Carpathian Journal of Earth and Environmental Sciences, August 2013, Vol. 8, No. 3, p. 97 - 102

AREAL VARIATION IN ICE COVER THICKNESS ON LAKE MORSKIE OKO (TATRA MOUNTAINS)

Adam CHOIŃSKI[1], Mariusz PTAK[1] & Agnieszka STRZELCZAK[2*]

[1]Institute of Physical Geography and Environmental Planning, Adam Mickiewicz University, Dzięgielowa 27, 61-680 Poznań, Poland; e-mail: marp114@wp.pl, choinski@amu.edu.pl,

[2]Faculty of Food Sciences and Fisheries, West Pomeranian University of Technology in Szczecin, Pawła VI 3, 71-459 Szczecin, Poland; e-mail: Agnieszka-Strzelczak@zut.edu.pl

Abstract: This study presents the changes in ice cover thickness on the surface of a mountain lake Morskie Oko (33.5 ha, 1392.8 m a.s.l.) located in the Tatra National Park in the Tatra Mountains (the highest mountain range of the Carpathians). The course of ice phenomena is similar to those observed on lakes in other parts of the world: over the last forty years the duration of ice phenomena decreased (by 9 days·decade^{-1}), similarly to the duration of compact ice cover (9.5 days·decade^{-1}) and the maximum ice cover thickness (2.2 cm·decade^{-1}). Another issue is the variation in the areal ice cover thickness – still little discussed comparing to long-term studies of ice phenomena. The thickness of ice on Morskie Oko was measured during eight field investigations carried out over years 2006-2012 and jointly 160 boreholes were made in different part of that water body. Results obtained from those field works showed a great areal variation in a given year as well as between consecutive years. Differences in ice cover thickness sometimes were slight and amounted to 3cm (24.03.2010) while in other cases turned out to be considerable (31 cm on 9.05.2006). The local conditions, for example topography (which influenced the shadowing of part of the lake, i.e. resulted in the isolation from sunlight) were the main factors that differentiated the aerial distribution of ice cover. The unshaded areas are subjected to faster ice melting which strongly influences the thickness of ice cover. Another phenomenon observed on 20.02.2012 was strictly connected with the under-ice circulation of water which washed away the ice.

Key words: ice phenomena, variability ice thickness, Mountain Lake, Carpathians, Tatra Mountains, Tatra National Park,

1. INTRODUCTION

Ice phenomena in the winter half a year are common for lakes located in moderate latitudes on the northern hemisphere of the Earth. The compact ice cover is of a particular importance since it can isolate water masses from the influence of external conditions even for a few months. Then, the processes occurring in lakes, which determine abiotic and biotic conditions (inflow of energy, overturn, oxygenation etc.), change. Mountain lakes, due to their location and longer duration of ice phenomena comparing to lowland lakes, are specific water bodies. Low level of anthropopression (no discharge of heated water from power stations, no industrial or municipal waste water) causes that those lakes can be useful in the investigation of natural processes influencing the formation and the ice phenomena duration. Ice cover of mountain lakes is in the sphere of interest of many researchers and their studies pick up the thread within a wide thematic scope (Felip et al., 1995; Livingstone, 1997; Lotter & Bigler, 2000; Piliposian & Appleby, 2003; Thompson, et al., 2005a; Thompson, et al., 2005b; Šporka, et al., 2006, Hendricks & Scherrer, 2008; Pociask- Karteczka & Choiński, 2012, etc.). Ice phenomena depend mainly on large-scale climatic factors but their influence can be altered by individual features of lakes and their surroundings (geology, topography etc.).

The aim of this study was to reveal how the ice cover of a mountain lake (with anthropopression excluded) can alternate and how carefully the results of ice cover measurements should be interpreted against the background of ice thickness variability caused by climatic conditions.

2. DATA AND METHODS

The investigation was performed on lake Morskie Oko (Fig. 1), formed when the valley was blocked by a moraine belt. The lake is located in the are of the Tatra National Park and is the largest lake (33.5 ha) in the Tatra Mountains, being the highest mountain range of the Carpathians. The volume of water in Morskie Oko amounts to $9935 \cdot 10^3$ m^3 while its average depth reaches 28.4 m. The brook Rybi Potok flows out from the lake at its northern part.

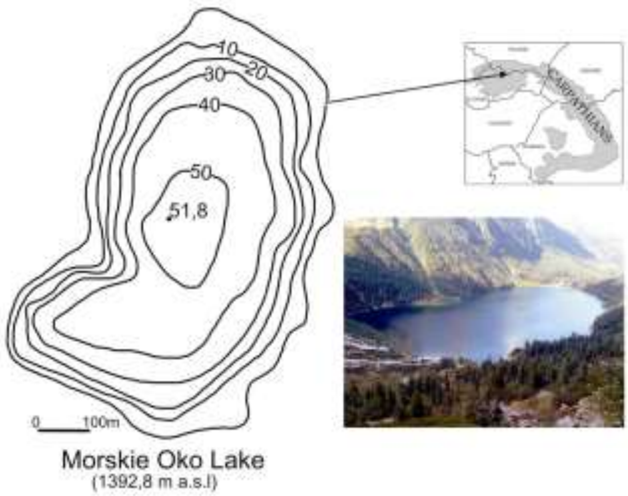

Figure 1. Location of lake Morskie Oko (bathymetric plan after Choiński & Strzelczak, 2011)

Morskie Oko is one of the lakes characterized by the highest altitudes in the Polish part of the Tatra Mountains but the only one which hydrological parameters have been continuously monitored (i.e. water level, the duration of ice phenomena as well as ice cover, measurements of ice cover thickness - every five days). Those data have been collected by the Institute of Meteorology and Water Management – national research-development unit. This study is based on a long-term time series from years 1971-2010 in order to show the variation in consecutive parameters connected with ice, i.e. the duration of ice phenomena, duration of ice cover as well as its maximum thickness. The last factor was based on measurements carried out at sites near the northern shore of the lake. The areal variation in ice cover was determined from data collected in years 2006-2012, when the bores were drilled in the ice cover on Morskie Oko (eight times altogether). Only a hand drill was used (Fig. 2) since the lake is located in the area of the Tatra National Park as well as due to the risk of avalanches in case of the use of internal combustion engine. Each time there were around 20 bores drilled what brought over 160 bores altogether. The locations of measurement sites were established based on GPS 12 Garmin. In a few cases the southern part of the lake was not investigated due to a high avalanche danger.

Figure 2. Bore drilling in ice on lake Morskie Oko.

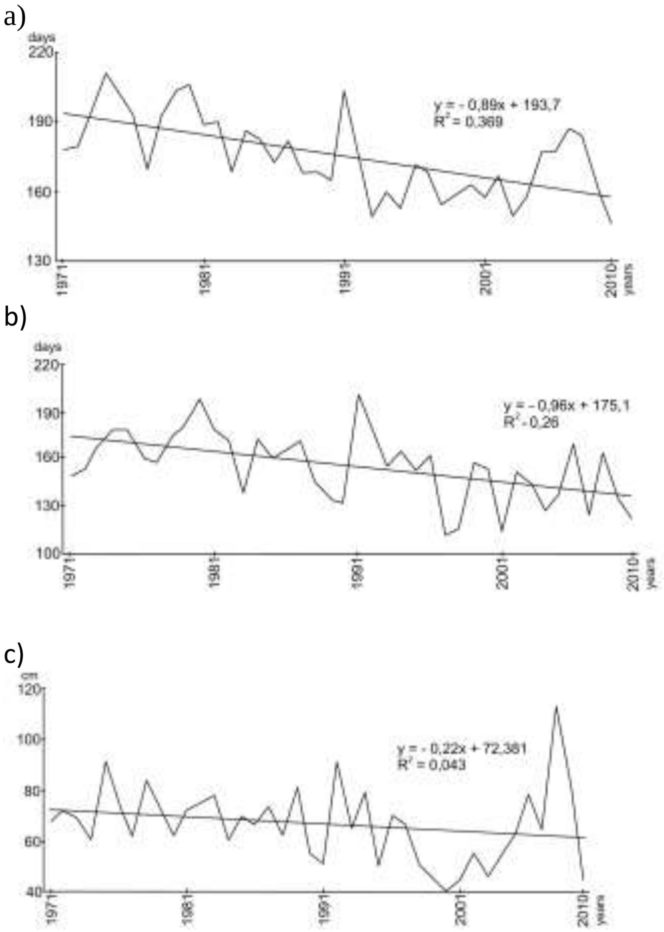

Figure 3. Variability of ice phenomena on lake Morskie Oko (1971-2010): a) duration of ice phenomena, b) duration of ice cover, c) maximum ice cover thickness.

The thickness of ice cover measured with a designed appliance allowed to determine its distribution over the area of lake Morskie Oko.

3. RESULTS

The areal variation in ice cove thickness needs to be analysed against the background of long-term changes in ice phenomena (Fig. 3).

The above presented characteristics show a moderate downward trend in the duration of ice phenomena (9 days·decade^{-1}), weaker trend for compact ice cover (9.5 days·decade^{-1}) and a slight decrease in the maximum thickness of ice cover (2.2 cm·decade^{-1}). Those results correspond with similar investigations on the course of ice phenomena in other parts of the world, (Livingstone 1999, Magnuson et al., 2000, Avinsky et al., 2003, Girjatowicz 2003, Marszelewski, & Skowron 2006, Latifovic & Pouliot 2007, Jensen et al., 2007, Karetnikov & Naumenko 2008, Skowron 2008, Howk 2009, Wang et al., 2012, etc.).

Another interesting issue, apart from well-recognized long-term changes in the dynamics of ice phenomena, is the variation in ice cover thickness within one water body. In case of lake Morskie Oko, this problem has been explored thanks to a series of field expeditions carried out over the last seven years. The first set of field measurements was performed on 05.05.2006. The ice cover revealed considerable variability and its thickness clearly increased from the south to the north. Maximum value, i.e. 54 cm, was observed near the northern shore while the ice was the thinnest near the western shore (23 cm). The average ice cover thickness amounted to 33.2 cm, which multiplied by the total lake area gave the volume of ice at the level of $111.2 \cdot 10^3$ m^3 (1.1% of lake water resources). Areal distributions in ice cover thickness on Morskie Oko recorded in consecutive years are shown in figure 4.

Another set of measurements was carried out on 27.01.2007. Its results were quite similar to those obtained one year earlier. Maximum ice cover thickness (42 cm) was recorded near the northern shore and slightly decreased southward. The thinnest ice cover, similarly to the previous study, was observed near the western shore and reached 35 cm. Thus, the difference between the thickest and the thinnest ice was not considerable and amounted to 7cm. The average ice cover thickness, calculated by the same formula, was at the level of 38.2 cm what gave $128.0 \cdot 10^3$ m^3 of ice (1.3% of lake water resources).

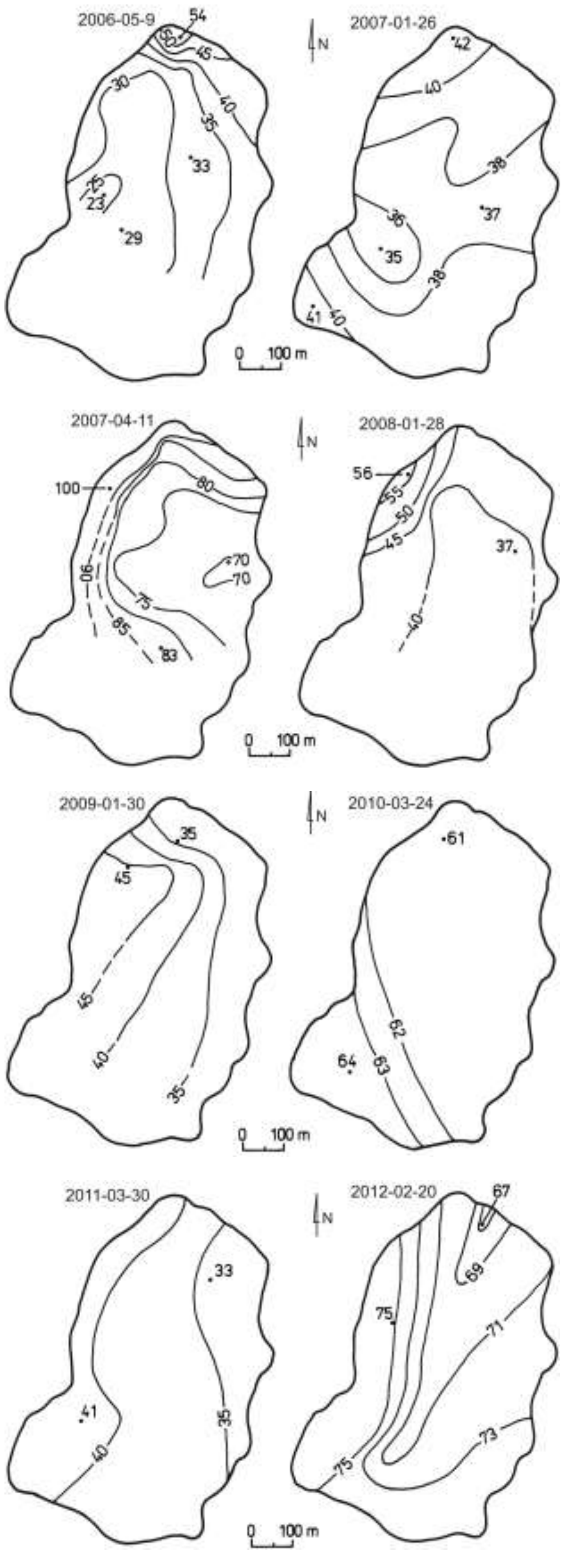

Figure.4. Areal variation in ice cover thickness on Morskie Oko – isolines in [cm]. Interrupted isolines are caused by missing measurements due to a high risk of avalanches.

On 11-12.04.2007 the third set of measurements was performed. This time the ice cover structure in the southern part of the lake was disturbed by an avalanche – the crushed ice was “masked” by snow. The areal variation in ice cover was comparable to the that observed earlier, i.e. the ice thickness decreased from the north to the south. However, the opposite distribution of ice cover was observed from the west to the east. In this case the thickness of ice decreased toward east. The thickest ice cover was recorded near the north-western shore where it reached 100 cm while the thinnest at the eastern shore – only 70 cm. The average ice cover thickness was the highest among the eight field measurements (80 cm, $266.7 \cdot 10^3$ m^3, 2.5% of lake water resources).

Results of field expedition carried out on 28.01.2008 were similar to those obtained in 2007. The maximum ice cover thickness was observed near the north-western shore (56 cm) and the minimum at the eastern shore (37 cm). The difference between those two locations was considerable and amounted to 19 cm. Taking into account the average thickness of ice cover (42 cm), the volume of ice was assessed at the level of $140.7 \cdot 10^3$ m^3, what gave 1.5% of lake water resources.

The fifth set of measurements was performed on 30.01.2009. In general, the distribution of isolines as well as the average ice cover thickness were similar to the one recorded in 2008 (42 and 39 cm, respectively). However, the ice was more homogenous with respect to its thickness, since the difference between the maximum and minimum values amounted to only 10 cm. The average ice cover thickness at the level of 39 cm resulted in the volume of ice equal to $130.6 \cdot 10^3$ m^3 (1.4% of lake water resources).

Field expedition in 2010 revealed the most homogenous ice cover thickness compared to the measurements from previous years. The difference between the thickest and the thinnest ice amounted to 3 cm. The maximum value was observed in the south-western part of the Morskie Oko. The average ice cover thickness amounted to 62 cm what gave the ice volume at the level of $207.7 \cdot 10^3 \cdot m^3$ (2.2% of lake water resources).

The distribution of isolines recorded on 30.03.2011 generally resembled the results from 2010. Again the thickest ice was observed in the south-western part of the lake and its thickness decreased from the west to the east. The variation in ice cover thickness was slight since the difference between the thickest and the thinnest ice amounted to only 8 cm. The average ice cover thickness at the level of 38 cm gave the volume of ice equal to $127.0 \cdot 10^3$ m^3 (1.3% of lake water resources).

The last series of measurements was performed on 20.02.2012 and brought different results. The thinnest ice was recorded at the outflow from Morskie Oko and a notch of 700 m appeared in the bottom part of the ice cover. That indicated water circulation under ice towards the outflow from Morskie Oko. The rate of outflow itself was assessed at the level of 0.7 $m^3 \cdot s^{-1}$. Again, the thickest ice was observed near the western shore and the thinnest near the eastern part. The variation in ice cover thickness was slight and amounted to 8 cm. In turn, the average ice thickness was considerable (72 cm). That gave the volume of ice at the level of $241.2 \cdot 10^3 m^3$ (2.5% of lake water resources).

4. DISCUSSION

The areal variation in ice cover thickness on Morskie Oko strongly depends on local conditions and, what was indicated by the last series of field measurements, on under-ice circulation of water. Individual features of the lake and its surroundings may trigger the changes in ice cover structure and its duration. Those factors can be various, for example increased ground water supply, what was observed by Vanek (1987). Choiński & Ptak (2012) proved that the variation in ice cover may be determined by hydro-geological conditions. Their analysis of lake Samołęskie (29.0 ha), located in a lowland part of Poland, brought the conclusion that the ice cover was by 40% thinnest near the western shore which was intensively supplied by ground waters. Barańczuk & Marchlewicz (2003) underlined that the diversity of ice cover on a given lake is mainly influenced by the inflow of waste waters. In turn, the analysis of morphometric parameters of over 120 lakes in North America (Williams & Stefan 2006) showed that their areas and depths only slightly influenced the ice cover. Similar conclusions were drawn by Karetnikov & Naumenko (2011) with regard to lake Ładoga. In this study on lake Morskie Oko, also no clear connection between ice cover thickness and lake depth at a given site was found. Since snow acts as an insulator, it varies the flow of solar energy. In respect of Morskie Oko, the thickness of snow cover is highly changeable in time and, unfortunately, it has not been monitored so far.

The main factor that seems to determine the ice cover thickness in case of Morskie Oko should be considered the topography of the surrounding area. The lake is bounded from three sides by the highest peaks of the Polish part of the Tatra Mountains. That cause that that Morskie Oko in winter (when the sun is low in the sky) is mostly shadowed. That contributes to the longer duration of ice cover. Similar influence of orographic conditions on ice cover was observed by

Ohlendorf et al., (2000) for lake Hagelseewli in the Alps. However, results obtained in this study seem be contradictory with the hypothesis of sunlight shadowing: the thickest ice was recorded in the western and northern part of the lake, where the lake received the highest solar radiation (Fig. 5). Therefore, this situation should be attributed to the ablation of snow covering ice and its repeated freezing. That led to the increase in ice cover and its stratification.

Figure 5. Shadow on lake Morskie Oko – refuge in the background.

Figure 6. Avalanche reaching Morskie Oko (people in the circle to show the scale of the phenomena)

The distribution of isolines of ice cover thickness obtained from the field measurements carried out in February 2012 shows that the bottom of ice was washed by water flowing to the brook Rybi Potok (outflow rate at the level of $0.7 m^3 \cdot s^{-1}$). That phenomenon was so strong that it determined the thickness of ice cover. Water circulation in lakes covered with ice may be caused by various factors, including water currents, vibrations of ice cover, convection currents when heat flows from bottom sediments, as well as solar radiation penetrating the ice (Bengtsson, 1996). Due to the fact, that the studied lake is oligotrophic, the heat emitted from bottom sediments is low or does not occur at all. Moreover, the influence of geothermal flux on the variation in ice cover thickness is very hard to assess since Morskie Oko is located in the National Park where no geological borehole drilling has been performed so far. Therefore, the cause of under-ice water circulation should be connected with other factors. Taking into account the distribution of isolines from the south to the north, we suppose that the supply of water deposits from scree plays the main role. The ice cover prevents the raise of water level and the surplus of water flows out from the lake. This theory needs to be confirmed by further, precise studies. However, due to a high avalanche danger occurring in the area of scree, such an investigation may be difficult to carry out (Fig. 6).

5. CONCLUSIONS

Investigations carried out within this study allow to draw the following conclusions:

- the areal variation in ice cover thickness on lake Morskie Oko may be slight and amount to 3 cm (24.03.2010) as well as particularly considerable (31 cm on 9.05.2006);
- the ice cover on the lake can be broken in the result of avalanche attacks;
- the areal distribution of maximum and minimum ice cover thickness may be either similar in consecutive years or totally different. That means that the extreme values of ice thickness in some periods may occur in different parts of the lake;
- conventional measurements of ice cover thickness at a given site may not be representative of the whole ice cover, and, thus, may considerably vary from the average values;
- long-term studies on changes in maximum and minimum thickness of ice cover performed at one site may bring incorrect conclusion about the influence of macro-scale factors on ice cover dynamics;
- the range of average ice cover thickness, taking into account the phase of ice conditions each year, varied considerably and amounted from 33 cm to 80 cm. That gave the ice volume ranging from $111.2 \cdot 10^3 m^3$ to 266.3 thou. m^3 (1.1 % to 2.8 % of lake water resources);
- relationship between ice cover thickness and water depth turned out to be ambiguous – either distinct or slight. That suggests that the depth of water is not the dominant factor determining the ice cover thickness;
- the main factors that influence the areal variation in ice cover thickness on lake Morskie Oko most probably are: different solar radiation (shadowing by surrounding mountains); outflow of lake water to brook Rybi Potok which causes the under-ice circulation of water; probable supply with water from scree or deeper sources.

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Received at: 18. 02. 2013
Revised at: 23. 07. 2013
Accepted for publication at: 29. 06. 2013
Published online at: 03. 07. 2013