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Climate change and Northern Hemisphere lake and river ice phenology

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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 time series from across 644 Northern Hemisphere lakes and river to explore historical patterns in lake and river ice phenology across four time periods (1931-1960, 1961-1990, 1991-2005, and 1931-2005). These time series show later breakup dates by 0.6 days per decade from 1931-2005 across North America and Europe, with trends closely correlating with temperature. Freezeup trends are more spatiotemporally complex 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 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. 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 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.

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). 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 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 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). In the last century the number of ice phenology observations have 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 individual time series from 644 Northern Hemisphere study sites. This database is used to explore the spatiotemporal variability of lake and river ice breakup/freezeup dates from 1931-2005. Observed changes are then compared with climate records and atmospheric/oceanic modes of variability to understand their respective roles in driving the observed ice phenology patterns.

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 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 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
North America	Hodgkins et al. (2005)	1930-2000	- River sites in New England show a decrease in ice season length of 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)	1693-2002	- In Finland there are significant trends towards earlier breakup in the later 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 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 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)	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. (2014)	1854-2004	- All 13 lake study sites demonstrated oscillatory dynamics were influential on 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

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 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 and Eurasia (Fig. 1). It is important to note that in the later part of the 1980s and 1990s many Russian and Canadian sites stopped recording data.

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. (2012). To understand the spatiotemporal patterns of ice phenology, four time periods were studied: 1931-1960, 1961-1990, 1991-2005, and 1931-2005. 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 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 sites had data with at least 90% coverage for either freezeup or breakup for at least one time period. These data provide ~2600 individual time series and are spread across the Northern Hemisphere (Fig. 1a) but are primarily concentrated in North America (Fig. 1b) and Fennoscandia (Fig. 1c). Time series covering 1931-2005 were available, with 88 sites (three rivers) having breakup data, 48 sites (two rivers) with freezeup data, and 37 sites (one river) with data for the number of annual open water days. Of these sites the majority in North America are to the east and west of the Laurentian Great Lakes (Fig. 1d). In northwest Europe the sites are predominantly in Sweden and Finland (Fig. 1e), with one site (Lej da San Murezzan) in Switzerland. In Russia there is only one site in the southwest of Lake Baikal.

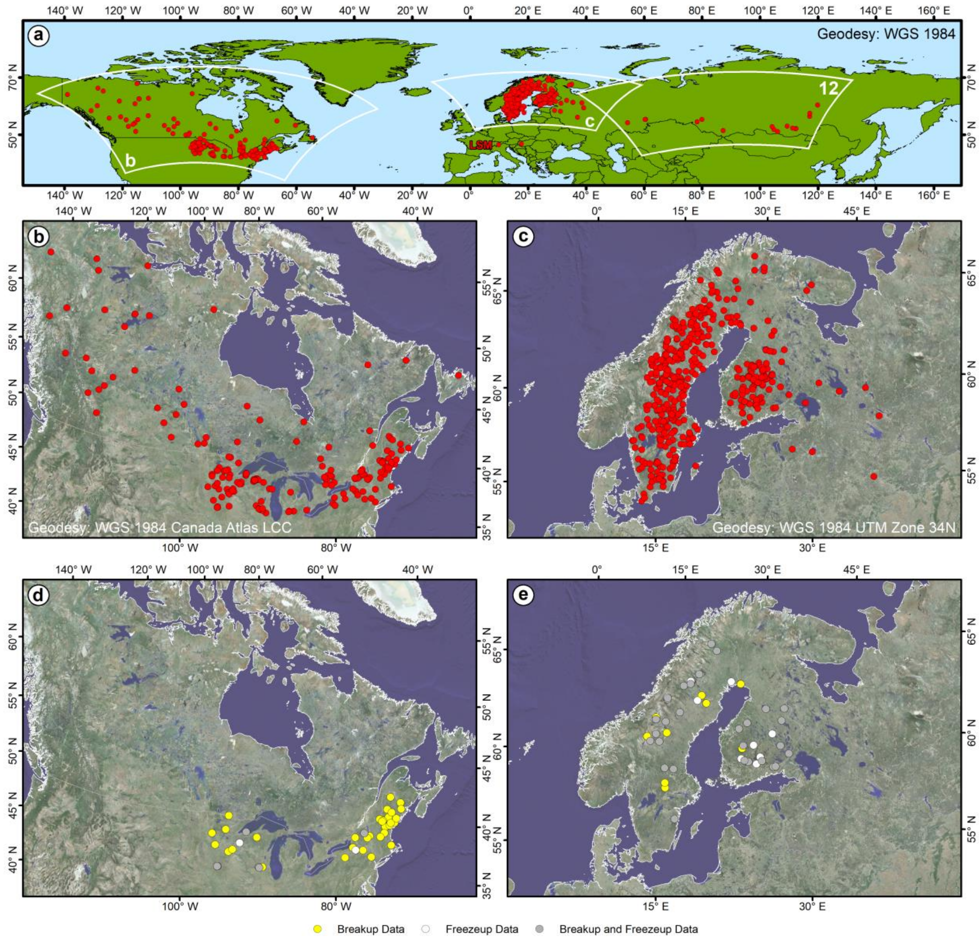


Figure 1: **a**) Map showing study sites (red circles) with time series containing at least 90% coverage for breakup and/or freezeup during at least one time period. Location of other panels and figures are shown; **b**) North American study sites; **c**) Fennoscandian study sites. Note that different 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 in subsequent figures.

Breakup/freezeup dates were first converted to Julian days. For some sites, freezeup or breakup in a specific year occasionally fell in a preceding or succeeding year and the Julian 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 day allocated was 370. Likewise, if breakup for the 1943 ice season occurred on the 28th December 1942 then the Julian date allocated was -3. These records were adjusted as necessary to calculate the number of annual open water days. The Julian day records were tested using the Mann-Kendall test where the null hypothesis (H_o) 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 does not calculate trend magnitude, so Sen's slope was used (Yue et al., 2002). These two statistical techniques are explained briefly below and a full definition is provided by Salmi et al. (2002).

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:

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

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

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

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

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

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.

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

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:

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

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 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 (FEN): 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. 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) were also extracted.

Ice breakup/freezeup records from the IPD were spatially averaged into three regional composite records corresponding to the three geographical regions (FEN, 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. Ice phenology change

A climate regime with increasing mean 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 earlier breakup, later freezeup dates, or a combination of both that leaves a relative increase in the number of open water days. Decadal trends 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 rather than a specific shift in the precise 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 are presented before an in-depth analysis of the changes observed in 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 Russia, likely owing to the extensive geographical spread of only a few study sites. In Europe, successive 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 year. This is evidenced by the increased clustering of breakup dates within the first 100 days of the 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.

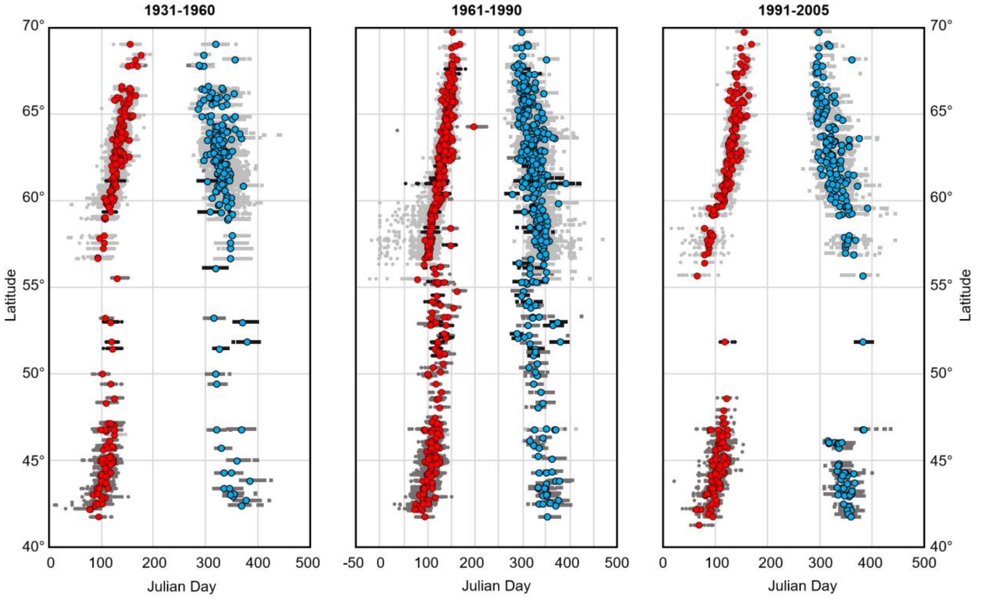


Figure 2: Summary graphs showing breakup and freezeup dates against latitude for the three short time periods. Red and blue data points represent study site median breakup and freezeup dates, respectively. Light grey observations are breakup/freezeup dates for study sites in Europe, dark grey sites across Russia, and intermediate grey is North American sites. 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.

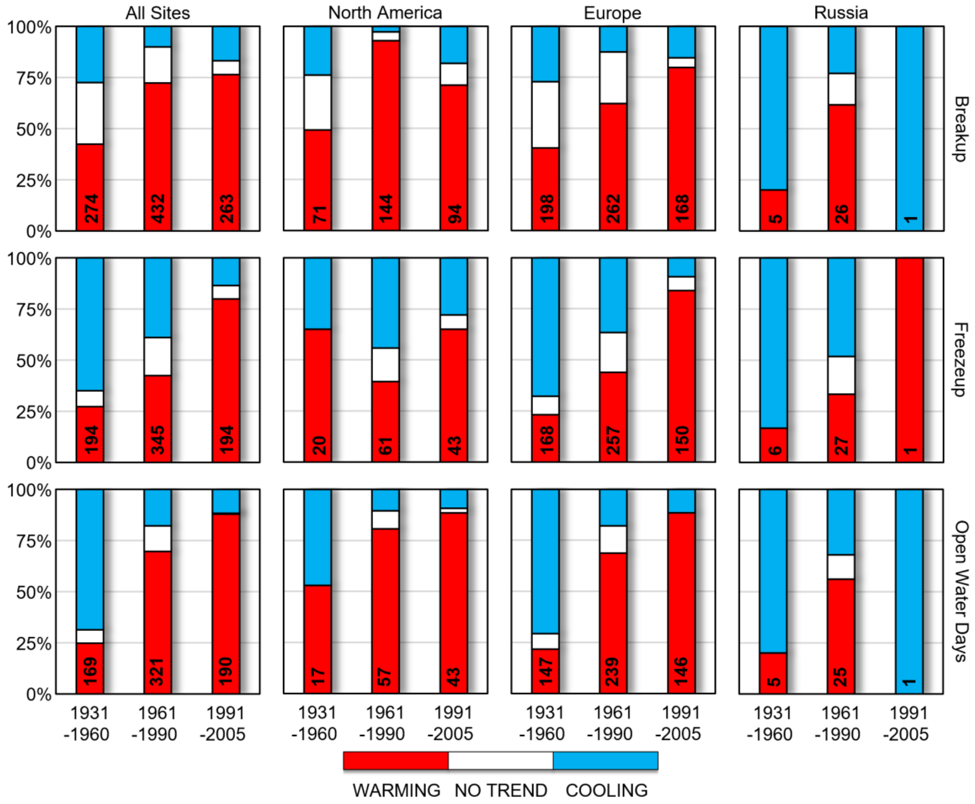


Figure 3: Summary charts showing generalised decadal patterns. The percentages are calculated as a proportion of the total number of sites for each time period (bold text – e.g. in the first panel, across the Northern Hemisphere data there are 263 sites with 1991-2005 breakup data. Note that a warming 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 open water charts a positive trend indicates an increase in the number of annual open water days.

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 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 Hemisphere	1931-1960	-0.14	-0.6	-0.16	-2.11	3.08	-1.82	-2.18	3.33	-1.92
	1961-1990	-1.51	-1.98	-1.53	0.22	0.07	0.21	1.94	1.46	1.92
	1991-2005	-3.47	-2.23	-3.44	7.78	11.98	7.83	12.25	14.77	12.28
	1931-2005	-0.59	-0.23	-0.58	-0.01	0.70	0.02	0.60	1.62	0.63
Europe	1931-1960	-0.11	-0.22	-0.12	-2.31	3.52	-2.13	-2.24	3.38	-2.09
	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	-1.09	-0.36	0.05	2.71	0.85	-1.39	3.29	-0.29
	1961-1990	-3.11	-1.92	-2.98	-0.24	0.04	-0.18	3.08	1.30	2.77
	1991-2005	-2.79	N/A	-2.79	5.09	N/A	5.09	9.29	N/A	9.29
	1931-2005	-0.66	N/A	-0.66	0.84	N/A	0.84	1.49	N/A	1.49
Russia	1931-1960	0.83	N/A	0.83	-1.92	N/A	-1.92	-2.47	N/A	-2.47
	1961-1990	-0.83	N/A	-0.83	-0.03	N/A	-0.03	1.03	N/A	1.03
	1991-2005	5.00	N/A	5.00	5.00	N/A	5.00	-2.00	N/A	-2.00
	1931-2005	0.00	N/A	0.00	1.04	N/A	1.04	1.53	N/A	1.53

Table 2: Breakdown of mean decadal trends for each time period where each value is the number of days change per decade. 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.

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. 4b). 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.

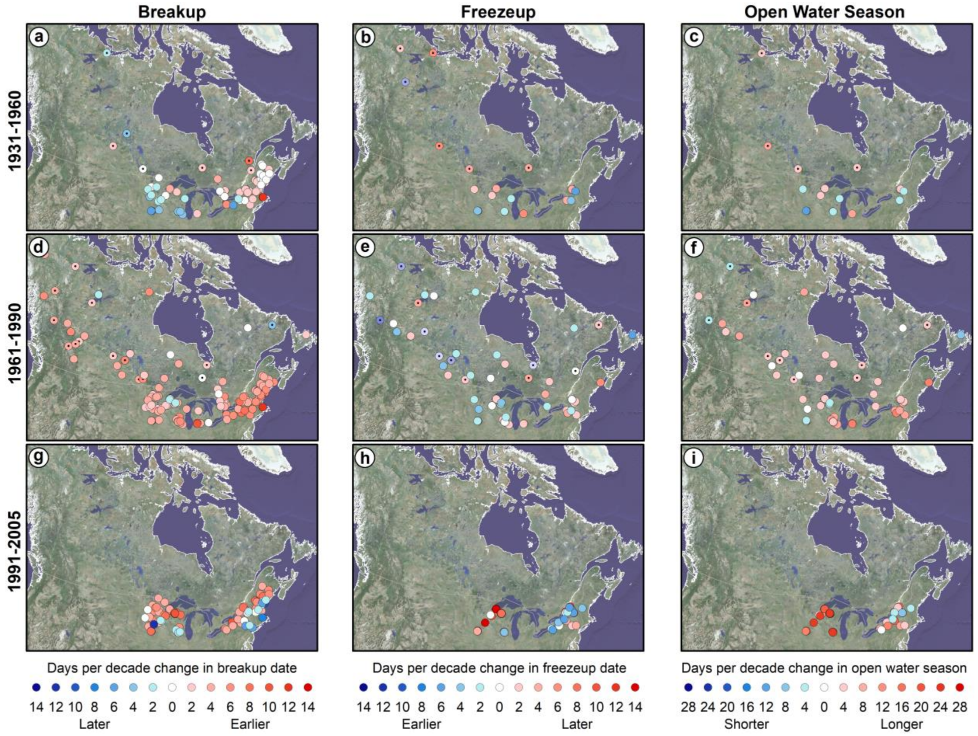


Figure 4: Decadal trends for breakup (**a**, **d**, and **g**), freezeup (**b**, **e**, and **h**), and length of the open water season (**c**, **f**, and **i**) in North America for the three individual time periods. Sites with a dot in the centre of the circle are river sites. Blue and red tones on 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} ($\alpha = 0.05$). 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 Bay (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).

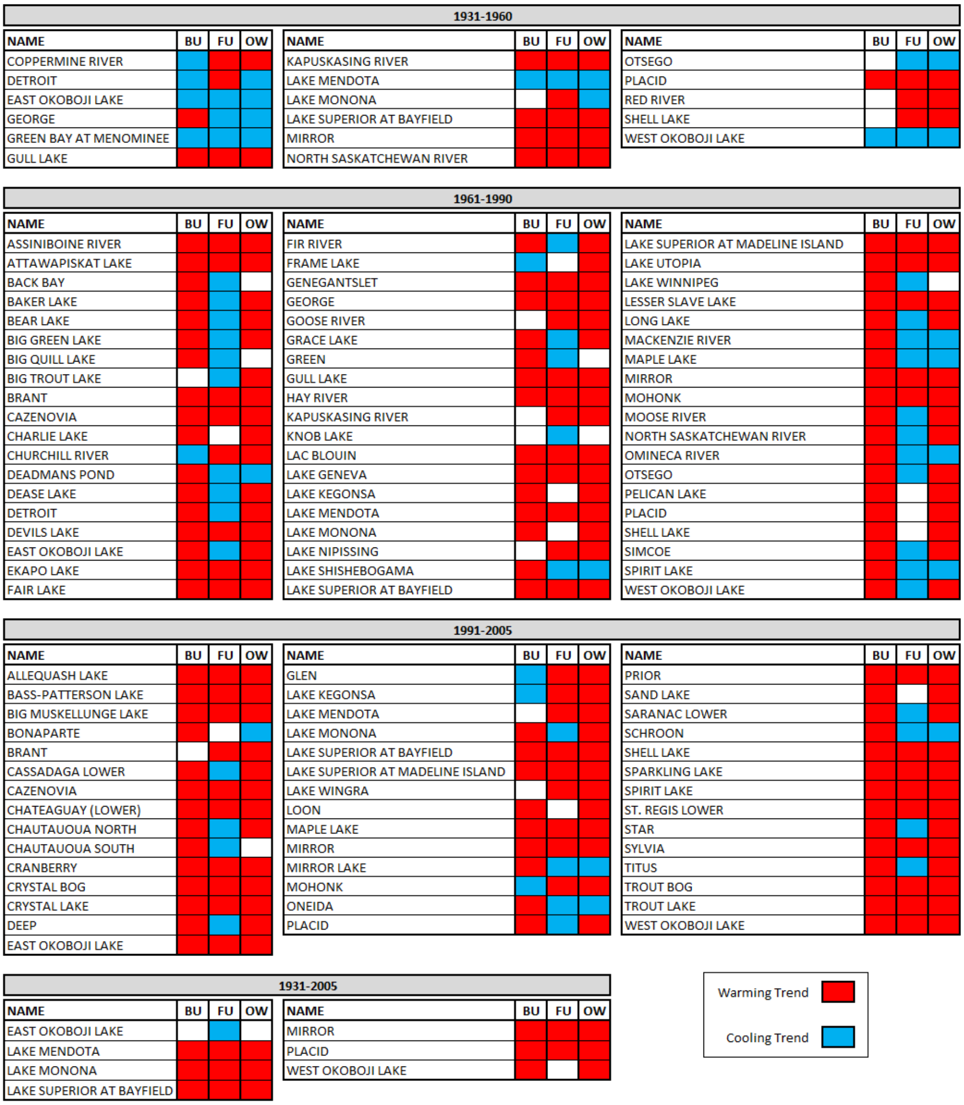
Freezeup date changes show that a longitudinal split occurs during 1961-1990. Sites are generally dominated by earlier freezeup trends in the west and later trends in the east (Fig. 4e). The mean trend direction across North America is for freezeup dates to become earlier by 0.2 days decade^{-1}. However, 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.

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	

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.

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.



1931-1960

NAME	BU	FU	OW	NAME	BU	FU	OW	NAME	BU	FU	OW
COPPERMINE RIVER	🟦	🟥	🟥	KAPUSKASING RIVER	🟥	🟥	🟥	OTSEGO		🟦	🟦
DETROIT	🟦	🟥	🟦	LAKE MENDOTA	🟦	🟦	🟦	PLACID	🟥	🟥	🟥
EAST OKOBOJI LAKE	🟦	🟦	🟦	LAKE MONONA		🟥	🟦	RED RIVER		🟥	🟥
GEORGE	🟥	🟦	🟦	LAKE SUPERIOR AT BAYFIELD	🟥	🟥	🟥	SHELL LAKE		🟥	🟥
GREEN BAY AT MENOMINEE	🟦	🟦	🟦	MIRROR	🟥	🟥	🟥	WEST OKOBOJI LAKE	🟦	🟦	🟦
GULL LAKE	🟥	🟥	🟥	NORTH SASKATCHEWAN RIVER	🟥	🟥	🟥				

1961-1990

NAME	BU	FU	OW	NAME	BU	FU	OW	NAME	BU	FU	OW
ASSINIBOINE RIVER	🟥	🟥	🟥	FIR RIVER	🟥	🟦	🟥	LAKE SUPERIOR AT MADELINE ISLAND	🟥	🟥	🟥
ATTAWAPISKAT LAKE	🟥	🟥	🟥	FRAME LAKE	🟦		🟥	LAKE UTOPIA	🟥	🟥	🟥
BACK BAY	🟥	🟦		GENEGANTSLET	🟥	🟥	🟥	LAKE WINNIPEG	🟥	🟦	
BAKER LAKE	🟥	🟦	🟥	GEORGE	🟥	🟥	🟥	LESSER SLAVE LAKE	🟥	🟥	🟥
BEAR LAKE	🟥	🟦	🟥	GOOSE RIVER		🟥	🟥	LONG LAKE	🟥	🟦	🟥
BIG GREEN LAKE	🟥	🟦	🟥	GRACE LAKE	🟥	🟦	🟥	MACKENZIE RIVER	🟥	🟦	🟦
BIG QUILL LAKE	🟥	🟦		GREEN	🟥	🟦		MAPLE LAKE	🟥	🟦	🟦
BIG TROUT LAKE		🟦	🟥	GULL LAKE	🟥	🟥	🟥	MIRROR	🟥	🟥	🟥
BRANT	🟥	🟥	🟥	HAY RIVER	🟥	🟥	🟥	MOHONK	🟥	🟥	🟥
CAZENOVIA	🟥	🟥	🟥	KAPUSKASING RIVER		🟥	🟥	MOOSE RIVER	🟥	🟦	🟥
CHARLIE LAKE	🟥		🟥	KNOB LAKE		🟦		NORTH SASKATCHEWAN RIVER	🟥	🟦	🟥
CHURCHILL RIVER	🟦	🟥	🟥	LAC BLOUIN	🟥	🟥	🟥	OMINECA RIVER	🟥	🟦	🟦
DEADMANS POND	🟥	🟦	🟦	LAKE GENEVA	🟥	🟥	🟥	OTSEGO	🟥	🟦	🟥
DEASE LAKE	🟥	🟦	🟥	LAKE KEGONSA	🟥		🟥	PELICAN LAKE	🟥		🟥
DETROIT	🟥	🟦	🟥	LAKE MENDOTA	🟥	🟥	🟥	PLACID	🟥		🟥
DEVILS LAKE	🟥	🟥	🟥	LAKE MONONA	🟥		🟥	SHELL LAKE	🟥		🟥
EAST OKOBOJI LAKE	🟥	🟦	🟥	LAKE NIPISSING		🟥	🟥	SIMCOE	🟥	🟦	🟥
EKAPO LAKE	🟥	🟥	🟥	LAKE SHISHEBOGAMA	🟥	🟦	🟦	SPIRIT LAKE	🟥	🟦	🟦
FAIR LAKE	🟥	🟥	🟥	LAKE SUPERIOR AT BAYFIELD	🟥	🟥	🟥	WEST OKOBOJI LAKE	🟥	🟦	🟥

1991-2005

NAME	BU	FU	OW	NAME	BU	FU	OW	NAME	BU	FU	OW
ALLEQUASH LAKE	🟥	🟥	🟥	GLEN	🟦	🟥	🟥	PRIOR	🟥	🟥	🟥
BASS-PATTERSON LAKE	🟥	🟥	🟥	LAKE KEGONSA	🟦	🟥	🟥	SAND LAKE	🟥		🟥
BIG MUSKELLUNGE LAKE	🟥	🟥	🟥	LAKE MENDOTA		🟥	🟥	SARANAC LOWER	🟥	🟦	🟥
BONAPARTE	🟥		🟦	LAKE MONONA	🟥	🟦	🟥	SCHROON	🟥	🟦	🟦
BRANT		🟥	🟥	LAKE SUPERIOR AT BAYFIELD	🟥	🟥	🟥	SHELL LAKE	🟥	🟥	🟥
CASSADAGA LOWER	🟥	🟦	🟥	LAKE SUPERIOR AT MADELINE ISLAND	🟥	🟥	🟥	SPARKLING LAKE	🟥	🟥	🟥
CAZENOVIA	🟥	🟥	🟥	LAKE WINGRA		🟥	🟥	SPIRIT LAKE	🟥	🟥	🟥
CHATEAGUAY (LOWER)	🟥	🟥	🟥	LOON	🟥		🟥	ST. REGIS LOWER	🟥	🟥	🟥
CHAUTAUOUA NORTH	🟥	🟦	🟥	MAPLE LAKE	🟥	🟥	🟥	STAR	🟥	🟦	🟥
CHAUTAUOUA SOUTH	🟥	🟦		MIRROR	🟥	🟥	🟥	SYLVIA	🟥	🟥	🟥
CRANBERRY	🟥	🟥	🟥	MIRROR LAKE	🟥	🟦	🟦	TITUS	🟥	🟦	🟥
CRYSTAL BOG	🟥	🟥	🟥	MOHONK	🟦	🟥	🟥	TROUT BOG	🟥	🟥	🟥
CRYSTAL LAKE	🟥	🟥	🟥	ONEIDA	🟥	🟦	🟦	TROUT LAKE	🟥	🟥	🟥
DEEP	🟥	🟦	🟥	PLACID	🟥	🟦	🟥	WEST OKOBOJI LAKE	🟥	🟥	🟥
EAST OKOBOJI LAKE	🟥	🟥	🟥								

1931-2005

NAME	BU	FU	OW	NAME	BU	FU	OW
EAST OKOBOJI LAKE		🟦		MIRROR	🟥	🟥	🟥
LAKE MENDOTA	🟥	🟥	🟥	PLACID	🟥	🟥	🟥
LAKE MONONA	🟥	🟥	🟥	WEST OKOBOJI LAKE	🟥		🟥
LAKE SUPERIOR AT BAYFIELD	🟥	🟥	🟥				

Warming Trend 🟥
Cooling Trend 🟦

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.

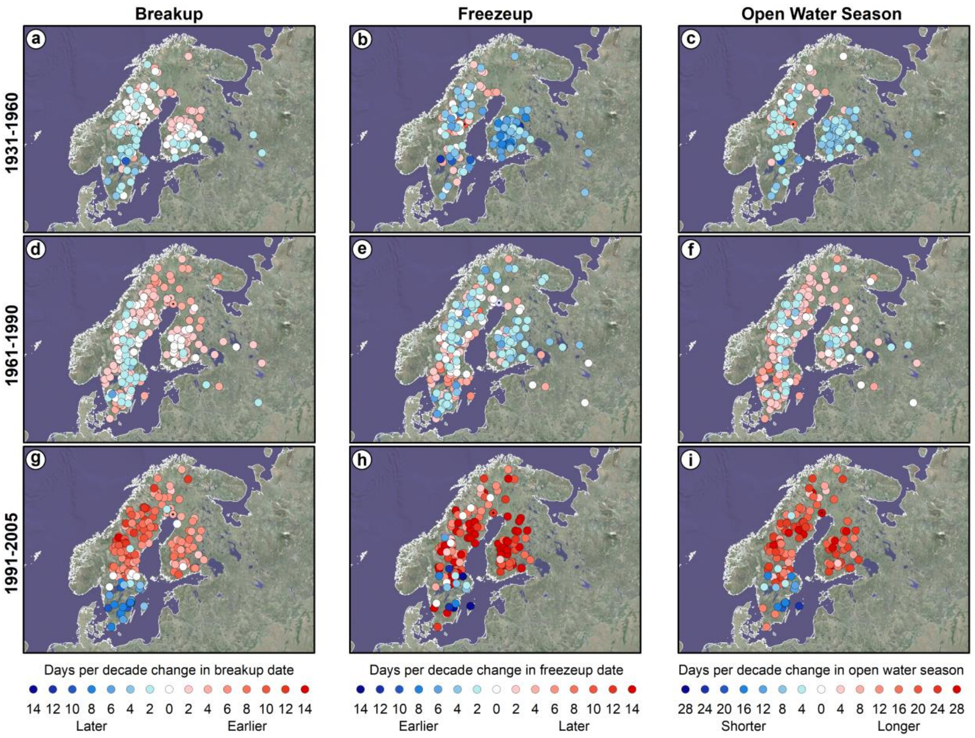
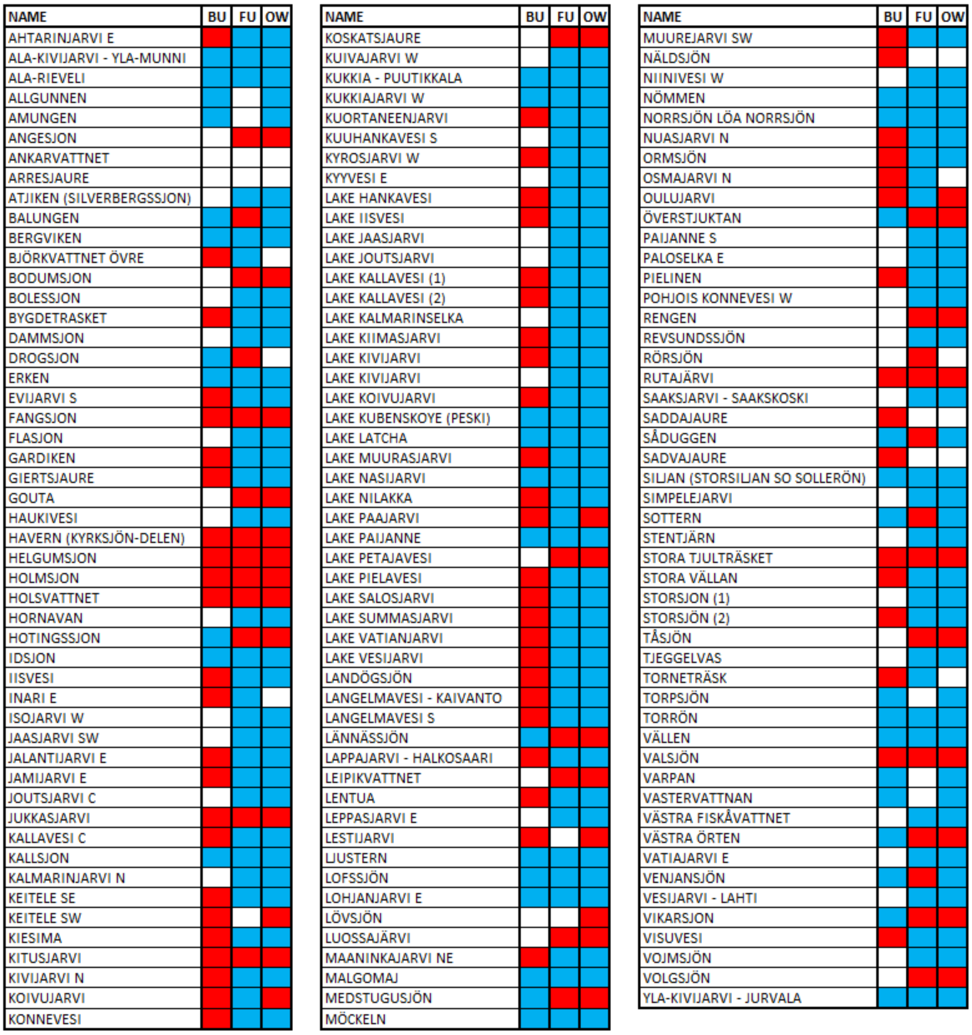


Figure 6: Decadal trends for breakup (**a**, **d**, and **g**), freezeup (**b**, **e**, and **h**), and length of the open water season (**c**, **f**, and **i**) in Fennoscandia for the three individual time periods. Sites with a dot in the centre of the circle are river sites. Blue and red tones on the scales related to cooling and warming signals, respectively.



NAME	BU	FU	OW
AHTARINJARVI E	🟥	🟦	🟦
ALA-KIVIJARVI - YLA-MUNNI	🟦	🟦	🟦
ALA-RIEVELI	🟦	🟦	🟦
ALLGUNNEN	🟦	⬜	🟦
AMUNGEN	🟦	⬜	🟦
ANGESJON	⬜	🟥	🟥
ANKARVATTNET	⬜	⬜	⬜
ARRESJAURE	⬜	⬜	⬜
ATJIKEN (SILVERBERGSSJON)	⬜	🟦	🟦
BALUNGEN	🟦	🟥	🟦
BERGVIKEN	🟦	🟦	🟦
BJÖRKVATTNET ÖVRE	🟥	🟦	⬜
BODUMSJON	⬜	🟥	🟥
BOLESSJON	⬜	🟦	🟦
BYGDETRASKET	🟥	🟦	🟦
DAMMSJON	⬜	🟦	🟦
DROGSJON	🟦	🟥	⬜
ERKEN	🟦	🟦	🟦
EVIJARVI S	🟥	🟦	🟦
FANGSJON	🟥	🟥	🟥
FLASJON	⬜	🟦	🟦
GARDIKEN	🟥	🟦	🟦
GIERTSJAURE	🟥	🟦	🟦
GOUTA	⬜	🟥	🟥
HAUKIVESI	⬜	🟦	🟦
HAVERN (KYRKSJÖN-DELEN)	🟥	🟥	🟥
HELGUMSJON	🟥	🟥	🟥
HOLMSJON	🟥	🟥	🟥
HOLSVATTNET	🟥	🟥	🟥
HORNAVAN	⬜	🟦	🟦
HOTINGSSJON	🟦	🟥	🟥
IDSJON	🟦	🟦	🟦
IISVESI	🟥	🟦	🟦
INARI E	🟥	🟦	⬜
ISOJARVI W	⬜	🟦	🟦
JAASJARVI SW	⬜	🟦	🟦
JALANTIJARVI E	🟥	🟦	🟦
JAMIJARVI E	🟥	🟦	🟦
JOUTSJARVI C	⬜	🟦	🟦
JUKKASJARVI	🟥	🟥	🟥
KALLAVESI C	🟥	🟦	🟦
KALLSJON	🟦	🟦	🟦
KALMARINJARVI N	⬜	🟦	🟦
KEITELE SE	🟥	🟦	🟦
KEITELE SW	🟥	⬜	🟥
KIESIMA	🟥	🟦	🟦
KITUSJARVI	🟥	🟥	🟥
KIVIJARVI N	🟥	🟦	🟦
KOIVUJARVI	🟥	🟦	🟥
KONNEVESI	🟥	🟦	🟦

NAME	BU	FU	OW
KOSKATSJAURE	⬜	🟥	🟥
KUIVAJARVI W	⬜	🟦	🟦
KUKKIA - PUUTIKKALA	🟦	🟦	🟦
KUKKIAJARVI W	🟦	🟦	🟦
KUORTANEENJARVI	🟥	🟦	🟦
KUUHANKAVESI S	⬜	🟦	🟦
KYROSJARVI W	🟥	🟦	🟦
KYYVESI E	⬜	🟦	🟦
LAKE HANKAVESI	🟥	🟦	🟦
LAKE IISVESI	🟥	🟦	🟦
LAKE JAASJARVI	⬜	🟦	🟦
LAKE JOUTSJARVI	⬜	🟦	🟦
LAKE KALLAVESI (1)	🟥	🟦	🟦
LAKE KALLAVESI (2)	🟥	🟦	🟦
LAKE KALMARINSELKA	⬜	🟦	🟦
LAKE KIIMASJARVI	🟥	🟦	🟦
LAKE KIVIJARVI	🟥	🟦	🟦
LAKE KIVIJARVI	⬜	🟦	🟦
LAKE KOIVUJARVI	🟥	🟦	🟦
LAKE KUBENSKOYE (PESKI)	🟦	🟦	🟦
LAKE LATCHA	🟦	🟦	🟦
LAKE MUURASJARVI	🟥	🟦	🟦
LAKE NASIJARVI	🟦	🟦	🟦
LAKE NILAKKA	🟥	🟦	🟦
LAKE PAAJARVI	🟥	🟦	🟥
LAKE PAIJANNE	🟦	🟦	🟦
LAKE PETAJAVESI	⬜	🟥	🟥
LAKE PIELAVESI	🟥	🟦	🟦
LAKE SALOSJARVI	🟥	🟦	🟦
LAKE SUMMASJARVI	🟥	🟦	🟦
LAKE VATIANJARVI	🟥	🟦	🟦
LAKE VESIJARVI	🟥	🟦	🟦
LANDÖGSJÖN	🟥	🟦	🟦
LANGELMAVESI - KAIVANTO	🟥	🟦	🟦
LANGELMAVESI S	🟥	🟦	🟦
LÄNNÄSSJÖN	🟦	🟥	🟥
LAPPAJARVI - HALKOSAARI	🟥	🟦	🟦
LEIPIKVATTNET	⬜	🟥	🟥
LENTUA	🟥	🟦	🟦
LEPPASJARVI E	⬜	🟦	🟦
LESTIJARVI	🟥	⬜	🟥
LJUSTERN	🟦	🟦	🟦
LOFSSJÖN	🟦	🟦	🟦
LOHJANJARVI E	🟦	🟦	🟦
LÖVSJÖN	⬜	⬜	🟥
LUOSSAJÄRVI	⬜	🟥	🟥
MAANINKAJARVI NE	🟥	🟦	🟦
MALGOMAJ	🟦	🟦	🟦
MEDSTUGUSJÖN	🟦	🟥	🟥
MÖCKELN	🟦	🟦	🟦

NAME	BU	FU	OW
MUUREJARVI SW	🟥	🟦	🟦
NÄLDSJÖN	🟥	⬜	⬜
NIINIVESI W	⬜	🟦	🟦
NÖMMEN	🟦	🟦	🟦
NORRSJÖN LÖA NORRSJÖN	🟦	🟦	🟦
NUASJARVI N	🟥	🟦	🟦
ORMSJÖN	🟥	🟦	🟦
OSMAJARVI N	🟥	🟦	⬜
OULUJARVI	🟥	🟦	🟥
ÖVERSTJUKTAN	🟦	🟥	🟥
PAIJANNE S	⬜	🟦	🟦
PALOSELKA E	⬜	🟦	🟦
PIELINEN	🟥	🟦	🟦
POHJOIS KONNEVESI W	⬜	🟦	🟦
RENGEN	⬜	🟥	🟥
REVSUNDSSJÖN	⬜	🟦	🟦
RÖRSJÖN	⬜	🟥	⬜
RUTAJÄRVI	🟥	🟥	🟥
SAAKSJARVI - SAAKSKOSKI	⬜	🟦	🟦
SADDAJAURE	🟥	⬜	⬜
SÅDUGGEN	🟦	🟥	🟦
SADVAJAURE	🟥	⬜	⬜
SILJAN (STORSILJAN SO SOLLERÖN)	🟦	🟦	🟦
SIMPELEJARVI	⬜	🟦	🟦
SOTTERN	🟦	🟥	🟦
STENTJÄRN	⬜	🟦	🟦
STORA TJULTRÄSKET	🟥	🟥	🟥
STORA VÄLLAN	🟥	🟦	🟦
STORSJON (1)	⬜	🟦	🟦
STORSJÖN (2)	🟥	🟦	🟦
TÅSJÖN	⬜	🟥	🟥
TJEGGELVAS	⬜	🟦	🟦
TORNETRÄSK	🟥	🟦	⬜
TORPSJÖN	🟦	⬜	🟦
TORRÖN	🟦	🟦	🟦
VÄLLEN	🟦	🟦	🟦
VALSJÖN	🟥	🟥	🟥
VARPAN	🟦	⬜	🟦
VASTERVATTNAN	🟦	⬜	🟦
VÄSTRA FISKÅVATTNET	⬜	🟦	🟦
VÄSTRA ÖRTEN	🟦	🟥	🟥
VATIAJARVI E	⬜	🟦	🟦
VENJANSJÖN	🟦	🟥	🟦
VESIJARVI - LAHTI	⬜	🟦	🟦
VIKARSJON	🟦	🟥	🟥
VISUVESI	🟥	🟦	🟦
VOJMSJÖN	⬜	🟦	🟦
VOLGSJÖN	⬜	🟥	🟥
YLA-KIVIJARVI - JURVALA	🟦	🟦	🟦

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

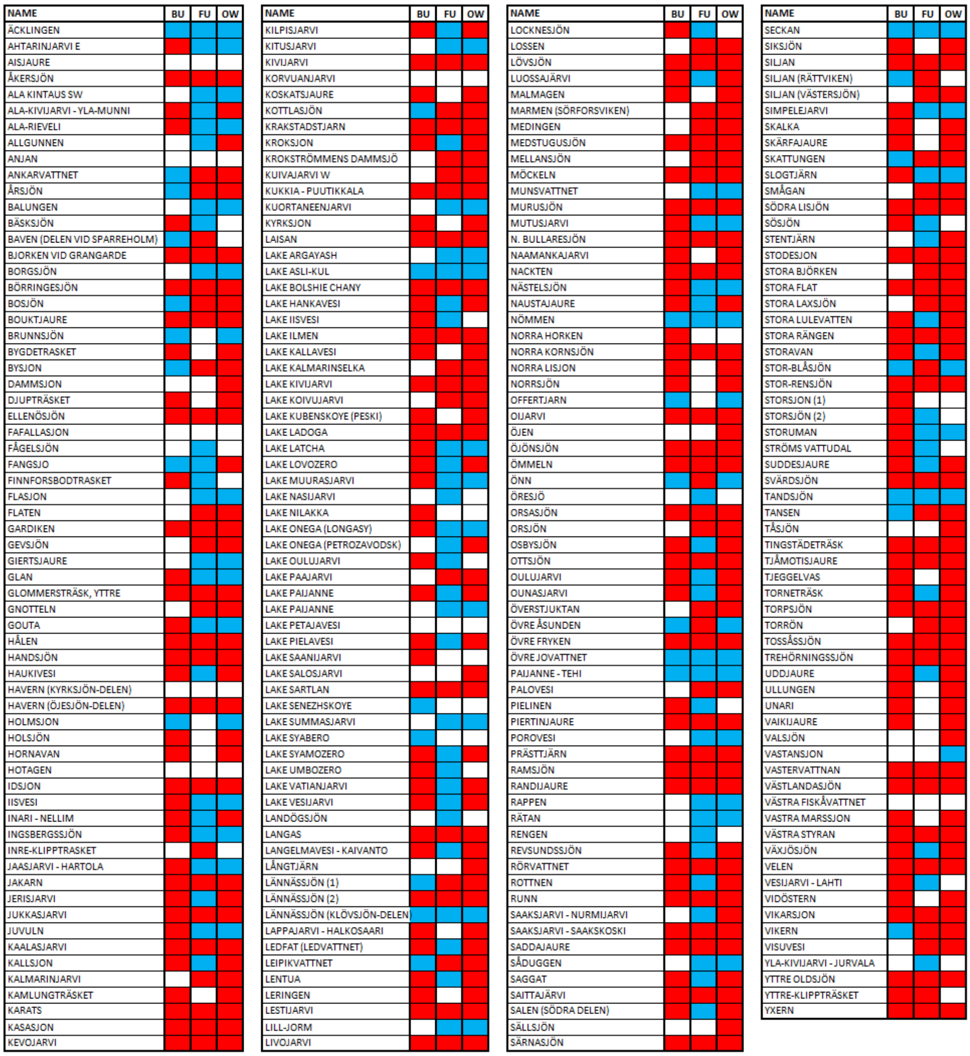
By 1961-1990 (Fig. 6d) additional sites are available across the region and more dominant trends have developed. Trends toward earlier breakup in northern Sweden and Finland have increased in magnitude compared to 1931-

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.



NAME	BU	FU	OW
ÄCKLINGEN	🟦	🟦	🟦
AHTARINJARVI E	🟥	🟦	🟦
AISJAURE	⬜	⬜	⬜
ÅKERSJÖN	🟥	🟥	🟥
ALA KINTAUS SW	⬜	🟦	🟦
ALA-KIVIJARVI - YLA-MUNNI	🟥	🟦	🟥
ALA-RIEVELI	🟥	🟦	🟦
ALLGUNNEN	⬜	🟦	🟥
ANJAN	⬜	⬜	⬜
ANKARVATTNET	🟦	🟥	🟥
ÅRSJÖN	🟦	🟥	🟥
BALUNGEN	⬜	🟦	🟦
BÄSKSJÖN	🟥	🟦	⬜
BAVEN (DELEN VID SPARREHOLM)	🟦	🟥	⬜
BJORKEN VID GRANGARDE	🟥	🟥	🟥
BORGSJÖN	⬜	🟦	🟦
BÖRRINGESJÖN	🟥	🟥	🟥
BOSJÖN	🟦	🟥	🟥
BOUKTJAURE	🟥	🟥	🟥
BRUNNSJÖN	🟦	⬜	🟦
BYGDETRASKET	🟥	⬜	🟥
BYSJON	🟦	🟥	🟥
DAMMSJON	⬜	⬜	🟥
DJUPTRÄSKET	🟥	⬜	🟥
ELLENÖSJÖN	🟥	🟥	🟥
FAFALLASJON	⬜	⬜	⬜
FÅGELSJÖN	⬜	🟦	⬜
FANGSJO	🟦	🟦	🟥
FINNFORSBODTRASKET	🟥	🟦	⬜
FLASJON	⬜	🟦	🟦
FLATEN	⬜	🟥	🟥
GARDIKEN	🟥	🟥	🟥
GEVSJÖN	⬜	🟥	🟥
GIERTSJAURE	⬜	🟦	🟦
GLAN	🟥	🟦	🟦
GLOMMERSTRÄSK, YTTRE	🟥	🟥	🟥
GNOTTELN	⬜	🟥	🟥
GOUTA	🟥	🟦	🟦
HÅLEN	🟥	🟥	🟥
HANDSJÖN	🟥	🟥	🟥
HAUKIVESI	🟥	🟦	🟥
HAVERN (KYRKSJÖN-DELEN)	⬜	⬜	⬜
HAVERN (ÖJESJÖN-DELEN)	🟥	🟥	🟥
HOLMSJON	🟦	⬜	🟦
HOLSJÖN	🟥	⬜	🟥
HORNAVAN	🟥	⬜	🟥
HOTAGEN	⬜	⬜	⬜
IDSJON	🟥	🟥	🟥
IISVESI	🟥	🟦	🟦
INARI - NELLIM	🟥	🟦	🟥
INGSBERGSSJÖN	🟥	🟦	🟦
INRE-KLIPPTRASKET	⬜	🟥	⬜
JAASJARVI - HARTOLA	🟥	🟦	🟦
JAKARN	🟥	🟥	🟥
JERISJARVI	🟥	🟦	🟥
JUKKASJARVI	🟥	🟥	🟥
JUVULN	🟥	🟦	🟦
KAALASJARVI	🟥	🟥	🟥
KALLSJON	🟥	🟦	🟥
KALMARINJARVI	⬜	🟥	🟥
KAMLUNGTRÄSKET	🟥	⬜	🟥
KARATS	🟥	🟥	🟥
KASASJON	🟥	🟥	🟥
KEVOJARVI	🟥	🟥	🟥
KILPISJARVI	🟥	🟦	🟥
KITUSJARVI	⬜	🟦	🟦
KIVIJARVI	🟥	🟥	🟥
KORVUANJARVI	⬜	⬜	⬜
KOSKATSJAURE	🟥	⬜	🟥
KOTTLASJÖN	🟦	🟥	🟥
KRAKSTADSTJARN	🟥	🟥	🟥
KROKSJON	🟥	🟦	🟥
KROKSTRÖMMENS DAMMSJÖ	⬜	🟥	🟥
KUIVAJARVI W	⬜	🟥	🟥
KUKKIA - PUUTIKKALA	🟥	🟥	🟥
KUORTANEENJARVI	⬜	🟦	🟦
KYRKSJON	🟥	⬜	🟥
LAISAN	🟥	🟥	🟥
LAKE ARGAYASH	⬜	🟦	🟦
LAKE ASLI-KUL	🟦	🟦	🟦
LAKE BOLSHIE CHANY	🟥	🟥	🟥
LAKE HANKAVESI	🟥	🟦	🟥
LAKE IISVESI	🟥	🟦	⬜
LAKE ILMEN	🟥	🟥	🟥
LAKE KALLAVESI	🟥	⬜	🟥
LAKE KALMARINSELKA	⬜	🟥	🟥
LAKE KIVIJARVI	🟥	🟥	🟥
LAKE KOIVUJARVI	⬜	🟥	🟥
LAKE KUBENSKOYE (PESKI)	🟥	⬜	🟥
LAKE LADOGA	🟥	🟥	🟥
LAKE LATCHA	🟥	🟦	🟦
LAKE LOVOZERO	🟥	🟦	🟥
LAKE MUURASJARVI	🟥	🟦	🟦
LAKE NASIJARVI	⬜	🟦	⬜
LAKE NILAKKA	🟥	⬜	⬜
LAKE ONEGA (LONGASY)	🟥	🟦	🟦
LAKE ONEGA (PETROZAVODSK)	⬜	🟦	🟥
LAKE OULUJARVI	🟥	🟦	⬜
LAKE PAAJARVI	⬜	🟥	🟥
LAKE PAIJANNE	🟥	🟦	🟥
LAKE PAIJANNE	⬜	🟦	🟦
LAKE PETAJAVESI	⬜	⬜	⬜
LAKE PIELAVESI	🟥	🟦	🟥
LAKE SAANIJARVI	🟥	⬜	⬜
LAKE SALOSJARVI	⬜	⬜	🟥
LAKE SARTLAN	🟥	🟥	🟥
LAKE SENEZHSKOYE	🟦	⬜	⬜
LAKE SUMMASJARVI	⬜	🟦	🟦
LAKE SYABERO	🟦	⬜	⬜
LAKE SYAMOZERO	🟥	🟦	🟥
LAKE UMBOZERO	🟥	🟦	⬜
LAKE VATIANJARVI	🟥	🟦	🟥
LAKE VESIJARVI	🟥	🟦	🟥
LANDÖGSJÖN	⬜	🟦	⬜
LANGAS	🟥	🟥	🟥
LANGELMAVESI - KAIVANTO	🟥	🟦	🟥
LÅNGTJÄRN	⬜	⬜	🟥
LÄNNÄSSJÖN (1)	🟦	🟥	🟥
LÄNNÄSSJÖN (2)	🟥	🟥	🟥
LÄNNÄSSJÖN (KLÖVSJÖN-DELEN)	🟦	🟦	🟦
LAPPAJARVI - HALKOSAARI	🟥	⬜	🟥
LEDFAT (LEDVATTNET)	🟥	🟦	🟥
LEIPIKVATTNET	🟦	🟥	🟥
LENTUA	🟥	🟦	🟥
LERINGEN	🟥	⬜	🟥
LESTIJARVI	🟥	🟥	🟥
LILL-JORM	⬜	🟦	🟦
LIVOJARVI	🟥	🟥	🟥
LOCKNESJÖN	🟥	🟦	⬜
LOSSEN	⬜	🟥	🟥
LÖVSJÖN	🟥	🟥	🟥
LUOSSAJÄRVI	🟥	🟦	🟥
MALMAGEN	🟥	⬜	🟥
MARMEN (SÖRFORSVIKEN)	⬜	🟥	🟥
MEDINGEN	⬜	🟥	🟥
MEDSTUGUSJÖN	🟥	🟥	🟥
MELLANSJÖN	⬜	🟥	🟥
MÖCKELN	🟥	🟥	🟥
MUNSVATTNET	⬜	🟦	🟦
MURUSJÖN	🟥	🟥	🟥
MUTUSJARVI	🟥	🟦	🟦
N. BULLARESJÖN	🟥	🟥	🟥
NAAMANKAJARVI	🟥	⬜	🟥
NACKTEN	🟥	🟥	🟥
NÄSTELSJÖN	🟥	🟦	🟦
NAUSTAJAURE	🟥	🟦	🟥
NÖMMEN	🟦	🟦	🟦
NORRA HORKEN	🟥	⬜	⬜
NORRA KORNSJÖN	🟥	🟥	🟥
NORRA LISJON	🟥	⬜	🟥
NORRSJÖN	🟥	⬜	🟥
OFFERTJARN	🟦	⬜	🟦
OIJARVI	🟥	🟥	🟥
ÖJEN	⬜	⬜	🟥
ÖJÖNSJÖN	🟥	🟥	🟥
ÖMMELN	🟥	🟥	🟥
ÖNN	🟦	🟥	🟦
ÖRESJÖ	⬜	🟦	⬜
ORSASJÖN	🟥	🟥	🟥
ORSJÖN	⬜	🟥	🟥
OSBYSJÖN	🟥	🟦	🟥
OTTSJÖN	🟥	🟥	🟥
OULUJARVI	🟥	🟦	🟥
OUNASJARVI	🟥	🟦	🟥
ÖVERSTJUKTAN	⬜	🟥	🟥
ÖVRE ÅSUNDEN	🟦	🟥	🟦
ÖVRE FRYKEN	🟥	🟥	🟥
ÖVRE JOVATTNET	🟦	🟦	🟦
PAIJANNE - TEHI	🟦	🟦	🟦
PALOVESI	⬜	🟥	🟥
PIELINEN	🟥	🟦	⬜
PIERTINJAURE	🟥	🟥	🟥
POROVESI	⬜	🟦	🟦
PRÄSTTJÄRN	🟥	🟥	🟥
RAMSJÖN	🟥	🟥	🟥
RANDIJAURE	🟥	🟥	🟥
RAPPEN	⬜	🟦	🟦
RÄTAN	⬜	🟦	🟦
RENGEN	⬜	🟦	⬜
REVSUNDSSJÖN	🟥	🟦	🟥
RÖRVATTNET	🟥	🟥	🟥
ROTTNEN	🟥	🟦	🟥
RUNN	🟥	🟥	🟥
SAAKSJARVI - NURMIJARVI	⬜	🟦	🟥
SAAKSJARVI - SAAKSKOSKI	🟥	🟥	🟥
SADDAJAURE	🟥	🟥	🟥
SÅDUGGEN	⬜	🟦	🟦
SAGGAT	🟥	🟦	🟥
SAITTAJÄRVI	🟥	🟥	🟥
SALEN (SÖDRA DELEN)	🟥	🟦	🟥
SÄLLSJÖN	⬜	⬜	🟥
SÄRNASJÖN	🟥	🟥	🟥
SECKAN	🟦	🟦	🟦
SIKSJÖN	🟥	⬜	🟥
SILJAN	🟥	🟥	🟥
SILJAN (RÄTTVIKEN)	🟦	🟥	⬜
SILJAN (VÄSTERSJÖN)	⬜	🟥	🟥
SIMPELEJARVI	🟥	🟦	🟦
SKALKA	🟥	⬜	🟥
SKÄRFAJAURE	🟥	⬜	🟥
SKATTUNGEN	🟦	🟥	🟥
SLOGTJÄRN	🟥	🟦	🟦
SMÅGAN	⬜	🟥	🟥
SÖDRA LISJÖN	🟥	🟥	🟥
SÖSJÖN	🟥	🟦	⬜
STENTJÄRN	⬜	🟦	🟥
STODESJON	🟥	🟥	🟥
STORA BJÖRKEN	⬜	🟥	🟥
STORA FLAT	🟥	🟥	🟥
STORA LAXSJÖN	⬜	🟥	🟥
STORA LULEVATTEN	🟥	🟦	🟥
STORA RÄNGEN	🟥	🟥	🟥
STORAVAN	🟥	🟦	🟥
STOR-BLÅSJÖN	🟦	🟥	🟦
STOR-RENSJÖN	🟥	🟥	🟥
STORSJON (1)	🟥	⬜	⬜
STORSJÖN (2)	🟥	🟦	⬜
STORUMAN	🟥	🟦	🟦
STRÖMS VATTUDAL	🟥	🟦	⬜
SUDDESJAURE	🟥	🟦	🟥
SVÄRDSJÖN	🟥	🟥	🟥
TANDSJÖN	🟦	🟦	🟦
TANSEN	🟦	🟥	🟥
TÅSJÖN	⬜	⬜	🟥
TINGSTÄDETRÄSK	🟥	🟥	🟥
TJÅMOTISJAURE	🟥	🟥	🟥
TJEGGELVAS	🟥	⬜	🟥
TORNETRÄSK	🟥	🟦	🟥
TORPSJÖN	🟥	🟥	🟥
TORRÖN	⬜	🟥	🟥
TOSSÅSSJÖN	🟥	🟥	🟥
TREHÖRNINGSSJÖN	🟥	🟥	🟥
UDDJAURE	🟥	🟦	🟥
ULLUNGEN	🟥	⬜	🟥
UNARI	🟥	⬜	🟥
VAIKIJAURE	🟥	⬜	🟥
VALSJÖN	⬜	⬜	🟥
VASTANSJON	⬜	⬜	🟦
VASTERVATTNAN	🟥	🟥	🟥
VÄSTLANDASJÖN	🟥	🟥	🟥
VÄSTRA FISKÅVATTNET	⬜	⬜	⬜
VASTRA MARSSJON	🟥	⬜	🟥
VÄSTRA STYRAN	🟥	🟥	🟥
VÄXJÖSJÖN	🟥	🟦	🟥
VELEN	🟥	🟥	🟥
VESIJARVI - LAHTI	🟥	🟦	⬜
VIDÖSTERN	🟥	⬜	🟥
VIKARSJON	🟥	🟥	🟥
VIKERN	🟦	🟥	🟥
VISUVESI	⬜	🟥	🟥
YLA-KIVIJARVI - JURVALA	⬜	🟦	⬜
YTTRE OLDSJÖN	🟥	🟥	🟥
YTTRE-KLIPPTRÄSKET	🟥	🟥	⬜
YXERN	🟥	🟥	🟥

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

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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.

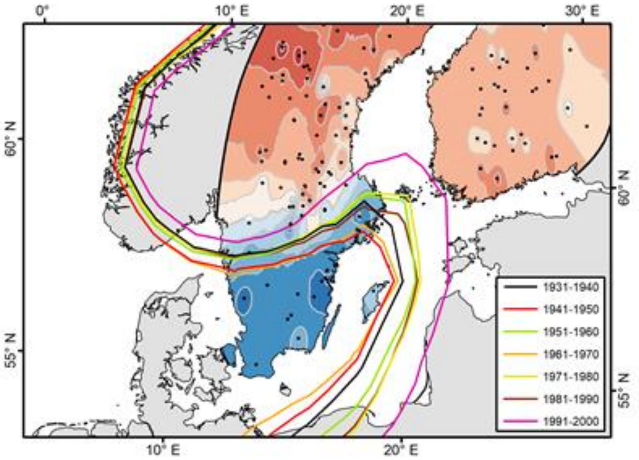


Figure 9: Breakup date trends in southern Sweden from 1991-2005 (see Fig. 6g for full area and scale). Note that site values have been interpolated into a surface for easier comparison. The polylines show the mean position of the 0 °C winter isotherm for several decades. Calculated from the 20th Century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

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.

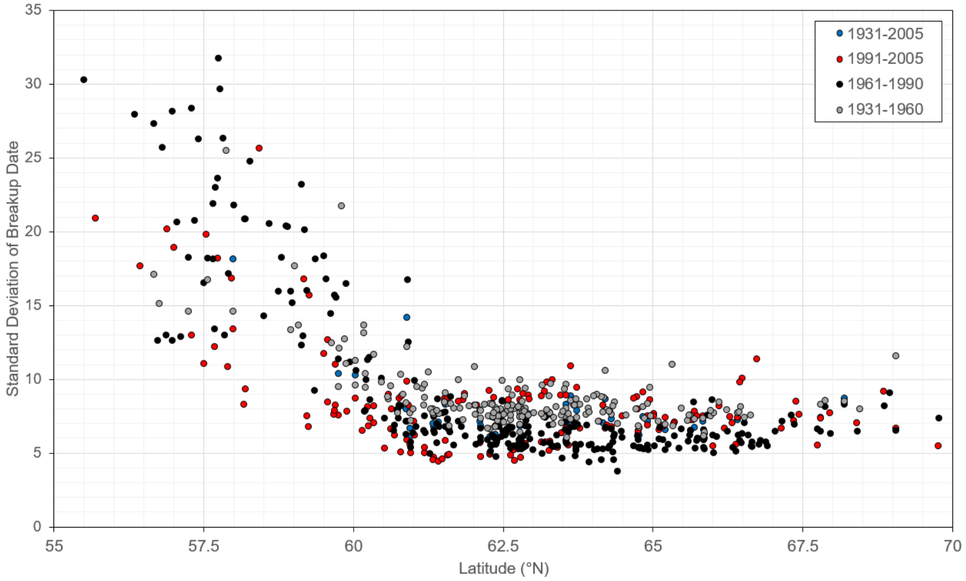


Figure 10: Standard deviation for breakup dates at Fennoscandian sites for different time periods. Note that, in accordance with Fig. 9, the sites that demonstrate the largest interannual variability are south of 60 °N and appear to be associated with the winter 0 °C isotherm.

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).

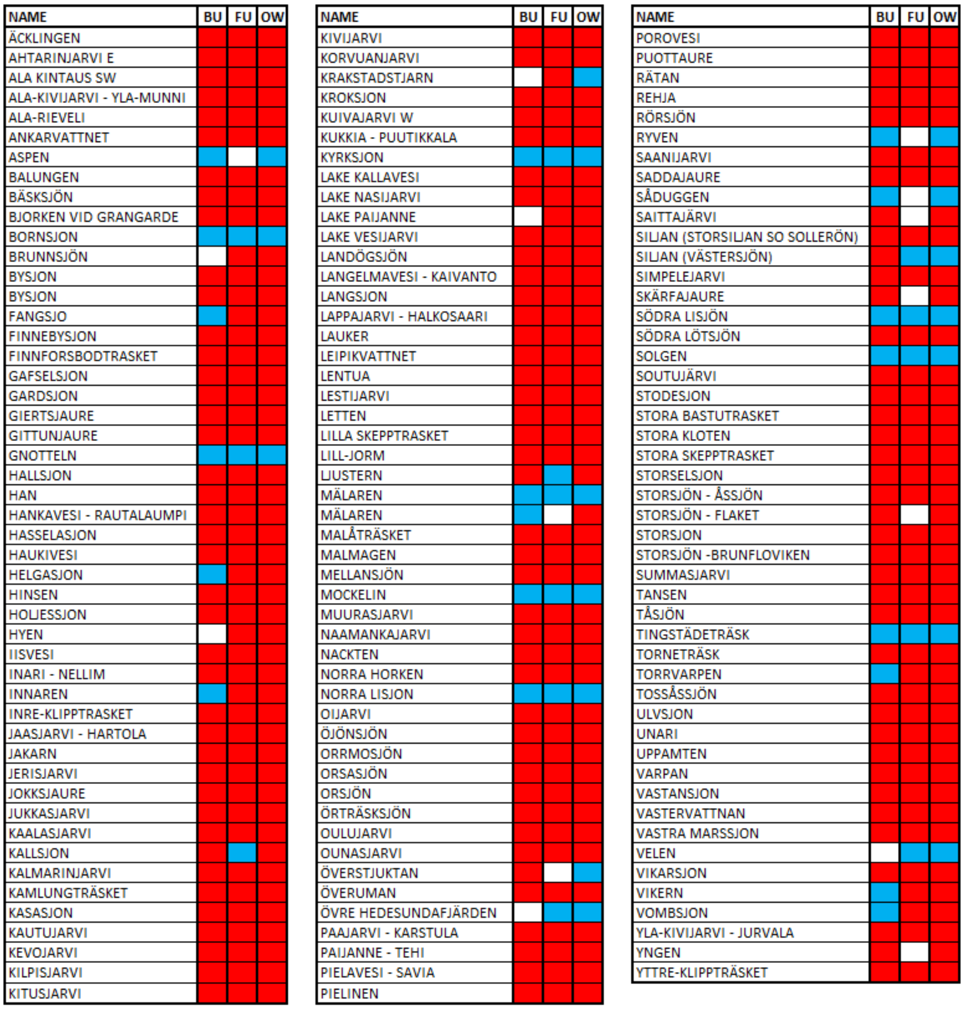
SITE	α	DECADEL CHANGE
GNOTTELN		3.3
KALLSJON		1.8
KYRKSJON	+	3.6
NORRA LISJON	*	3.7
SILJAN (VÄSTERSJÖN)	+	3.5
SÖDRA LISJÖN	*	3.6
TINGSTÄDETRÄSK	*	5.4
VELEN	**	4.9

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



NAME	BU	FU	OW
ÄCKLINGEN	🟥	🟥	🟥
AHTARINJARVI E	🟥	🟥	🟥
ALA KINTAUS SW	🟥	🟥	🟥
ALA-KIVIJARVI - YLA-MUNNI	🟥	🟥	🟥
ALA-RIEVELI	🟥	🟥	🟥
ANKARVATTNET	🟥	🟥	🟥
ASPEN	🟦	⬜	🟦
BALUNGEN	🟥	🟥	🟥
BÄSKSJÖN	🟥	🟥	🟥
BJORKEN VID GRANGARDE	🟥	🟥	🟥
BORNSJON	🟦	🟦	🟦
BRUNNSJÖN	⬜	🟥	🟥
BYSJON	🟥	🟥	🟥
BYSJON	🟥	🟥	🟥
FANGSJO	🟦	🟥	🟥
FINNEBYSJON	🟥	🟥	🟥
FINNFORSBODTRASKET	🟥	🟥	🟥
GAFSELSJON	🟥	🟥	🟥
GARDSJON	🟥	🟥	🟥
GIERTSJAURE	🟥	🟥	🟥
GITTUNJAURE	🟥	🟥	🟥
GNOTTELN	🟦	🟦	🟦
HALLSJON	🟥	🟥	🟥
HAN	🟥	🟥	🟥
HANKAVESI - RAUTALAUMPI	🟥	🟥	🟥
HASSELASJON	🟥	🟥	🟥
HAUKIVESI	🟥	🟥	🟥
HELGASJON	🟦	🟥	🟥
HINSEN	🟥	🟥	🟥
HOLJESSJON	🟥	🟥	🟥
HYEN	⬜	🟥	🟥
IISVESI	🟥	🟥	🟥
INARI - NELLIM	🟥	🟥	🟥
INNAREN	🟦	🟥	🟥
INRE-KLIPPTRASKET	🟥	🟥	🟥
JAASJARVI - HARTOLA	🟥	🟥	🟥
JAKARN	🟥	🟥	🟥
JERISJARVI	🟥	🟥	🟥
JOKKSJAURE	🟥	🟥	🟥
JUKKASJARVI	🟥	🟥	🟥
KAALASJARVI	🟥	🟥	🟥
KALLSJON	🟥	🟦	🟥
KALMARINJARVI	🟥	🟥	🟥
KAMLUNGTRÄSKET	🟥	🟥	🟥
KASASJON	🟥	🟥	🟥
KAUTUJARVI	🟥	🟥	🟥
KEVOJARVI	🟥	🟥	🟥
KILPISJARVI	🟥	🟥	🟥
KITUSJARVI	🟥	🟥	🟥

NAME	BU	FU	OW
KIVIJARVI	🟥	🟥	🟥
KORVUANJARVI	🟥	🟥	🟥
KRAKSTADSTJARN	⬜	🟥	🟦
KROKSJON	🟥	🟥	🟥
KUIVAJARVI W	🟥	🟥	🟥
KUKKIA - PUUTIKKALA	🟥	🟥	🟥
KYRKSJON	🟦	🟦	🟦
LAKE KALLAVESI	🟥	🟥	🟥
LAKE NASIJARVI	🟥	🟥	🟥
LAKE PAIJANNE	⬜	🟥	🟥
LAKE VESIJARVI	🟥	🟥	🟥
LANDÖGSJÖN	🟥	🟥	🟥
LANGELMAVESI - KAIVANTO	🟥	🟥	🟥
LANGSJON	🟥	🟥	🟥
LAPPAJARVI - HALKOSAARI	🟥	🟥	🟥
LAUKER	🟥	🟥	🟥
LEIPIKVATTNET	🟥	🟥	🟥
LENTUA	🟥	🟥	🟥
LESTIJARVI	🟥	🟥	🟥
LETTEN	🟥	🟥	🟥
LILLA SKEPPTRASKET	🟥	🟥	🟥
LILL-JORM	🟥	🟥	🟥
LJUSTERN	🟥	🟦	🟥
MÄLAREN	🟦	🟦	🟦
MÄLAREN	🟦	⬜	🟥
MALÅTRÄSKET	🟥	🟥	🟥
MALMAGEN	🟥	🟥	🟥
MELLANSJÖN	🟥	🟥	🟥
MOCKELIN	🟦	🟦	🟦
MUURASJARVI	🟥	🟥	🟥
NAAMANKAJARVI	🟥	🟥	🟥
NACKTEN	🟥	🟥	🟥
NORRA HORKEN	🟥	🟥	🟥
NORRA LISJON	🟦	🟦	🟦
OIJARVI	🟥	🟥	🟥
ÖJÖNSJÖN	🟥	🟥	🟥
ORRMOSJÖN	🟥	🟥	🟥
ORSASJÖN	🟥	🟥	🟥
ORSJÖN	🟥	🟥	🟥
ÖRTRÄSKSJÖN	🟥	🟥	🟥
OULUJARVI	🟥	🟥	🟥
OUNASJARVI	🟥	🟥	🟥
ÖVERSTJUKTAN	🟥	⬜	🟦
ÖVERUMAN	🟥	🟥	🟥
ÖVRE HEDESUNDAFJÄRDEN	⬜	🟦	🟦
PAAJARVI - KARSTULA	🟥	🟥	🟥
PAIJANNE - TEHI	🟥	🟥	🟥
PIELAVESI - SAVIA	🟥	🟥	🟥
PIELINEN	🟥	🟥	🟥

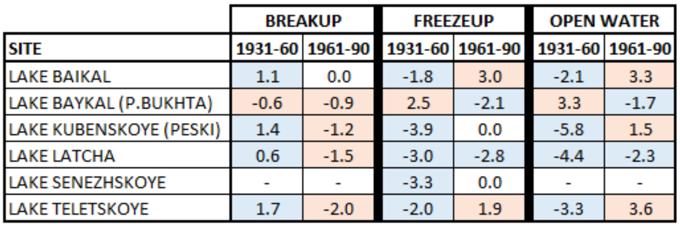
NAME	BU	FU	OW
POROVESI	🟥	🟥	🟥
PUOTTAURE	🟥	🟥	🟥
RÄTAN	🟥	🟥	🟥
REHJA	🟥	🟥	🟥
RÖRSJÖN	🟥	🟥	🟥
RYVEN	🟦	⬜	🟦
SAANIJARVI	🟥	🟥	🟥
SADDAJAURE	🟥	🟥	🟥
SÅDUGGEN	🟦	⬜	🟦
SAITTAJÄRVI	🟥	⬜	🟥
SILJAN (STORSILJAN SO SOLLERÖN)	🟥	🟥	🟥
SILJAN (VÄSTERSJÖN)	🟥	🟦	🟦
SIMPELEJARVI	🟥	🟥	🟥
SKÄRFAJAURE	🟥	⬜	🟥
SÖDRA LISJÖN	🟦	🟦	🟦
SÖDRA LÖTSJÖN	🟥	🟥	🟥
SOLGEN	🟦	🟦	🟦
SOUTUJÄRVI	🟥	🟥	🟥
STODESJON	🟥	🟥	🟥
STORA BASTUTRASKET	🟥	🟥	🟥
STORA KLOTEN	🟥	🟥	🟥
STORA SKEPPTRASKET	🟥	🟥	🟥
STORSELSJON	🟥	🟥	🟥
STORSJÖN - ÅSSJÖN	🟥	🟥	🟥
STORSJÖN - FLAKET	🟥	⬜	🟥
STORSJON	🟥	🟥	🟥
STORSJÖN -BRUNFLOVIKEN	🟥	🟥	🟥
SUMMASJARVI	🟥	🟥	🟥
TANSEN	🟥	🟥	🟥
TÅSJÖN	🟥	🟥	🟥
TINGSTÄDETRÄSK	🟦	🟦	🟦
TORNETRÄSK	🟥	🟥	🟥
TORRVARPEN	🟦	🟥	🟥
TOSSÅSSJÖN	🟥	🟥	🟥
ULVSJON	🟥	🟥	🟥
UNARI	🟥	🟥	🟥
UPPAMTEN	🟥	🟥	🟥
VARPAN	🟥	🟥	🟥
VASTANSJON	🟥	🟥	🟥
VASTERVATTNAN	🟥	🟥	🟥
VASTRA MARSSJON	🟥	🟥	🟥
VELEN	⬜	🟦	🟦
VIKARSJON	🟥	🟥	🟥
VIKERN	🟦	🟥	🟥
VOMBSJON	🟦	🟥	🟥
YLA-KIVIJARVI - JURVALA	🟥	🟥	🟥
YNGEN	🟥	⬜	🟥
YTTRE-KLIPPTRÄSKET	🟥	🟥	🟥

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.

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.

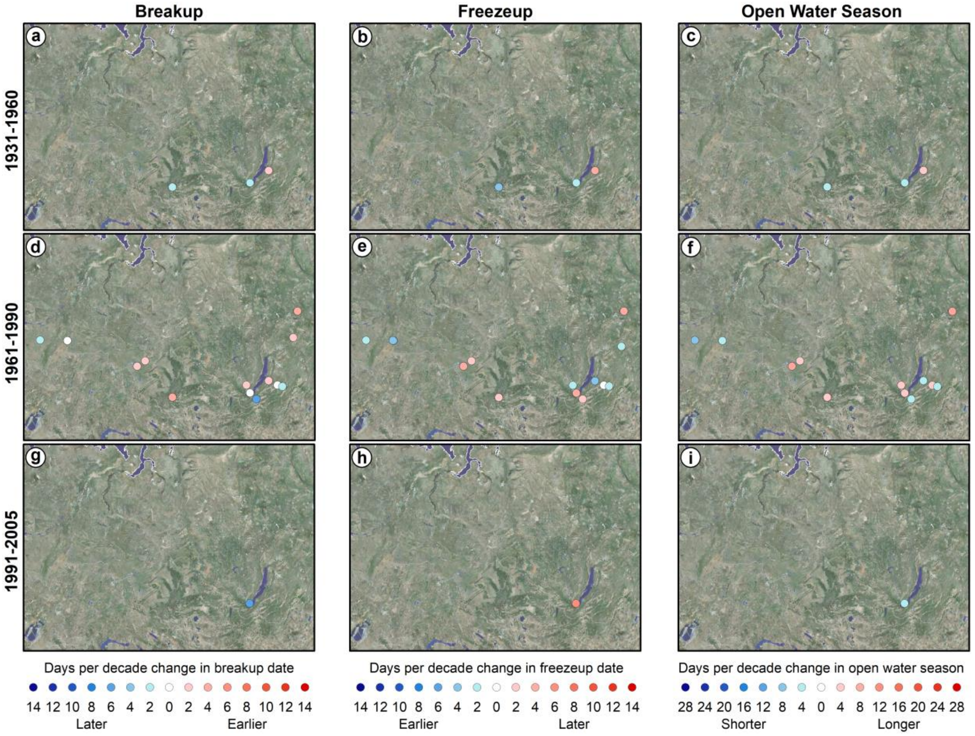


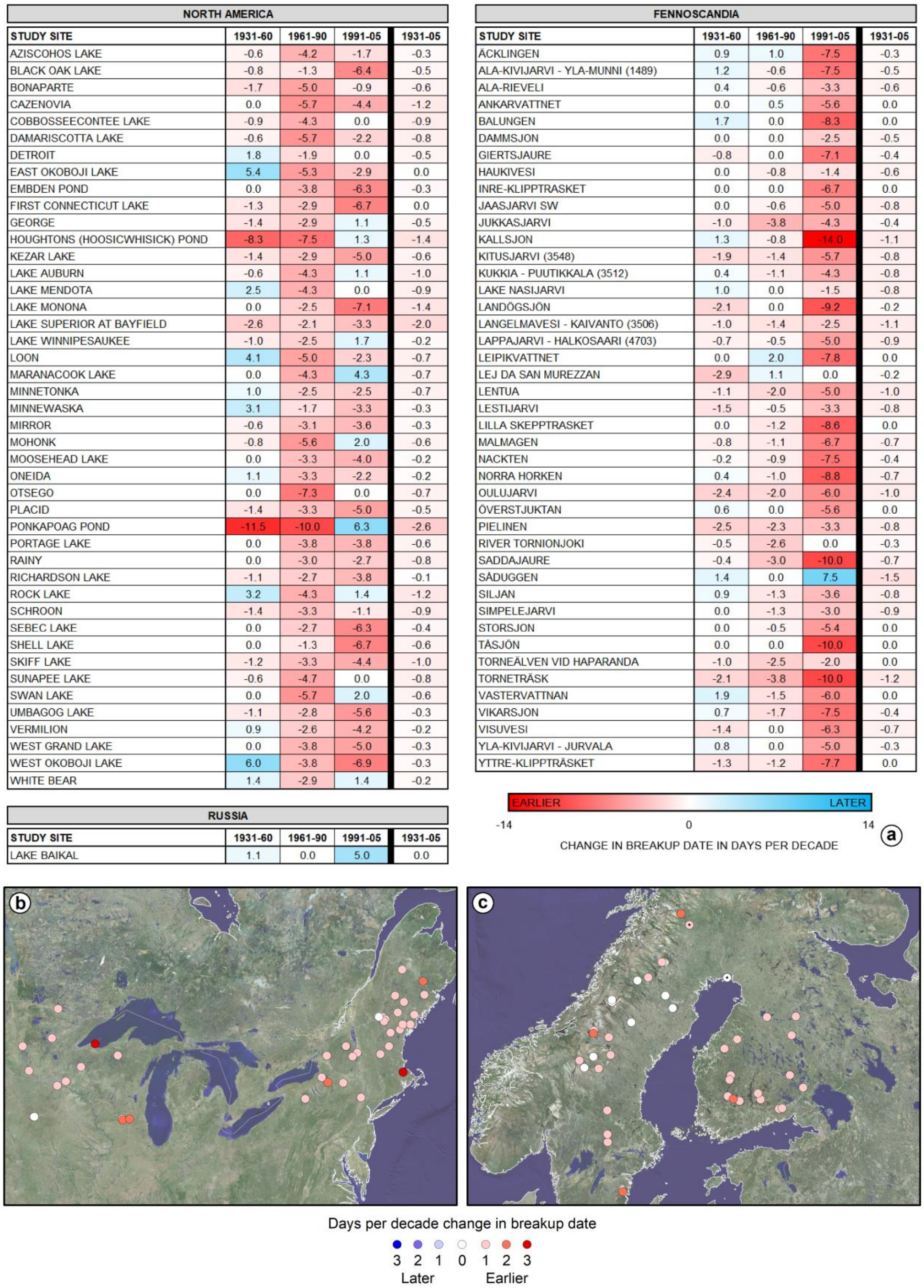
Figure 12: Decadal trends for breakup (**a**, **d**, and **g**), freezeup (**b**, **e**, and **h**), and length of the open water season (**c**, **f**, and **i**) in Russia for the three individual time periods. Blue and red tones on the scales related to cooling and warming signals inferred from changes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

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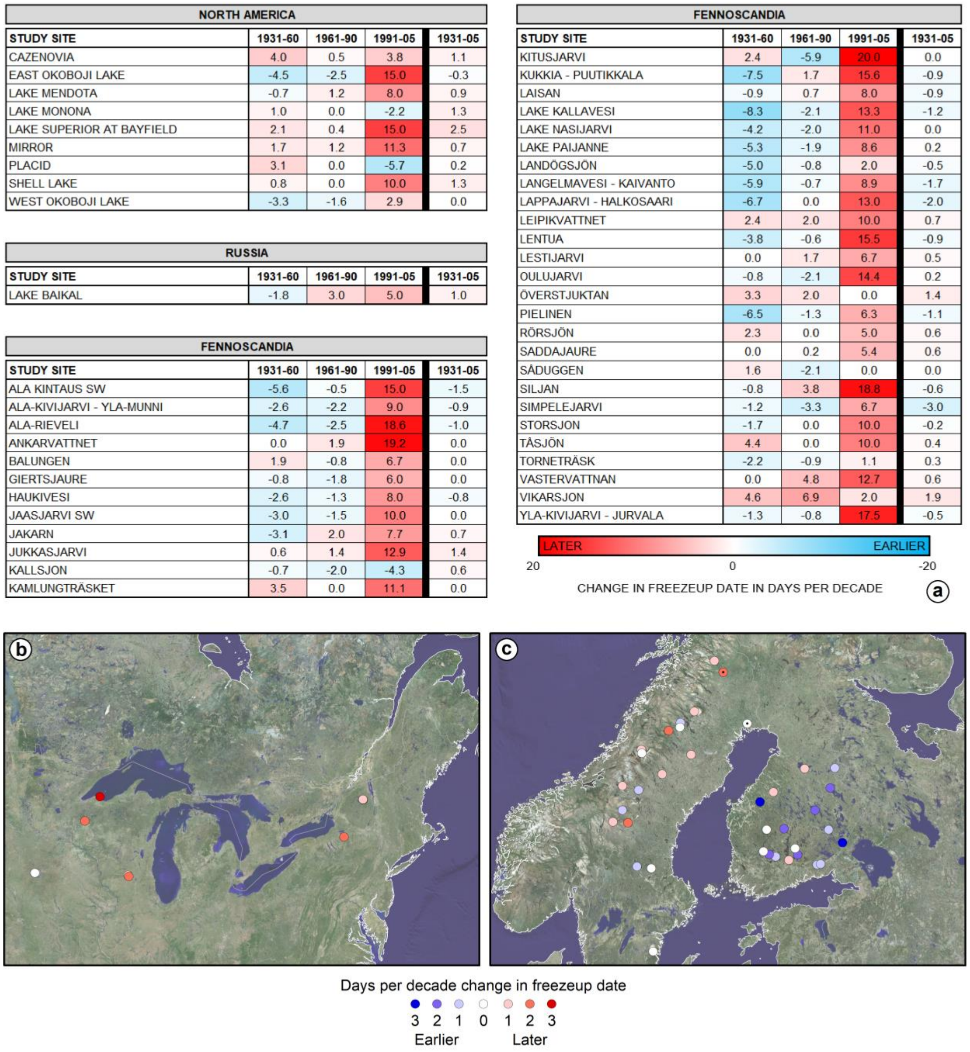


NORTH AMERICA

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

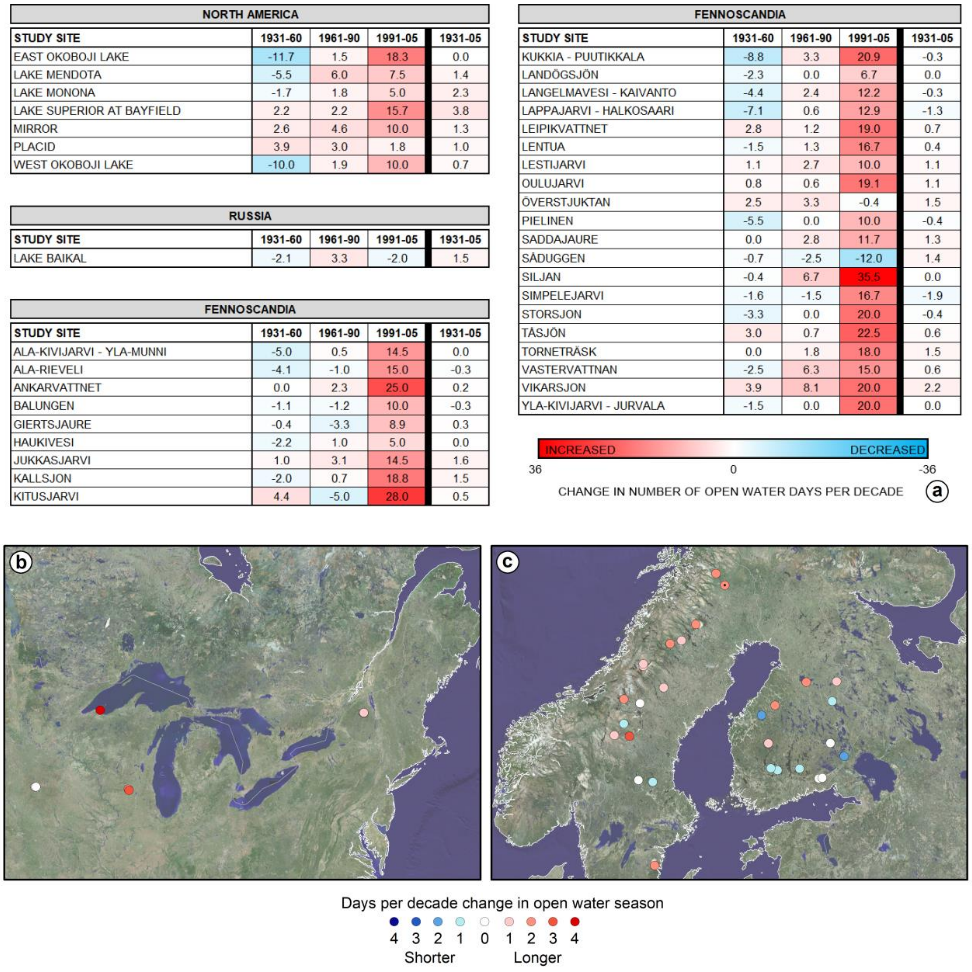
Figure 14: Summary of evidence for the long-term freezeup date trends for the 1931-2005 period: a) heat table demonstrating the decadal change for each site during each time period. The colouring of each cell shows the relative magnitude of that change compared to other sites and time periods; b-c) spatial 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

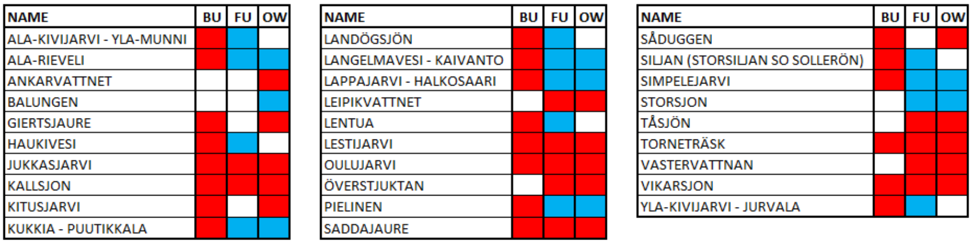
STUDY SITE	1931-60	1961-90	1991-05	1931-05
ALA-KIVIJARVI - YLA-MUNNI	-5.0	0.5	14.5	0.0
ALA-RIEVELI	-4.1	-1.0	15.0	-0.3
ANKARVATTNET	0.0	2.3	25.0	0.2
BALUNGEN	-1.1	-1.2	10.0	-0.3
GIERTSJAURE	-0.4	-3.3	8.9	0.3
HAUKIVESI	-2.2	1.0	5.0	0.0
JUKKASJARVI	1.0	3.1	14.5	1.6
KALLSJON	-2.0	0.7	18.8	1.5
KITUSJARVI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



NAME	BU	FU	OW
ALA-KIVIJARVI - YLA-MUNNI	🟥	🟦	⬜
ALA-RIEVELI	🟥	🟦	🟦
ANKARVATTNET	⬜	⬜	🟥
BALUNGEN	⬜	⬜	🟦
GIERTSJAURE	🟥	⬜	🟥
HAUKIVESI	🟥	🟦	⬜
JUKKASJARVI	🟥	🟥	🟥
KALLSJON	🟥	🟥	🟥
KITUSJARVI	🟥	⬜	🟥
KUKKIA - PUUTIKKALA	🟥	🟦	🟦

NAME	BU	FU	OW
LANDÖGSJÖN	🟥	🟦	⬜
LANGELMAVESI - KAIVANTO	🟥	🟦	🟦
LAPPAJARVI - HALKOSAARI	🟥	🟦	🟦
LEIPIKVATTNET	⬜	🟥	🟥
LENTUA	🟥	🟦	⬜
LESTIJARVI	🟥	🟥	🟥
OULUJARVI	🟥	🟥	🟥
ÖVERSTJUKTAN	⬜	🟥	🟥
PIELINEN	🟥	🟦	🟦
SADDAJAURE	🟥	🟥	🟥

NAME	BU	FU	OW
SÅDUGGEN	🟥	⬜	🟥
SILJAN (STORSILJAN SO SOLLERÖN)	🟥	🟦	⬜
SIMPELEJARVI	🟥	🟦	🟦
STORSJON	⬜	🟦	🟦
TÅSJÖN	⬜	🟥	🟥
TORNETRÄSK	🟥	🟥	🟥
VASTERVATTNAN	⬜	🟥	🟥
VIKARSJON	🟥	🟥	🟥
YLA-KIVIJARVI - JURVALA	🟥	🟦	⬜

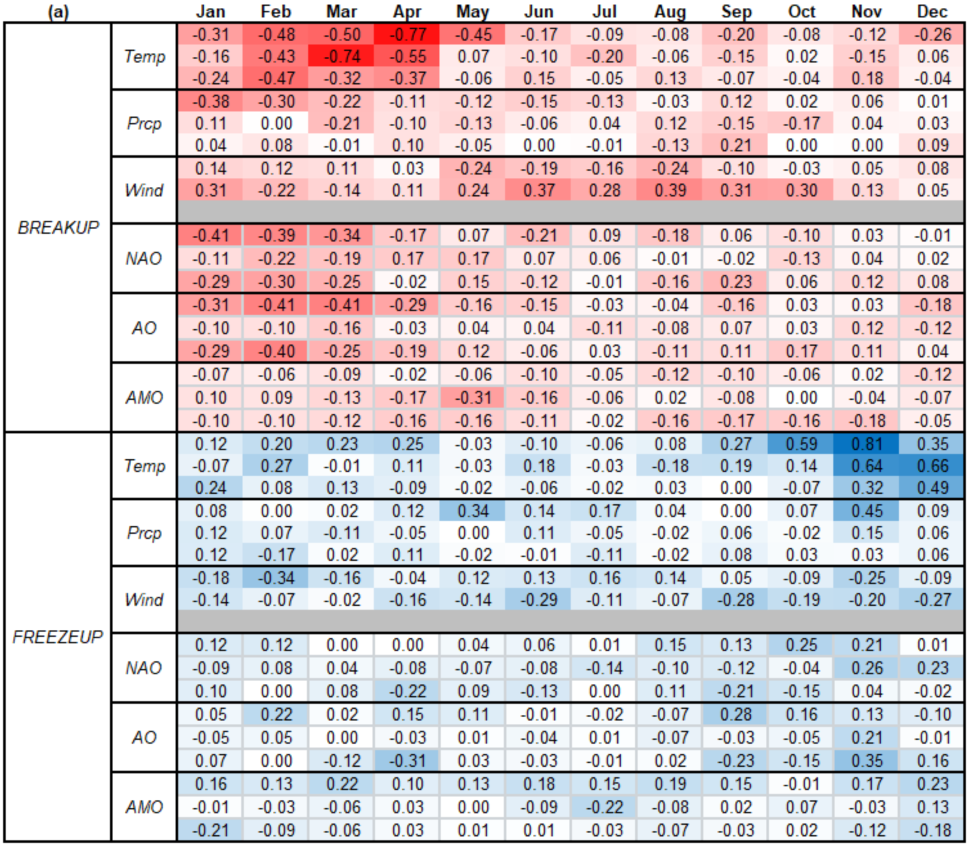
Figure 16: Comparison of how sites in Fennoscandia with an open water season calculation for the 1931-2005 time period. This reflects the relative changes in dates for breakup and freezeup. The red, white, and blue colours demonstrate whether the calculated trend reflects a warming trend (earlier breakup, 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.

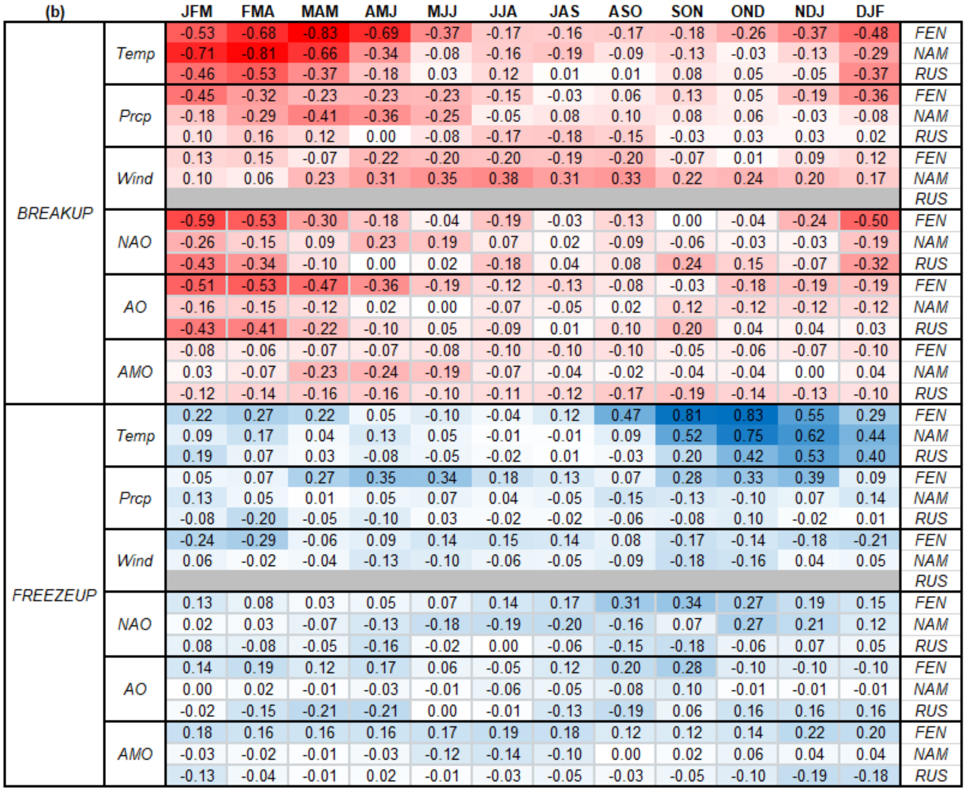
4. Causes of ice phenology change

Figure 17 shows the correlations between breakup/freezeup and a series of climatic variables and indices for each of the three study regions: Fennoscandia (FEN), 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 FEN and NAM, 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 and NAM respectively, and October-December temperatures correlating most strongly with freezeup at both FEN and NAM. These correlations are physically sensible, with breakup/freezeup occurring towards the end of the three month means. In RUS 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. This delayed response to falling winter temperatures at RUS compared to FEN and NAM may relate to the influence of other climatic or site-specific factors, especially since the RUS record applies to just a single 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

Figure 17: ‘Heatmap’ illustrating correlations between breakup/freezeup and a series of climatic variables and indices for each of the three study regions: Fennoscandia (FEN), 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.

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, while increasing spring precipitation (March and particularly the March-May mean) appears to exert a stronger influence on earlier breakup in NAM. 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, 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. 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 both NAM and RUS, while RUS also exhibits weak correlations between precipitation and breakup. There are also some relatively close associations between wind speed and breakup/freezeup at FEN and NAM (no wind speed data was available for RUS). Higher wind speeds in summer correlate most strongly with later breakup and earlier freezeup in NAM. The latter seems counter-intuitive since high wind speeds are generally thought to disrupt the water surface and delay freezup, 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 they could also simply be a product of chance.

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, 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 at a similar time of year are also apparent, while correlations in NAM are much weaker. Positive correlations (albeit not as strong) between freezeup and NAO/AO occur in autumn in FEN and early winter in NAM, 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 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 for the full time period are generally not as strong, with the exception of negative correlations between late spring AMO and breakup in NAM, 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.

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6. Summary and conclusions

Utilising a number of different datasets, a series of analyses have been used to investigate how the number of open water days per year and the timing breakup/freezeup dates have changed for water bodies that ephemerally freeze across the Northern Hemisphere. Four time periods (1931-1960, 1961-1990, 1991-2005, and 1931-2005) have been investigated across 644 sites with data in at least one of the time periods to provide ~2600 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 0.6 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. 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. This is likely because freezeup is not guaranteed to occur simply because temperatures have moved below 0 °C as water kinetics can prevent freezeup. In general, the number of open water days tend to display similar spatiotemporal patterns to those observed for breakup. This shows that even with the inconsistent nature of the changes in freezeup dates, the relative changes between breakup and freezeup dates has led, through time, to a reduction in the length of the ice season and consequently an increase in the number of open water days across the Northern Hemisphere.

Five key conclusions have been drawn from this research; (1) a warming signal is clearly observable in breakup and 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 well-aligned to temperature trends, (4) freezeup trends are more spatiotemporally complex and display weaker correlations with climate patterns, and (5) 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 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 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 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 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 with input on all from DM.

Competing interests

There are no competing interests to declare.

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