Recent trends in ice cover duration for Lake Morskie Oko (Tatra Mountains, East-Central Europe)

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ABSTRACT

The study examined the formation, break-up, and duration of ice phenomena and ice cover on Lake Morskie Oko (1,395.4 metres above sea level (masl)), which is a representative of high mountain lakes in the Tatra Mountains located in the western Carpathian Mountains with a maximum elevation of 2,655 masl in the period 1971–2010. The maximum thickness was analyzed additionally. The lake covers an area of nearly 32 hectares and its greatest depth is 51.8 m. Its water is very clear with transparency reaching 12.5 m in depth. The trend towards a delayed freeze-up reaches 4.1 days per decade (d decade^{-1}) ($p < 0.01$) and the ablation of ice on Lake Morskie Oko tends to take place earlier at a rate of 4.5 d decade^{-1} ($p < 0.05$). The time period with ice cover on the lake has been getting shorter at a rate of 10 d decade^{-1} during the time frame of interest. Results of ice cover research on Lake Morskie Oko are consistent with recent studies which have shown that ice duration on lakes throughout the Northern Hemisphere has decreased over the last few decades and they serve as new evidence which confirms a warming of the climate in this section of Europe.

Key words | climate change, high mountains, lake ice

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INTRODUCTION

Changes in lake ice, in addition to their significance in climate change studies, can have important consequences for aquatic ecosystems, especially for the peak spring phytoplankton bloom and the population dynamics of some species of zooplankton (Pugnetti & Bettinetti 1999; Psenner 2003). Moreover, the duration of ice cover influences the amount of evaporation and, thus, can contribute to changes in the water balance of the lake. Ice reduces the penetration of light into a body of water and reduces the amount of heat exchange between the water and the atmosphere. Ice has an impact on weather conditions as well. Heavy ice cover in the winter can reduce the amount of evaporation and thus can contribute to higher water levels the following spring. The spatial as well as the temporal characteristics of ice cover are of special interest to the shipping and fishing industries.

The interest in dates and prediction of lake ice cover started in the 1960s and was driven by both military and civilian transportation-over-ice concerns in the US and Canada. Bilello (1964) developed a method for predicting ice formation from shore to shore Mackenzie River at Fort Good Hope (Canada) on the based on the relationship between mean daily air temperature and previously observed dates of ice formation. The study of Gold (1971) showed that factors contributing to the failure of ice cover for vehicular traffic loads up to $P = 250\,h^2$ (where P is the total load in pounds and h is the thickness of the ice in inches) were: vehicle speed, thermal stress due to drop in temperature, and fatigue and quality of the ice cover.

Trends in duration of ice cover on lakes started to be an object of scientific interest in the 1980s when lake freeze-up/break-up was recognized as a useful indicator of a warming climate (Prowse *et al.* 2007). One of the most important research studies done at that time was a study by Palecki & Barry (1986). They derived statistical relationships between the freeze-up and break-up dates and air temperature for 63 lakes in Finland. In the southern part of the

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country, a change of 1.1 °C in November air temperature would represent a five-day change in the freeze-up date. A 1.0 °C change in April air temperature would represent a five-day change in the break-up date. These values varied for different regions. Significant changes towards earlier ice break-up in Finland, except for far northern lakes, and shorter ice cover duration were observed by Korhonen (2006). Similar studies were done for lakes in northern Canada by Lenormand & Duguay (2005). They identified differences in the freeze-up dates of coastal lakes as well as continental lakes. Yoo & D'Odorico (2002) investigated the dates of ice break-up on lakes and rivers in northern Europe in the Baltic region and they discovered a well-defined trend in ice phenology showing the earlier occurrence of ice break-up in the last several decades. The similar trend in the ice regime is exhibited by Lake Ladoga (Russia). The long-term trend (since 1943) in the duration of ice cover has amounted to a few days a century, mostly due to later freeze-up dates (Karetnikov & Naumenko 2008).

Assel & Robertson (1995) studied lengthy ice records from Grand Traverse Bay (1851), Michigan and Lake Mendota (1855), Wisconsin. Recent average break-up dates have been earlier than during the 1890–1980 time period. This situation appears to be a symptom of a warming climate. Assel and Robertson stated that ice records 'integrate climatic conditions during the seasons (winter-spring) when most warming is forecast to occur'. The results of an investigation of 20 Wisconsin lakes were published one year later: each series of ice records exhibited a trend towards earlier break-up dates (Anderson *et al.* 1996).

Some significant trends towards earlier spring break-up dates have been observed for most lakes in Canada from 1950 to 2000, presumably as a response to global warming (Duguay *et al.* 2006). Strong correlations between 0 °C isotherm dates and freeze-up/break-up dates at many locations across Canada reveal a high level of synchronization of these variables. Jensen *et al.* (2007) obtained similar results for 65 bodies of water across the Laurentian Great Lakes region. Although break-up dates and ice duration trends varied over the study area, average ice duration decreased by 5.3 d decade^{-1} during the recent period of rapid climate warming. Over the same time period, average fall through spring temperatures increased by 0.7 °C decade^{-1}.

A general review of river and lake ice research in the Northern Hemisphere was done by Magnuson *et al.* (2000). Data analysis, including sites in Russia, Finland, Japan, and the United States, provides consistent evidence of later freezing and earlier break-up throughout the Northern Hemisphere from 1846 to 1995. Over this 150-year period, the average rate of change in freeze dates was 5.8 days per 100 years (later) while the change in break-up dates averaged 6.5 days per 100 years (earlier). Furthermore, inter-year variability in both freeze-up and break-up dates has increased since 1950. Some longer time series indicate reduced ice cover (a warming trend) beginning as early as the 16th century with increasing rates of change after 1850.

There exists evidence of reduced ice cover duration on high mountain lakes in the Swiss Alps (Livingstone 1997). One such lake, Lake Lej da San Murezzan (1,768 meters above sea level (masl)), exhibits a trend towards earlier thaws (7.6 d century^{-1}). Relatively little research has been done on lakes in East-Central Europe. Marszelewski & Skowron (2006) studied ice break-up dates on six lakes in northern Poland for the period 1961–2000. They found that the latest ice break-up dates were recorded to occur much earlier than in the past on all the lakes studied. The length of the period with ice cover decreased at a rate of 8 to 9 d decade^{-1}, except for Lake Hańcza, the deepest lake in the European Lowland, where a rate of 4 d decade^{-1} was recorded. Choiński *et al.* (2010) studied Lake Morskie Oko located in the southern part of Poland, a lake which is representative of high mountain lakes in the Tatra Mountains. The authors stated decreasing trends in the duration of ice phenomena and ice cover on the lake in the period 1971–2007. The length of the period with ice cover decreased at a rate of 7.2 d decade^{-1}, and the length of the period with ice phenomena decreased at a rate of 9.5 d decade^{-1}. The change in freeze and breakup dates in the period 1971–2007 corresponds to an increase in winter season air temperature from November to May (1.4 °C century^{-1}) and particularly increasing trend in April and May (5 °C century^{-1}).

This article continues the research on the formation, break-up, and duration of ice phenomena and ice cover on Lake Morskie Oko (Figure 1). Moreover, maximal winter ice cover thicknesses were analyzed. It is interesting to examine if the tendencies discovered by Choiński *et al.* (2010) in Lake Morskie Oko continue in the coming years.

Figure 1 | Central and northern parts of the Morskie Oko Lake (Photo. A. Choiński).

Area of investigation

Lake Morskie Oko is located in the Tatra Mountains, the highest mountain range in the Western Carpathians with a maximum elevation of 2,655 masl (Mt. Gerlach, Slovakia) (Figure 2). The Tatras constitute only 0.56% of the territory of Poland and are the only part of the country featuring an alpine landscape. The Tatras' climate and vegetation are vertically differentiated. The elevation of the lake is 1,395.4 masl and lies within a cool climate zone (it is corresponding to an upper subalpine forest vegetation zone). The largest lake in the Tatras, it covers an area of nearly 32 hectares, being 868 m long, 566 m wide, and is 51.8 m at its greatest depth making it the fourth deepest lake in the range. The water is very clear with transparency reaching down to 12.5 m in depth. Mountain peaks surrounding the lake rise about 1,000 m above its surface. The presence of such high peaks in the vicinity causes an extreme reduction in the amount of solar radiation received by the lake. The amount of annual precipitation reaches 2,000 mm. This value is the highest level of precipitation in Poland. Hence, the Tatra Mts may be considered a macroscale natural 'water tower' of Poland.

Figure 2 | Location of the Tatra Mountains. Area of investigation marked with a rectangle.

DATA AND METHODS

Sets of freeze-up and break-up records, lake ice phenomena and continuous ice cover durations, and maximal winter ice cover thickness data for the 1971–2010 time period obtained from the Institute of Meteorology and Water Management were analyzed. Duration of lake ice phenomena is a period between the first date of ice appearance on the lake and the last day when the ice has completely disappeared. Duration of continuous ice cover (duration of ice) is defined as a period when the total surface of the lake is completely covered by ice. The criterion for 'total ice cover' could be, for example, a walk across the ice on Lake Constance to transport a Madonna figure between German and Swiss churches, a ritual which has been performed for centuries (Magnuson *et al.* 2000). The figure remained on one side of the lake until the next ice-covered winter, when it was possible to carry it back.

Lake Morskie Oko is the only lake in the Polish Tatra Mts with regular ice cover observations by Polish meteorological observation service. Unfortunately, Polish and Slovak state hydro-meteorological services do not monitor ice cover on lakes in the highest parts of the Carpathian Mts. Ice thickness on Lake Morskie Oko is measured every few days close to the northern shore of the lake, where the depth of the lake reaches over a dozen meters (Figure 3). Measurement was not made at the same location, nor at the same point and repeated measurements did not influence subsequent measurements. Temporal rates were calculated using slope parameters from linear regression of freeze-up and break-up dates and ice cover duration.

Figure 3 | Drilling before ice thickness measurements (Photo. J. Pociask-Karteczka).

RESULTS

The dates of formation of ice on Lake Morskie Oko have varied during the 1971–2010 time period. The lake's earliest freeze-up date was recorded in 1974 (November 4) and the latest freeze-up date was in 2001 (December 31), when the duration of ice cover on the lake was the shortest (112 days). The earliest ice break-up date was recorded in 1990 (March 30) and the latest in 1991 (May 31). The longest duration of ice cover occurred in 1991 and reached 200 days. Ice cover duration was interrupted twice by winter thaws during the investigated period: first during the winter of 1997 (10 days in March) and for the second time in 1999 (5 days in January). The maximal thickness of the lake's ice has varied from 44 cm (1999) to 92 cm (1975, 1992) and occurs mostly in the second half of March.

The main results of this analysis can be summarized as follows: continuous ice cover on the Morskie Oko Lake has a tendency to appear later and to disappear earlier, thence ice cover duration has been getting shorter at a rate of almost 10 d decade^{-1} (Figure 4).

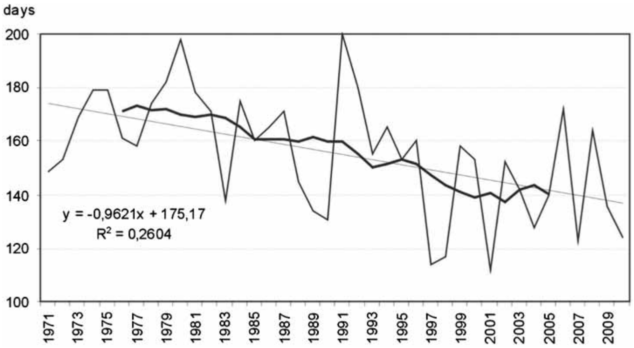

Figure 4 | Duration of permanent ice cover on Lake Morskie Oko from in 1971–2010 (bold: 11-year running mean).

Comparing the periods 1971–1980 and 2001–2010, the duration of both ice phenomena and ice cover shortened by 27 and 31 days, respectively. Ice cover in last decade (2001–2010) of the investigated period lasted only 139 days (Table 1).

There was a decreasing tendency in maximal thickness of ice cover on the Morskie Oko Lake in the period 1971–2000 (Figure 5). The thinnest ice cover occurred during the decade 1991–2000 (61 cm). During the last 10 years of

Table 1 | Characteristics of ice cover and ice phenomena on the Lake Morskie Oko in various periods in 1971–2010

Period	Duration of ice phenomena [days]	Duration of ice cover [days]	Maximum thickness of ice cover [cm]
1971–1980	193	170	72
1981–1990	177	157	69
1991–2000	166	156	61
2001–2010	166	139	65
1971–2010	**175**	**155**	**67**

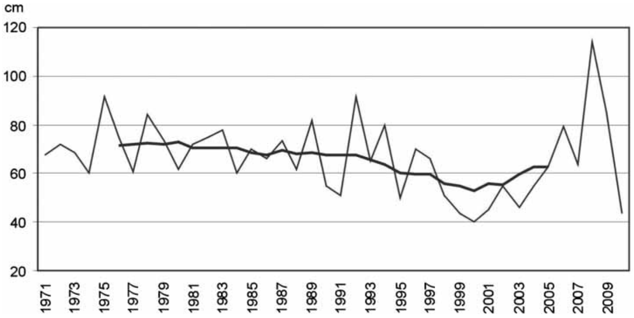

Figure 5 | Maximum thickness of ice cover on the Morskie Oko Lake in 1971–2010 (bold: 11-year running mean).

the analyzed period, the maximal thickness of the winter ice cover was 7 cm thinner than at the beginning of the investigated period (Table 1).

The lake tends to be covered completely by ice later at a rate of 4.1 d decade^{-1} ($y = 0.41x + 322$; $p < 0.01$), and the ablation of ice on the lake tends to take place earlier at a rate of 4.5 d decade^{-1} ($y = -0.45x + 322$; $p < 0.05$).

DISCUSSION

Our results correspond with research results obtained by Choiński *et al.* (2010) for Lake Morskie Oko for the 1971–2007 time period (Table 2). The length of the period with ice cover on Lake Morskie Oko has been getting shorter at a rate of 10 d decade^{-1} (Choiński *et al.* 2010). This is actually approximately 3 days more than was calculated for the period 1971–2007. Our results refer also to results obtained by Marszelewski & Skowron (2006) for six lakes in northern Poland for the 1961–2000 time period. This is similarly more than was calculated for the six lakes in northern Poland (for 1961–2000, 4–9 d decade^{-1}) and considerably more than the rate calculated for the lakes of the Northern Hemisphere by Magnuson *et al.* (2000; Table 2, Figure 6).

The high mountain lake, Lake Lej da San Murezzan (Swiss Alps; Livingstone 1997), represents a very slow trend towards earlier break-up dates (0.76 d decade^{-1}) in comparison with Lake Morskie Oko, which reveals a very strong decreasing trend that amounts to 4.5 d decade^{-1}.

CONCLUSIONS

The observed trend in ice phenomena and ice cover duration on Lake Morskie Oko is clear and reflects a gradually warming climate. It is consistent with recent studies which have shown that ice duration on lakes throughout the Northern Hemisphere has decreased over the last few decades. The results of this ice cover investigation for Lake Morskie Oko have to some extent filled a research gap in East-Central European long-term ice cover research. Kożuchowski *et al.* (2000) pointed out that climate change in Poland has been reflected by increasing temperature of the autumn–winter period. In this part of the Carpathian Mountains this warming tendency refers

Table 2 | Lake ice cover trends at various locations

Location	Data sets	Trends
Laurentian Great Lakes[a]	1975–2004	Rate of decrease in length of ice cover duration reaches 5.3 d decade^{-1} Freeze-up 3.3 d decade^{-1} later break-up 2.1 d decade^{-1} earlier
Southern Wisconsin[b]	1968–1988	Break-up 8.2 d decade^{-1} earlier
Northern Wisconsin[b]	1968–1988	Break-up 4.5 d decade^{-1} earlier
Grand Traverse Bay (Michigan)[c]	1851–1995	Freeze-up 1.14 d decade^{-1} later break-up 1.18 d decade^{-1} earlier
Lake Mendota (Wisconsin)[c]	1855–1995	Freeze-up 0.6 d decade^{-1} later break-up 0.75 d decade^{-1} earlier
Lake Baikal (Russia)[d,e]	1869–1994	Freeze-up 1.1 d decade^{-1} later break-up 0.5 d decade^{-1} earlier
Lej da San Murezzan (Swiss Alps)[f]	1832–1995	Break-up 0.76 d decade^{-1} earlier
Southern Finland[g]	1932–1971	Break-up in 1962–1971 occurred 13.6 days earlier than in 1932–1941
Ladoga Lake[h]	1943–2005	Rate of decrease in length of ice cover duration reaches 0.6 d decade^{-1}
European Lowland (northern Poland)[i]	1961–2000	Rate of decrease in length of ice cover duration reaches 4 to 9 d decade^{-1}
Lake Morskie Oko (southern Poland)[j]	1971–2007	Rate of decrease in length of ice cover duration reaches 7.2 d decade^{-1} Rate of decrease in length of ice phenomena reaches 9.5 d decade^{-1}
Lake Morskie Oko (southern Poland)	1971–2010	Rate of decrease in length of ice cover duration reaches 10 d decade^{-1} Freeze-up 4.1 d decade^{-1} later break-up 4.5 d decade^{-1} earlier
Northern Hemisphere[k]	1846–1995	Freeze-up 0.58 d decade^{-1} later break-up 0.65 d decade^{-1} earlier

[a]Jensen *et al*. (2007); [b]Anderson *et al*. (1996); [c]Assel & Robertson (1995); [d]Magnuson *et. al*. (2000); [e]Livingstone (1999); [f]Livingstone (1997); [g]Palecki & Barry (1986); [h]Karetnikov & Naumenko (2008); [i]Marszelewski & Skowron (2006); [j]Choiński *et al*. (2010); [k]Magnuson *et al*. (2000).

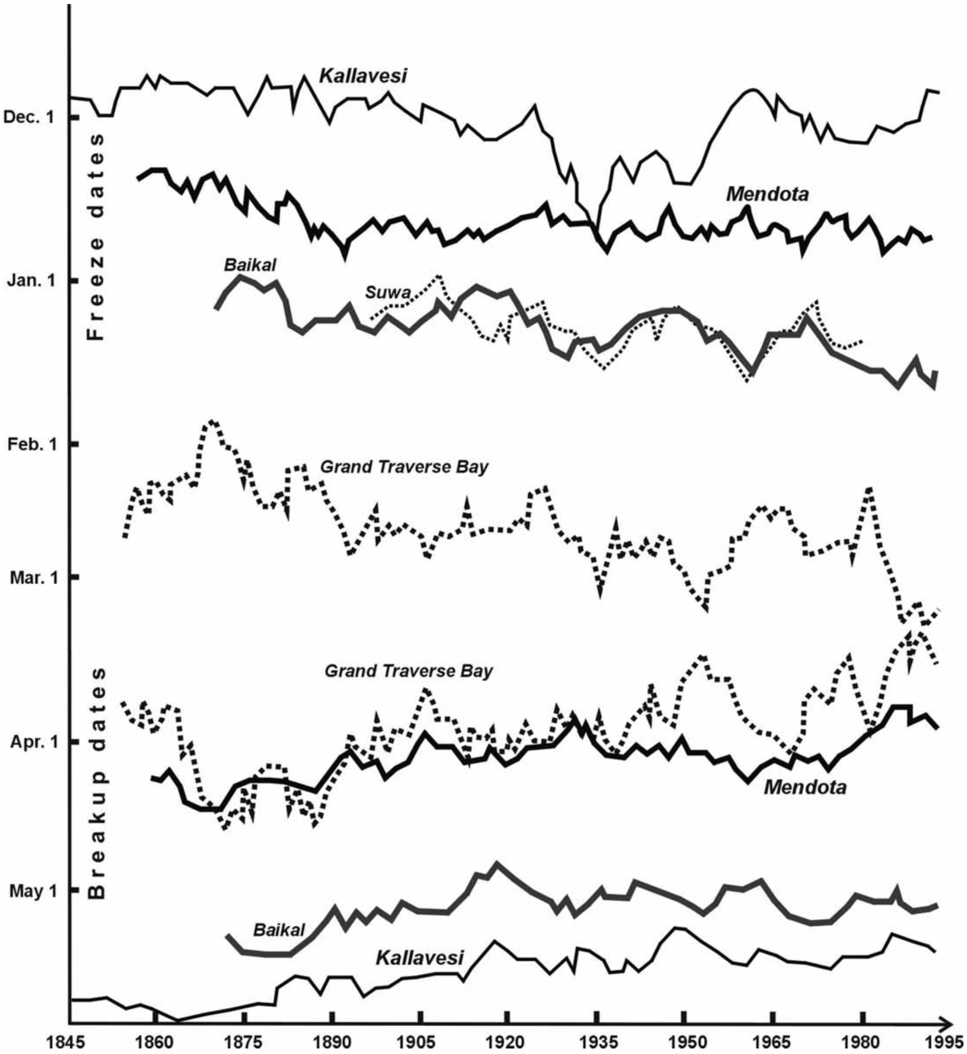

Figure 6 | Time series of freeze and breakup dates for selected lakes in the Northern Hemisphere (Magnuson *et al*. 2000, simplified).

especially to the considerably increasing trend of the air temperature of the seasons from November to May (1.4 °C·century^{-1}) and in April and May (5 °C·century^{-1}). However, it has to be noted that changes in lake ice cover reflect not only the influence of meteorological conditions, but they also arise from water circulation within the lake basin (Choiński *et al*. 2010). Similar research in other parts of the Tatra Mts should be undertaken, especially on the southern slopes of the Tatra Mts in Slovakia. Such research might offer insight into potential changes in ice conditions during the 21st century based on climate warming scenarios. Ice cover has both direct and indirect effects on human society as well as ecological systems. This is especially true in light of recent climate changes when unusual years are becoming more frequent and more extreme.

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