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

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Abstract. At high latitudes, long-term changes in riverine ice breakups are exemplary measures of climatic change and variation. This study compared cryophenological trends, patterns and changes for the rivers Aura (1749–2020), Torne (1693–2020) and Kokemäki (1793–2020), all located in Finland. The Kokemäki is a new series from the city of Pori. The findings show statistically significant cross-correlations between the Aura and Kokemäki rivers, while the correlations with Torne River were weaker. The weaker correlation was attributed to climatic differences caused by the latitudinal distance between the rivers. Taken together, the many results of this study suggest that in the south the spring climate has changed more rapidly and become less predictable than in the north. Climatic extremes – warmer and wetter winters – in the 2000s resulted in the first recorded no-freeze events in Aura and Kokemäki rivers. The no-freeze events were the final outcome of a rapid increase in early events and interannual variability the last 30 years. The number of early events have been increasing in all three rivers since the early or mid-1900s, but the earliest recorded breakup day in Torne River has changed only marginally the last 100 years. Our dynamic temperature analysis showed that the breakup event in Torne River requires higher temperatures than in the south and future changes in the timing of the breakup depend on April temperatures. In Finland, ice breakupcryophenological observations have been recorded for centuries for Aura River (1749–2020), Torne River (1693–2020) and Kokemäki River (1793–2020). The Kokemäki River is a newly revised, extended, and updated ice breakup series from the city of Pori, which is 120 km north of Aura River and 500 km south of Torne River. The Spearman analysis shows that the correlation between the ice-off event in Aura River and breakup event in Kokemäki rRivers is strong, while the correlation between the two southern rivers (Aura and Kokemäki) and Torne River is weaker. The difference is attributed to the longitudinal latitudinal distance between the rivers. Mean Ttemperature correlations are strong for all three rivers and the long term trends towards earlier breakups and ice offs are statistically significant. Aura and Kokemäki rivers show considerable changes. Aura and Kokemäki rivers have had two and three years respectively three years without a complete ice cover in the 21st

century. These are the first non-freeze events in over 270 years of recorded observations and occurred during record breaking temperature anomalies. In Torne River, however, the earliest recorded breakup date has changed only marginally the last 100 years. Moreover, the earliest recorded breakup date in the 21st century occurred only five days earlier than the earliest breakup date in the 18th century. This suggests that the climate in the south is changing more rapidly than in the north and therefore that the response to climate warming is not equally pronounced. Kokemäki River did not escape the hydroelectric power plant boom in the mid-1900s, and this has speeded up the breakup process. A qualitative analysis shows that exceptionally late events ice breakups occurred in all three rivers in 1807, 1810 and 1867. All three series show cThere are noticeable clusters of late events in the early 1800s in all three series, while an exceptionally early breakup event occurred in Aura and Kokemäki rivers in 1822. In the south, on the other hand, future changes depend much more on winter temperature and precipitation during the freeze-up period.

1 Introduction

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

Most cryophenological studies useemploy lake-ice data because lake-ice series are plentiful and they provide good spatial coverage. Such analyses have shown trends towards later freeze-ups and earlier breakups across the northern hemisphere (Newton and Mullan 2021; Benson et al, 2012; Korhonen 2006; Magnusson et al., 2000). The trends vary in time and scale depending on location but changes are typically associated with air temperatures and especially increased temperatures in cold climate regions since the 1960s (Mikkonen et al, 2015; Weyhenmeyer et al., 2011; Bonsal and Prowse, 2003; Serreze et al. 2000), but while there is a plethora of lake-ice series, long-term series are scarce. Most studies are therefore limited to periods that begin in the late 1800s or early 1900s (e.g. Newton and Mullan, 2021; Benson et al. 2012; Magnuson et al. 2000). Studies that employ large data sets are also limited in their temporal approaches because they are affected by differences in the observational periods or because the employed databases are not updated with observations from the first two decades of the 21st century (Newton and Mullan, 2021; Prowse et al., 2011). While these studies show trends towards earlier breakups across the northern hemisphere (Newton and Mullan 2021; Benson et al, 2012; Korhonen 2006; Magnusson et al., 2000), and have established that the trends relate to increased temperatures in cold climate regions since the 1960s (Mikkonen et al, 2015; Bonsal and Prowse, 2003; Serreze et al. 2000), they

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

In Finland, at least five river-ice series date back to the may overlook events caused by record setting extremes the last 20 years (Fisher et al., 2021). Extending series to previous centuries while also including the most recent observations is of essence. Aprovides an improved understanding of multicentennial breakup patterns and historically extreme events as, viewedmirrored against through events the last decades. Extended series also , provides a source for investigating past climate patters, abrupt changes and events that can be linked and the role ofto large-scale climatic drivers, such as the North Atlantic Oscillation (NAO) and sunspot cycles (Sharma et al., 2016; Prowse et al. 2012; Stonevicius et al., 2008).

In this article, we present a new multicentennial ice breakup series from Kokemäki River (in Swedish *Kumo älv*) and the observations made in Pori (*Björneborg*) in southern Finland. The series covers the period between 1793 and 2020 and we compare it to the Torne River (1693–2020) and Aura River series (1749–2020). The Kokemäki River series receives a more in-depth presentation than the two other series because it is presented for the first time. We chose not to present the Kokemäki River series on its own like the Torne River (Kajander, 1993; 1995) or the Aura River series (Norrgård and Helama, 2019), because it did not escape the hydroelectric power plant boom in the mid-1900s. Analysing the Kokemäki River series on its own would only have highlighted the need to compare the obtained observations to other series.

Observations of ice breakup and ice-off events started in several riverine societies in Finland in the 1700s (e.g. Leche, 1763; Rykatschew, 1887; Johansson, 1932) and in the 1800s, b. Before the long-term meteorological data was readily availableestablishment of meteorological networks, scientists used the breakup series river-ice seasonality to investigate climatic changesfunctioned as reliable indicator of seasonal change and long-term changes were investigated already in the 1800s (Hällström, 1842; Eklöf, 1850, Levänen, 1890). The professor of Meteorology Oscar Johansson (1932) extended some of the series to 1906 and thereafter they were dormant until -and during the first half of the 1900s (Johansson, 1932). Cryophenological research then stagnated until the early 1990s when Juha Kajander (1993; 1995) updated and extendeddocumented the observations for the Torne River in series from northern Finland. This series The series has became one of the longest climatic series based on historical records and it has often been compared to lake-ice records acrossfrom the northern hemisphere (e.g. Newton and Mullan, 2021; Sharma et al., 2016; Magnuson et al., 2000). In 2019, the The Torne River series was complemented with the series remained the only updated riverine climate series until In 2019the , we presented the Aura River series from Turku in southwestern Finland was presented in 2019 (Norrgård and Helama, 20, 2019). The present study conducts the first comparison between these series.. , but the series has not yet been compared to any other ice phenology series. The Torne River and Aura River series are unique in comparison to the Finnish lake-ice series because of their length. Moreover, most of the observations since the start of the series, unlike the lake-ice data (Korhonen, 2005), have been verified.

In this article, The current study further -we presents a newly compiled multicentennial ice breakup series fromor the Kokemäki River (in Swedish *Kumo älv*) based on observations from . The series is based on ice breakups observations made in the city of Pori (*Björneborg*) in southwest Finland. It spans from 1793 to 2020 The Kokemäki Riand it is compared to ver series covers the 1793–2020 period and we compare it to the Torne River (1693–2020) and- the Aura River series (1749–2020).

While the development of the breakups in Torne River mirror changes observed in lake ice breakups during the 1900s, i.e. the timing of the breakups are advancing (e.g. Magnuson et al., 2000). However,, the lack of multicentennial comparisons from nearby rivers means that thereprevious research arehas not been able to address no long-term perspectives on temporally extreme events and developments since the 1700s due to the lack of other multicentennial riverine series from Northern Europe. There are in the northern hemisphere several riverine series from both Russia and North America that start in the 1700s (Rykatschew, 1887; Magnuson et al., 2000) but they do not continue to date. Updated river-ice series are available from Latvia and Belarus, but except those for Daugava River in Latvia (Klavins et al. 2009) and Nemunas River in Lithuania (Stonevicius et al., 2008), which are both regulated, most series cover only the 1900s (Klavins et al., 2009).

Ice breakupCryophenological series from regulated rivers are usually approached with some caution because it is unclear how and if hydroelectric power plants have changed the timing of the breakup. There are to our knowledge no studies on this subject. For example, while the power plant in Kaunas, Lithuania, impacts the ice cover in Nemunas River as far as 50 km downstream (Stonevicius et al., 2008), we found no studies showing how the power plant impacts the timing of the breakup.

The reason might be that a reliable analysis requires a comparison with observations from an unregulated river nearby. Moreover, the length of the series should be long enough, especially the pre-power plant period, to give a valid analysis of the timing of the breakups before and after the power plant was built.

This paperstudy has four main objectives: (ia) to analyseexamine how if the largest power plant nearestclosest to Pori has changed may have affected the timing of the ice breakups in Kokemäki River; (bii) to analyse the long-term trends and the correlations between the rivers Aura River, Kokemäki River and Torne River series; (iiie) to analyse how the series correlate to mean temperature, sprecipitation and, in the case of Torne River, ice thickness; and (ivd) to examine variability and changes in the frequency of extreme events. do a qualitative assessment of extreme events to identify cold/warm springs and periods in northern Europe since the 1700s. The qualitative comparison provides a novel perspective on long term variability and the development of extreme events that has not been addressed before.

Long-term cryophenological series from lakes and rivers in the high latitudes are exemplary indicators of climate variability during winter (freeze-up) and spring (breakup). As such, long-term series of river ice breakups could be considered more unambiguous than long-term meteorological observations because the recording of cryophenological observations require no special equipment or instruments. In comparison to lake ice observations, river-ice breakup series often extend further back in history. In Finland, several river-ice series start in the 1700s (e.g. Leche, 1763; Rykatschew, 1887; Johansson, 1932) and the first long term analyses of these were conducted already in the 1800s (Hällström, 1842; Eklöf, 1850, Levänen, 1890) and early 1900s (Johansson, 1932). This could probably be attributed to early riverine societies' dependency on the river as an economic hub and trading route. Unfortunately, during the second half of the 1900s, all types of cryophenological observations from riverine societies have become scarcer and less detailed. This is a consequence of technological advancement and the fact that riverine societies have become less constrained by ice and less dependent on practical solutions such as ice bridges and ice roads. Climate is nowadays also often reduced to meteorological variables, which adds to the lack of detailed freeze-up or breakup observations. In other words, cryophenological observations have lost their value as climatic indicators in urban environments.

Ice breakup series from riverine societies may be affected by changes made in the riverine environment. Structures such as bridges, warm water drainage outlets and hydroelectric power plants may advance or delay the ice breakup process (e.g. Kajander, 1993). The human influence and radical environmental changes constitute major reasons to differentiate ice breakups in riverine societies from those observed in lakes. River-ice breakups therefore have a higher signal/noise ratio than lake ice observations, which are mainly determined by temperature (Prowse & Beltaos, 2002). We therefore begin this article (Section 2) with a short synopsis of the history of each observation site, i.e. the city from where the observations derive.

The Torne River series was compiled in the early 1990s (Kajander, 1993) and has since then been used extensively in climatic investigations (e.g. Sharma et al., 2016; Helama et al., 2013; Magnuson et al., 2000). However, long term comparisons between river ice breakups are few and there are probably several reasons explaining this. The series are spatially dispersed and few of the series that start in the 1700s continue to date. For example, there are discontinued, or not updated, series from Russia and North America, such as Red River (1799–1978) and River Mackenzie (1799–1981) (Magnuson et al., 2000). There are breakup series from Latvia and Belarus, but except for Daugava River in Latvia (Klavins et al. 2009) and Nemunas River in Lithuania (Stonevicius et al., 2008), which are both regulated, most series cover only the 1900s (Klavins et al., 2009). The power plant in Kaunas impacts the ice cover as far as 50km downstream (Stonevicius et al., 2008).

In Finland, two series are continuously updated. These are the Aura River (Norrgård and Helama, 2019) and the Torne River breakup series (e.g., Kajander, 1993; 1995; Helama, 2013). The Torne River series is the only river officially monitored by the Finnish Environment Institute (SYKE), which has kindly provided the data for this investigation. The ice-off date in Aura River is officially determined by the harbour master (Norrgård and Helama, 2019), but the breakup process has also been monitored by the first author of this article.

In this article, we present a new ice breakup series from Kokemäki River (in Swedish *Kumo älv*) and the observations made in Pori (*Björneborg*) in Finland. The series covers the period between 1793 and 2020. Here, the Kokemäki River series receives a more in-depth presentation than the two other series because this is the first time that the series is presented and analysed. Another reason for not presenting the Kokemäki River series on its own like the Torne River (Kajander, 1993; 1995) or the Aura River series (Norrgård and Helama, 2019), is because it did not escape the hydroelectric power plant boom in the mid-1900s. Climatic series from regulated rivers are approached with some caution because of the hypothetical anthropogenic impact on ice cover and timing of ice breakups. To our knowledge, however, there are no long-term empirical comparisons on this matter. Hence, we present the Kokemäki River series by comparing it to the Aura River and Torne River series. This should give a valid indication of how the largest power plant nearest Pori has affected the timing of the ice breakup in Kokemäki River. We will also compare and analyse the long term trends in all three series and the correlations between them. We also do a qualitative assessment of extreme breakup years and long-term trends in the three series to identify cold years and periods in northern Europe since the 1700s. The purpose of our qualitative approach is to provide a detailed perspective on historically cold springs (late breakups) in contrast to historically warm years (early breakups) and to identify years and periods when late and early events occurred simultaneously in all three series. This long-term comparison, the first ever of three rivers in Northern Europe, provides a novel perspective on breakup variability that has not been addressed before. It will also highlight the relative differences between the timing of the events in each century, particularly in the case of Torne River.

2 Study ettingsareas

River ice series differ from lake-ice series in that the observations derive from riverine societies, i.e. urban environments. In Mmulticentennial series, the timing of the ice breakup may therefore be affected by factors such as industrial activity population increase, societal development and changes made in the riverine environment. For example, Sstructures such as bridges may delay the breakup process while increased (terminated) , industrial warm water outlets and the use of ships to break the ice may advance (delay) the breakup processor delay the ice breakup process (e.g. Norrgård and Helama 2019; Sharma et al., 2016; Kajander, 1993). The impact of these factors is impossible to assess across centuries due to lack of quantifiable data. Norrgård and Helama (2019) assessed the impact of using ships to break the ice to speed up the breakup process in Aura River but the impact was difficult to determine with certainty. In this section we will give a short presentation of the historical development of each city and the riverine environment as the observations derive from urban environments but we are only assessing the impact of the hydroelectric power plant in Kokemäki River. Moreover, while lake ice breakup dates are mainly determined by temperature the breakup process in rivers link to both temperature and precipitation. Higher temperature starts weakening the ice at the same time as snowmelt or rain increases flow discharge until hydrodynamic forces then start breaking and moving the ice (Beltaos, 1997; Beltaos 2003). River ice breakups – considering the breakup process and changes in the riverine environment – therefore have a higher signal to noise ratio than lake-ice breakups (Prowse & Beltaos, 2002).

However, climate warming also affects the breakup process and thus the observations. The prevalence of thermal breakups, which also have increased in the 1900s, have made it difficult to determine the breakup date in Kokemäki River. A thermal breakup, as opposed to a dynamic breakup, is characterised by the ice being thinned and weakened from thermal inputs. Hence, there is much pre breakup warming but little breakage taking place, and the ice melts in situ if there is little to no flow increase (Beltaos and Prowse, 2009). The lack of a clear breakage is what has made it more difficult to determine the breakup date in Pori. In Aura River, the records suggest that thermal breakups have delayed the ice-off date and this is because spring is the driest season in Finland (Irannezhad et al., 2014). We acknowledge this because we are comparing the ice off event in Aura River to the ice breakup, or the initial movement of the ice, in Torne and Kokemäki rivers. We do not consider this a problem for the analyses because we are comparing the dates of the observed events. To improve readability we will hereafter use 'breakups' to refer to 'ice breakups' or 'ice offs', but we will distinguish when necessary.

The Aura River observation site in southwest Finland is circa 140 km south of Pori and 600 km south of Torne. According to the Köppen Climate Classification system, Torne River belongs to Dfc (subarctic) and the dominating cold climate predetermines that there are no mid-winter breakups. The mean ice cover period is four months, i.e. Torne River always freezes over the winter (Kajander, 1993). The Torne River breakups are dynamic and flood prone due to snowmelt in spring (e.g. Zachrisson, 1988; Ahopelto, 2015) but this subject is under investigated.

The observation sites for Aura and Kokemäki River are located within Köppen's subtype Dfb (warm-summer humid continental) and are, accordingly, the only breakup series in Finland that are not situated in the subarctic (Korhonen 2005, 2006). The obtained descriptions of the breakups in Aura and Kokemäki rivers indicate that they have been, for most part of the investigated periods, either thermal or dynamic. The records also indicate the sporadic occurrence of mid-winter breakups. Ice jams have occurred in both Turku and Pori (e.g. Norrgård, 2020; Huokuna, 2007), but they have generated more nuisance in Pori, which is considered the most significant flood risk area in Finland (Verta and Triipponen, 2011). Kokemäki River was dredged and the riverbanks were continuously reinforced throughout the 1900s to lessen the impact of ice jam floods. Most changes in the riverine environment were done in the 1970s and 1980s (Louekari, 2010; Huokuna, 2007) and several of the flood response constructions were built below or around the breakup observation site, which was where the ice jams usually occurred.

2.1 Tornio and Torne River

Torne River is one of the largest unregulated rivers in Northern Europe. -and fFrom Lake Torne in Sweden, tThe river flows southward from Lake Torne in the Arctic into the Bothnian Bay, the northernmost sub-basin of the Baltic Sea (Fig 1). The Torne Rriver has a watershed area of 40,157 km^2 and is 522 km long. ~~T long and over the last~~The last 180 km, before entering the Baltic Sea, the river~~,~~ ~~the river~~ marks the border between Finland and Sweden. The ~~Torne River i~~ice breakup observation site is in the Finnish city of Tornio (65°84'N, 24°15'E) and is situated about 3.5 km~~ilometres~~ from the mouth of the river. At the observation site, ~~T~~the river is approximately 260 meters wide. T~~wide at the observation site and t~~he breakup date signals when the ice starts to break up or move. The ice breakup is monitored by the Finnish Environment Institute (SYKE), which also measures ice thickness, discharge rates and snow cover thickness.

The average discharge at the observation site in Karunki (~~about~~ 23 km upstream from the breakup site) ~~was 360 m^3/s~~ during the 1911–2020 period was 388.75 ~~1961–1990 period~~m^3/s. The m~~During spring, the m~~aximum discharge on 11 June 1968 was 3667 m^3/s~~can be up to ten times the average~~. Torne River is unregulated but Tengeljoki River, one of the tributary rivers, hosts three hydroelectric power plants. The power plant closest to the ice breakup observation site in Tornio city is 80 km upstream and it should have no significant influence on the breakup process (Sharma et al., 2016).

~~The growth and development of the urban surroundings have probably had little or no impact on the breakup process.~~ Founded in 1612 on an island in the middle of the river, Tornio was ~~the northernmost city in the world for 168 years. The city was initially~~ known as a trading hub. In 1800, Tornio ~~he city has~~ ~~and it has remained quite small due to its northerly location. Tornio~~ had a population of 710 ~~in 1800~~, and in ~~as of~~ 2019, ~~the city had a population of~~ 22,000. The Swedish twin-city of Haparanda was founded on the western side of Tornio in 1842 and today the Tornio-Haparanda region has a combined population of about 32,000 inhabitants. ~~The growth and development of the urban surroundings have probably had little or no impact on the breakup process.~~

The number of bridges crossing the Torne River has increased ~~over its entire length~~ during the 20th century. However,~~,~~ ~~but~~ the only bridges in Tornio ~~re are only three bridges between the city and the mouth of the river.~~ are situated below the breakup observation site. Most anthropogenic impact on the breakup process was probably caused by log-driving dams built on the river in the 1900s (Kajander, 1993). Hundreds of these dams were built in the upstream tributaries and their purpose was to collect water that could carry logs to Torne River. The dams were demolished after the log-floating era ended in 1971 (Zachrisson, 1988).

~~There are currently three hydropower plants on Tengeljoki River, one of Torne's tributary rivers, and its drainage area. The only hydropower plant connected to Torne River (Portimokoski Power Plant, 11MW) is situated over 80 kilometres from the observations site in Torne, and it should have no significant influence on the breakup process.~~

2.2 Turku and Aura River

Aura River has a watershed area of 885 km^2 and is clearly the smallest of the three investigated rivers. The river has anthe -average discharge at the Halinen dike between 1938 and 2020 was 6.86of 8,5 m^3/s. The -with a maximum on 2 May 1966 ofwas 286 m^3/s. Aura River is is 70 km long and drains into the Baltic Sea. The breakup ice-off observations from Aura River originate derive from the city of Turku (60°45'N, 22°27'E), which is located at the mouth of the river. Within the city limits, the width of Aura River varies roughly between 35 and 100 meters and the depth varies between one and four meters. The Aura River breakup series depicts the ice-off date, which is when the river is ice free between the mouth of the river and Halinen dike (Norrgård and Helama, 2019). The dike is situated six kilometres from the mouth of the riverriver, and it is mentioned for the first time in the 14th century. The dike detaches the lower reaches from the upper reaches and it creates there are therefore a two--stage breakup processeses independent from each other (Norrgård and Helama, 2019). is mentioned in historical records the first time in 1352. Besides the dike, Aura River is, except for the dike, -has remained unregulated.

As of 2019, Turku had a population of Turku's population was approximately 191,000. -and an estimated 60,000 lived by the river. The city had a population of 4,500 in the 1730s, which then doubled by 1800. Turku has therefore always been considerably bigger than Tornio. Consequently, the breakup process in Aura River has probably been influenced, to some degreemore so than in Tornio, by industrial and urban development. The city has grownexpanded on both sides of its 'spine', as Aura River is sometimes referred to, and the most significant changes took place in the 20th century. Since 1939, the number of bridges crossing the river have grown from three to nine.–. The industrial area that dominated the riverbank near closer to the estuary, whichmouth of the river for almost 200 years was constantly growing from the mid-1700s onwards until most industries relocated after the mid-1900s and it has since then .but it, shifted away from the river in the mid-1900s. It seems likely that this has had some impact on the breakup process. For example, the shipyard industry that started in the 1740s, and had over 4,000 employees in the 1960s, relocated in the 1990s. The relocation of the shipyard industry meant that the industrial environment that used to dominate the riverbank has thereafterslowly been replaced by apartment buildings. While Iit seems plausible that the relocation of the the shipyard industries and their drainage outletsy may have delayed the breakup process it also seems equally plausible that bridges may have delayed the freeze-up process while the relocation of the shipyard industry may have delayed the breakup process. This still needs to be evaluated. For a more in-depth presentation of the Aura River series see and how it was compiled we refer the reader to Norrgård and Helama (2019).

2.3 Pori and Kokemäki River

Kokemäki River is 121 km long and the river drains into the Bothnian Sea, the largest sub-basin of the Baltic Sea, and has the largest river delta in the Nordic countries. Kokemäki rRiver has a catchment area of 27,046 km² and the average discharge at the power plant in Harjavalta between 1931 and 2020 was 24018,62 m³/s in the 2000s. The maximum recorded discharge on 5 May 1966 was 918was about 600 m³/s and the lowest about 50 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 plant is located in Äetsä (87 km from Pori) and was built in 1919, while the newest plant, built in 1951, acts as a divider between Liekovesi Lake and Kokemäki River (121 km from Pori). The second power plant was built in 1940 in the city of Kokemäki (46 km from Pori). The oldest power was built in 1919 in Äetsä (87 km from Pori), and the newest power plant in Tyrvää in 1950 (121 km from Pori).

The breakup observation site is in the city of Pori (61°48'N, 21°79'E) and lies about 11 km from the estuarycoastlinesea. The observations derive from the city centre and At the observation site tthe width of the river of river varies between 160 and 240 metres. The estimated depth varies between two and four metres. For most part of the period, Tthe ice breakup date determines , for most part of the period, when the ice between the Porinsilta Bridge (built 1926) and Kirjurinluoto Island begins to breakup or move. Some of There are some exceptions in the late 1900sthe observations in the latter part of the 1900s probably derive from a site about , when the observations seem to have been made 100 metres further upstreamm from Porinsilta Bridge. Porinsilta Bridge replaced a pontoon bridge that was in use between 1855 and 1926. The placement of the pontoon bridge is important as it provides a historical point of reference for the observations. As of 2019, Pori had population of 83,000.

As of 2019, Pori had population of 83,000. The city of Ice jams have been a spring nuisance in Pori and it is the most significant flood risk area in Finland (Verta and Triipponen, 2011). In Pori, Kokemäki River was dredged and the riverbanks reinforced throughout the 1900s to lessen the impact of ice jam floods. Several flood response constructions were built near the observation site in the 1970s and 1980s (Louekari, 2010; Huokuna, 2007). Porinsilta Bridge (built 1926) was the first iron bridge to cross the river in the city centre and it replaced a pontoon bridge that was in use between 1852 and 1926. The pontoon bridge was usually removed from its location to hinder it from being destroyed during the ice breakup. The river branches at Kirjurinluoto, which is where most of the ice jams occurred, but the branches merge again about six kilometres from the estuary. As of 2019, Pori had population of 83,000.

Pori was founded on the western side near the mouth of the river riverKokemäki River in 1558. The city was built for trading purposespurposes, and it quickly became an international trading port. However, pPostglacial uplifting made Kokemäki River Due to postglacial uplifting, the river became too shallow for bigger ships to enter and to enter, , which is why tthe main harbour migrated towards the sea in the 1770s. The city centre wasremained concentrated on one side the western side of the river until the city and did not expand expanded across the river inuntil the latter half of the 1800s. Unlike Turku, Pori and it dididhas not expanded towards the sea like Turkuestuarymouth of the river as Turku did.

The ice breakup observations therefore usually derive from the city centre or from further upstream.

Kokemäki River was used for log floating until 1967 and the sawmill and timber industry havse played an essential part in the history of Pori's history. The industrial area was built upstream butand close to the city centre. I The historical records indicate that several of these industries kept their own record of the ice breakups but these have not been located. Pori was founded on the western side near the mouth of river in 1558. The city was built for trading purposes and it quickly became an international trading port. Due to postglacial uplifting the river became too shallow for bigger ships to enter, which is why the main harbour migrated towards the sea and Reposaari, which became the official harbour in the 1770s.

IIce jams have been a spring nuisance in Pori, which is the most significant flood risk area in Finland (Verta and Triipponen, 2011). TheRecurring ice jam floods wereare the main reasons why the river was dredged, and the riverbanks were reinforced throughout the 1900s. Several flood response constructions were built during the 1900s and near the observation site in the 1970s and 1980s (Louekari, 2010; Huokuna, 2007).

The development of Pori, the growth of the city, is very different from that of Turku. Two of the most devastating fires in the city's history occurred in 1801 and 1852. Until the second fire, the city had mostly expanded on the western side and away from the river instead of following both sides of the river towards the estuary as in Turku. The city started expanding across the river in the late 1800s. The sawmill and timber industry have played an essential part in Pori's history and Kokemäki

River was used for log floating until 1967. The historical records indicate that several of these industries kept their own record of the ice breakups but these have not been located.

Kokemäki River did not escape the hydroelectric power plant boom and the river hosts four power plants. The plant nearest to Pori is located in Harjavalta (31 km from Pori) and has been functional since 1939. The 26-meter-high dam generates up to 105 MW. The second power plant was built in 1940 and it is located in the city of Kokemäki (46 km from Pori). The oldest power plant, built in 1919, is found in Äetsä (87 km from Pori) and the newest plant, built in 1951, acts as a divider between Liekovesi Lake and Kokemäki River (121 km from Pori).

2.3.13.1 Kokemäki River: material

We relied almost completelyentirely on newspaperss when updating the Kokemäki River series. Newspapers are exemplary sources because they used to diligently describe the breakup process until the mid 1900s. The Kokemäki River ice breakup series is based on descriptions obtained from local newspapers in Pori Aura River (Norrgård and Helama, 2019) and Torne River (Kajander, 1993) series are also based on observations from newspaper. 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.

s; Kajander, 1993). . The descriptionnewspapers are often detailed and occasionally provide daily and even sub-daily in-depth descriptions of how how the breakup progresseds. 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. All newspapers until 1939 were obtained from the Finnish National Library's digital database (https://digi.kansalliskirjasto.fi). We used the database to access all possible ice breakup observations relating to Kokemäki River and cross-referenced with local, regionalregional, and national newspapers.

The database provides easy and fast access to the newspapersnewspapers, but the search function was deemed unreliable, which is why we examined each newspaper was examined page by page. The most detailed observations were published in local newspapers from Pori. These were the Swedish newspaper *Björneborgs Tidning* (1860–1965) and the Finnish newspaper *Satakunnan Kansa*

~~(hereafter *SK*) (1873–). We relied mostly on *SK* after 1939 and we used the University of Turku newspaper affiliate in Raisio to manually search for articles until 2020. We gained access to the *newspaper's* internal database at the editorial office in Pori, which gave us access to the articles from the 1990s and 2000s. All articles were transcribed and the metadata is stored locally.~~

~~Several newspapers have published ice breakup series from Kokemäki River.~~ The ~~initial~~first breakup series ~~dates~~ for the Kokemäki River ~~series~~ was published under a pseudonym in *Åbo Tidningar* in July 1843 and covered~~s~~ the 1801–1843 period. ~~.~~An extended version (1801–1849) of the initial series was parallel-published ~~simultaneously~~ 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 ~~There are~~ four other ~~published~~ series that were sent to the newspapers, ~~after this~~ but the version that extended the breakup series to 1794 appeared~~was published~~ 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 ~~series~~ was found in the city archives and it spans the ~~covers the~~ 1794–1998 period. Its origin is unknown; however, ~~there are~~ two initials in the lower right-hand corner match the names in ~~that we managed to trace to~~ an article published in *SK* in 1996. This~~e article~~ suggests that the series had been monitored and ~~is the 'official' series~~ maintained by city employees since the 1950s. Finally, the current series does not include ~~This series was based on unknown observers. We found no~~ breakup dates for the ~~four~~ four years between 1999 and 2002. No observations were obtained after 2003 and the added ~~The breakup~~ dates therefore ~~after 2003~~ originate from the breakup guessing competition arranged by the local Lions Club.

2.4 General reflections on ice conditions~~ and breakups~~

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

Systematic records on freeze-up dates~~,~~ or ice thickness are not available for Aura River, which is 600 km south of Tornio. Leche (1763), Moberg (1857; 1890;1891;1892; 1893) and Levänen (1890) collected freeze-up dates and adding five additional observations for 1861–1865 from a local newspaper gives~~s~~ a mean ~~median~~ of 14~~6~~4.3 ice cover days (n=37; median 146). All observations were made before the 1900s and 23 were from the 1700s. ~~In practice, t~~The sporadic occurrence of midwinter breakups means that the length of the ice cover period is only indicative of ~~the~~actual ice conditions. For example, the freeze-up in 1771 was 20 November, and the ice had reached a thickness of 20 cm before heavy ~~but~~rains caused a midwinter breakup on 13 December~~(REF)~~. Midwinter breakups of various intensities have occurred between December and February throughout the 1749–2020 period. The last recorded midwinter breakup with at least 20 cm thick ice occurred in January 1999. During cold winters, the ice can reach a thickness of 70 cm or more, as reported ~~of~~ in the newspapers in April 1837 and March 2003. Records on ice conditions are sporadic, but the provided examples give some perspective on the conditions leading up to the first -no~~n~~-freeze event ~~in~~in 2008 (Norrgård and Helama, 2019).

A thermal breakup, as opposed to a dynamic breakup, is characterised by the ice being thinned and weakened from thermal inputs. There is little to no breakage of the ice, which melts in situ if there is little to no flow increase (Beltaos and Prowse, 2009). Thermal breakups appear in the records the describing the Aura River breakup process. They also appear in descriptions from Kokemäki River and in this case they ~~do not affect the reliability of the series because it denotes the day when the river is ice-free. thermal breakups clearly~~ affect the validity of some of the observations~~Kokemäki River series~~. For example, in March 1992, *SK* wrote that the ice melted in situ for the fourth year in a row. The city employee conducting the observations claimed that an official breakup date would not be recorded because a proper breakup date could not be determined. ~~Similar breakups occurred also in 1923 and 1934~~Thermal breakups have are not a new phenomenon in the Kokemäki River, but they are more sporadic than in the Aura River.

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

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

3 Data and methodsMETHODS

3.1 Obtaining and extracting breakup dates for Kokemäki River

A comparison of the in the newspapers previously published breakup series for Kokemäki River showed that they were not identical albeit the differences were minor; however, . The observers were unknown and the series did not reveal where the observations originated from.articles only state that they depict the ice breakup in Pori, but not exactly where in Pori. OurThe aim was therefore to homogenize the breakup dates with regard towith regard to site and event. The same approach was used when compiling the Aura River series (Norrgård and Helama, 2019). Thus, we used the previously published ice Thus, Previously publishedthe breakup series dates obtained from previous compilations were used as a date of reference points when scrutinizing the newspapers for precise observations from this period. It quickly became clear that themost newspaper articles described the breakup in focused on the city centre and the near the location of the first bridges (the Pontoon Bridge that was replaced by the and Porinsilta Bridge in 1926). The aim was thereafter to obtain observations that referred to this part of the river and described the same stage of the processbreakup process. Consequently, the compiled series describe the initial breakup or when the ice started moving in the city centre between Porinsilta and Kirjurinluoto Island.

The observations prior to 1863 could not be validated and a partial reason might be a devastating city fire in 1852. However, the series published *in Åbo Tidningar* in July 1843 declares that the series depicts the ice breakup in the city of Pori, and . Mmaps from the 1800s show that the city was small and concentrated, which is why so the observations most likely refer to the area where the bridges were later built. The breakup in 1852 was the only eventtime when the dates in the previously published series diverged significantlyconsiderably. The breakup was noted to have started in either early April or early May. The discrepancy may relate to a city fire that started on 22 May 1852 and destroyed three fourths of the city. However, itIt is likely is more likely that the ice moved in April but the actual breakup process was delayed until May. We chose tThe breakup in May was preferred as this was more consistent with the events in Aura River.

There are sTwoome remarks regarding the site and date:. First, some dates in the latter half of the 1900s are probably based on observations from the industrial area nearthe Linnansilta Bridge, which was (built in 1974). This became the Journalists used this 'new' place as thepoint of reference breakup site when the journalists they stopped making their own observations and started reporting about the breakup by interviewing city employees or other experts and stopped describing the breakup themselves, meteorologists or local residents. Observations from this part of the river may have advanced the reported breakup dates because the bridges below the observation site seem to have slowed down the breakup process. Second, as the frequency of thermal breakups increase in the 1900s it clearly affects the attempts to accurately record the breakup date as noted in the series we found in the city archives. Thermal breakups also provided less drama than dynamic breakups and ice jam floods, which is why they were not diligently covered by the newspapers. Finally, the dates obtained from the guessing competition are based on the movement of a closely monitored marker standing on the ice. Thus, the breakup date follows the marker and its movement instead of the breakup date in Kokemäki River when the ice starts breaking up in general. This might add a day or two to the actual breakup date.

The approach for completing the Kokemäki River series was the same as when compiling the Aura River series (Norrgård and Helama, 2019), i.e. to homogenize the breakup dates with regard to site and event. All published series were crosschecked against each other, and the analysis showed that none of the series were identical. The differences were minor except for the event in 1852. This year the breakup was noted to have started in either early April or early May. The city fire started on 22 May and ¾ of city burnt down, which may explain the discrepancies and why we found no observations of the breakup. We chose the breakup in May as this was more consistent with the event in Aura River.

Except for the series published in 1843, when the author explicitly explains that the series depicts the breakup in the city, the observation site is not mentioned. The observations prior to 1863 could not be validated. For the years after 1863, the published breakup series functioned as reference points when searching for observations in the newspapers.

The compiled series describe the breakup in the city centre between Porinsilta and Kirjurinluoto Island. There are, however, some remarks regarding the site and date. First, some dates in the latter half of the 1900s are probably observations from the industrial area near Linnansilta Bridge (built in 1974). As the journalists stopped reporting their own observations and started reporting breakup dates by interviewing city employees or meteorologists, they used this 'new' place as the official breakup site. Observations from this part of the river may have advanced the reported breakup dates because the bridges situated below the observation site seem to have slowed down the initial movement of the ice. Second, as the frequency of slow thermal breakups increase in the 1900s it clearly affects the attempts to accurately record when the ice started breaking up. Less dramatic ice breakups also weakened the interest to keep track of the breakup date. Finally, the dates obtained from the guessing competition are based on the movement of a closely monitored marker standing on the ice. Thus, the breakup date follows the marker and its movement instead of the date when the ice starts breaking up in general. This might add a day or two to the actual breakup date.

3.2 The vernal equinox

All dates in all three series ~~the Torne and Aura River series~~ follow the Gregorian calendar. The recorded dates were ~~The Kokemäki River series begins in 1793, which is why there was no need to realign the dates. We a~~adjusted ~~the breakup dates~~ according to the vernal equinox (VE) to conduct the analyses. This approach was preferred instead of the year to date approach ~~-~~due to the length of the series. ~~because c~~Calendar dates can in long-term cryophenological series that span several centuries ~~ould~~ result in overestimated trends~~, towards earlier springs~~ when they continue into the 21^{st} century (Sagarin, 2001; 2009). In practice, the vernal equinox has varied between 19 and 21 March. The vernal equinox dates for each series were obtained from NASA dataset homepage and adjusted to Finnish time zone (GMT+2).

3.3 ~~Temporally e~~Extreme events and variability

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

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

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

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

We included listed the 30 latest/earliest events to explore identify the simultaneous occurrence of temporally extreme events, i.e. unusually late or early breakups. In this analysis, we We used the calendric dates to rank the breakups. This is one way of identifying years or periods with exceptionally cold/warm springs. First, the timing of the breakups was compared over the period common to all three series (1793–2020). Second, the timing of the events was compared according to the length of the two longest series (1749–2020), i.e. between Torne and Aura rivers. Finally, we listed the extreme events for Torne River (1693–2020). . The timing of the events was analysed according to the length of each series but also adjusted and compared according to the length of the shorter series. For example, the latest breakups events for Torne River were identified for the entire length of the series (1693–), according to the length of the Aura River series (1749–) and, finally, according to the length of the Kokemäki River series (1793–). In the case of Torne River, there were, at the end of the list, multiple years when the breakup occurred on the same day. After we had ranked the breakup dates, we included breakups from earlier periods if there at the end of the list were years when the breakups occurred on the same day. For example, in the Torne River series (1693–) there were six years (1724, 1729, 1732, 1741, 1765 and 1866), when the breakup occurred as late as 25 May. The only years that could be included were , but the last events to be included in our analysis were the events in 1724 and 1729. CLEAR?!

3.4 Extreme events and variability

Variability was examined by analysing changes in the interquartile range (IQR) using 30-year non-overlapping windows. The IQR is the difference between the third (75 %) and first (25 %) quartile. Thus, the IQR gives the middle range or the dates when 50 % of the breakups occur. When the IQR is low it means that the middle 50% of the breakups are spaced close to each other and vice versa if the range is large. The second quartile (Q2) is the median value.

No freeze years were quantified as an ice breakup that occurred 1 January (VE 79). There are different methods for how to quantify no-freeze years. Benson et al. (2011) chose the earliest breakup date, while Sharma et al. (2016) treated them as censored values. Most solutions for treating a lack

~~of data are arbitrary because the rates of change will be underestimated. In a long-term breakup series from cold climate regions, recent no freeze years signal the most accentuated change caused by a warming climate.~~

~~The average from the three earlies/latest breakups was used to examine changes in extreme breakups. A similar approach was used by Benson et al. (2011).~~

3.4 Hydroelectric power plant impact

The ~~construction of the~~ hydroelectric power plant in Kokemäki River in Harjavalta ~~started in 1937 and~~ was taken into use in ~~came into use in~~ 1939. This year was therefore chosen as ~~. We chose 1939 as~~ the starting year for assessing whether the power plant changed ~~to assess the power plant's impact on~~ the timing of the ice breakup in Pori. The hypothesis was that sudden changes in the timing of the breakup should be visible as a distinguishable shift in the difference between the recorded breakup dates. First, ~~T~~the impact ~~of the hydroelectric power plant on the timing of the ice breakup in Kokemäki River~~ was assessed by analysing changes in the Spearman coefficient ~~(rho)~~ before and after 1939. Second, the breakup date in Kokemäki River was subtracted from the breakup ~~To address the changes more precisely, we also subtracted the breakup date, adjusted to the vernal equinox, in Kokemäki River from the~~ dates in Aura ~~and Torne rivers~~. ~~The hypothesis was that if the power plant had an immediate impact on the breakup process, then it should be visible as a shift in the difference between the recorded breakup datesbetween Aura and Kokemäki rivers.~~ Third, discharge rates measured at the site since 1931 was used to assess how the power plant changed the discharge leading up to the breakup date. The data is maintained by SYKE. The discharge for each day leading up to the breakup date was averaged in order to create a dynamic model that shows the discharge 60 days before the breakup and ten days after. We then compared the unregulated 1931–1938 period to the 1939–1998 period. This comparison facilitated only the recorded breakup dates and not the dates obtained from the breakup competition. This was considered the best approach because the difference between the breakup date and the guessing competition date is unknown.

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3.5 Cross-correlations, meteorological variables and trendsStatistical methods

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

Another model from FMI (Venäläinen et al., 2005) was used to analyse daily temperature development leading up to the breakup. The model is based on and b) the correlations between the ice breakup series and monthly mean temperature series. The breakup data for Aura and Kokemäki River was correlated against the monthly mean temperatures from Turku while the Torne River series was correlated with the monthly mean temperature series from Haparanda (Tuomenvirta et al., 2001; Tuomenvirta, 2004; Menne et al., 2012; Dienst et al., 2017). temperature data starting in 1961 and it also uses the kriging interpolation method. For this analysis the values of daily mean, maximum and minimum temperatures were calculated for Tornio (Torne River), Pori (Kokemäki River) and Turku (Aura River) over the 1961–2020 period. The temperatures for three variables (mean, maximum and minimum) were aligned according to the breakup date and calculated over an interval of 180 days before and 30 days after the breakup. The analysis thereby shows the change in local daily mean, maximum and minimum temperatures 180 days before and 30 days after the breakup date between 1961 and 2020.

Finally, the Mann-Kendall (MK) statistic (Kendall, 1970; Mann 1945) was used to determine the statistical significance of long-term trends and the rate of change (slope) was estimated using Sen's (1968) slope. These methods are commonly used to analyse temporal trends in

The first temperature analyseis wasere performed over the 1874–2010 period, which is common for the Turku (1873–2010) and Haparanda (1859–2014) temperature series. The second analysis was performed over the shorter 1960–2020 period. In this analysisFor the shorter period

For the shorter 1960–2020 period, we used data based on a spatial model collected by the Finnish Meteorological Institute (FMI). Beginning in 1961, the model is based on temperature and precipitation data from Finland, and it is supplemented with data from neighbouring countries. The model uses the kriging interpolation to account for the influence of topography and nearby water bodies (Aalto et al. 2013, 2016). Spatial variability in temperature and precipitation was explained

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using auxiliary information including mean elevation, sea percentage and lake percentage for building a spatially and temporally continuous gridded dataset, with grid size of 1 km. Aalto et al. (2013) chose kriging with external drift as the primary method due to its robustness and accuracy for this type of estimation, referring to an approach using external predictors (e.g. elevation) as covariates in the model. Over the 1960–2020 period, the breakup data for Aura, Kokemäki and Torne rivers were correlated against the monthly mean temperatures and precipitation sums estimated by the statistical model for the Aura, Kokemäki and Torne rivers observation sites.

Seasonal averages were calculated from the monthly values.

The meteorological data does not, unfortunately, allow site wise analyses of time series or a higher temporal resolution than fixed monthly values (Aalto et al., 2013; 2016). Nonetheless, illustrating the correlations on a monthly basis reflects the convention that historical records of ice breakup dates are commonly compared to mean monthly and/or seasonal (e.g. Newton and Mullan, 2021) or even annual temperature data (Hallerbäck et al., 2021). Comparison to monthly/seasonal data therefore fulfils the purpose of our study, which is to pinpoint the major climatic factors the ice breakup histories of the three rivers are most likely to indicate (factors onwards, meaning??).

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Temporal trends in the breakup datesbreakup series were calculated using approaches applied in analyses of phenological term 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). – We used the Mann-Kendall (MK) statistic (Kendall, 1970; Mann 1945) to determine the statistical significance of the trends. The rate of change (slope) was estimated using the Theil-Sen approach, also known as Sen's (1968) slope.

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4 Results

4.1 Temporal correlation

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The ice breakup events of all three rivers exhibit high variability (Fig. 1). If comparing the breakup events for all three rivers over the length of Kokemäki River series, then the average breakup day in Torne River was 52.7 (median 52) days after the vernal equinox, which translates to 13 May if vernal equinox occurs on 20 March. The corresponding averages for Kokemäki River was 25.8 (median 28) days and for Aura River 24.9 (median 27) days, which translates to 16 and respectively 15 April.

The correlation between Aura and Kokemäki rivers (1793–2020) is strong (rho = 0.896, p < 0.001). The correlation is, as could be expected because of the distance between the rivers, weaker between Torne and Kokemäki rivers (1793–2020) (rho = 0.569, p < 0.001) and even weaker between Torne and Aura rivers (1749–2020) (rho = 0.484, p < 0.001). The distance between Aura and Kokemäki Rivers (ca 120 km) as opposed to the distance between Aura River and Torne River (ca 600 km) partially explain the stronger and respectively weaker correlations.

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4.2 The impact of the power plant

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When comparing the degree of correlation, the results show that the correlation between Kokemäki and Aura rivers between 1793 and 1938 (rho = 0.889) is only slightly stronger than that between 1939 and 2020 (rho = 0.867). This suggests that the power plant has not had a considerable impact on the timing of the breakup, at least on year-to-year scales.

In practice, between 1793 and 1938, the average breakup in Kokemäki River commenced 3.2 days after Aura River was ice free (Fig. 2). There were 18 years when the breakup in Kokemäki River started at the same day as the ice-off in Aura River. Moreover, there were 18 years when the breakup in Kokemäki River started three days or earlier before the ice-off in Aura River. The only exceptions occurred in 1796 and 1832. These years the breakup in Kokemäki River started 5 respectively 9 days before the ice off in Aura River.

Since 1939, the process has reversed. After 1939, and now the breakup in Kokemäki River commences, on average 3.2 days before the ice-off Aura River. Thus, since the power plant was built, the ice breakup in Kokemäki River has advanced by 6.4 days. Compared to Torne River, the difference increased from 23.4 days between 1793 and 1938 to 33.8 days between 1939 and 2020.

The shift is neither direct nor linear. The breakup event in Kokemäki River preceded the Aura River ice-off event in only 60 per cent of the events between 1939 and 2020. Until the late 1950s the breakups were earlier in Kokemäki River only once in every second or third year. Thereafter, the breakups in Pori have invariably predated those in Turku. The most radical change occurred between 1959 and 1978, when the breakups averaged 7.3 days (range 1–19 days) earlier in Kokemäki River than the ice-off event in Aura River. Contrary to this, the breakup competition observations after 2003 showed less than one (0.94) day difference between Kokemäki and Aura rivers. This may be an underestimation when compared to past values. and iIt is probably an effect of the fact that the guessing competition dates did not determine when the ice started to break up but when the chosen monitored marker moved.

4.21 Extreme breakup eventss and periods

4.4.21.1 Early breakup events

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

Two striking observations are the scarcity of early ice breakup events in the 1800s, when compared to the 1700s, and the difference in range between the first and the thirtieth breakup event. In Torne River, the range is only seven days, while it is over 50 days in Aura and Kokemäki rivers.

The rivers Aura and Kokemäki had their first no-freeze event in 2008If interpolating the missing breakups dates in Kokemäki River between 1999 and 2002, using the Aura River events as a baseline, then all the 30 earliest breakups, except for the event in 1822, are from the 1900–2000 period, except for the event in 1822. The early event in 1822 is the fourth earliest ice off event in Aura River while it was not amongst the thirty earliest events in Torne River.

There are two winters when Aura River never froze completely. The first time was in 2008. The Aura River had its and the second no-freeze event in time was in 2020 whereas .the Kokemäki River had its second in The first time Kokemäki River did not freeze was also in 2008, but the second time was in 2015, and the third time in 2020. There is therefore a discrepancy between Aura and Kokemäki rivers., hHowever, it is worth noting that the ice-off event in ice breakup in 2015 was the second earliest ice-offbreakup in the Aura River series, which shows that 2015 was an unusual year also in Aura River. Please note that the non-freeze events are not included in Table 1.The no-freeze events in 2008 and 2020 occurred during the two warmest winters on record, the latter being slightly warmer than the former (Ilkka et al., 2012; Irannezhad et al., 2014; Lehtonen, 2021). The non-freeze event in Kokemäki River in 2015 also occurred during one of the warmest years on record (FMI,

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2016). In the context of record warm winters, it is worth noting that -Torne River had an exceptionally late breakup in 2020. One of the latest breakups in 60 years.

~~. It is **noticeable** that the breakup in Torne River was exceptionally late in 2020. There has only been one equally late event during the last 60 years.~~ Please note that T~~the non-freeze events are not included in Table 1.~~

In ~~the~~ Torne River ~~series~~, the 30 earliest events remain the same whether the series is set to start in 1693 or 1749. The earliest breakup in Torne occurred in 2014 and this was only one day earlier than the event in 1921. Hence, the earliest breakup date ~~has~~ remained ~~almost~~ unchanged for nearly 100 years. Even ~~In general,~~ the long-term change is negligible. For example, ~~It is also remarkable that~~ the earliest breakup date (2014) ~~was~~ occurred only five days earlier than the earliest breakup in the 1700s (1757). In contrast, there is a 48-day difference between the earliest (1990) ice-off event in Aura River ~~(1990)~~ and the earliest ice-off event in the 1700s (1750). ~~Hence~~These findings show that the~~, the~~ timing of the early ~~ice breakup~~ events in Kokemäki ~~River~~ and ~~the early ice-off events in~~ Aura ~~R~~rivers have ~~accelerated and~~ undergone a more radical change~~, and developed differently,~~ than the timing of the early events in Torne River. ~~Finally, while Aura and Kokemäki rivers did not freeze completely in 2020, Torne River produced an exceptionally late ice breakup. There has only been one equally late event during the last 60 years.~~

4.~~2~~1.2 Late breakup events

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

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

Over the 1793–2020 period, all three rivers shared late breakups in 1807, 1810, 1812, 1845, 1847, 1867 and 1881. Three of these events are from the early 1800s, and the number of events during the first two decades of the 1800s is considerable. More than one-third of the latest events in the Torne and Kokemäki rivers occur between 1800 and 1824. Yet the breakups were late in all three

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rivers only in 1807, 1810, and 1812. The concentration of events in the early 1700s and 1800s could possibly be attributed to the climatic effects caused by the Maunder Minimum (1645–1715) and the Dalton Minimum (1800–1824), which mainly affected the spring climate (e.g. Miyahara et al., 2021; Xoplaki et al., 2005). There were other smaller clusters of late events in, for example, the 1840s, but they do not stand out as much as the events during the first two decades of the 1800s.

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

4.2 Cross-correlations and changed in the discharges

4.2.1 Cross-correlations and changes caused by the power plant

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

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

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

4.2.2 Discharge patterns, changes and impacts

It seems probable that the power plant in Harjavalta changed the discharge rate, thereby causing the breakup date to pre-date the ice-off date in the Aura River. Comparing the 1931–1938 and 1939–1998 periods (Fig. 3) show how the average discharge rate prior to the breakup has changed. First, comparing the discharge in1934 to that in 1976 shows how the weekly pulses at the power plant affects the rate of discharge. Second, a clear flow peak used to appear one week after the breakup in the 1931–1938 period and this vanished after the power plant was built in 1939. Third, the average discharge until approximately ten days before the breakup has increased slightly since 1939. This could potentially have advanced the timing of the breakup. Finally, the average discharge rate at the breakup date has decreased from 382.13 m³/s in the 1931–1938 period, to 322.88 in the 1939–1998 period.

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

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

~~Table 2 shows that 18 of 30 latest events in the Torne River series (1693–2020) occurred before the start of the Aura River series in 1749~~, and ~~and 22 events occurred before the start of the Kokemäki~~

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series in 1793. This implies that the first half of the 1700s were considerably colder than the second half of the 1700s. The latest events in the early 1700s is only matched by the events in 1867, 1810 and 1807. Eleven of these 22 events occurred during the first two decades of the Torne River series. It isFrom a historical perspective it is surprising that the noteworthy that, but the breakup during the cold European winter in 1708/1709 (Luterbacher et al., 2004) is not amongst one of them. The breakup in 1709 is, surprisingly, not even one of the 100 latest breakup events.

In Aura River, The relative lateness of the events in the 1700s is also noteworthy in the Aura River series. Eight of the 30 latest events, over a period of 270 years, occurred in the 1700seight of the 30 latest events occurred in the 1700s, but the six latest events occurred in the 1800s.. This is remarkable considering that there are only 51 years of observations. All late events in the 1900s are found at the second half of the list. The relationship between the 1700s and 1800s is intriguing when considering that there are only 51 observations from the 1700s. There were more early events in the 1700s (see Table 1) than in the 1800s. The difference is minor but Iindicates t is noteworthy also and because the frequency of early events is also higher in the 1700s than in the 1800s (see Table 1). The difference is minor, but it This implies that there was greater climatic variation variability in the between extremely late and early events in the 1700s. The breakups in Aura and Torne rivers were simultaneously late only in than in the 1800s. The correlation between Aura and Torne was not high, but late events occurred in both series in 1763, 1780 and 1785.

If comparing the events in all three series over the length of the Kokemäki River series (1793–2020) period, i.e. the interval of the Kokemäki River series, then all three riverine societies experienced late ice breakups in 1807, 1810, 1812, 1845, 1847, 1867 and 1881. It is worth noting that there are three years (1807, 1810, and 1867) that are present in all versions of all series, regardless of their length. It is also worth noting that the number of events during the first two decades of the 1800s increases when the Torne and Aura series are shortened to match according to the length of the Kokemäki series. The change is smallest in the Aura River series but more than one-third of 37 percent of the latest events in the Torne series and 33 percent of the events in theand Kokemäki river series occur between 1800 and 1824. There are several small clusters of late events in all three series in, for example, the 1840s, but these are not as pronounced as the events during the first two decades of the 1800. However, despite the cluster of late events in the early 1800s, late events occurred simultaneously in all three riverine societiesrivers all cities experienced late events only in 1807, 1810, and 1812.

The range in the Aura River series is considerably shorter than in the other two series. In Torne River, while the range successively increases in Torne River as the series is shortened. The reason is, as shown in Table 1, that the event in 1867 event was exceptionally late in Torne River (and Kokemäki) and Kokemäki rivers, but not in Aura River (see Table 2). The events in 1807, 1810 and 1867 are the only years that are present in all versions of all series, regardless of their length.

The interdecadal variability is strong in all three series, as shown by 10-year spline line in Figure 1. There are several small clusters of late events in all three series in, for example, the 1840s, but these clusters are not as pronounced as the events during the first two decades of the 1800. The interdecadal variability is shown by the 10-year spline line in Figure 1.

4.3 Climatic correlations

4.3.1 Breakups according to monthly mean temperatures 1961–2020

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

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

4.3.2 Breakups according to monthly mean precipitation 1961–2020

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

4.3.3 Breakups according to daily mean temperatures 1961–2020

The breakup in Torne River has usually started about three months after the coldest winter days and when the daily mean temperature has reached approximately 4.6°C (Fig. 6). This was usually when

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the daily maximum was close to 10 °C and the minimum temperatures had surpassed the freezing point. These conditions have usually occurred around twenty days after the daily mean temperature has risen above the freezing point.

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

All three series exhibited strong and statistically significant correlations with mean winter and spring temperatures (Fig. 3a). The correlations were predominantly negative, indicating which means that higher than average spring temperatures have caused earlier breakups. Correlations with winter and spring precipitation were also mainly negative (Fig. 3b), but the correlations were considerably lower than those with temperature. Negative correlations with precipitation indicate, in general, that increased rains in winter and spring have caused earlier breakups in comparison to less rainy conditions.

Over the shorter 1961–2020 period, all three series exhibited particularly high correlations with two monthly temperature averages. For Aura River these were the mean temperatures of February (-0.77) and March (-0.74) and likewise for Kokemäki River February (-0.71) and March (-0.84). When compared to the February–March period, the correlation was slightly higher for the breakups in Kokemäki River (-0.89) than in Aura River (-0.86).

In Torne River, the mean temperature correlations, in this case April (-0.70) and May (-0.49), remained at the same level when compared to the April–May period (-0.70). In practice, higher correlations with April temperatures means that most of the breakups occur during last days of April or in early May. The breakup in Torne River in northern Finland obviously occurs later in spring than the breakups in the southern parts of Finland.in Aura and Kokemäki rivers due to its northerly location. The results indicate that the timing of the ice breakup in Aura and Kokemäki rives have a greater dependency on temperature than in Torne River. The temperature and the breakup dates are presented, for all three rivers, in Figure 4a-c.

The correlations with precipitation are less pronounced than those with temperature, which suggests that the influence of precipitation is secondary to temperature (Fig. 3b). The precipitation correlations for the months clearly predating the breakup dates (December and January) are markedly strong, even though non-significant in the case of Torne River. The correlation for February is statistically significant for Aura River, whereas the strongest correlation for Torne River occurred in May.

4.3.3 Breakups, ice thickness and snow cover in Torne River

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

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

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Over the extended 1874-2010 period, Kokemäki and Aura rivers showed notable correlationscorrelated (-0.5… 0.7) with the mean temperatures of February, March, and April (-0.5… 0.7). The fact that the ice-off event also correlated with mean temperatures in April breakup, in this case, was extended to April reflects the long-term change in mean temperatures in the timing of the breakup. For example, in Aura River there is a clear shift towards more frequent breakups ice-offs in March after the 1970s. Before this, breakups ice-offs occurred more frequently throughout all of April, and before the 1880s, even in May (Fig. 5). This progression or change in the timing of the breakup, across the respective length of all three series, is shown in Figure 5.

For Torne River, the extended period affected the mean temperature correlation pattern differently. The series still showed high correlations with the mean temperatures of April and May, however, the correlation to May temperatures increased from –0.49 to –0.70. This change mirrorsreflects a change in timing of the breakup similar to that in Aura and Kokemäki Rivers. In Torne River, however, the data shows that ice breakups in April are still quite rare, and the shift is towards more breakups in early May. Breakups have not occurred in June since 1867 (Fig. 5). A comparison between the spring temperatures and breakup the recorded dates showed a common pattern of variability over the instrumental period (Fig. 4d–f).

4.4 Temporal trends

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

The trends were pronounced for The trends are visible in Figure 1. The trends for each series were also statistically analysed for four different periods (see Table 3).

During the hydropower plant period in Kokemäki River (1939–2020), all three series exhibited statistically significant negative trends. These trends were especially pronounced for Kokemäki and Aura rivers over the 1939–2020 period. The slope showed a change of almost three weeks in both rivers. The slope of the trends indicated a change of 2.5 days per decade for Kokemäki River and 2.4 days per decade for Aura River. This is equal to a change of almost three weeks (20.5 and 19.5 days) in 82 years. The similarity in change suggests that the power plant has not influenced the timing of the breakup progressively. 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. For Torne River, the slope indicated a change of less than one day (0.8) per decade or almost one week (6.8 days) in 82 years. Thus, the change in the timing of the breakup has been considerably slower in the northern river than in the two southern rivers.

Over the 1793–2020 period, The trends between Aura and Kokemäki rivers diverged over the 1793–2020 period. During these 228 yearsthis period, the slopes of indicated a change of 24.0 days in Kokemäki River (26.2 days) and Aura River (17.4 days) diverged, and the development in Aura River was similar to that in Torne River (13.0 days). Moreover, the rate of change within the slope remained similar in Aura (15.3 days) and Torne (13.6) rivers even over the 1749–2020 period. Taken together, and 13.4 days in Aura River. Tthe similarities in change between rivers Aura and Torne implies that the calculated change in Kokemäki River is skewed. However, Kokemäki River had substantially more late events than Aura and Torne river in the 1800s and early 1900s (Fig. 6). Hence,

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the diverging trends in Kokemäki River may be attributed to a greater change in the late events (see below). seems too high to be caused by climate warming alone. is notable and in terms of actual climate change probably an overestimation. This assertion is supported by the 12.4-day change in Torne River, which is only one day less than the change in Aura River. Thus, the 24-day change in Kokemäki River is seem exaggerated notable even when considering the six-day change shift presumably caused by the we noted when addressing the effect of the power plant (see section 4.2).

Extending the analysis to the 1749–2020 period further supports the belief that the Kokemäki estimation may be skewed. Over this period, the change is 15.4 days in Aura River and 13.7 days in Torne River. Between 1693 and 2020, Torne River showed a change of 16.4 days, or five days per century.

Some traits of the temporal trends are also illustrated in Figure 5. For example, the last time the breakup occurred in June in Torne River was in 1867

, the last breakup in May in Aura River was in 1881 and correspondingly in 1924 in Kokemäki River. In Torne River, the first breakup in April was in 1894, whereas the first breakup in February occurred in 1990 in both Aura and Kokemäki rivers.

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

4.5.1 Frequency of early and late events

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

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

The average of the three earliest events in the 1991–2020 period shows that the earliness of the events have advanced considerably in Kokemäki and Aura rivers (Fig. 9a-c). The development was driven by the no-freeze events but also several events in early March and February (Fig. 8). In Torne River, as noted before, the change in the early extremes was negligible. However, the late

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extremes are affected by two unusually late events in 1996 and 2020. These are two of the latest ice breakups in almost 100 years. Moreover, there is only a 12-day range in the 75 percentiles in Torne River while the range is over 90 days in Aura and Kokemäki rivers. The change in the two southern rivers is therefore considerable and it stands out not only in the singular early events, but also when averaged.

4.5.2 Variability within the quartiles

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

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

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

5 Discussion

5.1 Changes since 1900

The key feature describing the breakups in Aura and Kokemäki rivers in the 21st century was increased interannual variability. The breakups have progressively advanced towards the freeze-up period and the exacerbated effect of the warming trend was the first no-freeze events. In the southern parts of Finland temperatures determine whether winter precipitation falls as snow or rain and in a warming climate the extreme events have exponential impacts. The no-freeze events in Aura River

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

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

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

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

In cold climate regions the apex of climate warming would be the occurrence of the first no-freeze events and secondly a increased frequency of this. In 1993, when discussing the Torne River ice breakup series, Kajander wrote that the winters in the boreal regions are long and cold enough to produce a strong ice cover of long duration in rivers. In 1993, it may have been an unimaginable dystopia that only 15 years later there would be rivers in boreal regions, in Finland, which for the first time in over 200 years, would not freeze up completely. However, climate warming is causing shorter, warmer, and wetter winters, and this affects the freeze-up process. Aura River never froze completely in 2008, and the phenomena repeated itself in 2020. In the second half of February 2020, when the ice cover reached its maximum extent, there were still small sections of the river, often under or near bridges, where there still was open water (author's observations). Precipitation (rain and snow variably) seemed to affect the freeze up process. The non-freeze events in 2008 and 2020 occurred during the two warmest winters on record, the latter being slightly warmer than the former (Ilkka et al., 2012; Irannezhad et al., 2014; Lehtonen, 2021). The non-freeze event in Kokemäki River in 2015 also occurred during one of the warmest years on record, especially February and March showed higher than normal mean temperatures (FMI, 2016). These non-freeze events are likely to become more frequent in the future. In the mid 21st century, two thirds of the winters are projected to be 20 days shorter relative to the late 20th century mean (Ruosteenoja et al., 2020). This scenario would most likely result in a shorter freeze-up window and increased years when Aura and Kokemäki rivers do not freeze completely.

The record warm winter in southern Finland in 2020 caused an unusually late breakup in Torne River. The late breakup could be explained by the fact that the winter temperatures were closer to normal and came with an excess of snow. The snow cover persisted longer than normally (Lehtonen, 2021)T and this may have maintained a higher surface albedo that delayed the melting of the underlying ice, thereby delaying the breakup (e.g. Prowse and Beltaos, 2002; Bieniek et al., 2011). The contrasting snow cover scenarios and increasing winter precipitation in the north (Irannezhad et al., 2014) may cause diverging trends between northern and southern river-ice breakups in the future. This is a topic in need of more in-depth investigations, but a similar phenomenon provides a potential explanation in the marginal changes of the extremely early breakups and why they have remained negligible in Torne River the last 100 years (see below). here are uncertainties related to the Kokemäki River series and its reliability after 1939. First, the dates from the breakup competition in Kokemäki River are skewed in comparison to the actual breakup date. Second, the power plant has affected the timing of the breakup, but the process seem to relate to events in the watershed area. In general, the power plant also plays a part in the freeze-up process. For example, December 2017 was wetter than normal and this increased the possibility for floods. However, the power plant reduced the discharge in the second half of January because the forecast predicted colder weather. Reducing the discharge enabled the river to freeze-up and reduced the risk for frazil ice jams. Thus, lowering the discharge or keeping it stable, if possible, closer to the breakup date, is another way to avoid floods.

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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.

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5.2 Changes before 1900

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

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

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

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

~~In a study of lake ice breakups in Finland, Korhonen (2005) noted that the change in days per 100 km, from south to north, was four days. The difference between Aura and Kokemäki River was initially 3.4 days, which corresponds with Korhonen's results. However, the construction of the hydroelectric power plant seems to have reversed the order between the two rivers. We are cautious in stating that the power plant caused the change because we have not addressed the hydrological response to climate change. The newspaper articles describing the breakups indicate that they became less dynamic and more thermal after the 1950s. It seems as if the river started melting upstream, closer to the power plant, first and after that, in Pori, the ice started melting in the middle of the river as opposed to breaking up across the length of the river at the same time. This was the process regardless of winter severity, as noted by the observers, and while bridges seemed to delay the breakup process, industrial warm water outlets were assumed speed up the melting process. The change, regardless of its cause, must have been tangible. For example, in 1972, *Satakunnan Kansa* published an interview with a 70-year-old man who had lived his entire life by the river. According to the man, the biggest change in the ice breakups occurred a decade earlier. This was confirmed in our analysis, which showed that the biggest change occurred after 1959, atwo decades after the power~~

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plant was built (see section 4.2). This shows that local knowledge and observations of breakup processes, even though semantic, can be extremely exact.

Aura River and Kokemäki River show greater change in their breakup dates than Torne River over the 1939–2020 period. Our qualitative comparison of the 30 earliest breakup dates shows that the change is marginal in Torne River. Since 1693, the range between the first and last breakup date of the 30 earliest events is only seven days. It is **remarkable** that the earliest event in the 2000s was only five days earlier than the earliest event in the 1700s. This should be compared to Aura and Kokemäki rivers where over a much shorter interval the range is over 50 days. Moreover, in Torne River, the earliest breakup date occurred on 26 April 2014, and this was only one day earlier than the breakup date in 1921. In other words, the last 100 years has caused a negligible change in the early extremes in Torne River. Opposite to this, the early breakup events in Aura and Kokemäki rivers have advanced progressively. Arguably, the warmer climate that is dominating in the two southern riverssouth is changing more rapidly, and with less predictability, 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). Thus, the response to increasing temperatures are not equally pronounced in the studied rivers. The detected trend towards earlier breakups in Torne River, mirrored against Table 1 and 2, suggests that it is not the extremely early events that are advancing at a record-breaking pace, which is the case in Aura and Kokemäki rivers, but the late events that have started occurring earlier.

In this paper, we have analysed time series from rivers that are longer than 220 years and the last year included in our analysis was 2020. Our series are longer than most of those from other ice breakup investigations, but our results reinforce their results, which is a trend towards earlier breakups. The change seems to be greater in Northern Europe when compared to Northern America. For example, a study of Yukon River at Dawson in northwest Canada (1896–2009) indicated a trend towards earlier breakup dates with an advance of five days per century (Janowicz 2010). This is smaller than the observed 82-year (1939–2020) trend in Aura (19.5 days) and Kokemäki (20.5 days) rivers but closer to the change in Torne River (6.8 days). In Torne River, Magnuson et al. (2000) noted a change of 6.6 days per 100 years during the 1846 to 1996 period. Our results (6.8 days), during a period of only 82 years suggest a minor increase in the rate of change when compared to the result of Magnuson et al. (2000). These changes probably relate to the fact that our period is 12 years shorter while it is also begins and ends laterning and ending later.

Sharma et al. (2016) paralleled the change in breakup dates with those in atmospheric carbon dioxide (CO_2) and January-April mean temperatures as the most important explanatory factors affecting the breakups in Torne River over the entire length of the series. Our analysis narrowed the

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breakup season, i.e. the months affecting the timing of the breakups, to the mean temperatures in April and May temperatures between 1874 and 2010.

The late event in 1867, the latest event in all three rivers, is known as the latest ice breakup event also in Lake Näsijärvi, Oulunjärvi, and Kallavesi (Korhonen, 2005; 2006). The Finnish lake-ice series are, however, too short to reflect the events in 1807 and 1810. These years stand out in the Torne and Kokemäki series but less so in the Aura River series. There is also the exceptionally late event in Aura River in 1852, which was the only year during which previous compilations for Kokemäki River diverged. In Torne River, the 1852 event, while it in Torne River is not even amongst the 100 latest events. The discrepancy highlights the validity of historical records and especially cryophenological series and observations (e.g. Helama et al., 2013; Kajander, 1993) but it is reasonable to assume that the discrepancy may relate to local climatic conditions. We gain some insight by comparing our results to previous research and three breakup series from nearby rivers in Finland and Russia. The Finnish river is Porvoo River (1771–1906) in Porvoo (60°23′N, 25°39′E) in southern Finland (Johansson, 1932). The Russian rivers are Neva River (1706–1882) in St Petersburg (59°56′N, 30°18′E) and Northern Dvina (1734–1879) in Archangel (64°32′N, 40°32′E) (Rykatschew, 1887). Johansson (1932) used all three series and based them on Rykatschew's compilation. The series have, to our knowledge, not been updated or homogenised since then. Here, we consider the potential inhomogeneities of these series a minor dilemma because we only use the series to identify the temporally extreme events. It also noteworthy that most of the widely used lake-ice series from Finland have been scrutinized only from 1961 onwards (Korhonen, 2005).

The breakup series from Neva River shows that the three latest events occurred in 1810, 1852, and 1807 (Rykatschew 1887). The corresponding events in Porvoo River occurred in 1852, 1867, and 1810 (Johansson, 1932). The 1807 event was the sixth latest in Porvoo River while the 1867 event was not amongst the ten latest in Neva River. The range between the three latest events is only five days in Porvoo River and two days in Neva River. The three latest in Northern Dvina was 1867, 1845, 1855 while 1810 was the fourth latest and 1807 not even in the 40 latest. Thus, some discrepancies remain between the northern and southern rivers, but the spring in 1852 seems to have been as cold as in 1867 in the southern rivers. However, all series highlight the breakup in 1810, which indicates that spring was cold across north-eastern Europe. All rivers, except for Northern Dvina, also indicate that the 1807 event as exceptional. Moreover, in Porvoo River 40 percent of the 30 latest ice breakups occurred in the 1800–1823 period. This period is also pronounced in Northern Dvina (23 percent) but less so in Neva River (10 percent).

We are inclined to ascribe the cluster of late events in the Finnish rivers in the early 1800s to the climatic effects caused by the Dalton Minimum (1800–1824), and accordingly the late events in

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the early 1700s in Torne River to the climatic effects of the Maunder Minimum (1645–1715), which has shown to have mainly affected the spring climate (e.g. Miyahara et al., 2021; Xoplaki et al., 2005). Apart from these solar anomalies, there is also an unknown volcanic eruption in 1809 (Toohey and Sigl, 2017) that might have affected spring conditions and thus the later ice breakups in 1810. However, in that case, we could have expected the effects of the Tambora eruption in 1815 to cause significantly later ice breakups in 1816, which was the case only in Torne River. Nonetheless, a more detailed assessments of the forcing factors behind these late events remain beyond the scope of this article. Our qualitative assessment of what caused the late events in the early 1800s is speculative, but it highlights the potentials provided by these extended climate series.

Finally, as in Aura and Kokemäki Rivers, the breakup in 1822 was exceptionally early in Porvoo and Neva Rivers, but not in Torne or Dvina rivers. Hence, there is clearly a difference in longitudinal and latitudinal direction. On the other hand, Helama et al. (2013), when comparing the Torne River series to a multi-station climate dataset, identified 1821 and 1845 as years with significant changes in the breakup date. Here, we note the breakup in 1845 as a unique event, one of the seven years shared by Aura, Kokemäki and Torne rivers in the 1800s, and one of the latest breakups in Northern Dvina and Neva River.

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6 Conclusions

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

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during the two warmest winters ever recorded in the history of meteorological observations in Finland. All three series had a cluster of late events in the early 1800s and these corresponded with the recorded events from other riverine series in northern Europe, especially the events in 1807 and 1810.

Data availability

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

Author contributions

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

Competing interest

The authors declare that they have no conflict of interest

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

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

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

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

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

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

(a)

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

(b)

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

* $p<0.001$

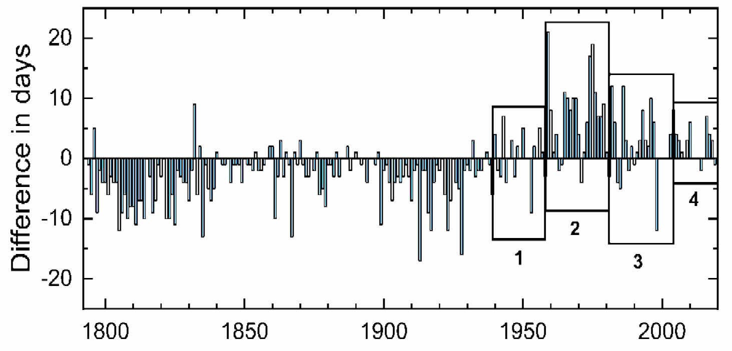

Figure 2. The difference in days between the breakup date in Kokemäki River and the ice-off event in Aura River. A negative value indicates the number of days the ice-off event in Aura River preceded the breakup date in Kokemäki River. Vice versa, a positive value shows how many days the breakup in Kokemäki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

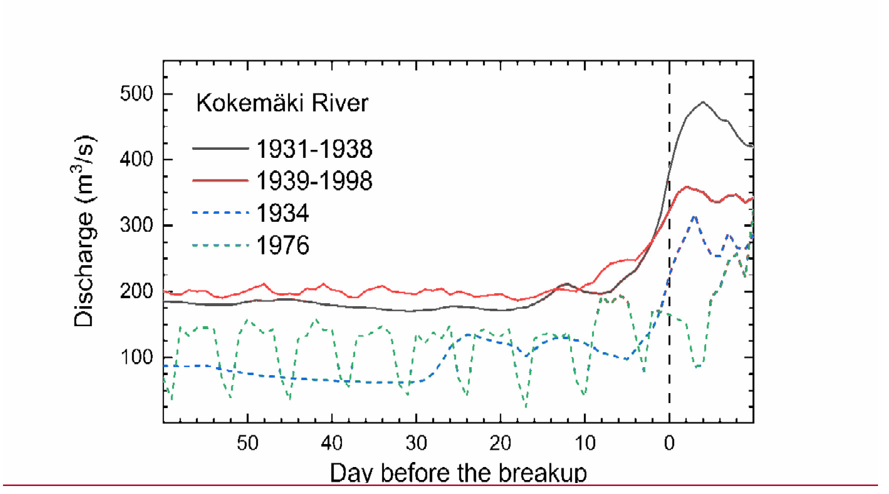

Figure 3. The discharge 60 days before and ten days after the breakup (0) in Kokemäki River. The black line shows the average discharge rate during the 1931–1938 period and the red line the average during the 1939-1998 period. The grey line depicts the discharge in 1934 and the yellow line depicts the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

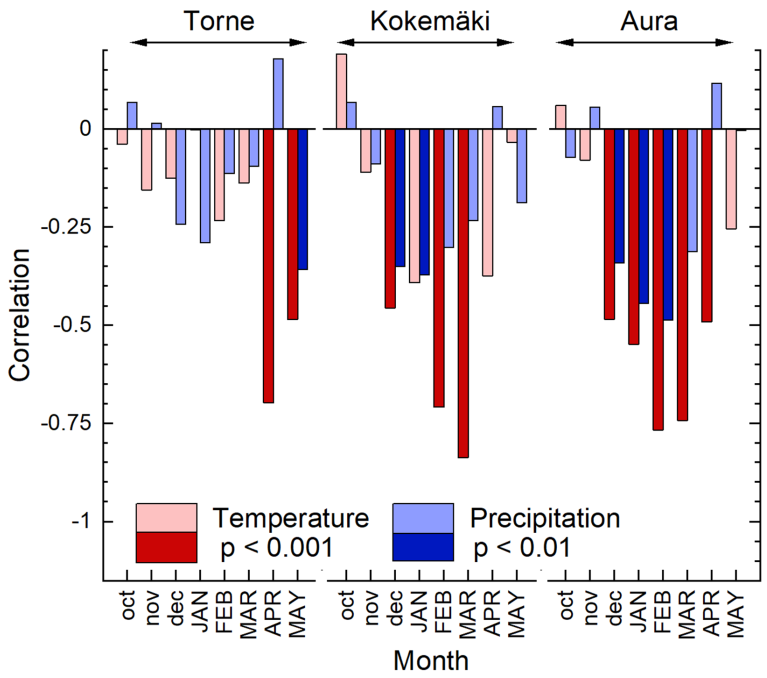

Figure 4. The figure shows Spearman's correlation between temperature, precipitation and ice breakup dates in Torne and Kokemäki rivers and, respectively, temperature and ice-off events in Aura River, during the 1961–2020 period.

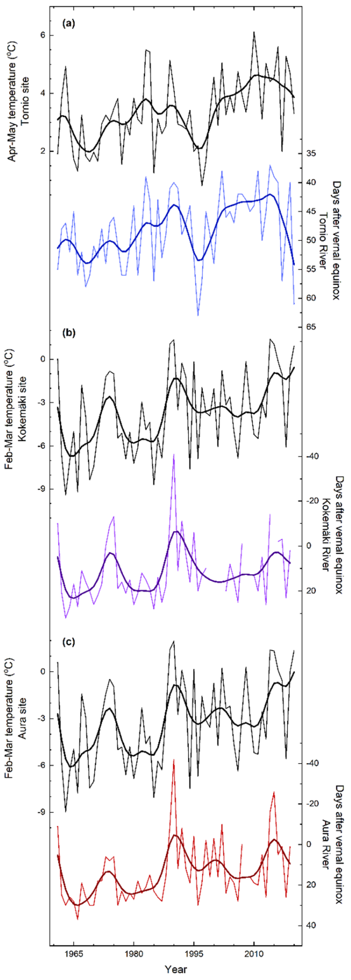

Figure 5. Variations in mean spring temperature and ice breakups. A comparison between the interpolated mean temperatures to the observation sites for (a) Torne, (b) Kokemäki and (c) Aura rivers over 1960–2020 period. The observed breakup dates (thin line) were smoothed using a 10-year spline function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

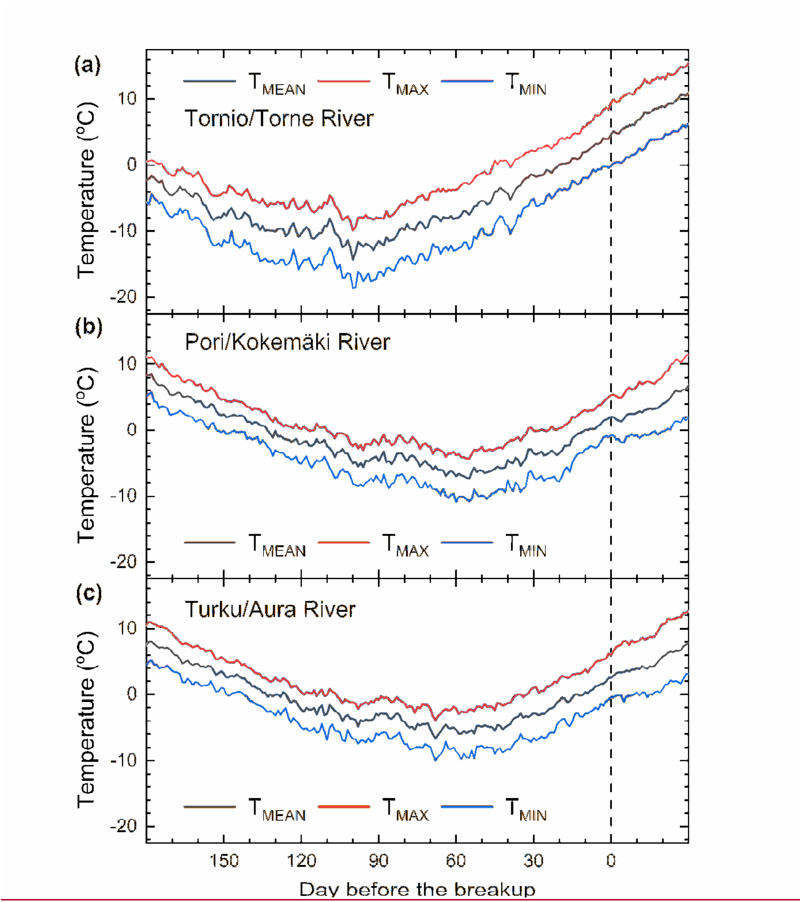

Figure 6. The lines show the temperature development 180 days before and 30 days after the breakup date in Tornio (Torne River), Pori (Kokemäki Rivers) and the ice-off event in Turku (Aura River). Zero (0) denotes the breakup and ice-off day in the respective rivers.

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

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(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

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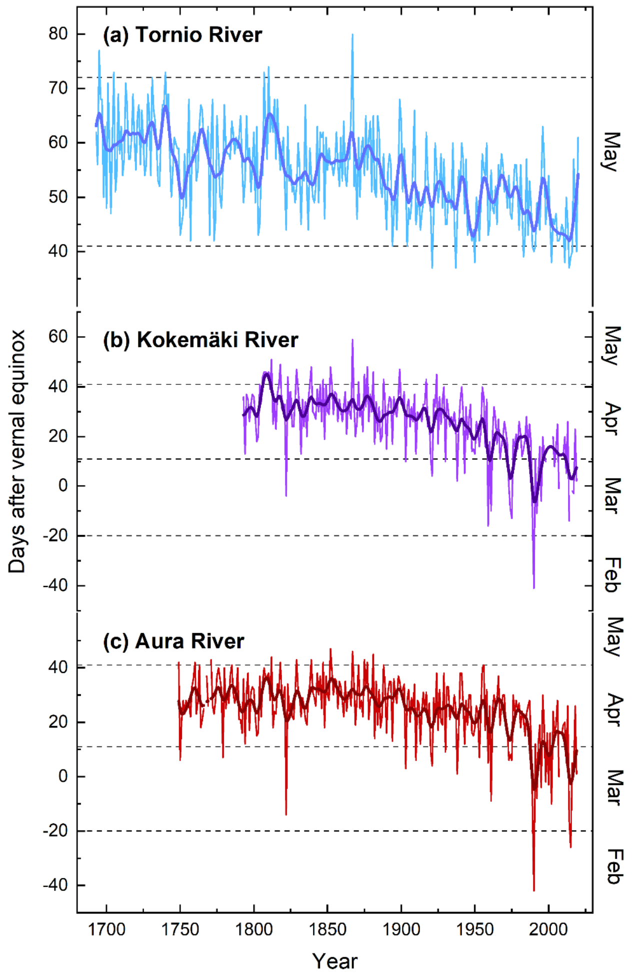

1765 Figure 7. Ice breakup dates relative to the vernal equinox in (a) Torne and (b) Kokemäki rivers, and the ice-off dates in (c) Aura River. The obtained dates (thin line) were smoothed to illustrate decadal and longer variations using a 10-year sling function (thick line).

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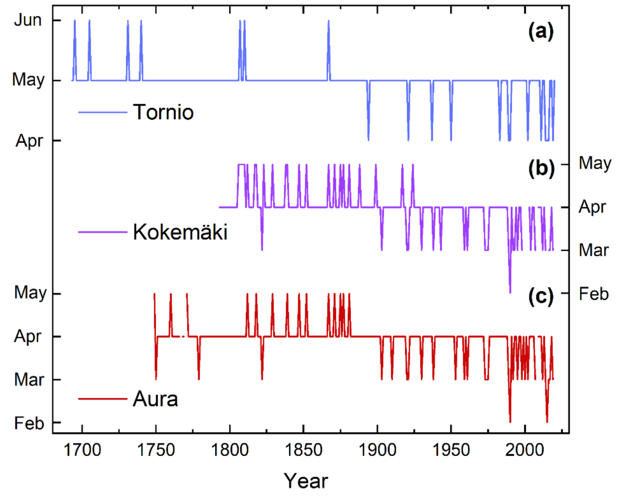

Figure 8. Occurrence of ice breakups in February, March, April, May, and June in (a) Torne River, (b) Kokemäki River and (c) Aura River.

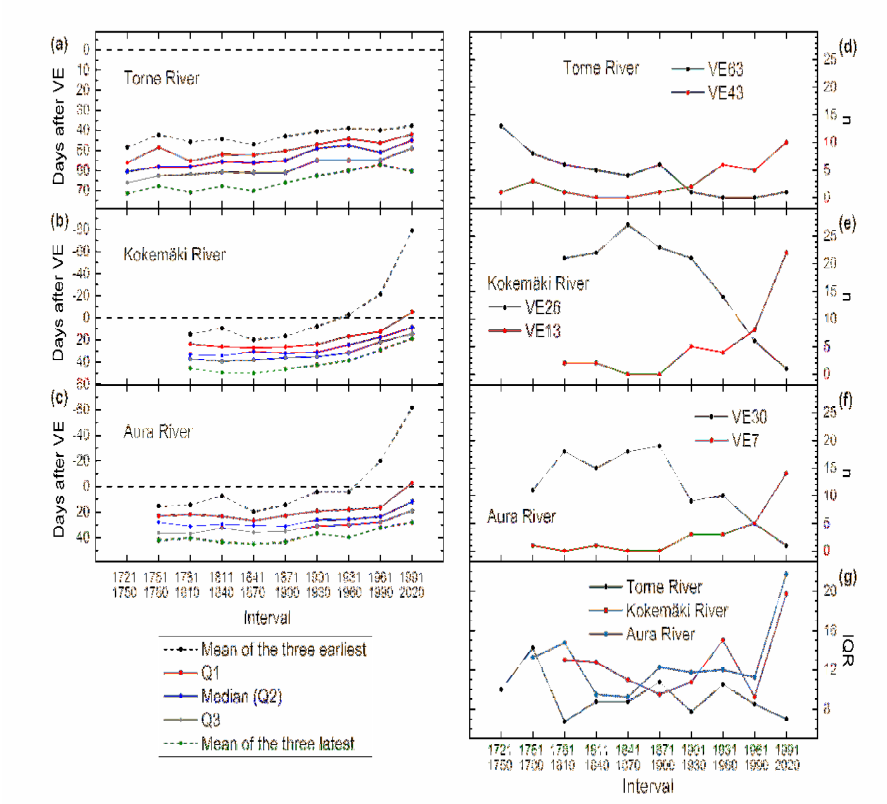

Fig 9. Ice breakups in the rivers Torne and Kokemäki and ice-offs in Aura River according to the vernal equinox (VE) in 30-year non-overlapping periods. The dotted line (0) in Figure (a-c) shows the vernal equinox and the other values are obtained from analysing the quartiles of each series in each period.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

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