning of the winter season (December). Substantial relationships were also recorded in the case of Przedni Staw Polski and Wielki Staw Polski, but they were directly proportional, which means that thick snow covered correspondingly thick ice (Table 5). Measurements on these lakes were taken in December and January. Moderate correlations were found for Czarny Staw Gąsienicowy and Czarny Staw Pod Rysami, but they were statistically significant only for the latter (Table 5). The thickness of the snow-ice cover on these lakes was investigated in February. Weak and statistically insignificant correlations were found for the measurements made for the layer of snow and ice lying on Zadni Staw Polski. In the second part of the season, the relationship between the snow cover thickness and ice sheet thickness was much weaker and statistically non-significant (Table 5).

3.4 Duration of ice phenomena

Ice first appeared on Morskie Oko on 13 November and two days later, on 15 November, the entire surface of the lake was frozen. The full ice cover lasted until 10 April and ice phenomena continued until 18 April. This means that ice phenomena lasted for 157 days and the full cover for 147 days. According to IMGW (the Polish national weather service) data, the ice reached its maximum thickness of 85.0 cm on 31 March.

On Czarny Staw Pod Rysami the ice phenomena started on 11 November and the ice cover on 15 November. This started breaking up on 26 April and the ice phenomena disappeared on 8 May. This puts the duration of the ice phenomena at 179 days and the ice cover at 163 days.

The ice phenomena on Czarny Staw Gąsienicowy started on 11 November and the ice cover on 14 November. This started breaking up on 21 April and the ice phenomena disappeared on 5 May. This puts the duration of the ice phenomena at 176 days and the ice cover 159 days.

The ice phenomena on Smreczyński Staw appeared on 10 November and the ice cover on 12 November. This started breaking up on 8 April and the ice phenomena disappeared on 23 April. This puts the duration of the ice phenomena at 165 days and the ice cover 148 days.

The ice cover on Zadni Staw Polski developed

on 9 November and broke up on 3 May 2018, lasting for 175 days. The ice phenomena on this lake were the most persistent of all the lakes and continued until 19 May.

The ice cover on Wielki Staw Polski developed on 9 December and broke up on 10 April lasting for 122 days.

The ice cover on Przedni Staw developed on 16 November and broke up on 28 April, lasting for 163 days.

4 Discussion

The amount of snow supplied and its redistribution by wind is the main factor behind the surface variability of the thickness of the ice cover on the lakes in the Tatras. This is connected with the fact that crystalline ice, which forms chiefly at the lake freezing stage, tends to represent only a few per cent of the thickness of the ice cover on these lakes (Choiński 2007a,b, 2016). In the subsequent stages of ice thickening, the key factor behind the ice growth is the addition of snow ice from the top (Leppäranta 1983, 2009; Solarski et al. 2011; Leppäranta 2015; Solarski 2017). Thus, an uneven distribution of snow leads to differences in ice thickening (Adams and Shaw 1967; Adams and Roulet 1980, 1984; Adams 1981, 1982, 1984; Bengtsson 1986). The highest values of ice thickness during the 2017/2018 winter were found at the points where snowdrifts had previously accumulated, while the lowest were in the areas where snow had been blown away (Figures 3, 4, 5). The delivery of snow onto the surface of the lakes through avalanches of various sizes provided another important factor contributing to the variability of the snow and the thickness of the ice cover on most of the lakes in the study. Indeed, the greatest thickness values were measured downslope from the avalanche tracks, where the snow masses released from the slopes were deposited (Żiak and Długosz 2015). On Czarny Staw Pod Rysami this was in the south-western sector (at the foot of Mt Kazalnica Mięguszwiecka). On Czarny Staw Gąsienicowy it was its western and north-western part (at the foot of Mt Kościelec and Przełęcz Karb). On the lakes in Dolina Pięciu Stawów these were either on the southern (Wielki Staw on the side of Mt Miedziany, Przedni Staw

near Opalony Wierch) or western (Zadni Staw at the foot of the slopes of Walentkowy Wierch) parts of the lake surface (Figures 3, 4, 5). In contrast, Morskie Oko and Smreczyński Staw, being more distant from avalanche-prone slopes, revealed no traces of avalanche deposition during the research period.

Local surface variations in ice thickness are also influenced by the density and orientation of cracks in the ice cover (ice tectonics) (Aihara et al. 2010; Choiński 2010). Near the ice cracks and crevices, the snow cover that accumulated on the ice was saturated with water. At times when the air temperature drops considerably, the thus formed layer of slush freezes creating a layer of snow ice, causing the thickness of the ice cover to increase locally (Aihara et al. 2010; Choiński 2010). There is already intensive formation of cracks and crevices on the Tatra lakes at the ice cover formation stage as a result of changes in the volume of ice under the influence of varying air temperatures. The process leads to a growth in the variations of ice thickness during the later stages of ice development. Ohlendorf et al. (2000) and Choiński (2007b) also drew attention to the role of topography in the formation and withdrawal of ice from Alpine lakes. Research conducted on the Tatra lakes during the 2017/2018 winter proves that the topography of the area around the lake basin influences the variations in the thickness of ice and the rate of its disintegration and retreat in spring. The largest ice thicknesses were found in those parts of the lakes, which were sheltered from solar radiation by the rocky faces of mountain ridges (Figure 3). In such areas, ice ablation proceeded at the slowest pace in spring. In the light of data on the potential annual insolation (Wojkowski 2015), the areas receiving the least solar energy include Czarny Staw Pod Rysami (entire lake), the southern part of Morskie Oko (at the foot of Mięguszwieckie Szczyty) and the south-western part of Czarny Staw Gąsienicowy (at the foot of Mt Kościelec). These areas receive no more than 1750 h a⁻¹ of potential annual insolation while elsewhere on the study lakes it ranges from 2000 to 3000 h a⁻¹.

Morskie Oko is the best investigated lake as regards the spatial differentiation of the thickness of the ice cover (Choiński 2007a, b; Choiński et al. 2013). Studies on the surface variability of ice thickness on this mountain lake have been

conducted since 2006 (Table 1). Since that date, researchers have made eight measurement expeditions, during which they have made 160 drills in the lake's ice sheet (Choiński et al. 2013). As shown by the research, the lake has shown considerable differences in the conditions of lake ice development from one winter to another, and the surface variation of the ice cover has been small (3 cm) or very large (31 cm) (Choiński 2007a, b; Choiński et al. 2013). Choiński (2007a, b) and Choiński et al. (2013) identified smaller differences in the thickness in their research carried out at the beginning of the ice season. The greatest variations in ice cover thickness (31.0 cm) were found by investigations carried out at the end of the first decade of May 2006. This confirms the observations made during research on the spatial differentiation of ice thickness on the Tatra lakes conducted in the 2017/2018 winter season. The differences in ice thickness increased during the winter season on account of the uneven addition of snow ice from the top of the ice cover (Figures 3, 4, 5).

In general, the volume of the ice and snow-ice covers grew during the winter season, which also translated into an increase in the percentage of both layers in the total volume of the lakes studied. Only in the case of Czarny Staw Gąsienicowy, where the second series of measurements was performed in the advanced ablation phase, had the volume of the ice and snow-ice covers declined (Table 4). The largest volume of the ice and snow-ice covers was calculated for Wielki Staw Polski, which is not much bigger in terms of area than Morskie Oko and is located nearly 300 metres higher (Table 4). As is demonstrated by the research of Choiński et al. (2014), in the years 2006-2013, which involved nine series of measurements, the volume of ice on Morskie Oko ranged from 111.2·10³ m³ (1.1% of the lake's water resources) to 266.7·10³ m³ (2.5% of the lake's volume). These values are similar to those measured on this lake in the 2017/2018 winter season (Table 3).

The ice and snow-ice covers constituted only a few per cent of the water volume of the study lakes, which results from their morphometric features: considerable average and maximum depths, which in turn translate into the amount of lake waters retained in them. The exception is the small and shallow Smreczyński Staw (Table 4).

A comparison of the Morskie Oko data for the 2014/2015 and 2016/2017 seasons (Gądek et al. 2020) plus those for 2017/2018 and 1963–2012 (Pawłowski 2018) reveals a distinct trend to a reduction in duration for both ice cover and ice phenomena. In the season 2017/2018, the latter began developing five days earlier and the former ten days earlier than the long-term average (1963–2012), but ended as many as 23 and 28 days earlier, respectively. Similar trends are recorded in other mountains of Central Europe (Livingstone 1997).

In the winter of 2017/2018, the ice cover on Morskie Oko was 16 cm thicker than the average for 1963–2012. This characteristic is less susceptible to the influence of climate-change and any change registered is not statistically significant (Ptak et al. 2017; Pawłowski 2018). The results of incidental ice thickness measurements made in the late 19th and early 20th century also do not significantly differ from the winter records of 2017/2018 (Table 1).

The long-term trends of ice phenomena on Morskie Oko correspond with the climate data. Over almost the last 70 years, the Tatra Mountains have experienced an increase in air temperature (Żmudzka 2011; Łupikasza and Szypuła 2019). This trend was significant from the 1980s (Łupikasza and Szypuła 2019), while the water temperature showed dynamic growth rates starting in 1997 (Zhu et al. 2020).

5 Conclusions

The results of the study suggest that snow cover plays a dominant role in the variability of the ice sheet thickness on the lakes surveyed in the study. The air temperature drop and the increase in snow cover with altitude translate into spatial variability in the thickness of lake ice cover. At the onset of the winter season, a thick snow cover may slow down the build-up of ice thickness on the water side, which in turn translates into a strong reverse correlation between the snow cover thickness and the thickness of the underlying ice. In subsequent stages, shifts in the weight of snow cover, due to snow being blown from place to place and, sometimes, also due to avalanche deliveries, may result in uneven pressure on the ice cover and

local variability in the ice growth on the snow-cover side. The thickest snow and ice covers on the lakes in the study developed in the spots with the most snow accumulation.

The ice phenomena and ice covers tended to last longer on lakes located higher up, but the topography surrounding the lake bowl also played a role. Lake ice tended to last the longest on the parts of the lake surface most shaded by mountain slopes and cliffs.

Despite the great variability of the ice thickness on the study lakes, single point measurements have been shown to be useful for determining long-term trends in the ice conditions as long as the measurement points were consistently stable.

The number of days with ice phenomena and ice cover on Morskie Oko in 2017/2018 was much lower than the long-term average. The onset of the ice phenomena and cover came earlier, but their disappearance was brought much further forward, which mostly fits well with the trends of contemporary variability in ice patterns on lakes in the Central European mountains.

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