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

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Abstract. At high latitudes and altitudes one of the main controls on hydrological and biogeochemical processes is the breakup and freezeup of lake and river ice. This study uses 3510 time series from across 678 Northern Hemisphere lakes and river to explore historical patterns in lake and river ice phenology across five overlapping time periods (1931-1960, 1946-1975, 1961-1990, 1976-2005, and 1931-2005). These time series show that the number of annual open water days increased by 0.63 days per decade from 1931-2005 across the Northern Hemisphere, with trends for breakup and, to a lesser extent, freezeup, closely correlating with regionally-averaged temperature. Breakup and freezeup trends display a spatiotemporally complex evolution and reveal considerable caveats with interpreting the implications of ice phenology changes at lake and river sites that may only have breakup or freezeup data, rather than both. These results provide an important contribution by showing regional variation in ice phenology trends through time that can be hidden by longer-term trends. The overlapping 30-year time periods also show evidence for an acceleration in warming trends through time. Understanding the changes on both long- and short-term timescales will be important for determining the causes of this change, the underlying biogeochemical processes associated with it, and the wider climatological significance as global temperatures rise.

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

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 - Lakes have a stronger and more coherent pattern compared to rivers
North America	Brammer et al. (2015)	1972-2013	- Ice season length decreased over the time period and was driven by earlier breakup
North America	Duguay et al. (2006)	1951-2000	- Earlier breakup trends in most lakes that were consistent with snow cover duration - Freezeup trends were more variable with later and earlier dates - Strong relationship is shown between 0 °C and breakup/freezeup dates in Canada
North America	Futter (2003)	1853-2001	- In Southern Ontario significant trends towards earlier breakup and an extension to the ice-free season length
North America	Ghanbari et al. (2009)	1855-2005	- PDO, ENSO, and NAO explain some, but not all ice phenology variability at Lake Mendota
North America	Hewitt et al. (2018)	1981-2015	- Lake ice breakup occurred 1.4 days per decade earlier and freezeup 2.3 days per decade later - Strong association with warming air temperatures
North America	Hodgkins et al. (2005)	1930-2000	- River sites in New England show a decrease in ice season length by 20 days
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 late 19th century to 2002 - Trends toward later freezeup leading to a reduction in ice season length
Europe	Marszelewski and Skowron (2006)	1961-2000	- Ice season length has been reducing by 0.8-0.9 days per year at six lakes in northern Poland
Europe	Nõges and Nõges (2014)	1922-2011	- Greater levels of snowfall associated with later breakup - Lake ice phenology trends were weak, despite significant air and lake surface temperature trends
Europe	Šarauskienė and Jurgelėnaitė (2008)	1931-2005	- In Lithuania warmer winters caused later freezeup and reduced ice season length
Europe	Stonevicius et al. (2008)	1812–2000	- Reduction in ice season length for the Nemunas River, Lithuania
Europe	Weyhenmeyer et al. (2004)	1960-2002	- Results from 196 Swedish lakes showing a nonlinear temperature response of breakup dates - Future climate change impacts will likely vary along a temperature gradient
Russia	Borshch et al. (2001)	1893-1991	- In European Russia freezeup occurs later and breakup occurs earlier - Rivers assessed in Siberia show insignificant and occasionally opposite trends
Russia	Karetnikov and Naumenko (2008)	1943-2007	- NAO is well correlated with the ice cover at Lake Ladoga
Russia	Kouraev et al. (2007)	1869-2004	- Lake Baikal trends change through time with period from 1990-2004 characterised by an increased ice season length
Russia	Livingstone (1999)	1869-1996	- Breakup relationship with NAO after 1920 at Lake Baikal
Russia	Smith (2000)	1917-1994	- Fluctuations of patterns between longer and shorter ice season lengths that are generally consistent with temperature trends
Russia	Todd and Mackay, (2003)	1869-1996	- Significant trends towards reduced ice season and ice thickness at Lake Baikal over the period of study
Russia	Vuglinsky (2002)	1917-1994	- Rivers in Asian Russia freeze earlier and breakup later compared to rivers in European Russia - This is due to antecedent climatological conditions
Asia	Batima et al. (Batima et al., 2004)	1945-1999	- River ice thickness and ice season length have decreased over the time period
Asia	Jiang et al. (2008)	1968-2001	- Yellow River has experienced later freezeup and earlier breakup, leading to a reduction of the ice season by 12-38 days at different sites along the river
Northern Hemisphere	Benson et al. (2012)	1855-2005	- For 75 lakes the trends towards earlier breakup, later freezeup and a shorter ice season duration were stronger for the most recent time period studied
Northern Hemisphere	Livingstone (2000b)	1865-1996	- NAO signal detected at a number of sites, but with variable strength across several Northern Hemisphere sites
Northern Hemisphere	Magnuson et al. (2000)	1846-1995	- Breakup on average 6.3 days per century earlier across multiple Northern Hemisphere sites - Freezeup on average 5.7 days later per century
Northern Hemisphere	Sharma and Magnuson (2014)	1854-2004	- All 13 lake study sites demonstrated oscillatory dynamics influenced ice breakup
Northern Hemisphere	Sharma et al. (2016)	1443-2014	- Trends towards later freezeup in Japan and earlier breakup in Finland - Strong linkage between these trends and climate change and variability
Northern Hemisphere	Sharma et al. (2019)	1443-2018	- Analysis of 513 sites shows the importance of air temperature, lake morphometry, elevation and shoreline geometry in governing ice cover - Future projections suggest an extensive loss of lake ice over the next generation

Northern Hemisphere	Šmejkalová et al. (2016)	2000-2013	- All areas showed significant trends of earlier breakup - The 0 °C isotherm shows the strongest relationship with ice phenology trends
Northern Hemisphere	Wynne (2000)	1896-1995	- Trend directions for four sites regularly switched over the 100 year time span

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

2. Materials and methods

The Global Lake and River Ice Phenology Database from the National Snow and Ice Data Centre (NSIDC) (available at: https://nsidc.org/data/lake_river_ice/ – Benson et al. (2013)) provides breakup/freezeup dates for 865 Northern Hemisphere sites. In this database the freezeup date is defined as the first day in which the water is completely ice covered and the breakup is the date of the last ice breakup before the open water season. Whilst the specific definitions for breakup/freezeup may vary between different sites, the precise definition is thought to be consistent at each site. Thus, if climate signals are present in the ice phenology data then they should still be observable and broadly comparable. This database is supplemented with data from the Swedish Meteorological and Hydrological Institute (SMHI) which contains 749 lakes and rivers using similar terminology. Data for 122 lakes and rivers were provided by the Finnish Meteorological Institute. Several sites were already in the NSIDC dataset but were updated where necessary. The three datasets were integrated to create the Ice Phenology Database (IPD) containing data across North America, Europe, and Russia (Fig. 1). It is important to note that in the later part of the 1980s and 1990s data for many Russian and Canadian sites are not recorded in the database.

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

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

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

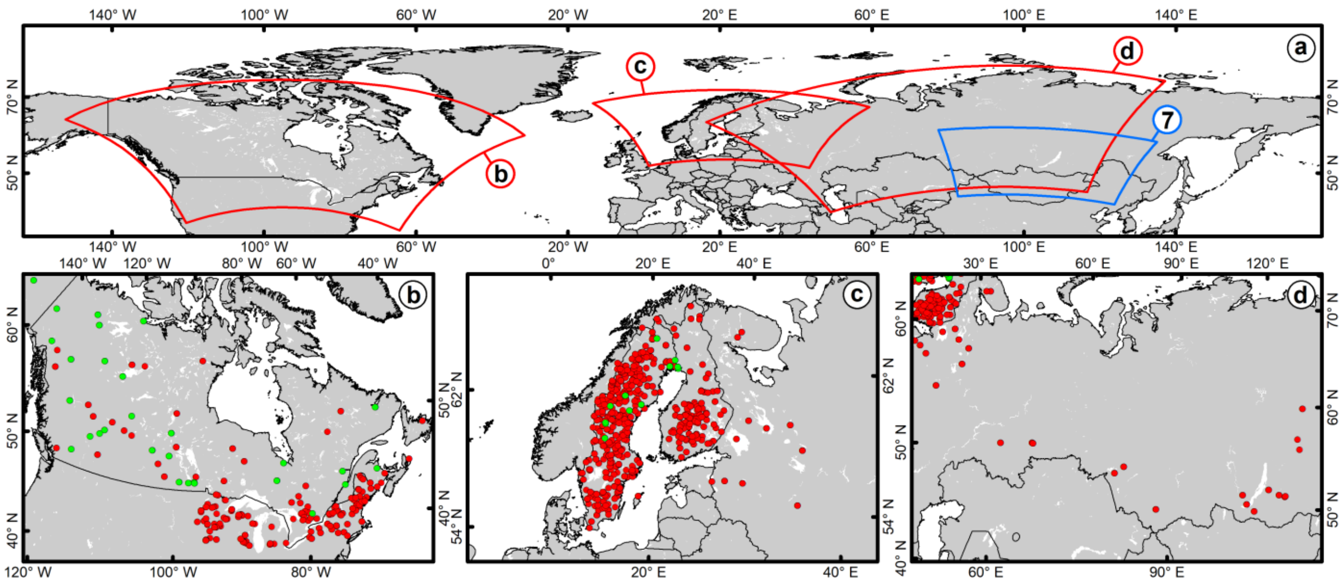

Figure 1: (**a**) Map showing the three main study areas. The red and green circles in panels (**b-d)** are lake and river sites, respectively, that have time series containing at least 90% coverage for breakup and/or freezeup during at least one time period. The majority of river sites are located in Canada, with Russia only having data available for lakes. The geographical extent used in panels (b-d) for each region of interest are the same in subsequent figures. The zoomed in extent of the Russian study are in Fig. 7 is shown by the blue outline on (a).

Breakup/freezeup dates were first converted to ordinal days. For some sites, freezeup or breakup in a specific year occasionally fell in a preceding or succeeding year and the ordinal date reflects this by providing a relative date – i.e. if freezeup for the 1941 ice season occurred on 5th January 1942 then the ordinal day allocated was 370. Likewise, if breakup for the 1943 ice season occurred on the 28th December 1942 then the ordinal date allocated was -3. These records were adjusted as necessary to calculate the number of annual open water days. The ordinal day records were tested using the Mann-Kendall test where the null hypothesis of no trend was tested against the alternative hypothesis that there is a monotonic trend in the time series. The Mann-Kendall test is a nonparametric test which detects trends without specifying if it is linear or nonlinear. It does not, however, calculate trend magnitude, so Sen's slope was also used (Yue et al., 2002). A full description of these combined methods can be found in Salmi et al. (2002). These two statistical techniques are commonly used in climate and environmental science as they can account for missing values. These methods were applied to all sites with at least 90% data (Table 2) for each individual time period to document the significance ($\alpha<0.1$), the magnitude of the slope, and decadal change derived from that magnitude. The 90% allowance means that the maximum number of sites were used for each of the five time periods. The trend magnitudes and directions were converted into the number of days change per decade in the date of breakup/freezeup or number of annual open water days at each site during each time period. The magnitude of the decadal change is mapped for all sites, with those that are statistically significant clearly identified in the symbology. To investigate short-term variations on the 75-year time period, residuals were calculated for breakup, freezeup, and open water days. Similar to Sharma and Magnuson (2014), a range of running means were applied, with an 11-year window shown to be most useful for the 75-year time series.

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

Oscillation (AO) (Thompson and Wallace, 2000), the Atlantic Multidecadal Oscillation (AMO) (van Oldenborgh et al., 2009), the North Atlantic Oscillation (NAO) (Jones et al., 1997), and the Southern Oscillation Index (SOI) (Ropelewski and Jones, 1987) were also extracted.

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

3. Results: Ice phenology change

A climate regime with increasing mean air temperatures would be expected to increase the number of annual open water days for sites that seasonally freeze through earlier breakup and/or later freezeup dates. The decadal trend for the number of annual open water days allows for an integrated observation of breakup/freezeup date changes relative to each other – i.e. the longevity of open water, rather than a specific shift in the precise breakup/freezeup dates. In this section the results from the Mann-Kendall and Sen's slope analysis are presented for the three main study areas: North America, Europe, and Russia. In total, 678 study sites provide at least one time series with ≥ 90% complete annual data across the four 30-year time periods and the one 75-year time period, with 3510 individual time series available (Table 2). A summary of the breakup/freezeup dates available for each of the four 30-year time periods is presented in Fig. 2. These data are used to determine decadal trend directions that have been summarised in Fig. 3 and in Table 3 as mean changes in breakup/freezeup dates, and the number of annual open water days. The general trends are first presented, before looking at the spatiotemporal trends across the three study regions.

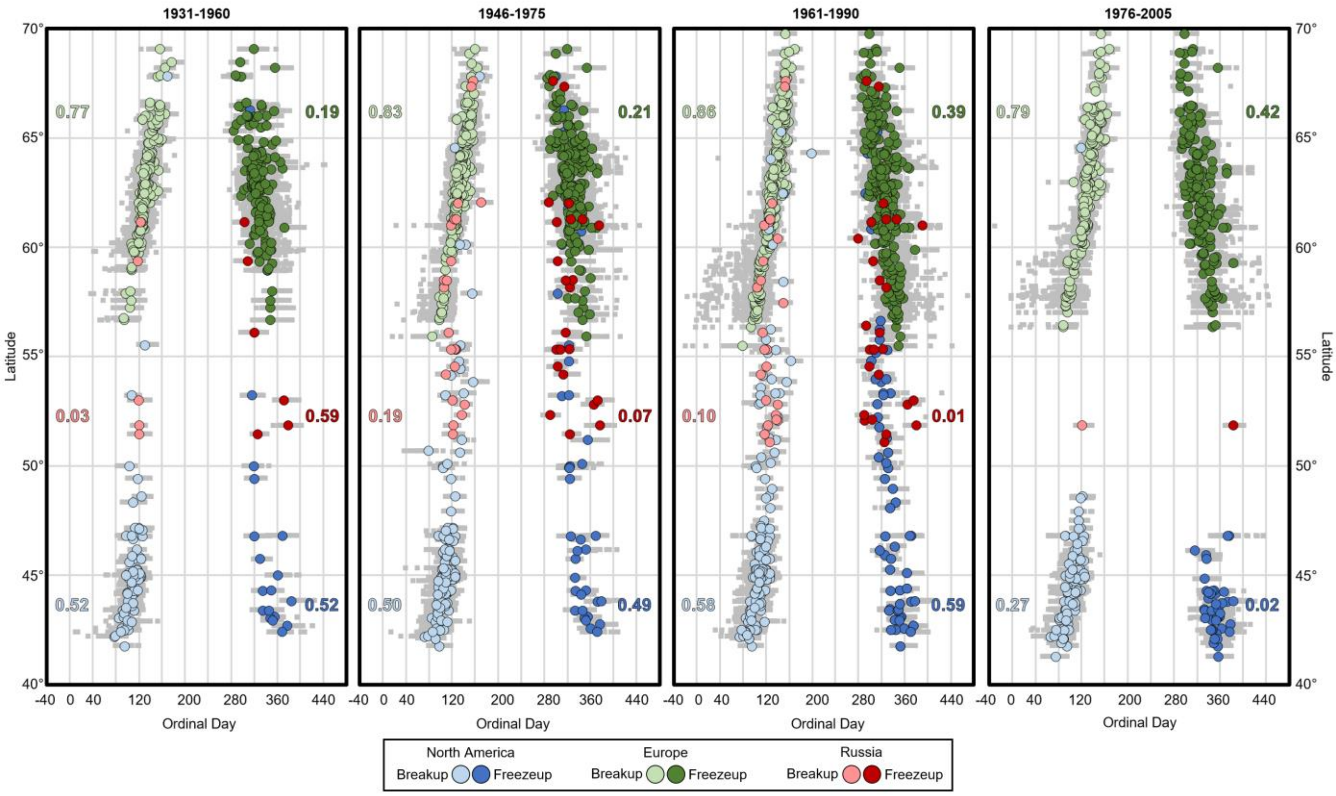

Figure 2: Summary graphs showing breakup and freezeup dates against latitude for all lake and river sites included in each of the four 30-year long time periods. The data are colour coded by region on the key. The numbers that are adjacent to the recorded dates are R^2 values for each set of regional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

3.1. General trends

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

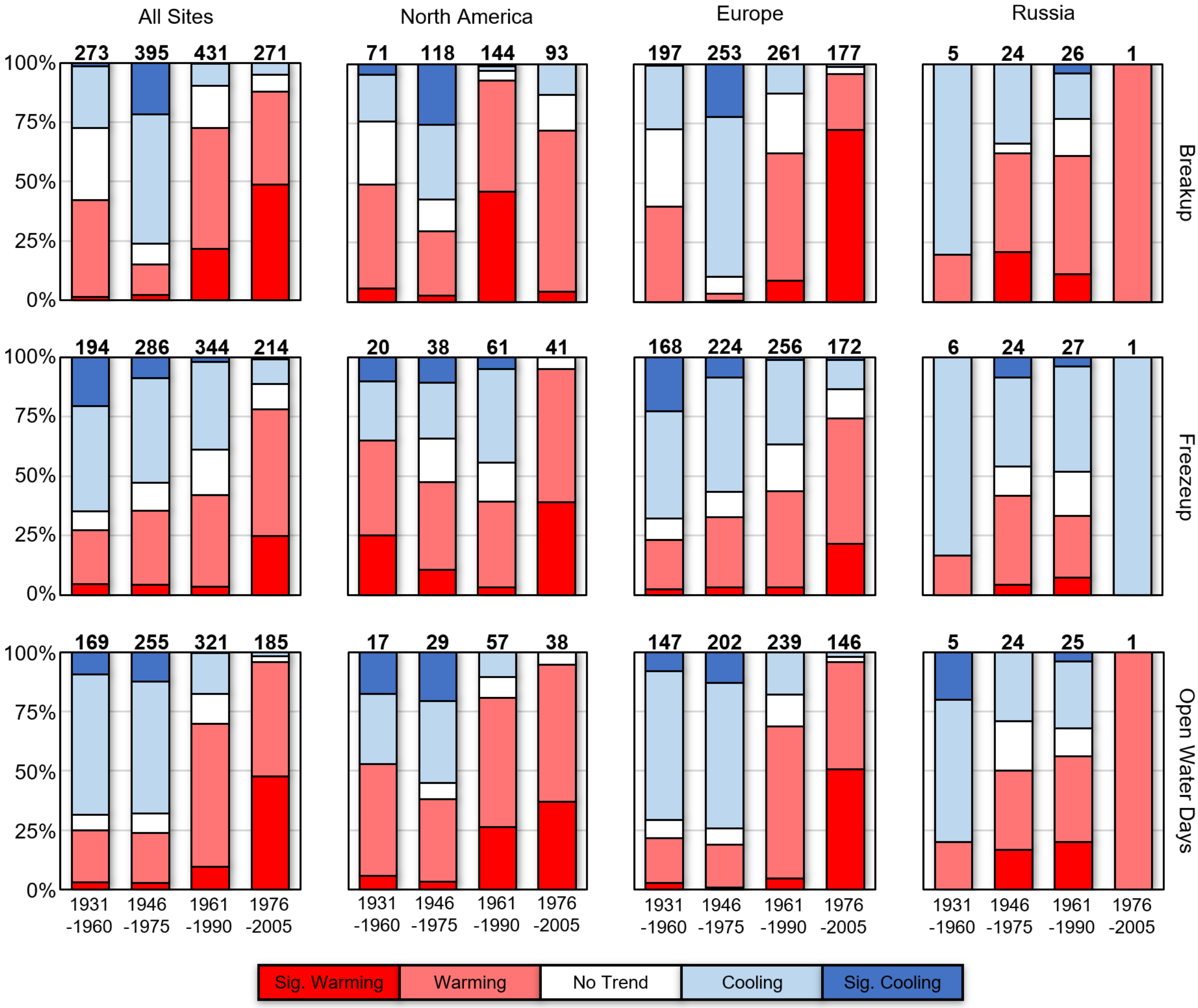

Figure 3: Summary charts showing generalised trends for all the sites contained within each of the 30-year time periods. The percentages are calculated as a proportion of the total number of sites for each time period (bold text – e.g. in the first panel, across all sites there are 273 sites with 1931-1960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

For each 30-year time period the proportion of trends displaying warming and cooling trends have been summarised in Fig. 3. This shows that through time the proportion of sites displaying warming trends has increased. Freezeup and the number of annual open waters days display a gradual increase in warming trends through time, and an increase in the proportion of sites with statistically significant warming trends. Mean decadal values show a gradual reduction in cooling trends from 1931-1960 to an increased warming during 1976-2005, albeit with high standard deviations when averaged across all sites (Table 3). Despite this consistent pattern, when observed at the three regional scales (discussed below), the proportion of warming and cooling patterns tend to fluctuate between the different time periods. It is only freezeup changes in Europe that show a similar pattern to that observed for all freezeup sites when combined, likely reflecting that data in Europe provides a larger proportion of the total number of sites (Fig. 3). What is common amongst all sites is that the 1976-2005 time period displays the largest proportion of sites with warming trends, with the exception of Russia (which has only one site), for freezeup and the number of open water days. For breakup the warming pattern for all sites also shows a longer-term increase through time that is interrupted by an increased proportion of sites displaying cooling trends from 1946-1975 (Fig. 3). This appears to be largely driven by an increase in the proportion of sites in Europe during that time period displaying either cooling or significant cooling trends. A similar interruption is also observed in North America, but is followed during 1961-1990 by a major increase in the number of warming trends. Similar to freezeup and the number of annual open water days, the mean decadal change for all sites shows warming trends develop and increase in magnitude by 1976-2005, again with the caveat that the standard deviation is high enough to switch trend direction (Table 3). The limited number of Russian sites with breakup data show a decrease through time in the proportion of cooling trends (Fig. 3).

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

		Breakup			Freezeup			Open Water		
		Lakes	Rivers	Total	Lakes	Rivers	Total	Lakes	Rivers	Total
All Sites	1931-1960	**-0.13** **(1.70)**	**-0.60** **(1.95)**	**-0.15** **(1.72)**	*-2.11* *(3.41)*	**3.08** **(3.06)**	*-1.82* *(3.60)*	*-2.18* *(4.05)*	**3.33** **(2.48)**	*-1.92* *(4.16)*
	1946-1975	*1.54* *(1.90)*	**-0.09** **(2.12)**	*1.45* *(1.95)*	*-0.59* *(3.36)*	**0.98** **(3.91)**	*-0.51* *(3.41)*	*-1.91* *(3.99)*	**1.23** **(3.10)**	*-1.80* *(4.00)*
	1961-1990	**-1.52** **(1.83)**	**-1.98** **(1.77)**	**-1.54** **(1.83)**	**0.22** **(2.12)**	**0.07** **(2.11)**	**0.21** **(2.12)**	**1.94** **(2.99)**	**1.46** **(1.88)**	**1.92** **(2.95)**
	1976-2005	**-2.86** **(2.19)**	**-1.18** **(1.26)**	**-2.81** **(2.18)**	**2.73** **(2.96)**	**0.64** **(1.36)**	**2.71** **(2.96)**	**5.88** **(4.06)**	**0.71** **(0.24)**	**5.83** **(4.08)**
	1931-2005	**-0.60** **(0.47)**	**-0.23** **(0.16)**	**-0.58** **(0.46)**	*-0.01* *(1.02)*	**0.70** **(0.70)**	**0.02** **(1.02)**	**0.60** **(1.04)**	**1.62** **(0.00)**	**0.63** **(1.04)**
North America	1931-1960	**-0.28** **(2.52)**	**-1.09** **(2.78)**	**-0.36** **(2.56)**	**0.05** **(2.92)**	**2.71** **(2.91)**	**0.85** **(3.16)**	*-1.39* *(4.99)*	**3.29** **(0.89)**	*-0.29* *(4.82)*
	1946-1975	*1.58* *(2.55)*	**-1.05** **(1.97)**	*1.27* *(2.63)*	*-0.17* *(2.29)*	**1.22** **(4.42)**	**0.23** **(3.13)**	*-2.47* *(4.52)*	**1.28** **(2.94)**	*-1.57* *(4.49)*
	1961-1990	**-3.11** **(1.83)**	**-1.92** **(1.95)**	**-2.98** **(1.88)**	*-0.24* *(1.85)*	**0.04** **(2.39)**	*-0.18* *(1.97)*	**3.08** **(3.22)**	**1.30** **(2.06)**	**2.77** **(3.12)**
	1976-2005	**-1.16** **(1.39)**	**-0.56** **(0.81)**	**-1.15** **(1.38)**	**3.61** **(2.32)**	X	**3.61** **(2.32)**	**4.15** **(2.84)**	X	**4.15** **(2.84)**
	1931-2005	**-0.66** **(0.50)**	X	**-0.66** **(0.50)**	**0.84** **(0.78)**	X	**0.84** **(0.78)**	**1.49** **(1.12)**	X	**1.49** **(1.12)**
Europe	1931-1960	**-0.10** **(1.31)**	**-0.22** **(0.64)**	**-0.10** **(1.29)**	*-2.31* *(3.43)*	**3.52** **(3.17)**	*-2.13* *(3.56)*	*-2.24* *(3.97)*	**3.38** **(3.39)**	*-2.09* *(4.06)*
	1946-1975	*1.75* *(1.31)*	*1.59* *(1.06)*	*1.75* *(1.31)*	*-0.78* *(3.27)*	**0.34** **(1.71)**	*-0.76* *(3.25)*	*-2.28* *(3.62)*	**1.08** **(3.58)**	*-2.25* *(3.64)*
	1961-1990	**-0.79** **(1.25)**	**-2.17** **(1.16)**	**-0.82** **(1.25)**	**0.34** **(2.17)**	**0.18** **(0.78)**	**0.33** **(2.16)**	**1.81** **(2.85)**	**1.99** **(0.82)**	**1.81** **(2.84)**
	1976-2005	**-3.77** **(1.98)**	**-1.43** **(1.31)**	**-3.70** **(2.00)**	**2.53** **(3.06)**	**0.64** **(1.36)**	**2.51** **(3.05)**	**6.38** **(4.20)**	**0.71** **(0.24)**	**6.30** **(4.22)**
	1931-2005	**-0.54** **(0.40)**	**-0.23** **(0.16)**	**-0.52** **(0.40)**	*-0.25* *(0.95)*	**0.70** **(0.70)**	*-0.20* *(0.97)*	**0.35** **(0.89)**	**1.62** **(0.00)**	**0.39** **(0.90)**
Russia	1931-1960	*0.83* *(0.79)*	X	*0.83* *(0.79)*	*-1.92* *(2.10)*	X	*-1.92* *(2.10)*	*-2.47* *(3.16)*	X	*-2.47* *(3.16)*
	1946-1975	**-0.75** **(2.15)**	X	**-0.75** **(2.15)**	**0.69** **(4.66)**	X	**0.69** **(4.66)**	**1.63** **(4.56)**	X	**1.63** **(4.56)**
	1961-1990	**-0.83** **(1.83)**	X	**-0.83** **(1.83)**	*-0.03* *(1.89)*	X	*-0.03* *(1.89)*	**1.03** **(3.16)**	X	**1.03** **(3.16)**
	1976-2005	**-0.53** **(0.00)**	X	**-0.53** **(0.00)**	*-0.50* *(0.00)*	X	*-0.50* *(0.00)*	**0.56** **(0.00)**	X	**0.56** **(0.00)**
	1931-2005	0.00 (0.00)	X	0.00 (0.00)	**1.04** **(0.00)**	X	**1.04** **(0.00)**	**1.53** **(0.00)**	X	**1.53** **(0.00)**

Table 3: Breakdown of mean decadal trends for each time period where each value is the number of days change per decade. The trend directions and magnitudes were derived from the Mann-Kendall and Sen’s Slope tests and provide a general overview of the prevalent patterns during each time period for each study area. The standard

deviation between the sites in each category is shown in the brackets beneath. Negative values represent earlier breakup (warming trend), earlier freezeup (cooling trend), and a reduced number of open water days (cooling trend). Positive values indicate the opposite. Bold and italic text has been added to aid in the interpretation of whether the mean values support warming (bold) or cooling (italic) trends. Boxes with "X" indicate time periods where no data were available.

3.2. North America

In North America, the only sites with consistent data are clustered around the Great Lakes. During 1931-1960, in the east, earlier breakup dates dominate, and in the west, later breakup (Fig. 4a), with a number of sites being statistically significant (Fig. 3). This variation explains the large standard deviation ($\sigma = 2.52$) of the mean trend toward 0.36 days per decade earlier breakup (Table 3). An east-west pattern is reversed in the 1946-1975 period, with later breakup more common in the east (Fig. 4d). Mean trends show breakup dates became 1.27 days per decade ($\sigma = 2.63$) later during 1946-1975, with the trend driven largely by lakes with later breakup dates (Table 3), many of which are statistically significant (Fig. 3). From 1961-1990, most sites display earlier breakup trends, with a mean change of 2.98 days per decade ($\sigma = 1.88$) (Table 3). Nearly half of all sites display significant breakup trends (Figs. 3, 4g), many of which previously displayed significant later breakup trends (Fig. 4d). Four sites show later breakup trends, of which one is geographically-isolated and the others are surrounded by lakes with earlier breakup trends, many of which are significant. This suggests local factors, such as human modification of water courses (Déry et al., 2005; Déry and Wood, 2005) or lake circulation patterns (Bennington et al., 2010), might account for local-scale heterogeneity. From 1976-2005 sites are clustered around the Great Lakes and demonstrate partial changes compared to the preceding time period (Fig. 4j). Whilst 72% of sites trend towards earlier breakup (Fig. 3), in the east several sites now display low magnitude earlier and later breakup trends. Earlier breakup decadal change for lakes, at 1.16 ($\alpha = 1.39$), is double that for rivers, at 0.56 ($\alpha = 0.81$) (Table 3). The standard deviation continues to show considerable variation around the mean.

Fewer sites with freezeup data are available compared to breakup (Table 2) and remain generally clustered around the Great Lakes (Fig. 4b). From 1931-1960 no clear geographical pattern exists, with 25% of sites displaying significant later freezeup trends for rivers and lakes (Fig. 3). Mean decadal trends show freezeup was 0.85 days per decade later, but this is associated with a high standard deviation ($\sigma = 3.16$) and a large difference in the mean trends for lakes and rivers (Table 3). During 1946-1975, spatial patterns remain varied (Fig. 4e) and sites with significant later and earlier freezeup trends each account for 10.5% of all sites (Fig. 3). Significant sites are both rivers and lakes and unlike breakup do not appear to be clustered east of the Great Lakes. The mean trend for lakes remains low at 0.17 days per decade earlier ($\sigma = 2.29$), whilst rivers are comparably higher with freezeup occurring 1.22 days per decade ($\sigma = 4.42$) later (Table 3). Freezeup date changes during 1961-1990 show that sites in the west more commonly trend toward earlier freezeup and in the east toward later breakup (Fig. 4h). Compared with the breakup trends for the same period, and freezeup trends for the preceding period, the proportion of sites with significant earlier (4.9%) and later (3.3%) freezeup dates is smaller (Fig. 3). The mean decadal trend of 0.18 days per decade ($\alpha = 1.97$) earlier freezeup dates for lakes and rivers combined is weaker than observed for earlier breakup during the same period (Table 3). From 1976-2005, freezeup trends demonstrate a clear pattern, with no sites displaying earlier freezeup trends (Fig. 4k) and 39% of sites showing significant later freezeup trends (Fig. 3). This is markedly different to all other time periods where spatial patterns were much more varied in the Great Lakes region (Fig. 4h). There are no river sites with freezeup data for this time period (Table 2) and mean values for lake changes show that freezeup was becoming later by 3.61 days per decade ($\alpha = 2.32$) (Table 3).

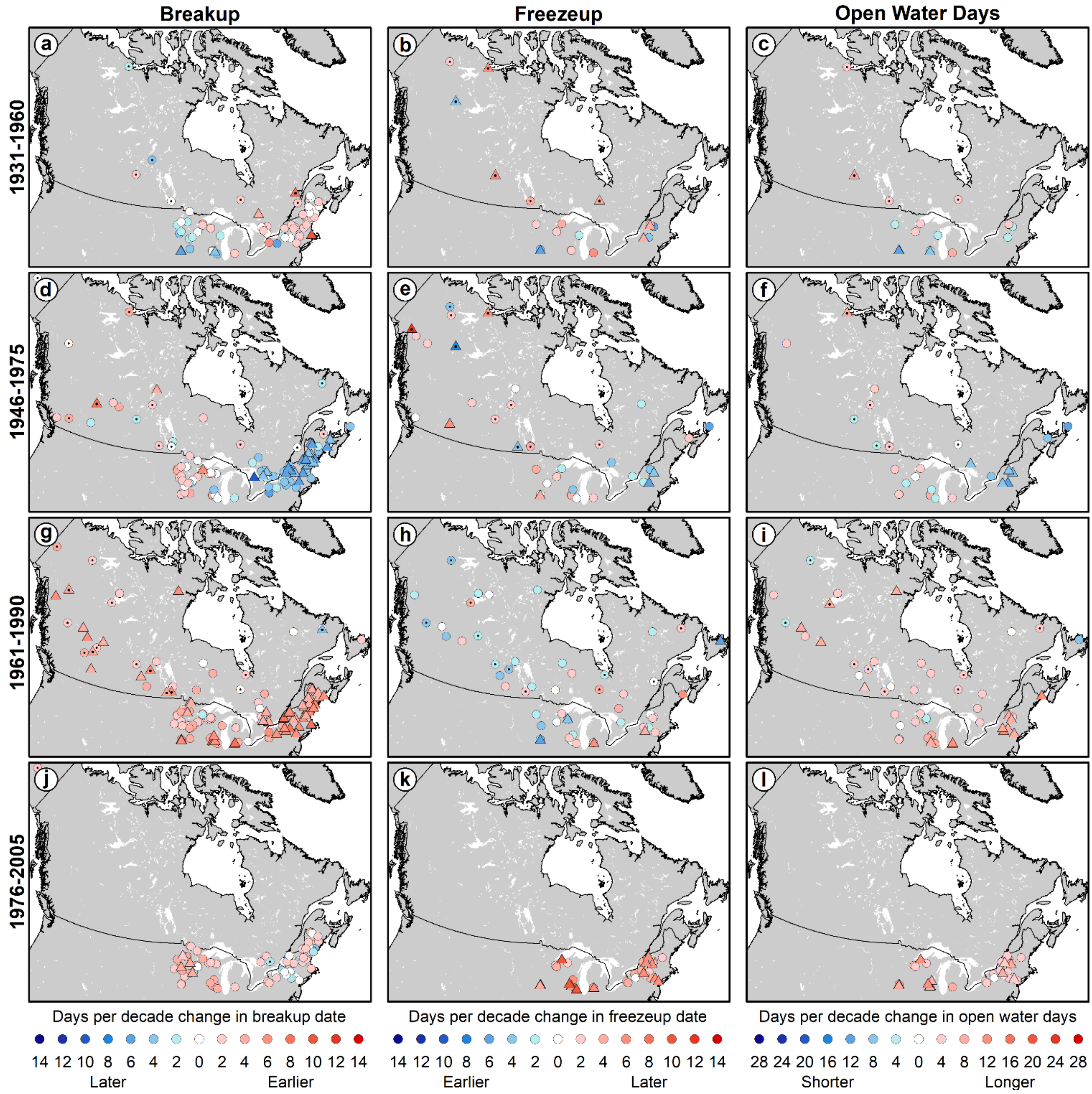

Figure 4: Decadal trends for breakup (**a**, **d**, **g**, and **j**), freezeup (**b**, **e**, **h**, and **k**), and the number of annual open water days (**c**, **f**, **i**, and **l**) in North America for the four individual time periods. The trend directions and magnitudes were derived from the Mann-Kendall and Sen's Slope tests. The triangles and circles indicate whether the trend was or was not statistically significant. Sites with a dot in the centre of the circle are river sites. Thus, a red triangle symbol with a dot in the middle indicates a river site that has a statistically significant warming trend over that time period. The blue and red tones on the scales are related to cooling and warming trends, respectively. Note that in some places the symbols overlap.

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

3.3. Europe

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

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

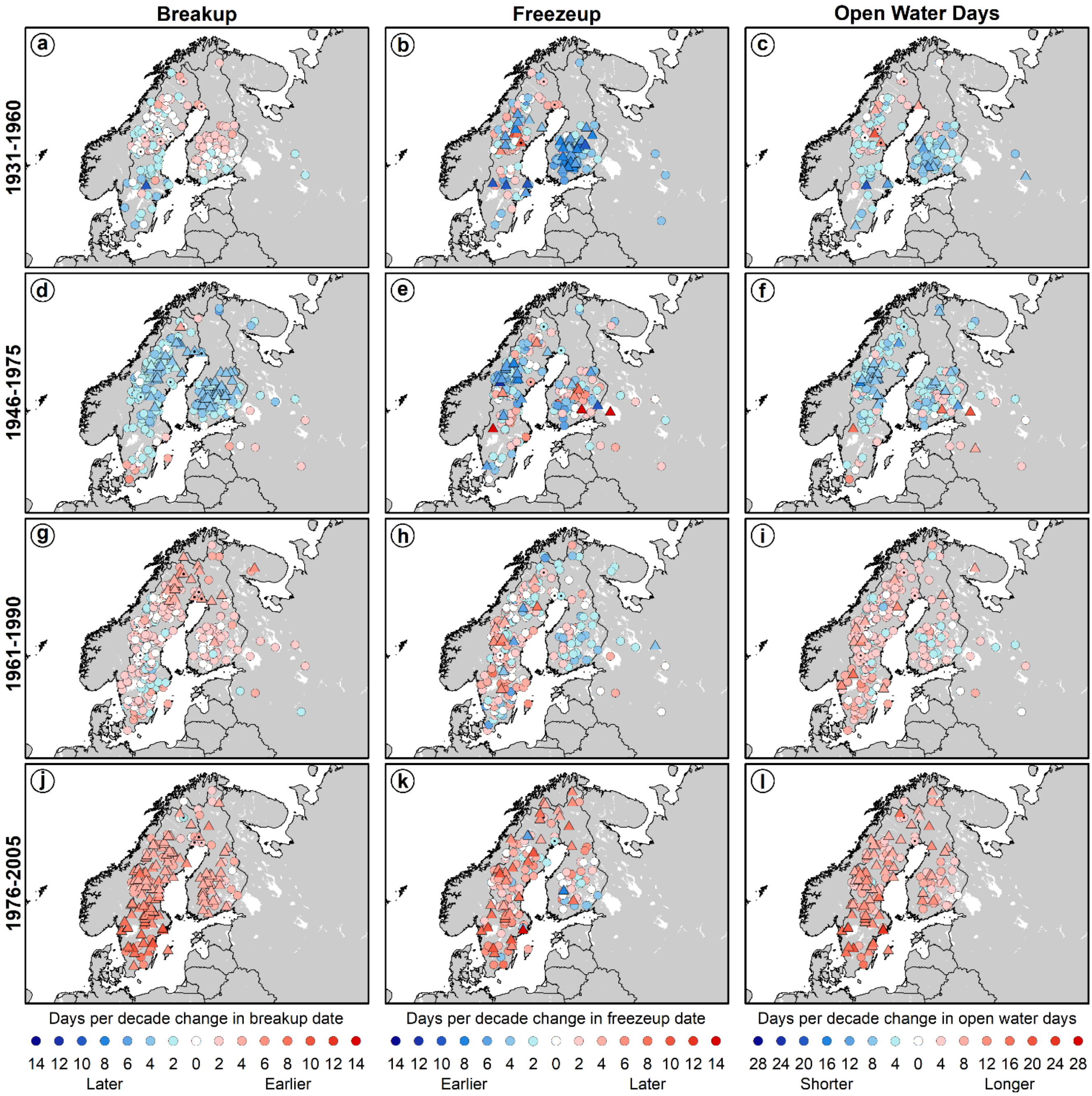

Figure 5: Decadal trends for breakup (**a**, **d**, **g**, and **j**), freezeup (**b**, **e**, **h**, and **k**), and the number of annual open water days (**c**, **f**, **i**, and **l**) in Europe for the four individual time periods. The trend directions and magnitudes were derived from the Mann-Kendall and Sen's Slope tests. The triangles and circles indicate whether the trend was or was not statistically significant. Sites with a dot in the centre of the circle are river sites. Thus, a red triangle symbol with a dot in the middle indicates a river site that has a statistically significant warming trend over that time period. The blue and red tones on the scales are related to cooling and warming trends, respectively. Note that in some places the symbols overlap.

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

3.4. Russia

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

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

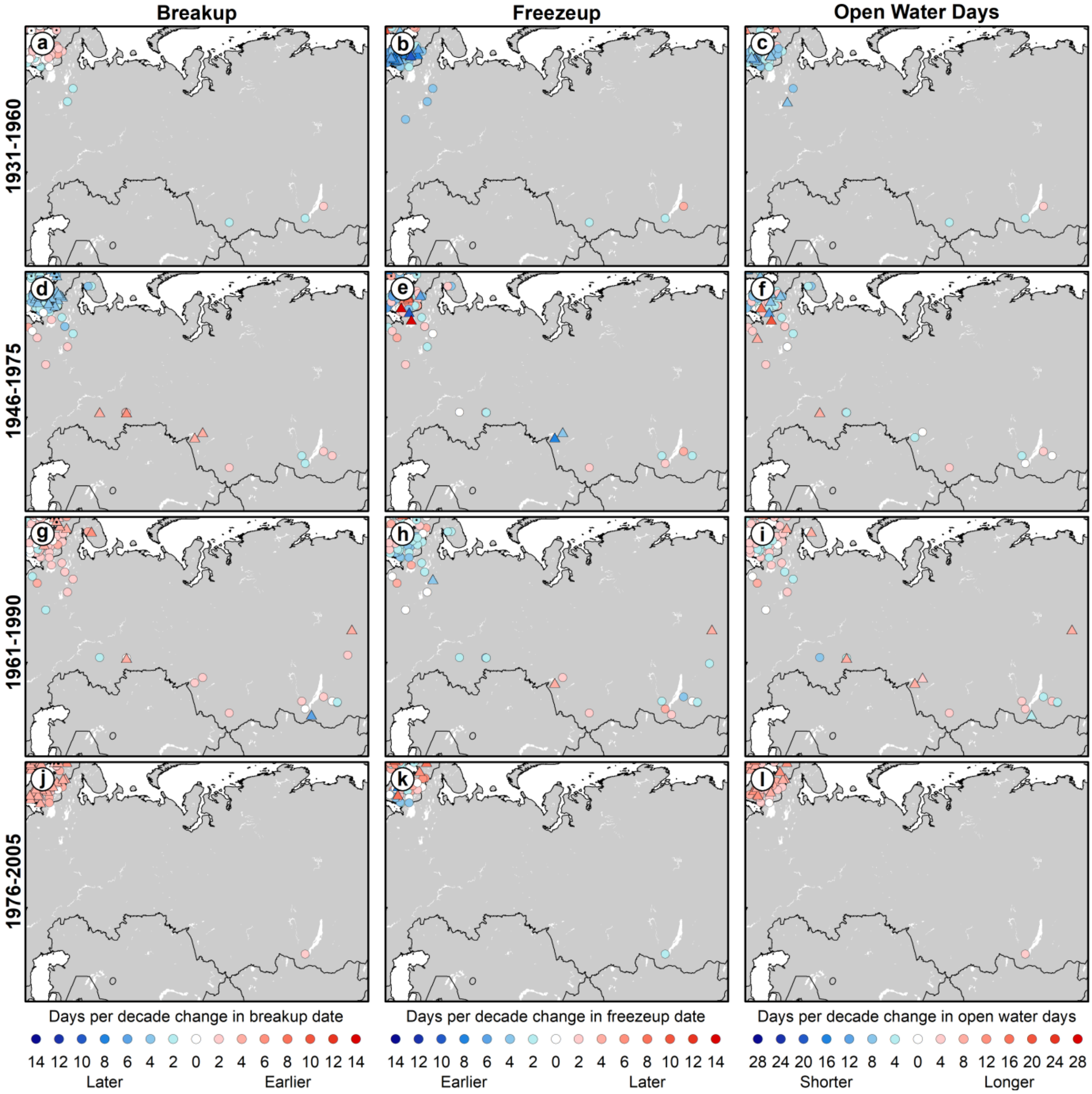

Figure 6: Decadal trends for breakup (**a**, **d**, **g**, and **j**), freezeup (**b**, **e**, **h**, and **k**), and the number of annual open water days (**c**, **f**, **i**, and **l**) in Russia for the four individual time periods. The trend directions and magnitudes were derived from the Mann-Kendall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

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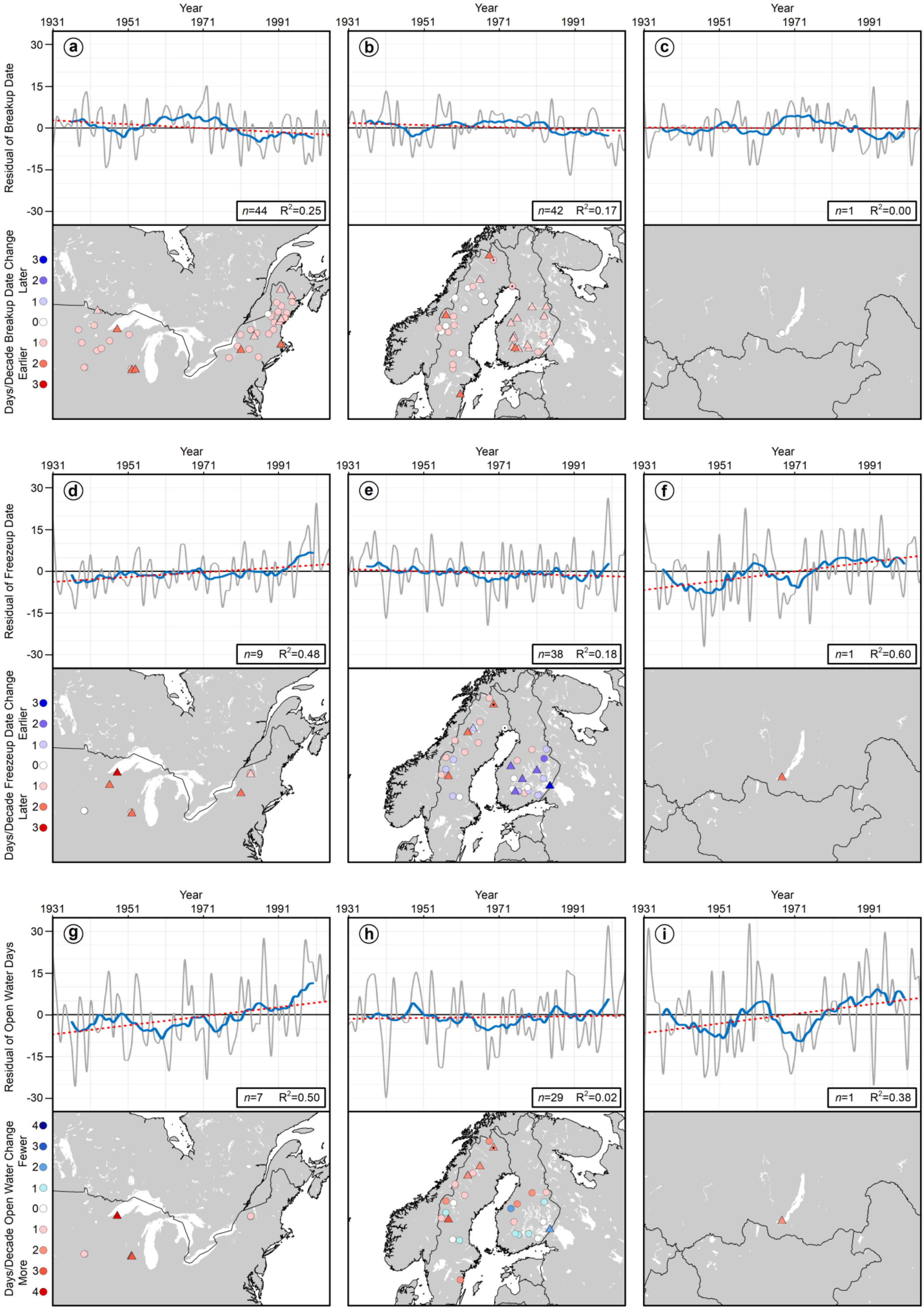

Year
1931
1951
1971
1991
a
b
c
d
e
f
g
h
i
Residual of Breakup Date
Residual of Freezeup Date
Residual of Open Water Days
n=44 R²=0.25
n=42 R²=0.17
n=1 R²=0.00
n=9 R²=0.48
n=38 R²=0.18
n=1 R²=0.60
n=7 R²=0.50
n=29 R²=0.02
n=1 R²=0.38
Days/Decade Breakup Date Change
Later
Earlier
Days/Decade Freezeup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

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

3.5. Sites with continuous data – 1931-2005

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

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

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

4. Results: Causes of ice phenology change

Correlations between breakup/freezeup dates and a series of regionally-averaged climatic variables and indices for each of the three study regions (Fig. 8): Europe (EUR), North America (NAM) and Russia (RUS), on a monthly basis and for three-monthly means over the time period 1931-2005. Unsurprisingly, rising temperatures appear to be the dominant control on the shift towards earlier breakup and later freezeup in the ice phenology records. Late winter and spring temperatures negatively correlate most strongly with breakup, which is expected since rising temperatures lead to more rapid ice melt and thus earlier breakup dates. Autumn and early winter temperatures positively correlate most strongly with freezeup, which is entirely as expected as increasing temperatures lead to delayed freezeup dates. In Europe and North America, the month preceding breakup (April and March, respectively) exhibits the strongest correlation with temperatures, whereas for freezeup the strongest correlation with temperatures occurs on the month of freezeup (November and December, respectively). This may relate to the gradual build-up of rising air temperatures required to break up ice to depth, as opposed to the more rapid onset of freezeup with falling autumn and winter air temperatures.

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

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

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

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

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

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

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

5. Discussion

The results presented for all three regions show that between different 30-year time periods there are fluctuations in the trend directions for breakup/freezeup dates and the number of annual open water days. The two most recent 30-year time periods in North America and Europe (Figs. 4-5) show that warming trends dominated. Warming trends for the number of annual open water days were initially driven by earlier breakup dates before then being increased further by later freezeup (see below). This is in line with other studies that capture long-term reductions in the ice season (Futter, 2003) and show that warming breakup trends are more common (Brammer et al., 2015; Jensen et al., 2007), and whilst freezeup trends do move toward warming patterns, they are often more variable (Duguay et al., 2006; Hewitt et al., 2018). The 30-year time period analyses documented here also show that some short-term variations lead to variable spatial patterns through time. For example, in the Great Lakes region, the two most recent time periods show consistent trends towards earlier breakup dates (Figs. 4g, 4j), which is corroborated in more localised studies (e.g. Magnuson et al., 2005), but the trends in the first two 30-year time periods show variability in the trend magnitude and direction of phenology changes, with sites to the west and east displaying opposing trends (Fig. 4a, 4d). The trends in this region, as well as more broadly across North America, Europe, and

Russia are dominantly driven by regionally-averaged temperature changes, with precipitation and teleconnections also helping to explain some of the variation (Fig. 8). Such a finding is not new (e.g. Blenckner et al., 2004; Bonsal et al., 2006; Duguay et al., 2006; Ghanbari et al., 2009; Hewitt et al., 2018; Livingstone, 1999; Sharma et al., 2013; Smith, 2000), but it does further confirm that the prevailing climate conditions can only partially account for some of the variability in ice phenology trends. What is interesting is the fact that strong correlations can be established despite correlating ice phenology records with spatially averaged climate data over large regions. This indicates that broad regional climate exerts a considerable degree of influence over changes in ice phenology. Such a finding is important because it means that site specific climate data, either from in situ observations or from numerical downscaling of climate models, may not be explicitly required to explain a large amount of the phenology variation. Whilst there are clearly merits in looking at sites with local data to better understand the underlying processes taking place and how this relates to the observed climatological trends (e.g. the influence of wind on ice phenology), being able to regionalise and simplify the analysis to sites across broad areas that do not have local climate observations is important for upscaling efforts to project larger-scale climatic changes.

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

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

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

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

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

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6. Conclusions

Utilising a number of different datasets, a series of analyses have been used to investigate how the number of annual open water days per year and the timing breakup/freezeup dates have changed for water bodies that ephemerally freeze across the Northern Hemisphere. Five overlapping time periods (1931-1960, 1946-1975, 1961-1990, 1976-

2005, and 1931-2005) have been investigated across 678 sites with data in at least one of the time periods to provide ~3510 time series of lake and river ice phenology change to be statistically, spatially, and temporally analysed. A warming signal has been observed that shows the number of annual open water days has increased by 0.63 days per decade across the Northern Hemisphere from 1931-2005. The breakup trends display a strong correlation with temperature observations in the weeks preceding breakup and during winter ice growth, suggesting that temperature can be confidently used to explain a large proportion of variability. Freezeup trends show the greatest variability that is less easily predicted from air temperature changes compared to breakup. This is likely because freezeup is not guaranteed to occur simply because temperatures have moved below 0 °C as water kinetics can prevent freezeup. When the time series are investigated on smaller timescales to explore temporal changes, trends for the number of open waters days show variation, with the two most recent 30-year time periods displaying a consistent trajectory towards more open water days that is nonlinear with respect to magnitude. In general, the number of open water days closely resemble breakup patterns, suggesting that breakup trends are the main driver in open water day trends. Four key conclusions have been drawn from this research; (1) an accelerating warming signal is clearly observable in breakup dates at many sites and is reasonably well-aligned to broad regional temperature trends, (2) freezeup trends are more spatiotemporally complex and display weaker temperature correlations, (3) the length of the open water season has generally increased through time and was predominantly driven by earlier breakup dates, and (4) that care needs to be taken when interpreting the implications of ice phenology changes at sites that only have breakup or freezeup data. These results highlight the need for a more detailed understanding of historical changes and their causes to fully unravel the potential implications of ice phenology when projecting future climate changes.

Data availability

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

Author contribution

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

Competing interests

There are no competing interests to declare.

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