Warming Climate Shortens Ice Durations and Alters Freeze and Breakup Patterns in Swedish Water Bodies

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Abstract.

Increasing air temperatures reduce the duration of ice cover on lakes and rivers, threatening to alter their water quality, ecology, biodiversity, and physical, economical and recreational function. Using a unique in-situ record of freeze and breakup dates, including records dating back to the beginning of the 18th century, we analyse changes in ice duration (i.e., first freeze to last breakup), freeze and breakup patterns across Sweden. Results indicate a significant trend in shorter ice duration (62%), later freeze (36%) and earlier breakup (58%) dates from 1913-2014. In the latter 3 decades (1985-2014), the mean observed ice durations have decreased by about 11 days in northern (above 60N) and 28 days in southern Sweden relative to the earlier three decades. In the same period, the average freeze date occurred about 10 days later and breakup date about 17 days earlier in southern Sweden. The rate of change is roughly twice as large in southern Sweden as in its northern part. Sweden has experienced an increase in occurrence of years with an extremely short ice cover duration (i.e., less than 50 days), which occurred about eight times more often in southern Sweden than previously observed. Our analysis indicates that even a 1 °C increase in air temperatures in southern (northern) Sweden results in a mean decrease of ice duration of 22.5 (7.6) days. Given that warming is expected to continue across Sweden during the 21st century, we expect increasingly significant impacts on ice cover duration and hence, ecology, water quality, transportation, and recreational activities in the region.

1 Introduction

The world's freshwater systems are critically important for all humans and they have experienced significant environmental changes due to human activities and anthropogenic climate change (Dudgeon et al., 2006; Vörösmarty et al., 2010). In the artic regions climate change is amplified, mainly due to temperature feedbacks and change in surface albedo (Pithan et al., 2014). A global mean temperature increase of +2 °C from the 'pre-industrial' level would result in a higher mean temperature increase in Scandinavia (Vautard et al., 2014). As temperatures are projected to continue to rise, they are expected to cause major physical, ecological, social, and economic changes (Parmesan and Yohe, 2003).

One impact of global warming is the reduction in ice cover duration of freshwater systems, often associated with both a later freeze and an earlier breakup of the ice cover (Duguay et al. ,2003). Previous studies show that ice duration of inland waters is strongly correlated with and driven by air temperature and solar radiation (Sharma et al., 2019; Kropácek et al., 2012; Duguay et al., 2015; Livingstonea and Adrian, 2009). Analysis from different parts of the world indicates that duration of ice cover on lakes and rivers is sensitive to climatic change and variability (Prowse et al., 2011; Benson et al., 2012; Beltaos and Prowse, 2009; Takács, 2011; Latifovic and Pouliot, 2007; Magnuson et al., 2000). Decreased ice cover duration and earlier ice breakup have critical ecological consequences, influencing the timing of photosynthesis (Quayle et al., 2002; Leppäranta et al., 2012), productivity and biodiversity of phytoplankton, and the occurrence of fish kill (Leppäranta et al., 2003; Watz et al., 2016), as well as shaping the vegetation of flowing waters (Lind et al. 2014). Changes in ice duration modulate the energy and moisture exchange over the water surface (Duguay et al., 2003) and the timing of vertical mixing and stratification in lakes (Bengtsson, 2011).

In Sweden, lakes cover about 9% of the total land area (Henestål et al., 2015) and surface water provides 50% of its drinking water (Rosborg, 2015). In many high-latitude regions, including parts of Sweden, ice cover is also an important part of transportation and communication (Jeffries et al., 2012; Knoll et al., 2019). The Swedish Transport Administration, Trafikverket, has expressed concerns regarding the stability and duration of ice roads (i.e., frozen water bodies) and has requested that further research be conducted on this topic. The mean temperature of winter months in Sweden are expect to increase more than the summer month, with models predicting that a global mean temperature increase of +2°C from pre-industrial would results in an increase of +1.5 in the south to +3 °C in the north of Sweden compared to mean temperature of 1971-2000 (Vautard et al., 2014). Thus, reliable information about the rate of change in ice cover duration, which we investigate here, is needed to advise policy and decision makers, inform impact and adaptation activities, and understand potential impacts on recreational activities (e.g., ice fishing, ice boating, skiing, spiritual ceremonies, and ice skating) (Kling et al., 2003; Knoll et al., 2019).

Previous studies have examined the timing of ice cover on lakes and rivers in Sweden. For instance, Eklund (1999) provided an overview of ice data, up to 1999, and described methods of ice cover observation. Weyhenmeyer et al. (2004) also analyzed ice-breakup data across Sweden and identified regional differences in the timing and length of ice cover across the country's water bodies. They concluded that cooler regions (i.e., northern Sweden) are less sensitive to increasing air temperature than temperate regions (i.e., southern Sweden) in terms of earlier breakup of ice cover. Comparing the colder time period of 1961–1990 to the warmer period of 1991-2002 (by 0.8ºC), they observed that ice breakup occurred 17 days earlier in the southern region during the latter period, but only 4 days earlier in the northern region. Hence, they concluded that increasing air temperature can drastically shift the timing of lake ice breakup in the warmer and southern regions of Sweden, while it is less drastic in the northern parts. Since a long time series of lake ice observations can serve as a proxy for climate change and provide a convenient climate index (Duguay et al., 2003), we extend these previous studies using more recent observations, longer records of ice duration, breakup, and freeze data, and more observation sites across the whole of Sweden.

Weyhenmeyer et al. (2011) investigated the ice phenology from 1213 lakes and 236 rivers in 12 different countries, including Sweden. They find a stronger decrease in ice duration across regions with shorter durations and air temperatures below 0 ˚C, such as southern Sweden below 61˚N. They suggested that 3.7% of the world's lakes larger than 0.1km^2 are at risk of becoming open-water systems in the near future. Sharma et al. (2019) estimate that the number of lakes with intermittent winter ice cover are increasing, from currently 14,800 lakes in the Northern Hemisphere to 35,300 with 2 °C warming and 230,400 with 8 °C, impacting up to about 400 and 650 million people.

In this study, we characterize the ice cover duration using in situ observations, from the Swedish Meteorological and Hydrological Institute, of ice cover freeze and breakup from 752 lake and river observation sites in Sweden (see the Methods and Data Section) to better understand the relationship between temperature variability and ice duration and associated trends. We quantify temporal and regional shifts in the distributions of ice freeze and breakup dates and ice durations across Sweden since they remain poorly understood. Compared with earlier studies (e.g., Weyhenmayer et al., 2004), we use more recent and updated observations on ice duration, breakup and freeze dates and their probability distributions, and quantify the sensitivity of ice properties to a unit degree of temperature change.

2 Methods and Data

2.1 Ice Data Observations, Monitoring, and Uncertainty

We used ice data records obtained mainly from the Swedish Meteorological and Hydrological Institute (SMHI), which include freeze and breakup dates. In total, the dataset includes observations from 752 observations sites, consisting of 677 (~90%) lakes and 75 (~10%) rivers. Observations span from 1700-2014, however the coverage and locations vary over time. Observation sites from 1871 can be seen in Figure 1. The number of observations from 1860-2014 are presented in Figure 2.

Since 1870 lake ice was observed systematically and manually from the shore by an observer responsible for monitoring that lake or the part or bay of the large lake (Eklund, 1999). Some records date back even longer and come for example from records taken from boats. While most observations used here were provided by SMHI, Torne River observations were made by the Finnish Environmental Institute (SYKE). The "freeze date" is defined as the first date from which the whole lake, except for small segments, is ice covered for a minimum of three consecutive days (Eklund, 1999). Moreover, the "breakup date" is the day the entire lake becomes free of ice, except for small parts of ice close to the shore and around obstacles (Eklund 1999).

In this study, we define ice duration as the number of days between the first freeze date and the last breakup date. The ice year is defined from September 1st to August 31st. The date September 1st was selected for practical reasons after finding very few observations of freeze dates prior to or breakup dates after it. Lakes and rivers may have multiple freeze and breakup dates during a winter period. For consistency, here we use the first freeze and last breakup dates for data analysis. Moreover, we do not separate years with no ice cover from years with no data, since no records exist for years without ice cover. The observations include lakes, and some rives with a variety of sizes. As for big lakes, such as Vänern (5,650 km²) or Mälaren (1,072 km²), a smaller somewhat separated part, often a bay, is observed.

One source of uncertainty is that the lengths of ice records vary significantly. Selecting a common period of overlap would lead to elimination of significant observations. To address this issue and to utilize all the observations, we have used different time periods for different statistical analysis. Depending on the method, we designed the periods such that we can incorporate as much of the data as possible in our analysis. Other potential sources of uncertainties include human error in observations and later manual digitalization. The SMHI notes that the definition of freeze and breakup during observations and digitalization of the data might not have always been consistent.

2.2 Statistical Tests, Trends, and Spatial Analyses

We analysed the mean breakup dates over ten-year intervals from 1871 to 2010 (Figure 1) using all observations over the time period, and implemented bivariate interpolation onto a grid for irregularly spaced input data. Bilinear interpolation is applied using algorithms from the R package 'Akima' and 'interp' function. The mean value was used for observations sites with more than one year of data (duplicates). As a result, each observation site is only represented once; however, the mean value used can be a combination of one to ten years of data for that point.

Records were tested for statistically significant trends over 1913 to 2014 for ice duration, freeze and/or breakup dates. A significance level of 95% was used to evaluate trends in the ice phenology variables (freeze date, breakup date, and ice duration). The Mann-Kendall R package 'Kendall' (McLeod, 2011) was used to perform the trend tests (Kendall 1938). Observation points with at least 81 years of recorded data from the 101-year time period (maximum of 20% missing data) were used in the analysis.

Moreover, we used ordinary least squares via the lm() function in the R package ‘stats’ to compute the slope of the best linear fit for the temperature and ice variables. The slopes serve as a measure of the change in the number of days (of ice duration, freeze date, or breakup date) per 1 °C temperature increase (Figure 6). 3 Results

3.1 Earlier ice breakup since the end of the 19th century

We analyze all breakup date observations from 1871 onward, since systematic observations started in 1870 (Eklund, 1999). Figure 1 presents the mean breakup dates from 1871 to 2010. We generated the maps shown in Figure 1 by bi-linearly interpolating the data gathered by the Swedish Meteorological and Hydrological Institute (SMHI) across the country. As time progresses in Figure 1, the area with breakup dates after June decreases (blue contour), and the areas of breakup prior to April (purple contour) and May (red contour) move northward. From 1871 to 1930 and 1951 to 1970 the geographical mean breakup pattern is similar, while the years 1931 to 1950 display a larger area with breakup before April. Ice breakup prior to June even extends into the northwest mountain areas of Sweden during 2001-2010. The largest differences in breakup dates are found in the later period of 1991 to 2010. In the last time period (2001-2010), the ice breakup generally occurred prior to the first day of June even in the northers part of Sweden. Figure 1 also presents where observations were recorded over each decade. Note that there is a change in the number of observation points (Figure 2). There are less observations in the first four decades and a decreasing number of records during the last two decades (see Figure 2d).

Further, we analyze all water bodies with observations of freeze and subsequent breakup dates in Sweden. For each day of the ice year (September-August) from 1860-2014, Figure 2 shows the fraction of observed water bodies across Sweden that are ice covered. In other words, the fraction represents the total number of ice observations for that specific day divided by the total number of observations available that year. To better understand the relative fraction of ice covered water bodies for a given year, which ranges from zero (days with no observed ice cover) to unity (days where all observed sites were ice covered), Figure 2d quantifies the number of available observations used per year. Figure 2 further demonstrates that a decrease in ice cover duration has occurred since the 1860s. Moreover, since the late 1980s, there is a noticeable increase in inter-annual variability and years with extremely short ice cover duration, especially in southern Sweden (see Figure 2), which we further investigate below.

The Torne River and a part of the lake Mälaren, Västeråsfjärden, have longest record of breakup dates in the data provided to us by SMHI. The Torne River, located in Sweden-Finland border (see Figure S6 in in the supplementary materials), have observations dating back to the 18th century (Johansson, 1932; Kajander, 1995; Korhonen, 2006). The data includes 291 years of breakup dates (1700-2009, except 1770-1789), recorded for the downstream portion of the Torne River, close to city of Haparanda. We find a significant trend in earlier ice breakup, using the Mann-Kendall trend test with a 99% significance level ($p<<0.01$). In addition, we consider the Västeråsfjärden, which is a waterway in the northwest part of the brackish lake Mälaren outside the city of Västerås, just below 60 °N in Sweden (See Figure S6). Despite 38 years of missing data, with the longest consecutive period of missing data being the 10-year period from 1974-1985, the Västeråsfjärden has long-term records with 234 years of breakup data (1711-2012) and 69 years of freeze dates (1870-1986). The lake displays a significant trend in later freeze (p-value < 0.002); however, we do not find a significant trend in earlier breakup. See Figure S1 in the supplementary material for breakup observations from Västeråsfjärden and Torne River.

3.2 Significantly reduced ice duration from 1913-2014

Now we characterize the water bodies with minimal missing data by analyzing trends in the observed ice duration and freeze and breakup dates (i.e., ice phenology variables) from 1913-2014 using the Mann-Kendall trend test (Kendall 1938) at a 95% significance level (Figure 3). Lakes and rivers with a maximum of 20% missing observations were included in the trend analysis of ice duration (40 water bodies), freeze date (47 water bodies) and breakup date (57 water bodies). Since the Mann-Kendall trend test is sensitive to missing data, and using a dataset with missing data is a source of uncertainty, we excluded many observations sites in this analysis to have higher confidence in the presented results. The time period was chosen to be able to look at long-term trends and include lakes and rivers in across the entire Sweden. A longer time period would result in less water bodies or more missing data.

A significant decreasing trend in ice cover duration was found for 24 of the 40 (62.5%) water bodies (Figure 3a). A significant trend in later freeze date was seen in 17 out of 47 (36%) water bodies (Figure 3b) and an earlier breakup was observed in 32 out of 55 (58%) water bodies (Figure 3c). The majority of water bodies with records of ice data from 1913-2014 show a significant trend in decreasing ice duration and earlier breakup. Only one lake exhibits a trend in earlier freeze, Lake Flåsjön (blue mark in Figure 3b). Forty water bodies displayed a significant trend in at least one of the ice variables associated with a warmer climate (i.e., decreasing ice cover duration (Figure 3a), later freeze (Figure 3b), or earlier breakup (Figure 3c). Sites with a significant trend were located both in southern (latitudes < 60°N) and northern Sweden, and included lakes of a variety of sizes. Fourteen water bodies showed a significant trend in all three ice variables associated with a warmer climate and out of these sites, all except one, are located above 60°N (i.e., northern Sweden). Hence, our findings indicate that the ice duration is shrinking over most of our study sites in Sweden mainly driven by an earlier ice breakup and in some cases later freeze date. For the lakes represented in Figure 3, linear regression analysis show that ice duration from 1913-2014 has decreased at -1.8 days per decade. In the same period, the freeze date occurred 0.8 day later per decade whereas the breakup date was observed 0.9 day earlier per decade. 3.3 Changes in timing of ice cover, 1985-2014 compared to 1955-1984

Figure 4 compares the distributions of observed ice duration and freeze and breakup dates for the two periods 1955-1984 and 1985-2014. The analysis includes all observed sites with a maximum of 20% missing data in the 30-year periods. Mann-Whitney-Wilcoxon test shows a significantly difference in the two samples at a 0.05 significance level for all analyzed groups in Figure 4 (Bauer, 1972; Hollander and Wolfe, 1973). Figures 4a and 4d demonstrate that the ice duration has decreased over the last 30 years, with a mean decrease of about 11 and 28 days in northern and southern Sweden, respectively. The shift in the mean ice duration is larger in southern Sweden compared to the northern region. Although shorter ice durations are more common in both regions during 1985-2014 than 1955-1985, the shape of the ice duration distribution between the two time periods also more greatly differs in southern Sweden. Over the more recent 30-year period in southern Sweden, the mean freeze date occurs 10 days later (Figure 4e), while the mean breakup date occurs 17 days earlier (Figure 4f) than previously observed. Considering the same time periods, the shifts in the mean timing of freeze and breakup are smaller in northern Sweden, with the mean freeze date observed about four days later (Figure 4b), and the mean breakup date occurring five days earlier (Figure 4c) in the last 30 years. Comparing the mean temperature of the two time periods using SMHI homogenized data, the mean temperature of the later period (1985-2014) is about 0.85 ºC warmer than during the earlier period (1955-1984).

Changes in the timing of ice cover have shifted the mean duration, resulting from an increase in extremely short durations (Figure 4). Figure 4d indicates that during 1985-2014 southern Sweden experienced a 750% increase in the number of years with less than 50 days of ice cover relative to the previous 30 years. In northern Sweden (Figure 4a), an increase of 300% was observed in the number of years with an ice cover duration of less than 100 days. Hence, Figure 4 highlights differences in the ice duration distributions related to the geographical locations of the observations (i.e., northern vs. southern Sweden), as well as the freeze date and the morphological aspects.

An increase in the interannual variability of ice cover duration could be an early warning sign of ecological regime shift (Carpenter et al., 2011). Magnuson et al. (1997) demonstrated that such an increase in interannual variability and more frequent, extremely short durations of lake ice cover have occurred since the 1950s across Canada, the United States, Finland, Switzerland, Russia, and Japan. We also find an increase in interannual variability across Swedish lakes and rivers. The observations in Figure 4 can be related to change in both mean and variance described by Benson et al. (2012). We acknowledge that missing data could result in different water bodies being represented differently in the two time periods. However, we do not expect this to be a major source of uncertainty.

3.4 Historical change in ice duration per 1ºC of warming

To better understand the drivers of variability in the ice cover durations observed above, Figure 5 characterizes the relationship between the local mean annual air temperatures (September-August) and ice durations using air temperature observations from the Climatic Research Unit (CRU) v 3.23 (Harris et al. 2014). A warmer mean annual air temperature corresponds to a shorter ice duration (Figure 5). These relationships are also considered with respect to latitude (Figure 5a) (719 water bodies), as well as mean depth (Figure 5b), volume (Figure 5c) and area (Figure 5d) (464 lakes). In Sweden, the climate is much colder in the northern regions compared to the southern (Figure 5a). The most northern lakes are frozen for a longer period than southern Sweden lakes. In fact, some southern lakes might not freeze at all in the winter. This results in latitude being the overall dominant factor compared to the size (depth, volume and area) of the lake. Larger water bodies (volume, depth, or area) generally have shorter ice durations compared to smaller ones. Larger water volumes in lakes, for instance, often result in a later freeze date and therefore contribute to a shorter ice duration. The breakup date however is not as sensitive to the size of the lake.

We also quantify the change in ice cover duration relative to air temperature for 464 lake water bodies using temperature and ice data from 1901-2014 (Figure 6). We applied linear regression to obtain the rate of change in ice duration for each lake relative to a historical air temperature. The results indicated that an increase in air temperature is related to a reduced ice duration (Figure 6a), a later freeze date (Figure 6b) and an earlier breakup date (Figure 6c). For lakes with a lower latitude (southern Sweden) we see more sensibility per 1°C increase than at higher latitudes. In southern Sweden (below 60N), mean ice duration decreases by 22.5 days per 1°C increase, with the mean breakup date occurring 11.2 days earlier, and the mean freeze date occurring 8.1 days later. In northern Sweden, the shift per 1°C increase is smaller, with mean values for ice cover duration decreasing by 7.6 days, the freeze date occurring 3.6 days later, and the breakup date occurring 4.4 days earlier per degree of warming (see also Figures S4 and S5 in Supplementary Materials for more information on breakup date and freeze temperature relationships).

4 Discussion and Conclusion

We show that for many water bodies in Sweden, freeze dates are occurring later in the season while breakup dates are occurring earlier (Figures 1-4). As a result, the ice cover duration has decreased in many of the observed lakes (Figures 2-4). Moreover, we find an increase in the number of years with extremely short ice cover duration (Figure 4), especially in the last 30 years (i.e., 1985-2014) in southern Sweden (latitudes < 60°N). The breakup date is similar for lakes in similar geographic regions and is not dependent on the size of the lake (Eklund 1999). As shown in Figure 1, earlier ice breakup observed over all of Sweden.

Earlier ice breakup affects the productivity and biodiversity of phytoplankton (Leppäranta et al. 2003), reduces winter dependent zooplankton species (Kling et al. 2003), and decreases fish production while increasing winter fish deaths (Watz et al. 2015), (Leppäranta et al. 2003). Moreover, with a decrease in ice duration, the photosynthesis in the lakes and rivers extends longer into the fall season and starts sooner in the spring (Kling et al. 2003). Longer durations without ice cover have a larger impact on the mixing patterns of the lake. Moreover, the depth of the mixing layer is related to light availably, phytoplankton density, and the carbon to nutrient ratio of phytoplankton, as well as zooplankton biomass, which may have effects on higher trophic levels (Berger et al. 2006).

We demonstrate that ice cover duration has reduced in Sweden, and thereby the periods with suitable conditions for the use of frozen rivers and lakes as ice roads in northern Sweden have decreased by approximately seven days of ice cover per degree Celsius of air temperature increase. Here, we investigate changes in the ice cover duration from first complete ice cover to complete breakup; however, further investigation of changes in ice thickness would be beneficial for assessing the safety of transportation over ice as well as the occurrence of multiple ice periods. Similarly, while the season for ice-related recreational activities will shorten, again, other factors such as ice thickness should be accounted for the safety of individuals partaking in activities on frozen water bodies.

In Sweden, a more drastic shift in ice breakup dates is expected with increasing air temperature in temperate regions (average air temperatures of 5 to 7°C) compared to colder regions (-2 to 2°C) (Weyhenmeyer et al., 2004). Our results reveal that drastic changes in southern Sweden appear to already be occurring (Figures 4). Similar results are also found in Finland, with a larger change in southern Finland compared to northern (Korhonen et al. 2006). Weyhenmeyer et al. (2004) found that the nonlinear relationship between breakup date and the mean annual temperature across Sweden can be represented using an arc cosine function. They also analyzed the amplitude of annual air temperature cycles as a proxy for solar radiation, concluding that in climate regions with larger temperature differences between winter and summer months, the sensitivity of ice duration to temperature changes is smaller than in regions with a smaller annual air temperature amplitude (difference from max to minimum temperature). Thus, lakes and rivers in the southern part of Sweden are more vulnerable to increasing temperature than regions with a larger temperature difference between summer and winter months.

During the period of 1959-2014, southern Sweden exhibited a large rate of change in ice duration relative to the studies found and referenced herein (Table S1 Supplementary Materials). According to SMHI harmonized temperature data, the mean change in air temperature in Sweden was about +0.09 °C per decade from 1901-2014 (Alexandersson and Moberg, 1997; Moberg and Alexandersson, 1997; Moberg and Bergström 1997). Here we observe 1.9 days per decade less ice duration during the same period. For comparison with previous studies, Table S1 (Supplementary Materials) summarizes the changes in ice duration, freeze date and breakup date from previous studies on inland ice cover (Magnusson et al., 2000; Benson et al., 2012; Takács, 2001; Latifovic et al., 2007; Jenset et al., 2007; Hodgkins, 2013). For the most part, our updated rates indicate more rapid change to ice properties in recent years. For example, in our analysis for the period 1959-2014, the corresponding rates of change for later freeze (+ 2 days per decade) and earlier breakup dates (-2.9 days per decade) across Sweden are, respectively, three and four times faster than those reported in Magnuson et al. (2000) for lakes across the Northern Hemisphere from 1846-1995 (Table S1).

Moreover, air temperatures at high latitudes are increasing more rapidly than the global mean temperature, making studies related to lake and river ice increasingly important. Historical data and model predictions indicate that the average temperature of cold days has increased more than the mean temperature in eastern and northern Europe (Vautard et al., 2014; Kjellström, 2004). Hence, the winter temperatures of this region is likely to be affected more by climate change than the annual mean temperature. Sharma (2021) suggests that that rapid changes in northern ice pattern can be due to the polar amplification (Post, 2018). More research in this area is warranted to quantify or isolate the effect of polar amplification and investigate other potential drivers such as oceanic/atmospheric circulation patters (Korhonen, 2019).

Future research is needed to assess the influence of reduced ice cover duration on the lake and river water quality and ecology including potential eutrophication, acidification, regulation, and flow pattern changes. The consequences of the release of nutrients and oxygen-demanding substances cannot yet be forecast for ice covered lakes (Bengtsson 2011). Given the significant changes in ice cover duration that we characterized across Sweden, incorporating ice cover into the overall picture of impacts on freshwater resources may be helpful for improving the understanding of variability within freshwater systems.

Finally, we acknowledge that regulation of lakes and rivers may also influence the trend in freeze and breakup dates, potentially leading to either an earlier or later freeze date than would naturally occur. Although, hydroelectric power plants expanded in Sweden in the period of 1950-1970, regulation is typically constant over time once it is established

Appendix

We use the air temperature data from the Climatic Research Unit (CRU) v 3.23 (Harris et al., 2014) to assess the relationship between temperature and all of the freeze date, breakup date, and ice duration observations (Figure 5 and 6). The spatial resolution of the CRU monthly mean air temperature data is 0.5x0.5 degrees and the temporal coverage is from 1901 to 2014. The average air temperature for the ice year was derived using the average of the monthly mean values from September to August.

We coupled the ice data record with information from SVAR (Swedish Water Archive 2012, SMHI) to derive information about the waterbody (such as location, areal extent, depth etc.). The geographic location and shape of the lakes was used to extract corresponding data from the lakes, using the shapefiles from SVAR (Swedish Water Archive 2012, SMHI). For larger lakes overlapping several CRU grid cells, we used the average temperature value of those cells to represent the air temperature over the lake (Figures 5 and 6). Our analysis includes all ice observations within the time period, where big lakes with multiple observations and lakes with more observations are more frequently represented than others (Figures 5 and 6).

In Figures 5 and 6, ice duration was coupled with mean annual temperature from September to August. The mean correlation of ice duration and air temperature (September-August) was $r = -0.54$. Freeze date was coupled with mean temperatures from October to December, and breakup dates with mean temperatures from March to May. The breakup date has a stronger mean correlation with temperature (r= -0.69, temperatures March-May) compared to the freeze date (r=+0.50, temperatures October-December).

Data availability

The ice freeze and breakup observations are available from the Swedish Meteorological and Hydrological Institute (SMHI). The ice data from 1950-today is now available in the ERA5 re-analysis data (https://doi.org/10.24381/cds.bd0915c6). Air temperature data is air available from the Climatic Research Unit (CRU). Lake and river information are available from Swedish Water Archive (SVAR) at SMHI.

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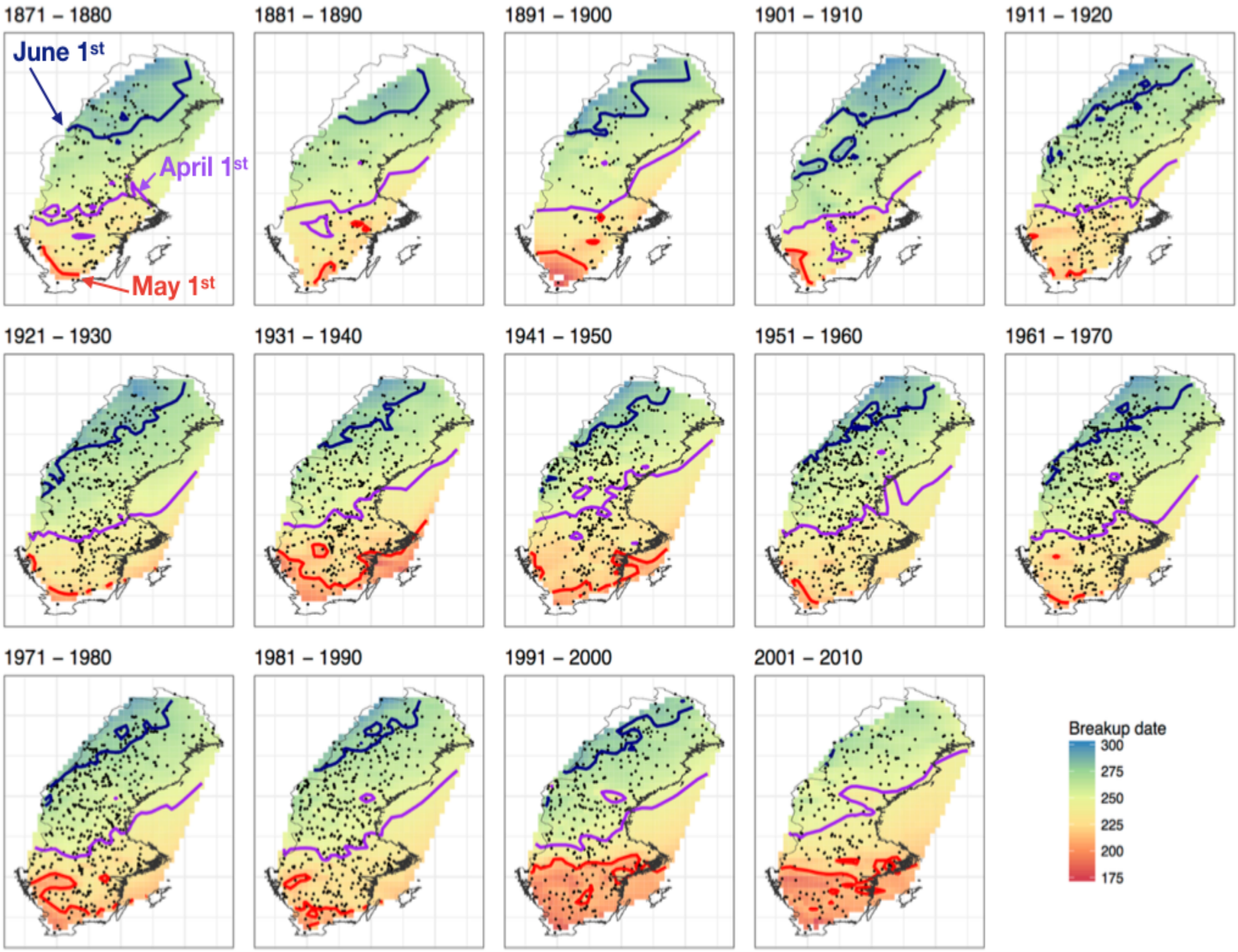
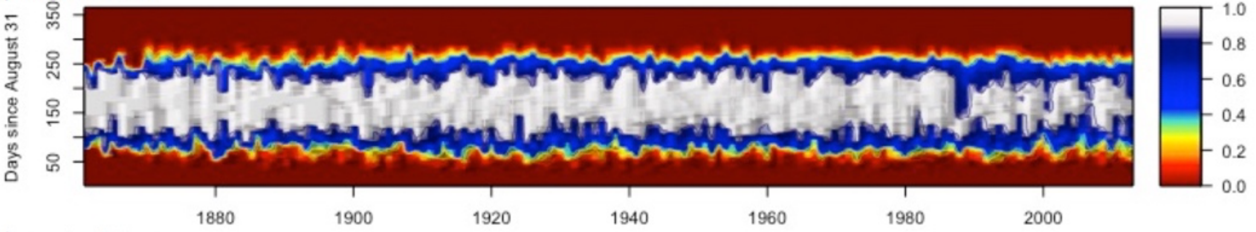
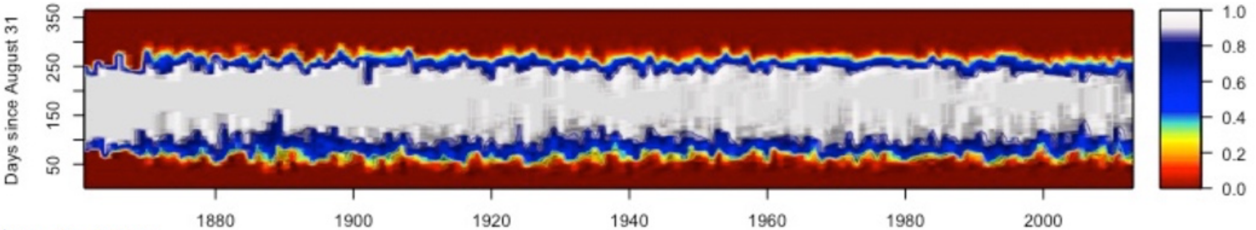


Figure 1: Mean ice breakup date over ten-year periods from 1871 to 2010, where shading represents the number of days after the 31st of August when ice breakup occurs. The blue, purple, and red contour lines respectively represent a breakup date by the first of June, the first of May, and the first of April. Black dots indicate the observation sites for each ten-year period.

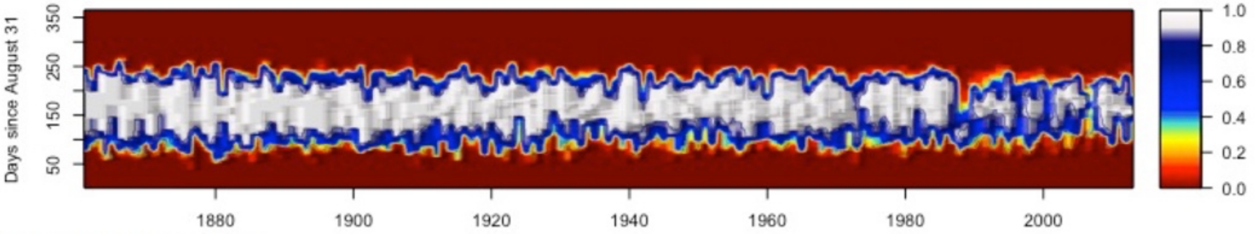
a) Sweden-wide



b) North of 60 N



c) South of 60 N



d) Number of observations

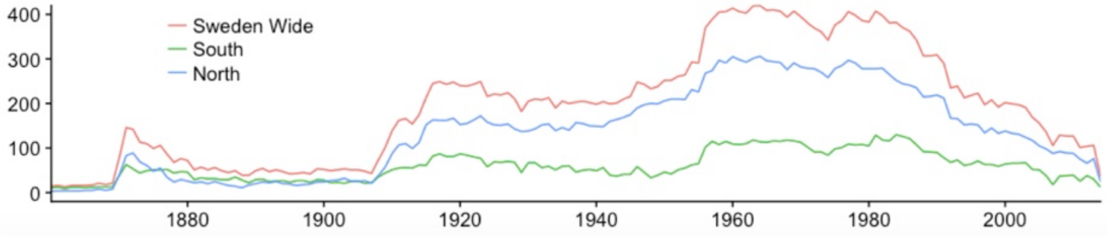


Figure 2: Fraction of the total number of observed lakes and rivers with ice cover each day of the ice year (September-August) for all observed water bodies from a) the entirety of Sweden and b) north and c) south of 60^{o}N in Sweden from 1860-2014. White-grey colouring represents days with 90% - 100% (i.e., 0.9-1.0) of lake-ice area covered. Plot d) displays the number of observations each year.

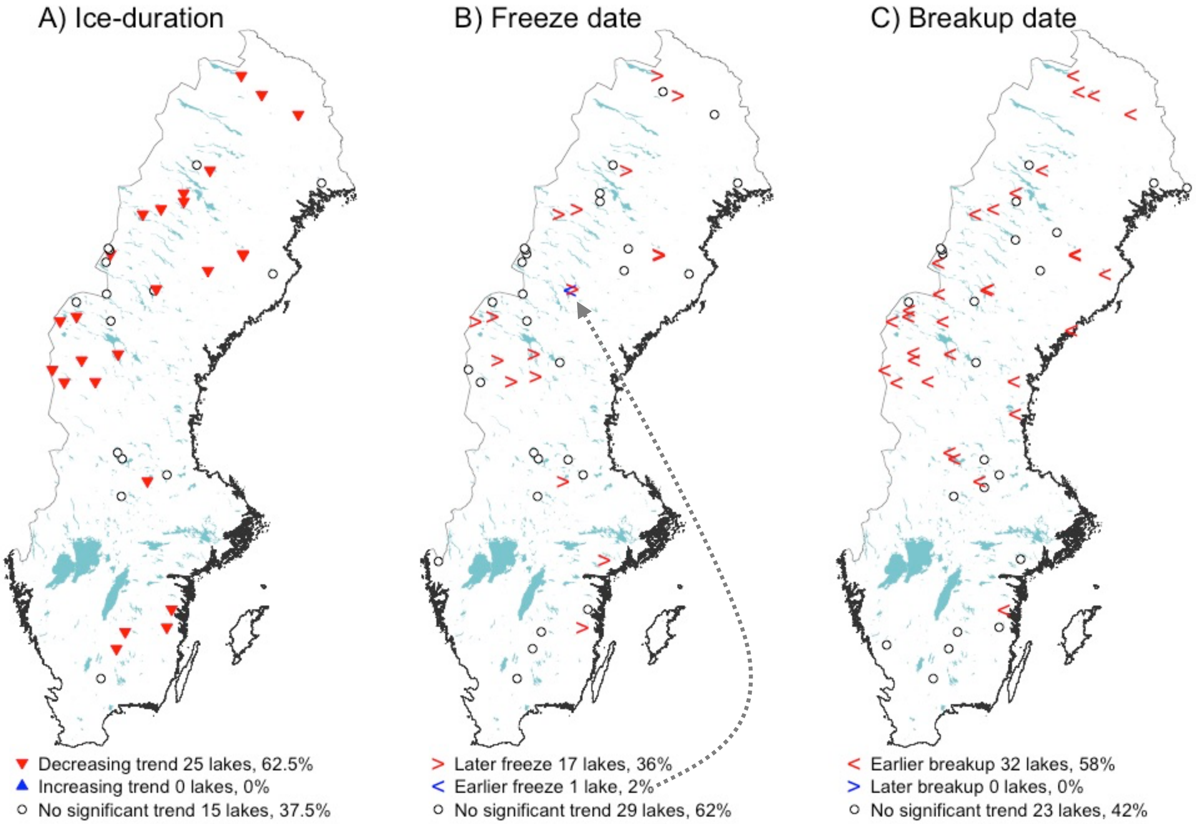


Figure 3: Trends in a) ice duration, b) freeze date, and c) breakup date during 1913-2014. The number of water bodies and the corresponding percentages of observation locations with statistically significant ($p<0.05$) or insignificant trends are indicated.

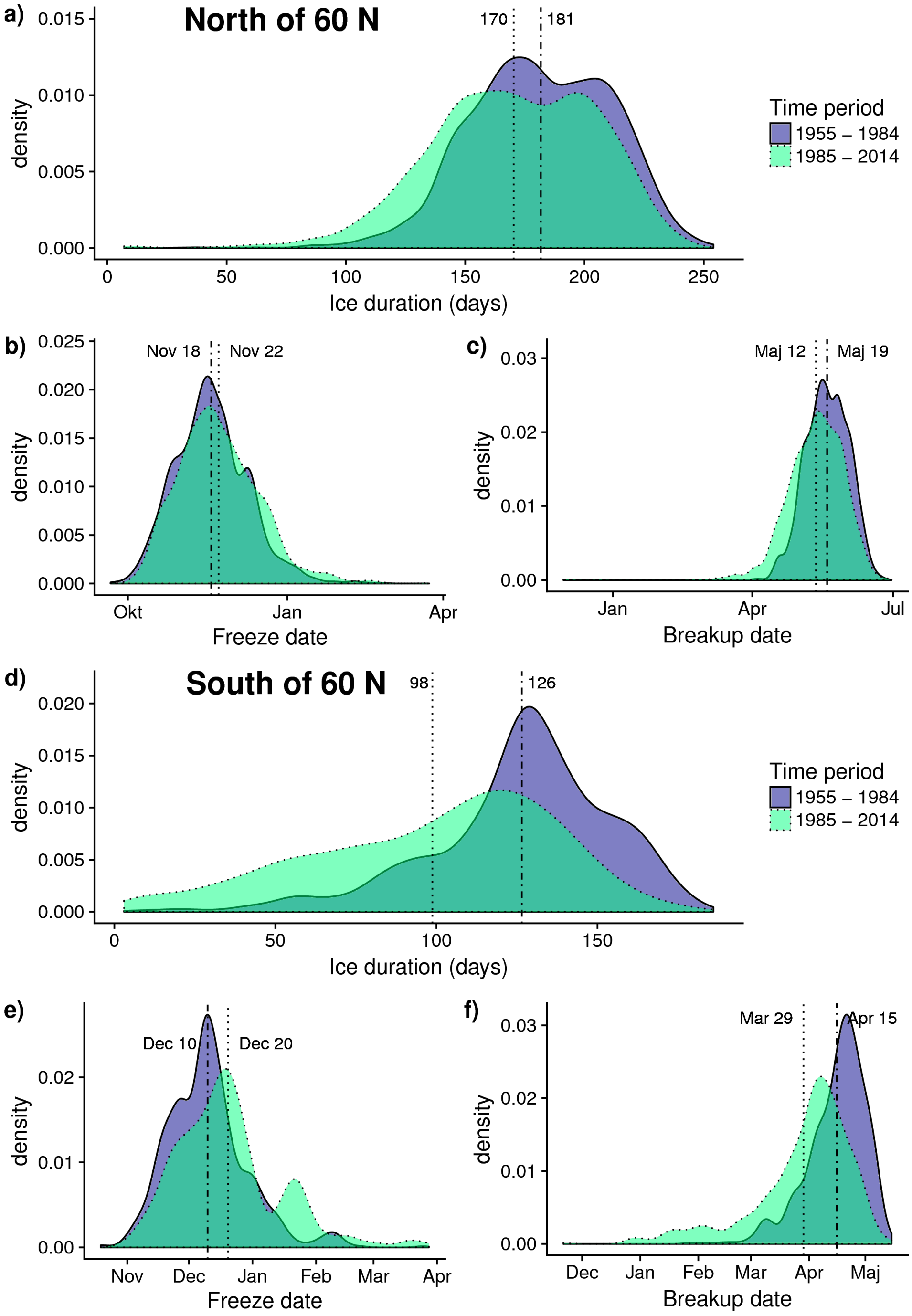


Figure 4: Probability density functions for ice duration (a,d) and freeze (b,e) and breakup dates (c,f) from northern (a-c) and southern (d-f) Sweden during 1955-1984 and 1985-2014. Vertical lines represent mean values, where dot-dashed and dotted lines represent the former and latter 30-year periods, respectively.

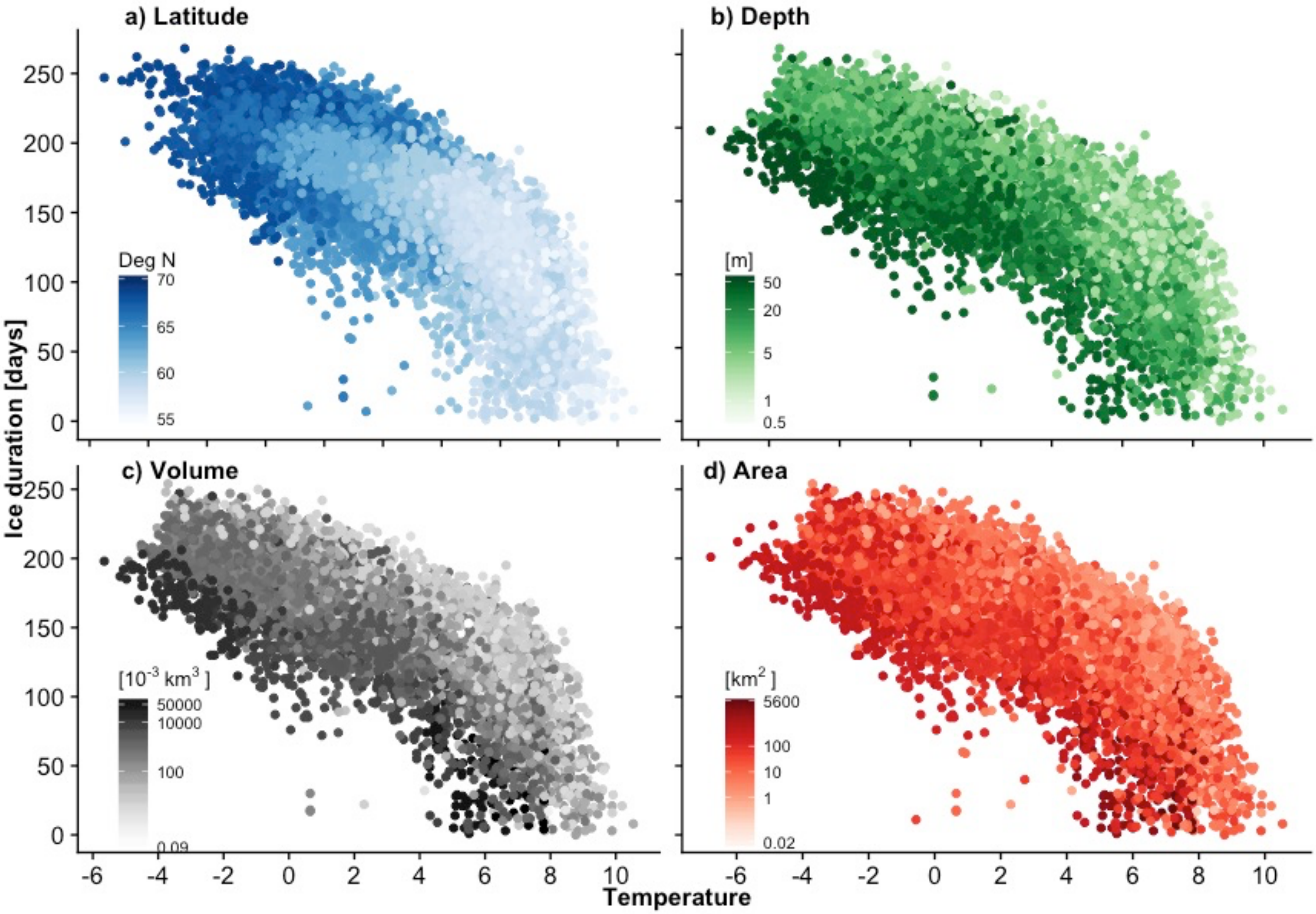
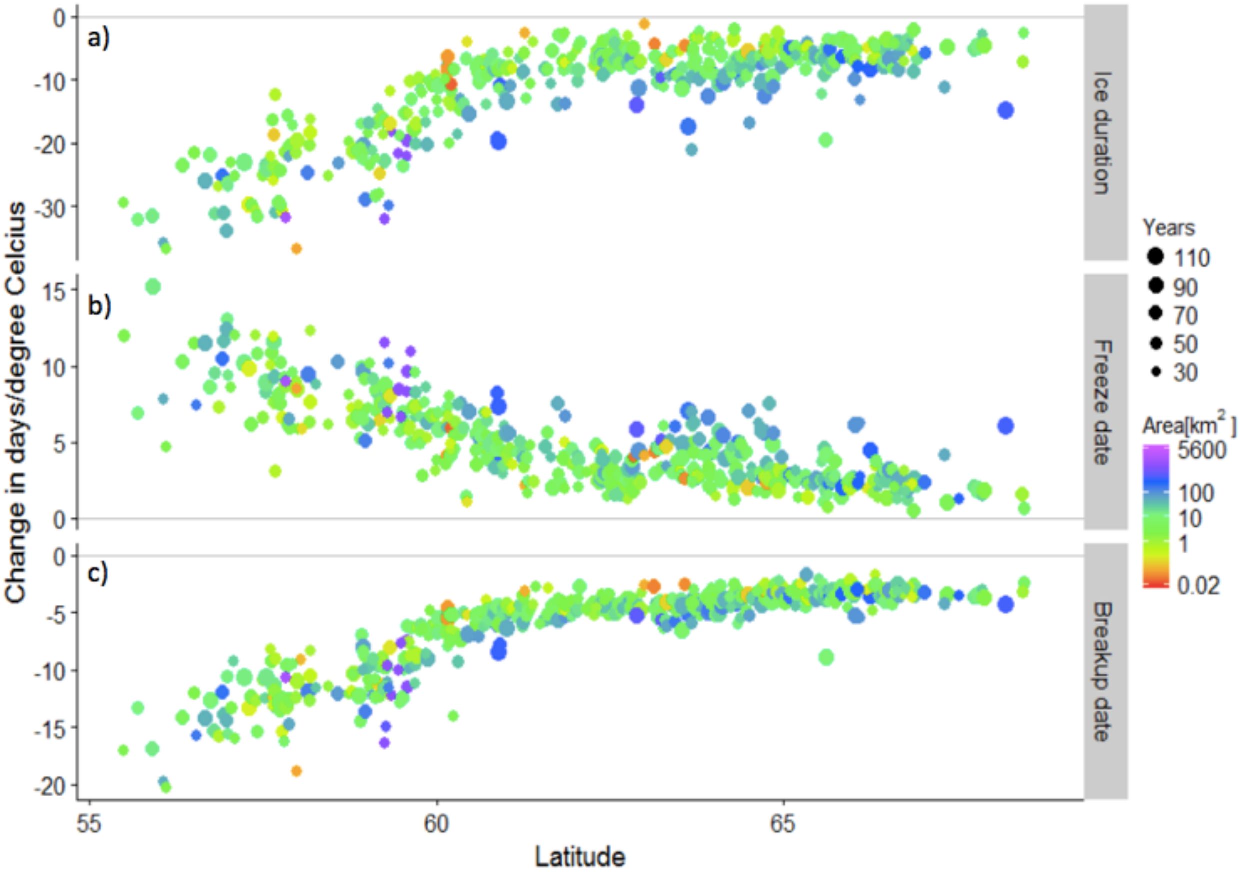


Figure 5: Ice duration (days) versus mean annual air temperature (September-August) (in degrees Celsius). Colours indicate the water body a) latitude, b) mean depth, c) volume, and d) area.



545 **Figure 6: Change (in days per 1°C increase in air temperature) in a) ice duration relative to annual mean temperature, b) freeze date relative to mean temperature from October-December, and c) breakup date relative to mean temperature from March-May based on the linear regression of air temperature and observation date each year for each lake. For the freeze and breakup, negative (positive) values represent earlier (later) dates with increasing temperature. Marker colours represent the area of the lake, while marker sizes denote the number of years with both lake ice and temperature observations.**

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