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Investigation of river ice regimes in some Norwegian water courses

Solomon B. Gebre[1], Knut T. Alfredsen[2]
[1,2]Department of Hydraulic and Environmental Engineering
Norwegian University of Science and Technology
S.P. Andersens Vei 5, 7491, Trondheim, Norway
[1]*solomon.gebre@ntnu.no*, [2]*knut.alfredsen@ntnu.no*

In the present study, freeze-up and break-up data for a number of rivers in Norway have been investigated for possible trends. The highest observation density is found for the period 1920s-1980s with only one station extending to year 2000. The Mann-Kendall non-parametric test is used to assess the significance of any possible trends in the data. The analysis resulted in mixed signals for both the freeze-up and break-up trends. Out of the 11 river stations investigated 5 stations showed positive trends towards later freeze-up two being significant at 10% level whereas 6 showed negative trends towards earlier freeze-up with one being significant. Regarding break-up, 6 of the stations showed negative trends towards earlier break-up whereas 4 stations showed positive trends towards later breakup, one being significant at 10% level. One station exhibited no trend. Further, a comparison was made with long series of lake ice phenology data for 12 lakes. The results give mixed signals with changes in freeze-up days ranging between -4.3 days/decade to +4.1 days/decade. Breakup on the other hand showed trend magnitudes ranging from -2.7 days per decade to +2.8 days per decade. To further understand the mechanisms controlling river ice breakup and freeze-up, we have investigated the relationship between observed breakup and hydro-climatic variables (temperature, precipitation and streamflow) as well as the NAO large scale teleconnection.

1. Introduction

Most rivers in Norway with the exception of a few coastal rivers undergo the formation and break up of river ice every year. Dynamic ice formation processes dominate the ice production in the steep and relatively shallow rivers of Norway (Tesaker 1994; Stickler and Alfredsen 2009; Stickler *et al.* 2010). River and lake ice play an important role in fresh-water management in cold regions including Norway. Hydropower production which is the dominant energy source in Norway is also heavily influenced by the ice regime of rivers. The ice regime of rivers and lakes is characterized by among other things the freeze-up and breakup dates and the ice duration. Ice phenology data are important variables to assess the inter-annual and long-term variability of cold regions' climate. They can also serve as good climate indicators and can be used as a proxy for detecting changes in the climate of a region ((Livingstone 1997; Magnuson *et al.* 2000).

A number of studies have been carried out to detect long-term changes and significant trends in river and lake ice regimes (Magnuson *et al.* 2000; Beltaos 2004; Duguay *et al.* 2006; Korhonen 2006; Klavins *et al.* 2009; Janowicz 2010), with most of the studies focused on Canada. According to (Magnuson *et al.* 2000), freeze and breakup dates of river and lake ice show a consistent evidence of later freezing and earlier breakup. There is very scant information in scientific publications regarding the ice regimes of Norwegian rivers, few examples include (Tvede 2004; Kvambekk and Melvold 2010). This we think is mainly because of the inaccessibility of long-term data series of river and lake ice data. Quite recently, however, the authors have been able to get some data sets of river and lake ice freeze-up and breakup dates from the Norwegian Water Resources and Energy Directorate (NVE). This has made it possible to carry out some exploratory analysis of the Norwegian river and lake ice phenology data.

Climate is increasingly being recognized as a major factor driving long-term changes in river and lake ice phenologies (Beltaos 2004; Beltaos and Prowse 2009). Hence, knowledge about how the climatic and hydrological variability influences the ice phenologies is very fundamental to predict the influence of climate change on river and lake ice regimes. Predictions of future climate for Norway show a marked increase in temperature with higher increases in the higher latitudes. The annual mean temperature over mainland Norway (1961-2000) ranges from -8.6 to +7.6 ^{o}C, with low temperatures in the south central highlands and in the north eastern part of the country. Future projections (Hadley GCM, A2 scenario) show an increase by between 2.3-4.2 ^{o}C , with a mean increase over mainland Norway of 3.2 ^{o}C for the 2080s compared with the baseline period of 1961-1990. Precipitation on the other hand changes by between -5 and +30% with a mean increase of 5.6%. These changes in climatic parameters will definitely influence the shape and scale of the hydrograph. In Norway, changes in input climate forcings in the future climate translate into consistent increases in discharges in winter while summer discharges will be reduced. Autumn and spring show mixed signals, with many parts of Norway showing increased discharges in autumn and reduced discharges in spring (Engen-Skaugen *et al.* 2005; Beldring *et al.* 2008; Gebre 2009).

Large scale atmospheric and oceanic phenomena or teleconnections are also responsible for regional and global climatic fluctuations. In the European part of the northern hemisphere, the North Atlantic Oscillation (NAO) is a major source of inter-annual and inter-decadal weather and climate variability(Gerten and Adrian 2000; Hurrell and Deser 2009). Quite a few studies have attempted to explain the variability in fresh water ice regimes using teleconnections. Klavins (2009) found a strong negative correlation between the NAO index and ice breakup events and ice duration in the Baltic region. Bonsal et al. (2006) on the other hand made a thorough analysis of the relationships between several large-scale teleconnection indices including the NAO and freshwater ice break/freeze-up dates over Canada. They found that the NAO indices have little to none discernible impacts on the ice dates.

The main objective of this paper is to carry out long-term trend analysis of ice break/freeze-up dates in some Norwegian rivers and try to explain the observed trends in terms of concomitant trends in climate variables (temperature and precipitation) and river discharges. We also investigate the role of large scale teleconnections namely, the North Atlantic Oscillation in the variability of river ice regimes. The paper is part of a bigger research project that aims to carry out the impact of climate change on river ice regimes and subsequent implication on infrastructure where hydropower is the main focus.

2. Data and Methods

2.1 Data

Ice observations

The river and lake-ice breakup and freeze-up dates were obtained from the Norwegian Water Resources and Energy Directorate (NVE). Observations of ice thickness were not available, and the ice date observations don't cover the whole of the country. Unfortunately also very scant observations are available after the 1990s. This period perhaps coincides with the automation of most of the gauging stations in Norway and there were no more dedicated personnel to monitor river and lake ice conditions. Observations representing freeze-up and breakup dates include: partial ice cover, complete ice cover, and gauging station clear of ice. Break-up and freeze-up dates are represented by respectively complete/partial ice cover and gauging station clear of ice. The term break-up date as used here refers to the first day on which the river station or the lake in the vicinity of the observation point was observed to be ice-free. Figure 1 shows the river and lake ice station locations used in this study, whereas Table 1 provides data summary of ice observation stations.

Meteorological and Hydrologic data

Monthly meteorological data (near surface air temperature and precipitation) were obtained from the Norwegian Meteorological Institute (usually referred to by the web address - met. no). The data were primarily downloaded from an online data repository called *eKlima* which gives free access to the data for all. Stations that have long-term records to suit the analysis were screened using the metadata. The representative station to each gauging station is identified by a simple Euclidean distance approach. Periods of meteorological data range from years 1910 to 1962 (starting period), and 2002 to 2010 (end period). Figure 2 shows the location of meteorological stations used in this study. Hydrologic data on river flows and stages were downloaded from the NVE data base using the institutional access that we have at the authors' institution. Periods of hydrometric data vary among the stations with the earliest period ranging from 1908 to 1970 and continuing up to 1996 and 2009. One station has hydrometric data that runs up to year 1964 only.

Data on teleconnection

The North Atlantic Oscillation (NAO) is the dominant large scale atmospheric variability that influences climate in countries surrounding the North Atlantic basin (Hurrell and Van Loon 1997; Cherry *et al.* 2005). It is also the dominant oscillation that affects climate patterns in Scandinavia including Norway. The NAO describes a large scale circulation over the North Atlantic and is computed as the normalized sea-level pressure (SLP) difference between the Icelandic sub-polar Low Pressure and the Azores subtropical High Pressure (Wanner *et al.* 2001; Uvo and Berndtsson 2002; Bonsal *et al.* 2006). The normalized three month NAO index anomalies were obtained from the webpage of Climate and Global Dynamics (CGD) at http://www.cgd.ucar.edu/cas/jhurrell/indices.data.html#naostatseas. The anomalies were normalized by the long-term seasonal mean (1864-1983) standard deviation. Positive values of the index indicate stronger-than-average westerlies over the middle latitudes (Hurrell and Deser 2009).

2.2 Methods

Trend detection

The rank-based non-parametric Mann-Kendall (MK) trend test (Mann 1945; Kendall and Gibbons 1990) is used to detect trends and to test the significance of the trends. The null hypothesis H_o that there is no trend is tested against the alternative hypothesis H_1 that there is a trend. The Mann-Kendall test was chosen because as a non-parametric test it doesn't have any presumption on the distribution of the variables being normally distributed (Hipel and McLeod 1994; Yue *et al.* 2002). This test is also less affected by outliers because its statistic is based on rank (the sign of differences), and not the absolute magnitudes. It is also a relatively robust method in handling missing data. A brief description of the method follows.

The standardized Mann–Kendall test statistic Z_{MK} is given by (Hipel and McLeod 1994; Yue *et al.* 2002),

$$Z_{MK} = \begin{cases} \frac{S-1}{\sqrt{Var(S)}} \quad , & if\ S > 0 \\ 0 \quad , & if\ S = 0 \\ \frac{S+1}{\sqrt{Var(S)}} \quad , & if\ S < 0 \end{cases} \tag{1}$$

Z_{MK} follows the standard normal distribution N(0,1), and the test statistic S is given by

$$S = \sum_{i=1}^{n-1} \sum_{k=i+1}^{n} sgn(x_k - x_i) \tag{2}$$

Where S is the sum of the signs of the slopes of all possible pairs in the dataset; x_k, x_i are the sequential data values, n is the length of the data set, and *sgn (x)* is equal to +1, 0, or -1 if x is greater than, equal to, or less than zero, respectively. The null hypothesis H_0 is accepted for a level of significance of α (for a two-tailed test) if $-Z_{1-\propto/2} \leq Z_{MK} \leq Z_{1-\propto/2}$.

The MK test doesn't tell us the magnitude of the trend detected in a dataset. We used the robust Sen's slope method - also called the Theil-Sen slope (Yue *et al.* 2002), to estimate the magnitude of a detected trend. The trend slope estimate (β) is given by

$$\beta = median\left(\frac{x_k - x_i}{k-i}\right) for\ all\ i > k \qquad [3]$$

Where β is the estimate of the slope of the trend and x_i is the i^{th} observation.

A significant level of 5% or less is mostly used for assessing trends in hydrological studies (for example (Xu *et al.* 2003; Bonsal *et al.* 2006; Korhonen 2006), though some authors have also investigated trends at a lower significant level of 10% (Yue *et al.* 2003; Beltaos 2004; Duguay *et al.* 2006; Janowicz 2010). In this study the observed trends, if any, in ice dates and other concurrent variables are evaluated at 10% significant level.

Association with other environmental variables

The trends in the ice dates are compared with variations in concomitant representative climate data (temperature and precipitation) and river flow data at the respective stations, and teleconnection indices. Linking ice phenology data to climatic variables, specially temperature and its derivatives (for example 0^oC isotherm dates) will enable us to forecast freeze-up and break-up conditions for future climate scenarios using data from Global Climate Models (Prowse *et al.* 2002).

The Pearson's correlation coefficient r, and the Spearman's rank correlation coefficient ρ, which is in fact the Pearson linear correlation computed on the ranks rather than the absolute values of the elements, have been widely used as a measure of testing associations between ice phenology and other environmental variables. The Spearman's rank correlation has the advantage in that it has no prior assumption on the distribution of the variables to be tested. The coefficients r and ρ are calculated by the formula:

$$r\ or\ \rho = \frac{\sum_i (x_i - \overline{x})(y_i - \overline{y})}{\sqrt{\sum_i (x_i - \overline{x})^2 \sum_i (y_i - \overline{y})^2}} \qquad [4]$$

Where,

ρ	is the Spearman rank correlation coefficient
r	is the Pearson correlation coefficient
x_i , y_i	are the ranks of the data pairs to be tested (Spearman's), or the normalized data pairs (Pearson's)

Where the Pearson's r is used the variables to be tested are de-trended or converted to standardized anomalies by subtracting the mean from each observation, and then dividing by the standard deviation. All the statistical analyses were performed using various libraries in the public domain R-Statistical package V.2.12 (http://www.r-project.org).

3. Results and analysis

The results of our analysis are presented as follows. First we present the results of trend analysis of river ice data and pertinent climatic (air temperature and precipitation), cryospheric (lake ice phenology) and hydrologic (streamflow) variables. Then we present the relative association of river ice data with hydro-climatic variables as well as the NAO teleconnection and try to explain the observed variability. It is worthwhile to note that river stations are abbreviated by the first four letters as shown in Table 1 (for eg., Storøygardsbrua is abbreviated as Stor and so on).

3.1 Trends

Trends in river and lake ice data

Anomalies from long-term means in the timing of freeze-up and breakup are depicted for all the eleven river ice stations in Figures 2 (freeze-up) and 3 (breakup). The anomalies are simple but effective way of showing the timing of the events in a given year compared with the long term average. Mean freeze-up dates range from as early as 19 Oct in the northern most Polm station to as late as 04 Dec at station Stor. Mean breakup dates on the other hand vary from 18 Mar at Ytri to 24 May at the northern most station Polm. The standard deviation in freeze-up dates ranges from 10 to 18 days, which shows a considerable year-on-year variability. The standard deviation for breakup dates (min=8, max=19) also reveals considerable variability in the same order as freeze-up dates. Multi-site correlation analysis has revealed that only the 4 stations in the middle part of Norway namely Self, Grun, Haga and Hogg show a consistent high correlation in both freeze- and breakup dates ($\rho > 0.75$ for freeze-up and $\rho > 0.65$ for breakup). The northern most station, Polm, depicts very low correlation both negative and positive in case of freeze-up ($-0.18 < \rho < 0.27$), and very low positive correlation ($0.04 < \rho < 0.29$).

Regarding freeze-up, 6 of the 11 stations show a negative trend or earlier freeze-up with Sen's slope (S) ranging from -0.2 to -3.3 days per decade, with only one station being significant (Ytri, p=0.022, and a trend magnitude of -3.3 days per decade). The other 5 stations have shown a positive trend (later freeze-up) three being statistically significant (Jond, p=0.073, S=1.2 days/decade), (Polm, p=0.027, S=0.9 days/decade) and (Stor, p=0.006, S = 11.1 days/decade). Regarding breakup, 6 of the 11 stations show a negative trend or earlier breakup (S between -0.5 to -3.5 days/decade) with only 1 being significant at 10% level (Etna, p=0.085, S= -0.9 days/decade). On the other hand, 4 stations showed a positive trend (S between 0.4 to 1.9 days/decade), with only 1 being significant (Dorg, p=0.059, S=1.5 days/decade). One station (Egaf) showed a zero trend magnitude. Tables 2 and 3 show a summary of the variability and trend in freeze-up and breakup time series respectively.

For the sake of brevity, the variability and trends in lake ice breakup are only explained briefly and trends are shown on a map. The prime objective of including lake ice phenology analysis is to see if they depict a different trend pattern compared with river ice time series. Out of the 14 lake ice time series 9 show positive trends towards later freeze-up and 5 of them are significant at 10% level. The magnitude of the trend (Sen's slope) has a maximum value of +4.1 days per decade. The remaining 5 stations show a negative trend towards earlier freeze-up with 2 of them being significant at the 10% level. Trend magnitudes ranged from 0 to -4.3 days per decade. If we consider lake ice breakup series, 6 show positive trends towards later breakup none being significant at 10% level, whereas the balance 8 stations show negative trend towards earlier breakup and 4 of them being significant at 10% level. Trend magnitudes for breakup range from

-2.7 days per decade to +2.8 days per decade. Figures 4 and 5 show respectively the trend values (Z_{MK}) for river and lake ice stations investigated in the study.

Trends in climatic conditions

Air temperature and precipitation are the most important climatic variables that influence both river ice processes and flow hydrographs (Prowse and Beltaos 2002; Beltaos 2004). Air temperature is a direct indicator of the energy balance in the atmosphere and precipitation together with air temperature determines the shape and scale of the flow hydrograph. A simple Euclidean distance approach has been used to find the nearest climate station having both temperature and precipitation data. In two instances, different stations have been used to represent precipitation and temperature for river gauging stations *Stor* and *Ytri*. Seasonal trend tests are carried out for autumn (Sept-Oct-Nov), winter (Dec-Jan-Feb) and spring (mar-Apr-May) mean values. The results are shown in table 4. Temperature shows a consistent increasing trend in all stations in winter and spring seasons, whereas autumn temperatures have an increasing trend in all but one station. The trends in precipitation are more or less the same though less pronounced.

Trends in hydrologic variables

The flow hydrograph is a major factor in the evolution of river ice processes (Beltaos 2004). The dates of freeze-up and breakup depend on the flow magnitudes during the autumn and spring respectively. It is reasonable to suggest that the hydrological variable relevant for freeze-up studies is the mean flow, where as it is the maximum flow that is pertinent to describe breakup. Breakup episodes during spring or in mid-winter occur especially when river flows increase suddenly due to snow melt or rain-on-snow events during warm spells. In the ice data considered in this study freeze-up occurs between October and December, and mean flows in these three months were examined for trends. Breakup occurs typically between March and May. The station Dorgefoss showed an extremely large negative trend with a Z statistic value close to -7. Further investigation into the flow regime led to the fact that the river was regulated for hydropower since 1968.

3.2 Association of river ice data with hydro-climatic variables and the NAO index

Hydro-climatic variables

Typically ice freeze-up and breakup dates correlate most strongly with air temperature in the month or two before the event (Magnuson *et al.* 2000). In the river ice data considered in this study freeze-up occurs between October and December, and correlations between freeze-up and mean monthly temperatures in the months September to December are examined. Breakup on the other hand occurs typically between March and May, and correlation of breakup dates and mean monthly temperatures in these three months are also examined. The rank based Spearman’s rho correlation coefficient is used for discerning the correlations. Seven of the eleven stations have the highest correlation of freeze-up dates with October mean temperatures whereas the remaining four stations are better correlated with November mean temperatures. Correlations are positive indicating that a higher mean monthly temperature in autumn months translates into delayed freeze-up. Breakup on the other hand is very highly correlated (all significant at 5% level) with March or April mean monthly temperatures, and May temperature for the northern most Polmak station.

Correlation of the ice dates with monthly precipitation is less clear. Only 6 of the 11 stations show a significant positive correlation between freeze-up and mean monthly precipitation in one of the months between September and December ($0.28 \leq \rho \leq 0.57$; $0.000 \leq p \leq 0.055$). Breakup on the other hand has a significant negative correlation with any one month between March and April in 5 of the stations ($-0.19 \leq \rho \leq -0.47$; $0.003 \leq p \leq 0.092$). This might be evidence of the fact that it is the snow-melt rather than the direct precipitation that drives the shape of the hydrograph in late winter-early spring and thereby the breakup process, as it will be shown that maximum daily flows are highly correlated with breakup.

Freeze-/breakup dates are highly influenced by autumn/spring flows with very significant correlation. Freeze-up is explained by mean monthly discharges in the month or one month earlier than it occurs. In two instances (Egaf and Stor), the correlation is not significant at the 10% level with Station Stor showing unexpected negative correlation with autumn discharges and needs further investigation. Breakup is highly negatively correlated with spring discharges which may be evidence of the fact that dynamic breakup events driven by maximum flows in rivers is the governing mode of breakup in these small rivers.

The NAO index

The association of the river ice phenology data (after standardizing it using the sample mean and standard deviation) with three-month average standardized NAO indices is shown by the Pearson's correlation coefficient values shown in Table 7. Freeze-up correlations with autumn (SON) NAO indices are very mixed with both positive and negative correlations. The relationship was significant only at station Selfoss with $r = 0.31$ ($p < 0.10$). Høggas and Jondalselv showed respectively a significant positive and negative correlation with summer (JJA) NAO indices. Three stations have shown significant correlation of breakup with the spring (MAM) NAO indices. The positive r values indicate that a stronger Icelandic Low (positive NAO) is associated with later freeze-/breakups and vice versa(Bonsal *et al.* 2006). Bonsal *et al.* (2006) also reported weak and incoherent correlation of NAO teleconnections with river ice phenologies in Canada. They also attributed the weaker correlations to be likely influenced by a greater combination of atmospheric heat fluxes including open-water heat storage which we also subscribe to. In addition, freeze-up processes in the steep and shallow rivers considered in this study are dominated by dynamic ice processes governed by stream characteristics such as the stream gradient and morphology (Tesaker 1994; Stickler and Alfredsen 2009; Stickler *et al.* 2010) which could outweigh the influence of large scale teleconnections.

4. Conclusion

This paper documents the observed trends in river and lake ice phenology (with more focus on river ice) and makes a comparison with other environmental variables and the NAO teleconnections to explain the variability. The environmental variables considered include lake ice phenology data, mean temperature and precipitation, and stream flow data. The null hypothesis of no trend was rejected at the 10% significant level for 4 of the 11 river ice stations for freeze-up and 2 of the 11 stations for breakup. Similar mixed trends are found for the lake ice series. Mean monthly temperature and mean daily flows in the autumn and particularly in the month of occurrence or one month earlier have shown significant correlation with freeze-up where as the variables important to explain breakup are mean monthly temperature and maximum daily flows in spring and especially in the month breakup occurs or one month earlier. The dependency of river ice phenology data on the NAO index is inconclusive and incoherent.

Further studies will be carried out to find the dependency of breakup events on daily temperatures and flows so that forecasts on ice breakup can be made based on forecasts of temperature and river flows.

The limitations of the present study lie in the fact that the data series don't extend to the present day to take account of climatic changes that might have accelerated since the 1990s. The authors will investigate further the possibility of using high resolution satellite data (Landsat images) to extend the phenology series to the present day to make the trend and correlation analysis up-to-date. Such an attempt has been made with reasonable success by various investigators in the big arctic rivers.

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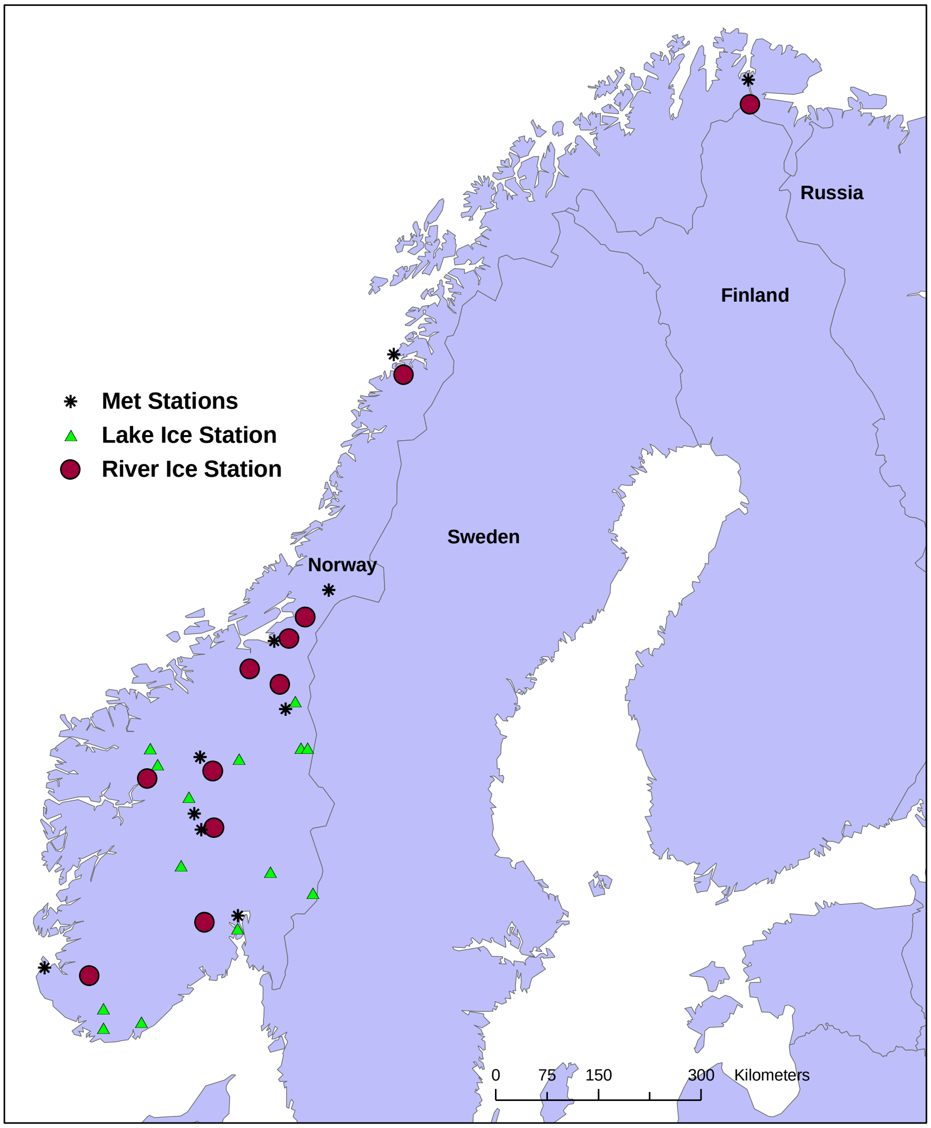

Figure 1. Figure showing the location of river and lake ice stations used in the study.

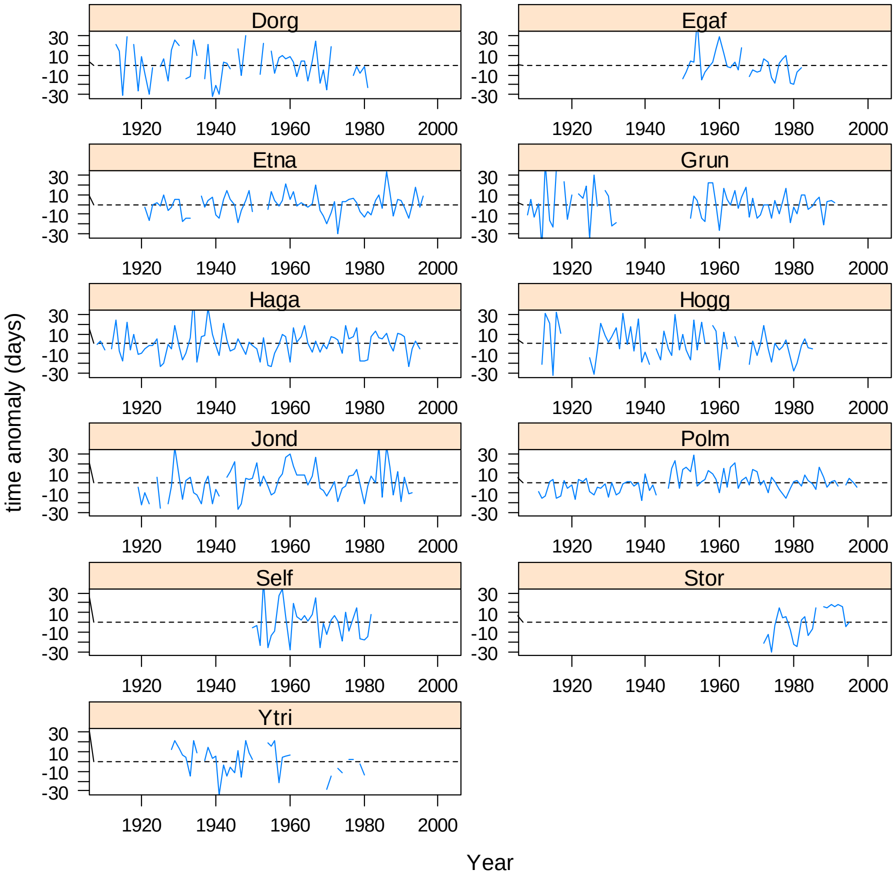

Figure 2. Time series of river ice freeze-up dates as anomalies from the long-term means.

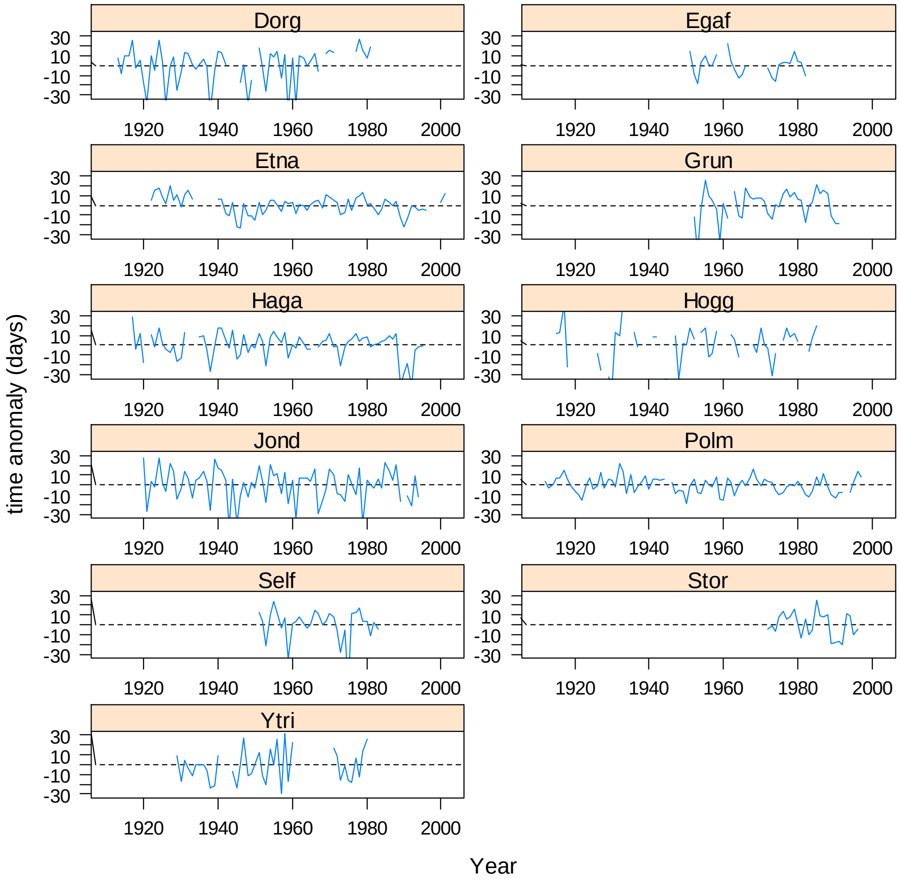

Figure 3. Time series of river ice break-up dates as anomalies from the long-term means.

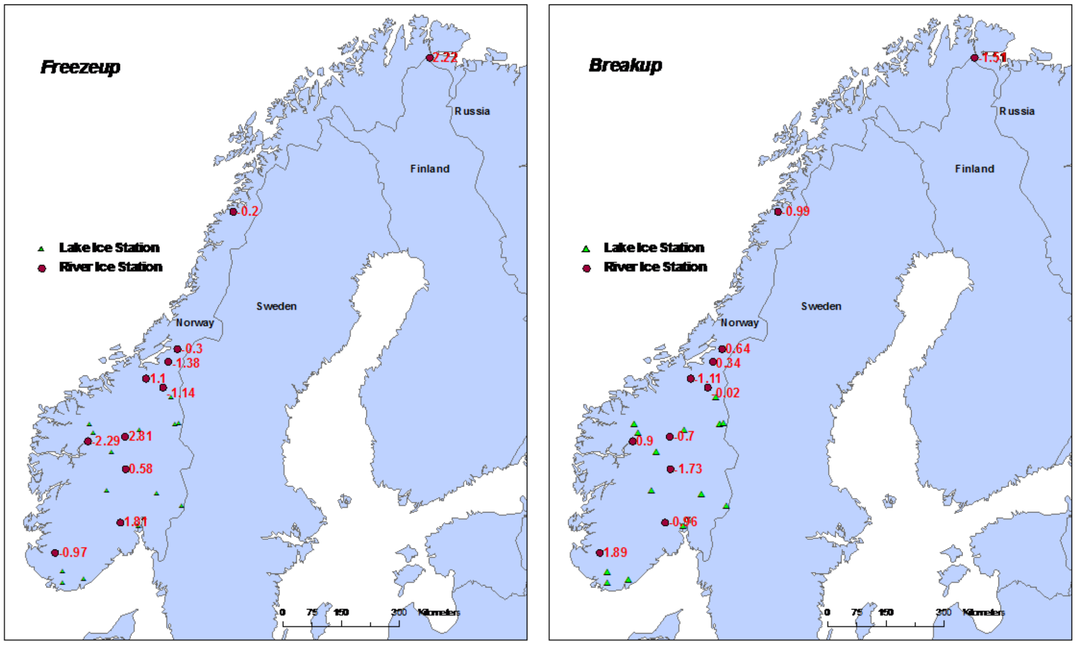

Figure 4. Z_{MK} values for river ice time series (values are significant at 10% level if $-1.64 \leq Z_{MK} \leq 1.64$).

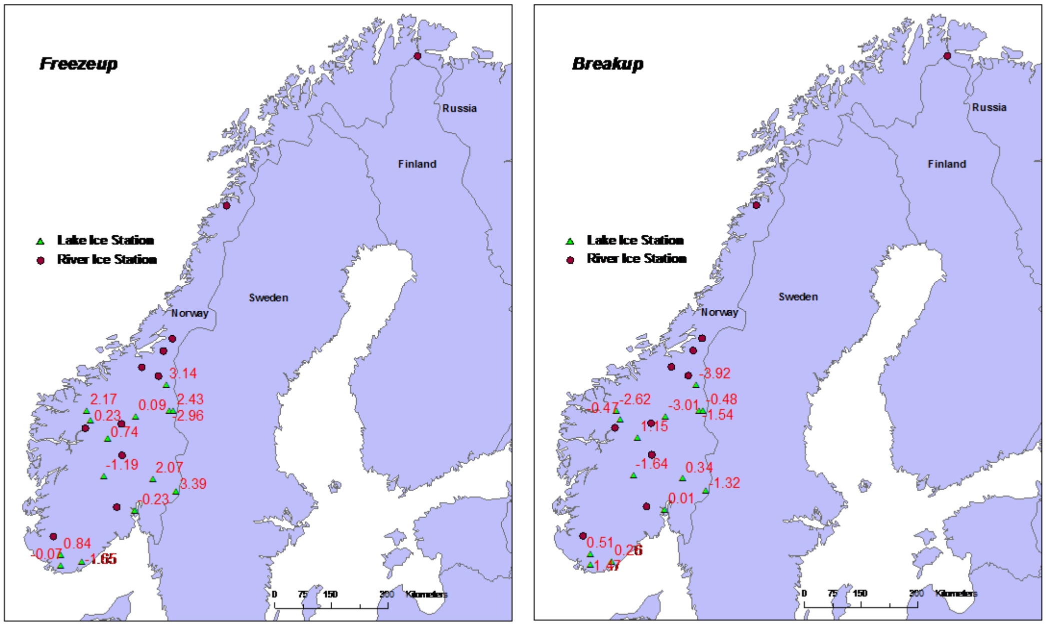

Figure 5. Z_{MK} values for lake ice time series (values are significant at 10% level if $-1.64 \leq Z_{MK} \leq 1.64$).

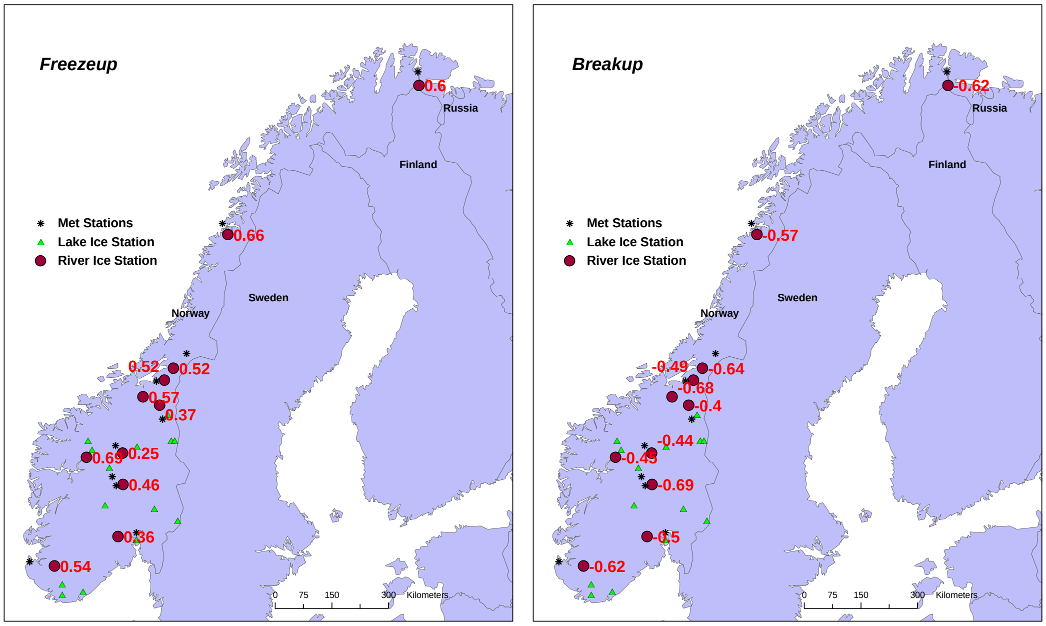

Figure 6. Spearman’s rho correlation between river ice dates and mean monthly temperature (values are for the best correlated month).

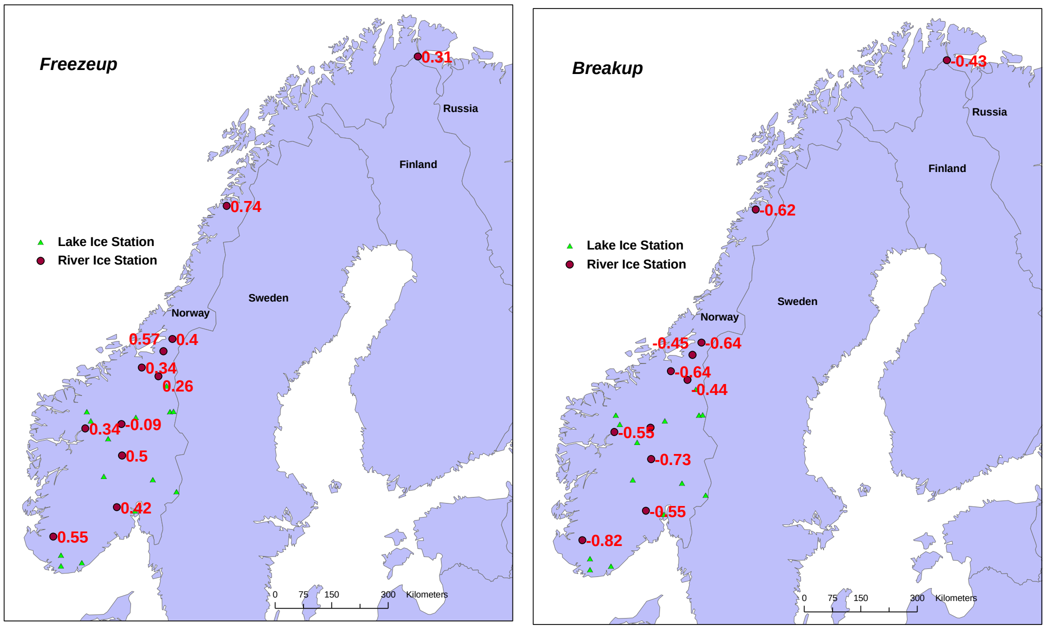

Figure 7. Spearman's rho correlation between river ice dates and river flows (values are for the best correlated month).

Table 1. Summary of river and lake ice observation stations used in the study.

S.No	Type	Station Name (Abbrev.)	Stn ID	Location		Data Length*	
				E	N	Freeze-up	Breakup
1	River	Dorgefoss (Dorg)	26.5	6.79	58.86	1913-1981 (57)	1913-1981 (69)
2		Egafoss (Egaf)	122.11	11.18	62.89	1950-1982(32)	1951-1982(32)
3		Etna (Etna)	12.7	9.63	60.95	1921-1996(72)	1922-2001(80)
4		Grunfoss (Grun)	127.6	11.81	63.79	1908-1991(62)	1952-1991(39)
5		Haga Bru (Haga)	122.2	10.28	63.07	1908-1995(87)	1913-1995(76)
6		Høggas Bru (Hogg)	124.2	11.36	63.49	1912-1985(65)	1913-1985(51)
7		Jondalselv (Jond)	15.2	9.59	59.71	1919-1993(72)	1920-1994(74)
8		Polmak (Polm)	234.1	28.06	70.07	1911-1997(84)	1912-1997(84)
9		Selfoss (Self)	161.2	14.69	67.00	1950-1982(33)	1951-1983(33)
10		Storøygardsbrua (Stor)	2.324	9.47	61.69	1972-1995(23)	1972-1996(25)
11		Ytri Bru (Ytri)	75.2	7.70	61.51	1928-1980(40)	1929-1980(41)
12	Lake	Atnsjøen	2.131	10.17	61.88	1951-2008(57)	1954-2009(54)
13		Aursunden	2.111	11.64	62.68	1902-2005(101)	1903-2005(100)
14		Breiddalsvatn	75.13	7.93	61.70	1967-2004(38)	1968-2005(38)
15		Femunden	311.4	11.87	62.07	1900-1995(83)	1901-1994(82)
16		Flaksvatn	20.3	8.21	58.33	1952-1989(38)	1952-1988(37)
17		Lelandsvatnet	23.3	7.29	58.19	1949-2000(52)	1950-1999(38)
18		Lygne	24.13	7.24	58.45	1925-2008(72)	1924-2009(72)
19		Mjøsa	2.825	11.21	60.43	1868-2005(98)	1864-2006(104)
20		Møkeren	313.1	12.37	60.17	1911-2006(73)	1911-2007(69)
21		Rauddalsvatnet	2.838	7.68	61.90	1967-2006(40)	1968-2005(38)
22		Rørvikvatn	80.1	10.45	59.66	1950-1997(47)	1951-1997(48)
23		Storsjoen	2.836	12.05	62.07	1967-2004(38)	1968-2005(38)
24		Tunhovdfjord	15.9	8.84	60.42	1920-1993(71)	1920-1994(68)
25		Vinsteren	2.167	8.87	61.32	1950-2004(54)	1951-2005(49)

*Numbers in brackets show the number of data points

Table 2. Trends and variability in river freeze-up dates.

River St.*	No. of Records	Mean	Std Dev	Min	Max	Sen's Trend (days/decade)
Dorg	57	333	17	301	363	-1.5
Egaf	32	317	14	298	362	-2.5
Etna	72	322	11	292	356	0.3
Grun	62	320	16	277	363	-0.2
Haga	87	314	13	291	361	0.6
Hogg	65	326	16	293	358	-1.6
Jond	72	315	15	288	353	1.2 (0.073)
Polm	84	291	10	273	320	0.9 (0.027)
Self	33	315	18	287	358	-0.8
Stor	23	334	15	303	352	11.1 (0.006)
Ytri	40	337	14	303	359	-3.3 (0.022)

*River stations are abbreviated by the first four letters

Table 3. Trends and variability in river breakup dates.

River St.	No. of Records	Mean	Std Dev	Min	Max	Sen's Trend (days/decade)
Dorg	60	111	18	64	138	1.5 (0.059)
Egaf	25	121	10	103	144	0.0
Etna	73	119	9	96	138	-0.9 (0.085)
Grun	39	110	15	61	136	1.6
Haga	77	107	13	66	136	-0.6
Hogg	51	104	19	61	149	0.4
Jond	74	104	16	61	131	-0.8
Polm	84	143	8	125	165	-0.5
Self	33	117	17	53	141	-2.1
Stor	25	127	12	106	152	-3.5
Ytri	41	76	17	46	108	1.9

Table 4. Trends of seasonal climatic data for representative stations.

River Station	**Nearest Met St.**	**Location N**	**E**	**Record**	**Z_{MK} (Temperature)***			**Z_{MK} (Precipitation)***		
					Autumn	**Winter**	**Spring**	**Autumn**	**Winter**	**Spring**
Dorg	44560	58.88	5.64	1936-2010	0.86	**2.48**	**3.01**	**2.45**	**3.42**	**2.83**
Egaf	10400	62.57	11.38	1910-2002	**2.01**	0.31	**2.91**	1.29	0.60	**2.19**
Etna	23160	60.92	9.29	1923-2010	0.47	0.47	2.09	-1.18	0.21	**2.82**
Grun	70850	64.16	12.47	1940-2010	0.09	**2.36**	**1.95**	0.71	**1.79**	0.29
Haga	10400	62.57	11.38	1910-2002	**2.01**	0.31	**2.91**	1.29	0.60	**2.19**
Hogg	69100	63.46	10.94	1946-2010	1.02	**2.26**	**2.73**	0.06	**1.74**	-0.92
Jond	19710	59.83	10.44	1914-2010	**3.01**	**2.38**	**3.56**	0.68	-0.13	**2.37**
Polm	96800	70.38	28.19	1951-2010	0.57	1.30	**2.26**	1.49	1.48	1.21
Self	82290	67.27	14.36	1954-2010	**2.53**	**2.62**	**2.16**	1.05	1.49	1.43
Stor	14600/ 23500	61.86 61.12	9.08 9.06	1949-2004 1962-2010	-0.82	1.02	1.70	-0.56	0.99	0.73
Ytri	14600/ 23500	61.86 61.12	9.08 9.06	1949-2005 1962-2010	-0.82	1.02	1.70	-0.56	0.99	0.73

*values in bold are significant at the 10% level

Table 5. Trend values for maximum and mean daily discharges (Mann-Kendall).

River Stn	**Record**	**Z_{MK} (max discharge)**			**Z_{MK} (mean discharge)**		
		Autumn	**Winter**	**Spring**	**Autumn**	**Winter**	**Spring**
Dorg	1913-2009	-6.70	-6.89	-7.15	-6.89	-7.41	-6.85
Egaf	1941-2009	-0.77	1.28	-1.31	0.49	1.11	1.25
Etna	1919-2009	-0.89	0.91	**-2.27***	-0.41	**2.11***	0.59
Grun	1951-2009	**-1.74**	-0.14	-1.23	**-1.73**	0.17	0.50
Haga	1908-2009	**-2.15***	0.41	1.32	-0.48	0.27	**2.74***
Hogg	1912-2009	-1.44	0.73	-0.74	-0.50	1.61	1.44
Jond	1919-2009	-0.57	-1.12	**-1.70**	-0.33	-0.10	-0.50
Polm	1911-2009	-0.03	0.57	0.72	0.79	-1.19	**2.40***
Self	1916-1998	1.27	-0.88	-0.02	-0.66	-1.46	-1.39
Stor	1970-1996	**1.68**	-1.15	-0.15	1.50	-1.33	0.31
Ytri	1918-1964	*Data length too short for analysis*					

*Bold: Significant at 5% level, Bold: Significant at 10% level

Table 6. Correlation of freeze-/breakup dates with monthly temperature.

Station	Mean FU Date	Mean BU Date	Month FU best Correlated	Spearman's rho(FU)	Month BU best Correlated	Spearman's rho(BU)
Dorg	30-Nov	22-Apr	Nov	0.54	Apr	-0.62
Egaf	14-Nov	02-May	Nov	0.37	Apr	-0.40
Etna	19-Nov	30-Apr	Nov	0.46	Apr	-0.69
Grun	17-Nov	21-Apr	Oct	0.52	Apr	-0.64
Haga	11-Nov	18-Apr	Oct	0.57	Mar	-0.68
Hogg	23-Nov	15-Apr	Nov	0.52	Mar	-0.49
Jond	12-Nov	15-Apr	Oct	0.36	Apr	-0.50
Polm	19-Oct	24-May	Oct	0.6	May	-0.62
Self	12-Nov	28-Apr	Nov	0.66	Apr	-0.57
Stor	01-Dec	08-May	Nov	0.25*	Mar	-0.44
Ytri	04-Dec	18-Mar	Nov	0.69	Mar	-0.45

*All correlations are significant at the 5% level except this value

Table 7. Correlation of freeze-/breakup dates with monthly mean flow (freeze-up) and maximum daily flow in a month (breakup).

Station	Mean FU Date	Mean BU Date	Month FU best Correlated	Spearman's rho(FU)	Month BU best Correlated	Spearman's rho(BU)
Dorg	30-Nov	22-Apr	Nov	0.55	Mar	-0.82
Egaf	14-Nov	02-May	Sep	0.26*	Mar	-0.44
Etna	19-Nov	30-Apr	Nov	0.50	Apr	-0.73
Grun	17-Nov	21-Apr	Nov	0.40	Mar	-0.64
Haga	11-Nov	18-Apr	Nov	0.34	Mar	-0.64
Hogg	23-Nov	15-Apr	Nov	0.57	Mar	-0.45
Jond	12-Nov	15-Apr	Oct	0.42	Mar	-0.55
Polm	19-Oct	24-May	Oct	0.31	Apr	-0.43
Self	12-Nov	28-Apr	Nov	0.74	Apr	-0.62
Stor	01-Dec	08-May	Sep	-0.09**	Apr	-0.28*
Ytri	04-Dec	18-Mar	Nov	0.34	Mar	-0.55

*Not significant at the 10% level ** value showing unusual negative correlation

Table 8. Correlations of freeze-/breakup time series with the NAO indices.

River Stn	**Freeze-up***				**Breakup***			
	DJF	MAM	JJA	SON	DJF	MAM	JJA	SON
Dorg	-0.01	0.05	-0.19	0.05	-0.11	-0.16	-0.13	-0.05
Egaf	0.12	0.17	0.20	-0.27	**0.45**	**-0.44**	0.21	0.22
Etna	0.08	0.11	-0.12	-0.13	0.01	0.04	**0.22**	0.16
Grun	0.10	-0.16	0.01	-0.03	-0.15	0.05	**-0.30**	-0.25
Haga	-0.05	0.17	0.01	-0.04	-0.11	-0.15	0.07	0.05
Hogg	-0.17	0.15	**0.26**	0.08	0.09	**-0.24**	0.17	0.01
Jond	-0.02	-0.10	**-0.21**	0.13	0.08	-0.08	-0.01	0.11
Polm	0.08	-0.12	0.09	-0.05	-0.11	**-0.21**	-0.12	-0.16
Self	0.02	-0.10	0.05	**0.31**	-0.24	0.14	-0.02	0.01
Stor	-0.15	0.16	-0.08	-0.11	-0.20	0.26	-0.05	0.01
Ytri	-0.15	-0.08	0.11	0.19	-0.18	0.01	0.21	0.08

*Bold values indicate correlations significant at 10% level