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Changes in ice phenology on polish lakes from 1961 to 2010 related to location and morphometry

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ABSTRACT

Observations of lake ice at the shore, complete ice cover, ice duration, ice thickness and other measures for 18 Polish lakes were collected for the 50 year period (1961–2010). Average ice dates in early winter became later: first appearance of ice along shore 2.3 days decade^{-1} and complete ice cover 1.2 days decade^{-1} while complete ice cover disappeared earlier (5.6 days decade^{-1}) as did last ice at the shore (4.3 days decade^{-1}). The duration of ice cover decreased by 5.6 days decade^{-1} and average ice thickness declined by 6.1 cm decade^{-1}. The magnitude of these values for individual lakes decreased from eastern to western Poland. This geographic gradient is likely related to regional atmospheric circulation because in winter this part of Europe is strongly affected by continental air, an influence that is greater in the east. A multivariate redundancy analysis (RDA), used in order to examine the dependence of ice measures on lake physical properties and location, indicated longitude and altitude as key factors explaining lake ice dynamics such as the disappearance of ice and ice cover, ice cover duration and thickness. Lake volume and average depth influenced mostly the appearance of ice and ice cover.

1. Introduction

Ice cover occurs on lakes located in polar and temperate zones as well as in alpine water bodies. The presence of ice cover on the surface of a lake isolates it from the influence of external conditions – it limits energy exchange (particularly thermal energy), blocks sunlight and eliminates wave mixing. As a result, physical, chemical and biological processes proceed in different conditions (Hutchinson, 1957; Dibike et al., 2012). Long duration of ice cover may lead to oxygen depletion which kills aquatic organisms (Power and Power, 1995; Hurst, 2007). On the other hand, ice cover is important from the economic point of view since, for instance, it facilitates winter transport (Prowse and Brown, 2010). Kirillin et al. (2012) noticed that the interest in lake ice seasons had increased among limnologists. That statement has been confirmed by many recent long-term studies of ice phenology (e.g. Schindler et al., 1990; Anderson et al., 1996; Magnuson et al., 2000; Korhonen, 2006; Marszelewski and Skowron, 2006; Kostecki, 2013). Those investigations often indicated a shortening of ice-cover duration and a decrease of maximum ice cover thickness, which usually had been attributed to increasing air temperatures.

In the present study we investigate the course of ice in postglacial lakes situated south of the Baltic Sea (territory of Poland). The main goals of the research were to: (1) broaden the global knowledge on ice conditions in lakes based on new, detailed data for a multiannual period (1961–2010) including start and end dates, duration and thickness of ice cover; (2) reveal long-term trends of changes in lake ice formation and determine the relative sensitivity of different ice variables to climate trends; (3) assess the driving factors of those changes with relation to both lake location (climatic conditions) and morphometric features.

2. Materials and methods

This study is based on data collected by the Institute of Meteorology and Water Management (IMGW) – a Polish national research institute established to offer various services in the field of meteorology and hydrology. Those observations include daily characteristics of lake ice cover ranging from the appearance of shore ice (freeze onset) and complete ice cover formation to their disappearance, complemented with the measurements of ice cover thickness (every five days). Since the lakes in Poland are rather of a small area, it was technically feasible to determine the dates of appearance and

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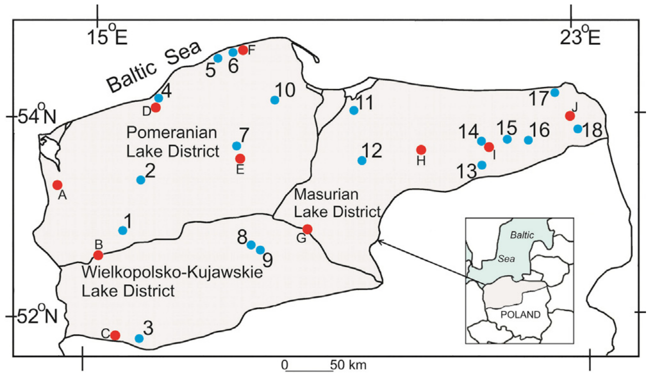

Fig. 1. Distribution of the lakes subject to ice monitoring in years 1961–2010. Lakes: 1 – Osiek, 2 – Lubie, 3 – Sławskie, 4 – Jamno, 5 – Gardno, 6 – Łebsko, 7 – Charzykowskie, 8 – Duże Żnińskie, 9 – Biskupińskie, 10 – Ostrzyckie, 11 – Druzno, 12 – Jeziorak, 13 – Nidzkie, 14 – Mikołajskie, 15 – Orzysz, 16 – Ełckie, 17 – Hańcza, 18 – Studzieniczne. Meteorological stations: A – Szczecin Dąbie, B – Gorzów Wielkopolski, C – Zielona Góra, D – Koszalin, E – Chojnice, F – Łeba, G – Toruń, H – Olsztyn, I – Mikolajki, J – Białystok. Grey colour – extent of glaciation during the last ice age within Poland.

disappearance of ice cover. The network of IMGW measuring sites changed a few times within the space of several decades, therefore complete time series are available only for some lakes. Taking into account that there are about 7000 lakes (with area ≥ 1 ha) located mainly in the northern part of Poland, the number of monitored lakes seems to be small. However, the data include lakes scattered over the area of three main lake districts in Poland and can therefore be regarded as representative of this part of Europe. The locations of the lakes and the meteorological stations (sources of air temperature data) are presented in Fig. 1. Geographical and morphometric parameters of the examined lakes are given in Table 1.

The following measures were used to describe lake ice phenology: first and last ice (I_start, I_end), beginning and end of ice cover (IC_start, IC_end), duration of ice and ice cover (I_duration, IC_duration), maximum ice cover thickness (Max_thickness).

The first and last ice were determined according to the definitions given by Girjatowicz (2003):

- first ice: the date on which any ice form was observed, except for glazing of submerged objects (stones, poles, etc.);
- last ice: the date on which the presence of any ice form (except for grounded ice) was recorded for the last time in a season.

The beginning and end of ice cover were determined following Marszelewski and Skowron (2006):

- first complete ice cover: the first day with the ice cover when 100% of lake area within a visible measurement sector was covered with ice;
- last complete ice cover: the last day with ice cover in a season (the day before the date of disintegration of the ice cover); according to the guidelines of IMGW, the ice cover ends when the main area of water is ice-free (at the same time shore ice can be present).

The remaining ice phenology factors were determined based on the study of Skowron (2011):

- duration of ice: number of days between the first and last day when any form of ice was observed (excluding periods of ice disappearance);
- duration of ice cover: number of days between the first appearance and final disappearance of ice cover (excluding periods of ice break-up);
- maximum ice cover thickness: maximum thickness measured in a season.

The durations of ice and ice cover are not necessarily equal to the difference between the start and end days, because of intermittent disappearance of ice cover, and because the start and end days are not available for the same years.

Average values for every year were calculated and then the trends of changes were determined for each factor and lake using linear regression. Analyses were performed in Statistica 10 (StatSoft, 2011). Additionally, the areal variation of selected parameters was determined with Surfer 8 software, using the kriging procedure.

Since the analyzed data set included multiple variables – dependent (ice conditions) and independent (lake geographical and morphometry parameters) – multivariate analysis, i.e. ordination, was chosen to find the axes representing regression predictors optimal for predicting the values of the response variables. Ordination primarily endeavours to represent complex, multivariate relationships as faithfully as possible in a low-dimensional space (Gauch, 1982). The reasons for using that kind of statistical analysis were as follows: (1) a single multivariate analysis saves time, in contrast to a separate univariate analysis for each dependent variable; (2) ideally and typically, dimensions of the "low dimensional space" will represent important and interpretable environmental gradients; (3) ordination is a noise reduction technique (Gauch, 1982);

Table 1
Geographical and morphometric parameters of the studied lakes.

No.	Lake	Latitude N	Longitude E	Altitude (m a.s.l.)	Area (ha)	Volume (10^6 m^3)	Mean depth (m)
1	Osiek	52°57′	15°41′	51.4	514.0	50.1	9.3
2	Lubie	53°27′	15°55′	95.4	1487.5	169.9	11.6
3	Sławskie	51°53′	16°01′	56.9	822.5	42.7	5.2
4	Jamno	54°16′	16°08′	0.1	2231.5	31.5	1.4
5	Gardno	54°39′	17°06′	0.3	2337.5	31.0	1.3
6	Łebsko	54°42′	17°24′	0.2	7020.0	117.5	1.6
7	Charzykowskie	53°46′	17°30′	120.0	1336.0	134.5	9.8
8	Duże Żnińskie	52°51′	17°43′	77.7	420.5	29.5	6.8
9	Biskupińskie	52°47′	17°44′	78.6	107.0	6.4	5.5
10	Ostrzyckie	54°14′	18°06′	160.1	296.0	20.8	6.7
11	Druzno	54°06′	19°26′	0.1	1147.5	17.4	1.2
12	Jeziorak	53°43′	19°37′	99.2	3152.5	141.6	4.1
13	Nidzkie	53°34′	21°32′	117.9	1750.0	113.9	6.2
14	Mikołajskie	53°46′	21°36′	115.7	424.0	55.7	11.2
15	Orzysz	53°50′	22°01′	119.8	1012.5	75.3	6.6
16	Ełckie	53°48′	22°20′	119.9	385.0	57.4	15.0
17	Hańcza	54°15′	22°48′	227.3	291.5	120.4	38.7
18	Studzieniczne	53°51′	23°06′	123.4	244.0	22.1	8.7