On thinning ice: effects of atmospheric warming, changes in wind speed and rainfall on ice conditions in temperate lakes (Northern Poland)

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Abstract

Northern Hemisphere lakes are losing their ice cover due to climate change. Here we explored six decades of observational data (1961-2017) showing trends in air temperature, wind speed and precipitation over northern Poland, as well as changes in the ice conditions for five lakes with different morphometry. We evaluated whether and to what extent climatic effects, including atmospheric warming, changing wind speed and precipitation during fall and winter, influence ice conditions in morphometrically different lakes in Northern Poland. Our analysis demonstrated that ice cover duration and thickness in decreased at rates of 5.4 days decade^{-1} and 2.5 cm decade^{-1}, respectively. Ice conditions were influenced (65-75%) by the direct effects of air temperature change and to some extent by an interaction of warming with wind speeds and rainfall (5-10%). While stronger autumnal winds result in longer ice cover duration, the effect of precipitation is bimodal with either an enhancement of ice formation by autumnal rain or accelerated ice loss during spring. To project future changes in ice conditions, we used a 1D hydrodynamic lake model forced with four climate model projections under low, medium and high Representative Concentration Pathway (RCP) scenarios. Our simulations demonstrate that current ice conditions will stabilize under the low emission scenario (RCP 2.6) but decrease under both the medium and high emission scenarios (RCP 6.0 and 8.5). During the 21st century, the studied lakes are projected to lose their ice at a rate between 4.5 and 10 days decade^{-1} and ice thickness will decrease by between 3.0 and 5.0 cm decade^{-1}. The rate of change will be more rapid in smaller rather than larger lakes and more so for those situated further inland. The probability of ice-free winters will increase for all lakes and among all future scenarios by between 4 and 69% with the highest potential frequency of ice-free winters in smaller and deeper but relatively wind-exposed lakes.

1. Introduction

Under the effects of global climate change, surface waters are currently warming at an unprecedented rate (Czernecki and Ptak, 2018; Woolway et al., 2019), and consequently lakes are losing their ice cover (Kainz et al., 2017; Ptak et al., 2018). Frozen lakes function differently than those without ice as turbulent mixing and light-dependent processes under the ice are greatly reduced (Ptak et al., 2019a). Ice and snow also reduce the interactions between the lake and the atmosphere; thus, hydrodynamic conditions are controlled by the solar radiation penetrating through the ice (Mironov et al., 2002), heat flows from sediments (Terzhevik et al., 2009) and lateral inflows (Bengtsson 1986; 1996). As the under-ice temperature at the water-ice interface is fixed at the freezing point the stratification and mixing patterns are controlled by convective motions and conductivity gradients (Kirillin et al., 2012; Bouffard et al., 2019). Thickness and duration of the ice cover have thus consequences not only for the hydrodynamics and biogeochemistry of lakes (Williams et al., 2004) but also for their oxygenation and plankton communities (Adrian et al., 1999; Bartosiewicz et al., 2019a). These effects, most pronounced in winter, have important implications for the functioning of lakes in the warm productive season (Hampton et al., 2017).

Ice conditions can influence the phenology and strength of thermal stratification (Preston et al., 2016), water retention times and associated changes in the water chemistry, the extent and composition of phytoplankton blooms (Adrian et al., 1999) and related shifts in the abundance of zooplankton and fishes (Helland et al., 2011). The cascading effects of changes in the ice cover duration on biological productivity are also reflected in its relevance for the economic (Prowse and Brown 2010) and socioeconomic importance of lakes (Orru et al., 2014). In this context it is important to underline that while most lakes in the northern hemisphere are gradually losing their ice, many that were regularly frozen in the past already remain now completely ice free during exceptionally warm winters (Sharma et al., 2019). The process and consequences of decreasing ice cover in lakes have been reported previously (Magnuson et al., 2000; Knoll et al., 2019). However, the processes responsible for the increased probability of complete ice loss in the near future (Benson et al., 2012; Sharma et al., 2016; Wu et al., 2018), which may have irreversible effect on, among other things, planktonic food webs as well as organic matter processing in lakes, are not well documented.

Changes in lake ice phenology are known to be influenced by air temperatures and ambient wind speeds (Arp et al., 2013), but also depend on lake size and shape in relation to prevalent wind directions (i.e., effective fetch, Magee and Wu, 2017). On the one hand, while changes in zonal winds related to large-scale climate oscillations drive the interannual variability in ice-off dates (Schmidt et al., 2019), changes in wind speed above individual lakes, as well as associated patterns of mixing, may drive regional differences in timing of lake ice formation. In addition, while rainfall in spring may accelerate ice cover thinning until breakup, rainfall in autumn also influence ice conditions (Leppäranta, 2010) by altering mixing intensity and temperatures in the water column (Rooney et al., 2018). Despite the potentially important interactions between warming temperatures and other components of recent climate change, such as atmospheric stilling (Woolway et al., 2019) and changes in precipitation (Caine, 2002), the mechanisms behind the interactive control of hydroclimate on lake ice remains largely unexplored. Localized effects such as distance from the coastline or regional weather patterns may control the responsiveness of the ice cover to interannual changes in atmospheric temperature and circulation (Weyhenmeyer et al., 2004). Notwithstanding these indirect effects, predictions show that temperate lakes will have less and thinner ice in the near future and that the rate of this decline may depend on the interaction between limnological characteristics and warming effects (Yao et al., 2014; Tan et al., 2018).

In this study we explored a rich meteorological dataset, including records of air temperature, wind speed and precipitation, collected between 1961 and 2017 in the vicinity of five temperate lakes in Northern Poland, where associated changes in ice cover phenology and thickness were available. We investigated the interaction between the effects of air temperature, rainfall and wind speed on ice phenology and thickness, as well as evaluated how the interactions between changes in these atmospheric drivers influence ice cover in the morphometrically different lakes. We also used a 1D hydrodynamic model forced by an ensemble of four climate model projections under low, medium and high Representative Concentration Pathway (RCP) scenarios to simulate changes in the ice conditions for the studied until the end of the 21st century.

2. Methods

2.1. Lakes

We studied five temperate lakes located in northern Poland (Fig. 2). Study lakes represent a gradient of depth, mixing regimes (Table 1), water transparency and productivity (as Secchi depth between 0.7 and 2.7m). Lakes also differ in morphometry from symmetric round to complex shapes with multiple sub-basins and these differences are reflected by wind exposition with fetch ranging from 3 to 13km.

2.2. Ice conditions and meteorology

The paper is based on data collected within a monitoring program at the Institute of Meteorology and Water Management – National Research Institute (IMiGW-PIB, Poland). Within this long-term monitoring program, the observations of ice conditions are conducted daily from the moment of ice formation to its disappearance (in the case of the analyzed lakes from November to April). Monitored parameters cover, among others, the term of formation of the ice cover, term of its breakup, and measurements of its thickness performed every fifth day at one sampling point located near the water gauge. Meteorological data were within the same long-term monitoring collected by the IMiGW-PIB (Poland) in the scope of standard monitoring for a network of stations throughout the country. Briefly, each IMGW meteorological station is located on a flat surface at least 100 m away from any group of buildings or tree stands and at least 100m from any open water surfaces (i.e., lakes, rivers, reservoirs). Each meteorological station is equipped with semi-automated (1965-1996) or fully automated (1996-2015) temperature logger positioned 2m above the ground and sheltered from the direct sunlight. Surface air temperatures in the historical period (prior 1990) were recorded with traditional manual methods (at least every 8h). More recently stations were equipped with automated temperature sensors and suitable data loggers (i.e., LB-710R thermo-hygrometer with LB-480 data logging module). Each meteorological station is equipped with Hellmann Rain Gage that allows to monitor daily rainfalls and with anemorumbometer (i.e., M63 M1) allowing to continuously monitor speed and direction of winds. Continuous, long term meteorological records were not always available from the stations located in the immediate proximity of the studied lakes; hence for some lakes we analyzed data from stations further afield (up to 20km for Lake C). However, the monthly average observations used for the studied lakes, all of which are located in the lowland area of Northern Poland, are representative of long term climatic effects in the region. Trends and effects between meteorology and ice conditions for the studied lakes were analyzed by correlation analysis (Pearson's) and multiple regression models (XLStat 2019). To remove any potential autocorrelation between the predictor variables within the regression models (i.e., unconclusive Durbin Watson test - DW), we used a Cochrane-Orcutt procedure ($1.95 > DW < 2.1$). Following this procedure, all residuals from the regression models were normally distributed; thus all of the model assumptions were fulfilled.

2.3. Simulating future ice conditions

To simulate historic and future (2020 to 2099) ice conditions (i.e., duration and thickness) in the studied lakes, we used the 1D hydrodynamic Freshwater Lake model, FLake (Mironov, 2008; Mironov et al., 2010), which has been tested extensively in past studies (Woolway and Merchant, 2019). In brief, FLake is process-based model which solves the heat budget of lakes at a daily resolution. The integrated approach implemented in FLake allows a realistic representation of the major physics behind turbulent and diffusive heat exchange in lakes; it includes an ice module, and a module to describe the vertical temperature structure of the thermally active layer of bottom sediments, as well as its interaction with the water column above. Noticeably, Flake is is one of the most commonly used models in lake studies and is also used as a module in numerical weather prediction (i.e., Rooney and Jones, 2010). The meteorological variables required to drive FLake are air temperature at 2 m, wind speed at 10 m, surface solar and thermal radiation, atmospheric pressure, and specific humidity. These atmospheric drivers were extracted for this study from four bias-corrected (to the EWEMBI reference dataset; Frieler et al., 2017; Lange, 2019) climate model projections from the Inter-Sectoral Impact Model Inter-comparison Project phase 2b (ISIMIP2b), HadGEM2-ES, GFDL-ESM2M, IPSL-CM5A-LR, and MIROC5 (see Supplementary Information S1). Future projections, which represent the evolution of the climate system subject to three different anthropogenic greenhouse gas emission scenarios covering the period 2020 to 2099, RCP 2.6 (low-emission scenario), 6.0 (medium-emission), and 8.5 (high-emission), are also investigated. These data were available at a daily time step and at a grid resolution of 0.5°. Time series data were extracted for the grid point situated closest to the center of each studied lake. Aside from meteorological data (see Supplementary Information File), FLake requires estimates of water transparency, lake depth and fetch. Given that Flake equations account for the influence of length and depth of the lake basin on temperature and ice conditions we assume that simulations, to some extent, account for the effects associated to differences in the size and shape of simulated lake basins.

Historical meteorological data (1965-2005) generated by the four climate models described above showed comparable rate of warming as observed over northern Poland during this study (Fig. S1). Future simulations showed either stabilization of air temperatures (RCP 2.6) or warming throughout the 21st century (RCP 6.0 and 8.5, Meinshausen et al., 2011; respectively). Comparison between Flake-simulated ice conditions (1965 to 2005) to future (2020-2099) predictions allowed us to also to estimate the relative increase in the probability of the ice-free winters for each of the monitored lake. This was done by assessing the frequency (in %) of events when the potential changes in the ice over duration or thickness may reach zero calculated as:

$$F_{\text{ice thick}} = \left\{ \frac{n | \overline{Ice} - SD(\overline{Ice}) \leq 0 |}{N} \right\} \times 100$$

where $\overline{Ice}$ is the expected (predicted average) ice thickness, SD is the standard deviation from the four climate models and under one of the three greenhouse gas emission scenarios, n gives the number of observation when annual ice thickness was reaching zero within the range of one standard deviation and N is the total number of observations.

3. Results

3.1. Changes in regional and local meteorological conditions (1961-2017)

Observed climate change in northern Poland (Kolendowicz et al., 2019; Tomczyk and Szyga-Pluta, 2019) is consistent with trends observed elsewhere, including positive trends in air temperature, a variable course of rainfall and a negative trend in wind speeds between fall and winter (i.e., the period between ice formation and ice break-up, Fig. 3F). However, on a local scale the magnitude (and to some extent even the direction) of these changes differ. For example, while warming over the last sixty years was significant for all weather stations, its magnitude ranged between 0.03 and 0.04°C y^{-1} (Fig. 3A and B, respectively). Similar variability was observed for trends in wind speed during fall and winter, which ranged between an increase of 0.009 ms^{-1} y^{-1} (Fig. 3A) and stilling between -0.001 and -0.02 ms^{-1} y^{-1} (Fig. 3B and E, respectively). Fall and wintertime rainfall increased throughout the region at rates between 0.07- and 0.2-mm y^{-1} (Fig. 3 E and B) and only decreased locally closer to the coast (Fig. 3A).

3.2. Changes in lake ice conditions and relationship to climate

All lakes considered in this study are losing their ice cover (Fig. 4A to F). Over the last sixty years, ice cover has formed later (on average by 1.4-day $decade^{-1}$) and disappeared faster (by 4-day $decade^{-1}$), which results in a total decrease of the duration of ice cover by 5.4 days $decade^{-1}$. On a more resolved spatial scale this decrease ranged between 3.9- and 7.8-day $decade^{-1}$ (Fig. 4. B and E). The ice cover for all lakes is also becoming thinner by 2.5 cm $decade^{-1}$ with rates of thinning ranging between 1.6- and 3.3-cm $decade^{-1}$ (Fig. 4B and D).

The multiple regression analysis revealed that ice conditions can be well simulated (predicted) for differently shaped temperate lakes (Fig. 5A to E) using a combination widely available meteorological data (temperature, wind, rainfall). The decrease in ice cover duration for all lakes is mostly influenced, and can be well predicted, by the effects of atmospheric warming (Fig. 5F and Table 2) but also by the effects of wind (September) and rainfall in autumn (November) and early spring (March). For all lakes, stronger winds in early autumn (i.e., October) had a negative influence on ice duration and thickness. However, stronger winds later in the season (i.e., November) resulted in the formation of thicker ice cover. Throughout the entire dataset the effect of rainfall was bimodal, with November rainfall resulting in an earlier formation of ice cover and rainfall in March stimulating ice loss. Generally, between individual lakes the thickness of ice cover for temperate lakes was influenced by the influence of changing temperature ($R^2 > 0.65$) with wind speed and rainfall contributing an additional 5-10% to variability explained by the model (Fig. 5; Table 2). On a seasonal timescale, and for individual lakes, the influence of different components of climate change varied. For example, while warming had a persistent negative effect on both ice cover duration and thickness, the effects of wind and rainfall were bimodal, having either a positive (autumn) or a negative (autumn and spring) influence on the ice cover duration and thickness (Table 2). The goodness of fit for the regression model also varied between individual lakes (Table 3). For example, while all the F values were significant, they ranged from 7.6 to 17.8 for regressions of ice cover thickness and from 6.7 to 15.2 for these on ice cover duration (Lake C & A, respectively). Similarly, the square root of the variance of residuals (RMSE) varied between 4.8 and 7.7 for thickness and between 13.4 and 19.3 for duration. The mean absolute percentage error (MAPE) varied from 13 to 39.5 (Lake E & B) for ice thickness and from 14.1 to 30.8 for ice cover duration (Lake E & D, respectively).

Future climate and ice conditions in morphometrically different lakes (2020-2100)

The performance of the FLake model, which was validated using historical ice cover observations between 1961 and 2005, was found to be moderately good (Ice Thickness $0.12<R^2<0.24$; $p<0.001$, Ice duration $0.14<R^2<0.18$, $p<0.001$, Fig. S2), with the range and rate of change in ice conditions over the observational record both well reflected by the simulations (Fig. S2). The FLake future simulations demonstrated that ice cover is likely to remain relatively stable under RCP 2.6, with potentially marginal increase in the average thickness (Fig. 6) and duration (Fig. 7) of ice cover by 0.3 to 1-cm decade^{-1} and 0.6 to 1.7-day decade^{-1}, respectively. By contrast, under RCP 6.0 and 8.5, ice cover thickness and duration are projected to decrease in all studied lakes. The rate of change in ice conditions vary between individual lakes as well as the RCP scenarios. That is, for the simulated future changes in ice cover thickness, the most pronounced decrease of 5 cm decade^{-1} was observed in Lake E under RCP 8.5. On the other hand, ice thickness in Lake A is suggested by the model to only decrease by 2.8 cm decade^{-1}. Overall, lake ice thickness in Northern Poland will likely decrease by between 3.7 and 3.9 cm decade^{-1} (RCP 6.0 and 8.5, respectively) within the current century. Decrease in ice cover duration will range between 4.5- and 10-day decade^{-1} for Lake A and E (RCP 6.0 and 8.5) with a mean ice cover duration loss for an average lake in this region between 7.1- and 9.5-day decade^{-1}.

For the modelled historical dataset (1965-2005) none of the monitored lakes demonstrated stable ice-free conditions. Therefore, the probability of ice-free winters increased for all the lakes and in all future climate scenarios. For RCP 2.6 the increase ranged from 4 to 46% in Lake A and B, respectively. For RCP 6.0 the probability of ice-free winter increased by between 8 to 58% and under RCP 8.5 the probability for these lakes to remain ice free increased by between 18 and 69%.

4. Discussion

The observed decrease in lake ice cover duration and thickness in Northern Poland is similar to those observed in lakes around the globe (Magee et al., 2016; Lopez et al., 2019; Sharma et al., 2019). The impact of recent climate change allowed us to explain a large fraction of this negative trend over the last sixty years. However, while most of the variability in ice conditions can be attributed to the effects of warming, seasonal changes in wind speed as well as rainfall also accounted for part of the trend. Interestingly, while lower winds during the freezing period stimulated ice formation, the relationship was reversed in fall when, in some of the studied lakes, stronger winds accelerated freezing likely due to enhanced evaporation and cooling. This effect illustrates the seasonality of meteorological influence on lake ice phenology when mixing and heat exchange (i.e., thermal homogenization) is controlled by shear forcing. For instance, calm conditions will trigger ice formation in lakes under freezing temperatures but only when surface waters previously cooled down more than deeper ones through wind-enhanced heat loss.

Conversely, effects of increasing precipitation were evident mostly during the break-up of ice cover. Precipitation can stimulate the thawing of lake ice as much or more than the effect of warming. We also provide some indications that the location and shape of the basin in relation to prevalent wind direction may be an important factor to consider for better predictions of future lake ice phenology. Notwithstanding the dominant effect of warming, associated changes (i.e., atmospheric stilling, higher winter and springtime rainfall) need to be accounted for on a possibly more temporally resolved (i.e., monthly) scale as similar trends may have contrasting effects on ice formation depending on the season and stratification stage (Table 2). These seasonal effects should be more closely considered to better understand and predict the rate of lake ice loss in the future.

The ubiquitous observational evidence of decreasing ice conditions in temperate and boreal lakes over the last century implies that ice cover is responding rapidly to the effects of global climate change. The rate at which ice cover is decreasing in lakes is globally variable (Sharma et al. 2019) and depends on the strength of climatic effects on the ice formation and break-up times as well as on the size and shape of each individual lake. Previous studies have reported a decline in the ice cover duration for lakes in Poland by between 1.0-day decade^{-1} (Ptak et al., 2017) for the deep alpine lake Morskie Oko and 8.2-day decade^{-1} for Lake Ełckie (Choiński et al., 2015). For the temperate lowland lakes considered here, the calculated trend varied between 3.9- and 7.8-day decade^{-1} (for lake B – Charzykowskie and E – Studzieniczne). These rates are comparable to those reported for other lakes in temperate latitudes (i.e., Bernhardt et al., 2012; Apsite et al., 2014; Soja et al., 2014) but a rather large range of changes is apparent despite comparable effects in average air temperature. For instance, in the relatively shallow Lake A (1.3 m deep), where the circulation is influenced by the oceanic climate and the water column mixes multiple times between summer and fall (polymixis; Ptak et al., 2019b), the ice cover formation is usually delayed until January. This lake already remains ice free during exceptionally warm winters (e.g., 2007/2008). Bottom waters of Lake B during the stratification period remain warm (>8ºC, Garbacz et al., 2008), and the hypolimnetic volume is moved upwards by sinking surface waters in fall. This buoyancy flux is the main cause of the mixing and likely one of the most important reasons for observed delay in the ice cover formation. By contrast, Lake C freezes relatively fast (on average frozen by mid-December). This lake, also polymictic, is at times exposed to strong winds along rather than across the lake and, thus, the wind-induced mixing is efficient (Woolway and Simpson, 2017). The shape and complexity of the lake basin in relation to mixing efficiency apparently also influence the responsiveness of the ice cover to changes in climate (Magee and Wu, 2017).

In our regression analyses we used the Cochrane-Orcutt method to eliminate autocorrelation. The model estimates including effects of temperature, wind and rainfall best explained the observations when compared to any reduced model configuration (i.e., relatively high F and low p values; Table 3). The analysis of errors (i.e., MSE, RMSE) generally resulted in higher values for the estimates of ice cover duration as compared to the estimated ice thickness. This potentially indicates that there are some other factors or interactions that were not considered in this study but could have improved the goodness of fit for the predicted changes in ice cover duration. Noticeably, greatest errors were estimated for analyses in Lake C (Table 3) which is, in fact, the studied lake with the most complex morphometry (Fig 2). This may potentially indicate that the effect of morphometry in lakes with complex shape should be considered more directly to improve our predicted ice phenology. Improved process understanding and future predictions will also require accounting for these effects and potential biases.

All study lakes will be losing their ice cover during the 21st century according to current climate projections (GHG, Figs. 6 & 7). In fact, among the lakes in Northern Poland, the deep and symmetrical Lake E will be losing its ice most rapidly (i.e., 4.8 cm decade^{-1} under RCP 8.5) and is likely to experience ice-free winters with much higher probability than in the past (up to 53% increase). Shallow westerly Lake B will be losing its ice cover at an average rate of 2.7 cm decade^{-1}, almost half the rate of Lake E. This inter-lake difference appears to result from the fact that the ice cover in Lake E is strongly influenced by the effect of changes in air temperatures (rapid warming under RCP 8.5) as compared to the relatively more important influence of hydroclimate in shallow Lake B. However, this also results from the fact that ice cover formation in Lake B was much delayed when compared to Lake E already by 2015 and the lake ice remained respectively thinner. Notwithstanding difference in rates of ice cover decrease, the probability of ice-free winters will also increase rapidly in Lake B (up to 69% under RCP 8.5). Effects of future climate on ice conditions will depend on the location and shape of the lake but also on the duration of recent ice cover that may influence the responsiveness of spring mixing/stratification patterns to atmospheric warming.

Recent studies have suggested that ice cover in shallow lakes that mix frequently will be relatively less influenced by atmospheric warming compared to lakes that are strongly stratified in summer (Magee and Wu, 2017). This conclusion, in part consistent with our findings (i.e., in Lake A), stems from the assumption that, as climate warms, deeper lakes will gain more heat throughout the upper and mid-water column since the diurnal heat losses will be less than in shallower polymictic lakes. This is correct when comparing deeper and shallower lakes under similar winds (and effective fetch) inducing heat loss or thermally homogenizing the water column. Once the lake size or fetch is considered, it may be more a function of prevalent wind direction and intensity of surface warming in the day that will control diurnal and seasonal heat exchange (Waples and Klump, 2002) and thus directly influence the exact timing of overturn and subsequent ice formation. We argue here that the stratification, mixing patterns and efficiency of heat exchange in summer and fall rather than size or depth may also have a more direct impact on future lake ice phenology.

Stratification in lakes is controlled by an interaction of heat fluxes with the wind energy inputs and inflows following heavy rainfall events (Laborde et al., 2010). Heavy rainfalls in autumn which occur simultaneously with strong winds at the lake surface, can be particularly important in triggering mixing and cooling throughout the water column (Kimura et al., 2017). In fact, large rainfall inflows (relatively to lake volume) have been suggested to control the lake-wide circulation patterns (Carmack 1979; Killworth and Carmack 1979). The changes in autumnal rainfalls may thus indirectly influence ice formation through accelerated or delayed mixing and temperature homogenization. Recent studies have also suggested that raindrops falling into water-unsaturated air will cool through evaporation thus their passage can lead to cooling of the air (Rooney et al., 2018). This mechanism may further enhance convective mixing in the surface at the end of a heavy rainfall event in autumn and allow for a more rapid ice formation. The timing of lake overturn and subsequent freezing during and after autumnal rain- and snowstorms will ultimately depend on the amount of energy required to overcome the density gradients between surface and bottom waters. Standard indices used in physical limnology (i.e., Schmidt or Wedderburn numbers; Imberger and Patterson, 1989) to describe the ratio between meteorological forcing and the gradient of pressure established by the stratification may provide an excellent proxy to investigate the effects of future stronger stratification on lake ice conditions.

Lakes are likely to stratify more strongly and for a longer period in the near future as a consequence of direct and indirect effects of climate and global environmental change (Woolway and Merchant, 2019, Bartosiewicz et al., 2019a, b). The seasonal as well as interannual changes in the strength of thermal stratification and efficiency of heat exchange should be considered for better predictions of the future lake ice phenology. For instance, while in currently polymictic lakes heat is gained and lost rapidly throughout the water column between summer and fall, these water bodies are likely to retain part of the heat for longer when the water column is most stably stratified. The efficiency of heat retention and downward transport will depend on the water column transparency (Ptak et al., 2018). In browning or greening lakes (Leech et al., 2018) the effects of atmospheric warming will accumulate rapidly in surface waters, leading to a thinner and warmer epilimnion ("thermal shielding"). Under such conditions lakes stratify early in spring and are more likely to remain stratified for longer in fall (Bartosiewicz et al., 2015). Stratification precludes thermal homogenization and can effectively result in delayed ice formation. On the other hand, thermally shielded bottom waters of less transparent lakes are likely to gain less heat during the summer and thus remain relatively cold throughout the summer (Bartosiewicz et al., 2016). Therefore, there will be less heat from deep waters to be lost during the overturn before the ice is formed (Ye et al., 2018). These contrasting effects, likely to influence lake ice phenology in the near future, need to be further explored to improve our understanding of ice processes and changes.

While changes of the stratification and heat retention in lakes will affect the timing of ice formation, the duration of the ice cover will in turn control the onset of stratification. This potential feedback effect, which to our knowledge has not been yet comprehensively studied, can result in a cascading change of the ice phenology in many shallow lakes around the globe. If a shallow lake mixes less often or even remains stably stratified during the summer in a warmer climate, the outcome for the timing of ice formation will depend on the amount of heat (temperature) of bottom waters. There are two possible scenarios that are worth considering. First, if bottom waters gain sufficient heat in springtime as stratification develops slowly, and still gain some heat over the summer (as a function of high transparency), then the ice formation will be delayed upon autumnal mixing until this heat is lost to the atmosphere. Second, if bottom waters do not gain much heat during the springtime when stratification develops rapidly and do not warm up over the summer (as a function of low transparency), ice formation will follow the autumnal overturn in short order. The overall outcome depends on whether faster and more enhanced stratification in less transparent lakes will be sufficiently strong to delay mixing (and following freezing) as much as upwelling of warmer bottom waters in more transparent lakes.

The enhanced warming of surface waters in less transparent lakes may interact with the effect of increased rainfall in the catchment and decreasing wind speeds over the lake to result in faster and stronger thermal stratification. While such a direct effect of these co-occurring processes on ice conditions in temperate lakes are apparent from the current study, their indirect effects through changes in water transparency and differential heating in the upper and lower water column require further investigation in the future. The arising feedback effect appears particularly important if we consider the major implications of the changing ice conditions for the functioning of lakes. For example, the duration of the ice cover, directly related to the onset and duration of thermal stratification, has been recognized as one of the major determinants of the springtime and summer warming trends (O'Reilly et al., 2015). The cascading influence of the ice phenology also affects the formation and magnitude of spring and summer growth of phytoplankton blooms (Adrian et al., 1999, Blenckner et al., 2007), their functional diversity (Özkundakci et al., 2016) and the abundance of zooplankton (Dokulil et al., 2014). Pronounced and long-lasting effects of warming air temperatures on the functioning of lakes may be further enhanced by accelerated warming of surface waters in ecosystems that are or will be losing their ice completely (Kintisch, 2015). Delayed ice formation and decreasing ice thickness and duration will all lead to less stable thermal conditions under the ice (Bruesewitz et al., 2015). These changes, in turn, may affect the primary production and oxygen dynamics in frozen lakes and are potentially related to effects throughout the aquatic food webs (Beall et al., 2016) and accelerated emission of greenhouse gases (Denfeld et al., 2016). Adding to potential effects on biology and biogeochemistry of lakes, future ice decline and predicted increased in the frequency of ice-free conditions will be likely to also affect ecosystem services and regional economy (Knoll et al., 2019)

Conclusions

This study supports the interactive effects of warming, stilling and changing precipitation patterns on the ice conditions in temperate lakes. Polish lakes are losing their ice, and this change is driven mostly by direct effects of temperature and to some extent by the effect of increasing rainfall. The effect of wind is either negative when it delays ice formation in fall or positive when it stimulates ice thickening throughout the winter. Predictive simulation, based on simple hydrodynamic model and an ensemble of four climate model projections, suggests that under continuing emissions, most lakes in northern Poland will be losing their ice cover rapidly and may become largely ice-free by the end of the century. The large spectrum of responsiveness in ice phenology and conditions to changing weather conditions most likely results from the interactive effects between surface meteorology, lake size and shape as well as the strength of thermal stratification. In this context it is important to underline that predicted changes in the mixing regime of global lakes will most likely have important consequences for ice phenology. Changes in ice phenology may also result in accelerated shifts toward different mixing of lakes. This potential effect needs to be further explored. Lake ecosystems that are prone to remain ice-free in consequence of warming or increased precipitation will function differently than in the past.

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Tables

Table. 1. Geographic coordinates (latitude – Lat.; longitude – Lon.) and limnological characteristics of the five study lakes in northern Poland (after: Choiński 2006, Ptak et al. 2018; arranged from west to east – A to E), including area, volume, mean and max depth, water transparency (as Secchi depth, SD) and wind fetch (FT).

ID	Lake	Lat.	Lon.	Area (ha)	Volume ($10^3 \times m^3$)	Mean depth (m)	Max depth (m)	SD (m)	FT (km)
A	Gardno	54.64	17.16	2337.5	30951	1.3	2.6	0.7	6.8
B	Charzykowskie	53.73	17.50	1336.0	134533	9.8	30.5	2.1	9.5
C	Jeziorak	53.59	19.55	3152.5	141594	4.1	12.9	0.8	13.3
D	Mikołajskie	53.80	21.56	424.0	55740	11.2	25.9	1.3	5.8
E	Studzieniczne	53.86	23.09	244.0	22074	8.7	30.5	2.7	3.4

Table 2. Standardized coefficients (beta coefficients) from the multiple regression analysis of the relationship between seasonal effects of weather conditions, including air temperature (November to March), wind speeds (September to January) and rainfall (November to March), and ice conditions in temperate lakes in northern Poland. Values in bold are given for parameters that significantly ($p<0.05$) improved the predictability.

	Lake A		Lake B		Lake C		Lake D		Lake E		All Lakes	
	Dur	Thick	Dur	Thick	Dur	Thick	Dur	Thick	Dur	Thick	Dur	Thick
Temp. Nov	0.01	**-0.16**	-0.02	0.11	-0.06	0.01	-0.06	-0.11	**-0.22**	-0.05	**-0.08**	-0.05
Dec	**-0.21**	-0.12	**-0.39**	0.15	**-0.20**	-0.05	**-0.43**	**-0.29**	**-0.30**	-0.14	**-0.30**	**-0.14**
Jan	**-0.35**	**-0.44**	**-0.38**	**-0.25**	**-0.29**	**-0.38**	**-0.30**	**-0.42**	-0.05	**-0.35**	**-0.23**	**-0.31**
Feb	**-0.33**	**-0.38**	0.05	-0.19	**-0.43**	**-0.42**	**-0.36**	**-0.41**	**-0.45**	**-0.52**	**-0.32**	**-0.43**
Mar	-0.05	0.04	**-0.22**	-0.15	-0.14	-0.01	-0.16	-0.09	**-0.23**	**-0.20**	**-0.20**	**-0.11**
Wind Sept	-0.02	0.05	0.09	0.02	-0.03	0.07	-0.10	0.05	-0.05	-0.11	0.05	0.02
Oct	**-0.09**	-0.06	-0.05	**-0.21**	-0.06	**-0.18**	-0.01	0.01	-0.15	**-0.18**	**-0.08**	**-0.08**
Nov	-0.02	**0.17**	**-0.13**	-0.14	0.06	**0.23**	0.08	**-0.23**	**0.31**	0.08	0.03	**0.15**
Dec	0.01	-0.14	-0.09	**-0.30**	0.12	-0.03	0.06	-0.11	0.07	0.10	0.01	-0.05
Jan	-0.12	-0.02	-0.02	0.07	0.01	0.04	0.12	**0.38**	-0.07	**0.35**	-0.02	0.04
Rain Nov	**0.13**	0.04	0.09	**-0.28**	0.04	0.02	-0.07	0.11	-0.03	-0.04	**0.12**	0.01
Dec	0.03	0.01	-0.08	0.07	**-0.16**	-0.06	0.04	-0.07	0.07	**-0.21**	0.06	-0.03
Jan	-0.08	0.08	**0.19**	-0.02	0.01	**-0.19**	-0.12	**-0.15**	**-0.13**	**-0.19**	-0.01	**-0.09**
Feb	-0.09	0.05	**-0.20**	-0.03	0.01	0.02	0.08	-0.02	-0.04	0.08	-0.01	0.01
Mar	**-0.12**	0.02	**-0.27**	**-0.22**	-0.08	0.03	-0.10	-0.09	0.01	0.06	**-0.12**	-0.04
R^2	**0.88**	**0.89**	**0.84**	**0.78**	**0.79**	**0.79**	**0.76**	**0.84**	**0.72**	**0.80**	**0.71**	**0.75**

Table 3. Goodness of fit statistics (MSE – mean square error; root-mean-square error – RMSE; MAPE – mean absolute percentage error and DW – Durbin Watson Statistics) for the regression analyses (Cochrane-Orcutt method) between changes in air temperature, wind and rainfall conditions on lake ice duration and thickness (1965-2015) in temperate lakes of Norther Poland.

	Lake A		Lake B		Lake C		Lake D		Lake E		All Lakes	
	Dur	Thick	Dur	Thick	Dur	Thick	Dur	Thick	Dur	Thick	Dur	Thick
DF	39	39	38	38	40	40	38	38	40	40	259	259
F	27.4	21.4	14.5	8.5	10.1	9.8	12.2	18.6	6.9	15.6	41.3	54.5
MSE	188.0	21.75	174.2	40.9	333.2	51.8	303.7	37.1	290.8	38.8	340.1	46.2
RSME	13.7	4.7	13.2	6.4	18.3	7.2	17.5	6.1	17.0	6.2	18.4	6.8
MAPE	14.9	17.7	26.4	25.3	12.0	15.5	21.6	13.3	12.9	9.5	41.4	22.9
DW	1.96	1.96	1.90	1.92	2.08	2.04	1.97	2.03	2.06	2.00	2.01	1.98

Table 4. The relative increase in the probability (%) of ice-free conditions for the study lakes between2020-2100 estimated using Flake model and an ensemble of four climate projections (GFDL-ESM2M, HadGEM, IPSL and MIROC5) simulated under three relevant GHG concentration trajectories – RCP 2.6 being the most conservative scenario (emissions declining by 2020 and reaching zero by 2100), RCP 6.0 being moderate (emissions peak around 2080, then decline) and RCP 8.5 being the least conservative (emissions continue to rise throughout the 21st century).

Lake	RCP2.6	RCP6.0	RCP8.5
A	3.8	8.9	17.7
B	46.8	58.2	69.2
C	10.1	25.3	40.5
D	35.4	41.8	63.3
E	16.5	34.2	54.4

Captions

Figure 1. Interactive effects of warming, changes in wind speed (stilling) and precipitation on lake ice formation (also as the Graphical Abstract) under three future greenhouse gas (GHG) emission scenarios. Size and direction (downward-negative, upward-positive) of arrows indicate the relative strength and direction of temperature, wind and rainfall on ice conditions in study lakes.

Figure 2. Location, morphometry and bathymetry of the study lakes as well as location of the nearest meteorological station with continuous record between 1961 and 2017. Arrows indicate prevalent wind directions (between 1980 and 2017).

Figure 3. Surface meteorology in the vicinity of temperate lakes in Northern Poland (A-Charzykowskie, B-Gardno, C-Jeziorak, D- Mikolajskie, E-Studzieniczne, F-average for the entire region) including air temperature (in red), wind speed (in black) and precipitation (in blue) as monthly averages between 1961 and 2017 for the five lakes (n = 257). R is given for all trends but significant ones ($p<0.05$) are shown in bold.

Figure 4. Changes in the ice cover conditions (thickness in grey and duration in black) for each temperate lake in northern Poland (A-E) and for all lakes together (F). R indicates temporal trends between 1961-2017, significant ($p<0.05$) ones are shown in bold.

Figure 5. Results of the regression analysis (predicted duration and thickeness) between air temperature, wind speeds, rainfall) and ice conditions (ice cover thickness in grey and duration in black) for each lake separately (panels A to E) and for all lakes together (panel F). All R^2 are significant at $p<0.01$.

Figure. 6. Flake simulation of changing ice cover thickness for each lake separately (A to E) and for an average temperate lake in northern Poland (F) between 2020 and 2099. The model was forced through an ensemble of four climate models (i.e., GFDL-ESM2M, HadGEM, IPSL and MIROC5). Climate changes between 2020 and 2099 were simulated under three relevant GHG concentration trajectories with RCP 2.6 being the most conservative scenario (emissions declining by 2020 and reaching zero by 2100), RCP 6.0 being moderate (emissions peak around 2080, then decline) and RCP 8.5 being the least conservative (emissions continue to rise throughout the 21st century). Shaded area around means for each prediction represent a standard error in prediction for each individual lake (A-E, as a range between the four climate models). Shaded areas around mean in panel F (All lakes) represent variability between individual lakes in the region.

Figure 7. Flake simulation of changing ice cover duration for each temperate lake separately (A to E) and for an average temperate lake in northern Poland (F) between 2020 and 2099. The model was forced with an ensemble of four climate projection models (GFDL-ESM2M, HadGEM, IPSL and MIROC5). Climate changes between 2020 and 2099 were simulated under three relevant GHG concentration trajectories with RCP 2.6 being the most conservative scenario (emissions declining by 2020 and reaching zero by 2100), RCP 6.0 being moderate (emissions peak around 2080, then decline) and RCP 8.5 being the least conservative (emissions continue to rise throughout the 21st century). Shaded area around means for each prediction represent a standard error in prediction for each individual lake (A-E, as a range between the four climate models). Shaded areas around mean in panel F (All lakes) represent variability between individual lakes in the region.

Figures:

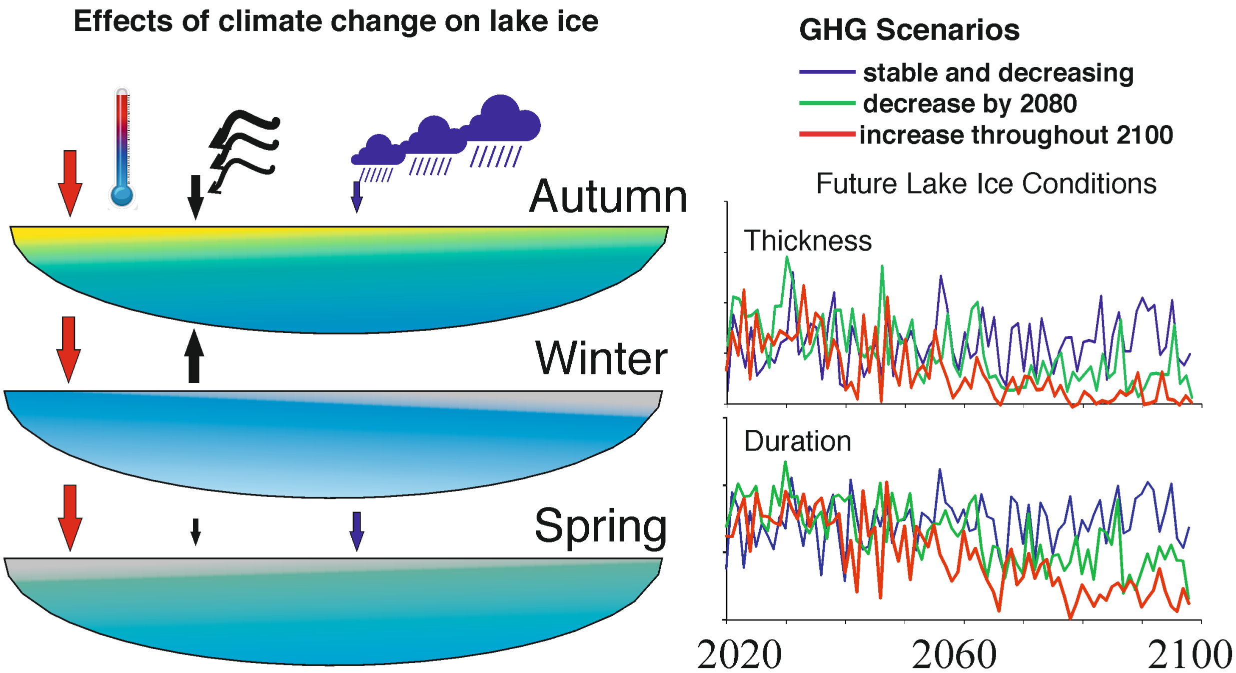
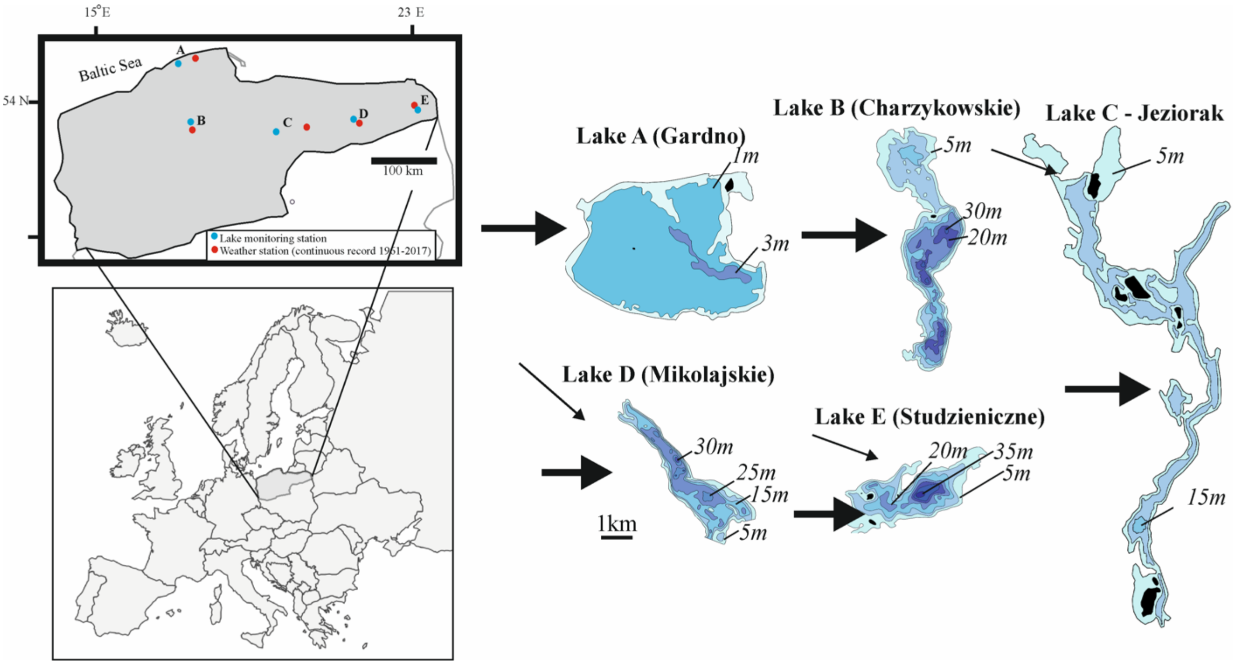


Fig. 1.

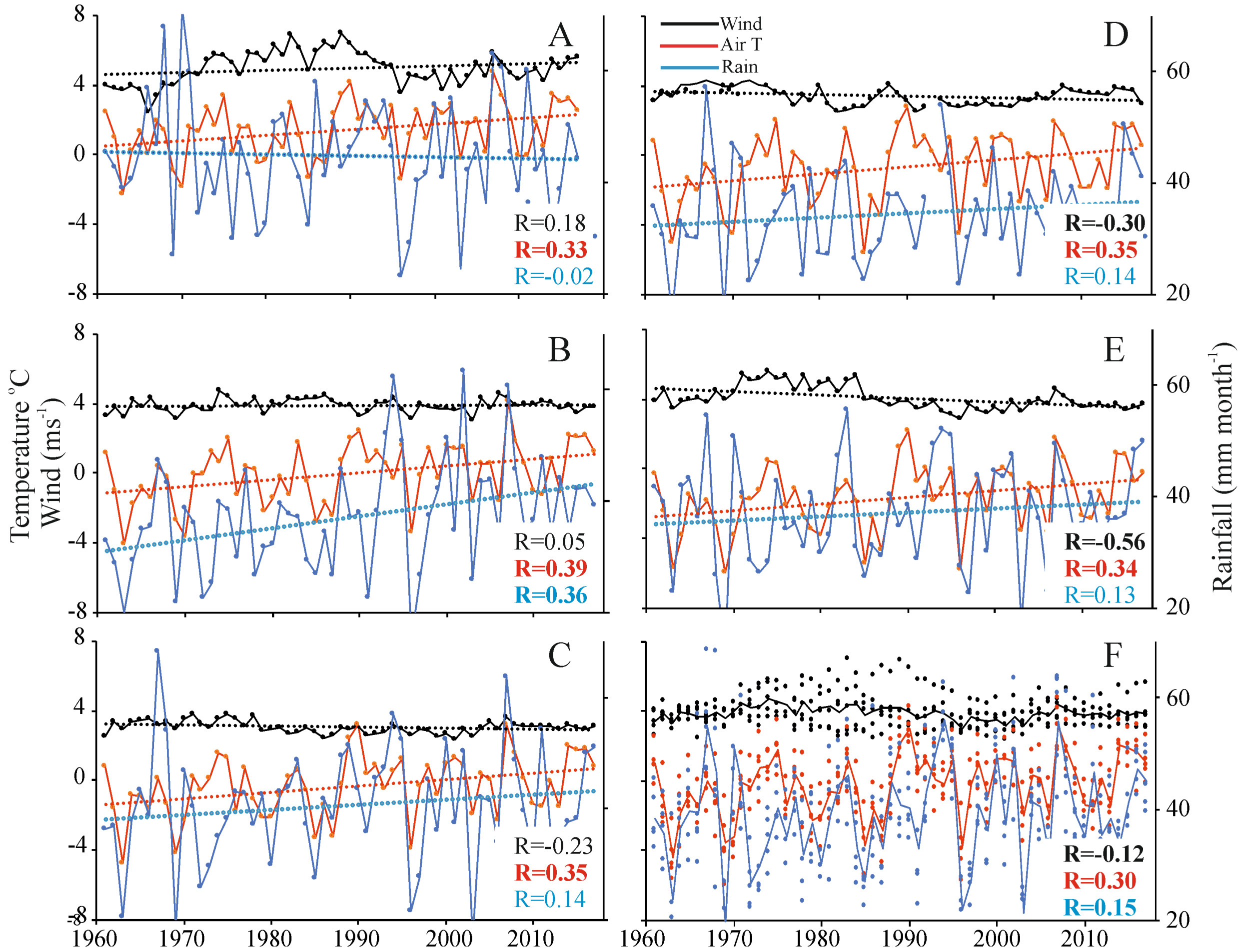


15°E
23 E
54 N
Baltic Sea
A
B
C
D
E
100 km
Lake monitoring station
Weather station (continuous record 1961-2017)
Lake A (Gardno)
1m
3m
Lake B (Charzykowskie)
5m
30m
20m
Lake C - Jeziorak
5m
15m
Lake D (Mikolajskie)
30m
25m
15m
5m
1km
Lake E (Studzieniczne)
20m
35m
5m

796

797 **Fig. 2.**

798


A
B
C
D
E
F
Wind
Air T
Rain
R=0.18
R=0.33
R=-0.02
R=0.05
R=0.39
R=0.36
R=-0.23
R=0.35
R=0.14
R=-0.30
R=0.35
R=0.14
R=-0.56
R=0.34
R=0.13
R=-0.12
R=0.30
R=0.15
Temperature °C
Wind (ms-1)
Rainfall (mm month-1)
1960
1970
1980
1990
2000
2010

799 **Fig. 3.**

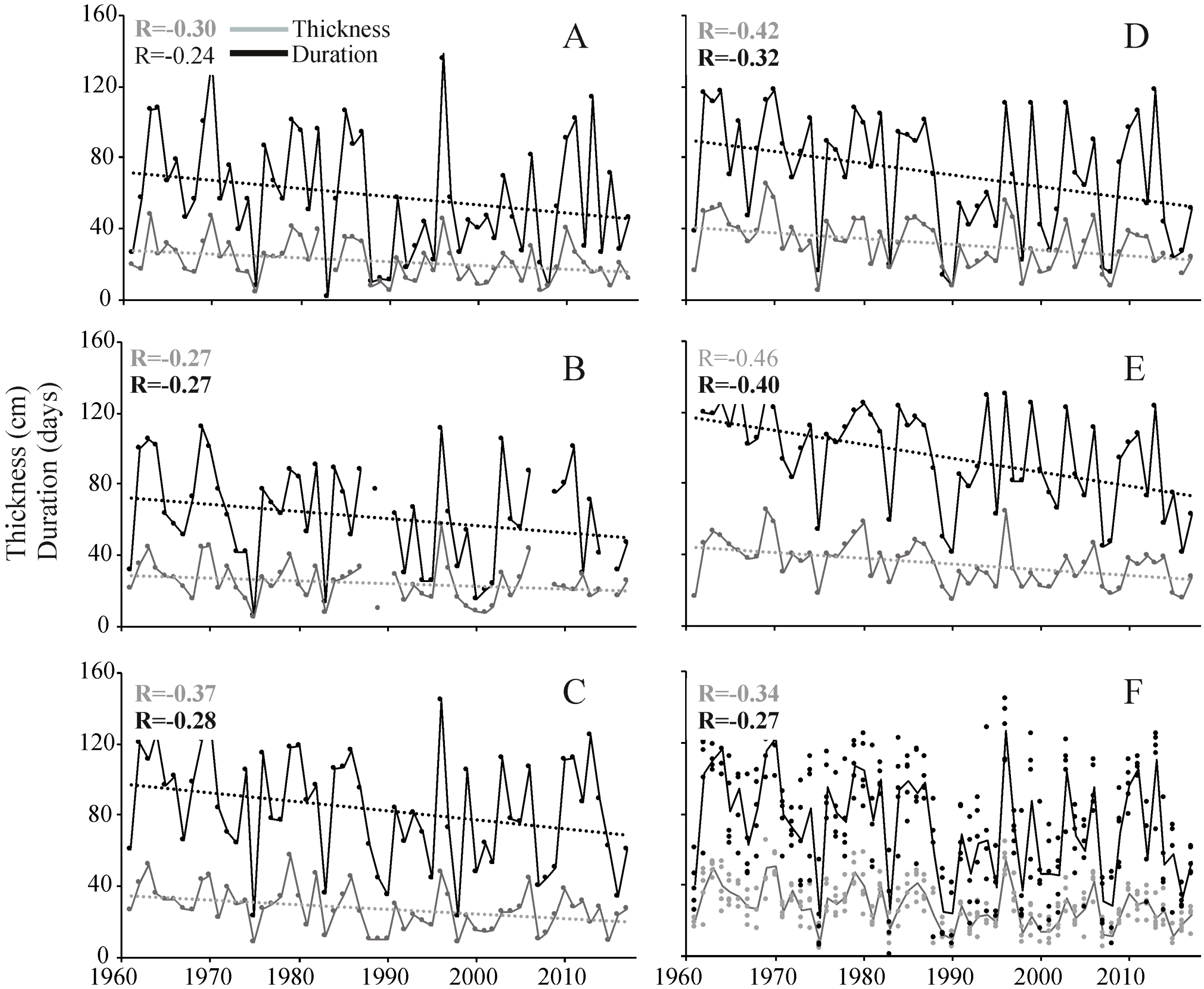

R=-0.30
R=-0.24
Thickness
Duration
A
R=-0.42
R=-0.32
D
R=-0.27
R=-0.27
B
R=-0.46
R=-0.40
E
R=-0.37
R=-0.28
C
R=-0.34
R=-0.27
F
Thickness (cm)
Duration (days)
0
40
80
120
160
1960
1970
1980
1990
2000
2010

Fig. 4.

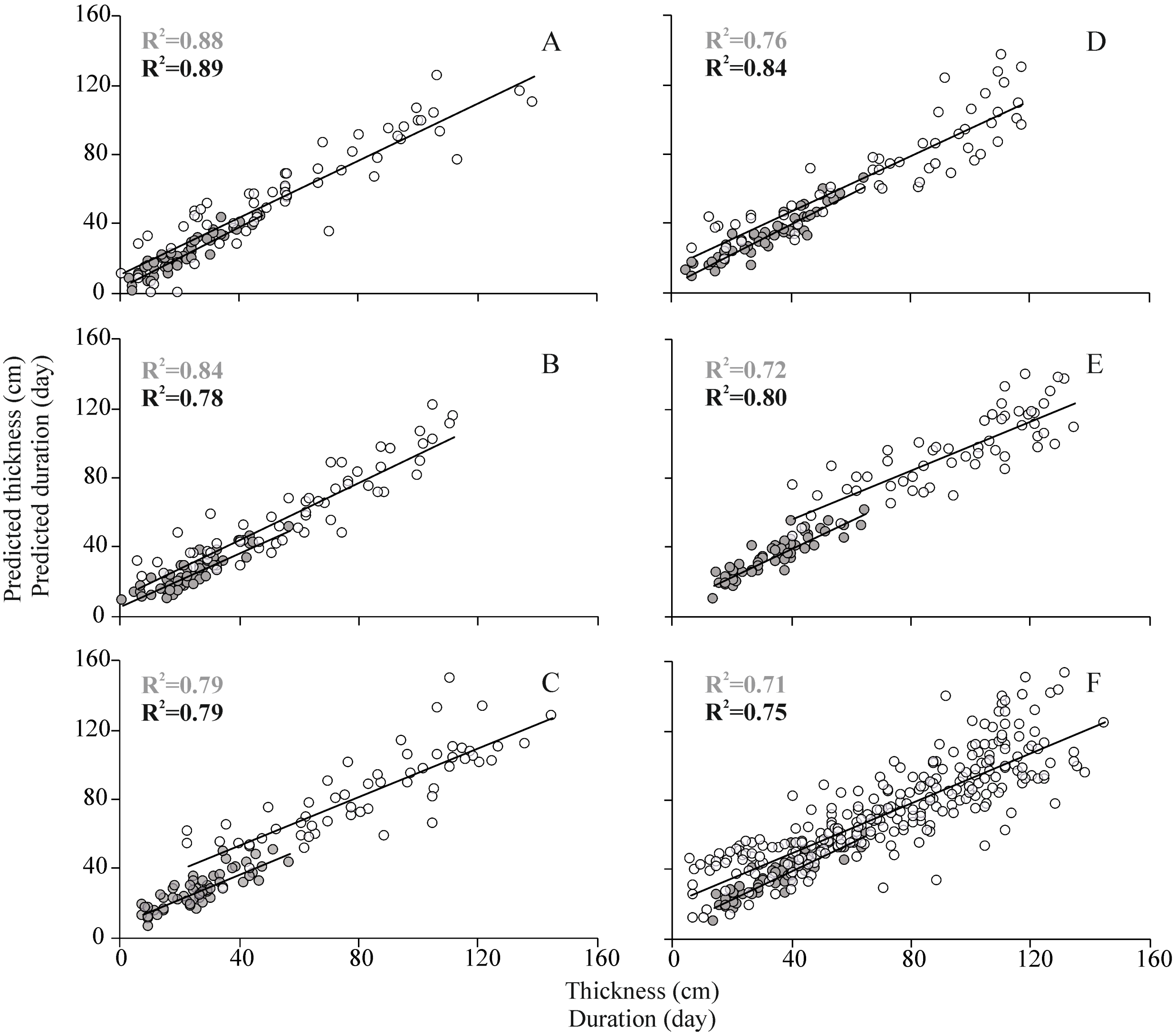

A
R²=0.88
R²=0.89
B
R²=0.84
R²=0.78
C
R²=0.79
R²=0.79
D
R²=0.76
R²=0.84
E
R²=0.72
R²=0.80
F
R²=0.71
R²=0.75
Predicted thickness (cm)
Predicted duration (day)
Thickness (cm)
Duration (day)
0
40
80
120
160

Fig. 5.

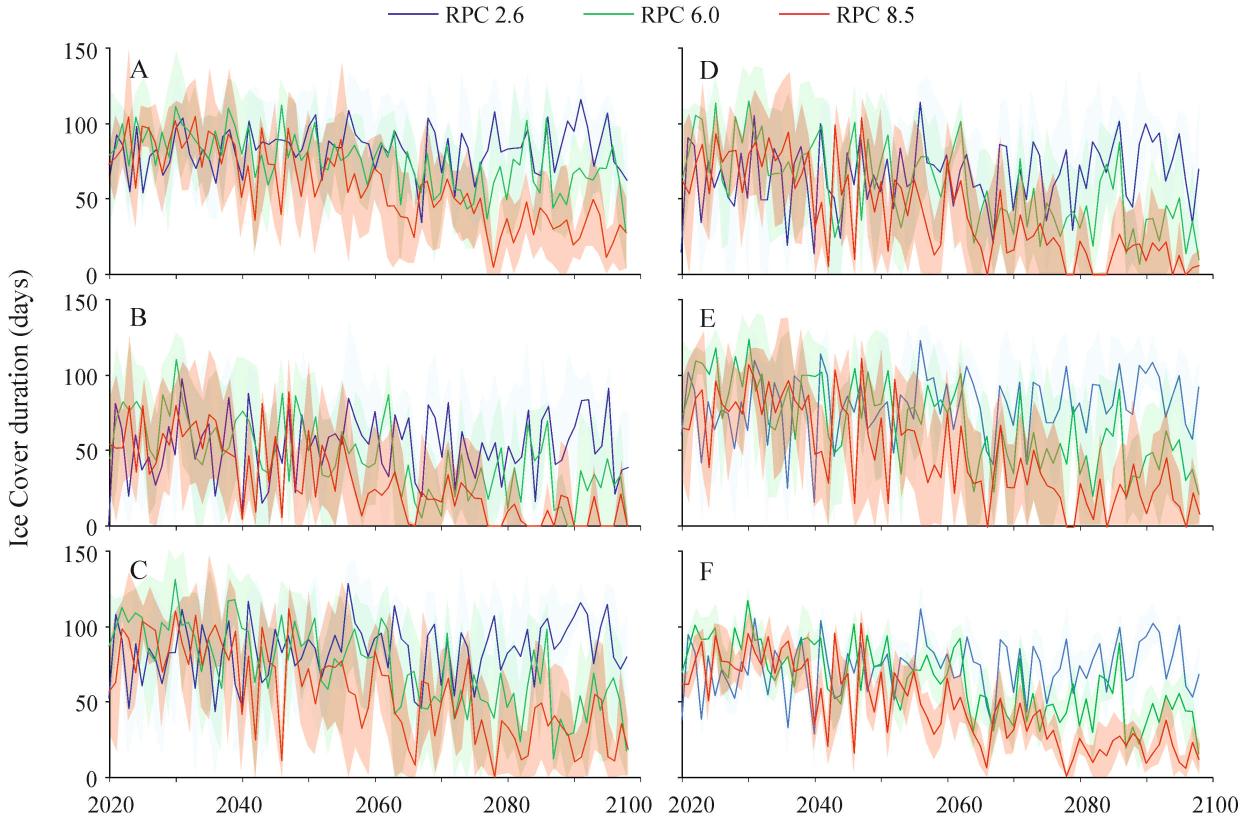

RPC 2.6
RPC 6.0
RPC 8.5
Ice Cover duration (days)
A
B
C
D
E
F
150
100
50
0
2020
2040
2060
2080
2100

Fig. 6.

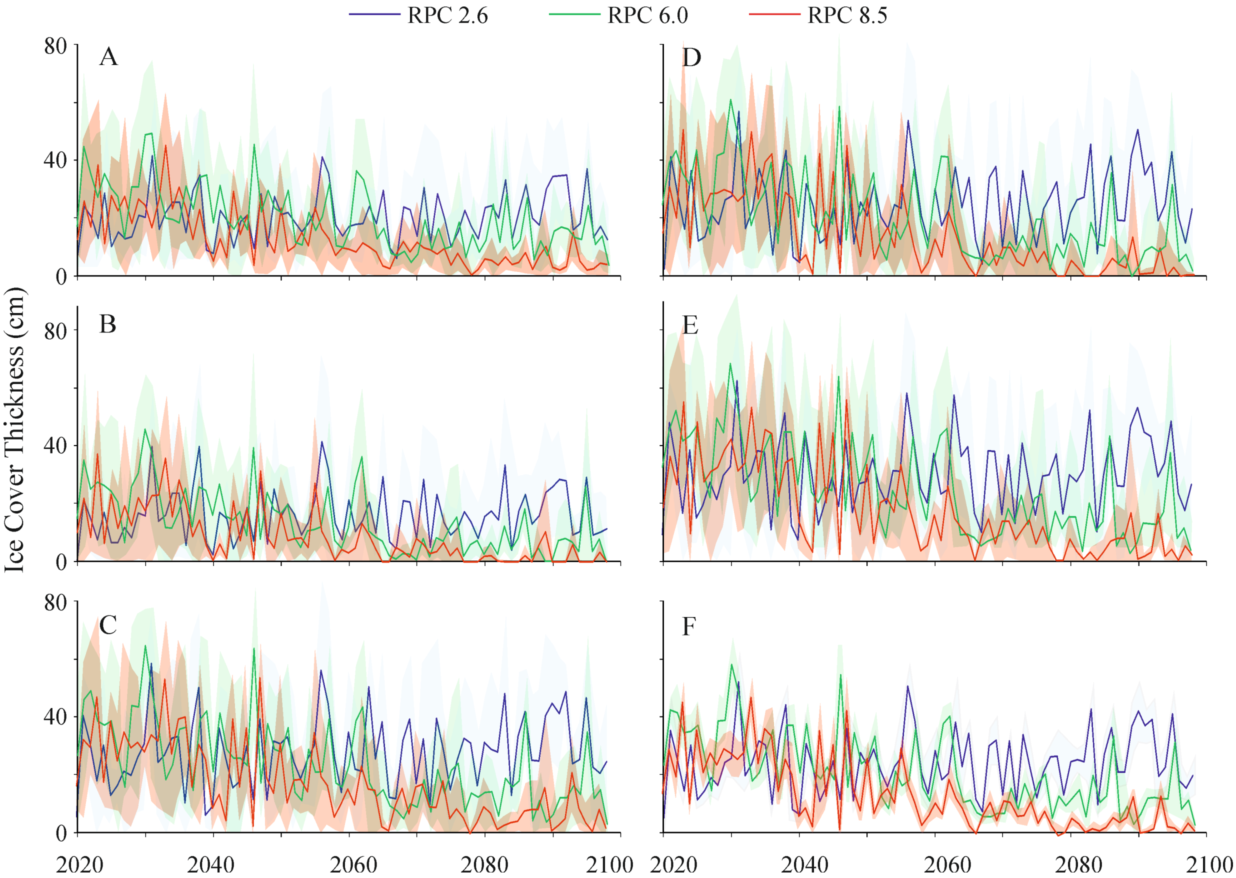

RPC 2.6
RPC 6.0
RPC 8.5
A
B
C
D
E
F
Ice Cover Thickness (cm)
80
40
0
2020
2040
2060
2080
2100

Fig. 7.