Tricentennial trends in spring ice breakups in three rivers in northern Europe

Stefan Norrgård[1] and Samuli Helama[2]

[1]Department of History, Åbo Akademi University, Turku, FI-20500, Finland
[2]Natural Resources Institute Finland, Rovaniemi, FI-96200, Finland

Correspondence to: S. Norrgård (stnorrga@abo.fi)

Abstract. At high latitudes, long-term changes in riverine ice breakups are exemplary measures of climatic change and variation. This study compared cryophenological trends, patterns and changes for the rivers Aura (1749–2020), Torne (1693–2020) and Kokemäki (1793–2020), all located in Finland. The Kokemäki is a new series from the city of Pori. The findings show statistically significant cross-correlations between the Aura and Kokemäki rivers, while the correlations with Torne River were weaker. The weaker correlation was attributed to climatic differences caused by the latitudinal distance between the rivers. Taken together, the many results of this study suggest that in the south the spring climate has changed more rapidly and become less predictable than in the north. Climatic extremes – warmer and wetter winters – in the 2000s resulted in the first recorded no-freeze events in Aura and Kokemäki rivers. The no-freeze events were the final outcome of a rapid increase in early events and interannual variability the last 30 years. The number of early events have been increasing in all three rivers since the early or mid-1900s, but the earliest recorded breakup day in Torne River has changed only marginally the last 100 years. Our dynamic temperature analysis showed that the breakup event in Torne River requires higher temperatures than in the south and future changes in the timing of the breakup depend on April temperatures. In the south, on the other hand, future changes depend much more on winter temperature and precipitation during the freeze-up period.

1 Introduction

Lakes and rivers in high latitudes are fundamental parts of the cryosphere. Records of freeze-up (winter) and breakup (spring) link to air temperature and provide valuable information on interannual and interdecadal climate variability. An improved understanding of historical and current freeze-up and breakup patterns helps to understand the spatiotemporal impact of climate warming. Some changes, such as an increase of open water winters or floods could have great socio-economic impacts and they could cause changes in the aquatic ecosystem or biogeochemical processes (Prowse et al., 2006; 2011)

Most cryophenological studies employ lake-ice data because lake-ice series are plentiful and they provide good spatial coverage. Such analyses have shown trends towards later freeze-ups and earlier breakups across the northern hemisphere (Newton and Mullan 2021; Benson et al, 2012; Korhonen 2006; Magnusson et al., 2000). The trends vary in time and scale depending on location but changes are typically associated with air temperatures and especially increased temperatures in cold climate regions since the 1960s (Mikkonen et al, 2015; Weyhenmeyer et al., 2011; Bonsal and Prowse, 2003**;** Serreze et al. 2000)

In contrast to lake-ice series, river-ice series usually extend further back in history. Longer series help to get a better picture of long-term changes, however, complete river-ice series are scarce. Most are discontinued and incomplete. For example, riverine series from Russia and North America start in the 1700s but they have been discontinued in the 1900s (Rykatschew, 1887; Magnuson et al., 2000). Updated river-ice series are available from Estonia, Belarus and Latvia, however, except for the regulated rivers of Daugava in Latvia (Klavins et al. 2009) and Nemunas in Lithuania (Stonevicius et al., 2008), most series cover only the 1900s (Klavins et al., 2009).

In Finland, at least five river-ice series date back to the 1700s (e.g. Rykatschew, 1887; Johansson, 1932) and in the 1800s, before long-term meteorological data was readily available, scientists used the breakup series to investigate climatic changes (Hällström, 1842; Eklöf, 1850, Levänen, 1890). The professor of Meteorology Oscar Johansson (1932) extended some of the series to 1906 and thereafter they were dormant until Juha Kajander (1993; 1995) documented the observations for Torne River in northern Finland. This series has often been compared to lake-ice records from the northern hemisphere (e.g. Newton and Mullan, 2021; Sharma et al., 2016; Magnuson et al., 2000). In 2019, the Torne River series was complemented with the Aura River series from Turku in southwest Finland (Norrgård and Helama, 2019). The present study conducts the first comparison between these series. The current study further presents a new multicentennial ice breakup series for the Kokemäki River (in Swedish *Kumo älv*) based on observations from the city of Pori (*Björneborg*) in southwest Finland. It spans from 1793 to 2020 and it is compared to the Torne River (1693–2020) and the Aura River series (1749–2020). This study has four main objectives: (i) to examine if the power plant closest to Pori has changed the timing of the ice breakups; (ii) to analyse the long-term trends and the correlations between the rivers Aura, Kokemäki and Torne; (iii) to analyse how the series correlate to temperature, precipitation and, in the case of Torne River, ice thickness; and (iv) to examine variability and changes in the frequency of extreme events.

2 Study areas

2.1 Tornio and Torne River

Torne River is one of the largest unregulated rivers in Northern Europe. The river flows southward from Lake Torne in the Arctic into the Bothnian Bay, the northernmost sub-basin of the Baltic Sea (Fig 1). Torne River has a watershed area of 40,157 km² and is 522 km long. The last 180 km, before entering the Baltic Sea, the river marks the border between Finland and Sweden. The ice breakup observation site is in the Finnish city of Tornio (65°84'N, 24°15'E) and is situated about 3.5 km from the mouth of the river. At the observation site, the river is approximately 260 meters wide. The breakup date signals when the ice starts to break up or move. The ice breakup is monitored by the Finnish Environment Institute (SYKE), which also measures ice thickness, discharge rates and snow cover thickness.

The average discharge at the observation site in Karunki (23 km upstream from the breakup site) during the 1911–2020 period was 388.75 m³/s. The maximum discharge on 11 June 1968 was 3667 m³/s. Torne River is unregulated but Tengeljoki River, one of the tributary rivers, hosts three hydroelectric power plants. The power plant closest to the ice breakup observation site in Tornio city is 80 km upstream and it should have no significant influence on the breakup process (Sharma et al., 2016).

Founded in 1612 on an island in the middle of the river, Tornio was known as a trading hub. In 1800, Tornio had a population of 710, and in 2019, 22,000. The Swedish twin-city of Haparanda was founded on the western side of Tornio in 1842 and today the Tornio-Haparanda region has a combined population of about 32,000 inhabitants. The number of bridges crossing the Torne River has increased during the 20th century. However, the only bridges in Tornio are situated below the breakup observation site. Most anthropogenic impact on the breakup process was probably caused by log-driving dams built on the river in the 1900s (Kajander, 1993). Hundreds of these dams were built in the upstream tributaries and their purpose was to collect water that could carry logs to Torne River. The dams were demolished after the log-floating era ended in 1971 (Zachrisson, 1988).

2.2 Turku and Aura River

Aura River has a watershed area of 885 km² and the average discharge at the Halinen dike between 1938 and 2020 was 6.86 m³/s. The maximum on 2 May 1966 was 286 m³/s. Aura River is 70 km long and drains into the Baltic Sea. The ice-off observations originate from the city of Turku (60°45'N, 22°27'E), which is located at the mouth of the river. Within the city limits, the width of Aura River varies between 35 and 100 meters and the depth varies between one and four meters. The Aura River series depicts the ice-off date, which is when the river is ice free between the mouth of the river and Halinen dike (Norrgård and Helama, 2019). The dike is situated six kilometres from the mouth of the river and it is mentioned for the first time in the 14th century. The dike detaches the lower reaches from the upper reaches and it creates a two-stage breakup process independent from each other (Norrgård and Helama, 2019). Aura River is, except for the dike, unregulated.

As of 2019, Turku had a population of approximately 191,000. The city had a population of 4,500 in the 1730s, which then doubled by 1800. The city expanded on both sides of its 'spine', as Aura River is sometimes referred to, and the most significant changes took place in the 20th century. Since 1939, the number of bridges crossing the river have grown from three to nine. The industrial area that dominated the riverbank near the mouth of the river for almost 200 years relocated after the mid-1900s and it has since then been replaced by apartment buildings. For a more in-depth presentation of the Aura River series see Norrgård and Helama (2019).

2.3 Pori and Kokemäki River

Kokemäki River is 121 km long and the river drains into the Bothnian Sea, the largest sub-basin of the Baltic Sea, and has the largest river delta in the Nordic countries. Kokemäki River has a catchment area of 27,046 km^2 and the average discharge at the power plant in Harjavalta between 1931 and 2020 was 218,62 m^3/s. The maximum recorded discharge on 5 May 1966 was 918 m^3/s. Daily discharge averages vary because of the upstream hydroelectric power plants. The plant nearest to Pori is in Harjavalta (31 km from Pori) and it has been in use since 1939. The 26-meter-high dam generates up to 105 MW and is the biggest of four hydroelectric power plants. The second power plant was built in 1940 in the city of Kokemäki (46 km from Pori). The oldest power was built in 1919 in Äetsä (87 km from Pori), and the newest power plant in Tyrvää in 1950 (121 km from Pori).

The breakup observation site is in the city of Pori (61°48'N, 21°79'E) and lies about 11 km from the sea. The observations derive from the city centre and the width of the river varies between 160 and 240 metres. The estimated depth varies between two and four metres. For most part of the period, the ice breakup date determines when the ice between the Porinsilta Bridge (built 1926) and Kirjurinluoto Island begins to breakup or move.

As of 2019, Pori had population of 83,000. The city of Pori was founded near the mouth of the river in 1558 and it quickly became an international trading port. Postglacial uplifting made Kokemäki River too shallow for bigger ships to enter and the main harbour migrated towards the sea in the 1770s. The city centre was concentrated on one side of the river until the city expanded across the river in the latter half of the 1800s. Pori has not expanded towards the sea like Turku.

Kokemäki River was used for log floating until 1967 and the timber industry has played an essential part in the history of Pori. The industrial area was built upstream and close to the city centre. Ice jams have been a nuisance in Pori, which is the most significant flood risk area in Finland (Verta and Triipponen, 2011). Recurring ice jam floods were the main reasons why the river was dredged and the riverbanks were reinforced throughout the 1900s. Several flood response constructions were built during the 1900s and near the observation site in the 1970s and 1980s (Louekari, 2010; Huokuna, 2007).

2.3.1 Kokemäki River: material

The Kokemäki River ice breakup series is based on descriptions obtained from local newspapers in Pori. These were the Swedish newspaper *Björneborgs Tidning* (1860–1965) and the Finnish newspaper *Satakunnan Kansa* (hereafter *SK*) (1873–). The newspapers until 1950 were obtained from the Finnish National Library's digital database (https://digi.kansalliskirjasto.fi) whereas recent newspapers were accessed via the University of Turku newspaper affiliate in Raisio and the *SK's* internal database at the editorial office in Pori. All articles were transcribed and the metadata is stored locally.

Newspapers are exemplary sources because they provide daily and sometimes sub-daily descriptions of the breakup process (Norrgård and Helama, 2019; Kajander, 1993). Newspapers often also contain entire breakup series submitted to the newspapers by the readers and these are invaluable when constructing breakup series. The first breakup series for the Kokemäki River was published under a pseudonym in *Åbo Tidningar* in July 1843 and covered the 1801–1843 period. An extended version (1801–1849) of the initial series was parallel-published in *Åbo Tidningar* and *Suometar* on 11 May 1849. This was later used to calculate change in the timing of the breakups (Eklöf, 1850). These were followed by four other series that were sent to the newspapers, but the version that extended the breakup series to 1794 appeared in *SK* in 1877. The Professor of Meteorology Oscar Johansson (1932) then extended the series to 1793 and 1906. The last version of the series was published in *SK* in 1984, but the most recently updated was found in the city archives and it spans the 1794–1998 period. Its origin is unknown; however, two initials in the lower right-hand corner match the names in an article published in *SK* in 1996. This suggests that the series had been monitored and maintained by city employees since the 1950s. Finally, the current series does not include breakup dates for the four years between 1999 and 2002. No observations were obtained after 2003 and the added dates therefore originate from the breakup guessing competition arranged by the local Lions Club.

2.4 General reflections on ice conditions

Low winter temperatures predetermine that Torne River always freezes. There are no midwinter breakups, and the mean ice cover period is five to six months (Kajander, 1993). Ice thickness has been measured at the observations site since 1964 and the date with most measurements and nearest the breakup date were from 30 March. Mean ice thickness for this day during the 1964–2020 period was 76.5 cm (n=54).

Systematic records on freeze-up dates or ice thickness are not available for Aura River, which is 600 km south of Tornio. Leche (1763), Moberg (1857; 1890;1891;1892; 1893) and Levänen (1890) collected freeze-up dates and adding five additional observations for 1861–1865 from a local newspaper gives a mean of 144.3 ice cover days (n=37; median 146). All observations were made before the 1900s and 23 were from the 1700s. The sporadic occurrence of mid-winter breakups means that the length of the ice cover period is only indicative of actual ice conditions. For example, the freeze-up in 1771 was 20 November, and the ice had reached a thickness of 20 cm before heavy rains caused a midwinter breakup on 13 December. Midwinter breakups of various intensities have occurred between December and February throughout the 1749–2020 period. The last recorded midwinter breakup with at least 20 cm thick ice occurred in January 1999. During cold winters, the ice can reach a thickness of 70 cm or more, as reported in the newspapers in April 1837 and March 2003. Records on ice conditions are sporadic, but the provided examples give some perspective on the conditions leading up to the first no-freeze event in 2008 (Norrgård and Helama, 2019).

A thermal breakup, as opposed to a dynamic breakup, is characterised by the ice being thinned and weakened from thermal inputs. There is little to no breakage of the ice, which melts in situ if there is little to no flow increase (Beltaos and Prowse, 2009). Thermal breakups appear in the records the describing the Aura River breakup process. They also appear in descriptions from Kokemäki River and in this case they affect the validity of some of the observations. For example, in March 1992, *SK* wrote that the ice melted in situ for the fourth year in a row. The city employee conducting the observations claimed that an official breakup date would not be recorded because a proper breakup date could not be determined. Thermal breakups have are not a new phenomenon in the Kokemäki River, but they are more sporadic than in the Aura River.

Dates on freeze-up, ice thickness or ice cover has not been systematically collected in Pori. The first breakup series from 1843 contained some dates and there are 11 years of observations between 1810 and 1844 (Moberg, 1857). These dates give a mean of 157.8 ice cover days (n=11; median 160). As in Turku, midwinter breakups may affect the actual number of ice cover days. For example, the freeze-up was 15 November in 1841, but a midwinter breakup 7 January 1842 occurred before the actual breakup 16 April. In Pori, ice jam floods have been a nuisance and parts of the river is dredged often to prevent floods. For example, it was dredged in 2014 and again in 2018.

Finally, the dates in the Aura River series denotes the ice-off event or when the river is ice-free whereas the dates in the Torne and Kokemäki river series describe the ice breakup, or the initial movement of the ice. In this paper, 'breakups' are hereafter used to refer to 'ice breakups' or 'ice-offs', but we will distinguish when necessary.

3 Data and methods

3.1 Obtaining and extracting breakup dates for Kokemäki River

A comparison of the in the newspapers published breakup series for Kokemäki River showed that the differences were minor; however, the series did not reveal where the observations originated from. The aim was therefore to homogenize the breakup dates with regard to site and event (Norrgård and Helama, 2019). Previously published series were used as a date of reference when scrutinizing the newspapers for observations from this period. It quickly became clear that the newspaper articles described the breakup in the city centre and near the location of the Pontoon Bridge that was replaced by the Porinsilta Bridge in 1926. The aim was thereafter to obtain observations that referred to this part of the river and described the same stage of the breakup process. Consequently, the compiled series describe the initial breakup or when the ice started moving in the city centre between Porinsilta and Kirjurinluoto Island.

The observations prior to 1863 could not be validated and a partial reason might be a devastating city fire in 1852. However, the series published *in Åbo Tidningar* in July 1843 declares that the series depicts the ice breakup in the city of Pori, and maps from the 1800s show that the city was small and concentrated, which is why the observations most likely refer to the area where the bridges were later built. The breakup in 1852 was the only time when the dates in the previously published series diverged considerably. The breakup was noted to have started in either early April or early May. The breakup in May was preferred as this was more consistent with the events in Aura River.

Two remarks regarding the site and date: First, some dates in the latter half of the 1900s are probably based on observations from the Linnansilta Bridge, which was built in 1974. This became the point of reference when the journalists started interviewing city employees or other experts and stopped describing the breakup themselves. Second, the dates obtained from the guessing competition are based on the movement of a closely monitored marker standing on the ice. Thus, the breakup date follows the marker and its movement instead of the breakup date in Kokemäki River in general.

3.2 The vernal equinox

All dates in all three series follow the Gregorian calendar. The recorded dates were adjusted according to the vernal equinox (VE) to conduct the analyses. This approach was preferred instead of the year to date approach due to the length of the series. Calendar dates can in long-term cryophenological series that span several centuries result in overestimated trends when they continue into the 21st century (Sagarin, 2001; 2009). In practice, the vernal equinox has varied between 19 and 21 March. The vernal equinox dates for each series were obtained from NASA dataset homepage and adjusted to Finnish time zone (GMT+2).

3.3 Extreme events and variability

The analysis of extreme events and variability is twofold. First, the 30 latest/earliest events were ranked according to their calendric dates and the timing of the breakups was compared over the period common to the three series (1793–2020). The timing of the events was also compared according to the length of the Aura River (1749–2020) and the Torne River series (1693–2020).

Second, breakup patterns, extreme events, and variability were also analysed according to the vernal equinox using 30-year non-overlapping windows in the interquartile range (IQR). The IQR is the difference between the third (75 %) and first (25 %) quartile. Thus, the IQR gives the middle range wherein the middle half of the breakups occur. The second quartile (Q2) is the median value.

For the purpose of performing the quartile analysis, no-freeze years were quantified as an ice breakup that occurred 1 January (VE-79). No-freeze events are challenging when quantifying dates because the rate of change is easily underestimated. For example, Benson et al. (2012) chose the earliest breakup date, while Sharma et al. (2016) treated them as censored values. However, these two studies used breakup series that included no-freeze already before or in the 1900s. Here, no-freeze events occur for the first time in the 21st century, which is why a more distinct approach was preferred. The Kokemäki River series include some gaps and the Aura River series was used to interpolate the breakup dates for Kokemäki River during the 1781–1792 period and again for 1999–2002.

Extreme events in each 30-year period were analysed according to i) the average of the three earliest/latest breakups and by analysing ii) the frequency of extreme events. The extremely late event was defined as the latest breakup in the 1991–2020 period. All breakups that in previous periods occurred on the same day or later were counted. Opposite to this, the earliest breakup was defined as the earliest breakup in the first period of each series. For example, the earliest breakup in Torne River was obtained from the 1721–1750 period; in Aura River from the 1751–1780 period and in Kokemäki River from the 1781–1810 period.

3.4 Hydroelectric power plant impact

The hydroelectric power plant in Kokemäki River in Harjavalta was taken into use in 1939. This year was therefore chosen as the starting year for assessing whether the power plant changed the timing of the ice breakup in Pori. The hypothesis was that sudden changes in the timing of the breakup should be visible as a distinguishable shift in the difference between the recorded breakup dates. First, the impact was assessed by analysing changes in the Spearman coefficient before and after 1939. Second, the breakup date in Kokemäki River was subtracted from the breakup dates in Aura. Third, discharge rates measured at the site since 1931 was used to assess how the power plant changed the discharge leading up to the breakup date. The data is maintained by SYKE. The discharge for each day leading up to the breakup date was averaged in order to create a dynamic model that shows the discharge 60 days before the breakup and ten days after. We then compared the unregulated 1931–1938 period to the 1939–1998 period. This comparison facilitated only the recorded breakup dates and not the dates obtained from the breakup competition. This was considered the best approach because the difference between the breakup date and the guessing competition date is unknown.

3.5 Cross-correlations, meteorological variables and trends

The Spearman coefficient was used to analyse i) cross-correlations between the series and the ii) correlations between the breakup series and monthly mean temperature and precipitation over the 1960–2020 period. The temperature and precipitation data derive from a spatial model made by the Finnish Meteorological Institute (FMI) (Aalto et al. 2013; 2016). Based on temperature and precipitation data from Finland the model is supplemented with data from neighbouring countries (Estonia, Norway, Russia, and Sweden). The model uses, due to its robustness and accuracy, the kriging interpolation to account for the influence of topography and nearby water bodies. The breakup data for Aura, Kokemäki and Torne rivers were correlated against the monthly mean temperatures and precipitation sums estimated by the model.

Another model from FMI (Venäläinen et al., 2005) was used to analyse daily temperature development leading up to the breakup. The model is based on temperature data starting in 1961 and it also uses the kriging interpolation method. For this analysis the values of daily mean, maximum and minimum temperatures were calculated for Tornio (Torne River), Pori (Kokemäki River) and Turku (Aura River) over the 1961–2020 period. The temperatures for three variables (mean, maximum and minimum) were aligned according to the breakup date and calculated over an interval of 180 days before and 30 days after the breakup. The analysis thereby shows the change in local daily mean, maximum and minimum temperatures 180 days before and 30 days after the breakup date between 1961 and 2020.

Finally, the Mann-Kendall (MK) statistic (Kendall, 1970; Mann 1945) was used to determine the statistical significance of long-term trends and the rate of change (slope) was estimated using Sen's (1968) slope. These methods are commonly used to analyse temporal trends in phenological series (e.g. Menzel, 2000; Gagnon and Gough 2005, 2006; Terhivuo et al., 2009; Benson et al., 2012; Šmejkalová et al., 2016; Helama et al., 2020).

4 Results

4.1 Extreme breakup events

4.1.1 Early breakup events

It is, based on previous research and the impact of climate warming, not a surprise that all three series are dominated by early breakups in the 1900s and 2000s (Tab 1). If the missing breakups dates (1999–2002) in Kokemäki River are interpolated, then all the 30 earliest breakups, except for the event in 1822, are from the 1900–2000 period. The event in 1822 was unique in Aura and Kokemäki rivers but not in Torne River. Comparing to three breakup series from nearby rivers in Finland and Russia shows that 1822 was early in Porvoo River (1771–1906) (Johansson, 1932) in Porvoo (60°23′N, 25°39′E) in south Finland and in Neva River (1706–1882) in St Petersburg (59°56′N, 30°18′E), Russia (Rykatschew, 1887). However, the breakup in 1822 was not early in Northern Dvina (1734–1879) in Archangel (64°32′N, 40°32′E), Russia, (Rykatschew, 1887). This suggests that the data is correct and that there was a climatic discrepancy between the north and south in 1822.

The rivers Aura and Kokemäki had their first no-freeze event in 2008. The Aura River had its second no-freeze event in 2020 whereas the Kokemäki River had its second in 2015, and the third in 2020. The no-freeze events in 2008 and 2020 occurred during the two warmest winters on record, the latter being slightly warmer than the former (Ilkka et al., 2012; Irannezhad et al., 2014; Lehtonen, 2021). The non-freeze event in Kokemäki River in 2015 also occurred during one of the warmest years on record (FMI, 2016). In the context of record warm winters, it is worth noting that Torne River had an exceptionally late breakup in 2020. One of the latest breakups in 60 years.

In Torne River, the 30 earliest events remain the same whether the series is set to start in 1693 or 1749. The earliest breakup in Torne occurred in 2014 and this was only one day earlier than the event in 1921. Hence, the earliest breakup date remained unchanged for nearly 100 years. Even the long-term change is negligible. For example, the earliest breakup date (2014) occurred only five days earlier than the earliest breakup in the 1700s (1757). In contrast, there is a 48-day difference between the earliest (1990) ice-off event in Aura River and the earliest ice-off event in the 1700s (1750). These findings show that the timing of the early events in Kokemäki and Aura rivers have undergone a more radical change than the timing of the early events in Torne River.

4.1.2 Late breakup events

Breakup events in the 1900s and 2000s dominated the list of earliest breakups, but there is less uniformity when it comes to the late events (Tab. 2). The reasons are the differences in the length of the series, but also the climatic conditions between the north and the south. For example, in Torne River (1693–2020) 18 of the 30 latest events occurred before the start of the Aura River series in 1749. Thus, the coldest springs the last 323 years clearly occurred during the first half of the 1700s. It is somewhat surprising that the breakup during the cold European winter in 1708/1709 (Luterbacher et al., 2004) is not amongst the 100 latest events in Torne River.

In Aura River (1749–2020), eight of the latest events occurred in the 1700s. However, the four latest events in all three series, except for the event in 1695 in Torne River, are from the 1800s.

Over the 1793–2020 period, all three rivers shared late breakups in 1807, 1810, 1812, 1845, 1847, 1867 and 1881. Three of these events are from the early 1800s, and the number of events during the first two decades of the 1800s is considerable. More than one-third of the latest events in the Torne and Kokemäki rivers occur between 1800 and 1824. Yet the breakups were late in all three rivers only in 1807, 1810, and 1812. The concentration of events in the early 1700s and 1800s could possibly be attributed to the climatic effects caused by the Maunder Minimum (1645–1715) and the Dalton Minimum (1800–1824), which mainly affected the spring climate (e.g. Miyahara et al., 2021; Xoplaki et al., 2005). There were other smaller clusters of late events in, for example, the 1840s, but they do not stand out as much as the events during the first two decades of the 1800s.

Finally, lake-ice research has highlighted the exceptionally late breakup in 1867 (Korhonen, 2005; 2006), the great famine year in Finland (Myllyntaus, 2009). The event in 1867 is one of the latest event in Aura, Torne and Kokemäki rivers; however, the riverine series also highlight the breakups in 1807 and 1810. These three events are the only events found in in the original length of all three series. 1807 and 1810 are less pronounced in Aura River because they are not amongst the top ten latest. However, the range in the Aura River is considerably shorter than in the other two rivers. The 1810 event was the 24 latest event but only eight days later than the latest. This should be contrasted to Kokemäki River where there is a 9 day difference between the first and second latest events.

4.2 Cross-correlations and changed in the discharges

4.2.1 Cross-correlations and changes caused by the power plant

Table 3a shows the average and median breakup dates and the cross-correlations between the three series across their respective lengths. The weakest correlation was between Aura and Torne rivers and this should probably be attributed to different climatic conditions caused by the distance (approximately 600 km) between the rivers. The strongest correlations were found between Aura River and Kokemäki rivers, which could be expected considering the distance (approximately 120 km) between the rivers. The correlations remained high when compared over the pre-power plant period (1793–1938) and the power plant period (1939–2020) (Tab. 3b).

When it comes to changes caused by the power plant in Harjavalta then the correlation coefficient fails to register small scale changes. Comparing the events in Aura and Kokemäki rivers in the 1793–1938 period, shows that the breakup in Kokemäki River started on average 3.2 days after the ice-off in Aura River (Tab. 3b). However, in the 1939–2020 period, the breakup in Kokemäki River started 3.2 days before the ice-off in Aura River. Thus, the Harjavalta power plant caused a 6.4-day change in the timing of the breakups; however, interannual variations were considerably larger (Fig. 3).

The dates from the breakup competition in Kokemäki River (2003–2020) show an average difference of 2.3 days before the Aura River ice off event. This is probably and underestimation when considering the actual breakup date. A newspaper article published in 2019 indicated that the breakup started approximately six days before the guessing competition marker. This suggests that the actual differences between the rivers were larger than indicated by the calculated differences. In this case more data is needed in order to assess the difference between the rivers.

4.2.2 Discharge patterns, changes and impacts

It seems probable that the power plant in Harjavalta changed the discharge rate, thereby causing the breakup date to pre-date the ice-off date in the Aura River. Comparing the 1931–1938 and 1939–1998 periods (Fig. 3) show how the average discharge rate prior to the breakup has changed. First, comparing the discharge in1934 to that in 1976 shows how the weekly pulses at the power plant affects the rate of discharge. Second, a clear flow peak used to appear one week after the breakup in the 1931–1938 period and this vanished after the power plant was built in 1939. Third, the average discharge until approximately ten days before the breakup has increased slightly since 1939. This could potentially have advanced the timing of the breakup. Finally, the average discharge rate at the breakup date has decreased from 382.13 m^3/s in the 1931–1938 period, to 322.88 in the 1939–1998 period.

The changes brought on by the power plant were initially subtle (Fig 2, box 1). It was not until after 1958 that the difference between the rivers Aura and Kokemäki appears unnatural. In the 1959–1979 period, the breakups started on average 7.3 days (range 1–21 days) before the ice-off in Aura River (Fig 2, box 2). This is probably an effect of increased mean winter discharge at Harjavalta (Korhonen and Kuusisto, 2010); however, it should probably be attributed to lake-level regulations in the watershed area. New regulations were introduced in 1957, 1980 and 2004 (Koskinen, 2006) and these years seem to concur with the highlighted boxes in Fig 2. For example, the 1957–1980 period include some of the largest interannual differences and these become smaller and more sporadic after 1981.

Finally, the Aura River had its first no-freeze event in 2008 and second in 2020. The average discharge for December, January and February in the winters of 2007/2008 and 2019/2020 were higher than in any other winter months in the 1938–2020 period. None of the months had the highest recorded discharges but these were the only years when the discharge rate was at least twice the long-term average in each month. This provides a plausible explanation to why the no-freeze events occurred in Aura River during these warmer winters. A similar pattern could not be observed for Kokemäki River.

4.3 Climatic correlations

4.3.1 Breakups according to monthly mean temperatures 1961–2020

All three series exhibited strong and statistically significant negative correlations with winter and spring temperatures (Fig. 4). This indicates that higher than average spring temperatures have caused earlier breakups and variability (Fig 5). Aura River exhibited particularly high correlations with February (-0.77) and March (-0.74) temperatures. Kokemäki River also showed high correlations with the same months, but the correlations were higher with March (-0.84) than February (-0.71). When compared to the February-March period, the correlation was slightly higher for the breakups in Kokemäki River (-0.89) than in Aura River (-0.86).

The breakup in northern Finland occurs later in spring than the breakups in the southern parts of the country. Thus, the mean temperature correlations for the Torne River were strongest with April (-0.70) and May (-0.49). The correlations remained at the same level when compared to the April-May period (-0.70). All of the breakups have occurred within a short window from late April to early May, which explains why the correlations are highest with April.

4.3.2 Breakups according to monthly mean precipitation 1961–2020

Correlations with winter and spring precipitation were mainly negative. However, the correlations were considerably weaker than those with temperature and precipitation is secondary to temperature (Fig. 4). The precipitation correlations for the winter months December and January are statistically significant in Kokemäki and Aura rivers. They are strong, even though non-significant, in Torne River. January showed the strongest correlations with Kokemäki River; February with Aura River and May with Torne River. The Aura River is therefore the only river that shows the highest correlations for both temperature and precipitation in the same month.

4.3.3 Breakups according to daily mean temperatures 1961–2020

The breakup in Torne River has usually started about three months after the coldest winter days and when the daily mean temperature has reached approximately 4.6°C (Fig. 6). This was usually when the daily maximum was close to 10 °C and the minimum temperatures had surpassed the freezing point. These conditions have usually occurred around twenty days after the daily mean temperature has risen above the freezing point.

The breakup in Kokemäki River has usually started at lower temperatures than the breakup in Torne River, i.e. the thermal input needs to be higher to generate the ideal conditions for the breakup in Torne River. In Pori, the breakups have usually started 10 days after the daily mean temperatures has risen above the freezing point. At the day of the breakup, the daily mean has usually been around 2°C and the maximum at 5 °C. The most noteworthy difference between Tornio and Pori was that the minimum temperature in Pori has gone below the freezing point three weeks after the breakup. A similar pattern was visible in Turku, however, the temperatures has not fallen below the freezing point as consistently or as much as in Pori. The ice-off event in Turku has usually occurred ten days after the daily mean has risen above freezing but at slightly higher temperatures than in Pori (mean 2.5°C and maximum 7°C). The difference is minimal, but higher temperatures could be explained by the fact that Aura River indicates the ice-off date.

4.3.3 Breakups, ice thickness and snow cover in Torne River

SYKE has measured the thickness of the ice in Torne River since the 1960s. Comparing the monthly mean values with the breakup dates shows the highest correlation, and the only with significant i.e. $p<0.05$ values, for April (rho 0.355, $p<0.012$, 1966–2019, n=49). Mean ice thickness was 77 cm and the mean breakup date for the 1966–2919 period was equal to 6 May (VE47) if vernal equinox was on 20 March. The negative trend ($p<0.05$) and Sen's slope (-0.267) shows that the ice has become about 14 cm thinner over the 1966–2019 period.

The fact that the earliest breakup date has not changed even though ice thickness has decreased tresses the temperature conditions in April. For example, the ice was 75 cm thick in 2014, the earliest breakup on records, but the ice was thinner and the breakup later on 22 occasions. This is acknowledged because the ice was too thin to be measured in 2020 (VE61), the extremely warm year with the unusually late breakup. A thicker snow cover could have maintained a higher surface albedo that delayed the melting of the underlying ice, thereby delaying the breakup (e.g. Prowse and Beltaos, 2002; Bieniek et al., 2011). However, SYKE has measured snow depth on the ice since 1978, but all correlations with the breakup date were non-significant for the 1978–2019 period.

4.4 Temporal trends

Table 1 showed that the breakups the last few decades have occurred earlier than ever before. Therefore, not surprisingly, all rivers show negative trends, i.e. the breakups are advancing towards the beginning of the year (Tab. 4, Fig. 7). It is over 140 years since the last ice-off event in May in the Aura River and almost 100 years since last breakup in the Kokemäki River (Fig. 8).

The trends were pronounced for Kokemäki and Aura rivers over the 1939–2020 period. The slope showed a change of almost three weeks in both rivers. The change was more drastic in the south than in the north where Torne River's slope indicated a change of less than one week.

Over the 1793–2020 period, the slopes of Kokemäki River (26.2 days) and Aura River (17.4 days) diverged, and the development in Aura River was similar to that in Torne River (13.0 days). Moreover, the rate of change within the slope remained similar in Aura (15.3 days) and Torne (13.6) rivers even over the 1749–2020 period. Taken together, the similarities in change between rivers Aura and Torne implies that the calculated change in Kokemäki River is skewed. However, Kokemäki River had substantially more late events than Aura and Torne river in the 1800s and early 1900s (Fig. 6). Hence, the diverging trends in Kokemäki River may be attributed to a greater change in the late events (see below).

4.5 Variability and extremes in 30-year non-overlapping periods

4.5.1 Frequency of early and late events

The long-term frequency of extremely early events has increased while the late events have decreased in all three rivers (Fig 9d-f). The first increase in early events occurred in the 1901–1930 period, but the most rapid increase occurred in the 1991–2020 period. A common phenomenon for all three rivers was that the extremely early breakups that occurred once in the first period constitute at least one third of all events in the 1991–2020 period.

The change that occurred in the 1901–1930 period is pivotal in Aura and Torne rivers because of the decrease in late events. The change was likely caused by spring warming and linked to the Early Twentieth Century Warming (e.g. Hegerl et al. 2018). Opposite to this, Kokemäki River showed an increase of early events but almost no change in the number of late events. For example, late events constituted more than two-thirds of all breakup event in the 1781–1810 and 1901–1930 periods. This is drastic difference in comparison to Aura River but it was followed by a rapid decrease of late events in the 1931–1960 period (Fig. 9e).

The average of the three earliest events in the 1991–2020 period shows that the earliness of the events have advanced considerably in Kokemäki and Aura rivers (Fig. 9a-c). The development was driven by the no-freeze events but also several events in early March and February (Fig. 8). In Torne River, as noted before, the change in the early extremes was negligible. However, the late extremes are affected by two unusually late events in 1996 and 2020. These are two of the latest ice breakups in almost 100 years. Moreover, there is only a 12-day range in the 75 percentiles in Torne River while the range is over 90 days in Aura and Kokemäki rivers. The change in the two southern rivers is therefore considerable and it stands out not only in the singular early events, but also when averaged.

4.5.2 Variability within the quartiles

Examining the quartiles shows that an increase of early events can increase and decrease variance in the interquartile range (IQR) in Torne River. The IQR showed greatest variability in the 1751–1780 period and it was caused by an increase of early events in the 25 percentiles (Fig. 9g). Variability remained stable after the 1840, but there has been a slight decrease in variability, caused by a rapid increase of early breakups, since the 1931–1960 period. The increase of early breakups has thereafter been explosive. For example, all the breakups in the 75 percentiles in the 1991–2020 period occurred before the median breakup date in the 1961–1990 period (Fig. 9a). This change has occurred at the same time as late events have increased. This is a conundrum but it is discussed in more detail below.

The change in Aura River is similar to that in Torne River. The magnitude of change is unprecedented: 28 of 30 ice-off events in the 1991–2020 period occurred before the median ice-off date in the 1961–1990 period. For example, the latest breakup in the 1991–2020 period occurred a week earlier than in the 1961–1990 period.

The IQR in Aura and Kokemäki rivers increased considerably in the 1991–2020 period. In Aura River, the IQR doubled from 11 days in the 1961–1990 period to 22 days in the 1991–2020 period. In Kokemäki River the change was from 9.25 to 18.5 days. The increase in variance, in both rivers, was caused by a rapid increase in the number of early events. All events in the 25 percentiles occurred before the vernal equinox (Fig 9b-e).

5 Discussion

5.1 Changes since 1900

The key feature describing the breakups in Aura and Kokemäki rivers in the 21st century was increased interannual variability. The breakups have progressively advanced towards the freeze-up period and the exacerbated effect of the warming trend was the first no-freeze events. In the southern parts of Finland temperatures determine whether winter precipitation falls as snow or rain and in a warming climate the extreme events have exponential impacts. The no-freeze events in Aura River (2008 and 2020) and Kokemäki River (2008, 2015 and 2020) occurred during some of the warmest and wettest winters on record (Ilkka et al., 2012; Irannezhad et al., 2014; Lehtonen, 2021; FMI, 2016). The determining role of temperature has changed. The freeze-up process is not determined solely by temperature but by precipitation, runoff and discharge rates. The no-freeze events in Aura River in 2008 can most likely be ascribed to increased winter discharge caused by higher temperatures and precipitation. January 2008 was the wettest since 1961 and so was February 2020. For example, during a short period in February 2020, the river was close to freezing (author's observation) but there were small sections that remained open. The lack of detailed observations prohibited a more in-depth analysis of the situation in Kokemäki River. Regardless, warmer winters have clouded the previously distinct difference between winter and spring and this has caused increased interannual variability. The warmer climate that is dominating in the south has changed more rapidly than the colder climate dominating in the north. A similar latitudinal shift has been noticed in Swedish lakes (Hallerbäck et al., 2021; Weyhenmeyer et al., 2005). The freeze-up process has become unpredictable and it cannot longer be taken for granted that the rivers freeze. Whether or not Aura River freezes in the future depends on the return period of climatic extremes (Fisher, 2021).

The number of early events has clearly increased also in Torne River. The change has progressed in two stages. The first stage started in the 1901–1931 period and the second stage started in the 1990s. The breakup trend follows the temperature trend (Klingbjer and Moberg, 2003) to a degree where the breakup has become almost predictable. The earliest breakup event (2014) was only one day earlier than the earliest event in the 1900s (1921) and this was only one week earlier than the earliest in the 1700s. Still, the general trend in Torne River was only 1.7 days less than in Aura River over the 1749–2020 period. Thus, it was the late events that have become unpredictable in Torne River and not the early events.

The record warm winter in 2020 caused the second latest breakup the last 100 years in Torne River and the question is what caused this strangely late event. SYKE did not measure ice thickness in Torne River in 2020. However, in March, the Centre for Economic Development, Transport and the Environment (ELY) measured the ice to 55 cm about three kilometres downstream from the breakup site. The long term mean was 73 cm (1966–2019, n=54), and the ice was therefore in 2020 almost 20 cm below the long-term mean and the thickness in 2014 (75 cm). The analysis in this study showed that ice thickness in March was non-significant for the breakup date, however, one of the findings was that the average breakup in Torne River starts about 20 days after the daily mean temperatures rise above 0°C. In 2014, daily mean temperatures rose above 0°C already on 12 April (Kersalo, 2014). In 2020, January to March were warmer than the average but April slightly colder and the nights were still cold at the end of month (Lehtonen, 2020). This slight difference in temperature development probably extended the breakup to 20 May. Thus, a warmer winter caused thinner than average ice, but a colder spring caused a later breakup. Arguably, April temperatures predetermine the breakup date in Torne River. Future changes in variability and extremes depend on whether warming is greater and more stable in winter or spring (Mikkonen et al., 2015; Ruosteenoja et al., 2020). In the 1991–2020 period, 25 of the last 30 events occurred within a 12 day period. Thus, a change in April temperatures could rapidly change the timing of the breakup and make it more erratic.

The stability in Torne River acts as a stark contrast to the erratic behaviour of the breakups in the southern rivers. The Aura River almost froze in the city centre in February 2020, but seesawing temperatures and precipitation hindered the river from freezing completely. At about the same time in Pori, Kokemäki River flooded and at the power plant river discharge peaked at 656,59 m³/s on 24 February.

There are uncertainties related to the Kokemäki River series and its reliability after 1939. First, the dates from the breakup competition in Kokemäki River are skewed in comparison to the actual breakup date. Second, the power plant has affected the timing of the breakup, but the process seem to relate to events in the watershed area. In general, the power plant also plays a part in the freeze-up process. For example, December 2017 was wetter than normal and this increased the possibility for floods. However, the power plant reduced the discharge in the second half of January because the forecast predicted colder weather. Reducing the discharge enabled the river to freeze-up and reduced the risk for frazil ice jams. Thus, lowering the discharge or keeping it stable, if possible, closer to the breakup date, is another way to avoid floods.

Our the analysis showed that the largest change in Kokemäki River occurred after 1959, two decades after the power plant was built. It is remarkable that this was picked up by the newspapers, who pointed out that the ice started melting in the middle of the river as opposed to breaking up across the length of the river as it used to do. This was the process regardless of winter severity. The change must have been tangible. In 1972, *Satakunnan Kansa* published an interview with a 70-year-old man who had lived his entire life by the river and he said that there was a change in the breakup process about a decade earlier. His observation was confirmed by the analyses in this study and it shows the reliability of cryophenological observations.

5.2 Changes before 1900

The strength of these breakups series are that they do not include no-freeze events before the 21st century. Thus, they directly show the effects of ongoing climatic warming and difference compared to the warming in the early 1900s. The length of the series is another strength and they provide insights to events that have not been assessed in detail before.

The ice-off in Aura River in 1852 was exceptionally late and this was the only breakup event in the Kokemäki River series were previous observations diverged. The observations also disagrees with the Torne River series where the 1852-event was not among the 100 latest. There are several observations from Aura River so clarity is gained by crosschecking with the previously mentioned Porvoo, Neva and Dvina rivers. (Johansson, 1932; Rykatschew, 1887).

The three latest events in the Neva River series occurred in 1810, 1852, and 1807 whereas the latest in Porvoo River occurred in 1852, 1867, and 1810. The three latest breakups in Northern Dvina were in 1867, 1845 and 1855. Thus, the event in 1852 was late in all rivers except for Torne and Dvina. Moreover, the event in 1822 (see section 4.2) was exceptionally early in all rivers except for Torne and Dvina. There is therefore a distinguishable difference between the rivers in the north and the south when it comes to 1822 and 1852. The discrepancies could be explained by local climatic conditions or blocking events. Nonetheless, five rivers (Dvina, Kokemäki, Neva, Porvoo and Torne of all six rivers) have 1867 and 1810 in their top ten latest events. It is only in Aura River that 1810 is not among the latest events.

A temperature record from Tornio's sister city Haparanda indicated that the 1810s was the coldest decade between 1802–2002 (Klingbjer and Moberg, 2003). The Torne and Kokemäki River series shows a cluster of late events in the early 1800s. It is not as distinct in Aura River and this is clearly depicted in Figure 1. An unknown volcanic eruption in 1809 (Toohey and Sigl, 2017) could have caused the late breakups in 1810 and the Dalton Minimum (1800–1824) could explain the late events during the first decades of the 1800s, however, a more detailed assessments of the forcing factors behind these late events remain beyond the scope of this article.

6 Conclusions

In this article, we compared three river-ice breakup series from Finland and presented a new ice breakup series for Kokemäki River in Pori (1793–2020). The Kokemäki River series was compared to the existing series from Aura River (1749–2020) in southwest Finland and Torne River (1693–2020) in the north. This study include the first analysis of three river-ice breakup series that extends across three centuries. Our analyses showed a trend towards earlier breakups in all three series; however, the change is manifested differently in Torne River in comparison to that in Aura and Kokemäki rivers. In Torne River the earliest recorded breakup has changed only slightly the last 100 years, while Aura and Kokemäki rivers have had years when the rivers did not freeze-up completely during winter. These no-freeze events – expressing the most extreme change for rivers that typically have frozen – exhibits a strong signal that the climate has changed. In Aura River, it would appear that higher winter temperatures do not necessarily cause no-freeze events, but they will if winter discharge also increased over the December–February period. This is in need of further research. The overall trend in the timing of the breakups correlates with the warming trend confirmed by instrumental observations and the events in 2008 and 2020 occurred during the two warmest winters ever recorded in the history of meteorological observations in Finland.

Data availability

The Torne River series, the discharge data and ice thickness data is managed by the Finnish Environment Institute (SYKE) and is available from their database Hertta. Temperature data is managed by the Finnish Meteorological Institute. The Aura and Kokemäki river series will be published following the final acceptance of the manuscript.

Author contributions

SN co-designed this research, wrote and edited the manuscript, collected and obtained as well as coded and transcribed the metadata (the ice breakup observations) for Kokemäki River. SN also collected the data and observations for Aura River and obtained the Torne River series from the Finnish Environment Institute. SN did the qualitative analysis and tables and performed the power plant analysis, the discharge analysis and the correlation analysis. SH contributed to the writing and editing of the manuscript and all analyses. SH performed the trend and climate analysis and made the figures and adjoining tables.

Competing interest

The authors declare that they have no conflict of interest

Acknowledgements

The authors would like to thank the Finnish Environment Institute and *Satakunnan Kansa* for their cooperation. The authors would also like to thank the personnel at the city archives in Pori and the library staff at the University of Turku newspaper affiliate in Raisio for their assistance. Stefan Norrgård was supported by the Swedish Literary Foundation and Fonden till Hedvigs Minne at Åbo Akademi University. Samuli Helama was supported by the Academy of Finland.

References

Aalto, J., Pirinen, P., and Jylhä, K.: New gridded daily climatology of Finland: Permutation-based uncertainty estimates and temporal trends in climate, J. Geophys. Res. Atmos., 121, 3807–3823, https://doi.org/10.1002/2015jd024651, 2016.

Aalto, J., Pirinen, P., Heikkinen, J., and Venäläinen, A.: Spatial interpolation of monthly climate data for Finland: comparing the performance of kriging and generalized additive models, Theor. Appl. Climatol., 112, 99–111, https://doi.org/10.1007/s00704-012-0716-9, 2013.

Beltaos, S. and Prowse, T.: River-ice hydrology in a shrinking cryosphere, Hydrol. Process, 23, 122–144, https://doi.org/10.1002/hyp.7165, 2009.

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

Bieniek, P. A., Bhatt, U. S., Rundquist, L. A., Lindsey, S. D., and Zhang, X. D.: Large-Scale Climate Controls of Interior Alaska River Ice Breakup, J. Clim., 24, 286-297, https://doi.org/10.1175/2010jcli3809.1, 2011.

Bonsal, B. R. and Prowse, T. D.: Trends and variability in spring and autumn 0 degrees C-isotherm dates over Canada, Clim. Change, 57, 341–358, https://doi.org/10.1023/a:1022810531237, 2003.

Eklöf JH., Jäänlähtö-ajaat Kokemäen virassa vuosina 1801–1849, todenvaihe-laskulla. Suomi. Tidskrift i Fosterländska ämnen. 1849. 9: 189–196, 1850.

Finnish Meteorological Institute (FMI), Year 2015 was the warmest in records: https://en.ilmatieteenlaitos.fi/press-release/132036967, last access: 7 October 2021, 2016.

Fischer, E. M., Sippel, S., and Knutti, R.: Increasing probability of record-shattering climate extremes, Nat. Clim. Change., 11, 689-695, https://doi.org/10.1038/s41558-021-01092-9, 2021.

Gagnon, A. S. and Gough, W. A.: Trends in the dates of ice freeze-up and breakup over Hudson Bay, Canada, Arctic, 58, 370–382, https://doi.org/10.14430/arctic451, 2005.

Gagnon, A. S. and Gough, W. A.: East-west asymmetry in long-term trends of landfast ice thickness in the Hudson Bay region, Canada, Clim. Res, 32, 177–186, https://doi.org/10.3354/cr032177, 2006.

Hallerbäck, S., Huning, L. S., Love, C., Persson, M., Stensen, K., Gustafsson, D., and AghaKouchak, A.: Warming Climate Shortens Ice Durations and Alters Freeze and Breakup Patterns in Swedish Water Bodies, The Cryosphere Discuss. [preprint], https://doi.org/10.5194/tc-2021-304, in review, 2021.

Hegerl, G. C., Bronnimann, S., Schurer, A., and Cowan, T.: The early 20th century warming: Anomalies, causes, and consequences, Wiley Interdiscip. Rev. Clim., 9, https://doi.org/10.1002/wcc.522, 2018.

Helama, S., Tolvanen, A., Karhu, J., Poikolainen, J., and Kubin, E.: Finnish National Phenological Network 1997-2017: from observations to trend detection, Int. J.Biometeorol, 64, 1783–1793, https://doi.org/10.1007/s00484-020-01961-6, 2020.

Huokuna, M.: Ice Jams in Pori, CGU HS Committee on River Ice processes and the Environment, in 14th Workshop on the Hydraulics of ice Covered Rivers, Quebec City, Canada, 19-22 June 2007, 2007.

Hällström, G. G.: Mutati Currente Saeculo Temporis, quo glacies fluminum Annuae Dissolutae sunt, Acta Soc. scient. Fenn., 129–150, 1842.

Ilkka, J., Heikki, T., and Väinö, N.: The variability of winter temperature, its impacts on society, and the potential use of seasonal forecasts in Finland, Weather, 67, 328-332, 10.1002/wea.1971, 2012.

Irannezhad, M., Marttila, H., and Klove, B.: Long-term variations and trends in precipitation in Finland, Int J Climatol, 34, 3139-3153, https://doi.org/10.1002/joc.3902, 2014.

Johansson O. V.: Isförhållanden vid Uleåborg och i Torne älv, Fennia 64(3), 1–44, Fennia, 1932.

Kajander, J.: Methodological Aspects on River Cryophenology Exemplified by a Tricentennial Break-up Series from Tornio, Geophysica 29, 73–95, 1993.

Kajander, J.: Cryophenological Records From Tornio. Mimeograph Series of the national Board of Waters and the Environment, Helsinki 1995.

Kendall, M. G.: Rank Correlation Methods. 4th Edition, Griffin, London, 1970.

Kersalo, J: Kuukauden loppupuolella lumipeite hupeni pohjoisessakin, Ilmastokatsaus 4 (The Finnish Meteorological Institute). https://www.ilmastokatsaus.fi/wp-content/uploads/2021/04/2014_04_huhtikuu.pdf, 2014

Klavins, M., Briede, A., and Rodinov, V.: Long term changes in ice and discharge regime of rivers in the Baltic region in relation to climatic variability, Clim. Change, 95, 485-498, https://doi.org/10.1007/s10584-009-9567-5, 2009.

Klingbjer, P. and Moberg, A.: A composite monthly temperature record from Tornedalen in northern Sweden, 1802-2002, 1465-1494, Int J Climatol, 23, https://doi.org/10.1002/joc.946, 2003.

Korhonen, J.: Suomen Vesistöjen Jääolot. Suomen Ympäristökeskus, Helsinki 2005.

Korhonen, J.: Long-term changes in lake ice cover in Finland, Nord. Hydrol., 37, 347–363, https://doi.org/10.2166/nh.2006.019, 2006.

Korhonen J., Kuusisto E.: Long-term changes in the discharge regime in Finland, Hydrol Res 41 (3-4), https://doi.org/10.2166/nh.2010.112, 2010

Koskinen M (ed.); Porin tulvat hallittuja riskejä?, Lounais-Suomen Ympäristökeskus, 2006.

Leche, J.: Utdrag af 12 års meteorologiska observationer, gjorda i Åbo: Sjette och sista stycket, Kongl. Vetensk. Acad. Handl., 257–268, 1763.

Lehtonen I.: Record mild winter of 2019/2020 in most of Finland, FMI's Climate Bulleting: Research letters, https://doi.org/10.35614/ISSN-2341-6408-IK-2021-02-RL, 2021.

Levänen, S., Bearbetning af tiderna för islossningar I Aura å, Fennia 3(10), 1890.

Louekari, S.: Pori, vesi ja maisema, in: Näkymätönt Porrii. Porin Veden historia, edited by (writers): Juuti, P. S., Katko, T. S., Louekari, S. M., Rajala, R. P., Porin Vesi, Saarijärvi, Finland 68–97, 2010.

Luterbacher, J., Dietrich, D., Xoplaki, E., Grosjean, M., and Wanner, H.: European seasonal and annual temperature variability, trends, and extremes since 1500, Science, 303, 1499–1503, https://doi.org/10.1126/science.1093877, 2004.

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

Mann, H. B.: Nonparametric tests against trend, Econometrica, 13, 245–259, https://doi.org/10.2307/1907187, 1945.

Menzel, A.: Trends in phenological phases in Europe between 1951 and 1996, Int. J.Biometeorol., 44, 76–81, https://doi.org/10.1007/s004840000054, 2000.

Mikkonen, S., Laine M., Mäkelä, H. M., Gregow, H., Tuomenvirta, H., Lahtinen, M,. Laaksonen, A.: Trends in average temperature in Finland, 1847–2013, Stoch Environ Res Risk Assess, 29, 1521–1529, https://doi.org/10.1007/s00477-014-0992-2, 2015.

Miyahara, H., Tokanai, F., Moriya, T., Takeyama, M., Sakurai, H., Horiuchi, K., and Hotta, H.: Gradual onset of the Maunder Minimum revealed by high-precision carbon-14 analyses, Sci. Rep., 11, https://doi.org/10.1038/s41598-021-84830-5, 2021.

Moberg, A.: Naturalhistoriska Daganteckningar gjorda i Finland Åren 1750–1845. Notiser ur Sällskapets Pro Fauna & Flora Fennica Förhandlingar (Tredje Häftet) 95–250, 1857.

Moberg, A.: Sammandra af de klimatologiska anteckningarne i Finland år 1889. In: Öfversigt af Finska Vetenskaps-societetens förhandlingar XXXV 1889–1890. Helsingfors: J Simeli Arfvingars Boktryckeri-Aktiebolag, 155–176, 1890.

Moberg, A.: Sammandra af de klimatologiska anteckningarne i Finland år 1890. In: Öfversigt af Finska Vetenskaps-societetens förhandlingar XXXV 1890–1891. Helsingfors: J Simeli Arfvingars Boktryckeri-Aktiebolag, 235–259, 1891.

Moberg, A.: Sammandra af de klimatologiska anteckningarne i Finland år 1891. In: Öfversigt af Finska Vetenskaps-societetens förhandlingar XXXV 1891–1892. Helsingfors: J Simeli Arfvingars Boktryckeri-Aktiebolag, 309–333, 1892.

Moberg, A.: Sammandra af de klimatologiska anteckningarne i Finland år 1892. In: Öfversigt af Finska Vetenskaps-societetens förhandlingar XXXV 1892–1893. Helsingfors: J Simeli Arfvingars Boktryckeri-Aktiebolag, 155–181, 1893.

Myllynthaus, T.: Summer Frost. A Natural Hazard with Fatal Consequences in Preindustrial Finland, in: Natural Disasters, Cultural Responses, edited by: Mauch C., Pfister C., Lexington Books, USA, 77–102, 2009.

Newton, A. M. W. and Mullan, D. J.: Climate change and Northern Hemisphere lake and river ice phenology from 1931-2005, The Cryosphere, 15, 2211-2234, https://doi.org/10.5194/tc-15-2211-2021, 2021.

Norrgård, S. and Helama, S.: Historical trends in spring ice breakup for the Aura River in Southwest Finland, AD 1749-2018, Holocene, 29, 953–963, https://doi.org/10.1177/0959683619831429, 2019.

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

Prowse, T. D., Wrona, F. J., Reist, J. D., Gibson, J. J., Hobbie, J. E., Levesque, L. M. J., and Vincent, W. F.: Climate change effects on hydroecology of Arctic freshwater ecosystems, Ambio, 35, 347-358, https://doi.org/10.1579/0044-7447(2006)35[347:cceoho]2.0.co;2, 2006.

Prowse, T., Alfredsen, K., Beltaos, S., Bonsal, B., Duguay, C., Korhola, A., McNamara, J., Pienitz, R., Vincent, W. F., Vuglinsky, V., and Weyhenmeyer, G. A.: Past and Future Changes in Arctic Lake and River Ice, Ambio, 40, 53-62, https://doi.org/10.1007/s13280-011-0216-7, 2011.

Ruosteenoja, K., Markkanen, T., and Räisänen, J.: Thermal seasons in northern Europe in projected future climate, Int J Climatol, 40, 4444–4462, https://doi.org/10.1002/joc.6466, 2020.

Rykatschew, M.: Über den auf- und zugang der gewasser des Russischen reiches. St. Petersburg, 1887.

Sagarin, R.: Phenology - False estimates of the advance of spring, Nature, 414, 600–600, https://doi.org/10.1038/414600a, 2001.

Sagarin, R.: Using nature's clock to measure phenology, Front Ecol Environ., 7, 296–296, https://doi.org/10.1890/09.wb.020, 2009.

Sen, P. K.: Estimates of the regression coefficient based on Kendall's tau, J. Am. Stat. Assoc., 63, 1379–1389, 1968.

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

Sharma, S., Magnuson, J. J., Batt, R. D., Winslow, L. A., Korhonen, J., and Aono, Y.: Direct observations of ice seasonality reveal changes in climate over the past 320–570 years, Sci. Rep., 6, https://doi.org/10.1038/srep25061, 2016.

Smejkalova, T., Edwards, M. E., and Dash, J.: Arctic lakes show strong decadal trend in earlier spring ice-out, Sci. Rep., 6, https://doi.org/10.1038/srep38449, 2016.

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

Terhivuo, J., Kubin, E., Karhu, J.: Phenological observations since the days of Linné in Finland, Ital. J. Agrometeorol. 14, 45–49, 2009.

Toohey, M. and Sigl, M.: Volcanic stratospheric sulfur injections and aerosol optical depth from 500 BCE to 1900 CE, Earth Syst. Sci. Data, 9, 809–831, https://doi.org/10.5194/essd-9-809-2017, 2017.

Venäläinen A., Tuomenvirta, H., Pirinen, P., Drebs, A.: A Basic Finnish Climate Data Set 1961–2000 – Descriptions and Illustrations, Finnish Meteorological Institute Reports No. 2005:5, https://doi.org/10.13140/RG.2.2.24473.62567, 2005.

Verta, O. M. and Triipponen, J. P.: The Kokemäki River Basin Flood Risk Management plan - - A national Pilot from Finland in Accordance with the EU Floods Directive, Irrig. Drain, 60, 84–90, https://doi.org/10.1002/ird.668, 2011.

Weyhenmeyer, G. A., Meili, M., and Livingstone, D. M.: Systematic differences in the trend towards earlier ice-out on Swedish lakes along a latitudinal temperature gradient, 29th Congress of the International-Association-of-Theoretical-and-Applied-Limnology, Lahti, FINLAND, Aug 08-14, WOS:000230666900039, 257–260, 2005.

Weyhenmeyer, G. A., Livingstone D. M., Meilis, M., Jensen, O., Benson, B., Magnuson J. J.; Large geographical differences in the sensitivity of ice-covered lakes and rivers in the Northern Hemisphere to temperature changes, Glob. Change Biol. Bioenergy, 17, 268–275, https://doi.org/10.1111/j.1365-2486.2010.02249.x, 2011.

Xoplaki, E., Luterbacher, J., Paeth, H., Dietrich, D., Steiner, N., Grosjean, M., and Wanner, H.: European spring and autumn temperature variability and change of extremes over the last half millennium, Geophys. Res. Lett., 32, https://doi.org/10.1029/2005gl023424, 2005.

Zachrisson, G.: Svåra islossningar i Torneälven i relation till klimat- och miljöförändringar, in: Nordisk Hydrologisk Konferens 1988, Nordisk NHP-rapport nr. 22 Del 1, Rovaniemi, Finland, 1-3 August 1988, 33–42, 1988.

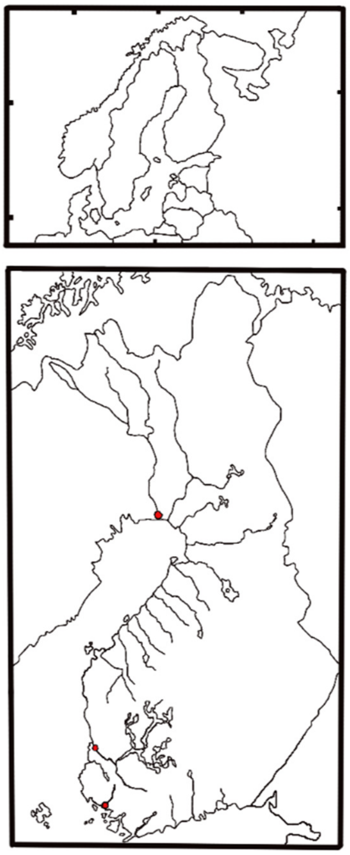

Figure 1. Northern Europe and Finland with the Finnish rivers marked out. The dots from north to south are Tornio (Torne River), Pori (Kokemäki River) and Turku (Aura River). The map also shows the lakes connected to the Kokemäki River watershed area.

Table 1. The 30 earliest ice breakup events in Torne and Kokemäki rivers, and the 30 earliest ice-off events in Aura River. Torne and Aura are fitted to correspond to the length of the shorter series. The number in the parenthesis shows the number of days relative to the earliest event (0). In Kokemäki River, for example, (+54) means that the ice breakup occurred 54 days after the earliest (0) event. The no-freeze events are not included.

	Periods				
	1693-2020	1749-2020	1793-2020		
Rivers	Torne	Aura	Torne	Aura	Kokemäki
	2014 (0)	1990 (0)	2014 (0)	1990 (0)	1990 (0)
	1921 (+1)	2015 (+17)	1921 (+1)	2015 (+17)	1959 (+26)
	1937 (+1)	2014 (+26)	1937 (+1)	2014 (+26)	2014 (+27)
	2002 (+1)	1822 (+29)	2002 (+1)	1822 (+29)	1975 (+29)
	1950 (+2)	2002 (+32)	1950 (+2)	2002 (+32)	1989 (+30)
	2011 (+2)	1961 (+33)	2011 (+2)	1961 (+33)	1992 (+30)
	1983 (+3)	1989 (+33)	1983 (+3)	1989 (+33)	1961 (+31)
	2015 (+3)	1992 (+34)	2015 (+3)	1992 (+34)	1974 (+33)
	1990 (+3)	1995 (+39)	1990 (+3)	1995 (+39)	1995 (+36)
	2016 (+3)	2000 (+39)	2016 (+3)	2000 (+39)	1822 (+38)
	1894 (+4)	1998 (+40)	1894 (+4)	1998 (+40)	2017 (+38)
	1989 (+4)	2007 (+43)	1989 (+4)	2007 (+43)	2016 (+39)
	2019 (+4)	2017 (+43)	2019 (+4)	2017 (+43)	2007 (+41)
	1904 (+5)	1938 (+44)	1904 (+5)	1938 (+44)	1973 (+41)
	1991 (+5)	2019 (+44)	1991 (+5)	2019 (+44)	1938 (+44)
	1757 (+5)	1903 (+46)	1948 (+5)	1903 (+46)	2019 (+44)
	1773 (+5)	1921 (+47)	1953 (+5)	1921 (+47)	1993 (+45)
	1948 (+5)	2012 (+47)	2006 (+5)	2012 (+47)	1921 (+46)
	1953 (+5)	2016 (+47)	2007 (+6)	2016 (+47)	2012 (+46)
	2006 (+5)	1959 (+48)	1984 (+6)	1959 (+48)	1943 (+47)
	2007 (+6)	1750 (+48)	2008 (+6)	1973 (+48)	2004 (+49)
	1750 (+6)	1973 (+48)	1803 (+7)	1910 (+49)	1998 (+51)
	1770 (+6)	1910 (+49)	1837 (+7)	1975 (+49)	1903 (+52)
	1984 (+6)	1975 (+49)	1890 (+7)	1953 (+49)	1930 (+52)
	2008 (+6)	1779 (+49)	1897 (+7)	1974 (+51)	1920 (+52)
	1803 (+7)	1953 (+49)	1945 (+7)	1920 (+51)	1967 (+53)
	1837 (+7)	1974 (+51)	1959 (+7)	1930 (+52)	1991 (+53)
	1890 (+7)	1920 (+51)	1980 (+7)	1794 (+54)	1794 (+54)
	1897 (+7)	1930 (+52)	1986 (+7)	1993 (+54)	1832 (+54)
	1945 (+7)	1794 (+54)	1994 (+7)	1913 (+55)	1982 (+54)
Range	7	54	7	55	54
	Number of events per century				
1700s	4	3		1	1
1800s	5	1	5	1	2
1900s	12	17	16	19	20
2000s	9	9	9	9	7

Table 2. The 30 latest ice breakup events in Torne and Kokemäki rivers and the 30 latest ice-off events in Aura River. Torne and Aura are fitted to correspond to the length of the shorter series. The number in the parenthesis shows the number of days relative to the latest event (0). In Torne River, for example, (-14) means that the ice breakup occurred 14 days before the latest (0) event.

	Periods					
	1693–2020	1749–2020		1793–2020		
River	Torne	Torne	Aura	Torne	Aura	Kokemäki
	1867 (0)	1867 (0)	1852 (0)	1867 (0)	1852 (0)	1867 (0)
	1695 (-4)	1810 (-6)	1867 (0)	1810 (-6)	1867 (0)	1812 (-9)
	1810 (-6)	1807 (-7)	1881 (-2)	1807 (-7)	1881 (-2)	1818 (-10)
	1807 (-7)	1814 (-12)	1812 (-3)	1814 (-12)	1812 (-3)	1839 (-11)
	1705 (-8)	1756 (-13)	1839 (-3)	1816 (-13)	1839 (-3)	1852 (-12)
	1731 (-8)	1772 (-13)	1875 (-3)	1835 (-13)	1875 (-3)	1877 (-12)
	1740 (-8)	1816 (-13)	1771 (-4)	1899 (-13)	1818 (-4)	1807 (-13)
	1701 (-10)	1835 (-13)	1818 (-4)	1909 (-14)	1829 (-4)	1810 (-13)
	1713 (-10)	1899 (-13)	1829 (-4)	1866 (-15)	1847 (-4)	1829 (-13)
	1718 (-11)	1764 (-14)	1847 (-4)	1795 (-16)	1871 (-5)	1899 (-13)
	1708 (-12)	1780 (-14)	1749 (-5)	1812 (-16)	1877 (-5)	1808 (-14)
	1728 (-12)	1909 (-14)	1760 (-5)	1876 (-16)	1807 (-6)	1809 (-14)
	1742 (-12)	1765 (-15)	1871 (-5)	1879 (-16)	1888 (-6)	1875 (-14)
	1814 (-12)	1866 (-15)	1877 (-5)	1881 (-16)	1955 (-6)	1881 (-14)
	1714 (-13)	1775 (-16)	1763 (-6)	1884 (-16)	1956 (-6)	1806 (-15)
	1739 (-13)	1791 (-16)	1785 (-6)	1900 (-16)	1810 (-8)	1823 (-15)
	1756 (-13)	1795 (-16)	1807 (-6)	1802 (-17)	1843 (-8)	1924 (-15)
	1772 (-13)	1812 (-16)	1888 (-6)	1823 (-17)	1853 (-8)	1847 (-16)
	1816 (-13)	1876 (-16)	1955 (-6)	1843 (-17)	1929 (-8)	1917 (-16)
	1835 (-13)	1881 (-16)	1956 (-6)	1861 (-17)	1941 (-8)	1871 (-17)
	1899 (-13)	1884 (-16)	1776 (-7)	1811 (-18)	1809 (-9)	1888 (-17)
	1696 (-14)	1879 (-16)	1780 (-7)	1813 (-18)	1924 (-9)	1817 (-18)
	1697 (-14)	1900 (-16)	1789 (-7)	1847 (-18)	1940 (-9)	1838 (-18)
	1722 (-14)	1785 (-17)	1810 (-8)	1917 (-18)	1966 (-9)	1804 (-19)
	1738 (-14)	1802 (-17)	1843 (-8)	1996 (-18)	1796 (-10)	1845 (-19)
	1764 (-14)	1823 (-17)	1853 (-8)	1800 (-19)	1804 (-10)	1849 (-19)
	1780 (-14)	1843 (-17)	1929 (-8)	1808 (-19)	1845 (-10)	1853 (-19)
	1909 (-14)	1861 (-17)	1941 (-8)	1845 (-19)	1849 (-10)	1929 (-19)
	1724 (-15)	1763 (-18)	1809 (-9)	1846 (-19)	1855 (-10)	1941 (-19)
	1729 (-15)	1769 (-18)	1924 (-9)	1856 (-19)	1898 (-10)	1955 (-19)
Range	15	18	9	19	10	19
	Number of events per century					
1600s	3					
1700s	19	11	8	1	1	
1800s	7	17	17	25	22	25
1900s	1	2	5	4	7	5

Table 3. Part (a) of the table shows the average (Avr) and median (MD) breakup date, according to the vernal equinox, for Torne (TR) and Kokemäki (KR) rivers and the average ice-off date for Aura River (AR). The table also shows the cross-correlations (rho) between the three series. Part (b) shows the correlations and subtracted differences between AR and KR before and after the power plant period. The negative value indicates that the ice-off event in AR occurred before the breakup event in KR. The 2003–2020 period shows the difference for the guessing competition breakup dates.

(a)

	Torne River (TR)		Aura River (AR)		Kokemäki River (KR)	
TR 1693–2020	Avr 52.7	MD 52				
AR 1749–2020	0.484*		Avr 24.9	MD 27		
KR 1793–2020	0.569*		0.896*		Avr 25.8	MD 28
KR 1793–1998	0.538*		0.886*			

(b)

	KR Hydro Power period		
AR 1793–1938		0.889*	-3.2 days
AR 1939–2020		0.867*	3.2 days
AR 2003–2020			2.3 days

* p<0.001

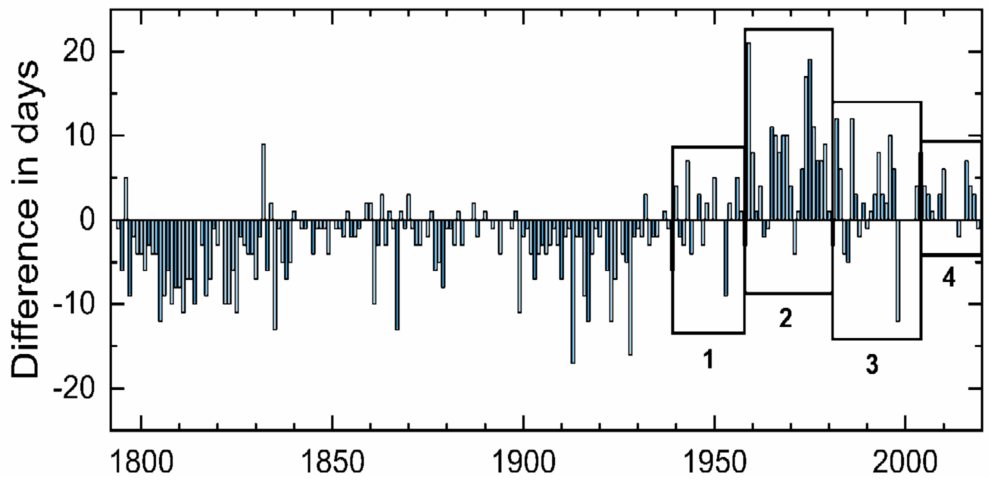

Figure 2. The difference in days between the breakup date in Kokemäki River and the ice-off event in Aura River. A negative value indicates the number of days the ice-off event in Aura River preceded the breakup date in Kokemäki River. Vice versa, a positive value shows how many days the breakup in Kokemäki River occurred before the ice-off date in Aura River. The boxes indicate periods of water level regulations in the watershed area. See section 4.1 for more information.

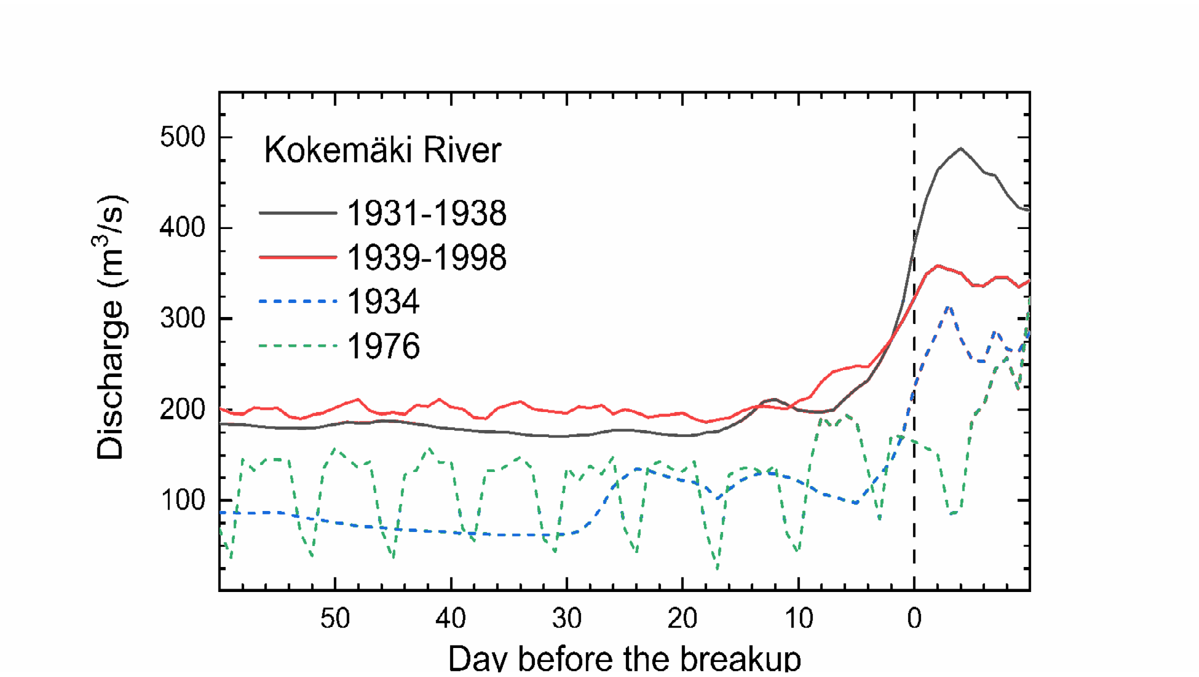

Figure 3. The discharge 60 days before and ten days after the breakup (0) in Kokemäki River. The black line shows the average discharge rate during the 1931–1938 period and the red line the average during the 1939-1998 period. The grey line depicts the discharge in 1934 and the yellow line depicts the weekly discharge cycle in 1974.

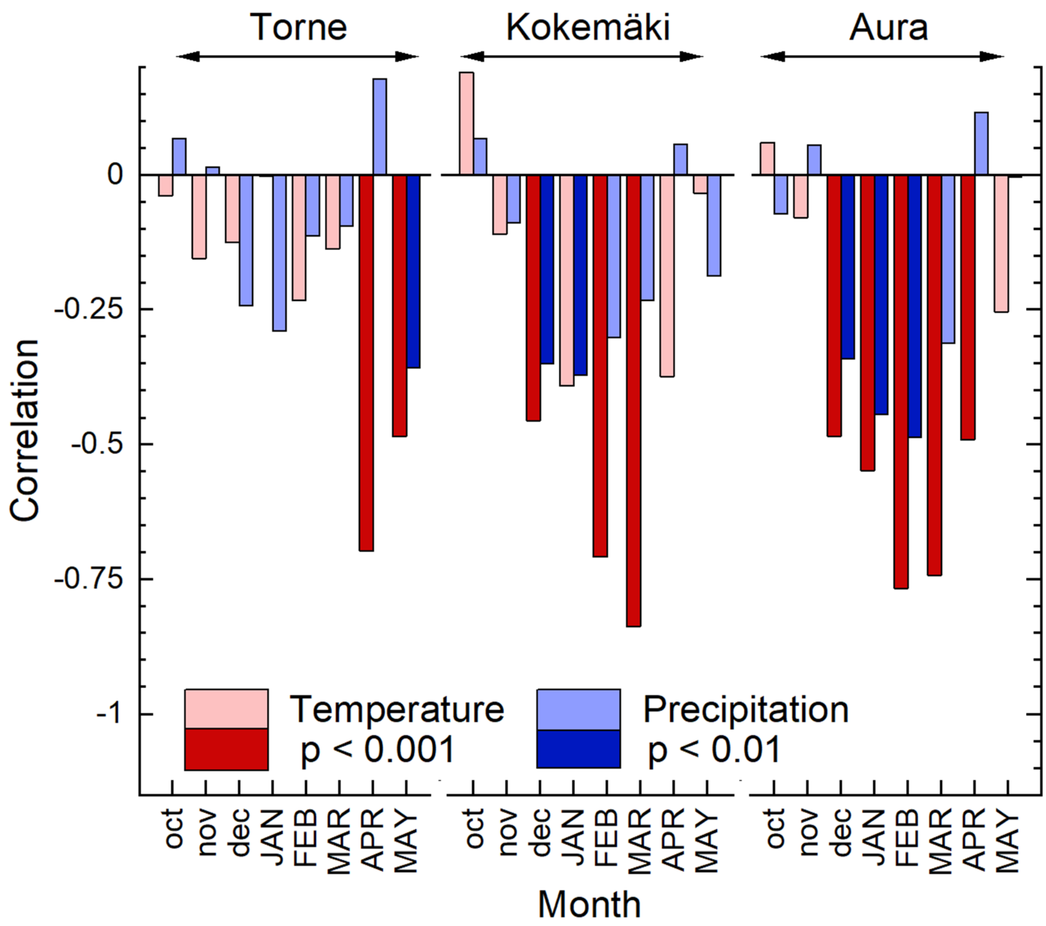

Figure 4. The figure shows Spearman's correlation between temperature, precipitation and ice breakup dates in Torne and Kokemäki rivers and, respectively, temperature and ice-off events in Aura River, during the 1961–2020 period.

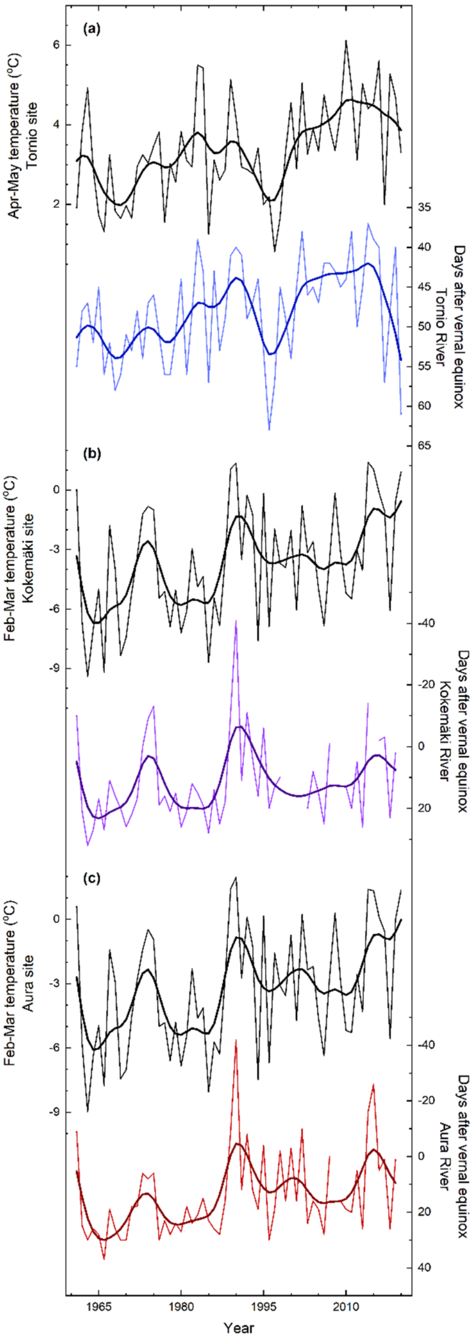

Figure 5. Variations in mean spring temperature and ice breakups. A comparison between the interpolated mean temperatures to the observation sites for (a) Torne, (b) Kokemäki and (c) Aura rivers over 1960–2020 period. The observed breakup dates (thin line) were smoothed using a 10-year spline function (thick line) to illustrate decadal and longer variations. NB: the axis that shows the breakup dates are inverted.

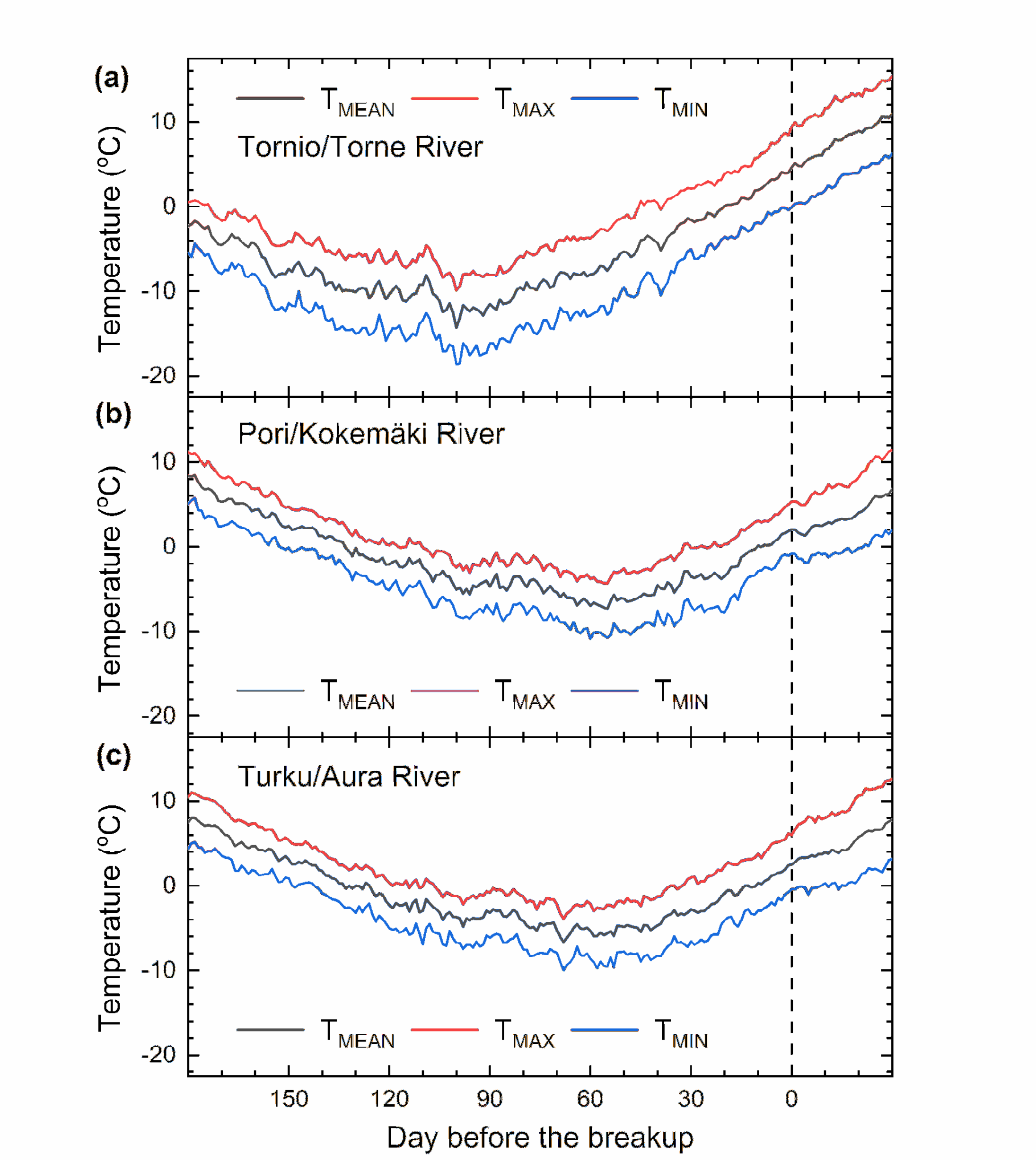

Figure 6. The lines show the temperature development 180 days before and 30 days after the breakup date in Tornio (Torne River), Pori (Kokemäki Rivers) and the ice-off event in Turku (Aura River). Zero (0) denotes the breakup and ice-off day in the respective rivers.

Table 3. Long-term change in the Torne (TR), Kokemäki (KR) and Aura (AR) river series. The table shows the Mann-Kendall statistic (MK), the associated statistical significance (p), the Sen's slope (Slope) and the number of years (n) over which the statistics were calculated. The periods are (a) the hydroelectric power-plant period in Kokemäki River (1939–2020); (b) the period common to all three series (1793–2020); (c) the period common to the Torne and Aura river series (1749–2020); (d) the entire length of the Torne River series (1693–2020); and (e) the period for which all rivers have recorded observations (1793-1998).

(a)	TR	KR	AR	(b)	TR	KR	AR
MK	-2.5	-4	-3.9		-7.5	-9.2	-7.2
p	< 0.05	< 0.001	< 0.001		< 0.001	< 0.001	< 0.001
Sens's	-0.083	-0.250	-0.235		-0.057	-0.115	-0.077
n	82	75	80		228	221	226

(c)	TR	AR		(d)	TR
MK	-8.1	-6.9			-10.3
p	< 0.001	< 0.001			< 0.001
Sens's	-0.050	-0.057			-0.050
n	272	268			328

(e)	TR	KR	AR
MK	-5.9	-8.0	-5.5
p	< 0.001	< 0.001	< 0.001
Sens's	-0.051	-0.109	-0.062
n	206	206	206

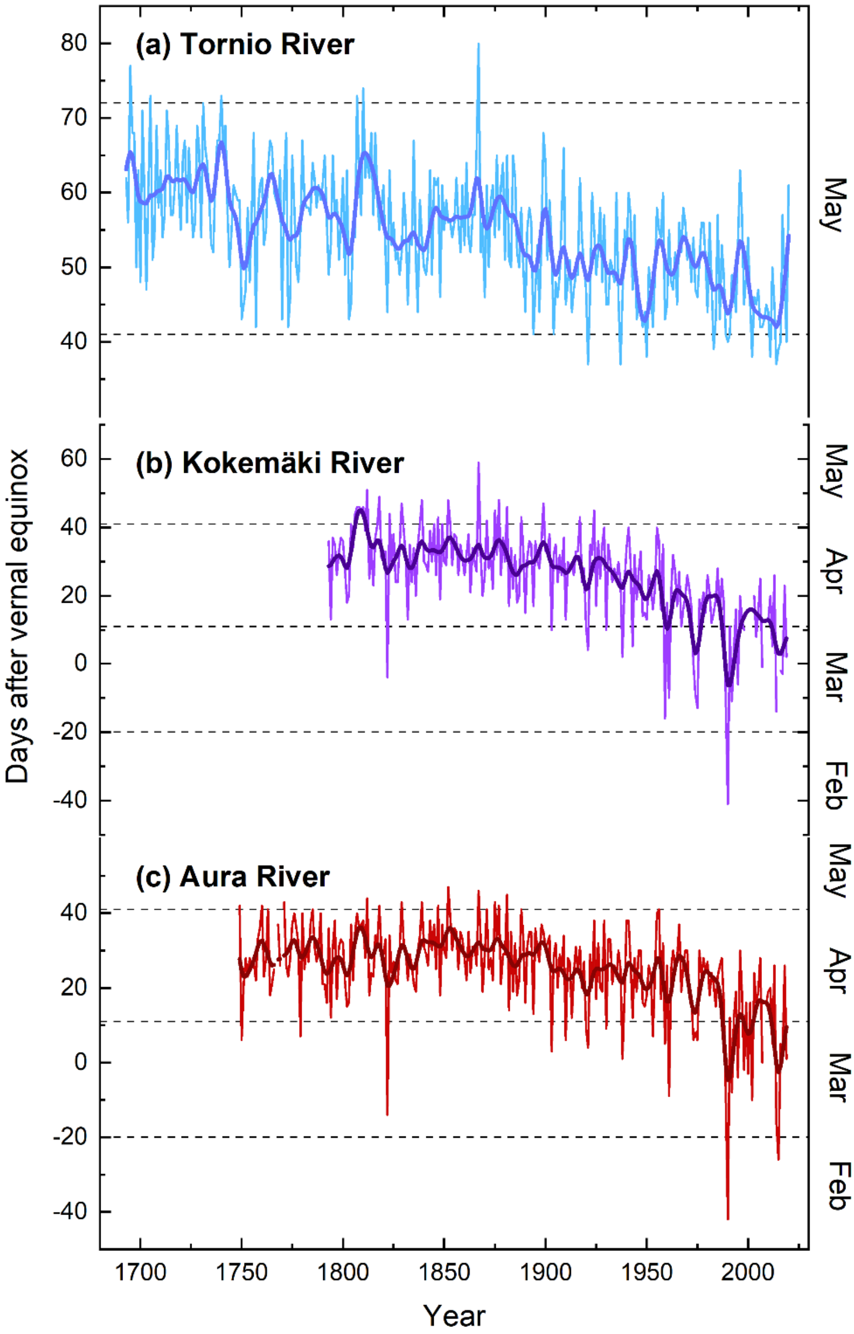

Figure 7. Ice breakup dates relative to the vernal equinox in (a) Torne and (b) Kokemäki rivers, and the ice-off dates in (c) Aura River. The obtained dates (thin line) were smoothed to illustrate decadal and longer variations using a 10-year sling function (thick line).

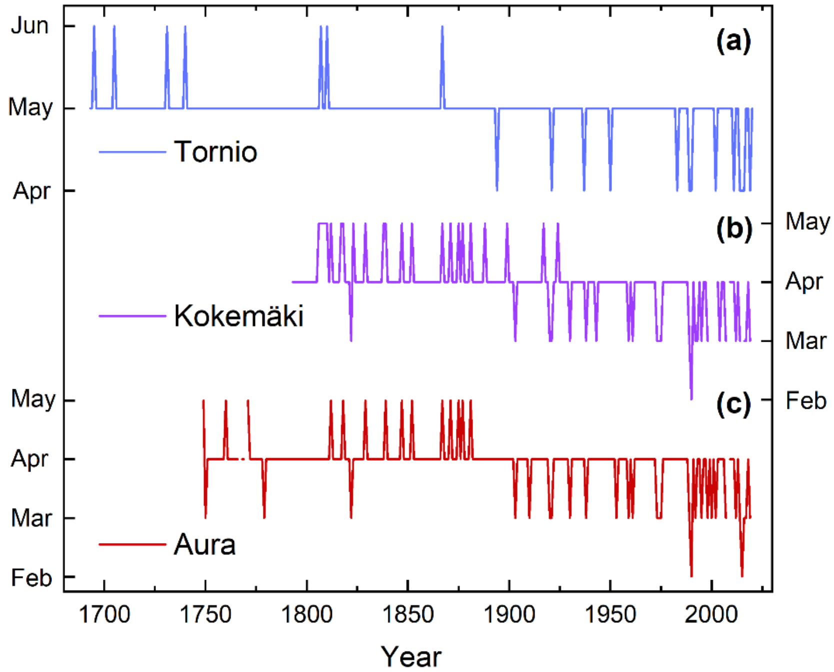

Figure 8. Occurrence of ice breakups in February, March, April, May, and June in (a) Torne River, (b) Kokemäki River and (c) Aura River.

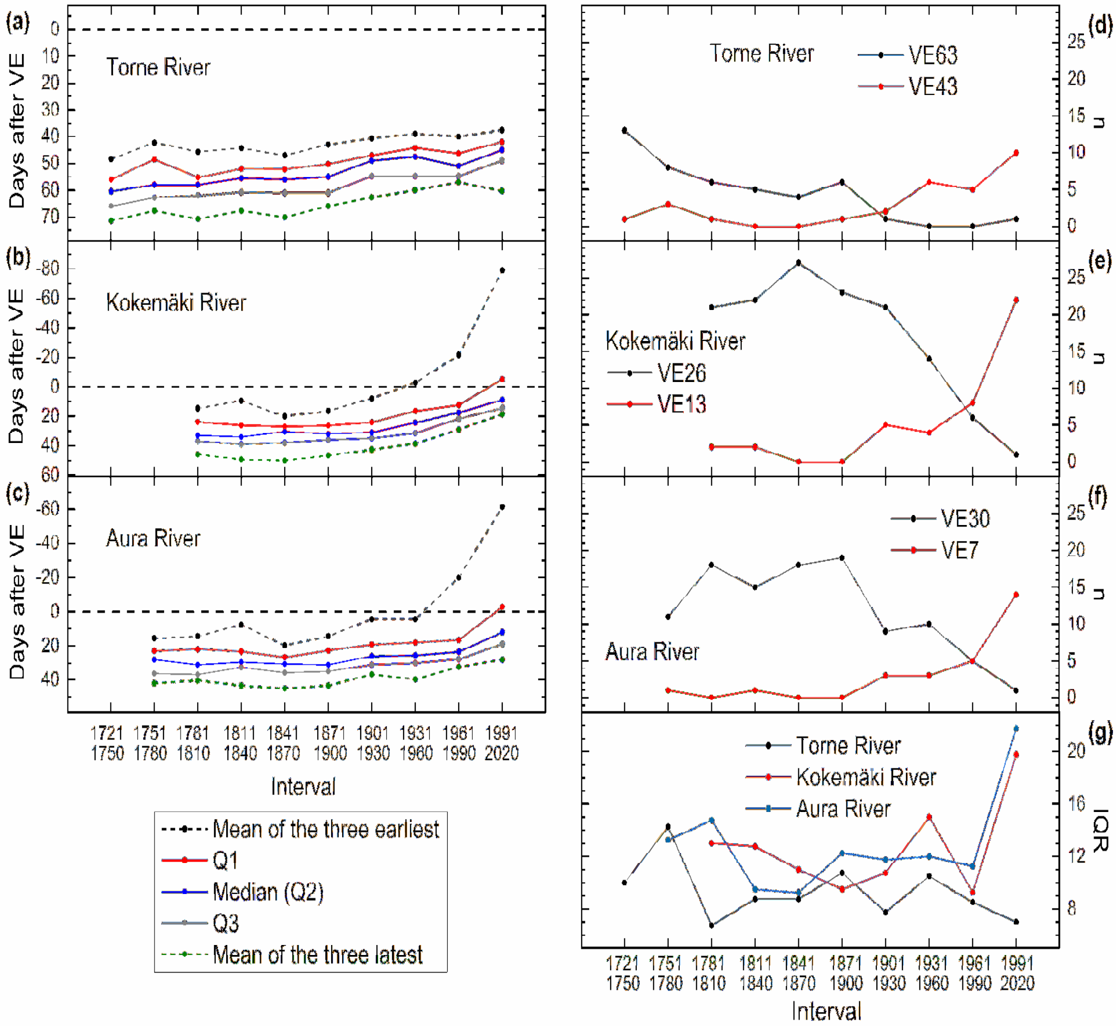

Fig 9. Ice breakups in the rivers Torne and Kokemäki and ice-offs in Aura River according to the vernal equinox (VE) in 30-year non-overlapping periods. The dotted line (0) in Figure (a-c) shows the vernal equinox and the other values are obtained from analysing the quartiles of each series in each period. Figures d-f shows the frequency of early and late events in each river. For more details on how these were chosen, see methods. The last figure (g) shows the interquartile range in each period.