Tricentennial trends in spring ice break-ups ~~i~~on three rivers in ~~n~~Northern Europe

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Abstract. At high latitudes, long-term changes in riverine ice break-ups are exemplary measures of climatic change and variation. This study compare~~d~~s cryophenological trends, patterns and changes for the rivers Aura (1749–2020), Torne (1693–2020) and Kokemäki (1793–2020);~~,~~ all sites are located in Finland. The Kokemäki River series is a new series from the city of Pori. The findings show statistically significant cross-correlations between the Aura and Kokemäki rivers but weaker cross ~~, while the~~ correlations with the Torne River~~ were weaker~~. ~~The~~ We attribute the latter~~weaker correlation was attributed~~ to climatic differences caused by the higher latitude of the Torne River~~inal distance between the rivers~~. Taken together, the many results of this study suggest that ~~in the south~~ the spring climate in the south 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 ~~i~~on~~n~~ the Aura and Kokemäki rivers. This was the culmination ~~e no-freeze events were the final outcome~~ of a rapid increase in early ice break-up events and interannual variability over the last 30 years. The number of early events has ~~have been~~ increased~~ing~~ in all three rivers since the early or mid-1900s, but the earliest recorded break-up day o~~i~~n the Torne River has changed only marginally in the last 100 years. Our dynamic temperature analysis shows~~ed~~ that the ice break-up on the ~~event in~~ Torne River requires higher temperatures than in the south and future changes in the timing of the break-up depend on April temperatures. In the south, on the other hand, future changes future changes concerns the return period of no-freeze events, which depend on temperature and precipitation during winter.

1 Introduction

High latitude ~~L~~lakes and rivers constitute ~~in high latitudes are~~ fundamental parts of the cryosphere. Records of freeze-up (winter) and break-up (spring) are linked to air temperature and provide valuable ~~information on interannual and interdecadal~~ climate variability information on interannual to longer scales. ~~An i~~Improved understanding of historical and current freeze-up and break-up patterns can provide insights into~~helps to understand~~ the spatiotemporal impact of climate warming. Some changes, such as an increase of open water winters or floods, could ~~have~~ create considerable~~great~~ socio-economic impacts and they could cause alterations in ~~changes in the~~ aquatic ecosystems or ~~or~~ biogeochemical processes (Prowse et al., 20~~06~~11; 20~~11~~06)

Most cryophenological studies employ lake-ice data because lake-ice series are plentiful and ~~they~~ provide good spatial coverage. Their findings indicate ~~Such analyses have shown~~ trends towards later freeze-ups and earlier break-ups across the ~~n~~Northern ~~h~~Hemisphere (Sharma et al. 2021; Newton and Mullan 2021; Benson et al, 2012; Korhonen 2006; Magnusson et al., 2000). These trends vary in time and scale depending on the location, but they ~~changes~~ are typically associated with air temperatures, in particular higher temperatures in cold-climate regions, ~~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, r~~River-ice ~~series~~ data series ~~usually~~ commonly extend further back in history than lake-ice series, with several beginning in the 1700s (Magnusson et al, 2000; Rykatschew, 1887). These data series are often derived from port cities and the observations were collected in connection with overseas trading and transport concerns. Several series have been ~~. 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)~~discontinued in the 1900s, or they have not been updated, but there are also exceptions, such as Daugava River in Latvia (Klavins et. al 2009).

~~. 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. ~~–~~ Johansson, 1932~~Rykatschew, 1887; Johansson, 1932~~). ~~and i~~In the 1800s, before long-term meteorological data ~~was~~ were readily available, ~~scientists used the~~such ~~breakup~~ series were used to investigate climatic changes (Levänen, 1890; ~~Hällström, 1842;~~ Eklöf, 1850; Hällström, 1842~~, Levänen, 1890~~). Professor of Meteorology ~~The professor of Meteorology~~ Oscar Johansson (1932)

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~~extended~~ updated some of these series to 1906, but they lost their value as climatic indicators ~~and thereafter they were dormant~~ until Juha Kajander (199~~3~~5; 199~~5~~3) highlighted their importance by document~~ed~~ing ~~the~~ observations for the 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. In addition, ~~T~~the current study ~~further~~ presents a new ~~mult~~tri~~i~~centennial ice break-up series for the Kokemäki River (in Swedish *Kumo älv*) based on observations from the city of Pori (*Björneborg*) in southwest Finland. ~~It~~ The series spans from 1793 to 2020 and ~~it~~ is compared to the Torne River (1693–2020) and ~~the~~ Aura River series (1749–2020). This study pursues ~~has~~ four main objectives: (i) to examine ~~if~~whether the power plant closest to Pori has changed the timing of ~~the~~ ice break-ups,~~;~~ (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~~with temperature, precipitation and, in the case of the Torne ~~River~~, ice thickness,~~;~~ and (iv) to examine long-term variability and changes in the frequency of extreme events.

2 Study areas

2.1 Tornio and Torne River

The Torne River is one of the largest unregulated rivers in Northern Europe, flowing ~~. The river flows~~ southward from Lake Torne in the Arctic ~~-~~into the Bothnian Bay, the northernmost sub-basin of the Baltic Sea (Fig 1). Moreover, the river, which ~~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 for the last 180 km of its length. The ice break-up observation site is situated 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. Tornio had a population of 22,000 inhabitants in 2019. At the observation site, the river is approximately 260 meters wide. The break-up date refers~~s~~ to the day ~~ignals~~ when the ice begins~~starts~~ to break up or move, and it is ~~. 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 break-up site) during the period 1911–2020 ~~period~~ was 388.75 m^3/s. The maximum discharge on 11 June 1968 was 3,667 m^3/s. The Torne River is unregulated, but the Tengeljoki River, one of the

Torne's tributariestributary rivers, hosts three hydroelectric power plants. The power plant closest to the town of the ice breakup observation site in Tornio city is 80 km upstream and therefore and it should have no significant influence on the break-up process (Sharma et al., 2016).

Tornio is twinned with the Swedish town of Haparanda, established on the western side of Tornio. The wider Tornio-Haparanda region has a combined population of about 32,000 inhabitants. In 2019, 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 71022,000, and it is twinned with the , and in 2019, 22,000. The Swedish town twin city of Haparanda, established on the was founded on the western side of Tornio in 1842. Together, the towns comprise and today the wider Tornio-Haparanda region, with a has a combined population of about 32,000 inhabitants inhabitants. The strongest 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 break-up process was likely to have been probably caused by log-driving dams built on the river in the 1900s (Kajander, 1993). However, Hundreds of these dams were built in the upstream tributaries and their purpose was to collect water that could carry logs to Torne River. Tthese dams were demolished after the log-floating era ended in 1971 (Zachrisson, 1988).

2.2 Turku and Aura River

The Aura River, which is 70 km long and drains into the Archipelago Sea, a sub-basin of the Baltic Sea, has a watershed area of 885 km^2 and anthe average discharge at the Halinen dike (between 1938–and 2020) of was 6.86 m^3/s. The maximum discharge, recorded on 2 May 1966, was 286 m^3/s. Aura River is 70 km long and drains into the Baltic Sea. The data series ice-off observations originate from the city of Turku (60°45'N, 22°27'E), which is located at the mouth of the river. Turku had a population of 191,000 inhabitants in 2019. Inside Within the city limits, the width of the Aura River varies between 35 and 100 meters, with its depth varying 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 the Halinen dike (Norrgård and Helama, 2019). The dike, which is situated six kilometres from the mouth of the river, was first and it is mentioned in historical records for the first time in the 14th century. The dike detaches separates the lower reaches from the upper reaches, creating two independent and it creates a two-stage break-up processes independent from each other (Norrgård and Helama, 2019). Except for the dike, the Aura River is, except for the dike, unregulated.

As of 2019, Turku straddles the Aura River and has always done so. Turku, with had a population of approximately 191,000 inhabitants in 2019, straddles the Aura River. The city had a population of 4,500 in the 1730s, which then doubled by 1800. . The city's The cityriverine environment changed considerably expanded on both sides of its 'spine', as Aura River is sometimes referred to, and the most significant changes took place in the mid-to-late 20th century: . Since 1939, the number of bridges crossing the river grew have grown from three two to nine while the industrial area – which is likely to have exerted the most anthropogenic impact on the ice-off – was replaced by . 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

The Kokemäki River, which is 121 km long and the river drains into the Bothnian Sea, the largest sub-basin of the Baltic Sea, features and has the largest river delta in the Nordic countries. The river Kokemäki River has a catchment area of 27,046 km² and thean average discharge at the power plant in Harjavalta hydroelectric power plant of between 1931 and 2020 was 218,.62 m³/s (1931–2020). The maximum recorded discharge occurred on 5 May 1966 and was 918 m³/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 ice break-up observation site is situated in the city of Pori (61°48'N, 21°79'E) and lies about 11 km from the sea. Pori had a population of 83,000 inhabitants in 2019. The ice break-up observations for the river, which has an estimated width of derive from the city centre and the width of the river varies between 160 and 240 metres and a depth of between . The estimated depth varies between two and four metres, have been obtained from the city centre. For most of the period covered by the data series, part of the period, the ice break-up date refers

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to the day determines when the ice between the Porinsilta Bridge (built in 1926) and Kirjurinluoto Island begins to break-up or move. In Pori, daily discharge averages vary because of the Harjavalta plant and three other hydroelectric plants upstream. Harjavalta, the largest plant on the river, is also the closest of the four plants to Pori (31 km) and has been in operation since 1939. The next plant was built in 1940 and it is located in the city of Kokemäki (46 km from Pori). This is followed by the oldest power of the four, built in Äetsä in 1919 (87 km from Pori), and the newest, built in Tyrvää in 1950 (121 km from Pori).

As of 2019, Pori, with ha da population of 83,000 inhabitants in 2019, did not. 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 until the latter half of the 1800s, which affects the number break-up observations. The Pori has not expanded towards the sea like Turku.

Kokemäki River was used for log floating until 1967, and a large industrial area was located near the city centre. Due to recurring ice jam floods, 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 tthe river was dredged and the riverbanks were reinforced– throughout the 1900ss and -2000s. Several fFlood response constructions were built during the 1900s and near the observation site in the 1970s and 1980s (Verta and Triipponen, 2011;(Louekari, 2010; Huokuna, 2007; Koskinen 2006).

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 the Torne River always freezes. There are no midwinter break-ups, and the mean ice cover period is five to six months (Kajander, 1993). Ice thickness has been measured at the observation~~s~~ site since 1964, most frequently on 30 March, with the mean thickness during the period ~~and the date with most measurements and nearest the breakup date were from 30 March. Mean ice thickness for this day during the~~ 1964–20~~20~~19 being ~~period was~~ 76.5 cm (n=54).

Systematic records on freeze-up dates or ice thickness are ~~not~~ unavailable for the Aura River~~,~~. However, some freeze-up dates were recorded and collected by ~~which is 600 km south of Tornio.~~ Leche (1763), Moberg (1893; 1892; 1891; 1890; 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~~ These observations were made before the 1900s, with ~~and~~ 23 ~~were~~ from the 1700s. The sporadic occurrence of mid-winter break-ups means that the length of the ice cover period is only indicative of actual ice conditions. For example, in 1771, the freeze-up occurred on 20 November~~in 1771 was 20 November~~, and the ice had reached a thickness of 20 cm before heavy rains caused a midwinter break-up on 13 December. Midwinter break-ups of various intensities have occurred between December and February throughout the 1749–2020 period. The last recorded midwinter break-up involving ice ~~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~~ newspaper reports from ~~s in~~ April 1837 and March 2003 testify. Records on ice conditions are sporadic, but the ~~provided~~ examples provided above offer ~~give~~ some perspective on the conditions leading up to the first no-freeze event in 2008 (Norrgård and Helama, 2019).

Thermal break-ups appear in the Aura River. A thermal break-up, as opposed to a dynamic break-up, is characterised by the ~~ice being~~ thinning and weakening of the ice by ~~ed and weakened from~~ thermal inputs. In this process, ~~T~~there is little to no breakage of the ice, which melts in situ unless the ~~if there is little to no~~ flow ~~increase~~increases (Beltaos and Prowse, 2009). Such ~~Thermal breakups appear in the records the describing the Aura River breakup process. The~~break-ups~~y~~ also appear ~~i~~on the ~~descriptions from~~ Kokemäki River, affecting ~~and in this case they affect~~ the validity of some break-up ~~of the~~ observations. For example, in March 1992, ~~SK~~ a local newspaper reported ~~wrote~~ that the ice had melted in situ for the fourth year in a row. The city employee conducting the observations claimed that an official break-up date would not be recorded, as the exact date, ~~because a proper breakup date~~ could not be determined. ~~Thermal~~ Similar break-ups also occurred in the 1920s~~have are not a new phenomenon in the Kokemäki River~~, but they ~~are~~have been, in general, rarer ~~more sporadic~~ than ~~i~~on the Aura River.

Dates on freeze-up, ice thickness or ice cover ~~has~~ have not been systematically collected in Pori. However, ~~The~~ a ~~first~~ break-up series published in ~~from 1~~1843 (see below) containing ~~contained~~ 11 years of ~~some~~ freeze-up dates ~~and there are 11 years of observations~~ between 1810 and 1844 gives ~~(Moberg, 1857). These dates give~~ a mean of 157.8 ice cover days (n=11; median 160). As in Turku, midwinter break-ups may affect the actual number of ice cover days. For example, in 1841, the freeze-up ~~was~~occurred on 15 November ~~in 1841,~~, but a midwinter break-up on 7 January 1842 took place ~~occurred~~ before the actual break-up on ~~1~~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, t~~The dates in the Aura River series denote~~s~~ the ice-off event or the day when the river ~~is~~ was ice-free, whereas the dates in the Torne and Kokemäki river series describe the ice

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break-up, or the initial movement of the ice. In this paper, 'break-ups' are hereafter used to refer to both 'ice break-ups' or 'ice-offs', but we will distinguish between the two when necessary.

3 Data and methods

3.1 Kokemäki River: material

The Kokemäki River ice break-up series is mostly based on descriptions obtained from the local Swedish newspaper *Björneborgs Tidning* (1860–1965) and the Finnish newspaper *Satakunnan Kansa* (hereafter *SK*) (1873–). Newspapers editions prior to 1950 were obtained from the Finnish National Library's digital database, while more recent newspaper articles were accessed via the University of Turku's newspaper affiliate in Raisio and the *SK's* internal database at the editorial office in Pori. All articles were transcribed and the metadata stored locally.

Newspapers are exemplary sources because they provide daily and sometimes sub-daily descriptions of the break-up process (Norrgård and Helama, 2019; Kajander, 1993). Newspapers also often contain break-up series submitted by readers. The first break-up series for the Kokemäki River was published under a pseudonym in *Åbo Tidningar* in July 1843 and covered the period 1801–1843. An extended version (1801–1849) of the initial series was parallel published in *Åbo Tidningar* and *Suometar* on 11 May 1849. This was used to calculate changes in the timing of the break-ups (Eklöf, 1850). We found at least four other series published in the 19th century, ending with a version published in *SK* in 1877, which extended the break-up series to 1794. Fifty-five years later, Johansson (1932) extended the series to 1793 and 1906. An additional extended version was published in *SK* in 1984, but the most recently updated series, actually a chart spanning the period 1794–1998, was found in the city archives. 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 maintained by city employees since the 1950s. We found no break-up dates for the four years between 1999 and 2002. The dates between 2003 and 2020 originate from a break-up guessing competition arranged by the local Lions Club.

3.1.2 ~~Obtaining and extracting breakup dates for~~ Kokemäki River: creating the series

~~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 create an ice break-up series with homogenized ~~the~~

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break-up dates with regard to site and event ~~(Norrgård and Helama, 2019)~~. Dates obtained from ~~P~~previously published ~~series~~ series were used for ~~as a date of~~ reference when scrutinizing the newspapers for observations ~~from this period~~. The majority of ~~It quickly became clear that the~~ newspaper articles described the break-up ~~in the city centre and~~ near the location of the ~~the~~ ~~P~~Pontoon ~~B~~Bridge, which was ~~that was~~ replaced by ~~the~~ Porinsilta Bridge in 1926. ~~Th~~The aim was therefore ~~thereafter~~ to obtain observations that referred to this part of the river and described the same stage of the break-up process. Consequently, the newly compiled ~~compiled~~ series describe the initial day of break-up or the day when the ice started moving ~~in the city centre~~ between Porinsilta Bridge and Kirjurinluoto Island.

The break-up ~~observations~~ dates 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 stated~~declares~~ that it ~~the series~~ depicts the ice break-up in the city of Pori. As maps~~, and maps~~ from the 1800s show that the city was small and concentrated, ~~which is why~~ the observations thus most likely refer to the area where the bridge~~s~~ were later built. The break-up in 1852 was the only time when the dates in the previously published series diverged considerably. The break-up was noted to have begun ~~started~~ in either early April or early May. The reason for this discrepancy might be the devastating city fire in 1852. The break-up in May was preferred, as this was more consistent with the event~~s~~ ~~i~~on Aura River.

~~Two remarks regarding the site and date: First, s~~Some dates in the latter half of the 1900s are ~~probably~~ likely to be based on observations ~~from~~ near the Linnansilta Bridge (~~, which was~~ ~~b~~built ~~in~~ 1974). This should have no significant impact on the analysis. ~~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 break-up date follows the marker and its movement instead of the break-up date on the~~in~~ Kokemäki River in general.

3.2 The vernal equinox

All dates ~~in all three series~~ follow the Gregorian calendar, and ~~.~~ t~~T~~hey ~~-recorded dates~~ were adjusted according to the vernal equinox (VE) ~~to conduct the analyses~~. The break-up was thereafter counted as the number of days before or after the equinox. This approach was preferred over the year-to-date approach (e.g. Sharma et al., 2016) ~~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 break-up series span several centurieswhen 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's dataset homepage and adjusted to the Finnish time zone (GMT+2).

3.3 Extreme events and variability

The We performed a two-fold 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 break-ups 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, break-up 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 provides the middle range in which wherein the middle half of the break-ups occur. The second quartile (Q2) is the median value.

For the purpose of performing the quartile analysis, nNo-freeze years were quantified as an ice break-up that occurred on 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 break-up date, while Sharma et al. (2016) treated them as censored values. However, these two studies used breakup series that included no-freeze events already before or in the 1900s. In our data,Here, no-freeze events occurred for the first time in the 21st century, which is why a more distinct approach was preferred.

TThe Kokemäki River series include some gaps and the Aura River series was used to interpolate estimate the break-up dates for the Kokemäki River during the periods 1781–1792 period and again for 1999–2002. The break-up dates for Kokemäki River were extracted by adding three (3) days, the average difference between the sites, to the recorded ice-off date on Aura River. This approach enabled us to include the break-ups between 1793 and 1810, which otherwise would have been excluded from the long-term analysis.

None of the extracted values was either extremely late or early.

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

3.4 The impact of the ~~H~~hydroelectric power plant ~~impact~~

The construction of the hydroelectric power plant in ~~Kokemäki River~~Harjavalta began in 1937, and it was operational at the end of ~~in Harjavalta was taken into use in 1~~1939. Aerial pictures from the construction site suggest that 1938 was the last year when the break-up was unaffected by the dam. The break-up in 1939 ~~This year~~ was therefore set ~~therefore chosen~~ as the first event~~starting year~~ that could have been influenced by ~~for assessing whether the power plant changed the timing of the ice breakup in Pori~~the power plant~~. 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~~. Several methods were employed to establish this impact and the reason for the change. First, ~~the~~ impact was assessed by analysing changes in ~~the~~ Spearman's correlation coefficient before and after 1939. Second, the break-up date in Kokemäki River was subtracted from the ice-off~~breakup~~ dates for the~~in~~ Aura River to reveal changes in the internal relationship between the rivers. Third, annual discharge rates were compared, as the break-up process is often induced by increased discharge rates caused by snowmelt (Beltaos and Prowse, 2009). In this case, discharge rates have been measured at the site since 1931, and these measurements were ~~were~~ used to assess whether ~~how~~ the power plant had influenced overall ~~changed the d~~discharge~~. leading up to the breakup date. The data is maintained by SYKE. The d~~Discharge rates for each day leading up to the break-up date were~~as~~ averaged ~~in order~~over the unregulated 1931–1938 period and the regulated 1939–1998 period to create a dynamic model depicting ~~that shows the~~ discharge rates 60 days before the break-up and 10~~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 t~~The break-up dates obtained from the guessing ~~breakup~~ competition were excluded ~~. This was considered the best approach~~ because ~~the difference between the breakup date and the guessing competition date is unknown.~~ they did not depict the actual break-up date.

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3.5 Cross-correlations, meteorological variables and trends

~~The~~ Spearman's correlation coefficient was used to analyse ~~i)~~ cross-correlations between the break-up series and correlations ~~and the ii) correlations between~~ between the break-up series and monthly mean temperature and precipitation sums over the 1960–2020 period. The temperature and precipitation data derive from a spatial model constructed ~~made~~ by the Finnish Meteorological Institute (FMI) (Aalto et al. 201~~3~~6; 201~~6~~3). The model is ~~B~~based on ~~temperature and precipitation~~ data from Finland ~~the model is~~ supplemented with data from neighbouring countries (Estonia, Norway, Russia, and Sweden). It~~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 created by the FMI ~~from FMI~~ (Venäläinen et al., 2005) was used to analyse daily temperature development leading up to the break-up. This model also ~~The model is based on temperature data starting in 1961 and it also~~ employs ~~uses the~~ kriging interpolation ~~method~~. For this ~~analysis~~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 period 1961–2020 ~~period~~. The temperatures for three variables (mean, maximum and minimum) were aligned according to the break-up date and calculated over an interval of 180 days before and 30 days after the break-up. The analysis thereby shows the change in ~~local~~ daily mean, maximum and minimum temperatures 180 days before and 30 days after the break-up date between 1961 and 2020.

~~Finally, t~~The Mann-Kendall (MK) ~~statistic~~ test (Kendall, 1970; Mann 1945) was used to determine the statistical significance of long-term trends. ~~and t~~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 break-up events

4.1.1 Early break-up events

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

The first no-freeze events on ~~rivers~~ Aura and Kokemäki rives occurred ~~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~~ the second event in ~~2015,~~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 (Lehtonen, 2021~~Ilkka et al., 2012~~; Irannezhad et al., 2014; Ilkka et al., 2012~~Lehtonen, 2021~~). The no~~n~~-freeze event ~~i~~on the Kokemäki River in 2015 also occurred during one of the warmest years on record (FMI, 2016). In this ~~e~~ context~~ of record warm winters~~, it is worth noting that Torne River had one of the latest ~~an exceptionally~~ late break-ups in 60 years in 2020~~. One of the latest breakups in 60 years~~.

O~~I~~n the Torne~~ River~~, the ~~30 earliest events remain the same whether the series is set to start in 1693 or 1749. The~~ earliest break-up ~~in Torne~~ occurred in 2014, ~~and this was only~~ one day earlier than the previous record ~~event~~ in 1921. Hence, the earliest break-up date had remained unchanged for nearly 100 years. Additionally, ~~Even the long-term change is negligible. For example,~~ the event in ~~earliest breakup date (~~2014~~)~~ occurred only five days earlier than the earliest break-up in the 1700s (1757). ~~In~~ By contrast, there is a 48-day difference between the all-time earliest ~~(1990)~~ ice-off event ~~i~~on the 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 break-up events

Table 2 shows a lack of Breakup events in the 1900s and 2000s dominated the list of earliest breakups, but there is less uniformity regardingwhen it comes to the late break-up events (Tab. 2). The This discrepancy is caused by reasons are the differences in series the length of the seriesand , but also the climatic conditions between the north and the south. For example, ion Torne River (1693–2020), 18 of the 30 latest events occurred before the start of the Aura River series in 1749. Thus, tThe coldest springs therefore the last 323 years ecclearly occurred during the first half of the 1700s. However, It is somewhat surprising that the break-up during the cold European winter in 1708/1709 (Luterbacher et al., 2004) iswas not amongst the 100 latest break-upevents in Torne River.

IOn the Aura River (1749–2020), eight of the latest events occurred in the 1700s. It is worth noting that However, the four latest events in all three series, except for the event iin 1695 ion the Torne River, are from the 1800s.

Over the period common to the three series (1793–2020), each river had period, all three rivers shared late break-ups in 1807, 1810, 1812, 1845, 1847, 1867 and 1881. In general, 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 ion the Torne and Kokemäki rivers occurred between 1800 and 1824. Nevertheless, Yet the break-ups were late oin all three rivers only in 1807, 1810, and 1812. The concentration of late events in the early 1700s and 1800s could possibly be attributed to the climatic effects caused of the 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 sSmaller clusters of late events also occurin, for example, in the 1840s, but they are less prominent than the do not stand out as much as the events of the earlyduring the first two decades of the 1800s.

Finally, lLake-ice research has highlighted the exceptionally late break-up in 1867 (Korhonen, 2005; 2006), the great famine year in Finland (Myllyntaus, 2009). The event in 1867 is one of the latest event oin the Aura, Torne and Kokemäki rivers; however, thethese extended riverine series also highlight reveal the exceptionally late break-ups in 1807 and 1810. These three events are the only events found in in the original length of all three series. 1807

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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 rates

4.2.1 Cross-correlations and changes caused by the power plant

Table 3a shows the average and median break-up dates and the cross- correlations between the three series across their respective lengths. The weakest correlation was between the Aura and Torne rivers. -and tThis was most likely due to should probably be attributed to different climatic conditions, as the distance -caused by the distance (approximately 600 km) between the rivers (approximately 600 km) is considerable. In turn, Tthe strongest correlations were found between the Aura River and Kokemäki rivers, which could be expected considering the relatively short distance (approximately 120 km) between the them rivers(approximately 120 km). These correlations remained high for both the when compared over the pre-power plant period (1793–1938) and the power plant period (1939–2020) (Tab. 3b).

For the period 1793–1938, 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 results show that the break-up ion the Kokemäki River Kokemäki River started on average 3.2 days after the ice-off ion the Aura River (Tab. 3b). Thereafter, However, iin the period 1939–2020 period, the break-up ion the Kokemäki River started 3.2 days before the ice-off ion the Aura River. Thus, it would seem as if the Harjavalta power plant caused a 6.4-day change in the timing of the break-ups. Some ; however, iinterannual variations differences were considerably larger than 6.4 dayswere considerably larger (Fig. 32), but the overall difference was too small to affect the Spearman's coefficient. .

The dates from the break-up competition in Kokemäki River (2003–2020) were an average of show an average difference of 2.3 days earlier than the before the Aura River's ice -off event. However, -The actual difference was most likely greater than this. is is probably and underestimation when considering the actual breakup date.For example, -A newspaper article published in 2019, -indicated that the break-up on the Kokemäki River appears to have begunstarted approximately six days before the guessing competition marker moved. This was the only year for which we found a break-up observation that could be compared to the date from the guessing competition. This six-day difference cannot be used to estimate the break-up dates for the remaining years, especially considering the sporadic variance in the interannual differences between 1939 and 1998. 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

Korhonen and Kuusisto (2010) demonstrated that a significant increase in winter (DJF) discharge rates had occurred at the Harjavalta power plant Iover the period 1931–2004. This study did not separate the pre-power plant and power plant periods, but the power plant has clearly changed discharge patterns prior to ice break-up. This is shown in t 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 1976figure 3, which compares shows the unregulated discharge rates in 1934 with the unnatural how the weekly pulses generated by the power plant before the break-up at the power plantin 1976 affects the rate of discharge. Moreover, as the same figure shows, Second, a clear flow peak used to appear one week after the break-up between in the 1931 and– 1938, but this period was far more modest in the period and this vanished after the power plant was built in 1939–1998. ThirdFurthermore, the average discharge rate until approximately ten days before the break-up has increased slightly since 1939. During 1931–1938, the median discharge rate before the break-up was 181.19 m^3/s but this changed to 206.78 m^3/s in 1939–2020. Increased discharge rates are one of the driving forces during break-upThis . Thus, increased discharge rates 60 days prior to the break-up date may be a contributing factor to earlier could potentially have advanced the timing of the break-ups when compared to the Aura River (Fig. 2). Finally, at on the recorded break-up day, the average discharge rate has decreased 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 m^3/s in the 1939–1998 period (Fig. 3)..

It seems likely that the above-mentioned changes combined to advance break-ups on the Kokemäki River. On an interannual level, and when compared to the Aura River, the shift in break-up dates The changes brought on by the power plant remainedwere initially subtlealmost indistinguishable until 1958 (Fig 2, box 1).. It was not until after 1958 that the difference

~~between the rivers Aura and Kokemäki appears unnatural.~~ Thereafter, ~~I~~in the period 1959–1979 ~~period~~ (box 2 in Fig. 2)~~,~~, the break-up~~s~~ on ~~-~~the Kokemäki River began ~~started o~~an average of 7.3 days (range 1–21 days) before the ice-off ~~i~~on the Aura River~~ (Fig 2, box 2)~~. However, increased discharge rates do not explain the interannual differences in this period. For example, in 1959, the break-up on Kokemäki River occurred 21 days before the ice-off event on the Aura River, but the discharge rates were almost half below the average. Figure 2 presents the differences in the periods 1939–1968, 1959–1979, and 1980–2004. Over these periods, the average discharge rates 60 days before the break-up increased from 177.73 m³/s to 205.09 m³/s and finally to 239.24 m³/s, respectively. However, the difference between the Aura and Kokemäki rivers does not increase commensurately. It is unclear why this is so. The discharge rates at the Halinen dike increased from 7.04 m³/s to 7.31 m³/s to 7.79 m³/s during the same periods, which does not explain the discrepancy between the rivers either. Hence, the interannual differences between the rivers were caused by other factors than simply increased discharge rates. ~~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.~~

As mentioned earlier, ~~Finally, t~~the Aura River had its first no-freeze event in 2008 and its second event in 2020. The average discharge rates for December, January and February in ~~the winters of~~ 2007/2008 and 2019/2020 were higher than in any other winter months in the period 1938–2020~~ period~~. None of these months contained the absolute ~~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 for~~to~~ ~~why~~ the no-freeze events ~~occurred i~~on the Aura River~~ during these warmer winters~~. A similar pattern could not be observed for the Kokemäki River.

4.3 Climatic correlations

4.3.1 Break-ups according to monthly mean temperatures 1961–2020

~~All three~~The series exhibited strong and statistically significant negative correlations with winter and spring temperatures (Fig. 4). This indicates that increased ~~higher than average~~ spring temperatures ~~temperatures~~ have caused earlier break-ups~~ and variability~~ (Fig. 5). The Aura

River ice-offs exhibited particularly high correlations with February (-0.77) and March (-0.74) temperatures. The Kokemäki River break-ups also ~~also~~ showed high correlations with these ~~same~~ months, but the correlations were higher with March (-0.84) than February (-0.71). For the ~~When compared to the~~ February-March period, the correlation was slightly higher for the ~~breakups in~~ Kokemäki River (-0.89) than for the ~~in A~~Aura River (-0.86).

The ~~breakup~~ Torne River~~in northern Finland~~ break-ups occur~~s~~ later in spring than on Aura and Kokemäki rivers.~~the breakups in the southern parts of the country.~~ Most break-ups have occurred in late April or May, and since the 1960s in late April or early May. T~~hus, t~~he mean temperature correlations for the Torne River were therefore strongest with April (-0.70) and May (-0.49). The correlations were similar for the ~~remained at the same level when compared to the~~ period 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 Break-ups according to monthly mean precipitation 1961–2020

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Correlations with winter and spring precipitation were mainly negative and ~~. However, the correlations were~~ considerably weaker than th~~ose~~e correlations ~~with~~ for temperature ~~and precipitation is secondary to temperature~~ (Fig. 4)~~.~~. Nevertheless, ~~T~~the precipitation correlations for ~~the winter months~~ December and January ~~are~~were statistically significant for the ~~in~~ Kokemäki and Aura rivers. On the Torne River the correlations ~~They ar~~were~~e~~ relatively strong, ~~even~~ though non-significant~~, in Torne River~~. January showed the strongest correlations with the Kokemäki River break-up dates; February with the Aura River ice-off events and May with the Torne River ice break-ups. The Aura River ice-offs were thus the only break-up event with ~~is therefore the only river that shows~~ the highest correlations for both temperature and precipitation in the same month.

4.3.3 Break-ups according to daily mean temperatures 1961–2020

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The break-up ~~i~~on the Torne River ~~has usually~~ commonly begins approximately ~~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~~ occurred, according to the data,~~usually~~ when the daily maximum was close to 10 °C and the minimum above ~~temperatures had surpassed the~~ freezing point. In general, ~~T~~these conditions ~~have usually~~ occurred approximately 20~~around twenty~~ days after the daily mean temperature ha~~s~~d risen above ~~the~~ freezing point.

By contrast, The breakup in Kokemäki break-ups have typically begun River has usually started at lower temperatures than the break-ups ion the 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 break-ups have usually begun started 10 days after the daily mean temperatures rose has risen above the freezing point. AtOn the day of the break-up, the daily mean was has usuallygenerally 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 commonly oscillated above and below has gone below the freezing point even three weeks after the break-up. A similar pattern was visible in Turku, although, however, the temperatures hasdid not fallen - below the freezing point as consistently or as much as in Pori. The Turku ice-off event in Turku has usually occurred regularly occurred ten10 days after the daily mean has risen above freezing point, but at slightly higher temperatures than in Pori (mean 2.5°C and maximum 7°C). The post-event difference between the Aura and Kokemäki rivers may be an effect of the The difference is minimal, but higher temperatures could be explained by the fact that Aura River indicates the ice-off date. Harjavalta power plant. It causes an earlier break-up after which the discharge rates hinder the freezing process.

4.3.3 Break-ups, ice thickness and snow cover in Torne River

SYKE has measured the thickness of the ice in Torne River since the 1960s. The negative trend (p<0.05) and slope (-0.267) indicate that the ice on the Torne has become 14.5 cm thinner between 1966 and 2019. Over the same period, mean ice thickness was 77 cm and the break-up date 6 May (VE47, if the vernal equinox was on 20 March). The only significant correlation (p<0.05) between break-up dates and mean ice-thickness was for AprilComparing 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). The relationship between ice thickness and break-up dates is interesting. 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 break-up on records (VE37), but the ice was thinner and the break-up later on 22 occasions. This is further underscored by the warm winter with the unusually late break-up in

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2020 (VE61), when acknowledged because the ice was too thin to be measured. Other measurements indicate that the ice was approximately 50 cm thick (this is discussed more in section 5.1). in 2020 (VE61), the extremely warm year with the unusually late breakup. A tThicker snow cover could have maintained a higher surface albedo, thereby that delaying the delayed the melting of the underlying ice and thus, thereby delaying the break-up (e.g. Prowse and Beltaos, 2002; Bieniek et al., 2011). However, SYKE has measured snow depth on the ice since 1978, but and all correlations with the break-up date were proved non-significant for the period 1978–2019 period.

4.4 Temporal trends

The data series for all three Table 1 showed that the breakups the last few decades have occurred earlier than ever before. Therefore, not surprisingly, all rivers show negative break-up trends , i.e. the breakups are advancing towards the beginning of the year (Tab. 4, Fig. 7). Break-ups are withdrawing towards the beginning of the year, and I it is now over 140 years since the last May-ice off event ion the May in the Aura River and almost 100 years since last breakup in May-event on 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 period 1793–202000 period, the slopes offor the Kokemäki River (26.2 days) and the Aura River (17.4 days) diverged. , and tBy contrast,he development ion the Aura River was similar to that ion the Torne River (13.0 days). Moreover, the rate of change within the slope remained similar ion the Aura (15.3 days) and Torne (13.6) rivers even between over the 1749 and– 2020 period. Taken together, the similarities in change between therivers Aura and Torne implyies that the calculated change in Kokemäki River is may be skewed. Nonetheless, the However, Kokemäki River hadexperienced substantially more late events than the Aura and Torne river in the 1800s and early 1900s (Fig. 96). Hence, the diverging trends infor the Kokemäki River may be attributed to a greater change in the late rather than early events (see below).

Over the period 1939–2020, break-up trends were pronounced for both the Kokemäki and Aura, with a change of almost three weeks for both rivers. Torne River's slope, on the other hand, indicated a change of less than one week, which underscores the difference between the south and north.

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 ~~i~~on all three rivers (Fig 9d–~~–~~f). The first increase in early events occurred between ~~in the~~ 1901 and ~~–~~1930 ~~period~~, but ~~but~~ the most rapid increase took place between ~~increase occurred in the~~ 1991 and~~–~~ 2020 ~~period~~. ~~A common phenomenon f~~For all three ~~three~~ rivers, ~~was that~~ the extremely early break-ups that occurred once in the first period constitute at least one third of all events in the period 1991–2020 ~~period~~.

The decrease in late events during the period ~~change that occurred in the~~ 1901–1930 ~~period~~ is pivotal for the ~~in~~ Aura and Torne rivers ~~because of the decrease in late events~~. In Turku, the press reacted to the earliness of the break-up events (Norrgård, 2020). Moreover, according to Benson et al. (2012), some lakes had their first no-freeze events in the early 1900s. Th~~e~~is ~~change was likely caused by s~~spring warming is likely to have been ~~and lin~~caused by ~~ked~~ the ~~to the~~period sometimes referred to as the Early Twentieth Century Warming, which is estimated to have occurred ~~–~~between the 1890s and 1940s (e.g. Hegerl et al. 2018). On the Kokemäki River, however, ~~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~~a decrease of late events did not occur until after 1931 (Fig. 9e) ~~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~~ events on the Kokemäki and Aura rivers has changed considerably after ~~in the~~ 1991~~–2020 period shows that the earliness of the events have advanced considerably in Kokemäki and Aura rivers~~ (Fig. 9a–~~–~~c). This development~~The development~~ was driven by the no-freeze events and ~~the no-freeze events but also~~ several events in early March and February (Fig. 8). By contrast, ~~f~~~~In~~or the ~~–~~Torne River (Fig. 9a), ~~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, t~~This explains why there is ~~only~~ a 12-day range in the 75 percentiles for the ~~in~~ Torne River while that range ~~the range~~ is over 90 days ~~in~~ for the Aura and

Kokemäki rivers. It should be noted that while t~~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.~~he average of the late extremes have increased in the Torne River series, the mean is primarily affected by two of the latest break-ups in almost 100 years, which occurred in 1996 and 2020.

4.5.2 Variability within the quartiles

For the Torne River, ~~Examining~~ the quartiles show~~s~~ 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 period 1751–1780 and ~~-period and~~ this~~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 break-ups, ~~since~~ occurred after the period 1931–1960~~ period~~. The increase of earlier~~y~~ break-ups has thereafter been ~~explosive~~rapid. ~~For example, a~~All ~~the~~ break-ups in the 75 percentiles between ~~in the~~ 1991 and –2020~~ period~~ occurred before the median break-up date in the previous period~~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.~~

For the ~~The change in~~ Aura River, ~~tis similar to that in Torne River. T~~he magnitude of change is unprecedented: 28 of 30 ice-off events ~~in the~~ between 1991 and~~–~~ 2020~~ period~~ occurred before the median ice-off date in the period ~~in the~~ 1961–1990~~ period~~. Moreover, ~~For example, t~~the latest ~~breakup~~ ice-off event in the period 1991–2020 ~~period~~ occurred ~~a week~~seven days earlier than in the previous period~~than in the 1961–1990 period~~.

The IQR for the ~~in~~ Aura and Kokemäki rivers also increased considerably after 1991~~in the 1991–2020 period~~. For the Aura River~~In Aura River~~, the IQR doubled from 11 days in the period 1961–1990 ~~period~~ to 22 days in the period 1991–2020~~ period~~. O~~I~~n the Kokemäki ~~River~~River, the change was from 9.25 to 18.5 days. The increase in variance, ~~in~~ for both rivers, was caused by a rapid rise ~~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~~ feature describing the break-up patterns~~s~~ ~~i~~on the Aura and Kokemäki rivers the last 30 years~~in the 21st century~~ was the increase~~d~~ in interannual variability. The timespan between the freeze-up and break-ups have progressively shortened, and, ~~advanced towards the~~

~~freeze-up period and the~~ exacerbated by a general ~~effect of the~~ warming trend, ~~was~~ the first no-freeze events occurred~~.~~ o~~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 i~~n the Aura ~~River~~ (2008 and 2020) and the Kokemäki ~~River~~ (2008, 2015 and 2020) rivers. The no-freeze events took place ~~occurred~~ during ~~some of~~ the warmest and wettest winters on record (~~Ilkka et al., 2012;~~ Lehtonen, 2021; Irannezhad et al., 2014; ~~Lehtonen, 2021;~~ FMI, 2016; Ilkka et al., 2012). ~~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 2008 no-freeze event~~s~~ o~~i~~n the 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, as ~~and so~~ was February 2020. ~~For example, d~~During a short period in February 2020, the river was close to freezing (author's observation), but ~~there were~~ small sections ~~that~~ of the river never froze completely~~remained open~~. Meanwhile, in Pori, Kokemäki River flooded, with the discharge peaking at 656.59 m³/s on 24 February.

The loss of river-ice are historically unique events in Finland. ~~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.~~ Socioeconomically and culturally, the impact is meager. Citizens and businesses, in for example Turku, stopped being dependent and exploiting the ice already in the 1900s. Nowadays, the ice is often considered too weak to walk on and many have progressively alienated themselves from the river-ice. Where once people relied on the river-ice to get across the river, it is now almost considered an exotic event if the ice is strong enough to walk on. Whether the Aura and Kokemäki rivers freeze in the future depends on the return period of climatic extremes (Fisher, 2021). Studies have showed that ice-free years are becoming more frequent in lakes, and will continue to do so in the future (Sharma et al., 2021; Filazzola et al., 2020). The changes in Aura and Kokemäki rivers suggests that the warmer climate that is dominating in the south has changed more rapidly and in greater magnitude 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).

There are uncertainties related to the reliability of the Kokemäki River series. First, the dates from the break-up guessing competition on Kokemäki River are not fully comparable to the break-up dates before 1998. Observations of the actual break-up would improve the series. Second, we could not establish with certainty to what extent the Harjavalta power plant changed

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the timing of the break-up in Pori, even though it is evident that increased discharge rates has affected the ice regime. Finally, the largest shift in the timing of the break-ups occurred post 1959, two decades after the power plant was constructed. The change in the break-up process, however, was tangible, as evidenced by a 1972 interview in *Satakunnan Kansa,* where a 70-year-old man who had lived his entire life by the river remarked that a distinct change in the break-up process occurred about a decade earlier. The ice started melting in the middle of the river and not across its length.

~~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).~~

On the Torne River, the ~~The number of early events has clearly increased also in Torne River. The change~~shift ~~has~~ towards earlier break-ups has progressed in two stages. The first stage began during the period ~~started in the~~ 1901–1931, while ~~period and~~ the second stage started ~~started~~ in the 1990s. Unlike on the Aura and Kokemäki rivers, extremely early break-ups on the Torne has not progressively approached the freeze-up date. ~~The breakup trend follows the temperature trend (Klingbjer and Moberg, 2003) to a degree where the breakup has become almost predictable.~~ The earliest recorded break-up event ~~(~~occurred in the 2000s, and it ~~2014) w~~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. Instead, the timing of break-ups has changed such that 25 of the last 30 events occurred within the same 12-day period between 1991 and 2020. This indicates that April temperatures predetermine the break-up date. A rapid increase in April temperatures would render the break-up more erratic. Future changes in variability and extremes therefore depend on whether warming is greater in the winter or spring (see Ruosteenoja et al., 2020; Mikkonen et al., 2015).

~~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 event in 2020 was ~~The record warm winter in 2020 caused~~ the second latest break-up in ~~the last~~ 100 years on the Torne River ~~in Torne River and the question is what caused this strangely late event~~. This was surprising, considering that the 2019/2020 winter was one of the warmest on record. While temperatures were closer to normal in Lapland, and came with an excess of snow, the mean temperature was 2–5 °C above the long-term mean (Lehtonen, 2021). Only the mean temperature for April (0.1 °C) was lower than the long-term mean (0.4 °C). This could have been decisive for the break-up, as our dynamic analysis highlighted the importance

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of thermal input before the break-up. At least, it should be recognized that ice thickness did not cause the late break-up. In March 2020, -SYKE did not measure ice thickness in Torne River in 2020. However, in March, the national broadcasting company (YLE) reported that the Centre for Economic Development, Transport and the Environment (ELY) had measured the ice toat 55 cm about three kilometres downstream from the break-up site. This was almost Th20 cm thinner than the e long-term mean at the break-up site was 73 cm (1966–2019, n=54, 73 cm). Moreover, it -wasand the ice was therefore in 2020 almost 20 cm thinner than during the early break-up ofbelow the long-term mean and the thickness in 2014 (75 cm) and 45 cm thinner than record late break-up in 1996 (90 cm). As- our analysis demonstrated, ice thickness in March was non-significant for the break-up date. 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. Hence, future case studies could attempt to determine the factors that caused the lateness of the event in 2020.

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

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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 first half of the 1700s was the coldest period on the Torne River and this is only matched by the lateness of events in all three rivers around the 1810s. Figure 7 indicates that this represents one of the coldest periods at all sites. Previous research has identified this as one of the coldest periods in Haparanda (Klingbjer and Moberg, 2003) and Stockholm (Leijonhufvud et al., 2010) but also other parts of Europe. Our series therefore mirror the colder periods at other sites. Some have argued that an unidentified volcanic eruption in 1809 (Toohey and Sigl, 2017) and the Tambora eruption in 1815 caused a colder decade between 1810 and 1819 (Cole Dai et al., 2009). A detailed assessment of the forcing factors behind this colder decade remain beyond the scope of this article. However, our data indicated that 1807 produced a late break-up at all sites and, furthermore, Table 2 shows that there were several late events during the first decade of the 1800s. These could be independent events or imply the presence of other forcing factors, such as the Dalton Minimum (1800–1824).

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The data for the Aura, Kokemäki and Torne rivers diverged with regard to the lateness of the break-up event in 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.

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The ice-off in Aura River in 1852. The Aura River experienced one of the latest ice-off events, while the Torne River's break-up was not even amongst 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 to confirm the validity of the ~~from~~ Aura River event, which is why we choose to ~~so clarity is gained by~~ crosscheck~~ing~~ the event in 1852 with the previously mentioned Porvoo, Neva and Dvina rivers~~.~~ (Johansson, 1932; Rykatschew, 1887).

The three latest events ~~i~~on the Neva River series occurred in 1810, 1852, and 1807, whereas the latest events ~~i~~on the Porvoo River occurred in 1852, 1867, and 1810. In turn, ~~T~~the three latest break-ups ~~i~~on the ~~n~~ Northern Dvina were in 1867, 1845 and 1855. Thus, the event in 1852 was late in all rivers except the ~~for~~ Torne and Dvina. Moreover, the event in 1822 ~~(see section 4.2)~~ was exceptionally early ~~i~~on all rivers except the ~~for~~ Torne and Dvina. There is therefore a distinct~~guishable~~ difference between the rivers in the north and the south when it comes to 1822 and 1852. These discrepancies could be explained by, for instance, ~~local climatic conditions or~~atmospheric blocking events. Nonetheless, the break-up event of 1867 and 1810 were among the top 10 latest for five of the six rivers (Dvina, Kokemäki, Neva, Porvoo and Torne~~ of all six rivers~~). ~~have 1867 and 1810 in their top ten latest events.~~ It is only ~~i~~on the Aura River that the ice-off event in 1810 ~~is~~was not among the 10 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, w~~We ~~compared three river-ice breakup series from Finland and~~ presented a new ice break-up series for the Kokemäki River in Pori (1793–2020) and compared it ~~. The Kokemäki River series was compared~~ to the existing series for the ~~rom~~ Aura River (1749–2020), in southwest Finland, and the Torne River (1693–2020), in ~~the north~~Lapland. ~~This study include the first analysis of three river-ice breakup series that extends across three centuries.~~ Our analyses showed a trend towards earlier break-ups in all three series. However, that ~~; however, the~~ change ~~is~~was manifested differently ~~i~~on the Torne River- compared ~~in comparison~~

to the ~~that in~~ Aura and Kokemäki rivers. ~~I~~On the Torne River, the earliest recorded break-up has changed only slightly over the last 100 years. ~~, while~~ The Aura and Kokemäki rivers, on the other hand, recorded ~~have had~~ their first ~~years when the rivers did~~ no~~t~~-freeze~~-up~~ events in the 2000s ~~completely during winter~~. These ~~no-freeze~~ events ~~— expressing~~express the most radical ~~extreme~~ form of change for rivers that, from a historical perspective, used to freeze-up every winter. ~~typically have frozen — exhibits a strong signal that the climate has changed.~~ ~~I~~On Aura River, it ~~would~~ appears that no-freeze events occur due to higher winter temperatures and increased ~~do not necessarily cause no-freeze events, but they will if~~ winter discharge. However, ~~also increased over the December–February period.~~ ~~T~~this speculative suggestion requires ~~is in need of~~ further research. Finally, ~~T~~the overall trend in the timing of ~~the~~ ice break-ups correlates with the warming trend confirmed by instrumental observations, with the events in ~~and the events in~~ 2008 and 2020 occurring ~~ed~~ 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 break-up 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

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Figure 1. Northern Europe and Finland with the Finnish rivers marked out. The squares 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 break-up events in the Torne and Kokemäki rivers, and the 30 earliest ice-off events in the Aura River. The 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 the Kokemäki River, for example, (+54) means that the ice break-up 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 break-up events in the 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 the Torne River, for example, (-14) means that the ice break-up occurred 14 days before the latest (0) event.

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	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) break-up date, according to the vernal equinox, for the Torne (TR) and Kokemäki (KR) rivers and the average ice-off date for the Aura River (AR). The table also shows the cross-correlations (rho) between

the three series. Part (b) shows the correlations and subtracted differences between the AR and KR before and after the power plant period. The negative value indicates that the ice-off event in the AR occurred before the break-up event in the KR. The 2003–2020 period shows the difference for the guessing competition break-up 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

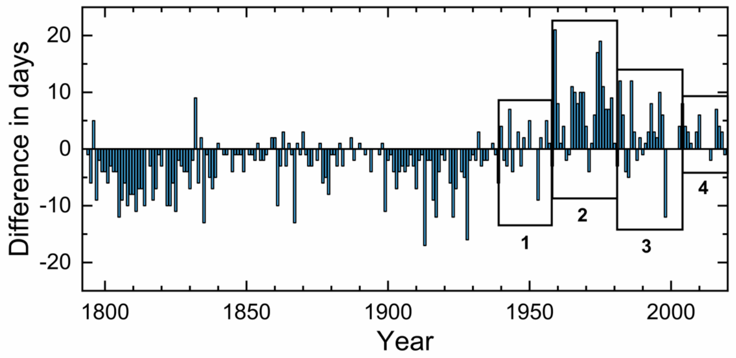

Figure 2. The difference in days between the break-up date in the Kokemäki River and the ice-off event in the Aura River. A negative value indicates the number of days the ice-off event in Aura River preceded the break-up date in Kokemäki River. Vice versa, a positive value shows how many days the break-up in the Kokemäki River occurred before the ice-off date in the Aura River. See section 4.1 for more information on the boxes.

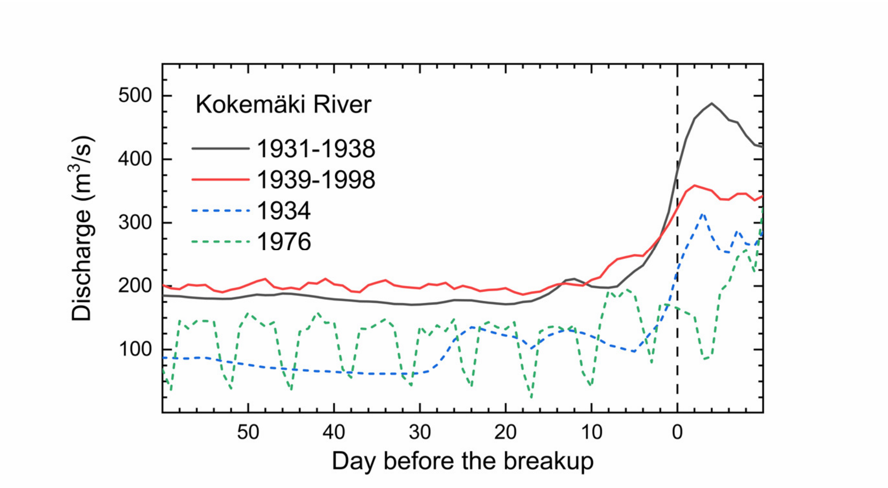

Figure 3. The discharge 60 days before and ten days after the break-up (0) in Kokemäki River. The black line shows the average discharge rate during the 1931–1938 period and the red line the average during the 1939–1998 period. The grey line depicts the discharge in 1934 and the yellow line depicts the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

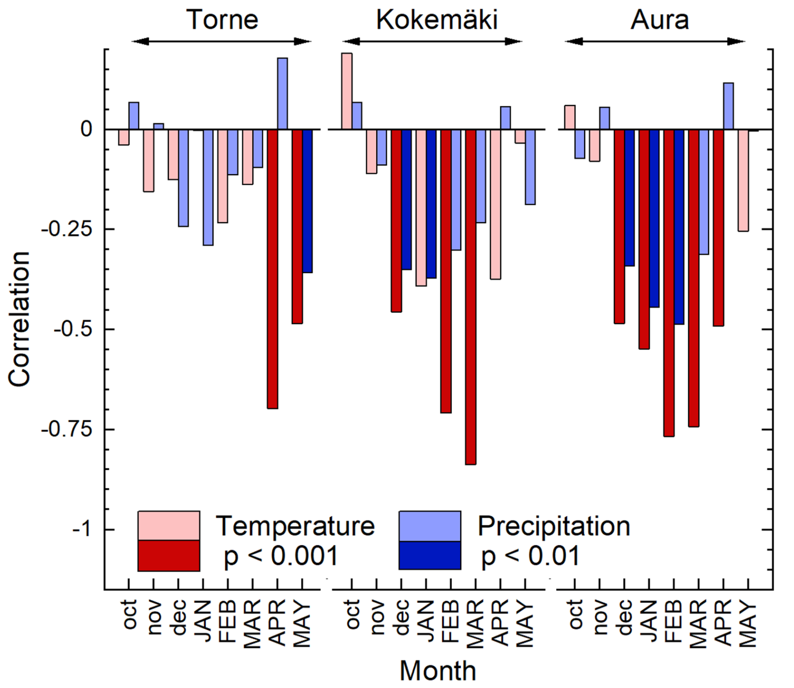

Figure 4. The figure shows Spearman's correlation between temperature, precipitation and ice break-up dates in the Torne and Kokemäki rivers and, respectively, temperature and ice-off events in the Aura River, during the 1961–2020 period.

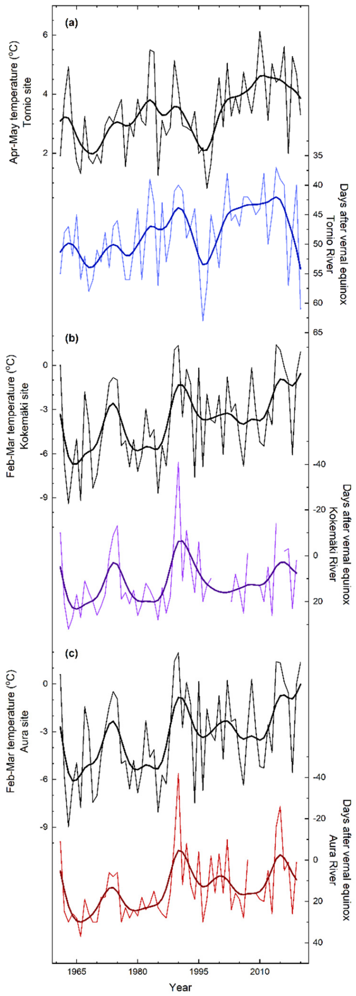

Figure 5. Variations in mean spring temperature and ice break-ups. A comparison between the interpolated mean temperatures to the observation sites for (a) Torne, (b) Kokemäki and (c) Aura rivers over 1960–2020 period. The observed break-up dates (thin line) were smoothed using a 10-year spline function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

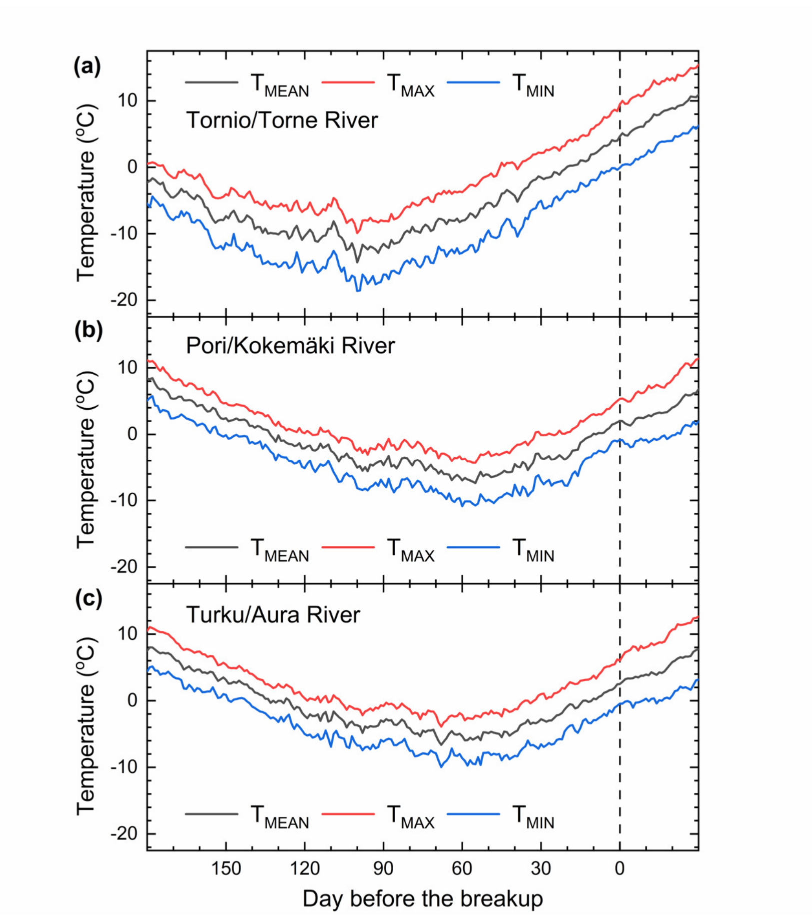

Figure 6. The lines show the temperature development 180 days before and 30 days after the break-up date in Tornio (Torne River), Pori (Kokemäki Rivers) and the ice-off event in Turku (Aura River). Zero (0) denotes the break-up and ice-off day in the respective rivers.

Table 4. 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 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

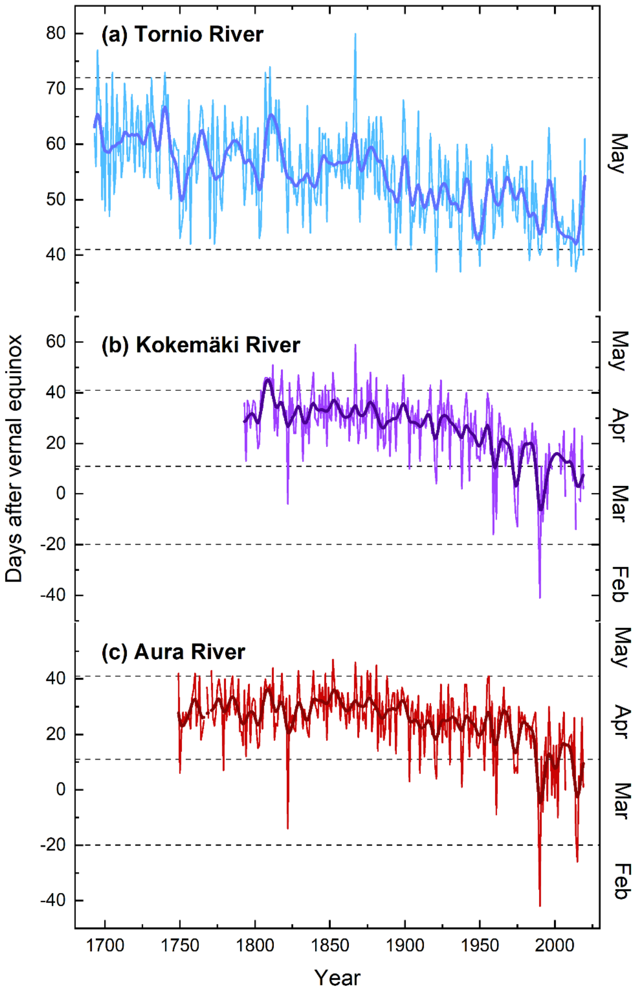

Figure 7. Ice break-up dates relative to the vernal equinox on (a) the Torne and (b) Kokemäki rivers, and the ice-off dates in (c) the Aura River. The obtained dates (thin line) were smoothed to illustrate decadal and longer variations using a 10-year sling function (thick line).

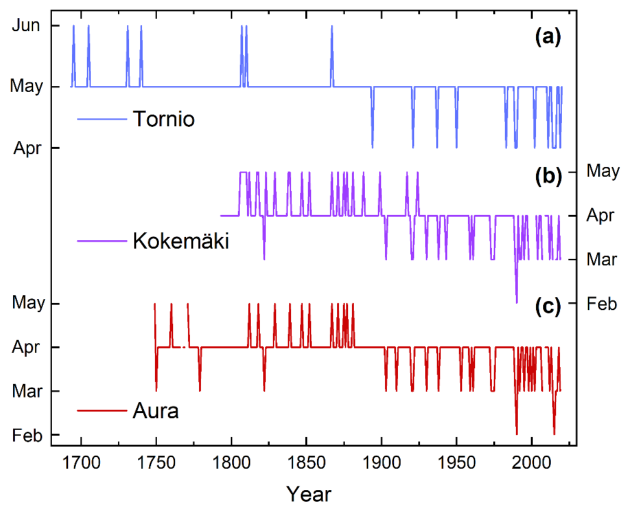

Figure 8. Occurrence of ice break-up events in February, March, April, May, and June on (a) the Torne River, (b) the Kokemäki River and the corresponding ice-off events for (c) Aura River.

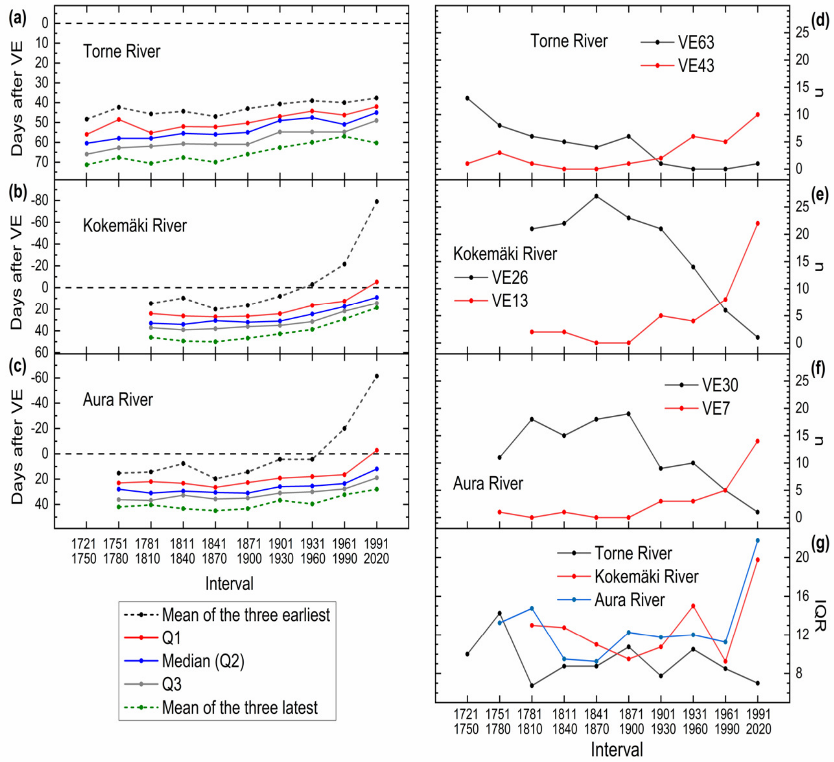

Fig 9. Ice break-ups on the rivers the Torne and Kokemäki and ice-offs on the Aura River according to the vernal equinox (VE) in 30-year non-overlapping periods. The dotted line (0) in Figure (a-c) marks the vernal equinox. The values are obtained from analysing the quartiles of each series in each period. 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.

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