Climate change and Northern Hemisphere lake and river ice phenology from 1931-2005

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Abstract. At high latitudes and altitudes one of the main controls on hydrological and biogeochemical processes is the breakup and freezeup of lake and river ice. This study uses ~~~2600~~3510 time series from across ~~644~~678 Northern Hemisphere lakes and river to explore historical patterns in lake and river ice phenology across ~~four~~five overlapping time periods (1931-1960, 1946-1975, 1961-1990, ~~1991~~1976-2005, and 1931-2005). These time series show ~~later breakup dates~~ that the number of annual open water days increased by 0.~~6~~63 days per decade from 1931-2005 across ~~North America and Europe~~the Northern Hemisphere, with trends for breakup and, to a lesser extent, freezeup, closely correlating with regionally-averaged temperature. ~~Freezeup~~ Breakup and freezeup trends ~~are more~~display a spatiotemporally complex evolution and reveal considerable caveats with ~~those in Europe negligible compared to later freezeup trends for North America. For the most recent time period (1991-2005) high magnitude trends towards later freezeup that are considerably larger than in other time periods are observed. Freezeup trends show a more limited correlation with climate and this is likely because~~interpreting the implications of ice phenology changes at lake and river sites that may only have breakup or freezeup ~~is not guaranteed to occur simply by temperatures dropping below 0 °C. Across the Northern Hemisphere the length of the open water season is shown to have increased through time, with the magnitude at its largest in the most recent time period.~~data, rather than both. These results provide an important contribution ~~that can be used to help understand how ice phenology patterns may change in the future with an expected rise in global mean air temperatures. Observations of~~by showing regional variation in ice phenology trends through time that can be hidden by longer-term trends. The

overlapping 30-year time periods also show evidence for an acceleration in warming trends through time shows the importance of non-linear responses to climate forcings. This will be crucial because it is probable that lake and river ice phenology changes, brought about by rising air temperatures, may in turn begin to feedback into the climate system. Thus, understanding historical changes, causes, and consequences is required to fully unravel the potential implications of future ice phenology change.. Understanding the changes on both long- and short-term timescales will be important for determining the causes of this change, the underlying biogeochemical processes associated with it, and the wider climatological significance as global temperatures rise.

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Keywords: Lake ice, River ice, Ice phenology, Climate change

1. Introduction

One of the main controls on hydrological and biogeochemical processes at high latitudes is the freezeup and breakup of lake and river ice (Bengtsson, 2011; Rees et al., 2008; Stottlemyer and Toczydlowski, 1999). Ice phenology is governed by the geographical setting (heat exchange, wind, precipitation, latitude, and altitude) and the morphometry and heat storage capacity of the water body (Jeffries and Morris, 2007; Korhonen, 2006; Leppäranta, 2015; Livingstone and Adrian, 2009; Weyhenmeyer et al., 2004; Williams, 1965; Williams and Stefan, 2006)(Jeffries and Morris, 2007; Korhonen, 2006; Leppäranta, 2015; Livingstone and Adrian, 2009; Weyhenmeyer et al., 2004; Williams, 1965; Williams and Stefan, 2006). Though preceding surface air temperatures provide a seasonal energy flux that is well correlated with breakup/freezeup (Assel and Robertson, 1995; Brown and Duguay, 2010; Jeffries and Morris, 2007; Livingstone, 1997; Palecki and Barry, 1986), cycles of temperature linked to large-scale climatic indices have also occasionally been observed to impact ice phenology (Livingstone, 2000a).

The majority of lakes and rivers that seasonally freeze are in the Northern Hemisphere and most research has ~~tended to focus~~focused on breakup/freezeup dates, ice season length and ice thickness (Duguay et al., 2003; Prowse et al., 2011). As acknowledged by the IPCC (2013), an assessment of changes in broader ice phenology is complicated by, among several factors, the tendency to consider only local areas. Although trends vary, there is a proclivity for breakup/freezeup records to lean toward shorter ice seasons that are correlated with temperature trends (Table 1). Changes in ice breakup/freezeup dates, therefore, provide an additional data source for investigating climate patterns (Assel et al., 2003). Whilst the current literature supports observations of a warming climate, the full spatiotemporal variation seen in smaller case studies has not been transferred to a hemispheric scale. This is important because over the next century temperature rise is expected to continue across the Arctic, where lakes and rivers subjected to freeze and thaw cycles are predominantly located (Collins et al., 2013). Understanding historical patterns and changes in lake and river ice phenology is required to confidently project future evolution and climate system feedbacks ~~(Brown and Duguay, 2011; Emilson et al., 2018).~~(Brown and Duguay, 2011; Emilson et al., 2018). In the last century the number of ice phenology observations ~~have~~has increased markedly due to their importance for energy and water balances (Rouse et al., 2003; Weyhenmeyer et al., 2011) and infrastructure such as ice roads (Mullan et al., 2017). This paper explores the hemispheric spatiotemporal trends in ice phenology by investigating an extensive database containing ~~~2600~~3510 individual time series from ~~644~~678 Northern Hemisphere study sites. ~~This~~The aim of this work is to use this database ~~is used~~ to explore ~~the~~how spatiotemporal ~~variability of~~trends in lake and river ice breakup/freezeup dates and the number of annual open water days have changed across several 30-year long overlapping time periods from 1931-2005. ~~Observed changes~~Sites with data available for the full 1931-2005 time period are ~~then~~used to investigate how short-term trends observed from 30-year long records compare to longer-term changes. Sites with data for the full 1931-2005 time period are also compared with regional climate ~~records and atmospheric/oceanic modes~~drivers (e.g. temperature) to investigate how much of the variability ~~to understand their respective roles~~ in ~~driving the observed~~lake and river ice phenology ~~patterns~~can be attributed to longer-term regional climate changes.

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Region	Reference	Time Period	Key Observations
North America	Assel and Robertson (1995)	1851-1993	- Breakup dates have become earlier since 1940 with air temperatures increasing during the winter season at Lake Michigan
North America	Assel et al. (2003)	1963-2001	- Great Lakes show a reduction in the maximum fraction of lake surface ice coverage
North America	Bai et al. (2012)	1963-2010	- Great Lakes show ice cover has detectable relationships with NAO and ENSO
North America	Bennington et al. (2010)	1979-2006	- Model results show increased Lake Superior surface temperatures and declining ice coverage of 886 km^2 per year
North America	Bonsal et al. (2006)	1950-1999	- Ice phenology influenced by extreme phases of PNA, PDO, ENSO and NP in Canada - ~~Lake~~Lakes have a stronger and more coherent pattern compared to rivers
North America	Brammer et al. (2015)	1972-2013	- Ice season length decreased over the time period and was driven by earlier breakup
North America	Duguay et al. (2006)	1951-2000	- Earlier breakup trends in most lakes that were consistent with snow cover duration - Freezeup trends were more variable with later and earlier dates - Strong relationship is shown between 0 °C and breakup/freezeup dates in Canada
North America	Futter (2003)	1853-2001	- In Southern Ontario significant trends towards earlier breakup and an extension to the ice-free season length
North America	Ghanbari et al. (2009)	1855-2005	- PDO, ENSO, and NAO explain some, but not all ice phenology variability at Lake Mendota
North America	Hewitt et al. (2018)	1981-2015	- Lake ice breakup occurred 1.4 days per decade earlier and freezeup 2.3 days per decade later ~~over the time period~~ - Strong association with warming air ~~temperature patterns~~temperatures
North America	Hodgkins et al. (2005)	1930-2000	- River sites in New England show a decrease in ice season length ~~of~~by 20 days ~~per year~~
North America	Jensen et al. (2007)	1975-2004	- Recent trends for changes in breakup/freezeup dates were larger than historical trends, with ice duration decreasing by 5.3 days per decade in the Great Lakes region
North America	Lacroix et al. (2005)	1822-1999	- Across Canada breakup dates tend to be earlier whilst freezeup trends tend to be spatiotemporally more variable
North America	Latifovic and Pouliot (2007)	1950-2004	- Average of 0.18 days per year earlier breakup and 0.12 days per year later freezeup for the majority of sites in Canada
North America	Magnuson et al. (2005)	1977-2002	- Lakes in the Great Lakes region show a generally coherent pattern for breakup
North America	Sharma et al. (2013)	1905-2004	- Linear trends in rain and snowfall in the month prior to breakup, air temperature in the winter, and large-scale climatic oscillations all significantly influence breakup timing
North America	White et al. (2007)	1912-2001	- Earlier breakup and later freezeup for a number of river sites across Alaska and Maine
Europe	Blenckner et al. (2004)	1961-2002	- NAO and ice cover show strong relationship that is less pronounced in the north compared to the south in Sweden and Finland
Europe	Gebre and Alfredsen (2011)	1864-2009	- Variable trends towards later and earlier breakup/freezeup for rivers in Norway - Temperature and river discharge important for breakup/freezeup
Europe	George (2007)	1933-2000	- Reduction in the number of days with ice and frequency of ice cover - NAO strong influence on annual variability at Lake Windermere
Europe	~~Korhonen (2006)~~Korhonen (2006)	1693-2002	- In Finland there are significant trends towards earlier breakup in the ~~later~~late 19th century to 2002 - Trends toward later freezeup leading to a reduction in ice season length
Europe	Marszelewski and Skowron (2006)	1961-2000	- Ice season length has been reducing by 0.8-0.9 days per year at six lakes in northern Poland
Europe	Nõges and Nõges (2014)	1922-2011	- Greater levels of snowfall associated with later breakup - Lake ice phenology trends were weak, despite significant air and lake surface temperature trends

Europe	Šarauskienė and Jurgelėnaitė (2008)	1931-2005	- In Lithuania warmer winters caused later freezeup and reduced ice season length
Europe	Stonevicius et al. (2008)	1812–2000	- Reduction in ice season length for the Nemunas River, Lithuania
Europe	Weyhenmeyer et al. (2004)	1960-2002	- Results from 196 Swedish lakes showing a nonlinear temperature response of breakup dates - Future climate change impacts will likely vary along a temperature gradient
Russia	Borshch et al. (2001)	1893-1991	- In European Russia freezeup occurs later and breakup occurs earlier - Rivers assessed in Siberia show insignificant and occasionally opposite trends
Russia	Karetnikov and Naumenko (2008)	1943-2007	- NAO is well correlated with the ice cover at Lake Ladoga
Russia	Kouraev et al. (2007)	1869-2004	- Lake Baikal trends change through time with period from 1990-2004 characterised by an increased ice season length
Russia	Livingstone (1999)	1869-1996	- Breakup relationship with NAO after 1920 at Lake Baikal
Russia	Smith (2000)	1917-1994	- Fluctuations of patterns between longer and shorter ice season lengths that are generally consistent with temperature trends
Russia	Todd and Mackay, (2003)	1869-1996	- Significant trends towards reduced ice season and ice thickness at Lake Baikal over the period of study
Russia	Vuglinsky (2002)	1917-1994	- Rivers in Asian Russia ~~form~~freeze earlier and breakup later compared to rivers in European Russia - This is due to antecedent climatological conditions
Asia	Batima et al. (Batima et al., 2004)	1945-1999	- River ice thickness and ice season length have decreased over the time period
Asia	Jiang et al. (2008)	1968-2001	- Yellow River ~~in~~ has experienced later freezeup and earlier breakup, leading to a reduction of the ice season by 12-38 days at different sites along the river
Northern Hemisphere	Benson et al. (2012)	1855-2005	- For 75 lakes the trends towards earlier breakup, later freezeup and a shorter ice season duration were stronger for the most recent time period studied
Northern Hemisphere	Livingstone (2000b)	1865-1996	- NAO signal detected at a number of sites, but with variable strength across several Northern Hemisphere sites
Northern Hemisphere	~~Magnuson et al. (2000a)~~Magnuson et al. (2000)	1846-1995	- Breakup on average 6.3 days per century earlier across multiple Northern Hemisphere sites - Freezeup on average 5.7 days later per century
Northern Hemisphere	Sharma ~~et al.~~and Magnuson (2014)	1854-2004	- All 13 lake study sites demonstrated oscillatory dynamics ~~were influential on~~influenced ice breakup
Northern Hemisphere	Sharma et al. (2016)	1443-2014	- Trends towards later freezeup in Japan and earlier breakup in Finland - Strong linkage between these trends and climate change and variability
Northern Hemisphere	Sharma et al. (2019)	1443-2018	- Analysis of 513 sites shows the importance of air temperature, lake morphometry, elevation and shoreline geometry in governing ice cover - Future projections suggest an extensive loss of lake ice over the next generation
Northern Hemisphere	Šmejkalová et al. (2016)	2000-2013	- All areas showed significant trends of earlier breakup - The 0 °C isotherm shows the strongest relationship with ice phenology trends
Northern Hemisphere	Wynne (2000)	1896-1995	- Trend directions for four sites regularly switched over the 100 year time span

Table 1: Summary of ice phenology trend observations from across the Northern Hemisphere. Note this is not meant to be an exhaustive list, but ~~intends to provide~~provides a general overview of ice phenology changes.

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2. Materials and methods

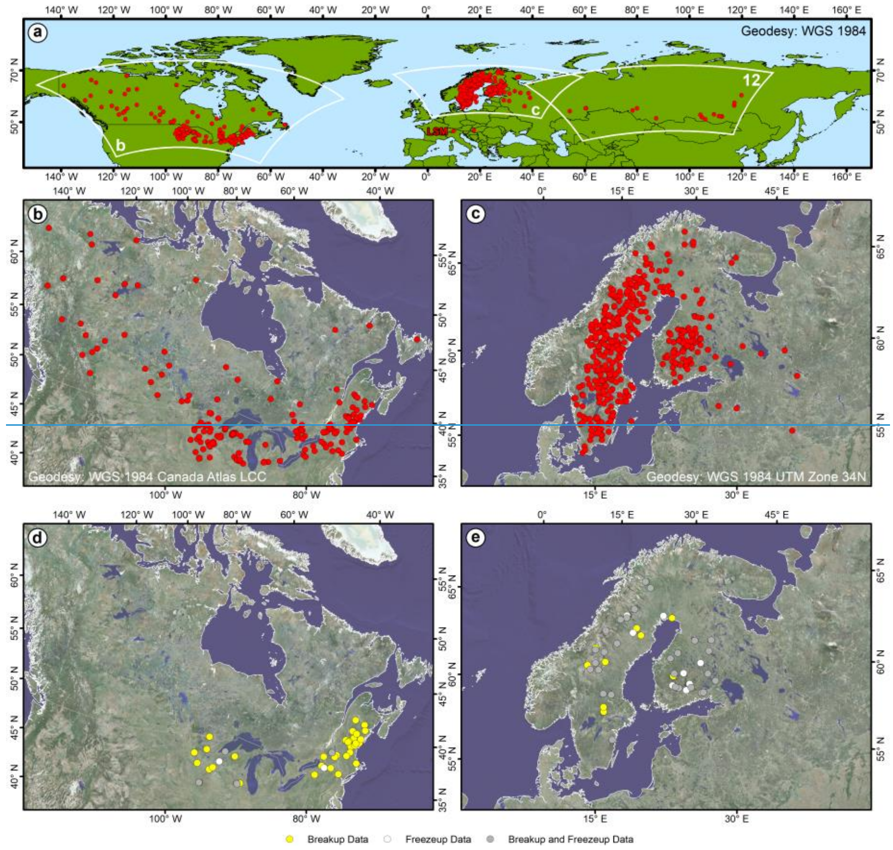
The Global Lake and River Ice Phenology Database from the National Snow and Ice Data Centre (NSIDC) (available at: https://nsidc.org/data/lake_river_ice/ – Benson et al. (2013)) provides breakup/freezeup dates for 865 Northern Hemisphere sites. In this database the freezeup date is defined as the first day in which the water is completely ice covered and the breakup is the date of the last ice breakup before the open water season. Whilst the specific definitions for breakup/freezeup may vary between different sites, the precise definition is thought to be consistent at each site. Thus, if climate signals are present in the ice phenology data then they should still be observable and broadly comparable. This database is supplemented with data from the Swedish Meteorological and Hydrological Institute (SMHI) which contains 749 lakes and rivers using similar terminology. Data for 122 lakes and rivers were provided by the Finnish Meteorological Institute. Several sites were already in the NSIDC dataset but were updated where necessary. The three datasets were integrated to create the Ice Phenology Database (IPD) containing data across North America, Europe, and ~~Eurasia~~Russia (Fig. 1). It is important to note that in the

	Breakup						Freezeup						Annual Open Water Days					
	Lakes			Rivers			Lakes			Rivers			Lakes			Rivers		
	NAM	EUR	RUS	NAM	EUR	RUS	NAM	EUR	RUS	NAM	EUR	RUS	NAM	EUR	RUS	NAM	EUR	RUS
1931-1960	64	188	5	7	9	0	14	163	6	6	5	0	13	143	5	4	4	0
1946-1975	104	245	24	14	8	0	27	220	24	11	4	0	22	200	24	7	2	0
1961-1990	128	255	26	16	6	0	49	252	27	12	4	0	47	236	25	10	3	0
1976-2005	91	172	1	2	5	0	41	170	1	0	2	0	38	144	1	0	2	0
1931-2005	44	39	1	0	3	0	9	36	1	0	2	0	7	28	1	0	1	0

later part of the 1980s and 1990s data for many Russian and Canadian sites ~~stopped recording data.~~ are not recorded in the database.

Table 2: Summary of the number of sites with at least 90% annual data available for breakup, freezeup, or annual open water days across the five time periods and geographical regions.

Prior to 1931 data are sparse and many of the longer time series have been explored by Magnuson et al. ~~(2000b) and Benson et al.~~(2000) and Benson et al. (2012). To ~~understand~~investigate the spatiotemporal patterns of ice phenology, ~~four~~five overlapping time periods were studied: 1931-1960, 1946-1975, 1961-1990, ~~1991~~1976-2005, and 1931-2005. These are investigated across three broad areas: North America, Europe, and Russia. All study sites in the database which fall within these time periods and have a maximum of 10% missing values were included. These specific time periods ~~have been~~were chosen as they offer the opportunity to include as much data from the IPD as possible. Initial analysis showed that of the 1736 lakes and rivers in the IPD, ~~644~~678 sites had ~~data with at least~~ ≥ 90% ~~coverage~~annual data for either freezeup or breakup for at least one of the time periods within one of the three regions. The number of sites contained within each time period~~. These data provide ~2600~~ and for each geographical area is shown in Table 2. The final dataset provides 3510 individual time series ~~and are~~ spread across the Northern Hemisphere (Fig. 1a~~)~~), but ~~are~~ primarily concentrated in North America (Fig. 1b) and ~~Fennoscandia~~Europe (Fig. 1c). ~~Time series covering~~ Data on breakup, freezeup, and annual open water days for the 1931-2005 time period were available~~, with 88 sites (three rivers) having breakup data~~ for 87, 48~~ sites (two rivers) with freezeup data~~, and 37 sites~~ (one river) with data for the number of annual open water days. Of~~, respectively (Table 2). The majority of these sites ~~the majority in North America~~ are ~~to the east and west of~~clustered around the Laurentian Great Lakes ~~(Fig. 1d). In northwest Europe the sites are predominantly in~~in North America, Sweden and Finland ~~(Fig. 1e), with one site (Lej da San Murezzan)~~ in ~~Switzerland~~Europe. In Russia there is only one site in the southwest of Lake Baikal.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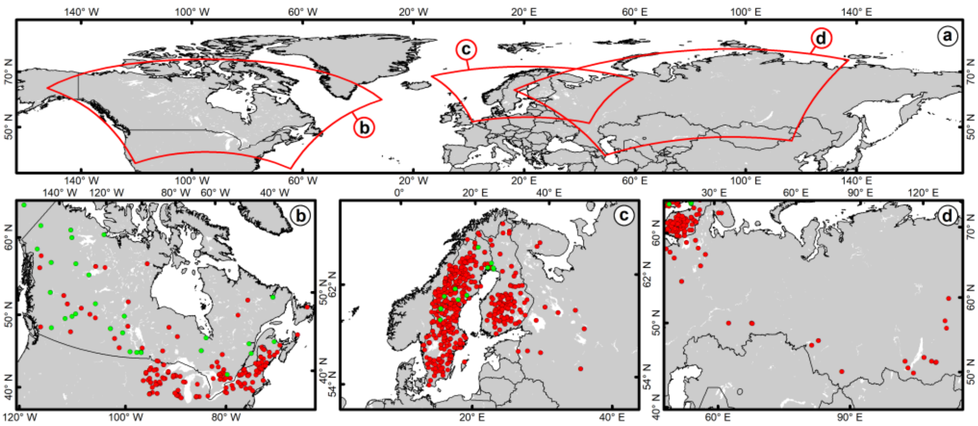

Figure 1: ~~(~~**a**) Map showing the three main study ~~sites (~~areas. The red and green circles~~) with~~ in panels (**b-d**) are lake and river sites, respectively, that have time series containing at least 90% coverage for breakup and/or freezeup during at least one time period. ~~Location of other panels and figures are shown; **b**) North American study sites; **c**) Fennoscandian study sites. Note that different geodesies are used to best display sites; **d**) North American sites with data for 1931-2005; **e**) Fennoscandian sites with data for 1931-2005. The satellite imagery shown is from the MDA NaturalVue satellite layer from ArcMAP Online. Geodesy, geographical extent, and satellite imagery used in panels (a-e) are used~~The majority of river sites are located in Canada, with Russia only having data available for lakes. The geographical extent used in panels (b-d) for each region of interest are the same in subsequent figures.

Breakup/freezeup dates were first converted to ~~Julian~~ordinal days. For some sites, freezeup or breakup in a specific year occasionally fell in a preceding or succeeding year and the ~~Julian~~ordinal date reflects this by providing a relative date – i.e. if freezeup for the 1941 ice season occurred on 5th January 1942 then the ~~Julian~~ordinal day allocated was 370. Likewise, if breakup for the 1943 ice season occurred on the 28th December 1942 then the ~~Julian~~ordinal date allocated was -3. These records were adjusted as necessary to calculate the number of annual open water days. The ~~Julian~~ordinal day records were tested using the Mann-Kendall test where the null hypothesis ~~(H_0)~~ of no trend was tested against the alternative hypothesis ~~(H_1)~~ that there is a monotonic trend in the time series. The Mann-Kendall test is a nonparametric test which detects trends without specifying if it is linear or nonlinear. It does not, however, calculate trend magnitude, so Sen's slope was also used (Yue et al., 2002). ~~These two statistical techniques are explained briefly below and a~~A full ~~definition is provided by~~description of these combined methods can be found in Salmi et al. (2002). These two statistical techniques are commonly used in climate and environmental science as they can account for missing values. These methods were applied to all sites with at least 90% data (Table 2) for each individual time period to document the significance (α<0.1), the magnitude of the slope, and decadal change derived from that magnitude. The 90% allowance means that the maximum number of sites were used for each of the five time periods. The trend magnitudes and directions were converted into the number of days change per decade in the date of breakup/freezeup or number of annual open water days at each site during each time period. The magnitude of the decadal change is mapped for all sites, with those that are statistically significant clearly identified in the symbology. To investigate short-term variations on the 75-year time period, residuals were calculated for breakup, freezeup, and open water days. Similar to Sharma and Magnuson

(2014), a range of running means were applied, with an 11-year window shown to be most useful for the 75-year time series.

The Mann-Kendall test is a nonparametric test which detects trends without specifying if it is linear or nonlinear. It is used widely in environmental science as it can account for missing values. It is based on the test statistic S which is defined in eq.1 and 2:

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^{n} sgn(x_j - x_k) \quad (1)$$

where x_j and x_k are the sequential data values in years j and k, n is the length of the dataset, and

$$\text{sgn}(x_j - x_k) = \begin{cases} +1 & \text{if } x_j - x_k > 0 \\ 0 & \text{if } x_j - x_k = 0 \\ -1 & \text{if } x_j - x_k < 0 \end{cases} \quad (2)$$

When $n \geq 10$, the variance of S is approximated by eq.3 which accounts for ties in the data:

$$VAR(S) = \frac{1}{18}\left[n(n-1)(2n+5) - \sum_{p=1}^{q} t_p(t_p - 1)(2t_p + 5)\right] \quad (3)$$

Where q is the number of tied groups and t_p is the number of data values in the p^{th} group. The standard Z statistic is then computed by using eq.4 to show how significant any trends are and whether the H_o can be rejected at α significance level.

$$Z = \begin{cases} \frac{S-1}{\sqrt{VAR(S)}} & \text{if } S > 0 \\ 0 & \text{if } S = 0 \\ \frac{S+1}{\sqrt{VAR(S)}} & \text{if } S < 0 \end{cases} \quad (4)$$

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If any trends are present then they can be estimated using the nonparametric Sen's slope. The trend slope (β) is given by eq.5 where x_k is the k^{th} observation:

$$\beta = \text{median}\left(\frac{x_j - x_k}{j - k}\right) \text{for all } j > k \qquad (5)$$

A new database was created which included significance, slope, and decadal change for each site. These were mapped to show spatiotemporal change during different time periods.

A range of climate variables and atmospheric/oceanic modes of variability were downloaded from KNMI Climate Explorer (http://climexp.knmi.nl/) to facilitate examination of potential regional drivers of ice phenology change. Monthly mean temperatures and precipitation were extracted from the Climatic Research Unit (CRU) Time-Series (TS) Version 4.01 (Harris et al., 2014). CRU TS4.01 applies angular-distance weighting (ADW) interpolation to monthly observational data derived from national meteorological services to produce monthly gridded mean temperatures and precipitation at a spatial resolution of 0.5° latitude x 0.5° longitude. Wind speed data were extracted from the International Comprehensive Ocean-Atmosphere Data Set (ICOADS) 2-degree Enhanced Dataset, which provides simple gridded monthly wind speeds for 2° latitude x 2° longitude grid boxes (Freeman et al., 2017). All these data were downloaded as a spatially averaged regional time series for three geographical regions – Fennoscandia (FENencompassing only study sites with data for the full 1931-2005 time period – Europe (EUR): 57.5-68.5°N, 12-29°E; North America (NAM): 42.5-47°N, 73.5-95.5°W; and Russia (RUS): 51.5-52°N, 104.5-105°E. Data were extracted for 1931-2005 to correspond with the length of the IPD. We elected for this regionalised strategy because (1) the computational and human resources needed to analyse climate records for each individual site are vast; and (2) we were interested in establishing broader regional climate drivers of ice phenology rather than developing correlations with local climate, which we would expect to be very strong. For 1931-2005 monthly data on the Arctic Oscillation (AO) (Thompson and Wallace, 2000), the Atlantic Multidecadal Oscillation (AMO) (van Oldenborgh et al., 2009), and the North Atlantic Oscillation (NAO) (Jones et al., 1997), and the Southern Oscillation Index (SOI) (Ropelewski and Jones, 1987) were also extracted.

Ice breakup/freezeup records from the IPD were spatially averaged into three regional composite records corresponding to the three geographical regions (FENEUR, NAM, and RUS) defined above. Statistical relationships were then examined between ice breakup/freezeup dates and climate records (maximum temperatures and modes of variability) using Pearson Product-Moment Correlation. These relationships were analysed on a monthly basis, first for each of the twelve calendar months, and second for twelve sliding windows of three-month means (e.g. mean of January, February, March, then mean of February, March, April etc.).

3. Results: Ice phenology change

A climate regime with increasing mean air temperatures would be expected to increase the number of annual open water days for sites ~~with seasonal freezing. This reduction in ice cover could result from~~ that seasonally freeze through earlier breakup~~,~~ and/or later freezeup dates~~, or a combination of both that leaves a relative increase in the number of open water days. Decadal trends~~. The decadal trend for the number of annual open water days allows for an integrated observation of breakup/freezeup date changes relative to each other – i.e. the longevity of ~~ice covers~~open water, rather than a specific shift in the precise breakup/freezeup~~/break~~ dates. ~~The statistical analysis outlined in the methods has been carried out for each study site with freezeup and/or breakup dates shown in Fig. 2. This is used to determine decadal trend directions in each time period for ~2600 individual time series. These have been summarised in Fig. 3 as a proportion of total observations for each time period and in Table 2 as mean values for breakup, freezeup, and the number of open water days. The analyses carried out suggest that although spatiotemporally variable, there is a dominance for trends to display a signal of reduced ice cover and an increase in the magnitude of that reduction through time.~~ In this section the ~~general patterns~~ results from the Mann-Kendall and Sen's slope analysis are presented ~~before an in-depth analysis of the changes observed in~~ for the three main study areas~~, and the 1931-2005 trends for sites with continuous data.~~

:~~**3.1. General trends**~~

~~The combined time series and spread of dates for breakup/freezeup across each time period~~ ~~are summarised in Fig. 2. This shows that for breakup, the median date of ice breakup in each period is correlated with the study site latitude. This is the case for both Europe and~~ North America, ~~but not~~Europe, and Russia~~, likely owing to the extensive geographical spread of only a few study sites.~~. In ~~Europe, successive~~total, 678 study sites provide at least

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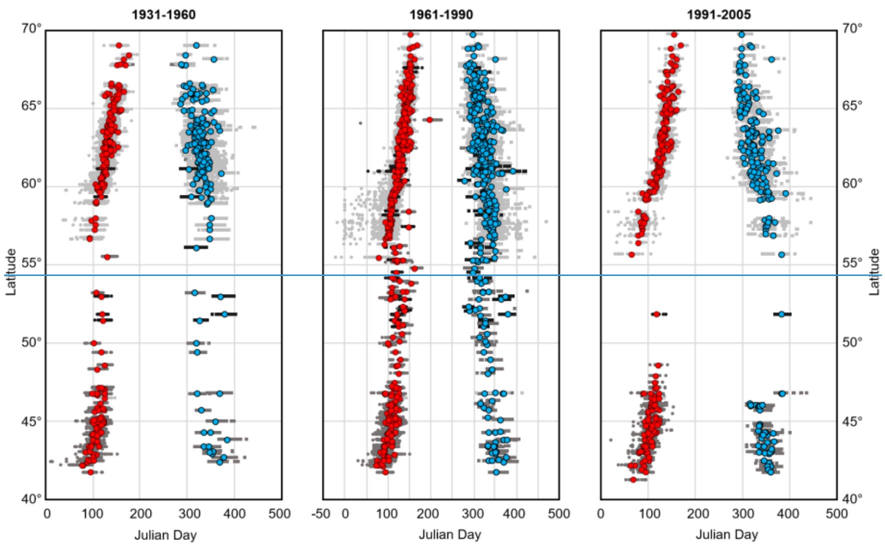
one time series with ≥ 90% complete annual data across the four 30-year time periods ~~show a general shift toward earlier median breakup dates, as is shown by the increased number of study sites with median breakup dates within the first 100-125 days of each year. The earliest breakup dates observed at each European site shows that many of the study sites have experienced a systematic shift in the breakup date to earlier in the~~ and the one 75-year~~. This is evidenced by~~ time period, with 3510 individual time series available (Table 2). A summary of the ~~increased clustering of~~ breakup/freezeup dates ~~within the first 100 days~~available for each of the four 30-year ~~during 1991-2005 compared to 1931-1960, particularly at study sites between 55°N and 60°N (Fig. 2). The North American sites show a similar shift in the spread of breakup dates to earlier in the year. Russian observations are too few to draw strong conclusions. An important observation is the reduction in North American (mainly Canadian) and Russian study sites in the mid-latitudes (47°N to 55°N) from 1991-2005.~~ time periods is presented in Fig. 2. These data are used to determine decadal trend directions that have been summarised in Fig. 3 and in Table 3 as mean changes in breakup/freezeup dates, and the number of annual open water days. The general trends are first presented, before looking at the spatiotemporal trends across the three study regions.



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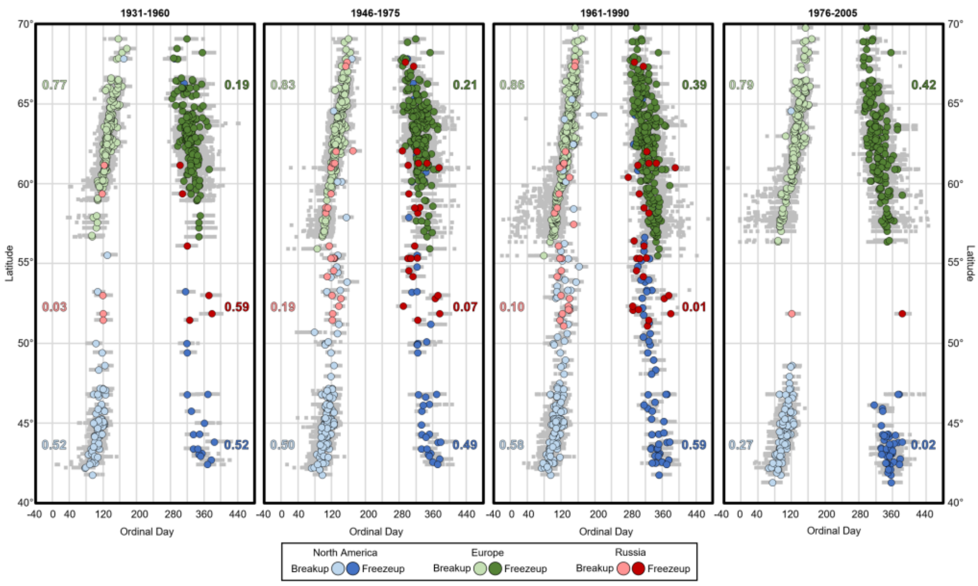

Figure 2: Summary graphs showing breakup and freezeup dates against latitude for ~~the three short time periods. Red and~~all lake and river sites included in each of the four 30-year long time periods. The data are colour coded by region on the key. The numbers that are adjacent to the recorded dates are R^2 values for each set of regional data. These are also colour coloured coded on the key – e.g. light blue data shows the median breakup dates for North America and an R^2 value between median date and latitude of 0.52. The underlying grey points ~~represent study site median breakup and freezeup dates, respectively. Light grey observations are breakup/freezeup dates for study sites in Europe, dark grey sites across Russia, and intermediate grey is North American sites.~~show the total ranges of dates that were recorded for each site in each time period. Note that some European breakup observations ~~between 1961-1990~~ demonstrate that breakup occurred in the December preceding the start of that years' open water season – i.e. a very early winter cessation of the ice season. Likewise there are sites in all study areas where freezeup dates were sufficiently late that it did not occur until late in the winter season – i.e. January of February of the following year.

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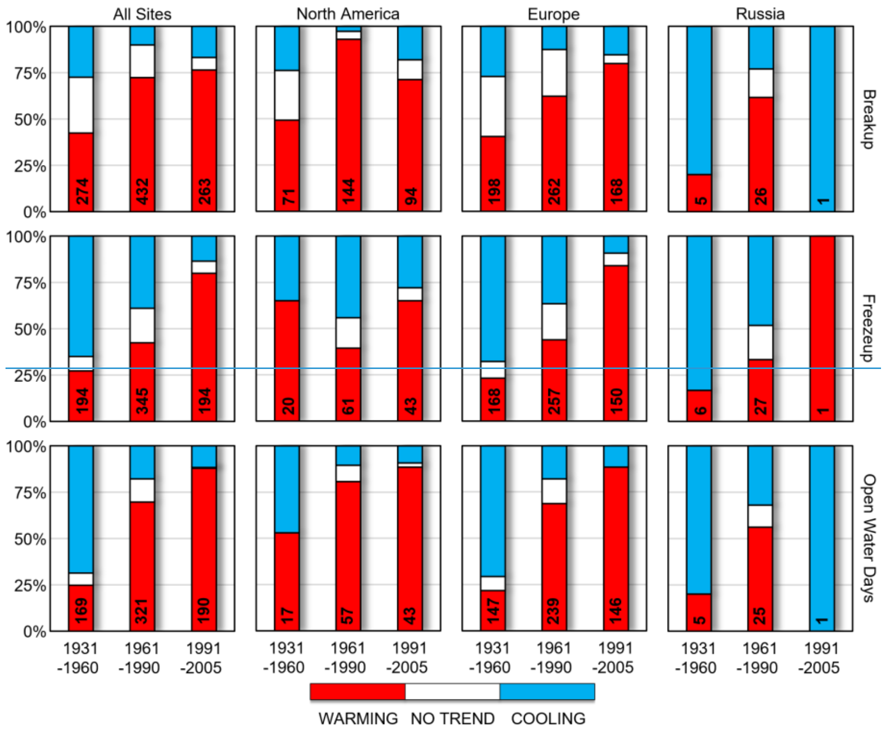
3.1. General trends

The combined time series and spread of dates for breakup/freezeup across each time period



is summarised in Fig. 2. In North America across all time periods the majority of sites are in a band of latitude between 42-55°. There is a moderate correlation between median breakup dates and latitude, with the R^2 values typically ≥ 0.50 showing that breakup date becomes later with increasing latitude (Fig. 2). The one exception to this is for the 1976-2005 time period where the R^2 value is 0.27. However, one site in the northwest of the region has a latitude 16° more northerly than any other site and appears to skew the correlation as when this outlier is removed the R^2 value increases to 0.48. An additional caveat is that this time period also marks a reduction in the latitudinal range of the sites included in the database. Median freezeup dates in North America also show a moderate correlation (R^2 = 0.49-0.59) with latitude, with freezeup occurring earlier in the year with increasing latitude. Similar to breakup, the 1976-2005 time period shows the weakest correlation, but is not associated with an anomalous high latitude site. Unlike North America, where sites cover a wide range of longitude, in Europe the data are generally restricted to a narrower range in Sweden and Finland (Fig. 1). In all four of the 30-year time periods there is a strong correlation (R^2 = 0.77-0.86) between median breakup dates and latitude (Fig. 2). Freezeup dates appear to show some association with latitude, but trends are very weak in the first two time periods (R^2 = 0.19-0.21) and weak in the last two (R^2 = 0.39-0.42). The range of breakup/freezeup dates recorded at European sites (grey points in Fig. 2) become more scattered through time, especially south of 60 °N. This shows greater variability in breakup/freezeup dates at lower latitude sites and that the time window in which ice breakup/freezeup occurs appears to have become wider from 1961-2005. These date shifts also show that in the latter two time periods, compared with the first two time periods, there is an increased occurrence of breakup dates within the first 40 days of the year and freezeup dates shifting to a later part of the winter season – i.e. freezeup not occurring until January and February of the following year. The wide longitudinal and latitudinal spread of a comparatively small number of lakes in Russia for any time period (Table 2) precludes any confident correlations or associations. Although it is sporadic and not consistent in study areas or time periods, additional analysis of all the lake and river sites show that occasionally median dates were weakly or very weakly (R^2 = 0.05-0.25) correlated with other criteria such as lake area and elevation.

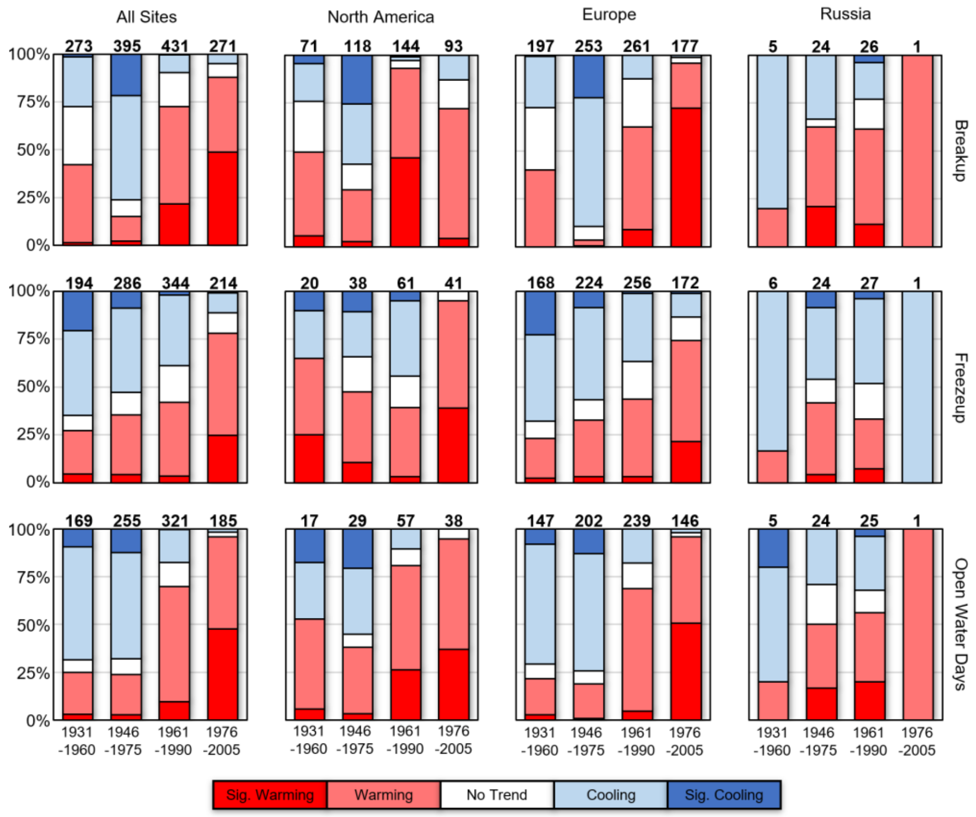


Figure 3: Summary charts showing generalised ~~decadal patterns~~trends for all the sites contained within each of the 30-year time periods. The percentages are calculated as a proportion of the total number of sites for each time period (bold text – e.g. in the first panel, across ~~the Northern Hemisphere data~~ all sites there are ~~263~~273 sites with ~~1991-2005~~1931-1960 breakup data~~. Note that~~). The trends are derived from the Mann-Kendall analysis for each site, where the direction and statistical significance (α<0.1) are recorded as a warming, cooling, or no trend. A warming trend for breakup or freezeup dates is determined by a negative (earlier date) or positive (later date) trend, respectively. A cooling trend for breakup or freezeup dates displays a positive (later date) or negative (earlier date) trend, respectively. For the number of annual open water ~~charts~~days a positive ~~trend~~ Mann-Kendall value indicates an increase ~~in the number of annual open water days~~. Sig. Warming/Cooling on the key indicates sites where that trend was statistically significant.

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When all sites are considered there is a clear increase through time in the proportion of sites displaying earlier breakup. Sites displaying no or later breakup decadal trends decrease through time, albeit with the smallest proportion observed from 1961-1990 (Fig. 3). At a regional extent the breakup trends for Europe are similar to those shown for all sites. For North America the pattern is temporally complex as 1961-1990 shows the greatest proportion of sites with earlier breakup trends. However, from the 1931-1960 period to the 1991-2005 period there is an overall increase in the proportion of sites experiencing earlier breakup. For Russian sites it is clear that from 1931-1960 to 1961-1990 there is a considerable increase in the proportion of sites with warming trends, but a caveat is the small sample size for For each 30-year time period the proportion of trends displaying warming and cooling trends have been summarised in Fig. 3. This shows that through time the proportion of sites displaying warming trends has increased. Freezeup and the number of annual open waters days display a gradual increase in warming trends through time, and an increase in the proportion of sites with statistically significant warming trends. Mean decadal values show a gradual reduction in cooling trends from 1931-1960 to an increased warming during 1976-2005, albeit with high standard deviations when averaged across all sites (Table 3). Despite this consistent pattern, when observed at the three regional scales (discussed below), the proportion of warming and cooling patterns tend to fluctuate between the different time periods. It is only freezeup changes in Europe that show a similar pattern to that observed for all freezeup sites when combined, likely reflecting that data in Europe provides a larger proportion of the total number of sites (Fig. 3). What is common amongst all sites is that the 1976-2005 time period displays the largest proportion of sites with warming trends, with the exception of Russia (which has only one site), for freezeup and the number of open water days. For breakup the warming pattern for all sites also shows a longer-term increase through time that is interrupted by an increased proportion of sites displaying cooling trends from 1946-1975 (Fig. 3). This appears to be largely driven by an increase in the proportion of sites in Europe during that time period displaying either cooling or significant cooling trends. A similar interruption is also observed in North America, but is followed during 1961-1990 by a major increase in the number of warming trends. Similar to freezeup and the number of annual open water days, the mean decadal change for all sites shows warming trends develop and increase in magnitude by 1976-2005, again with the caveat that the standard deviation is high enough to switch trend direction (Table 3). The limited number of Russian sites with breakup data show a decrease through time in the proportion of cooling trends (Fig. 3).

For breakup, freezeup, and annual open water days there is general pattern towards warming through time and mean values increase in the magnitude of change. This increase in magnitude is sufficient so that during 1976-2005 breakup is 2.81 days per decade earlier (σ = 2.18) and the number of annual open water days increased by 5.83 per decade (σ = 4.08) for all sites. The standard deviation from these sites is lower than the mean magnitude of change, meaning variation higher than one standard deviation is required to potentially move across a zero value and change trend direction – i.e. whilst the standard deviation is larger than most other time periods, the higher magnitude means that more of this variability is in one trend direction (Table 3). A difference is also observed for the evolution of lakes and rivers, where rivers appear to show a more consistent warming pattern for breakup, freezeup, and the number of annual open water days through time (Table 3).

1931-1960 over a large area. For 1991-2005 there is only one site showing a cooling trend (Fig. 3).

Mean values for decadal change are summarised in Table 2 for the three shorter time periods. This shows that for breakup there are warming trends (i.e. negative values) that are broadly consistent through time, with a notable increase in the magnitude of decadal change - i.e. from 0.16 days decade^{-1} earlier breakup during 1931-1960 to 3.44 days decade^{-1} earlier breakup during 1991-2005. This is the case for both lakes and rivers in Europe and North America, with a minor exception that during 1961-1990 the magnitude of warming in North America was larger than the time periods before and after. In Russia, long-term trends are limited by the single site for 1991-2005, but it does show from 1931-1960 to 1961-1990 the decadal change values move from cooling to warming trends.

The data show that across the Northern Hemisphere there is a larger spread in freezeup dates (Fig. 2). A correlation between freezeup date and latitude is observed, but this is not as strong compared to breakup. In Europe there is a general pattern toward a greater proportion of the freezeup dates occurring later in the year by 1991-2005 compared to 1931-1960. In North America freezeup dates spread between 40°N and 46°N do not appear to change significantly between all three time periods, with the exception that median dates are less spread from 1991-2005. Russian sites are difficult to assess due to geographical coverage, but it is notable that from 1961-1990 the sites at similar latitudes can have very different median freezeup dates.

The decadal trends through time show an increased proportion of sites with later freezeup and a decreased proportion displaying earlier freezeup (Fig. 3). The proportion of sites with no decadal trend is similar from the earliest time period to the latest, but with the middle period (1961-1990) showing an increase in the proportion of sites displaying no decadal trends. The same patterns are evident for the European sites. Freezeup trends in North America show that the earliest and latest periods (1931-1960 and 1991-2005) have similar proportions of sites showing later freezeup trends – the same is true for earlier freezeup trends. The interim 1961-1990 shows a pronounced increase in the proportion of sites with earlier freezeup trends and a decrease in the number of sites with later freezeup trends compared with the previous and subsequent time periods. In Russia, from 1931-1960 to 1961-1990 there is an increased proportion of sites with later freezeup decadal trends and a reduction in earlier freezeup trends through time. Only one site is available for 1991-2005 and it shows later freezeup (Fig. 3).

		Breakup			Freezeup			Open Water		
		Lakes	Rivers	Total	Lakes	Rivers	Total	Lakes	Rivers	Total
Northern HemisphereAll Sites	1931-1960	-0.1413 (1.70)	-0.660 (1.95)	-0.1615 (1.72)	-2.11 (3.41)	3.08 (3.06)	-1.82 (3.60)	-2.18 (4.05)	3.33 (2.48)	-1.92 (4.16)
	1946-1975	1.54 (1.90)	-0.09 (2.12)	1.45 (1.95)	-0.59 (3.36)	0.98 (3.91)	-0.51 (3.41)	-1.91 (3.99)	1.23 (3.10)	-1.80 (4.00)
	1961-1990	-1.5152 (1.83)	-1.98 (1.77)	-1.5354 (1.83)	0.22 (2.12)	0.07 (2.11)	0.21 (2.12)	1.94 (2.99)	1.46 (1.88)	1.92 (2.95)
	19911976-2005	-3.472.8	-2.231.1	-3.442.8	7.782.73 (2.96)	11.980.64 (1.36)	7.832.71 (2.96)	12.255.88 (4.06)	14.770.71 (0.24)	12.285.83 (4.08)
	1931-2005	-0.5960 (0.47)	-0.23 (0.16)	-0.58 (0.46)	-0.01 (1.02)	0.70 (0.70)	0.02 (1.02)	0.60 (1.04)	1.62 (0.00)	0.63 (1.04)
	1961-1990	-0.78	-2.17	-0.81	0.34	0.18	0.33	1.81	1.99	1.81
	1991-2005	-3.91	-2.23	-3.86	8.59	11.98	8.63	13.24	14.77	13.26
	1931-2005	-0.53	-0.23	-0.51	0.25	0.70	-0.20	0.35	1.62	0.39
North America	1931-1960	-0.28 (2.52)	-1.09 (2.78)	-0.36 (2.56)	0.05 (2.92)	2.71 (2.91)	0.85 (3.16)	-1.39 (4.99)	3.29 (0.89)	-0.29 (4.82)
	1946-1975	1.58 (2.55)	-1.05 (1.97)	1.27 (2.63)	-0.17 (2.29)	1.22 (4.42)	0.23 (3.13)	-2.47 (4.52)	1.28 (2.94)	-1.57 (4.49)
	1961-1990	-3.11 (1.83)	-1.92 (1.95)	-2.98 (1.88)	-0.24 (1.85)	0.04 (2.39)	-0.18 (1.97)	3.08 (3.22)	1.30 (2.06)	2.77 (3.12)
	19911976-2005	-2.791.1	N/A-0.56	-2.791.1	5.093.61 (2.32)	N/A	5.093.61 (2.32)	9.294.15 (2.84)	N/A	9.294.15 (2.84)
	1931-2005	-0.66 (0.50)	N/A	-0.66 (0.50)	0.84 (0.78)	N/A	0.84 (0.78)	1.49 (1.12)	N/A	1.49 (1.12)
Europe	1931-1960	-0.10 (1.31)	-0.22 (0.64)	-0.10 (1.29)	-2.31 (3.43)	3.52 (3.17)	-2.13 (3.56)	-2.24 (3.97)	3.38 (3.39)	-2.09 (4.06)
	1946-1975	1.75 (1.31)	1.59 (1.06)	1.75 (1.31)	-0.78 (3.27)	0.34 (1.71)	-0.76 (3.25)	-2.28 (3.62)	1.08 (3.58)	-2.25 (3.64)

	1961-1990	-0.79 (1.25)	-2.17 (1.16)	-0.82 (1.25)	0.34 (2.17)	0.18 (0.78)	0.33 (2.16)	1.81 (2.85)	1.99 (0.82)	1.81 (2.84)
	1976-2005	-3.77 (1.98)	-1.43 (1.31)	-3.70 (2.00)	2.53 (3.06)	0.64 (1.36)	2.51 (3.05)	6.38 (4.20)	0.71 (0.24)	6.30 (4.22)
	1931-2005	-0.54 (0.40)	-0.23 (0.16)	-0.52 (0.40)	-0.25 (0.95)	0.70 (0.70)	-0.20 (0.97)	0.35 (0.89)	1.62 (0.00)	0.39 (0.90)
Russia	1931-1960	0.83 (0.79)	~~N/A~~	0.83 (0.79)	-1.92 (2.10)	~~N/A~~	-1.92 (2.10)	-2.47 (3.16)	~~N/A~~	-2.47 (3.16)
	1946-1975	-0.75 (2.15)		-0.75 (2.15)	0.69 (4.66)		0.69 (4.66)	1.63 (4.56)		1.63 (4.56)
	1961-1990	-0.83 (1.83)	~~N/A~~	-0.83 (1.83)	-0.03 (1.89)	~~N/A~~	-0.03 (1.89)	1.03 (3.16)	~~N/A~~	1.03 (3.16)
	~~1991~~1976-2005	~~5~~-0.53 (0.00)	~~N/A~~	~~5~~-0.53 (0.00)	~~5~~-0.50 (0.00)	~~N/A~~	~~5~~-0.50 (0.00)	~~-2~~0.56 (0.00)	~~N/A~~	~~-2~~0.56 (0.00)
	1931-2005	0.00 (0.00)	~~N/A~~	0.00 (0.00)	1.04 (0.00)	~~N/A~~	1.04 (0.00)	1.53 (0.00)	~~N/A~~	1.53 (0.00)

Table ~~2~~3: Breakdown of mean decadal trends for each time period where each value is the number of days change per decade. The trend directions and magnitudes were derived from the Mann-Kendall and Sen's Slope tests and provide a general overview of the prevalent patterns during each time period for each study area. The standard deviation between the sites in each category is shown in the brackets beneath. Negative values represent earlier breakup (warming trend), earlier freezeup (cooling trend) and reduced number of open water days (cooling trend). Positive values indicate the opposite. Colours have been added to the box to aid in interpretation of whether the mean values support warming (red) or cooling (blue) trends. The grey boxes are for time periods were no data are available.

3.2. North America

In North America, the only sites with consistent data are clustered around the Great Lakes. During 1931-1960, in the east, earlier breakup dates dominate, and in the west, later breakup (Fig. 4a), with a number of sites being statistically significant (Fig. 3). This variation explains the large standard deviation (σ = 2.52) of the mean trend toward 0.36 days per decade earlier breakup (Table 3). An east-west pattern is reversed in the 1946-1975 period, with later breakup more common in the east (Fig. 4d). ~~Decadal lake freezeup changes across all Northern Hemisphere sites show a clear change in the trend direction from earlier freezeup (negative trends) to later freezeup (positive trends) through time (Table 2). Similar to the values for breakup, the magnitude of decadal changes for~~

freezeup increases through time, though they are notably higher for freezeup than breakup – i.e. from 1.82 days decade^{-1} earlier freezeup during 1931-1960 to 7.83 days decade^{-1} later freezeup during 1991-2005. River sites appear to experience the trends toward later freezeup dates earlier than for lakes, possibly suggesting differences in how lakes and rivers have responded to climatic changes. In Europe there is a steady change from earlier freezeup trends that match the hemispheric pattern. In North America the lakes experience low magnitude trends close to zero for the first two time periods, suggesting limited changes in freezeup dates. From 1991-2005 the lakes in North America (which are only in the United States due to a reduction in Canadian monitoring) display later freezeup trends (i.e. 5.09 days decade^{-1}). The Russian sites show a decline in strength of the cooling trend from 1931-1960 to 1961-1990, with only one site record for the 1991-2005 period.

Trends in the number of open water days per year allow for any changes in breakup and freezeup dates to be integrated together to explore the relative changes. This means that a general signal can be extracted from sites that may have conflicting patterns of warming and cooling for the breakup/freezeup dates – i.e. if breakup dates were becoming earlier at a faster rate than earlier freezeup then this will be reflected with a relative widening of the open water season. When all sites are considered there is a shift towards an increased proportion of sites with warming trends (i.e. less days with ice cover) (Fig. 3). This is the same for both Europe and North America. Russian sites are hampered by the lack of sites for 1991-2005 but show from 1931-1960 to 1961-1990 there is an increase in the proportion of warming trends. European and (to a lesser extent) the Russian sites show that the increased proportion of sites with more open water days is matched by an increased proportion of sites displaying earlier breakup and later freezeup. In North America across the three time periods the proportion of sites with a warming trends increases through time. During 1961-1990 although there is an increase in the number of open water days, compared to the previous period, this is primarily due to earlier breakup trends that are stronger than earlier freezeup trends. These movements show that whilst the ice-free season is widening through time in North America, the relative contribution from changes in breakup/freezeup date changes through time (Fig. 3).

All Northern Hemisphere sites, and when considered on a more regional scale (acknowledging the caveat associated with the Russian data availability for 1991-2005) there is a clear trend toward an increased number of annual open water days. This trend is similar to that experienced for both breakup and freezeup, showing a clear increase in magnitude through time for each region with a 2.18 days decade^{-1} reduction in the number of open water days for 1931-1960 to an increase in the number of open water days by 12.28 days decade^{-1} for 1991-2005.

3.2. North America

3.2.1. 1931-1960

In North America, interpretation of regional ice phenology changes is limited by continuity and location of sites (Fig. 4). The only area consistently documented is around the Laurentian Great Lakes. During 1931-1960 a longitudinal split in the dominant decadal breakup patterns is apparent (Fig. 4a). In the east warming decadal trends (earlier breakup) dominate and in the west cooling trends (later breakup). Breakup trends appear to correlate well with rising temperatures in coastal regions and cooling temperatures in the interior (Balling and Idso, 1989). Mean trends suggest that breakup was occurring 0.4 days decade^{-1} earlier during this period, with the trend being stronger for rivers (1.1 days decade^{-1}) compared to lakes (0.28 days decade^{-1}).

Compared to breakup, there is typically less than 50% of the number of sites available for freezeup from 1931-1960 and these are again concentrated around the Great Lakes (Fig. Mean trends show breakup dates became 1.27 days per decade (σ = 2.63) later during 1946-1975, with the trend driven largely by lakes with later breakup dates (Table 3), many of which are statistically significant (Fig. 3). From 1961-1990, most sites display earlier breakup trends, with a mean change of 2.98 days per decade (σ = 1.88) (Table 3). Nearly half of all sites display significant breakup trends (Figs. 3, 4g), many of which previously displayed significant later breakup trends (Fig. 4d). Four sites show later breakup trends, of which one is geographically-isolated and the others are surrounded by lakes with earlier breakup trends, many of which are significant. This suggests local factors, such as human modification of water courses4b). The mean trend was toward later freezeup of 0.9 days decade^{-1}. Like breakup trends, river freezeup changes (2.7 days decade^{-1} later) were greater than lakes (0.1 days decade^{-1} later). No dominant spatial patterns are apparent. Whilst most North American rivers display later freezeup, the Liard River in northern Canada displays a statistically significant (α=0.1) earlier freezeup trend of 3.1 days decade^{-1} from 1931-1960, showing that not all the rivers are responding in the same trend direction.

Trends for annual open water days for 1931-1960 are mixed, with sites in the east and west both exhibiting reduced and extended seasons (Fig. 4c). This is broadly similar to the heterogeneous patterns observed for breakup/freezeup, with an overall reduction of 0.3 days decade^{-1} in the number of open water days (Table 2). At a number of sites, the open water season has reduced due to later breakup and earlier freezeup. At other sites this reduction is reflected by warming and cooling trends (e.g. earlier breakup and earlier freezeup) where larger magnitude cooling trends have reduced open water season length (Fig. 5). The result at Lake Monona is peculiar in that it demonstrates no discernible trends for changes in the breakup date but a warming trend in the freezeup date, culminating in a reduction in the open water season. It is not clear why this is the case but it likely reflects the greater variability of freezeup dates (which varied across two months) compared to the variability of breakup dates (varied across one month). This greater range is also reflected by the greater standard deviation (used as a measure of interannual variability) for freezeup (14) compared to breakup (eight). Greater freezeup date variability means that the estimated trend is more vulnerable to years with extreme dates.

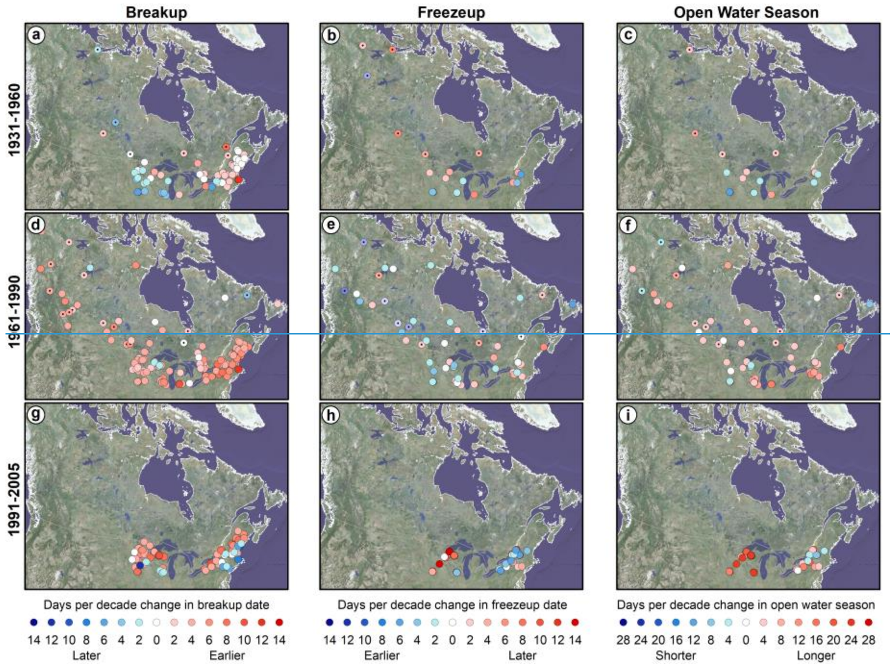


Figure 4: Decadal trends for breakup (**a**, **d**, and **g**), freezeup (**b**, **e**, and **h**), and length of the open water season (**c**, **f**, and **i**) in North America for the three individual time periods. Sites with a dot in the centre of the circle are river sites. Blue and red tones on the scales related to cooling and warming trends, respectively.

3.2.2. 1961-1990

During 1961-1990 the number of study sites increases and these sites show earlier breakup trends expanding to the west (Fig. 4d). The mean trends show breakup was earlier by 3.0 days decade^{-1}, an increased magnitude of change compared to 1931-1960. A number of the sites that experienced later breakup during 1931-1960 show a change toward earlier breakup decadal trends. Only four North American sites experience later breakup during 1961-1990 and appear to be out of sync with adjacent sites, or have been subjected to unique circumstances that can explain opposing trends. For example, Frame Lake in northwest Canada shows a later breakup of 0.2 days decade^{-1} and this is contrasted by two adjacent sites, Back Bay Lake and the Hay River, that experienced breakup occurring 1.3 and 1.7 days decade^{-1} earlier, respectively. No immediate reasons are clear why Frame Lake is responding differently to adjacent sites. A second site in Canada, the Churchill River near the Gulf of St. Lawrence, displays later breakup of 3.1 days decade^{-1} (α = 0.05). On this particular river, discharge has decreased due to dam construction in the 1960s (Déry et al., 2005; Déry and Wood, 2005) and since the rising limb of the spring hydrograph is important for mechanical ice breakup (Prowse and Beltaos, 2002), flow diversion likely made the rising limb a shallower gradient, meaning it takes longer for ice to reach a mechanical threshold where it breaks apart.

In the United States, Chequamegon Bay in southern Lake Superior displays later breakup trends of 0.7 days decade^{-1} for 1961-1990. Two other sites on Lake Superior at Bayfield and Madeline Island show earlier breakup of 2.1 and 1.9 days decade^{-1}, respectively. The dominant circulation in the southern part of Lake Superior is toward Chequamegon Bayor lake circulation patterns (Bennington et al., 2010), concentrating ice in the bay, hindering mechanical ice breakup. Thus, removal of ice is reliant on thermal processes as spring surface air temperatures increase. It is also worth noting that for Chequamegon Bay during 1931-1960 the trends lean toward an earlier breakup date of 1.4 days decade^{-1}, highlighting the complex temporal variability. The other site in the United States with a later breakup trend is Mystery Lake. Here trends of later breakup by 0.2 days decade^{-1} for 1961-1990 are contrasted by two adjacent sites within just 2 km (Lakes Nebish and Escanaba) that show earlier breakup trends of ~1.4 days decade^{-1}. There is no clear explanation for these differences, but given the small magnitude of change at Lake Mystery it may be that it is responding differently due to site specific factors (e.g. bathymetry).might account for local-scale heterogeneity. From 1976-2005 sites are clustered around the Great Lakes and demonstrate partial changes compared to the preceding time period (Fig. 4j). Whilst 72% of sites trend towards earlier breakup (Fig. 3), in the east several sites now display low magnitude earlier and later breakup trends. Earlier breakup decadal change for lakes, at 1.16 (α = 1.39), is double that for rivers, at 0.56 (α = 0.81) (Table 3). The standard deviation continues to show considerable variation around the mean.

Fewer sites with freezeup data are available compared to breakup (Table 2) and remain generally clustered around the Great Lakes (Fig. 4b). Freezeup date changes show that a longitudinal split occurs during 1961-1990. Sites are generally dominated by earlier freezeup trends in the west and later trends in the east (Fig. 4e). The mean trend direction across North America is for freezeup dates to become earlier by 0.2 days decade^{-1}. However, it is clear that there is almost an equal number of sites showing later freezeup (24 sites) as there are showing earlier freezeup (27 sites). Ten sites display no trends at all. Whilst lakes show an overall trend direction change to earlier freezeup (0.2 days decade^{-1}), rivers maintained a small trend toward later freezeup (0.04 days decade^{-1}), albeit at a considerably reduced magnitude compared to 1931-1960, and with a split between sites showing different trends (five later freezeup, six earlier freezeup, and one no trend).

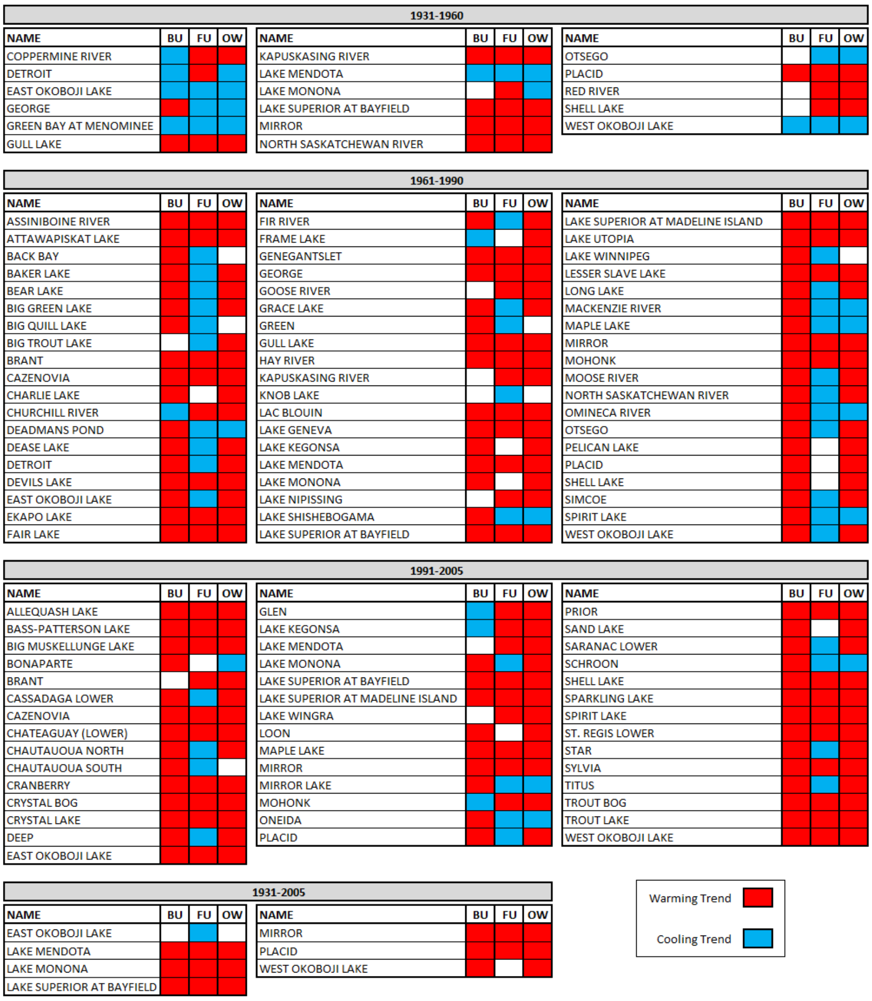
During 1961-1990, 15 sites have continuous data from the first time period, with eight sites maintaining the same trend direction, and the rest showing changes in trend direction. Of these changes, two sites changed to earlier freezeup, two changed to later freezeup, and three changed to no trend from 1931-1960 to 1961-1990 (Table 3). Trends for the full 1931-1990 period show the majority of sites had later freezeup trends, three displayed no trends, and three showed earlier freezeup (two of which are statistically significant at α=0.1) (Table 3). At most sites, even if there is no trend direction change between the two periods, during 1961-1990 the magnitude of the trend experienced is reduced compared to 1931-1960. Similar to breakup, a number of the sites demonstrate that shorter 30 year trends are occasionally superimposed onto longer 60 years trends. Of specific interest is how this superimposition relates to the two sites demonstrating statistically significant trends toward earlier freezeup, East Okoboji Lake and George. Whilst these sites show trends indicative of cooling, it is notable that the trends towards cooling reduce in magnitude through time from 1931-1960 to 1961-1990 – possibly hinting that cooling trends are beginning to diminish and warming air temperatures are taking longer to be manifest as changes in trend direction compared to other sites.

Table 3: Summary decadal change statistics for sites across North America with freezeup data available for either the 1931-1990 or 1961-2005. The statistical significance values are for the longer-term 1931-1990 period. Levels of significance (α) are: *** = 0.001, ** = 0.01, * = 0.05, + = 0.1. The negative value indicates the direction of the trend, i.e. earlier freezeup.

SITE	1931-1960	1961-1990	1991-2005	1931-1990	α	1961-2005	α	1931-2005	α
BRANT	-	1.6	10.0	-		1.3		-	
CAZENOVIA	4.0	0.5	3.8	0.0		2.5	*	1.1	+
DETROIT	0.9	-0.6	-	1.1	*	-		-	
EAST OKOBOJI LAKE	-4.5	-2.5	15.0	-1.3	+	0.2		-0.3	
GEORGE	-4.4	1.1	-	-1.8	+	-		-	
GULL LAKE	4.5	0.3	-	2.1	+	-		-	
KAPUSKASING RIVER	3.8	2.2	-	1.8	*	-		-	
LAKE KEGONSA	-	0.0	4.0	-		1.0		-	
LAKE MENDOTA	-0.7	1.2	8.0	0.0		2.5	+	0.9	
LAKE MONONA	1.0	0.0	-2.2	1.0		1.4		1.3	*
LAKE SUPERIOR AT BAYFIELD	2.1	0.4	15.0	0.4		4.5	***	2.5	**
LAKE SUPERIOR AT MADELINE ISLAND	-	0.4	15.0	-		4.5	***	-	
MAPLE LAKE	-	-3.1	14.2	-		-1.3		-	
MIRROR	1.7	1.2	11.3	0.7		1.3		0.7	+
MOHONK	-	1.5	3.3	-		2.5	*	-	
NORTH SASKATCHEWAN RIVER	4.3	-0.4	-	2.1	**	-		-	
OTSEGO	-3.3	-0.8	-	-1.3		-		-	
PLACID	3.1	0.0	-5.7	0.5		-0.4		0.2	
SHELL LAKE	0.8	0.0	10.0	1.3	*	0.8		1.3	*
SPIRIT LAKE	-	-5.0	14.2	-		-0.9		-	
WEST OKOBOJI LAKE	-3.3	-1.6	2.9	0.0		-0.3		0	

Changes in the length of the open water season from 1961-1990 (Fig. 4f) show similarity to breakup trends (Fig. 4c). The mean trend shows the open water season was growing by 2.8 days decade^{-1} (Table 2). This is contrasted, particularly in the western part of the region, with freezeup trends that generally show earlier freezeup dates (Fig. 4e). Similar to some sites in the previous time period, often the magnitude of earlier breakup trends is larger than earlier freezeup trends, increasing the open water season length (Fig. 5). At several sites changes in open water season length appears more complex than the trends for individual breakup/freezeup dates. For example, Big Trough Lake and Frame Lake display no trend and a cooling trend for breakup, respectively, and a cooling trend and no trend for freezeup, respectively. Despite neither site demonstrating a warming breakup/freezeup trend, the

~~length of their open water season increased by ~1 day decade^{-1}, suggesting a general warming pattern that is more complicated than its constituent parts.~~



~~**Figure 5**: Comparison of how sites in North America with an open water season calculation. This reflects the relative changes in dates for breakup and freezeup. The red, blue, and white colours demonstrate whether the calculated trend reflects a warming trend (earlier breakup, later freezeup, or increased open water season), a cooling trend (the opposite), and no trend, respectively. Abbreviations are: BU – breakup, FU – freezeup, and OW open water.~~

3.2.3. 1991-2005

From 1991-2005 most sites display earlier breakup trends (Fig. 4g). Whilst the overall trend of 2.8 days decade^{-1} earlier breakup is reduced compared to 1961-1990 (3.0 days decade^{-1}), it is evident that the magnitude of change has remained similar or increased at a number of sites with 1961-2005 time series. For example, Lake Monona displays earlier breakup trends of 2.5 days decade^{-1} for 1961-1990 that increases to 7.1 days decade^{-1} earlier breakup for 1991-2005. There are a small number of sites displaying the opposite pattern – e.g. at Houghtons Pond the breakup trends were 7.5 days decade^{-1} earlier for 1961-1990 and 1.25 days decade^{-1} later from 1991-2005. This highlights that whilst earlier breakup trends dominate, this is not temporally consistent at all sites. It is also not spatially consistent, as is indicated by a number of sites along the eastern seaboard displaying later breakup. These sites tend to display higher standard deviation values for breakup dates compared to elsewhere, reflecting a greater annual variability in breakup dates and that shorter trends are more likely to fluctuate. The maritime location of these sites and adjacent warm ocean currents that propagate past the region likely modulate temperatures so they are closer to zero and require only minor temperature changes to go between frozen and melting conditions. Thus, they experience greater variability compared to sites further inland. Importantly, these eastern seaboard sites show that, when there are data available for 1961-2005, the trend is toward earlier breakup (Table 4) – suggesting later breakup trends are superimposed onto longer earlier breakup trends.

Freezeup trends from 1991-2005 (Fig. 4h) show a mixed signal, but with a general trend toward later freezeup of 5.1 days decade^{-1} (Table 2). Similar to 1961-1990 there is a longitudinal split, albeit with the caveat that the data available for 1991-2005 are considerably more spatially-restricted. In the western part of the Great Lakes region there is an increase in the number of sites showing warming decadal freezeup trends. Sites demonstrating earlier freezeup are located to the east of the Great Lakes. Of these sites only two have data for the preceding period; Lake Monona and Placid. These sites show that from 1961-2005 the trends are again mixed, with Lake Monona displaying later freezeup of 1.4 days decade^{-1} and Placid showing earlier freezeup of 0.4 days decade^{-1} (Table 3). Some of the sites displaying large magnitude trends towards later freezeup from 1991-2005 also show low magnitude earlier freezeup trends over the longer 1961-2005 period (e.g. Spirit Lake; Table 3). At East Okoboji Lake, fluctuations in the magnitude and trend direction are observed across all time periods that result in earlier freezeup trends of 1.3 days decade^{-1} during 1931-1990 and later freezeup trends of 0.2 days decade^{-1} during the

1961-2005 period. This is marked by a change in direction and magnitude of the trends at this site through time, indicating at first a reduction in the earlier freezeup trends before switching to later freezeup trends (Table 3). The variability in trend magnitude and direction is likely due to the combination of factors that control water freezeup – e.g. even if water temperatures are low enough to freeze, wind and water movement can mechanically prevent freezeup as the kinetic energy means that it is harder for the water to stabilise or smaller ice patches to agglomerate (Beltaos and Prowse, 2009), potentially requiring more heat and kinetic energy to be withdrawn – the complexity involved in allowing water freezeup likely acts as an important control on these fluctuating trends.

SITE	α	DECADEL CHANGE
DAMARISCOTTA LAKE		-2.2
HOUGHTONS (HOOSICWHISICK) POND	+	-3.6
LAKE AUBURN	**	-3.2
LAKE WINNIPESAUKEE	*	-1.8
MARANACOOK LAKE	*	-2.5
MOHONK	+	-2.3
PONKAPOAG POND	**	-6.4
SWAN LAKE	*	-2.5

Table 4: Decadal breakup trends for the 1961-2005 period at sites along the eastern seaboard of the United States that demonstrate a cooling trend during the 1991-2005 period. Levels of significance (α) are: *** = 0.001, ** = 0.01, * = 0.05, + = 0.1. This table shows that, despite the cooling trend during the 1991-2005 period that is observed at these sites, these trends are superimposed onto a longer-term warming trend. The negative value indicates the direction of the trend, i.e. earlier breakup.

From 1991-2005 overall trends reflect a widening of the open water season (Fig. 4i) and an increased magnitude of change to 9.3 days decade^{-1} (Table 2). This warming pattern is reflected in the general patterns of earlier breakup and later freezeup (Fig. 5). At sites with conflicting trend directions between breakup/freezeup a variable response in the ice season length is observed. At some sites with a cooling breakup/freezeup trend and an opposing warming breakup/freezeup trend the changes in the length of the open water season typically reflect the breakup/freezeup trend that is larger. However, as noted above, this is not always the case (e.g. Bonaparte) and reflects that interpreting changes in the length of the open water season requires the context of breakup/freezeup changes.

3.3. Fennoscandia

3.3.1. 1931-1960

In Fennoscandia, apart from northern Finland and northwest Russia, there is a higher density of data compared with North America (Fig. 6). Breakup dates during 1931-1960 display earlier and later trends, as well as sites exhibiting no observable trend (Fig. 6a). The only spatial trend is that most sites with warming decadal trends are in southern Finland and later breakup trends in southern Sweden. Whilst there appears to be a latitudinal split separating the trend directions in the northern and southern areas of Fennoscandia, the overall values show breakup from 1931-1960 occurring 0.1 days decade^{-1} earlier. Earlier breakup trends were stronger for rivers (0.2 days decade^{-1}) than for lakes (0.1 days decade^{-1}).

During 1931-1960 (Fig. 6b) Finland is predominantly characterised by low magnitude earlier freezeup trends and much of Sweden shows both warming and cooling trends with no obvious spatial patterns. Mean values show a general earlier freezeup pattern by 2.1 days decade^{-1}. However, this is only the case for lakes as rivers display later freezeup trends of 3.5 days decade^{-1}, suggesting that rivers have responded quicker to increases in air temperature.

During 1931-1960 trends are almost identical between freezeup and open water season length in Finland (Fig. 6b, 6c). In Sweden, trends are varied, reflecting similar heterogeneous patterns of change for breakup/freezeup dates. Where individual sites demonstrate opposing warming and cooling trends for breakup and freezeup the typical response in the length of the open water season is to see a relative reduction in its length (Fig. 7), suggesting that changes in freezeup dates are bigger than breakup date changes, causing the open water season to shift and reduce. This is reflected by the observation that the majority of sites display cooling trends (Fig. 3) and mean values show in Fennoscandia a reduction in the open water season by 2.2 days decade^{-1}. This is only the case for lakes, as rivers show strong trends toward an increase in the length of the open water season by 3.4 days decade^{-1} – suggesting that rivers are responding faster to temperature increases.

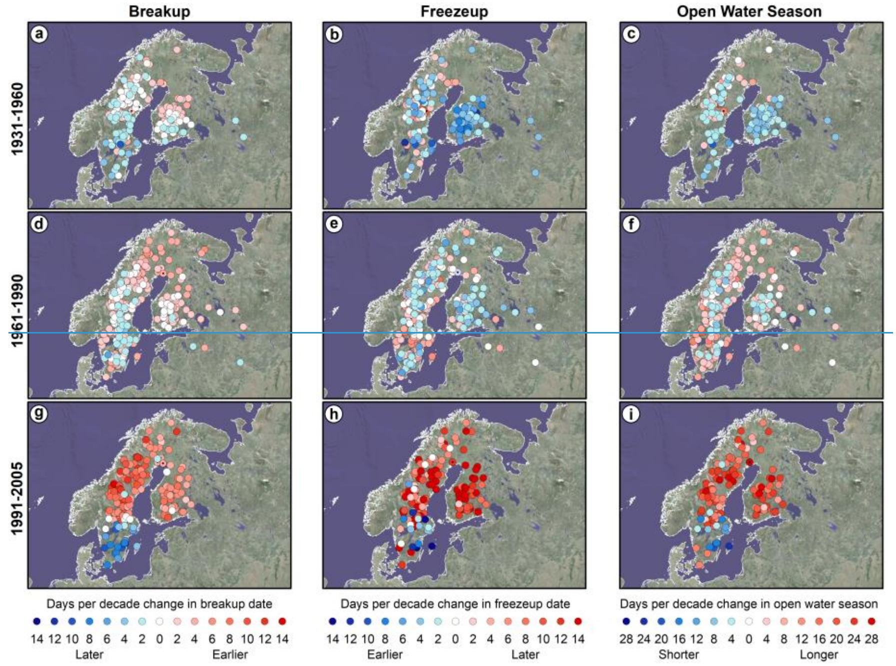


Figure 6: Decadal trends for breakup (**a**, **d**, and **g**), freezeup (**b**, **e**, and **h**), and length of the open water season (**c**, **f**, and **i**) in Fennoscandia for the three individual time periods.From 1931-1960 no clear geographical pattern exists, with 25% of sites displaying significant later freezeup trends for rivers and lakes (Fig. 3). Mean decadal trends show freezeup was 0.85 days per decade later, but this is associated with a high standard deviation (σ = 3.16) and a large difference in the mean trends for lakes and rivers (Table 3). During 1946-1975, spatial patterns remain varied (Fig. 4e) and sites with significant later and earlier freezeup trends each account for 10.5% of all sites (Fig. 3). Significant sites are both rivers and lakes and unlike breakup do not appear to be clustered east of the Great Lakes. The mean trend for lakes remains low at 0.17 days per decade earlier (σ = 2.29), whilst rivers are comparably higher with freezeup occurring 1.22 days per decade (σ = 4.42) later (Table 3). Freezeup date changes during 1961-1990 show that sites in the west more commonly trend toward earlier freezeup and in the east toward later breakup (Fig. 4h). Compared with the breakup trends for the same period, and freezeup trends for the preceding period, the proportion of sites with significant earlier (4.9%) and later (3.3%) freezeup dates is smaller (Fig. 3). The mean decadal trend of 0.18 days per decade (α = 1.97) earlier freezeup dates for lakes and rivers combined is weaker than observed for earlier breakup during the same period (Table 3). From 1976-2005, freezeup trends demonstrate

a clear pattern, with no sites displaying earlier freezeup trends (Fig. 4k) and 39% of sites showing significant later freezeup trends (Fig. 3). This is markedly different to all other time periods where spatial patterns were much more varied in the Great Lakes region (Fig. 4h). There are no river sites with freezeup data for this time period (Table 2) and mean values for lake changes show that freezeup was becoming later by 3.61 days per decade (α = 2.32) (Table 3).

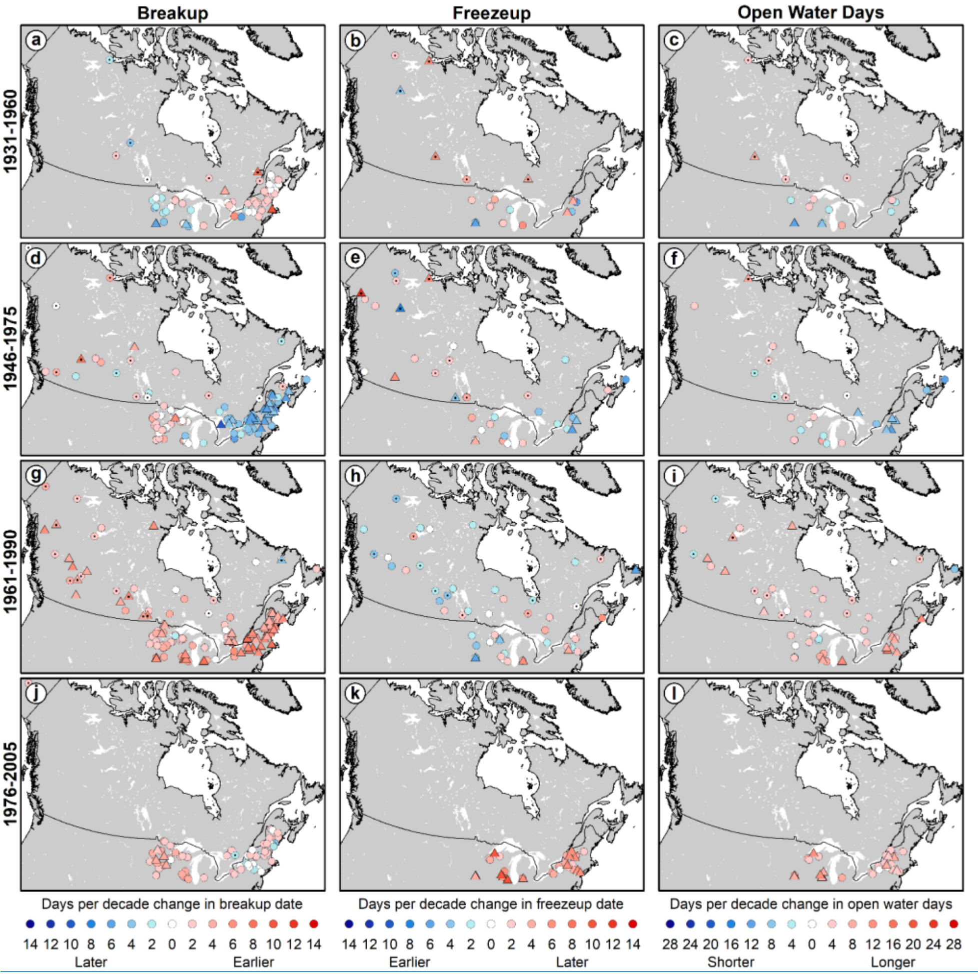
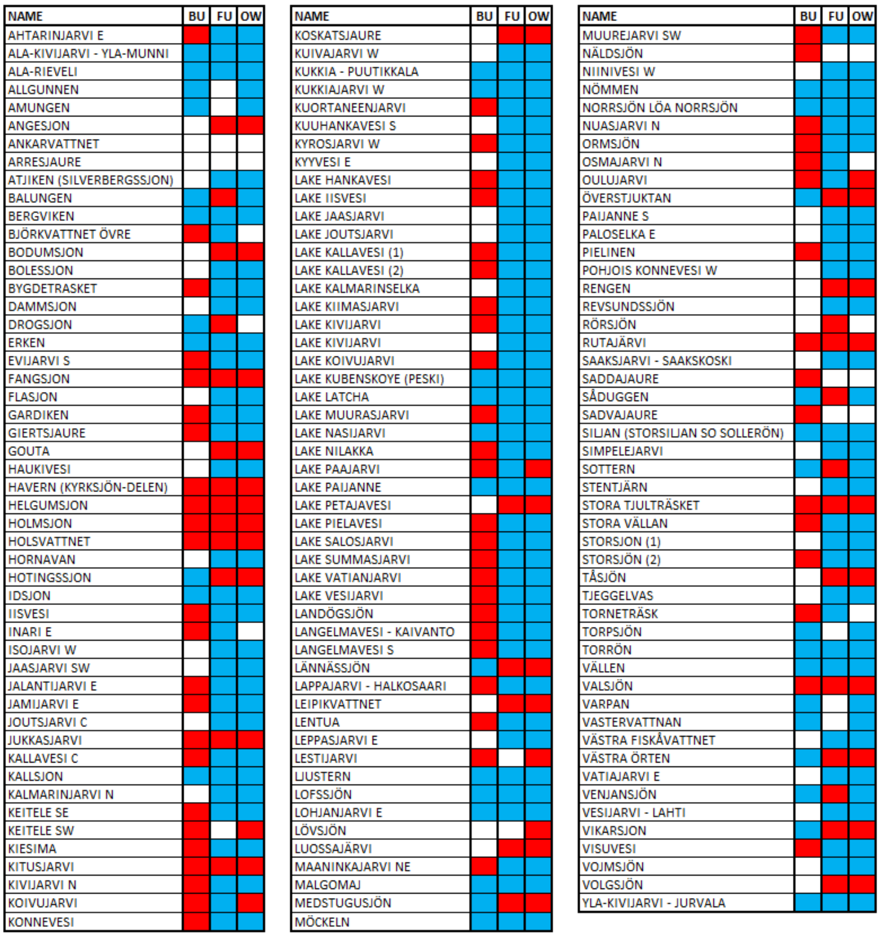


Figure 4: Decadal trends for breakup (**a**, **d**, **g**, and **j**), freezeup (**b**, **e**, **h**, and **k**), and the number of annual open water days (**c**, **f**, **i**, and **l**) in North America for the four individual time periods. The trend directions and magnitudes were derived from the Mann-Kendall and Sen's Slope tests. The triangles and circles indicate whether the trend

was or was not statistically significant. Sites with a dot in the centre of the circle are river sites. ~~Blue~~Thus, a red triangle symbol with a dot in the middle indicates a river site that has a statistically significant warming trend over that time period. The blue and red tones on the scales are related to cooling and warming ~~signals~~trends, respectively.



~~**Figure 7**: Comparison of how sites in Fennoscandia with an open water season calculation. This reflects the relative changes in dates for breakup and freezeup. The red, blue, and white colours demonstrate whether the calculated trend reflects a warming trend (earlier breakup, later freezeup, or increased open water season), a cooling trend (the opposite), or no trend, respectively. Abbreviations are: BU – breakup, FU – freezeup, and OW open water.~~

3.3.2. 1961-1990

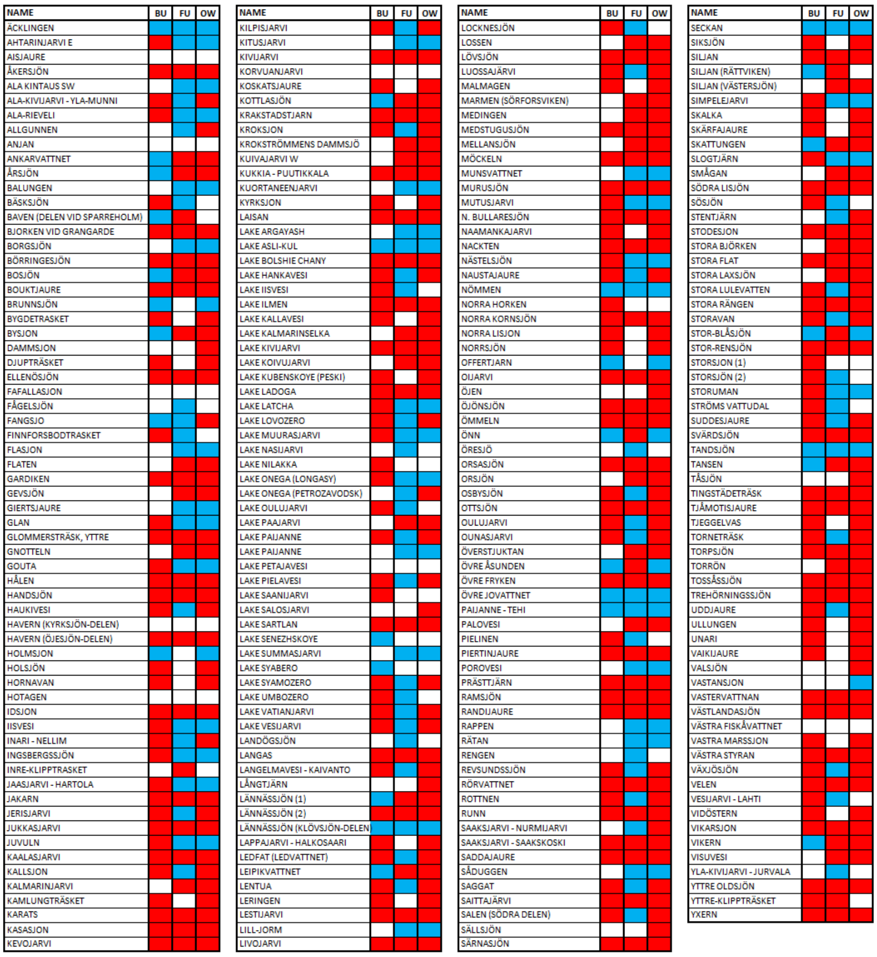
By 1961-1990 (Fig. 6d) additional sites are available across the region and more dominant trends have developed. Trends toward earlier breakup in northern Sweden and Finland have increased in magnitude compared to 1931-1960, whilst many of the trends in southern Sweden that previously indicated later breakup (Fig. 6a) have switched to earlier breakup. Similar to the patterns observed for 1931-1960, the magnitude of change leading to earlier breakup is stronger for rivers (2.2 days decade^{-1}) than for lakes (0.8 days decade^{-1}). These changes are also reflected in the increased magnitude for all sites toward an earlier breakup date of 0.8 days decade^{-1} from 1961-1990.

In the 1961-1990 period (Fig. 6e) no clear spatial patterns have yet developed, but there is a clear decrease in sites with earlier freezeup trends compared to 1931-1960, with mean freezeup dates occurring 0.3 days decade^{-1} later. This is partly due to 89 new sites with freezeup data and many sites with data covering both periods switching from earlier freezeup to later freezeup, or from earlier freezeup to no trend. This is shown in Table 5 where sites with data covering 1931-1990 generally show a cooling trend in the 1931-1960 period that either reduced in magnitude (n=28) or completely switched to no trend (n=11) or a warming trend (n=17). This potentially indicates that rising air temperatures were beginning to take effect from 1961-1990.

TYPE OF TREND CHANGE	NUMBER OF SITES
Increased magnitude of a cooling trend	4
Switch to cooling trend from warming trend	7
Switch to cooling trend from no trend	1
Decreased magnitude of a cooling trend	28
Switch to no trend from cooling trend	11
Switch to no trend from warming trend	9
Decreased magnitude of a warming trend	3
Switch to warming trend from no trend	7
Switch to warming trend from cooling trend	17
Increased magnitude of a warming trend	3

Table 5: The number of sites and different types of changes in decadal trend direction from the 1931-1960 time period to the 1961-1990 time period in Fennoscandia. This shows that the majority of sites with data covering the

~~two time periods are either experiencing reduced earlier freezeup trends, or they are completely switching to later freezeup trends.~~



~~**Figure 8**: Comparison of how sites in Fennoscandia with an open water season calculation for the 1961-1990 time period. This reflects the relative changes in dates for breakup and freezeup. The red, blue, and white colours demonstrate whether the calculated trend reflects a warming trend (earlier breakup, later freezeup, or increased open water season), a cooling trend (the opposite), or no trend, respectively. Abbreviations are: BU – breakup, FU – freezeup, and OW open water.~~

Across Fennoscandia during the 1961-1990 time period the majority of sites exhibit a trend towards an increase in the open water season length (Fig. 6f), with a mean increase of 1.8 days decade^{-1} (Table 2). This pattern is similar to breakup (Fig. 6d) but markedly different to freezeup, where many sites in the east demonstrate earlier freezeup trends (Fig. 6e). During this time period it is clear that breakup trends are changing the most and are driving the observed changes in the open water season. It is notable that most sites that show a reduction in the open water season do so because either they have both cooling breakup and freezeup trends, or because cooling freezeup trends are stronger than warming breakup trends (Fig. 8).

3.3.3. 1991-2005

In the 1991-2005 period there is a clear dominance for earlier breakup trends in Sweden, with the only area that experienced later breakup trends in the south (Fig. 6g). Across all sites in Fennoscandia breakup has occurred earlier at a rate 3.9 days decade^{-1}. Unlike the previous time periods, the magnitude of change was larger for lakes (3.9 days decade^{-1}) than it was for rivers (2.2 days decade^{-1}). A key observation from this final time period is that for the majority of sites that had data for the 1961-1990 period not only have they maintained the earlier breakup trends but they also increased in magnitude.

A clear latitude distinction has developed at ~60 °N which partitions later and earlier breakup trends to the north and south, respectively (Fig. 6g). Northern latitudes showed a gradual change from cooling to warming trends but the south has shown through the different periods a switch in trend direction. Two reasons are proposed for why this boundary has developed. Firstly, it has been acknowledged, and increasingly observed, that rising global air temperatures have tended to be amplified at higher latitudes compared to the global mean (Chylek et al., 2009; Serreze et al., 2000). This pattern has been observed across northern parts of Fennoscandia where temperature increase since 1950 has been greater than in the south (Hansen et al., 2006). This amplification correlates well with the changes observed towards earlier ice breakup dates. Secondly, the position of the winter 0 °C isotherm is likely to have had an important influence on the ice phenology in southern Sweden. As is shown in Fig. 9 the mean decadal position of the winter 0 °C isotherm has, albeit with some variation, migrated northward between 1931-2000 – suggesting the colder, perennial temperatures of the Arctic are not penetrating as far south. For the 1991-

2005 period the positon of the 1991-2000 isotherm (Fig. 9) shares a latitudinal position separating warming and cooling trends. This relationship between the breakup date and the position of the 0 °C isotherm is also reflected in the standard deviation of breakup date (used as a measure of interannual variability), which shows that the sites with the greatest interannual variability are south of or around the 0 °C winter isotherm (Fig. 10). This association is not surprising as sites that are situated near the 0 °C isotherm will require only small temperature changes to move between melting and freezing conditions. Thus, short term weather events have a greater influence on the breakup date when temperature conditions are already close to 0 °C — unlike at higher latitudes where the temperature changes need to be sustained for longer to bring about breakup.

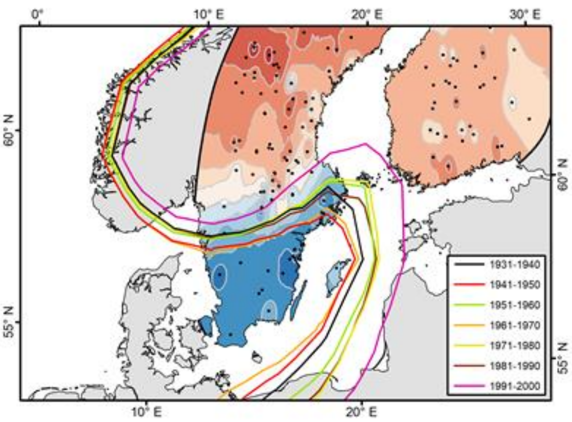


Figure 9: Breakup date trends in southern Sweden from 1991-2005 (see Fig. 6g for full area and scale). Note that site values have been interpolated into a surface for easier comparison. The polylines show the mean position of the 0 °C winter isotherm for several decades. Calculated from the 20th Century Reanalysis project (cf. Compo et al., 2011).in some places the symbols overlap.

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Trends for annual open water days during 1931-1960 are broadly similar to those for freezeup, with a comparable number of sites showing more or fewer open water days (Fig. 4c). Four of the 17 sites show significant trends (note that two sites overlap on Fig. 4c) and this variability reflects the low mean value of 0.29 fewer annual open water days per decade (σ = 4.82) and is mostly associated with lakes (Table 3). From 1946-1975 the number of annual open water days closely matches breakup trends, with 20.7% of sites displaying significant trends towards a decrease (Fig. 3), all of which are east of the Great Lakes (Fig. 4f). Reduced annual open water days are observed for lakes rather than rivers, which display a mean increase (Table 3). Annual open water days during 1961-1990 are similar to breakup patterns during the same period, including in western Canada where freezeup dates were earlier (Fig. 4i). The low magnitude of freezeup trends compared to high magnitude breakup trends in the same area are having a larger impact on the number of annual open water days. The majority of sites trend towards more open water days, with 26.3% being significant (Fig. 3) and spread across North America (Fig. 4i). The mean magnitude of change shows the number of annual open water days increased by 2.77 days per decade (α = 3.12), with the changes for lakes being larger in magnitude than rivers (Table 3). Most sites with data for the number of annual open water days in the preceding time period show the trend direction changed or reduced in magnitude, even when the 1946-1975 trend was a significant reduction in open water days (Fig. 4f and 4i). Patterns from 1976-2005 reflect that most sites display earlier breakup and later freezeup dates, extending the length of the open water season by 4.15 more days per decade (α = 2.84) (Table 3, Fig. 4l). In total, 36.8% of sites display significant trends towards more open water days (Fig. 3), maintaining warming trends from the preceding time period but with less variability in the magnitude of that change.

3.3. Europe

In Europe, 1931-1960 breakup trends show a proclivity for sites to display non-significant earlier breakup or no trend at all (Fig. 3). Most sites trending towards earlier breakup dates are at higher latitudes compared to those displaying later breakup (Fig. 5a). The lack of observable trends is reflected by the low magnitude of the mean trend towards earlier breakup by 0.10 days per decade (α = 1.29) for lakes and rivers (Table 3). In 1946-1975 most sites show later breakup dates by 1.75 days per decade (α = 1.31) (Table 3), with the only observable spatial pattern being that of the 22.1% of sites displaying significant later breakup trends (Fig. 3), most are located in areas where earlier breakup was common in the preceding time period (Fig. 5d). By 1961-1990 decadal breakup trends switched from predominantly later to earlier breakup. Of the 261 sites, 53.6% display earlier breakup, with a further 8.8% being significant (Fig. 3), with a change toward earlier breakup dates by 0.82 days per decade (α = 1.25), but the variability remains large enough that one standard deviation of change is enough to switch trend direction (Table 3). Northern sites make up the majority with significant earlier breakup trends for both lakes and rivers (Fig. 5g). There remains spatial variability, with 12.6% of sites showing later breakup trends. The magnitude of the trend towards earlier river breakup dates is almost three times that of lakes (Table 3). From 1976-2005 most sites display earlier breakup trends (Fig. 5j), of which 72.3% are significant (Fig. 3). During this period the breakup date has become earlier by a mean of 3.70 days per decade (α = 2.00), with the magnitude of change experienced in lakes over double that for rivers (Table 3).

During 1931-1960, a total of 45.2% of sites display earlier freezeup, with a further 22.6% being statistically significant (Figs. 3, 5b). Freezeup decadal trends show lake freezeup became earlier by 2.31 days per decade (α = 3.43) (Table 3). The large standard deviation reflects highly variable trend magnitudes towards both later and earlier freezeup (Fig. 5b). The five river sites trend towards later freezeup dates by 3.52 days per decade (α = 3.17). From 1946-1975, spatial patterns in southern Finland (Fig. 5e), where many sites previously displayed significant earlier freezeup dates, there is now considerable variability, more so than for breakup (Fig. 5d), with both earlier and later significant freezeup trends. Compared to 1931-1960 there is a considerable drop in the number of sites displaying significant earlier freezeup trends to 8.4% (Fig. 3). Mean lake decadal trends show earlier freezeup reduced to 0.78 days per decade (α = 3.27), but with considerable variation (Table 3). Rivers continue to have opposing trends, but also experienced a reduction in trend magnitude. During 1961-1990 there is a clear increase in sites displaying later freezeup trends and a reduction in trend magnitude for sites showing earlier freezeup (Fig. 5h). Freezeup and breakup trends in Sweden both display a warming pattern, whilst in Finland they are generally opposed (Fig. 5g, 5h). The decline in earlier freezeup lake trends is now characterised by later freezeup of 0.34 days per decade (α = 2.17) (Table 3). In the final time period the region is characterised by later freezeup trends (Fig. 5k), which is similar to breakup trends (Fig. 5j). Later freezeup trends account for 52.9% of sites, with another 21.5% displaying significant later freezeup. A small number of sites display significant earlier freezeup trends, but these are out of synchrony with the wider area (Fig. 5k). This time period is the culmination of a gradual reduction in earlier freezeup trend magnitude for lakes during 1931-1960, before a switch to later freezeup dates, and then a magnitude increase in later freezeup date to 2.51 days per decade (α = 3.05) (Table 3). Through all four time periods rivers have displayed trends towards later freezeup dates (Table 3).

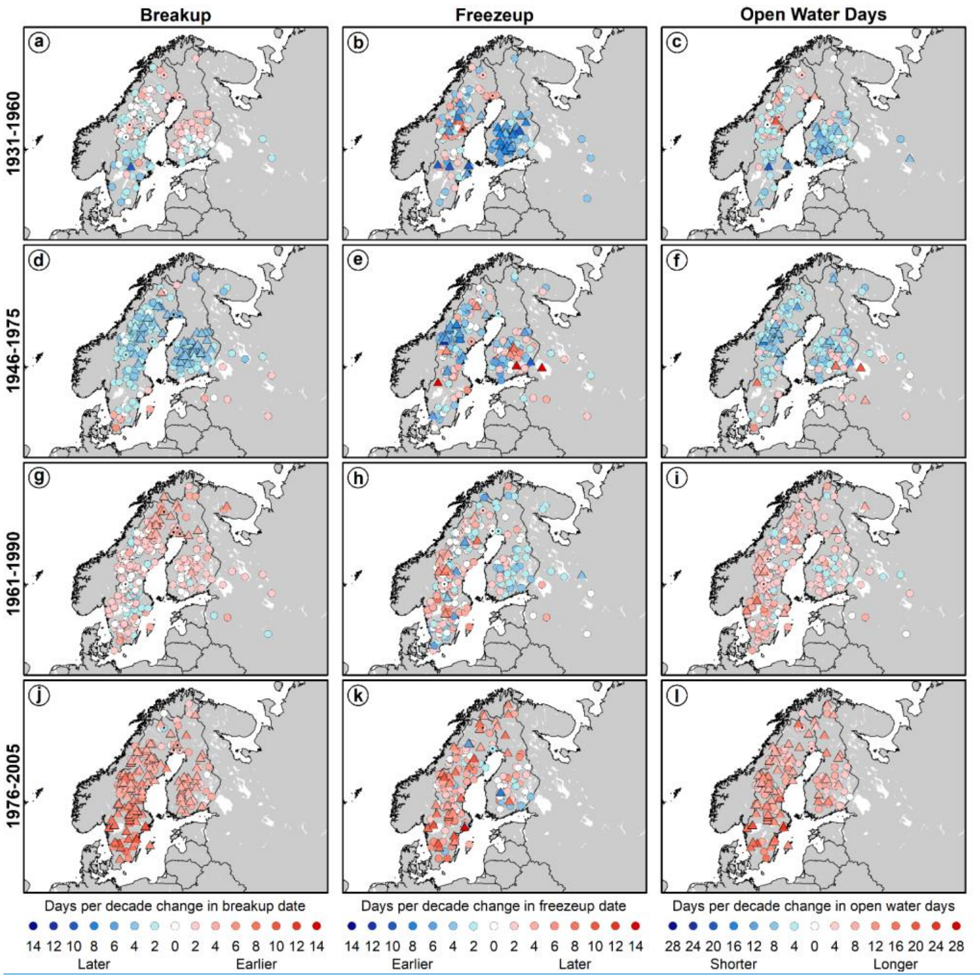

Figure 5: Decadal trends for breakup (**a**, **d**, **g**, and **j**), freezeup (**b**, **e**, **h**, and **k**), and the number of annual open water days (**c**, **f**, **i**, and **l**) in Europe for the four individual time periods. The trend directions and magnitudes were derived from the Mann-Kendall and Sen's Slope tests. The triangles and circles indicate whether the trend was or was not statistically significant. Sites with a dot in the centre of the circle are river sites. ~~The amplification of high latitude temperature increases and the position of the 0 °C isotherm can, perhaps explain why there is a clear boundary between the climatic response of the different regions, but it is insufficient to explain why the trends are opposing. Breakup dates at sites in this region show a pattern where initial trends toward later breakup occurred from 1991-1996 before they became earlier after 1998. The difference in the slopes for later and earlier segments~~

of the time series for breakup are such that the steeper gradient for later breakup from 1991-1996 was large enough to override the shallower gradient for earlier breakup in the second half of the period – thus, resulting in an overall trend from 1991-2005 of later breakup dates. As southern Swedish climate is strongly correlated to the NAO, the decreasing temperature trend leading to later breakup is associated with a weakening of the NAO in the early 1990s (Blenckner et al., 2004). Therefore, a reduction in the pressure gradient (a weakened NAO) allowing colder Arctic air to descend southward could have shifted temperatures already close to 0 °C below freezing.

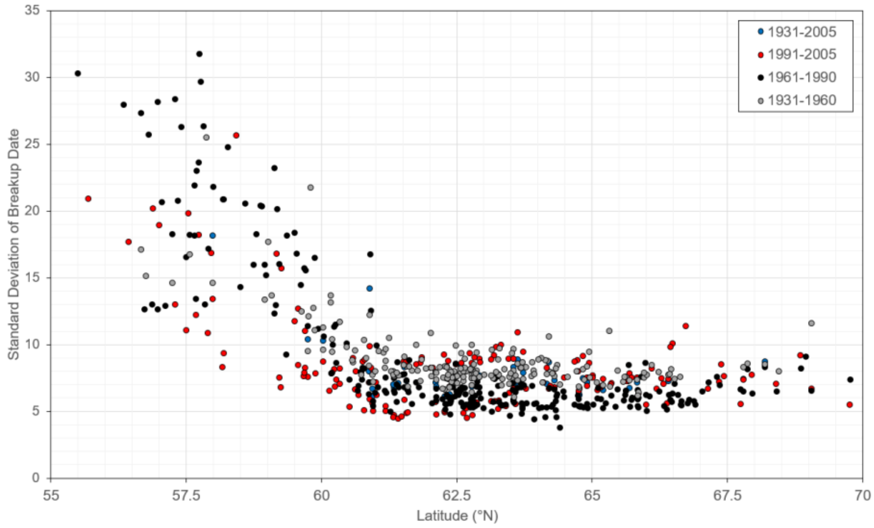

Figure 10: Standard deviation for breakup dates at Fennoscandian sites for different time periods. Note that, in accordance with Fig. 9, the sites that demonstrate the largest interannual variability are south of 60 °N and appear to be associated with the winter 0 °C isotherm.

By exploring the individual time series for sites in this area in more detail and over a longer timescale, it becomes clear that these trends towards later breakup in southern Sweden during 1991-2005 are short-term and superimposed on top of long-term warming trends and earlier breakup. Of the sites in southern Sweden that demonstrate a cooling trend for 1991-2005, one site has continuous data covering 1931-2005. At Såduggen the breakup dates were occurring 1.5 days decade^{-1} earlier during 1931-2005 even though the most recent time period shows strong cooling trends (see section 3.5; Fig. 9). For the southern sites 12 have data covering 1961-2005 and show earlier breakup trends of 3.6-5.0 days decade^{-1} (Table 6). At 11 of the 12 sites analysed the earlier trends in breakup date were significant at or above the α = 0.1 significance level with several being significant at α = 0.01 (Table 6). At two other sites in Fennoscandia there are trends towards later breakup during 1991-2005. However, as above for the sites at lower latitudes, the Djupträsket and Sösjön lakes show that when breakup trends are investigated over the 1961-2005 period they display earlier breakup of 1.6 and 0.8 days decade^{-1}, respectively. Again, this highlights that recent cooling trends appear to be short term fluctuations of a longer warming trend.

SITE	α	DECADEL CHANGE
ASPEN	***	-4.4
FAFALLASJON	*	-4.3
FANGSJO		-3.6
GNOTTELN	*	-4.1
KRAKSTADSTJARN	**	-5.3
NORRA LISJON	**	-3.7
ÖNN	+	-3.6
SÅDUGGEN	*	-3.9
SÖDRA LISJÖN	**	-3.8
TINGSTÄDETRÄSK	*	-4.4
TREHÖRNINGSSJÖN	*	-5.0
VIKERN	*	-5.0

Table 6: Decadal breakup trends for the 1961-2005 period at sites in Sweden that demonstrate a cooling trend during the 1991-2005 period. Levels of significance (α) are: *** = 0.001, ** = 0.01, * = 0.05, + = 0.1. This table shows that, despite the cooling trend during the 1991-2005 period that is observed at these sites, these trends are superimposed onto a longer-term warming trend. The negative value indicates the direction of the trend, i.e. earlier breakup.

From 1991-2005 (Fig. 6h) freezeup trends closely resemble those for breakup (Fig. 6g and 9) and the development of a latitudinal boundary at ~ 60 °N, albeit slightly less consistent. The main difference in this region for freezeup patterns compared to breakup patterns is that the southern Sweden sites do not display a completely uniform pattern of cooling, with the western area showing later freezeup trends similar to those observed elsewhere in Fennoscandia. At the sites with earlier freezeup patterns for 1961-2005 it can be shown that these cooling trends are again short term fluctuations on a longer-term warming trend (Table 7). As described above for breakup, the southern latitudes display greater variation due to their proximity to the 0 °C isotherm where only small temperature changes are required to move between frozen and unfrozen conditions (assuming other parameters, such as wind, allow freezing to occur).

SITE	α	DECADEL CHANGE
GNOTTELN		3.3
KALLSJON		1.8
KYRKSJON	+	3.6
NORRA LISJON	*	3.7
SILJAN (VÄSTERSJÖN)	+	3.5
SÖDRA LISJÖN	*	3.6
TINGSTÄDETRÄSK	*	5.4
VELEN	**	4.9

Table 7: Decadal freezeup trends for 1961-2005 at sites in Sweden that demonstrate a cooling trend during the 1991-2005 period. Levels of significance (α) are: *** = 0.001, ** = 0.01, * = 0.05, + = 0.1. This table shows that, despite the cooling trend during the 1991-2005 period that is observed at these sites, these trends are superimposed onto a longer-term warming trend. The positive value indicates the direction of the trend, i.e. later freezeup.

The open water season length from 1991-2005 shows ubiquitous trends, with the majority of sites (Fig. 6i) showing an increased length and a mean increase of 13.3 day decade^{-1} (Table 2). Sites demonstrating a reduction in the length of the open water season are typically the same sites that experienced earlier freezeup during this period (Fig. 6h). Sites in southern Sweden with a reduced open water season length from 1991-2005, show, when compared against the 1961-2005 time series that all sites have longer-term trends for an increased water season length (Table 8). One of these sites (Såduggen) also has data for 1931-1960 and shows that across the entire time period these short-term fluctuations of a reduced open water season are superimposed on top of a longer-term increase (see section 3.5; Fig. 11). What is clearly noticeable from comparing Fig. 7, 8, and 11 is that through time more sites are displaying warming patterns of earlier breakup, later freezeup, and increased open water season lengths, suggesting that these records provide compelling evidence that ongoing surface temperature changes have led to concomitant changes in lake and river ice phenology patterns.

SITE	α	DECADEL CHANGE
GNOTTELN	*	0.7
KRAKSTADSTJARN	**	1.1
KYRKSJON	**	0.7
NORRA LISJON	**	0.8
SÅDUGGEN	*	0.6
SILJAN (VÄSTERSJÖN)	**	0.8
SÖDRA LISJÖN	**	0.8
TINGSTÄDETRÄSK	**	0.9
VELEN	***	0.9

Table 8: Decadal trends in the open water season length for 1961-2005 at sites in southern Sweden that demonstrate a cooling trend during the 1991-2005 period. Levels of significance (α) are: *** = 0.001, ** = 0.01, * = 0.05, + = 0.1. This table shows that, despite the cooling trend during the 1991-2005 period that is observed at these sites, these trends are superimposed onto a longer-term warming trend. The positive value indicates the direction of the trend, i.e. increased length of the open water season

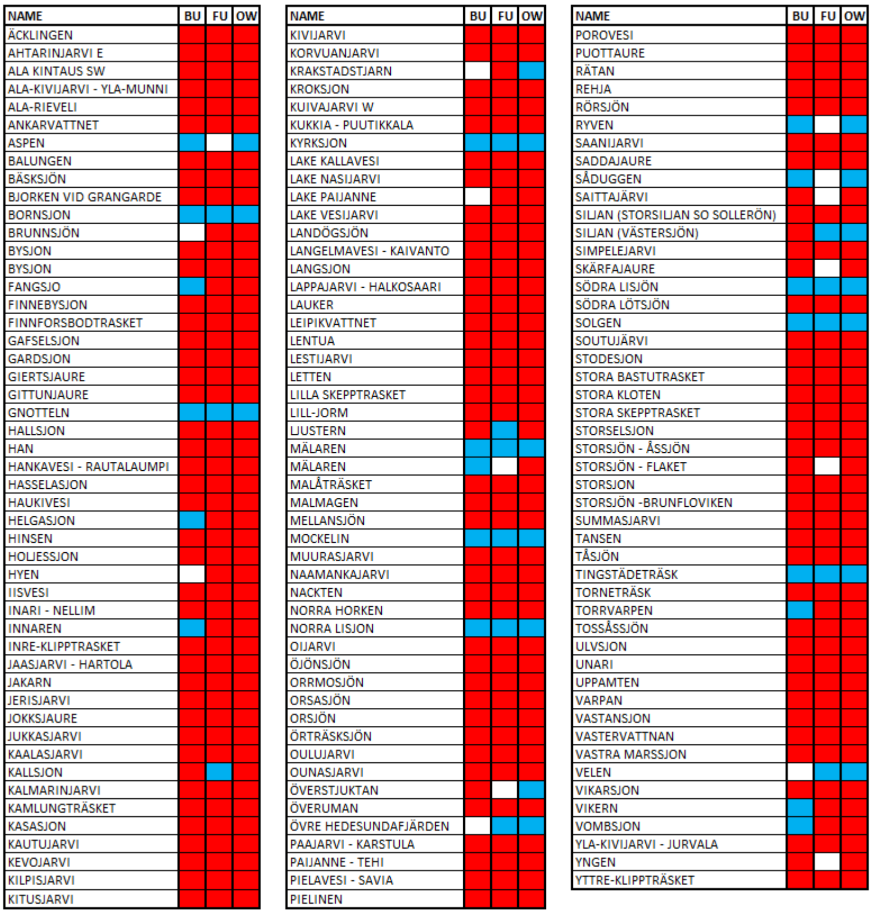

Figure 11: Comparison of how sites in Fennoscandia with an open water season calculation for the 1991-2005 time period. This reflects the relative changes in dates for breakup and freezeup. The red, blue, and white colours demonstrate whether the calculated trend reflects a warming trend (earlier breakup, later freezeup, or increased open water season), a cooling trend (opposite), or no trend, respectively. Abbreviations are: BU – breakup, FU – freezeup, and OW open water.

Thus, a red triangle symbol with a dot in the middle indicates a river site that has a statistically significant warming trend over that time period. The blue and red tones on the scales are related to cooling and warming trends, respectively. Note that in some places the symbols overlap.

Spatial patterns in the number of annual open water days from 1931-1960 (Fig. 5c) are similar to those observed for freezeup, with most sites displaying decreases (Fig. 3). Across all sites a mean reduction of 2.09 days per decade (α = 4.06) is associated with considerable variation, whilst lakes and rivers show opposing trends (Table 3). During 1946-1975 open water days (Fig. 5f) remain broadly similar to freezeup trends patterns for the same period (Fig. 5e), albeit with local-scale changes that appear to be associated with significant later breakup trends in southern Finland (Fig. 5d). The proportion of sites showing fewer open water days remains broadly the same, as do mean trend values (Fig. 3, Table 3). The increased trend magnitude for river open water days is halved compared to the previous time period, but this reflects the fact that only two river sites have data. Spatial patterns for open water days during 1961-1990 (Fig. 5i) closely resemble breakup (Fig. 5g), except for southern Finland where earlier freezeup trends (Fig. 5h) cause several sites to display fewer open water days. Most sites show an increase in open water days (Fig. 3), with a mean increase of 1.81 days per decade (α = 2.84) (Table 3). From 1976-2005, trends in the number of annual open water days are similar to breakup (Figs. 5l, 5j), with a near-uniform increase, with 50.7% of sites significant (Fig. 3). A minority of sites showing fewer open water days have breakup and freezeup dates becoming earlier during the time period – i.e. earlier freezeup trends are strong enough to reduce the open water season. Earlier breakup and later freezeup trends lead to a mean increase in open water days of 6.30 days per decade (α = 4.22) (Table 3), with the trend being considerably stronger for lakes than for rivers.

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3.4. Russia

~~The sparse availability of Russian data means that broad spatiotemporal trends are not possible. Only a few sites with breakup, freezeup, or open water data are covered by both the 1931-1960 and 1961-1990 periods. During 1991-2005 data are only available for Lake Baikal, which is discussed above and displayed on Fig. 3. Sites with data available for 1931-1990 periods generally show trends towards later breakup during 1931-1960 of 0.8 days decade^{-1} that have changed towards earlier breakup of 0.8 days decade^{-1} from 1961-1990 (Table 2 and 9; Figs. 12a, 12b). However, the limited spatiotemporal availability of the data make any inferences somewhat spurious on a large scale. Freezeup trends show a similar switch from earlier freezeup trends of 0.8 days decade^{-1} in the earlier time period to either later freezeup trends or no trends in the latter period (Table 2 and 9; Figs. 12c, 12d).~~

	BREAKUP		FREEZEUP		OPEN WATER	
SITE	1931-60	1961-90	1931-60	1961-90	1931-60	1961-90
LAKE BAIKAL	1.1	0.0	-1.8	3.0	-2.1	3.3
LAKE BAYKAL (P.BUKHTA)	-0.6	-0.9	2.5	-2.1	3.3	-1.7
LAKE KUBENSKOYE (PESKI)	1.4	-1.2	-3.9	0.0	-5.8	1.5
LAKE LATCHA	0.6	-1.5	-3.0	-2.8	-4.4	-2.3
LAKE SENEZHSKOYE	-	-	-3.3	0.0	-	-
LAKE TELETSKOYE	1.7	-2.0	-2.0	1.9	-3.3	3.6

Table 9: Summary statistics sites across Russia with data available for more than one time period. The red and blue colouring indicates whether the decadal trend is a warming or cooling trend, respectively.

Only five sites have sufficient data to generate the open water season and it demonstrates a mixed climate signal. From 1931-1960 the majority of sites display increased ice season length due to both later breakup and earlier freezeup (Table 9). During 1961-1990 most sites show an increased open water season length due to earlier breakup and later freezeup. However, this is not the case for all sites as two sites demonstrating earlier freezeup trends for 1961-1990 have a larger magnitude of change than earlier breakup trends (Table 9). This means that whilst breakup is becoming earlier, freezeup is also becoming earlier but at a faster rate, resulting in an increase in the ice season. Data for 1991-2005, and therefore the full 1931-2005 time period, are only available for Lake Baikal (Fig. 13; Table 9). This shows that the breakup date occurred earlier over the course of the 1931-1960 and 1991-2005 periods, with the intervening 1961-1990 period demonstrating no trend. Freezeup data for 1991-2005 show a trend towards later freezeup of 5.0 days decade^{-1}. This site shows large variability in breakup/freezeup through each of the time periods, resulting in fluctuations in the length of the open water season through time, with the 1991-2005 period showing a reduction in the number of open water days.

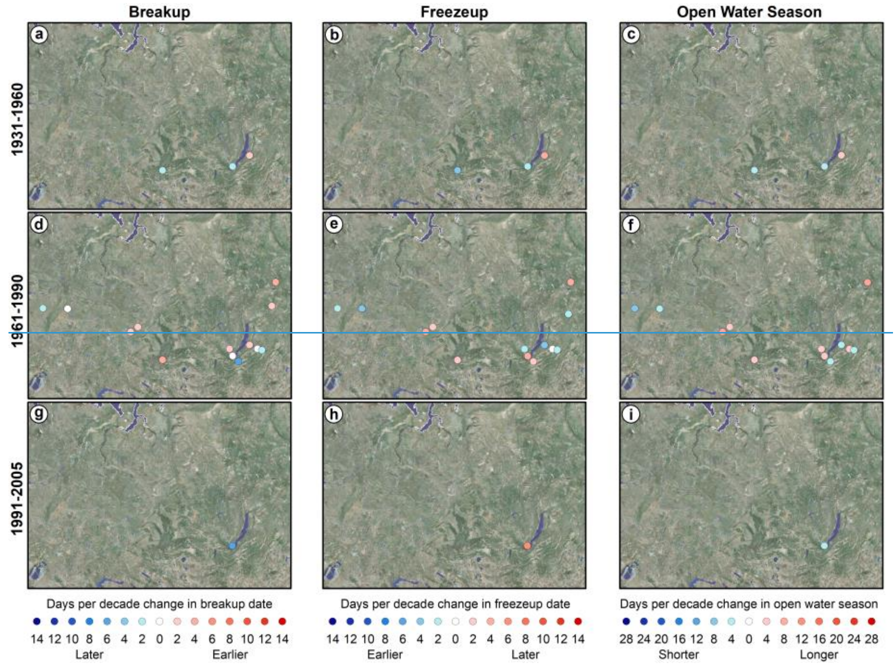


Figure 12: Decadal trends for breakup (**a**, **d**, and **g**), freezeup (**b**, **e**, and **h**), and length of the open water season (**c**, **f**, and **i**) in Russia for the three individual time periods. Blue and red tones on the scales related to cooling and warming signals inferred from changes in the open water season length, respectively.

3.5. Sites with continuous data – 1931-2005

3.5.1. Breakup

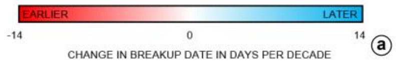
Decadal changes in breakup dates for each site with data for 1931-2005 suggest large-scale and broadly uniform hemispheric changes (Fig. 13a). From 1931-1960 period there is considerable heterogeneity in the decadal changes that have been observed, but by 1961-1990 the response becomes considerably more homogenous as more sites demonstrate earlier breakup trends. In the 1991-2005 period there is an increase in the magnitude of the warming trends for the vast majority of sites (Fig. 13a) – i.e. a general ramping up in the magnitude of warming trends through time. During each of the latter two periods the dominant trend toward warming is, however, not reflective of all sites. Indeed, a number of sites, such as Ponkapoag Pond in North America and Såduggen in Fennoscandia, demonstrate a high magnitude decadal change towards a later breakup date that is out of synchrony with the patterns observed in the preceding time periods – highlighting a temporally complex response. It is notable at these sites that despite these fluctuations there is a longer-term shift towards earlier breakup dates at both sites – i.e. short-term trends superimposed on to longer term trends.

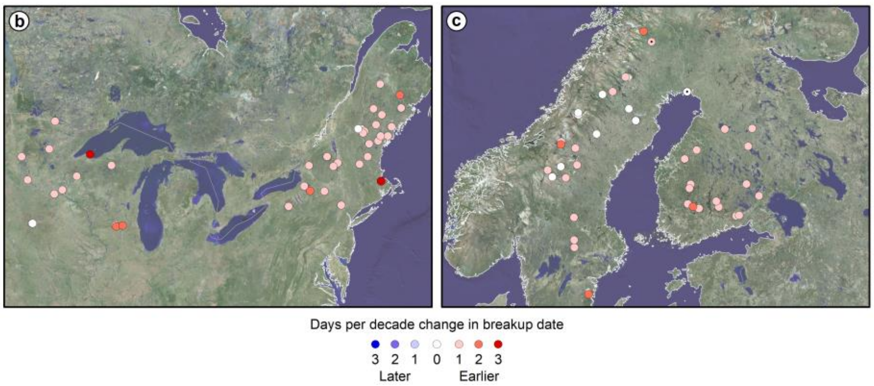
When the decadal trends for all 88 sites are plotted for 1931-2005 the majority (84%) demonstrate earlier breakup decadal trends. The remaining sites suggest no trend in decadal change for breakup dates, whilst none suggest that breakup dates became later. For the 44 North American sites that cover 1931-2005, 42 of them display earlier breakup trends with a mean of 0.7 days decade^{-1}. The other two sites display no clear decadal trend. Across Fennoscandia there are 43 sites with continuous data covering 1931-2005. Whilst these sites are generally restricted to the southern part of Finland, in Sweden they cover a full transect across the length of the country. Of these 43 sites, none show a trend towards later breakup dates, 11 show no trends, and the rest are showing earlier breakup. Broadly across Fennoscandia there is a shift toward earlier breakup dates of 0.5 days decade^{-1}.

NORTH AMERICA				
STUDY SITE	1931-60	1961-90	1991-05	1931-05
AZISCOHOS LAKE	-0.6	-4.2	-1.7	-0.3
BLACK OAK LAKE	-0.8	-1.3	-6.4	-0.5
BONAPARTE	-1.7	-5.0	-0.9	-0.6
CAZENOVIA	0.0	-5.7	-4.4	-1.2
COBBOSSEECONTEE LAKE	-0.9	-4.3	0.0	-0.9
DAMARISCOTTA LAKE	-0.6	-5.7	-2.2	-0.8
DETROIT	1.8	-1.9	0.0	-0.5
EAST OKOBOJI LAKE	5.4	-5.3	-2.9	0.0
EMBDEN POND	0.0	-3.8	-6.3	-0.3
FIRST CONNECTICUT LAKE	-1.3	-2.9	-6.7	0.0
GEORGE	-1.4	-2.9	1.1	-0.5
HOUGHTONS (HOOSICWHISICK) POND	-8.3	-7.5	1.3	-1.4
KEZAR LAKE	-1.4	-2.9	-5.0	-0.6
LAKE AUBURN	-0.6	-4.3	1.1	-1.0
LAKE MENDOTA	2.5	-4.3	0.0	-0.9
LAKE MONONA	0.0	-2.5	-7.1	-1.4
LAKE SUPERIOR AT BAYFIELD	-2.6	-2.1	-3.3	-2.0
LAKE WINNIPESAUKEE	-1.0	-2.5	1.7	-0.2
LOON	4.1	-5.0	-2.3	-0.7
MARANACOOK LAKE	0.0	-4.3	4.3	-0.7
MINNETONKA	1.0	-2.5	-2.5	-0.7
MINNEWASKA	3.1	-1.7	-3.3	-0.3
MIRROR	-0.6	-3.1	-3.6	-0.3
MOHONK	-0.8	-5.6	2.0	-0.6
MOOSEHEAD LAKE	0.0	-3.3	-4.0	-0.2
ONEIDA	1.1	-3.3	-2.2	-0.2
OTSEGO	0.0	-7.3	0.0	-0.7
PLACID	-1.4	-3.3	-5.0	-0.5
PONKAPOAG POND	-11.5	-10.0	6.3	-2.6
PORTAGE LAKE	0.0	-3.8	-3.8	-0.6
RAINY	0.0	-3.0	-2.7	-0.8
RICHARDSON LAKE	-1.1	-2.7	-3.8	-0.1
ROCK LAKE	3.2	-4.3	1.4	-1.2
SCHROON	-1.4	-3.3	-1.1	-0.9
SEBEC LAKE	0.0	-2.7	-6.3	-0.4
~~SHELL LAKE~~	~~0.0~~	~~-1.3~~	~~-6.7~~	~~-0.6~~
SKIFF LAKE	-1.2	-3.3	-4.4	-1.0
SUNAPEE LAKE	-0.6	-4.7	0.0	-0.8
SWAN LAKE	0.0	-5.7	2.0	-0.6
UMBAGOG LAKE	-1.1	-2.8	-5.6	-0.3
VERMILION	0.9	-2.6	-4.2	-0.2
WEST GRAND LAKE	0.0	-3.8	-5.0	-0.3
WEST OKOBOJI LAKE	6.0	-3.8	-6.9	-0.3
WHITE BEAR	1.4	-2.9	1.4	-0.2

RUSSIA				
STUDY SITE	1931-60	1961-90	1991-05	1931-05
LAKE BAIKAL	1.1	0.0	5.0	0.0

FENNOSCANDIA				
STUDY SITE	1931-60	1961-90	1991-05	1931-05
ÄCKLINGEN	0.9	1.0	-7.5	-0.3
ALA-KIVIJARVI - YLA-MUNNI (1489)	1.2	-0.6	-7.5	-0.5
ALA-RIEVELI	0.4	-0.6	-3.3	-0.6
ANKARVATTNET	0.0	0.5	-5.6	0.0
BALUNGEN	1.7	0.0	-8.3	0.0
DAMMSJON	0.0	0.0	-2.5	-0.5
GIERTSJAURE	-0.8	0.0	-7.1	-0.4
HAUKIVESI	0.0	-0.8	-1.4	-0.6
INRE-KLIPPTRASKET	0.0	0.0	-6.7	0.0
JAASJARVI SW	0.0	-0.6	-5.0	-0.8
JUKKASJARVI	-1.0	-3.8	-4.3	-0.4
KALLSJON	1.3	-0.8	-14.0	-1.1
KITUSJARVI (3548)	-1.9	-1.4	-5.7	-0.8
KUKKIA - PUUTIKKALA (3512)	0.4	-1.1	-4.3	-0.8
LAKE NASIJARVI	1.0	0.0	-1.5	-0.8
LANDÖGSJÖN	-2.1	0.0	-9.2	-0.2
LANGELMAVESI - KAIVANTO (3506)	-1.0	-1.4	-2.5	-1.1
LAPPAJARVI - HALKOSAARI (4703)	-0.7	-0.5	-5.0	-0.9
LEIPIKVATTNET	0.0	2.0	-7.8	0.0
LEJ DA SAN MUREZZAN	-2.9	1.1	0.0	-0.2
LENTUA	-1.1	-2.0	-5.0	-1.0
LESTIJARVI	-1.5	-0.5	-3.3	-0.8
LILLA SKEPPTRASKET	0.0	-1.2	-8.6	0.0
MALMAGEN	-0.8	-1.1	-6.7	-0.7
NACKTEN	-0.2	-0.9	-7.5	-0.4
NORRA HORKEN	0.4	-1.0	-8.8	-0.7
OULUJARVI	-2.4	-2.0	-6.0	-1.0
ÖVERSTJUKTAN	0.6	0.0	-5.6	0.0
PIELINEN	-2.5	-2.3	-3.3	-0.8
RIVER TORNIONJOKI	-0.5	-2.6	0.0	-0.3
SADDAJAURE	-0.4	-3.0	-10.0	-0.7
SÅDUGGEN	1.4	0.0	7.5	-1.5
SILJAN	0.9	-1.3	-3.6	-0.8
SIMPELEJARVI	0.0	-1.3	-3.0	-0.9
STORSJON	0.0	-0.5	-5.4	0.0
~~TÅSJÖN~~	~~0.0~~	~~0.0~~	~~-10.0~~	~~0.0~~
TORNEÄLVEN VID HAPARANDA	-1.0	-2.5	-2.0	0.0
TORNETRÄSK	-2.1	-3.8	-10.0	-1.2
VASTERVATTNAN	1.9	-1.5	-6.0	0.0
VIKARSJON	0.7	-1.7	-7.5	-0.4
VISUVESI	-1.4	0.0	-6.3	-0.7
YLA-KIVIJARVI - JURVALA	0.8	0.0	-5.0	-0.3
YTTRE-KLIPPTRÄSKET	-1.3	-1.2	-7.7	0.0





~~**Figure 13**: Summary of evidence for the long-term breakup date trends for the 1931-2005 period: **a**) heat table demonstrating the decadal change for each site during each time period. The colouring of each cell shows the relative magnitude of that change compared to other sites and time periods; **b-c**) spatial pattern of the decadal trends~~

for North America and Fennoscandia during the 1931-2005 time period. Two sites are not displayed on the maps: Lej da San Murezzan (location shown on Fig. 1a) and Lake Baikal (location Fig. 12a).

In Fennoscandia, during the earliest two time periods the magnitude of earlier river breakup dates was shown to be larger than for lakes until the final 1991-2005 period. When these individual trends are explored for 1931-2005 it can be shown that on a longer timescale lakes experienced a greater change in breakup dates, on average 0.6 days decade^{-1} earlier, compared to 0.2 days decade^{-1} earlier for rivers. Whilst acknowledging the caveats of a limited number of sites, the above evidence suggests that during the early and middle part of the 20th century rivers were responding to increased surface air temperatures faster than lakes. This may be explained, possibly, by the river flow gradient causing waves and ripples which instigates air turbulence and greater interaction of water and air causing a faster transfer of atmospheric heat. Whilst ripples and waves do form on still water bodies, this is likely limited compared to actively flowing rivers, causing a slower response time in lake temperatures to air temperature increases. As the lakes gradually experience this warming the same reasons may also restrict heat exchange from the lake to the atmosphere. Though the physics require further study, it is possible this thermal legacy allowed lakes to gradually become a heat sink and might explain why over longer timescales the lakes begin to demonstrate larger changes than for rivers.

In Russia only Lake Baikal has data for 1931-2005, which shows no trend in the breakup date. Lake Baikal has been the focus of other studies investigating changes in ice phenology at timescales over 100 years. This showed that breakup was occurring earlier by 5.1-5.2 days century^{-1} (Livingstone, 1999; Magnuson et al., 2000b). Through different parts of these time series it has been shown that the magnitude of change varied by as much as 30 days century^{-1} but this was not sustained through the duration of the time period (Livingstone, 1999; Magnuson et al., 2000b).

3.5.2. Freezeup

Decadal trend changes for the 48 sites with freezeup dates for 1931-2005 show a less clear picture compared to breakup (Fig. 14a). From 1931-1960 there is a mixed pattern with most sites displaying either a warming or cooling trend in the date of freezeup. When this is compared to 1961-1990 there is similar dichotomy in the patterns observed, albeit with a small reduction in the number of sites with cooling decadal change (down from 28 sites during 1931-1960 to 23 sites during 1961-1990). For many of sites, particularly those that had a cooling pattern from 1931-1960, the magnitude of the cooling decadal change is reduced during 1961-1990. From 1991-2005 there is a clear increase in the number and magnitude of warming trends. The decadal trends for 1931-2005 do not display any clear spatial pattern (Fig. 14a). Of the sites available with 1931-2005 freezeup dates, 17 show a cooling and 22 a warming decadal trend, with the rest displaying no trend. It is noticeable that when the decadal patterns are considered on longer timescales, the magnitude of the trends are also considerably reduced when compared to each of the three shorter time periods. Sites with a decadal trend value between 1 and -1 days decade^{-1} account for ~73% of the sites – thus, highlighting that freezeup trends are clearly more complex than those observed for breakup.

Russia is limited to just the site at Lake Baikal, which trends towards later freezeup of 1.0 days decade^{-1}, showing a gradual switch from cooling conditions to warmer conditions that increases in magnitude through time (Fig. 14). In North America, whilst a majority of sites display a warming decadal trend for the freezeup dates during the 1931-2005 period, owing to the limited number of sites and their wide geographical spread it is impossible to draw any clear conclusions (Fig. 14b). Long-term trends across North America are restricted to nine sites around the Great Lakes. Of these sites, seven display long-term warming trends towards later freezeup, whilst West and East Okoboji Lake demonstrate no trend and a cooling trend, respectively (Fig. 14). The trends at both of these sites have shown a gradual transition from earlier freezeup to later freezeup. At East Okoboji Lake this progression toward later freezeup is reflected in the long-term trends discussed above for 1961-2005 (Table 3). Thus, it is likely that the large magnitude trend towards earlier freezeup experienced in the 1931-1960 is perhaps large enough to skew the trend in a direction that is not representative of the more recent changes at the study site. The same can be said of West Okoboji Lake where freezeup dates have become later.

NORTH AMERICA

STUDY SITE	1931-60	1961-90	1991-05	1931-05
CAZENOVIA	4.0	0.5	3.8	1.1
EAST OKOBOJI LAKE	-4.5	-2.5	15.0	-0.3
LAKE MENDOTA	-0.7	1.2	8.0	0.9
LAKE MONONA	1.0	0.0	-2.2	1.3
LAKE SUPERIOR AT BAYFIELD	2.1	0.4	15.0	2.5
MIRROR	1.7	1.2	11.3	0.7
PLACID	3.1	0.0	-5.7	0.2
SHELL LAKE	0.8	0.0	10.0	1.3
WEST OKOBOJI LAKE	-3.3	-1.6	2.9	0.0

RUSSIA

STUDY SITE	1931-60	1961-90	1991-05	1931-05
LAKE BAIKAL	-1.8	3.0	5.0	1.0

FENNOSCANDIA

STUDY SITE	1931-60	1961-90	1991-05	1931-05
ALA KINTAUS SW	-5.6	-0.5	15.0	-1.5
ALA-KIVIJARVI - YLA-MUNNI	-2.6	-2.2	9.0	-0.9
ALA-RIEVELI	-4.7	-2.5	18.6	-1.0
ANKARVATTNET	0.0	1.9	19.2	0.0
BALUNGEN	1.9	-0.8	6.7	0.0
GIERTSJAURE	-0.8	-1.8	6.0	0.0
HAUKIVESI	-2.6	-1.3	8.0	-0.8
JAASJARVI SW	-3.0	-1.5	10.0	0.0
JAKARN	-3.1	2.0	7.7	0.7
JUKKASJARVI	0.6	1.4	12.9	1.4
KALLSJON	-0.7	-2.0	-4.3	0.6
KAMLUNGTRÄSKET	3.5	0.0	11.1	0.0

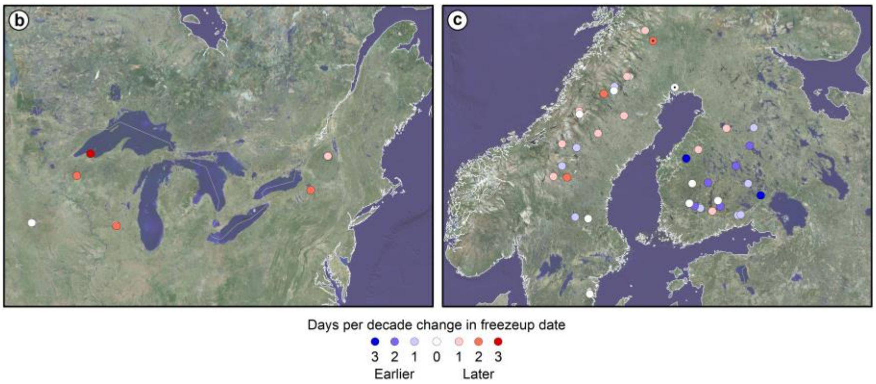
FENNOSCANDIA

STUDY SITE	1931-60	1961-90	1991-05	1931-05
KITUSJARVI	2.4	-5.9	20.0	0.0
KUKKIA - PUUTIKKALA	-7.5	1.7	15.6	-0.9
LAISAN	-0.9	0.7	8.0	-0.9
LAKE KALLAVESI	-8.3	-2.1	13.3	-1.2
LAKE NASIJARVI	-4.2	-2.0	11.0	0.0
LAKE PAIJANNE	-5.3	-1.9	8.6	0.2
LANDÖGSJÖN	-5.0	-0.8	2.0	-0.5
LANGELMAVESI - KAIVANTO	-5.9	-0.7	8.9	-1.7
LAPPAJARVI - HALKOSAARI	-6.7	0.0	13.0	-2.0
LEIPIKVATTNET	2.4	2.0	10.0	0.7
LENTUA	-3.8	-0.6	15.5	-0.9
LESTIJARVI	0.0	1.7	6.7	0.5
OULUJARVI	-0.8	-2.1	14.4	0.2
ÖVERSTJUKTAN	3.3	2.0	0.0	1.4
PIELINEN	-6.5	-1.3	6.3	-1.1
RÖRSJÖN	2.3	0.0	5.0	0.6
SADDAJAURE	0.0	0.2	5.4	0.6
SÅDUGGEN	1.6	-2.1	0.0	0.0
SILJAN	-0.8	3.8	18.8	-0.6
SIMPELEJARVI	-1.2	-3.3	6.7	-3.0
STORSJON	-1.7	0.0	10.0	-0.2
TÅSJÖN	4.4	0.0	10.0	0.4
TORNETRÄSK	-2.2	-0.9	1.1	0.3
VASTERVATTNAN	0.0	4.8	12.7	0.6
VIKARSJON	4.6	6.9	2.0	1.9
YLA-KIVIJARVI - JURVALA	-1.3	-0.8	17.5	-0.5

LATER — EARLIER

20 0 -20

CHANGE IN FREEZEUP DATE IN DAYS PER DECADE (a)



~~**Figure 14**: Summary of evidence for the long-term freezeup date trends for the 1931-2005 period: a) heat table demonstrating the decadal change for each site during each time period. The colouring of each cell shows the relative magnitude of that change compared to other sites and time periods; b-c) spatial pattern of the decadal trends for North America and Fennoscandia during 1931-2005. One site is not displayed on the maps, Lake Baikal, which is located on Fig. 12a.~~

~~In Fennoscandia, there are 38 sites with data for 1931-2005 that show a somewhat varied pattern (Fig. 6h and 14). A total of 16 sites display earlier freezeup trends that are concentrated in southern Finland. There are 14 sites displaying trends towards later freezeup that are primarily concentrated along the western margin of Sweden. Eight~~

sites display no trends at all. This heterogeneous pattern is markedly different to breakup trends (Fig. 13) and is perhaps not surprising given the conditions that are required for ice crystal formation. Thus, breakup is dominated by thermal characteristics of the climate whilst freezeup is a result of not just the thermal properties of the environment but also water kinetics. This likely explains why the breakup and freezeup patterns do not simply reflect observed increases in air temperatures.

3.5.3. Open water season

The decadal patterns for the number of annual open water days from 1931-1960 generally indicate a reduced open water season (Fig. 15a). However, by 1961-1990 a systematic change causes the majority of sites (~73%) to display an increase in the number of annual open water days. This swing from cooling patterns to warming patterns is typically of an order of several days per decade. By 1991-2005 the number of sites with an increased open water season increases to 93%. As the number of open water days encapsulates the relative changes in breakup/freezeup dates, the increased magnitude shown above for breakup/freezeup (Figs 13a, 14a) is also captured in the open water season length, with many sites demonstrating an order of magnitude increase in the warming trend (Fig. 15a).

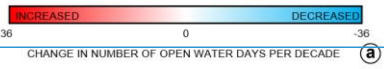
For 1931-2005 the longer-term record shows that warming decadal trends account for 23 of the 37 sites. All of the sites displaying a cooling trend for 1931-2005 show that in the shorter time periods that comprise this longer-term record there is common pattern where cooling trends in the 1931-1960 period reduce in magnitude during the 1961-1990 period, before reversing and becoming strong warming trends in the 1991-2005 period. As with the patterns described above for freezeup, the limited availability of sites in North America make it impossible to discern any spatial patterns (Fig. 15b). In Fennoscandia, similar to freezeup, there appears to be variability in warming and cooling trends (Fig. 15c).

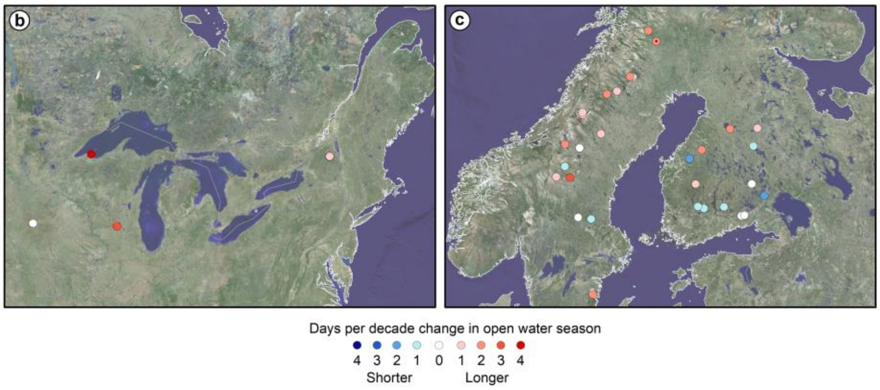
NORTH AMERICA				
STUDY SITE	1931-60	1961-90	1991-05	1931-05
EAST OKOBOJI LAKE	-11.7	1.5	18.3	0.0
LAKE MENDOTA	-5.5	6.0	7.5	1.4
LAKE MONONA	-1.7	1.8	5.0	2.3
LAKE SUPERIOR AT BAYFIELD	2.2	2.2	15.7	3.8
MIRROR	2.6	4.6	10.0	1.3
PLACID	3.9	3.0	1.8	1.0
WEST OKOBOJI LAKE	-10.0	1.9	10.0	0.7

RUSSIA				
STUDY SITE	1931-60	1961-90	1991-05	1931-05
LAKE BAIKAL	-2.1	3.3	-2.0	1.5

FENNOSCANDIA				
STUDY SITE	1931-60	1961-90	1991-05	1931-05
ALA-KIVIJARVI - YLA-MUNNI	-5.0	0.5	14.5	0.0
ALA-RIEVELI	-4.1	-1.0	15.0	-0.3
ANKARVATTNET	0.0	2.3	25.0	0.2
BALUNGEN	-1.1	-1.2	10.0	-0.3
GIERTSJAURE	-0.4	-3.3	8.9	0.3
HAUKIVESI	-2.2	1.0	5.0	0.0
JUKKASJARVI	1.0	3.1	14.5	1.6
KALLSJON	-2.0	0.7	18.8	1.5
KITUSJARVI	4.4	-5.0	28.0	0.5

FENNOSCANDIA				
STUDY SITE	1931-60	1961-90	1991-05	1931-05
KUKKIA - PUUTIKKALA	-8.8	3.3	20.9	-0.3
LANDÖGSJÖN	-2.3	0.0	6.7	0.0
LANGELMAVESI - KAIVANTO	-4.4	2.4	12.2	-0.3
LAPPAJARVI - HALKOSAARI	-7.1	0.6	12.9	-1.3
LEIPIKVATTNET	2.8	1.2	19.0	0.7
LENTUA	-1.5	1.3	16.7	0.4
LESTIJARVI	1.1	2.7	10.0	1.1
OULUJARVI	0.8	0.6	19.1	1.1
ÖVERSTJUKTAN	2.5	3.3	-0.4	1.5
PIELINEN	-5.5	0.0	10.0	-0.4
SADDAJAURE	0.0	2.8	11.7	1.3
SÅDUGGEN	-0.7	-2.5	-12.0	1.4
SILJAN	-0.4	6.7	35.5	0.0
SIMPELEJARVI	-1.6	-1.5	16.7	-1.9
STORSJON	-3.3	0.0	20.0	-0.4
TÅSJÖN	3.0	0.7	22.5	0.6
TORNETRÄSK	0.0	1.8	18.0	1.5
VASTERVATTNAN	-2.5	6.3	15.0	0.6
VIKARSJON	3.9	8.1	20.0	2.2
YLA-KIVIJARVI - JURVALA	-1.5	0.0	20.0	0.0





~~**Figure 15**: Summary of evidence for the long-term trends in the number of open water days each year for the 1931-2005 period: a) heat table demonstrating the decadal change for each site during each time period. The colouring of each cell shows the relative magnitude of that change compared to other sites and time periods; b-c) spatial pattern of the decadal trends for North America and Fennoscandia during 1931-2005. One site is not displayed on the maps, Lake Baikal, which is located on Fig. 7a.~~

~~Across the full 1931-2005 time period it is clear there is a long-term increase in the number of open water days per year at Lake Baikal in Russia (Fig. 15a). In North America, the number of sites with breakup/freezeup data for 1931-2005 is restricted to only seven sites (Fig. 15b) with a mean value of 1.5 days decade^{-1} more open water days~~

(Table 2). The long-term trends demonstrate a consistent pattern of both earlier breakup and later freezeup, resulting in a lengthening of the open water season (Fig. 5). Only East Okoboji Lake shows a different pattern, where there is no clear observable trend in the length of the open water season, despite the freezeup date becoming earlier during this period. This clearly reflects the earlier freezeup trends of 0.3 days decade^{-1} is not large enough to result in a significant shift in the length of the open water season.

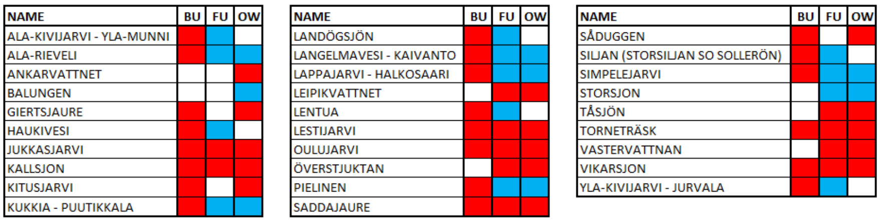


Figure 16: Comparison of how sites in Fennoscandia with an open water season calculation for the 1931-2005 time period. This reflects the relative changes in dates for breakup and freezeup. The red, white, and blue colours demonstrate whether the calculated trend reflects a warming trend (earlier breakup, later freezeup, or increased open water season), a cooling trend (the opposite), or no trend, respectively. Abbreviations are: BU – breakup, FU – freezeup, and OW open water.

During 1931-2005 in Fennoscandia there is considerable spatial variability with no clear trends, except for a slight tendency for sites in Sweden to display increased open water season lengths compared to Finland, which shows a reduction (Fig. 15c). This variability is reflected by the low magnitude of the mean decadal change of 0.4 days decade^{-1} increase open water season length (Table 2). It is notable that on this longer time scale that none of the sites show later breakup, with the vast majority showing a warming signal of earlier breakup (Fig. 16). As a consequence, most of the sites showing a reduction in the length of the open water season do so because trends for earlier freezeup are larger than those for earlier breakup. This suggests that not only is there a change in the precise length of the open water season, but there is a shift in when it occurs. This is also the case for several sites, such as Haukivesi (Fig. 16), that show both earlier breakup and freezeup, so although there is no change in open water season length, there is change in when it occurs – potentially having implications for biogeochemical cycles.

In Russia there are only a few sites across the four 30-year time periods with breakup, freezeup, or open water day data, with the 1976-2005 time period only having one site at Lake Baikal (Table 2). The majority of the data are clustered in northwest Russia, with a number of individual sites spread out across the Kazakhstan border region and around Lake Baikal in the east (Fig. 6). The lack of spatiotemporal consistency makes it difficult to determine any prevailing trends. Broadly there is a reduction in the number of sites displaying later breakup dates through time (Fig. 3), as is also reflected by the changes in mean breakup date from 0.83 days per decade ($\alpha = 0.79$) later in 1931-1960 to 0.83 days per decade ($\alpha = 1.83$) earlier from 1961-1990 (Table 3), albeit with the latter associated with more variability. For breakup trends, in the northwest there are two sites with continuous data across the first three time periods (Fig. 6a, 6d, 6g) and these show a gradual change from later to earlier breakup through time. The adjacent sites in this area also show a tendency for earlier breakup dates during these time periods. The border region sites generally display earlier breakup dates, many of which are statistically significant during the 1946-1975 time period. Around Lake Baikal there is considerable variation between different sites, with no dominant trends, even for the one continuous site through all four 30-year time periods (Fig. 6j).

Between the four 30-year time periods, sites with freezeup data covering at least two time periods demonstrate considerably more variation than breakup (Fig. 6b, 6e, 6h). Between different time periods the freezeup dates for the same sites can move in opposing directions, and in some cases, such as in the Kazakhstan border region, these freezeup date changes have been significant. Long-term there is an apparent reduction in the number of sites displaying earlier freezeup trends (Fig. 3), but this is caveated by the low number of sites with data and the much larger standard deviations associated with decadal trends (Table 3). Changes in the number of annual open water days across Russia capture a slightly more consistent pattern compared to changes in breakup and freezeup dates, but it remains spatially chaotic, with no dominant spatial patterns observable (Fig. 6c, 6g, 6i). In all three regions, northwest Russia, the Kazakhstan border region, and around Lake Baikal there is a shift through time for most sites with continuous data to display more annual open water days per decade, a number of which are statistically significant (Fig. 3). However, these values are again associated with considerable variation around what is generally a low magnitude decadal mean (Table 3). The one site with continuous data through all four time periods, Lake Baikal, shows a gradual switch from fewer annual water days during the first time period, to no observable trend, before demonstrating more open water days in the final two time periods, suggesting a gradual warming signal.

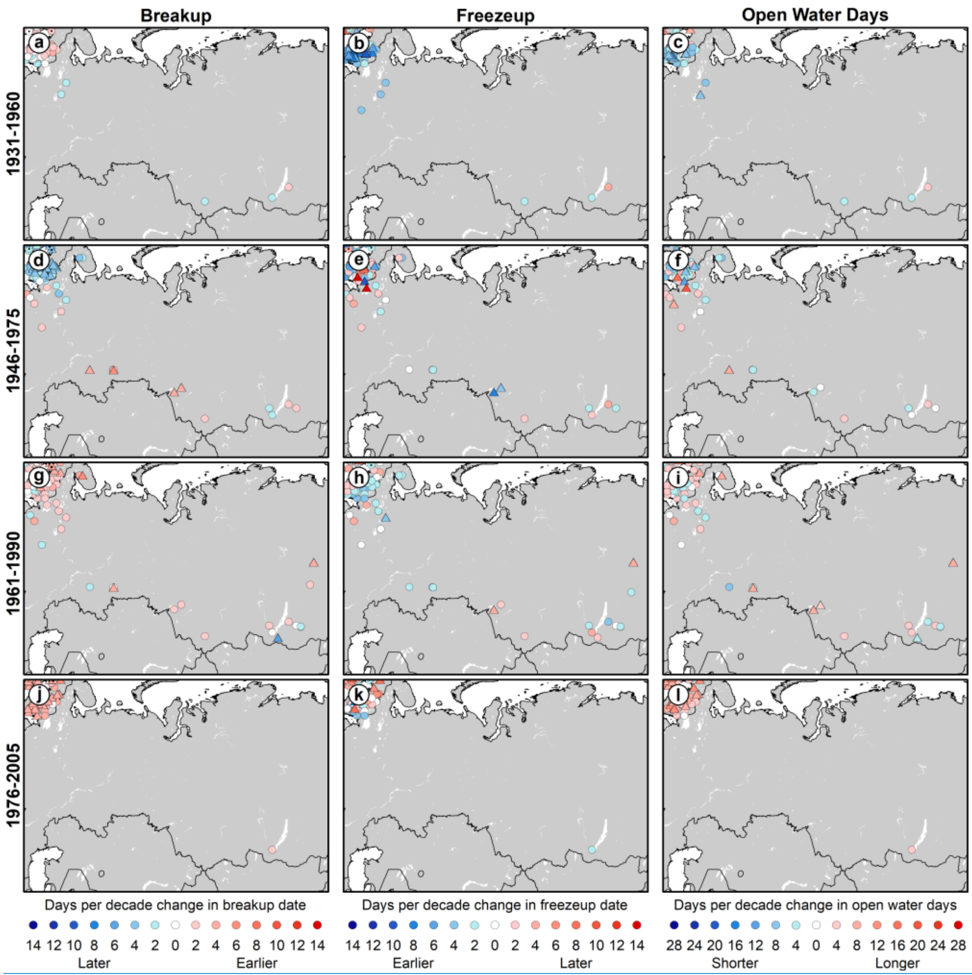
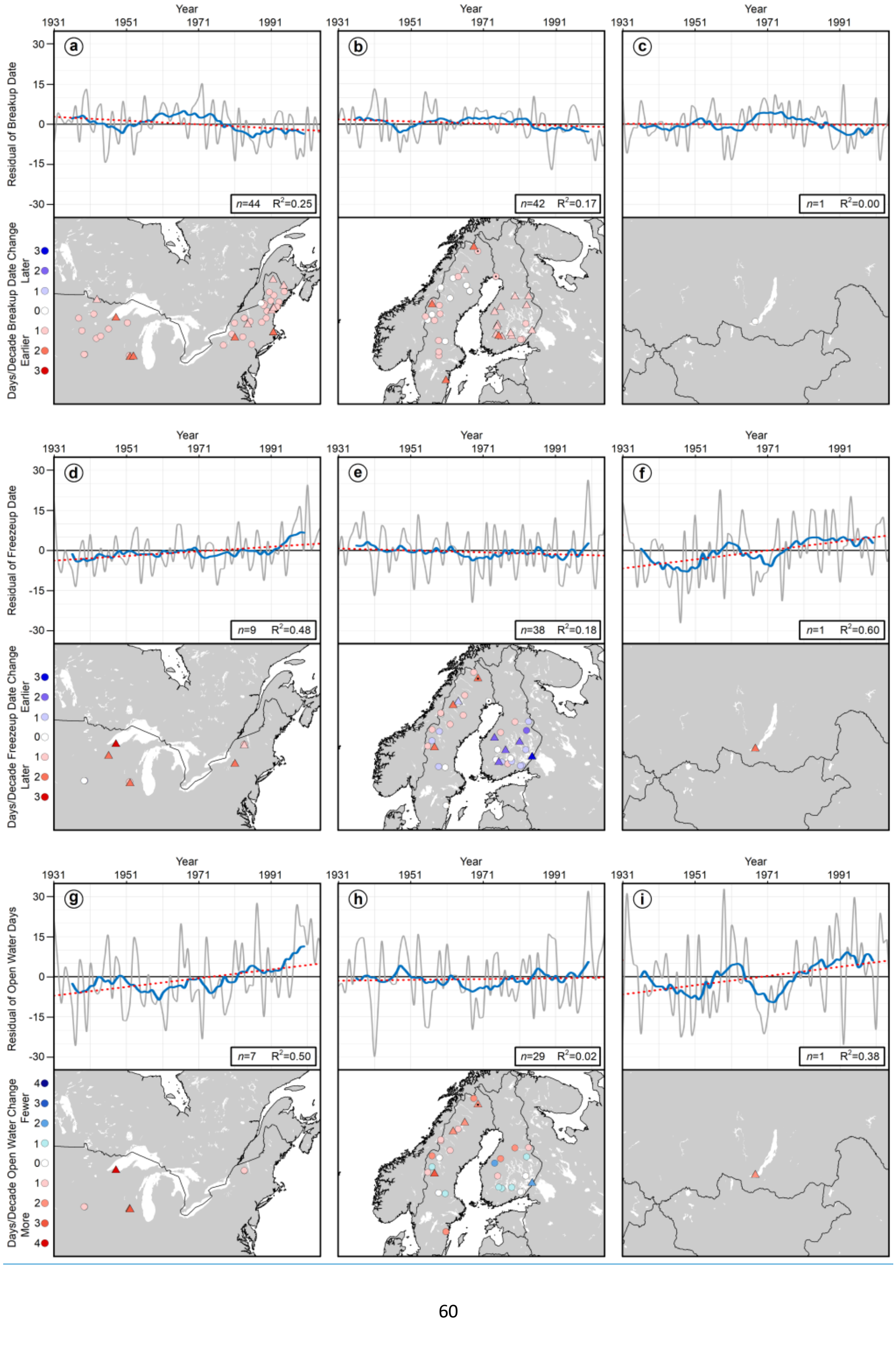


Figure 6: Decadal trends for breakup (**a**, **d**, **g**, and **j**), freezeup (**b**, **e**, **h**, and **k**), and the number of annual open water days (**c**, **f**, **i**, and **l**) in Russia for the four individual time periods. The trend directions and magnitudes were derived from the Mann-Kendall and Sen's Slope tests. The triangles and circles indicate whether the trend was or was not statistically significant. Sites with a dot in the centre of the circle are river sites. Thus, a red triangle symbol with a dot in the middle indicates a river site that has a statistically significant warming trend over that time period. The blue and red tones on the scales are related to cooling and warming trends, respectively. Note that in some places the symbols overlap.



Year
1931
1951
1971
1991
a
b
c
d
e
f
g
h
i
Residual of Breakup Date
Residual of Freezeup Date
Residual of Open Water Days
30
15
0
-15
-30
n=44 R2=0.25
n=42 R2=0.17
n=1 R2=0.00
n=9 R2=0.48
n=38 R2=0.18
n=1 R2=0.60
n=7 R2=0.50
n=29 R2=0.02
n=1 R2=0.38
Days/Decade Breakup Date Change
Later
Earlier
Days/Decade Freezeup Date Change
Earlier
Later
Days/Decade Open Water Change
Fewer
More

Figure 7: The graphs show the annual residuals (grey) with an 11-year running mean (blue) for ice breakup (**a-c**), freezeup (**d-f**), and number of annual open water days (**g-i**) across the three regions of study. The dashed red line shows the linear trend for the 11-year running mean and is associated with the labelled R^2 values. The associated maps show the decadal trends for breakup (**a-c**), freezeup (**d-f**), and the number of annual open water days (**g-i**). The trend directions and magnitudes were derived from the Mann-Kendall and Sen's Slope tests for the full 1931-2005 time period. The triangles and circles indicate whether the trend was or was not statistically significant. Sites with a dot in the centre of the circle are river sites. Thus, a red triangle symbol with a dot in the middle indicates a river site that has a statistically significant warming trend from 1931-2005. The blue and red tones on the scales are related to cooling and warming trends, respectively. Note that in some places the symbols overlap.

3.5. Sites with continuous data – 1931-2005

Data covering the full 1931-2005 time period in North America are clustered around the Great Lakes region. Over this period mean breakup dates became earlier by 0.66 days per decade (α = 0.50) (Table 3), with 66% of sites displaying earlier breakup trends and 29.5% showing significant earlier breakup dates. No dominant spatial patterns are observed, with earlier breakup dates observed across the entire Great Lakes region, except for two sites displaying no trend (Fig. 7a). The extent of sites with freezeup data limits spatial analysis, but of the nine sites with data, 55.6% show statistically significant later freezeup dates (Fig. 7d), with freezeup, on average, occurring 0.84 days per decade (α = 0.78) later through time (Table 3). Sites with both breakup and freezeup data (Fig. 7g) show 42.9% have a significant trend towards more open water days, with the mean being an extra 1.49 days per decade (α = 1.12) (Table 2). Residuals calculated from mean breakup and freezeup dates, as well as annual open water days, across all North American sites show how the 30-year time period trends (Fig. 4) appear to be superimposed onto a longer-term warming pattern, particularly the cooling trend towards later breakup dates from 1946-1975 (Fig. 4d, Table 3). Breakup dates, when viewed as a running 11-year annual mean (Fig. 7a), show a weak (R^2 = 0.25) trend towards earlier breakup, whilst freezeup trends display a moderate trend (R^2 = 0.48) towards later freezeup (Fig. 7a, 7d). Breakup and freezeup trends combined show that once shorter-term variability is removed, there is a moderate trend towards more annual open water days per year (R^2 = 0.50) (Fig. 7g)

Sites for the 1931-2005 period in Europe cover much of the length of Sweden and southern Finland. Breakup date changes over this time period suggest that it was becoming 0.52 days per decade earlier (α = 0.40) (Table 3). Most of the significant trends are located in southern Finland, with Sweden characterised by sites with low magnitude earlier breakup or no observable trend (Fig. 7b). Lakes and rivers both trend towards earlier breakup, albeit with rivers displaying a lower magnitude. Freezeup trends demonstrate greater variability than breakup, with freezeup dates becoming earlier by 0.20 days per decade (α = 0.97) (Table 3). However, lakes and rivers show opposing trends, with rivers demonstrating later freezeup by 0.70 days per decade (α = 0.70) (Table 3). Spatial patterns in freezeup dates vary more than breakup dates, with significant trends towards earlier freezeup dates in Finland and later freezeup in Sweden (Fig. 7e). These heterogeneous changes in freezeup dates are also reflected in the low magnitude mean trend of 0.39 more open water days per decade (α = 0.90) (Table 3). The spatial patterns remain varied but are more similar to freezeup dates (Fig. 7h). For all three phenomena, the 11-year running mean of the residuals display very weak correlations through time.

In Russia only Lake Baikal has data for 1931-2005 and shows there is no observable change in breakup dates (Fig. 7c), in contrast to the freezeup dates which have become significantly later by 1.04 days per decade (Table 3, Fig 7f). Unsurprisingly, when the two are combined there is a significant trend towards 1.53 more annual open water days over the 75-year time period (Fig. 7i). The 11-year running mean of the residuals show strong trends towards later freezeup (R^2 = 0.60) and moderate trends towards more open water days per year (R^2 = 0.38).

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4. Results: Causes of ice phenology change

Figure 17 shows the correlationsCorrelations between breakup/freezeup dates and a series of regionally-averaged climatic variables and indices for each of the three study regions: Fennoscandia (FEN (Fig. 8): Europe (EUR), North America (NAM) and Russia (RUS), on a monthly basis and for three-monthly means over the time period 1931-2005. Unsurprisingly, rising temperatures appear to be the dominant control on the shift towards earlier breakup and later freezeup in the ice phenology records. Late winter and spring temperatures negatively correlate most strongly with breakup, which is expected since rising temperatures lead to more rapid ice melt and thus earlier breakup dates. Autumn and early winter temperatures positively correlate most strongly with freezeup, which is entirely as expected as increasing temperatures lead to delayed freezeup dates. At FENIn Europe and NAMNorth

America, the month preceding breakup (April and March, respectively) exhibits the strongest correlation with temperatures, whereas for freezeup the strongest correlation with temperatures occurs on the month of freezeup (November and December, respectively). This may relate to the gradual build-up of rising air temperatures required to break up ice to depth, as opposed to the more rapid onset of freezeup with falling autumn and winter air temperatures.

The three-month temperature means exhibit even stronger correlations with breakup and freezeup, with March-May temperatures and February-April temperatures correlating most strongly with breakup ~~at FEN~~in Europe and ~~NAM~~North America, respectively, and October-December temperatures correlating most strongly with freezeup ~~at~~in both ~~FEN~~Europe and ~~NAM~~North America. These correlations are physically sensible, with breakup/freezeup occurring towards the end of the three month means. In ~~RUS~~Russia, strongest correlations with breakup occur in February – three months prior to the mean breakup date in early May, which may relate to an increased ice thickness and hence longer time period required to cause breakup. However, when considering the three month temperatures means, the strongest correlations with breakup occurs during February-May – which fits more closely with the mean breakup date. Temperatures during the month preceding freezeup (December) and particularly the three-month mean period October-December correlate most strongly with freezeup dates at ~~RUS~~Russia. This delayed response to falling winter temperatures ~~at RUS~~in Russia compared to ~~FEN~~Europe and ~~NAM~~North America may relate to the influence of other climatic or site-specific factors, especially since the ~~RUS~~Russian record applies to ~~just a single~~only one lake.

(a)		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
BREAKUP	*Temp*	-0.31	-0.48	-0.50	-0.77	-0.45	-0.17	-0.09	-0.08	-0.20	-0.08	-0.12	-0.26
		-0.16	-0.43	-0.74	-0.55	0.07	-0.10	-0.20	-0.06	-0.15	0.02	-0.15	0.06
		-0.24	-0.47	-0.32	-0.37	-0.06	0.15	-0.05	0.13	-0.07	-0.04	0.18	-0.04
	Prcp	-0.38	-0.30	-0.22	-0.11	-0.12	-0.15	-0.13	-0.03	0.12	0.02	0.06	0.01
		0.11	0.00	-0.21	-0.10	-0.13	-0.06	0.04	0.12	-0.15	-0.17	0.04	0.03
		0.04	0.08	-0.01	0.10	-0.05	0.00	-0.01	-0.13	0.21	0.00	0.00	0.09
	Wind	0.14	0.12	0.11	0.03	-0.24	-0.19	-0.16	-0.24	-0.10	-0.03	0.05	0.08
		0.31	-0.22	-0.14	0.11	0.24	0.37	0.28	0.39	0.31	0.30	0.13	0.05
	NAO	-0.41	-0.39	-0.34	-0.17	0.07	-0.21	0.09	-0.18	0.06	-0.10	0.03	-0.01
		-0.11	-0.22	-0.19	0.17	0.17	0.07	0.06	-0.01	-0.02	-0.13	0.04	0.02
		-0.29	-0.30	-0.25	-0.02	0.15	-0.12	-0.01	-0.16	0.23	0.06	0.12	0.08
	AO	-0.31	-0.41	-0.41	-0.29	-0.16	-0.15	-0.03	-0.04	-0.16	0.03	0.03	-0.18
		-0.10	-0.10	-0.16	-0.03	0.04	0.04	-0.11	-0.08	0.07	0.03	0.12	-0.12
		-0.29	-0.40	-0.25	-0.19	0.12	-0.06	0.03	-0.11	0.11	0.17	0.11	0.04
	AMO	-0.07	-0.06	-0.09	-0.02	-0.06	-0.10	-0.05	-0.12	-0.10	-0.06	0.02	-0.12
		0.10	0.09	-0.13	-0.17	-0.31	-0.16	-0.06	0.02	-0.08	0.00	-0.04	-0.07
		-0.10	-0.10	-0.12	-0.16	-0.16	-0.11	-0.02	-0.16	-0.17	-0.16	-0.18	-0.05
FREEZEUP	*Temp*	0.12	0.20	0.23	0.25	-0.03	-0.10	-0.06	0.08	0.27	0.59	0.81	0.35
		-0.07	0.27	-0.01	0.11	-0.03	0.18	-0.03	-0.18	0.19	0.14	0.64	0.66
		0.24	0.08	0.13	-0.09	-0.02	-0.06	-0.02	0.03	0.00	-0.07	0.32	0.49
	Prcp	0.08	0.00	0.02	0.12	0.34	0.14	0.17	0.04	0.00	0.07	0.45	0.09
		0.12	0.07	-0.11	-0.05	0.00	0.11	-0.05	-0.02	0.06	-0.02	0.15	0.06
		0.12	-0.17	0.02	0.11	-0.02	-0.01	-0.11	-0.02	0.08	0.03	0.03	0.06
	Wind	-0.18	-0.34	-0.16	-0.04	0.12	0.13	0.16	0.14	0.05	-0.09	-0.25	-0.09
		-0.14	-0.07	-0.02	-0.16	-0.14	-0.29	-0.11	-0.07	-0.28	-0.19	-0.20	-0.27
	NAO	0.12	0.12	0.00	0.00	0.04	0.06	0.01	0.15	0.13	0.25	0.21	0.01
		-0.09	0.08	0.04	-0.08	-0.07	-0.08	-0.14	-0.10	-0.12	-0.04	0.26	0.23
		0.10	0.00	0.08	-0.22	0.09	-0.13	0.00	0.11	-0.21	-0.15	0.04	-0.02
	AO	0.05	0.22	0.02	0.15	0.11	-0.01	-0.02	-0.07	0.28	0.16	0.13	-0.10
		-0.05	0.05	0.00	-0.03	0.01	-0.04	0.01	-0.07	-0.03	-0.05	0.21	-0.01
		0.07	0.00	-0.12	-0.31	0.03	-0.03	-0.01	0.02	-0.23	-0.15	0.35	0.16
	AMO	0.16	0.13	0.22	0.10	0.13	0.18	0.15	0.19	0.15	-0.01	0.17	0.23
		-0.01	-0.03	-0.06	0.03	0.00	-0.09	-0.22	-0.08	0.02	0.07	-0.03	0.13
		-0.21	-0.09	-0.06	0.03	0.01	0.01	-0.03	-0.07	-0.03	0.02	-0.12	-0.18

(b)		JFM	FMA	MAM	AMJ	MJJ	JJA	JAS	ASO	SON	OND	NDJ	DJF	
BREAKUP	*Temp*	-0.53	-0.68	-0.83	-0.69	-0.37	-0.17	-0.16	-0.17	-0.18	-0.26	-0.37	-0.48	*FEN*
		-0.71	-0.81	-0.66	-0.34	-0.08	-0.16	-0.19	-0.09	-0.13	-0.03	-0.13	-0.29	*NAM*
		-0.46	-0.53	-0.37	-0.18	0.03	0.12	0.01	0.01	0.08	0.05	-0.05	-0.37	*RUS*
	Prcp	-0.45	-0.32	-0.23	-0.23	-0.23	-0.15	-0.03	0.06	0.13	0.05	-0.19	-0.36	*FEN*
		-0.18	-0.29	-0.41	-0.36	-0.25	-0.05	0.08	0.10	0.08	0.06	-0.03	-0.08	*NAM*
		0.10	0.16	0.12	0.00	-0.08	-0.17	-0.18	-0.15	-0.03	0.03	0.03	0.02	*RUS*
	Wind	0.13	0.15	-0.07	-0.22	-0.20	-0.20	-0.19	-0.20	-0.07	0.01	0.09	0.12	*FEN*
		0.10	0.06	0.23	0.31	0.35	0.38	0.31	0.33	0.22	0.24	0.20	0.17	*NAM*
														RUS
	NAO	-0.59	-0.53	-0.30	-0.18	-0.04	-0.19	-0.03	-0.13	0.00	-0.04	-0.24	-0.50	*FEN*
		-0.26	-0.15	0.09	0.23	0.19	0.07	0.02	-0.09	-0.06	-0.03	-0.03	-0.19	*NAM*
		-0.43	-0.34	-0.10	0.00	0.02	-0.18	0.04	0.08	0.24	0.15	-0.07	-0.32	*RUS*
	AO	-0.51	-0.53	-0.47	-0.36	-0.19	-0.12	-0.13	-0.08	-0.03	-0.18	-0.19	-0.19	*FEN*
		-0.16	-0.15	-0.12	0.02	0.00	-0.07	-0.05	0.02	0.12	-0.12	-0.12	-0.12	*NAM*
		-0.43	-0.41	-0.22	-0.10	0.05	-0.09	0.01	0.10	0.20	0.04	0.04	0.03	*RUS*
	AMO	-0.08	-0.06	-0.07	-0.07	-0.08	-0.10	-0.10	-0.10	-0.05	-0.06	-0.07	-0.10	*FEN*
		0.03	-0.07	-0.23	-0.24	-0.19	-0.07	-0.04	-0.02	-0.04	-0.04	0.00	0.04	*NAM*
		-0.12	-0.14	-0.16	-0.16	-0.10	-0.11	-0.12	-0.17	-0.19	-0.14	-0.13	-0.10	*RUS*
FREEZEUP	*Temp*	0.22	0.27	0.22	0.05	-0.10	-0.04	0.12	0.47	0.81	0.83	0.55	0.29	*FEN*
		0.09	0.17	0.04	0.13	0.05	-0.01	-0.01	0.09	0.52	0.75	0.62	0.44	*NAM*
		0.19	0.07	0.03	-0.08	-0.05	-0.02	0.01	-0.03	0.20	0.42	0.53	0.40	*RUS*
	Prcp	0.05	0.07	0.27	0.35	0.34	0.18	0.13	0.07	0.28	0.33	0.39	0.09	*FEN*
		0.13	0.05	0.01	0.05	0.07	0.04	-0.05	-0.15	-0.13	-0.10	0.07	0.14	*NAM*
		-0.08	-0.20	-0.05	-0.10	0.03	-0.02	-0.02	-0.06	-0.08	0.10	-0.02	0.01	*RUS*
	Wind	-0.24	-0.29	-0.06	0.09	0.14	0.15	0.14	0.08	-0.17	-0.14	-0.18	-0.21	*FEN*
		0.06	-0.02	-0.04	-0.13	-0.10	-0.06	-0.05	-0.09	-0.18	-0.16	0.04	0.05	*NAM*
														RUS
	NAO	0.13	0.08	0.03	0.05	0.07	0.14	0.17	0.31	0.34	0.27	0.19	0.15	*FEN*
		0.02	0.03	-0.07	-0.13	-0.18	-0.19	-0.20	-0.16	0.07	0.27	0.21	0.12	*NAM*
		0.08	-0.08	-0.05	-0.16	-0.02	0.00	-0.06	-0.15	-0.18	-0.06	0.07	0.05	*RUS*
	AO	0.14	0.19	0.12	0.17	0.06	-0.05	0.12	0.20	0.28	-0.10	-0.10	-0.10	*FEN*
		0.00	0.02	-0.01	-0.03	-0.01	-0.06	-0.05	-0.08	0.10	-0.01	-0.01	-0.01	*NAM*
		-0.02	-0.15	-0.21	-0.21	0.00	-0.01	-0.13	-0.19	0.06	0.16	0.16	0.16	*RUS*
	AMO	0.18	0.16	0.16	0.16	0.17	0.19	0.18	0.12	0.12	0.14	0.22	0.20	*FEN*
		-0.03	-0.02	-0.01	-0.03	-0.12	-0.14	-0.10	0.00	0.02	0.06	0.04	0.04	*NAM*
		-0.13	-0.04	-0.01	0.02	-0.01	-0.03	-0.05	-0.03	-0.05	-0.10	-0.19	-0.18	*RUS*

(a)		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
BREAKUP	Temp	-0.31	-0.48	-0.50	-0.77	-0.45	-0.17	-0.09	-0.08	-0.20	-0.08	-0.12	-0.26	EUR
		-0.16	-0.43	-0.74	-0.55	0.07	-0.10	-0.20	-0.06	-0.15	0.02	-0.15	0.06	NAM
		-0.24	-0.47	-0.32	-0.37	-0.06	0.15	-0.05	0.13	-0.07	-0.04	0.18	-0.04	RUS
	Prcp	-0.38	-0.30	-0.22	-0.11	-0.12	-0.15	-0.13	-0.03	0.12	0.02	0.06	0.01	EUR
		0.11	0.00	-0.21	-0.10	-0.13	-0.06	0.04	0.12	-0.15	-0.17	0.04	0.03	NAM
		0.04	0.08	-0.01	0.10	-0.05	0.00	-0.01	-0.13	0.21	0.00	0.00	0.09	RUS
	Wind	0.14	0.12	0.11	0.03	-0.24	-0.19	-0.16	-0.24	-0.10	-0.03	0.05	0.08	EUR
		0.31	-0.22	-0.14	0.11	0.24	0.37	0.28	0.39	0.31	0.30	0.13	0.05	NAM
														RUS
	NAO	-0.41	-0.39	-0.34	-0.17	0.07	-0.21	0.09	-0.18	0.06	-0.10	0.03	-0.01	EUR
		-0.11	-0.22	-0.19	0.17	0.17	0.07	0.06	-0.01	-0.02	-0.13	0.04	0.02	NAM
		-0.29	-0.30	-0.25	-0.02	0.15	-0.12	-0.01	-0.16	0.23	0.06	0.12	0.08	RUS
	AO	-0.31	-0.41	-0.41	-0.29	-0.16	-0.15	-0.03	-0.04	-0.16	0.03	0.03	-0.18	EUR
		-0.10	-0.10	-0.16	-0.03	0.04	0.04	-0.11	-0.08	0.07	0.03	0.12	-0.12	NAM
		-0.29	-0.40	-0.25	-0.19	0.12	-0.06	0.03	-0.11	0.11	0.17	0.11	0.04	RUS
	AMO	-0.07	-0.06	-0.09	-0.02	-0.06	-0.10	-0.05	-0.12	-0.10	-0.06	0.02	-0.12	EUR
		0.10	0.09	-0.13	-0.17	-0.31	-0.16	-0.06	0.02	-0.08	0.00	-0.04	-0.07	NAM
		-0.10	-0.10	-0.12	-0.16	-0.16	-0.11	-0.02	-0.16	-0.17	-0.16	-0.18	-0.05	RUS
	SOI	0.17	0.16	0.08	0.12	0.11	0.08	0.10	0.14	0.17	0.08	0.03	0.06	EUR
		-0.03	-0.17	-0.17	-0.10	-0.17	-0.09	-0.27	-0.13	-0.12	-0.04	-0.09	-0.10	NAM
		0.00	0.07	0.06	-0.09	-0.07	-0.04	0.05	-0.01	-0.02	-0.03	-0.15	-0.05	RUS
FREEZEUP	Temp	0.12	0.20	0.23	0.25	-0.03	-0.10	-0.06	0.08	0.27	0.59	0.81	0.35	EUR
		-0.07	0.27	-0.01	0.11	-0.03	0.18	-0.03	-0.18	0.19	0.14	0.64	0.66	NAM
		0.24	0.08	0.13	-0.09	-0.02	-0.06	-0.02	0.03	0.00	-0.07	0.32	0.49	RUS
	Prcp	0.08	0.00	0.02	0.12	0.34	0.14	0.17	0.04	0.00	0.07	0.45	0.09	EUR
		0.12	0.07	-0.11	-0.05	0.00	0.11	-0.05	-0.02	0.06	-0.02	0.15	0.06	NAM
		0.12	-0.17	0.02	0.11	-0.02	-0.01	-0.11	-0.02	0.08	0.03	0.03	0.06	RUS
	Wind	-0.18	-0.34	-0.16	-0.04	0.12	0.13	0.16	0.14	0.05	-0.09	-0.25	-0.09	EUR
		-0.14	-0.07	-0.02	-0.16	-0.14	-0.29	-0.11	-0.07	-0.28	-0.19	-0.20	-0.27	NAM
														RUS
	NAO	0.12	0.12	0.00	0.00	0.04	0.06	0.01	0.15	0.13	0.25	0.21	0.01	EUR
		-0.09	0.08	0.04	-0.08	-0.07	-0.08	-0.14	-0.10	-0.12	-0.04	0.26	0.23	NAM
		0.10	0.00	0.08	-0.22	0.09	-0.13	0.00	0.11	-0.21	-0.15	0.04	-0.02	RUS
	AO	0.05	0.22	0.02	0.15	0.11	-0.01	-0.02	-0.07	0.28	0.16	0.13	-0.10	EUR
		-0.05	0.05	0.00	-0.03	0.01	-0.04	0.01	-0.07	-0.03	-0.05	0.21	-0.01	NAM
		0.07	0.00	-0.12	-0.31	0.03	-0.03	-0.01	0.02	-0.23	-0.15	0.35	0.16	RUS
	AMO	0.16	0.13	0.22	0.10	0.13	0.18	0.15	0.19	0.15	-0.01	0.17	0.23	EUR
		-0.01	-0.03	-0.06	0.03	0.00	-0.09	-0.22	-0.08	0.02	0.07	-0.03	0.13	NAM
		-0.21	-0.09	-0.06	0.03	0.01	0.01	-0.03	-0.07	-0.03	0.02	-0.12	-0.18	RUS
	SOI	-0.01	-0.07	-0.06	0.04	-0.04	-0.11	-0.11	-0.20	-0.17	-0.15	0.03	0.06	EUR
		0.09	0.12	0.17	0.11	0.11	0.01	0.03	0.04	-0.01	-0.19	-0.13	-0.08	NAM
		0.33	0.31	0.26	0.34	0.36	0.18	0.25	0.20	0.16	0.05	0.09	-0.02	RUS

(b)		JFM	FMA	MAM	AMJ	MJJ	JJA	JAS	ASO	SON	OND	NDJ	DJF	
BREAKUP	Temp	-0.53	-0.68	-0.83	-0.69	-0.37	-0.17	-0.16	-0.17	-0.18	-0.26	-0.37	-0.48	EUR
		-0.71	-0.81	-0.66	-0.34	-0.08	-0.16	-0.19	-0.09	-0.13	-0.03	-0.13	-0.29	NAM
		-0.46	-0.53	-0.37	-0.18	0.03	0.12	0.01	0.01	0.08	0.05	-0.05	-0.37	RUS
	Prcp	-0.45	-0.32	-0.23	-0.23	-0.23	-0.15	-0.03	0.06	0.13	0.05	-0.19	-0.36	EUR
		-0.18	-0.29	-0.41	-0.36	-0.25	-0.05	0.08	0.10	0.08	0.06	-0.03	-0.08	NAM
		0.10	0.16	0.12	0.00	-0.08	-0.17	-0.18	-0.15	-0.03	0.03	0.03	0.02	RUS
	Wind	0.13	0.15	-0.07	-0.22	-0.20	-0.20	-0.19	-0.20	-0.07	0.01	0.09	0.12	EUR
		0.10	0.06	0.23	0.31	0.35	0.38	0.31	0.33	0.22	0.24	0.20	0.17	NAM
														RUS
	NAO	-0.59	-0.53	-0.30	-0.18	-0.04	-0.19	-0.03	-0.13	0.00	-0.04	-0.24	-0.50	EUR
		-0.26	-0.15	0.09	0.23	0.19	0.07	0.02	-0.09	-0.06	-0.03	-0.03	-0.19	NAM
		-0.43	-0.34	-0.10	0.00	0.02	-0.18	0.04	0.08	0.24	0.15	-0.07	-0.32	RUS
	AO	-0.51	-0.53	-0.47	-0.36	-0.19	-0.12	-0.13	-0.08	-0.03	-0.18	-0.19	-0.19	EUR
		-0.16	-0.15	-0.12	0.02	0.00	-0.07	-0.05	0.02	0.12	-0.12	-0.12	-0.12	NAM
		-0.43	-0.41	-0.22	-0.10	0.05	-0.09	0.01	0.10	0.20	0.04	0.04	0.03	RUS
	AMO	-0.08	-0.06	-0.07	-0.07	-0.08	-0.10	-0.10	-0.10	-0.05	-0.06	-0.07	-0.10	EUR
		0.03	-0.07	-0.23	-0.24	-0.19	-0.07	-0.04	-0.02	-0.04	-0.04	0.00	0.04	NAM
		-0.12	-0.14	-0.16	-0.16	-0.10	-0.11	-0.12	-0.17	-0.19	-0.14	-0.13	-0.10	RUS
	SOI	0.15	0.13	0.11	0.11	0.10	0.12	0.15	0.14	0.10	0.06	0.12	0.13	EUR
		-0.13	-0.16	-0.16	-0.13	-0.19	-0.18	-0.20	-0.11	-0.09	-0.08	-0.14	-0.15	NAM
		0.05	0.02	-0.03	-0.07	-0.02	0.00	0.01	-0.02	-0.08	-0.08	-0.04	0.01	RUS
FREEZEUP	Temp	0.22	0.27	0.22	0.05	-0.10	-0.04	0.12	0.47	0.81	0.83	0.55	0.29	EUR
		0.09	0.17	0.04	0.13	0.05	-0.01	-0.01	0.09	0.52	0.75	0.62	0.44	NAM
		0.19	0.07	0.03	-0.08	-0.05	-0.02	0.01	-0.03	0.20	0.42	0.53	0.40	RUS
	Prcp	0.05	0.07	0.27	0.35	0.34	0.18	0.13	0.07	0.28	0.33	0.39	0.09	EUR
		0.13	0.05	0.01	0.05	0.07	0.04	-0.05	-0.15	-0.13	-0.10	0.07	0.14	NAM
		-0.08	-0.20	-0.05	-0.10	0.03	-0.02	-0.02	-0.06	-0.08	0.10	-0.02	0.01	RUS
	Wind	-0.24	-0.29	-0.06	0.09	0.14	0.15	0.14	0.08	-0.17	-0.14	-0.18	-0.21	EUR
		0.06	-0.02	-0.04	-0.13	-0.10	-0.06	-0.05	-0.09	-0.18	-0.16	0.04	0.05	NAM
														RUS
	NAO	0.13	0.08	0.03	0.05	0.07	0.14	0.17	0.31	0.34	0.27	0.19	0.15	EUR
		0.02	0.03	-0.07	-0.13	-0.18	-0.19	-0.20	-0.16	0.07	0.27	0.21	0.12	NAM
		0.08	-0.08	-0.05	-0.16	-0.02	0.00	-0.06	-0.15	-0.18	-0.06	0.07	0.05	RUS
	AO	0.14	0.19	0.12	0.17	0.06	-0.05	0.12	0.20	0.28	-0.10	-0.10	-0.10	EUR
		0.00	0.02	-0.01	-0.03	-0.01	-0.06	-0.05	-0.08	0.10	-0.01	-0.01	-0.01	NAM
		-0.02	-0.15	-0.21	-0.21	0.00	-0.01	-0.13	-0.19	0.06	0.16	0.16	0.16	RUS
	AMO	0.18	0.16	0.16	0.16	0.17	0.19	0.18	0.12	0.12	0.14	0.22	0.20	EUR
		-0.03	-0.02	-0.01	-0.03	-0.12	-0.14	-0.10	0.00	0.02	0.06	0.04	0.04	NAM
		-0.13	-0.04	-0.01	0.02	-0.01	-0.03	-0.05	-0.03	-0.05	-0.10	-0.19	-0.18	RUS
	SOI	-0.05	-0.03	-0.02	-0.04	-0.10	-0.15	-0.17	-0.19	-0.11	-0.02	-0.01	-0.01	EUR
		0.14	0.14	0.14	0.08	0.05	0.03	0.02	-0.06	-0.13	-0.15	0.02	0.07	NAM
		0.33	0.32	0.34	0.31	0.28	0.23	0.22	0.15	0.11	0.04	0.25	0.24	RUS

Figure ~~17~~8: 'Heatmap' illustrating correlations between breakup/freezeup and a series of climatic variables and indices for each of the three study regions: ~~Fennoscandia (FEN~~Europe (EUR), North America (NAM) and Russia (RUS) on a monthly basis (**a**) and for three-monthly means (**b**) where JFM is the mean of January, February and March etc., over the time period 1931-2005. The grey line for Russia displays that there were no wind data available.

Although temperature exhibits the strongest correlations with both breakup and freezeup, precipitation also appears to play an important role in some instances. Increasing winter precipitation (January and particularly the January-

March mean) is associated with earlier breakup in ~~FEN~~Europe, while increasing spring precipitation (March and particularly the March-May mean) appears to exert a stronger influence on earlier breakup in ~~NAM.~~North America. The latter likely relates to increasing precipitation as rainfall, which aids in the melting of ice (Beltaos and Burrell, 2003). The rising winter precipitation in ~~FEN~~Europe, presumably as snowfall, may also be associated with earlier breakup since snowfall settling on ice can insulate the ice surface and prevent further thickening during the winter (Park et al., 2016) – therefore, potentially promoting earlier breakup. Rising precipitation in November (and to a lesser extent the November-January mean) is associated with later freezeup in ~~FEN~~Europe. This may relate to increased discharge into lakes or rivers, making it harder for surfaces to stabilise and freeze. The correlations between precipitation and freezeup are weak ~~at~~in both ~~NAM~~North America and ~~RUS~~Russia, while ~~RUS~~Russia also exhibits weak correlations between precipitation and breakup. There are also some relatively close associations between wind speed and breakup/freezeup ~~at FEN~~in Europe and ~~NAM~~North America (no wind speed data was available for ~~RUS~~Russia). Higher wind speeds in summer correlate most strongly with later breakup and earlier freezeup in ~~NAM~~North America. The latter seems counter-intuitive since high wind speeds are generally thought to disrupt the water surface and delay ~~freezup~~freezeup, while the former does not have any particularly relevant temporal connection. These correlations are not particularly strong compared to those of temperature with breakup/freezeup and to a lesser extent precipitation, ~~while~~thus, they ~~could also simply~~ be a product of chance that relates to false positives.

In terms of the atmospheric/oceanic modes of variability, some strong correlations exist with breakup and to a lesser extent freezeup in all regions. Most notably there are strong negative correlations between breakup and winter/early spring NAO and AO, i.e. when NAO/AO are in a positive phase, breakup occurs earlier. This is particularly true in ~~FEN~~Europe, where a strong positive phase of NAO and AO for the January-March mean and the February-April mean respectively are associated with earlier breakup. Correlations for ~~RUS~~Russia at a similar time of year are also apparent, while correlations in ~~NAM~~North America are much weaker. Positive correlations (albeit not as strong) between freezeup and NAO/AO occur in autumn in ~~FEN~~Europe and early winter in ~~NAM~~North America, i.e. when NAO/AO are in a positive phase, freezeup occurs later. These findings are expected, since a stronger positive NAO/AO phase results in an increase in stronger westerly winds, drawing warmer air across northern Europe feeding from the North Atlantic Drift and the Norwegian Current (Hurrell, 1995). A strong positive NAO/AO promotes later freezeup in late autumn/early winter, and earlier breakup in spring. Trends towards earlier breakup and later freezeup throughout the latter third of the 20th century may relate to the positive trends of the NAO and the closely associated AO for much of the 1970s and 1980s, with historical highs in the early 1990s (Cohen and Barlow, 2005). Correlations with AMO and SOI for the full time period are generally not as strong, with the exception of negative correlations between late spring AMO and breakup in ~~NAM~~North America, i.e. when AMO experiences a warm phase, earlier break up occurs. During warm phases of the AMO, elevated sea surface temperatures in the North Atlantic bring about warmer and drier conditions across much of North America (Enfield et al., 2001) – hence the association between earlier breakup with the AMO in this region. There are also positive correlations between winter and spring SOI and freezeup in Russia (i.e. when SOI experiences a positive phase, later breakup occurs).

~~**6. Summary and conclusions**~~

All correlations were established between local ice phenology records and the broad regional climate for each region rather than the local climate corresponding to each site. Examining the latter, while more labour intensive, would likely reveal stronger correlations on a site by site basis – acknowledging the fact that synoptic and local climate forcings can greatly influence the timing of lake and river ice freezeup and breakup. The broader geographical approach we have taken also has clear merit, however, as it demonstrates that wider regional climate exerts considerable influence over ice phenology. We also acknowledge the potential for 'false positive' correlations when assessing so many correlations in a matrix as we do in Figure 8. This provides reason to be cautious when interpreting these findings.

5. Discussion

The results presented for all three regions show that between different 30-year time periods there are fluctuations in the trend directions for breakup/freezeup dates and the number of annual open water days. The two most recent 30-year time periods in North America and Europe (Figs. 4-5) show that warming trends dominated. Warming trends for the number of annual open water days were initially driven by earlier breakup dates before then being increased further by later freezeup (see below). This is in line with other studies that capture long-term reductions in the ice season (Futter, 2003) and show that warming breakup trends are more common (Brammer et al., 2015; Jensen et al., 2007), and whilst freezeup trends do move toward warming patterns, they are often more variable (Duguay et al., 2006; Hewitt et al., 2018). The 30-year time period analyses documented here also show that some short-term variations lead to variable spatial patterns through time. For example, in the Great Lakes region, the two most recent time periods show consistent trends towards earlier breakup dates (Figs. 4g, 4j), which is corroborated in more localised studies (e.g. Magnuson et al., 2005), but the trends in the first two 30-year time periods show variability in the trend magnitude and direction of phenology changes, with sites to the west and east displaying opposing trends (Fig. 4a, 4d). The trends in this region, as well as more broadly across North America, Europe, and Russia are dominantly driven by regionally-averaged temperature changes, with precipitation and teleconnections also helping to explain some of the variation (Fig. 8). Such a finding is not new (e.g. Blenckner et al., 2004; Bonsal et al., 2006; Duguay et al., 2006; Ghanbari et al., 2009; Hewitt et al., 2018; Livingstone, 1999; Sharma et al., 2013; Smith, 2000), but it does further confirm that the prevailing climate conditions can only partially account for some of the variability in ice phenology trends. What is interesting is the fact that strong correlations can be established despite correlating ice phenology records with spatially averaged climate data over large regions. This indicates that broad regional climate exerts a considerable degree of influence over changes in ice phenology. Such a finding is important because it means that site specific climate data, either from in situ observations or from numerical downscaling of climate models, may not be explicitly required to explain a large amount of the phenology variation. Whilst there are clearly merits in looking at sites with local data to better understand the underlying processes taking place and how this relates to the observed climatological trends (e.g. the influence of wind on ice phenology), being able to regionalise and simplify the analysis to sites across broad areas that do not have local climate observations is important for upscaling efforts to project larger-scale climatic changes.

Across the longer 75-year time period the results broadly match those previously published (Table 1) and show general warming patterns for breakup across all regions (Fig. 7). Freezeup patterns in Europe show less consistent patterns through time, with many sites showing earlier and later freezeup trends (Fig. 7e). Whilst these freezeup trends do evolve into warming trends in the latest time period, this is not fully captured in the 75-year time period studied here, but it is documented in other studies looking at longer records (e.g. Korhonen, 2006). It is also notable that the standard deviation of the trends derived from the Mann-Kendall and Sen's Slope analyses for freezeup tend to be higher than those for breakup (Table 3). Although temperatures appear to be able to explain a large proportion of variations in freezeup dates, at least in Europe, it does not account for why the variability is larger than for breakup, which is also well correlated with temperature changes (Fig. 8). Whilst breakup is dominated by thermal characteristics of the climate, freezeup is a result of not just the thermal properties of the environment but also water kinetics – e.g. even if water temperatures are low enough to freeze, wind and water movement can mechanically prohibit freezeup as the kinetic energy makes it harder for the water to stabilise or ice patches to agglomerate (Beltaos and Prowse, 2009). The complexity involved in water freezeup likely acts as an important control on these fluctuating trends and would benefit from additional study to explore how this can be accounted for in models (e.g. Bruce et al., 2018). This likely explains why the breakup and freezeup patterns do not simply reflect observed increases in air temperatures.

Unlike lakes, and with the exception of European river breakup trends from 1946-1975, the mean ice phenology trends for rivers show a more consistent warming pattern through most time periods for all regions (Table 3). Whilst acknowledging the caveats of a limited number of sites, the above evidence suggests that during the 20th century, rivers were responding to increased surface air temperatures faster than lakes. This may be explained, possibly, by the river flow gradient causing waves and ripples which instigates air turbulence and greater interaction of water and air causing a faster transfer of atmospheric heat. Whilst ripples and waves do form on still water bodies, this is likely limited compared to actively flowing rivers, causing a slower response time in lake temperatures to air temperature increases. As the lakes gradually experience this warming the same reasons may also restrict heat exchange from the lake to the atmosphere. Though the physics require further study, it is possible this thermal legacy allowed lakes to gradually become a heat sink and might explain why over longer timescales the lakes begin to demonstrate larger magnitude warming trends than rivers, particularly in the 1976-2005 time period (Table 3).

Changes in the number of open water days may relate to movements in breakup and/or freezeup dates, allowing the relative influence of date changes to be compared. Figure 9 summarises sites with open water data across all time periods in each region and separates breakup/freezeup combinations into warming, cooling, and no trends – e.g. 35.2% of North American sites during 1931-1960 had earlier breakup, later freezeup, and more open water days. In all three regions there is a gradual reduction through time in the proportion of sites displaying fewer open water days caused by later breakup and earlier freezeup dates. Most other sites are characterised by showing the same trend direction towards earlier or later dates, where either later breakup or earlier freezeup trends (cooling trends) are stronger than later freezeup or earlier breakup trends (warming trends), thus, reducing the relative number of open water days (Fig. 9). Through time there is a reduction in the number of sites displaying significant trends towards fewer open water days, which contrasts with an increasing proportion of sites displaying more open water days, with the trends at many sites becoming significant in the later time periods (Figs. 4-6, 9). Most changes appear to be dominated by sites with both earlier breakup and later freezeup dates, or where earlier breakup or later freezeup trends are larger in magnitude than later breakup and earlier freezeup (Fig. 9). Some anomalous sites with no warming breakup or freezeup trends relate to low magnitude trends close to zero. All sites combined, most that display trends towards more or fewer open water days do so because both breakup and freezeup date trends are moving in opposite directions – earlier breakup and later freezeup in the case of more open water days, and the opposite trends where there are fewer open waters days – suggesting changes across different seasons. During 1931-2005 most sites display an increase in open water days that is predominately driven by earlier breakup and later freezeup dates in North America. This aligns well with other studies looking at a range of different sites across the region showing ice season length was driven by either earlier breakup (Brammer et al., 2015; Futter, 2003) or both earlier breakup and later freezeup (Latifovic and Pouliot, 2007). In Europe the pattern is more mixed with a number of sites showing that earlier freezeup trends are enough to reduce the number of open water days for ~25% of sites, irrespective of a warming pattern in earlier breakup dates. In some circumstances the ice-free season shifts – e.g. 17.3% of sites in Europe during 1931-2005 display earlier breakup and earlier freezeup – without actually changing its length, potentially having consequences on biogeochemical cycles in areas that have lakes responding at different rates and in different trend directions. The majority of sites do, however, display trends towards more open water days, but from a range of different breakup and freezeup trend combinations, with most related to earlier breakup and later freezeup dates (Fig. 9). This is similar to observations from Finland looking at a longer time period and documenting reduced ice season lengths (Korhonen, 2006). The one Russian site shows more open water days being driven by later freezeup dates. Combined, these results match well with numerous other studies across the Northern Hemisphere showing earlier breakup and freezeup dates (e.g. Magnuson et al., 2000; Table 1), with the addition that the strength of these changes has increased in more recent times and that the changes in the number of open water days are not always associated with both warming breakup and freezeup dates (Figs. 4-7, 9). This suggests that it is not just the length of time that is important for understanding the context of the trends that are documented (e.g. Wynne, 2000), but also which phenomena is being investigated as there are numerous examples where warming trends in either the breakup or freezeup date are not matched with a correlative increase in the number of open water days. Thus, environmental changes inferred from only breakup or freezeup data are potentially misleading as they might not reflect wider changes in the ice season length, and should be interpreted cautiously.

Pattern			North America					Europe					Russia				
BU	FU	OW	1931-1960	1946-1975	1961-1990	1976-2005	1931-2005	1931-1960	1946-1975	1961-1990	1976-2005	1931-2005	1931-1960	1946-1975	1961-1990	1976-2005	1931-2005
Red	Red	Red	35.2 (1)	24.3 (1)	35.0 (11)	60.6 (12)	71.4 (3)	6.8 (3)	0.5	28.4 (10)	70.4 (73)	24.2 (3)	20.0	24.9 (2)	28.0 (4)		
Red	Blue	Red		3.4	24.5 (2)			2.0		12.6	9.6	3.4		8.3	12.0 (1)	100.0	
Red	White	Red		3.4	10.5 (2)		14.3	1.4	0.5	9.6	13.0 (1)	10.3		8.3 (2)	4.0		
Blue	Blue	Red							0.5	0.4							
Blue	Red	Red	5.9	3.4	1.8	7.9		4.1	13.8 (2)	4.2	0.7			4.2			
Blue	White	Red			1.8				0.5								
White	White	Red				2.6		0.7	0.5	2.9		3.4			4.0		
White	Red	Red	11.8	6.9	5.3	23.7 (2)		6.8 (1)	1.5	9.2 (1)	2.1	13.9 (1)		4.2	4.0		100 (1)
White	Blue	Red			1.8				1.0	1.3					4.0		
% of Sites			52.9	41.4	80.7	94.8	85.7	21.8	18.8	68.6	95.8	55.2	20	49.9	56	100	100
Red	Red	Blue															
Red	Blue	Blue	5.9	3.4	10.5			28.5 (6)	0.5	6.3	2.1	20.7 (1)		8.3	12.0		
Red	White	Blue		6.9													
Blue	Blue	Blue	23.5 (3)	27.7 (5)				14.3 (6)	48.9 (26)	2.9			80 (1)	12.5	8.0		
Blue	Red	Blue	5.9	6.9				2.7	13.9	1.3				4.2	4.0 (1)		
Blue	White	Blue		6.9 (1)				3.4	7.4	1.3				4.2	4.0		
White	White	Blue		3.4						0.4		3.4					
White	Red	Blue	5.9														
White	Blue	Blue	5.9					21.8	3.5	5.9		3.4			4.0		
% of Sites			47.1	55.2	10.5	0	0	70.7	74.2	18.1	2.1	27.5	80	29.2	32	0	0
Red	Red	White		3.4						0.4							
Red	Blue	White			7.0			2.7	0.5	4.2	1.4	17.3		12.5	4.0		
Red	White	White				2.6		2.0		1.7							
Blue	Blue	White							1.0					4.2			
Blue	Red	White						0.7	4.0	0.8	0.7			4.2			
Blue	White	White							1.5						8.0		
White	White	White						1.4		3.3							
White	Red	White				2.6		0.7		0.4							
White	Blue	White			1.8		14.3			2.5							
% of Sites			0	3.4	8.8	5.2	14.3	7.5	7.0	13.3	2.1	17.3	0.0	20.9	12.0	0.0	0.0
Number of Sites			17	29	57	38	7	147	202	239	146	29	5	24	25	1	1
Sig. Cooling			3	6	0	0	0	12	26	0	0	1	1	0	1	0	0
Sig. Warming			1	1	15	14	3	4	2	11	74	4	0	4	5	0	1

Figure 9: Summary of trends for sites with data for breakup (BU), freezeup (FU), and open water day (OW) trends that were derived from the Mann-Kendall and Sen's Slope analysis. On the left, where the pattern is shown as red the phenomena had a warming trend, as blue a cooling trend, and as white no trend – thus, the top row shows breakup was earlier, freezeup later, and the number of open water days increased. The values in the different columns show the proportion of sites during each time period that experienced the specific trend combination, with the number in brackets the amount of sites with open water day trends that were significant (Sig.) – e.g. 23.5% of North American sites from 1931-1960 had a combination of later breakup, earlier freezeup, and fewer open water days, all cooling trends, with three of these sites displaying an open water days trend that was significant. This allows for the relative contributions of trend directions for breakup and freezeup changes to be compared against changes in the number of open water days. The dark red cells show specific combinations of trends during that time period which were not experienced at any sites.

6. Conclusions

Utilising a number of different datasets, a series of analyses have been used to investigate how the number of annual open water days per year and the timing breakup/freezeup dates have changed for water bodies that ephemerally freeze across the Northern Hemisphere. ~~Four~~Five overlapping time periods (1931-1960, 1946-1975, 1961-1990, ~~1991~~1976-2005, and 1931-2005) have been investigated across ~~644~~678 sites with data in at least one of the time periods to provide ~~~2600~~3510 time series of lake and river ice phenology change to be statistically, spatially, and temporally analysed. A warming signal has been observed that shows the ~~breakup dates for sites with continuous data in the 1931-2005 period have occurred on average~~number of annual open water days has increased by 0.~~6~~63 days per decade ~~earlier~~ across the ~~NH. Freezeup trends for the same time period show greater variation between later and earlier freezeup dates and indicate a more complex response to observed temperature rise. Thus, freezeup trends display a less predictable response to temperature changes when compared to breakup. When the time series are investigated on smaller timescales to explore temporal changes, the breakup trends show a consistent trajectory towards earlier breakup dates that is nonlinear with respect to magnitude – i.e. the magnitude of the shift toward earlier breakup increases through the three periods~~Northern Hemisphere from 1931-2005. The breakup trends display a strong correlation with temperature observations in the weeks preceding breakup and during winter ice growth, suggesting that temperature can be confidently used to ~~predict breakup date. Freezeup trends are generally much more variable through time and display a complex relationship with climate.~~explain a large proportion of variability. Freezeup trends show the greatest variability that is less easily predicted from air temperature changes compared to breakup. This is likely because freezeup is not guaranteed to occur simply because temperatures have moved below 0 °C as water kinetics can prevent freezeup. When the time series are investigated on smaller timescales to explore temporal changes, trends for the number of open waters days show variation, with the two most recent 30-year time periods displaying a consistent trajectory towards more open water days that is nonlinear with respect to magnitude. In general, the number of open water days ~~tend to display similar spatiotemporal~~closely resemble breakup patterns~~ to those observed for breakup. This shows that even with the inconsistent nature of the changes in freezeup dates, the relative changes between~~ , suggesting that breakup ~~and freezeup dates has led, through time, to a reduction in~~trends are the ~~length of the ice season and consequently an increase in the number of open water days across the Northern Hemisphere.~~

~~Five~~main driver in open water day trends. Four key conclusions have been drawn from this research; (1) ~~a~~an accelerating warming signal is clearly observable in breakup ~~and~~dates at many sites~~, (2) this warming signal has~~

~~accelerated through time for many sites, (3) the causes of the spatiotemporal variability and magnitude of trends is generally~~ and is reasonably well-aligned to broad regional temperature trends, (~~4~~2) freezeup trends are more spatiotemporally complex and display weaker temperature correlations~~ with climate patterns, and (5~~, (3) the length of the open water season has generally increased through time~~. The results presented here provide an important contribution that can be used to help understand how~~ and was predominantly driven by earlier breakup dates, and (4) that care needs to be taken when interpreting the implications of ice phenology ~~patterns may change in the future with an expected rise in global mean temperatures. The observed acceleration of warming trends through time for many sites highlights the importance of non-linear responses to climate forcings and will require a greater understanding of how this will impact not just lake and river hydrology, but also the impact that reduced ice cover will~~changes at sites that only have ~~on local energy balances and biogeochemical processes. It is possible (if not probable) that changes in lake and river ice phenology patterns, brought about by warmer air temperatures, may in turn begin to feedback into the climate system by the release of additional greenhouse gases (e.g. CH_4). This highlights~~breakup or freezeup data. These results highlight the need for a more detailed understanding of historical changes and their causes to fully unravel the potential implications of ice phenology ~~change for the projection of~~when projecting future climate changes.

Data availability

All of the raw data are available through the National Snow and Ice Data Centre or by contacted the relevant meteorological institutes.

Author contribution

AMWN led the project analysis, writing, ~~and~~ figure preparation, and revisions with input on all from ~~DM~~DJM.

Competing interests

There are no competing interests to declare.

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References

Assel, R., Cronk, K. and Norton, D.: Recent trends in Laurentian Great Lakes ice cover, Clim. Change, doi:10.1023/A:1022140604052, 2003.

Assel, R. A. and Robertson, D. M.: Changes in winter air temperatures near Lake Michigan, 1851-1993, as determined from regional lake-ice records, Limnol. Oceanogr., doi:10.4319/lo.1995.40.1.0165, 1995.

Bai, X., Wang, J., Sellinger, C., Clites, A. and Assel, R.: Interannual variability of Great Lakes ice cover and its relationship to NAO and ENSO, J. Geophys. Res. Ocean., doi:10.1029/2010JC006932, 2012.

~~Balling, R. C. and Idso, S. B.: Historical temperature trends in the United States and the effect of urban population growth, J. Geophys. Res., 94, 3359–3363, doi:10.1029/JD094iD03p03359, 1989.~~

Batima, P., Batnasan, N. and Bolormaa, B.: Trends in River and Lake Ice in Mongolia, AIACC Work. Pap., 2004.

Beltaos, S. and Burrell, B. C.: Climatic change and river ice breakup, Can. J. Civ. Eng., 30, 145–155, doi:10.1139/l02-042, 2003.

Beltaos, S. and Prowse, T.: River-ice hydrology in a shrinking cryosphere, Hydrol. Process., doi:10.1002/hyp.7165, 2009.

Bengtsson, L.: Ice-covered lakes: Environment and climate-required research, Hydrol. Process., doi:10.1002/hyp.8098, 2011.

Bennington, V., McKinley, G. A., Kimura, N. and Wu, C. H.: General circulation of Lake Superior: Mean, variability, and trends from 1979 to 2006, J. Geophys. Res. Ocean., 115, doi:10.1029/2010JC006261, 2010.

Benson, B., Magnuson, J. and Sharma, S.: Global Lake and River Ice Phenology Database, Version 1, NSIDC Natl. Snow Ice Data Center, Boulder, 2013.

Benson, B. J., Magnuson, J. J., Jensen, O. P., Card, V. M., Hodgkins, G., Korhonen, J., Livingstone, D. M., Stewart, K. M., Weyhenmeyer, G. A. and Granin, N. G.: Extreme events, trends, and variability in Northern Hemisphere lake-ice phenology (1855-2005), Clim. Change, 112, 299–323, doi:10.1007/s10584-011-0212-8, 2012.

Blenckner, T., Järvinen, M. and Weyhenmeyer, G. A.: Atmospheric circulation and its impact on ice phenology in Scandinavia, Boreal Environ. Res., 9, 371–380, 2004.

Bonsal, B. R., Prowse, T. D., Duguay, C. R. and Lacroix, M. P.: Impacts of large-scale teleconnections on freshwater-ice break/freeze-up dates over Canada, J. Hydrol., 330, 340–353, doi:10.1016/j.jhydrol.2006.03.022, 2006.

Borshch, S. V., Ginzburg, B. M. and Soldatova, I. I.: Modeling the Development of Ice Phenomena in Rivers as Applied to the Assessment of Probable Changes in Ice Conditions at Various Scenarios of the Future Climate, Water Resour., 28, 194–200, doi:10.1023/A:1010387802874, 2001.

Brammer, J. R., Samson, J. and Humphries, M. M.: Declining availability of outdoor skating in Canada, Nat. Clim. Chang., 5, 2–4, doi:10.1038/nclimate2465, 2015.

Brown, L. C. and Duguay, C. R.: The response and role of ice cover in lake-climate interactions, Prog. Phys. Geogr., 34(5), 671–704, doi:10.1177/0309133310375653, 2010.

Brown, L. C. and Duguay, C. R.: The fate of lake ice in the North American Arctic, Cryosphere, 5, 869–892, doi:10.5194/tc-5-869-2011, 2011.

~~Chylek, P., Folland, C. K., Lesins, G., Dubey, M. K. and Wang, M.: Arctic air temperature change amplification~~

and the Atlantic Multidecadal Oscillation, Geophys. Res. Lett., 36, doi:10.1029/2009GL038777, 2009.

Bruce, L. C., Frassl, M. A., Arhonditsis, G. B., Gal, G., Hamilton, D. P., Hanson, P. C., Hetherington, A. L., Melack, J. M., Read, J. S., Rinke, K., Rigosi, A., Trolle, D., Winslow, L., Adrian, R., Ayala, A. I., Bocaniov, S. A., Boehrer, B., Boon, C., Brookes, J. D., Bueche, T., Busch, B. D., Copetti, D., Cortés, A., de Eyto, E., Elliott, J. A., Gallina, N., Gilboa, Y., Guyennon, N., Huang, L., Kerimoglu, O., Lenters, J. D., MacIntyre, S., Makler-Pick, V., McBride, C. G., Moreira, S., Özkundakci, D., Pilotti, M., Rueda, F. J., Rusak, J. A., Samal, N. R., Schmid, M., Shatwell, T., Snorthheim, C., Soulignac, F., Valerio, G., van der Linden, L., Vetter, M., Vinçon-Leite, B., Wang, J., Weber, M., Wickramaratne, C., Woolway, R. I., Yao, H. and Hipsey, M. R.: A multi-lake comparative analysis of the General Lake Model (GLM): Stress-testing across a global observatory network, Environ. Model. Softw., 102, 274–291, doi:10.1016/j.envsoft.2017.11.016, 2018.

Cohen, J. and Barlow, M.: The NAO, the AO, and global warming: How closely related?, J. Clim., 18, 4498–4513, doi:10.1175/JCLI3530.1, 2005.

Collins, M., Knutti, R., Arblaster, J., Dufresne, J.-L., Fichefet, T., Friedlingstein, P., Gao, X., Gutowski, W. J., Johns, T., Krinner, G., Shongwe, M., Tebaldi, C., Weaver, A. J. and Wehner, M.: Long-term Climate Change: Projections, Commitments and Irreversibility, in Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, pp. 1029–1136., 2013.

Compo, G. P., Whitaker, J. S., Sardeshmukh, P. D., Matsui, N., Allan, R. J., Yin, X., Gleason, B. E., Vose, R. S., Rutledge, G., Bessemoulin, P., BroNnimann, S., Brunet, M., Crouthamel, R. I., Grant, A. N., Groisman, P. Y., Jones, P. D., Kruk, M. C., Kruger, A. C., Marshall, G. J., Maugeri, M., Mok, H. Y., Nordli, O., Ross, T. F., Trigo, R. M., Wang, X. L., Woodruff, S. D. and Worley, S. J.: The Twentieth Century Reanalysis Project, Q. J. R. Meteorol. Soc., 137, 1–28, doi:10.1002/qj.776, 2011.

Déry, S. J. and Wood, E. F.: Decreasing river discharge in northern Canada, Geophys. Res. Lett., 32, doi:10.1029/2005GL022845, 2005.

Déry, S. J., Stieglitz, M., McKenna, E. C. and Wood, E. F.: Characteristics and trends of river discharge into Hudson, James, and Ungava Bays, 1964-2000, J. Clim., 18, 2540–2557, doi:10.1175/JCLI3440.1, 2005.

Duguay, C. R., Flato, G. M., Jeffries, M. O., Ménard, P., Morris, K. and Rouse, W. R.: Ice-cover variability on shallow lakes at high latitudes: Model simulations and observations, Hydrol. Process., 17, 3465–3483, doi:10.1002/hyp.1394, 2003.

Duguay, C. R., Prowse, T. D., Bonsal, B. R., Brown, R. D., Lacroix, M. P. and Ménard, P.: Recent trends in Canadian lake ice cover, Hydrol. Process., 20, 781–801, doi:10.1002/hyp.6131, 2006.

Emilson, E. J. S., Carson, M. A., Yakimovich, K. M., Osterholz, H., Dittmar, T., Gunn, J. M., Mykytczuk, N. C. S., Basiliko, N. and Tanentzap, A. J.: Climate-driven shifts in sediment chemistry enhance methane production in northern lakes, Nat. Commun., doi:10.1038/s41467-018-04236-2, 2018.

Enfield, D. B., Mestas-Nuñez, A. M. and Trimble, P. J.: The Atlantic multidecadal oscillation and its relation to rainfall and river flows in the continental U.S, Geophys. Res. Lett., 28(10), 2077–2080, doi:10.1029/2000GL012745, 2001.

Freeman, E., Woodruff, S. D., Worley, S. J., Lubker, S. J., Kent, E. C., Angel, W. E., Berry, D. I., Brohan, P., Eastman, R., Gates, L., Gloeden, W., Ji, Z., Lawrimore, J., Rayner, N. A., Rosenhagen, G. and Smith, S. R.: ICOADS Release 3.0: a major update to the historical marine climate record, Int. J. Climatol., 37, 2211–2237, doi:10.1002/joc.4775, 2017.

Futter, M. N.: Patterns and trends in southern Ontario lake ice phenology, Environ. Monit. Assess., doi:10.1023/A:1025549913965, 2003.

Gebre, S. B. and Alfredsen, K. T.: Investigation of river ice regimes in some Norwegian water courses, in 16th Workshop on River Ice, CGU HS Committee on River Ice Processes and the Environment, Winnipeg, Manitoba, Manitoba., 2011.

George, D. G.: The impact of the North Atlantic oscillation on the development of ice on Lake Windermere, Clim. Change, 81, 455–468, doi:10.1007/s10584-006-9115-5, 2007.

Ghanbari, R. N., Bravo, H. R., Magnuson, J. J., Hyzer, W. G. and Benson, B. J.: Coherence between lake ice cover, local climate and teleconnections (Lake Mendota, Wisconsin), J. Hydrol., 374, 282–293, doi:10.1016/j.jhydrol.2009.06.024, 2009.

~~Hansen, J., Ruedy, R., Lea, D. W., Sato, M., Medina-Elizade, M. and Lo, K.: Global temperature change, Proc. Natl. Acad. Sci., 103(39), 14288.14293, doi:10.1073/pnas.0606291103, 2006.~~

Harris, I., Jones, P. D., Osborn, T. J. and Lister, D. H.: Updated high-resolution grids of monthly climatic observations - the CRU TS3.10 Dataset, Int. J. Climatol., 34, 623–642, doi:10.1002/joc.3711, 2014.

Hewitt, B. A., Lopez, L. S., Gaibisels, K. M., Murdoch, A., Higgins, S. N., Magnuson, J. J., Paterson, A. M., Rusak, J. A., Yao, H. and Sharma, S.: Historical trends, drivers, and future projections of ice phenology in small north temperate lakes in the Laurentian Great Lakes Region, Water (Switzerland), doi:10.3390/w10010070, 2018.

Hodgkins, G. A., Dudley, R. W. and Huntington, T. G.: Changes in the number and timing of days of ice-affected flow on northern New England rivers, 1930-2000, Clim. Change, 71, 319–340, doi:10.1007/s10584-005-5926-z, 2005.

Hurrell, J. W.: Decadal trends in the North Atlantic oscillation: Regional temperatures and precipitation, Science (80-.)., 269, 676–679, doi:10.1126/science.269.5224.676, 1995.

IPCC: Summary for Policymakers., 2013.

Jeffries, M. O. and Morris, K.: Some aspects of ice phenology on ponds in central Alaska, USA, Ann. Glaciol., 46, 397–403, doi:10.3189/172756407782871576, 2007.

Jensen, O. P., Benson, B. J., Magnuson, J. J., Card, V. M., Futter, M. N., Soranno, P. A. and Stewart, K. M.: Spatial analysis of ice phenology trends across the Laurentian Great Lakes region during a recent warming period, Limnol. Oceanogr., 52(5), 2013–2026, doi:10.4319/lo.2007.52.5.2013, 2007.

Jiang, Y., Dong, W., Yang, S. and Ma, J.: Long-term changes in ice phenology of the Yellow River in the past decades, J. Clim., 21, 4879–4886, doi:10.1175/2008JCLI1872.1, 2008.

Jones, P. D., Jonsson, T. and Wheeler, D.: Extension to the North Atlantic oscillation using early instrumental pressure observations from Gibraltar and south-west Iceland, Int. J. Climatol., 17, 1433–1450, doi:10.1002/(sici)1097-0088(19971115)17:13<1433::aid-joc203>3.0.co;2-p, 1997.

Karetnikov, S. G. and Naumenko, M. A.: Recent trends in Lake Ladoga ice cover, Hydrobiologia, 599, 41–48, doi:10.1007/s10750-007-9211-1, 2008.

Korhonen, J.: Long-term changes in lake ice cover in Finland*, Nord. Hydrol., 4, 347–363, doi:10.2166/nh.2006.019, 2006.

Kouraev, A. V., Semovski, S. V., Shimaraev, M. N., Mognard, N. M., Legrés, B. and Remy, F.: The ice regime of Lake Baikal from historical and satellite data: Relationship to air temperature, dynamical, and other factors, Limnol. Oceanogr., 52, 1268–1286, doi:10.4319/lo.2007.52.3.1268, 2007.

Lacroix, M. P., Prowse, T. D., Bonsal, B. R., Duguay, C. R. and Menard, P.: River ice trends in Canada, 13th Work. Hydraul. ice Cover. rivers, Hanover, NH, Sept. 15-16, 2005, 2005.

Latifovic, R. and Pouliot, D.: Analysis of climate change impacts on lake ice phenology in Canada using the historical satellite data record, Remote Sens. Environ., 106, 492–507, doi:10.1016/j.rse.2006.09.015, 2007.

Leppäranta, M.: Freezing of lakes and the evolution of their ice cover., 2015.

Livingstone, D. M.: Break-up dates of Alpine lakes as proxy data for local and regional mean surface air temperatures, Clim. Change, 37(2), 407–439, doi:10.1023/A:1005371925924, 1997.

Livingstone, D. M.: Ice break-up on southern Lake Baikal and its relationship to local and regional air temperatures in Siberia and to the North Atlantic Oscillation, Limnol. Oceanogr., 44, 1486–1497, doi:10.4319/lo.1999.44.6.1486, 1999.

Livingstone, D. M.: Large-scale climatic forcing detected in historical observations of lake ice break-up, Int. Vereinigung für Theor. und Angew. Limnol. Verhandlungen, 27, 2775–2783, 2000a.

Livingstone, D. M.: Large-scale climatic forcing detected in historical observations of lake ice break-up, Verh. Internat. Verein. Limnol., 27, 2775–2783, 2000b.

Livingstone, D. M. and Adrian, R.: Modeling the duration of intermittent ice cover on a lake for climate-change studies, Limnol. Oceanogr., 54, 1709–1722, doi:10.4319/lo.2009.54.5.1709, 2009.

Magnuson, J. J., Robertson, D. M., Benson, B. J., Wynne, R. H., Livingstone, D. M., Arai, T., Assel, R. A., Barry, R. G., Card, V., Kuusisto, E., Granin, N. G., Prowse, T. D., Stewart, K. M. and Vuglinski, V. S.: Historical trends in lake and river ice cover in the Northern Hemisphere, Science (80-.)., 289(5485), 1743–1746, doi:10.1126/science.289.5485.1743, 2000a2000.

Magnuson, J. J., Robertson, D. M., Benson, B. J., Wynne, R. H., Livingstone, D. M., Arai, T., Assel, R. A., Barry, R. G., Card, V., Kuusisto, E., Granin, N. G., Prowse, T. D., Stewart, K. M. and Vuglinski, V. S.: Historical trends in lake and river ice cover in the Northern Hemisphere, Science (80-.)., doi:10.1126/science.289.5485.1743, 2000b.

Magnuson, J. J., Benson, B. J., Jensen, O. P., Clark, T. B., Card, V., Futter, M. N., Soranno, P. A. and Stewart, K. M.: Persistence of coherence of ice-off dates for inland lakes across the Laurentian Great Lakes region, Int. Vereinigung für Theor. und Angew. Limnol., 29, 521–527, 2005.

Marszelewski, W. and Skowron, R.: Ice cover as an indicator of winter air temperature changes: Case study of the Polish Lowland lakes, Hydrol. Sci. J., 51, 336–349, doi:10.1623/hysj.51.2.336, 2006.

Mullan, D., Swindles, G., Patterson, T., Galloway, J., Macumber, A., Falck, H., Crossley, L., Chen, J. and Pisaric, M.: Climate change and the long-term viability of the World's busiest heavy haul ice road, Theor. Appl. Climatol., 129, 1089–1108, doi:10.1007/s00704-016-1830-x, 2017.

Nõges, P. and Nõges, T.: Weak trends in ice phenology of Estonian large lakes despite significant warming trends, Hydrobiologia, 731, 5–18, doi:10.1007/s10750-013-1572-z, 2014.

van Oldenborgh, G. J., te Raa, L. A., Dijkstra, H. A. and Philip, S. Y.: Frequency- or amplitude-dependent effects of the Atlantic meridional overturning on the tropical Pacific Ocean, Ocean Sci., 5, 293–301, doi:10.5194/os-5-293-2009, 2009.

Palecki, M. A. and Barry, R. G.: Freeze-up and Break-up of Lakes as an Index of Temperature Changes during the Transition Seasons: A Case Study for Finland, J. Clim. Appl. Meteorol., 25, 893–902, doi:10.1175/1520-0450(1986)025<0893:FUABUO>2.0.CO;2, 1986.

Park, H., Yoshikawa, Y., Oshima, K., Kim, Y., Ngo-Duc, T., Kimball, J. S. and Yang, D.: Quantification of warming climate-induced changes in terrestrial Arctic river ice thickness and phenology, J. Clim., 29, 1733–1754, doi:10.1175/JCLI-D-15-0569.1, 2016.

Prowse, T., Alfredsen, K., Beltaos, S., Bonsal, B., Duguay, C., Korhola, A., McNamara, J., Pienitz, R., Vincent, W. F., Vuglinsky, V. and Weyhenmeyer, G. A.: Past and future changes in arctic lake and river ice, Ambio, 40, 53–62, doi:10.1007/s13280-011-0216-7, 2011.

~~Prowse, T. D. and Beltaos, S.: Climatic control of river-ice hydrology: A review, Hydrol. Process., 16, 805–822, doi:10.1002/hyp.369, 2002.~~

Rees, W. G., Stammler, F. M., Danks, F. S. and Vitebsky, P.: Vulnerability of European reindeer husbandry to global change, Clim. Change, doi:10.1007/s10584-007-9345-1, 2008.

Rouse, W. R., Oswald, C. M., Binyamin, J., Blanken, P. D., Schertzer, W. M. and Spence, C.: Interannual and Seasonal Variability of the Surface Energy Balance and Temperature of Central Great Slave Lake, J. Hydrometeorol., 4(4), 720–730, doi:10.1175/1525-7541(2003)004<0720:IASVOT>2.0.CO;2, 2003.

Salmi, T., Maatta, A., Anttila, P., Ruoho-Airola, T. and Amnell, T.: Detecting Trends of Annual Values of Atmospheric Pollutants by the Mann-Kendall Test and Sen's Solpe Estimates the Excel Template Application MAKESENS, Finnish Meteorol. Institute, Air Qual. Res., doi:456-789X, 2002.

Šarauskienė, D. and Jurgelėnaitė, A.: Impact of Climate Change on River Ice Phenology in Lithuania, Environ. Res. Eng. Manag., 46, 13–22, 2008.

~~Serreze, M. C., Walsh, J. E., Chapin, F. S., Osterkamp, T., Dyurgerov, M., Romanovsky, V., Oechel, W. C., Morison, J., Zhang, T. and Barry, R. G.: Observational evidence of recent change in the northern high-latitude environment, Clim. Change, 46, 159–207, doi:10.1023/a:1005504031923, 2000.~~

Sharma, S. and Magnuson, J. J.: Oscillatory dynamics do not mask linear trends in the timing of ice breakup for Northern Hemisphere lakes from 1855 to 2004, Clim. Change, 124, 835–847, doi:10.1007/s10584-014-1125-0, 2014.

Sharma, S., Magnuson, J. J., Mendoza, G. and Carpenter, S. R.: Influences of local weather, large-scale climatic drivers, and the ca. 11 year solar cycle on lake ice breakup dates; 1905-2004, Clim. Change, 118, 857–870, doi:10.1007/s10584-012-0670-7, 2013.

Sharma, S., Magnuson, J. J., Batt, R. D., Winslow, L. A., Korhonen, J. and Aono, Y.: Direct observations of ice seasonality reveal changes in climate over the past 320-570 years, Sci. Rep., 25061, doi:10.1038/srep25061, 2016.

Sharma, S., Blagrave, K., Magnuson, J. J., O'Reilly, C. M., Oliver, S., Batt, R. D., Magee, M. R., Straile, D., Weyhenmeyer, G. A., Winslow, L. and Woolway, R. I.: Widespread loss of lake ice around the Northern Hemisphere in a warming world, Nat. Clim. Chang., doi:10.1038/s41558-018-0393-5, 2019.

Šmejkalová, T., Edwards, M. E. and Dash, J.: Arctic lakes show strong decadal trend in earlier spring ice-out, Sci. Rep., 38449, doi:10.1038/srep38449, 2016.

Smith, L. C.: Trends in russian arctic river-ice formation and breakup, 1917 to 1994, Phys. Geogr., 21, 46–56, doi:10.1080/02723646.2000.10642698, 2000.

Stonevicius, E., Stankunavicius, G. and Kilkus, K.: Ice regime dynamics in the Nemunas River, Lithuania, Clim. Res., 36, 17–28, doi:10.3354/cr00707, 2008.

Stottlemyer, R. and Toczydlowski, D.: Seasonal change in precipitation, snowpack, snowmelt, soil water and streamwater chemistry, northern Michigan, Hydrol. Process., doi:10.1002/(SICI)1099-1085(199910)13:14/15<2215::AID-HYP882>3.0.CO;2-V, 1999.

Thompson, D. W. J. and Wallace, J. M.: Annular modes in the extratropical circulation. Part I: Month-to-month variability, J. Clim., 13, 1000–1016, doi:10.1175/1520-0442(2000)013<1000:AMITEC>2.0.CO;2, 2000.

Todd, M. C. and Mackay, A. W.: Large-scale climatic controls on Lake Baikal Ice Cover, J. Clim., 16, 3186–3199, doi:10.1175/1520-0442(2003)016<3186:LCCOLB>2.0.CO;2, 2003.

Vuglinsky, V. S.: Peculiarities of ice events in Russian Arctic rivers, Hydrol. Process., 16, 905–913, doi:10.1002/hyp.365, 2002.

Weyhenmeyer, G. A., Meili, M. and Livingstone, D. M.: Nonlinear temperature response of lake ice breakup, Geophys. Res. Lett., doi:10.1029/2004GL019530, 2004.

Weyhenmeyer, G. A., Livingstone, D. M., Meili, M., Jensen, O., Benson, B. and Magnuson, J. J.: Large geographical differences in the sensitivity of ice-covered lakes and rivers in the Northern Hemisphere to temperature changes, Glob. Chang. Biol., doi:10.1111/j.1365-2486.2010.02249.x, 2011.

White, K. D., Tuthill, A. M., Vuyovich, C. M. and Weyrick, P. B.: Observed Climate Variability Impacts and River Ice in the United States., 2007.

Williams, G. P.: Correlating Freeze-Up and Break-Up with Weather Conditions, Can. Geotech. J., 2, 313–326, doi:10.1139/t65-047, 1965.

Williams, S. G. and Stefan, H. G.: Modeling of Lake Ice Characteristics in North America Using Climate, Geography, and Lake Bathymetry, J. Cold Reg. Eng., 20, 140–167, doi:10.1061/(ASCE)0887-381X(2006)20:4(140), 2006.

Wynne, R. H.: Statistical modeling of lake ice phenology: Issues and implications, Int. Vereinigung für Theor. und Angew. Limnol. Verhandlungen, 27(5), 2820–2825, 2000.

Yue, S., Pilon, P. and Cavadias, G.: Power of the Mann-Kendall and Spearman's rho tests for detecting monotonic trends in hydrological series, J. Hydrol., 259, 254–271, doi:10.1016/S0022-1694(01)00594-7, 2002.