Identifying flood deposits in lake sediments

Changing frequencies and potential links to long-term climate change

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Scientific environment

This study was done at the Department of Earth Science at the University of Bergen and at the Bjerknes Centre for Climate Research (BCCR).

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Thanks to my parents for keeping things in perspective, and making an effort to figure out a scientific terminology quite different from their own.

To my closest family, Karianne and Wilhelm, thank you for having patience with me, and for always being loving and encouraging. I love you both.

Eivind W. N. Støren

Bergen, February 2011

Foreword

At the time of writing (end of January 2011) more than 200,000 people have been evacuated from their homes due to flooding in Queensland, Australia, and the number of people killed by floods and associated landslides in Brazil is close to one thousand. These and other recent natural disasters have initiated a debate as to the degree to which such events may be linked to anthropogenic forced climate change. NCAR climatologist Kevin Trenberth, for example, goes far in blaming global warming for the recent extreme events: "Certain events would have been extremely unlikely to have occurred without global warming, and that includes the Russian heat wave and wild fires, and the Pakistan, Chinese, and Indian floods" (Reuters 12 January 2011).

Although this thesis does not address the influence of anthropogenic forcing on either global climate or local-scale extreme events, such debates create the social and political framework of the time, and clearly emphasise the need to pay attention to the frequency of such events in a changing climate. The presented work focuses on the natural variability of the frequency of extreme events from a long-term climate perspective (the last 10 000 years) – mechanisms that have to be understood before reliable predictions for the future can be made.

The study was initiated in August 2006. The Faculty of Mathematics and Natural Sciences at the University of Bergen funded the position as part of the University's contribution to the Centre of Excellence at Bjerknes Centre for Climate Research. The following foundations gave additional economical contributions to the fieldwork etc.: *Nansenfondet og de dermed forbundne fond*, *Hans og Helga Reuschs legat til fremme av studiet av geografi og geologi*, *Det alminnelige naturvienskapelige forskningsfond and Bergen myrdyrkningsforenings fond.*

Abstract

This thesis consists of an introduction and three individual papers that investigate the possibility for identifying the sedimentary imprint of catchment processes in lake sediments, emphasising on extreme events and in particular those deposited by river floods. Three individual lake sediment basins in southern Norway have been studied and changes in the frequency of such events are reconstructed for the last *c*. 10,000 years.

In Paper I, the sediments of the glacier-fed Lake Russvatnet in eastern Jotunheimen (61′ N 8′ E) were studied. The record comprises a combination of glacier-derived material produced by the glacier Blackwellbreen and also several episodic processes in the catchment area such as floods and debris flows. In order to distinguish late-Holocene (last 4000 years) river floods and mass movements from glacier fluctuations, the sedimentary record from Russvatnet was analysed for grain-size distribution and minerogenic content, which allowed for discrete mass-movement and river-flood deposits to be recognized. Twenty-two such episodic events were identified; 11 mass movement events and 11 river-flood events. Enhanced river-flood and colluvial activity are observed at 4000–3400, 2900–2500, 2000–1400 and 1000–500 cal. years BP, suggesting a decreasing trend over the last 4000 years. At *c*. 2300 cal. years BP a shift in sedimentation regime from a paraglacial to a glacially dominated regime was observed, followed by a Neoglacial expansion period after 2300 cal. years BP.

In Paper II we examine the possibility for objectively identifying flood deposits in lake sediments and hence construct Holocene flood records that may reveal changes in the long-term frequency of river floods. The method for identifying flood deposits was successfully applied to a high-resolution lake sediment core retrieved from Meringsdalsvatnet in eastern Jotunheimen (61′ N 9′ E) resulting in a detailed record of river-flood activity covering the last *c*. 10,000 years, including floods that have also been recorded by instrumental and historical data. The minimum number of individual floods recorded for this period is *c*. 100. On centennial timescales significant change in flood frequency is observed that arguably can be attributed to

large-scale climatic changes such as the varying amount of winter precipitation and number of summer rainstorms. The flood frequency was low during the early Holocene (9770–7700 cal. years BP), and was even lower for the period that followed, lasting until 5500 cal. years BP. For the next 2500 years, a modest increase in flood activity followed. This trend was truncated at 2500 cal. years BP by a sudden shift towards increased flooding frequency. With the exception of a short interval around 1000 cal. years BP, when the number of floods was again low, this tendency of increased flood activity prevailed until the present day; including Stor-Ofsen, a large flood that occurred in AD 1789, and also three other historically documented river floods.

In Parer III we compared the record from Jotunheimen to a second continuous, high-resolution palaeoflood record from Butjønna (62′ N 10′ E) and found that both the frequency and distribution of flood events over southern Norway has changed significantly during the Holocene. The present regional-discharge regime is dominated by spring–summer snowmelt, and results indicate that the changing flood frequency cannot be explained by local conditions associated with the respective catchments of the two lakes, but rather by long-term variations of solid winter precipitation and related snowmelt. Applying available instrumental winter-precipitation data and associated sea-level pressure re-analysis data as a modern analogue, we document that atmospheric-circulation anomalies, significantly different from the North Atlantic Oscillation (NAO), have some potential in explaining the variability of the two different palaeoflood records. Centennial-scale patterns in shifting flood frequency might be indicative of shifts in atmospheric circulation and can shed light on past pressure variations in the North Atlantic region, in areas not dominated by the NAO. Major shifts were found at about 2300, 1200 and 200 cal. years BP.

This thesis presents and applies approaches to detect rapid geological events in lake sediment archives, and indicates that there have been significant changes in the frequency of floods and possibly debris flows over the Holocene. These changes may partly be linked to climatic, particularly precipitation, fluctuations, but also to other mechanisms such as land uplift, changing seasons and vegetation changes.

List of publications

Paper I

Støren, E.N. Dahl, S.O and Lie, Ø. (2008). Separation of late-Holocene episodic paraglacial events and glacier fluctuations in eastern Jotunheimen, central southern Norway. *The Holocene* 18,8, pp. 1179–1191.

Paper II

Støren, E.N., Dahl, S.O, Nesje, A. and Paasche, Ø. (2010). Identifying the sedimentary imprint of high-frequency Holocene river floods in lake sediments: Development and application of a new method. *Quaternary Science Reviews* 29, pp. 3021–3033.

Paper III

Støren, E.N., Kolstad, E.W. and Paasche, Ø. (submitted) Linking past flood frequencies in Norway to regional atmospheric circulation anomalies. *Submitted to Journal of Quaternary Science*

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Outline

This thesis consists of an introduction and three individual papers. An underlying aim for this study has been to improve the current understanding of how catchment processes can be identified in lake-sediment deposits. For reconstructions of various environmental processes –based on lake sediment archives– this is a fundamental premise for obtaining reliable results. In the following introduction, I will give a short overview of the scientific background, the objectives of the study and summarize the scientific results. In Paper I, we focus on the recognition of sedimentary units in a lake-sediment core that is related to dominant catchment processes, such as mass-wasting events and floods, but also glacier activity. In Paper II we continue on this thread, and present and apply an approach that objectively identifies high-frequency flood events in a lake-sediment record, reconstructing a high-resolution record of Holocene flood frequency. A main implication of the findings in Papers I and II is that it is possible to detect such sedimentary events and that there is a potential in studying the long-term impact of climate change on the frequency of extreme events, and in particular floods. In Paper III, we use instrumental data to investigate to what extent regional atmospheric-circulation patterns impact local winter precipitation and the distribution and subsequently shed light on changes in the frequency and distribution of floods over southern Norway during the last c. 6600 years.

Dybt inde i de umaadelige Fjeldegne, som udbrede sig der, hvor Agershuus og Bergens Stifter paa deres nordligere Grændser beröre hinanden, hæve sig — udmærkede fra alle övrige — de kolossalske *Jotunfjelde* *) med den evige Snee og de blaanende Gletschere.

Translation: Deep in the vast mountain areas, where eastern and western Norway meet, rises – beyond all others – the colossal Jotunfjelde with eternal snow and indiscernible blue glaciers.*

Clipping (and translation) form the introduction to *Magazin for Naturvidensaberne* in 1823, where B. M. Keilhau gave the first geological report from Jotunheimen (Keilhau, 1823). *Keilhau named the mountains *Jotunfjelde* (meaning giant-mountains). The poet Aa O. Vinje gave the modern name, Jotunheimen, in 1862 (Thorsnæs, 2009).

Introduction

River floods and debris flows are among the most common and destructive of all natural hazards on Earth. Major river floods in Pakistan and China were among the top five most costly and deadly natural disasters in 2010 (MunichRE, 2011), and the societal impact of such extreme events has recently received increased attention, not only because of the substantial costs associated with natural disasters, but also because the natural cycles causing these extreme events appear to be changing (IPCC, 2007). A number of Earth System Models (ESMs) and Atmosphere–Ocean General Circulation Models (AOGCMs) predict changes in the regional distribution of precipitation due to global warming (e.g. Allen and Ingram, 2002; Solomon *et al.*, 2009), including an increase in the frequency and magnitude of hydrologic extremes.

River floods are commonly defined as a rapid increase in discharge, that overtops the banks and temporarily inundate land areas not normally covered by water (e.g. EU Directive on the Assessment and Management of Flood Risk, 2007). Magnitudes of floods are defined by their recurrence interval or return period (10-, 200- or 500-year flood), which is the average number of years between floods of a certain size (10, 200 or 500 years) over a period of time (Figure 1a). Extremes are events of exceptionally high magnitude that differ substantially from the mean value in the available dataset, often expressed by a number of standard deviations or percentiles. Extremes tend do be of short duration and have low frequency, but following a change in the mean state, the number of events defined as extremes in the previous period may change, if the frequency distribution remains the same (Figure 1b). River floods are extreme events in terms of discharge, but also in terms of erosion, sediment transport, and damage potential. Debris flows are similarly extreme events in that they have a high recurrence interval and constitute an exceptionally high and rapid sediment transport that may create a substantial geomorphological and sedimentological change over a short time period.

The connection between climate change and the frequency and magnitude of extreme events is complex and not fully understood. The ability of river catchments to store water and release it after a certain period of time is likely to modulate the discharge, either as a buffer-effect preventing a flood, or conversely, as a direct cause of the flood, such as in the case of an ice-jam break or *jøkulhlaup*. Such effects are dependent on a number of parameters and may vary regarding time scale, due to the changing water saturation of the ground; on seasonal scale, due to snow cover and ground frost; decadal scale, due to vegetation changes; and centennial to millennial scale, due to glacier fluctuations and landscape development, including tectonic movement.

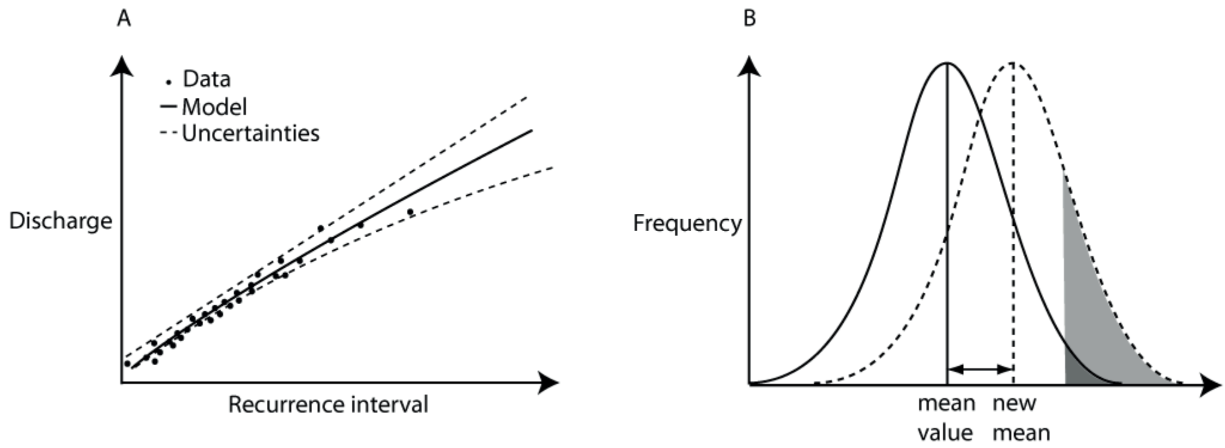


Figure 1: A) Conceptual figure showing recurrence intervals of increasing discharge values. Extreme-value modelling is often based on a limited set of data and uncertainties increase for high magnitude, low frequency events. B) Conceptual figure of expected change in the number of extreme events (as defined by the first distribution) following a change in the mean state (after Mitchell et al., 1990).

Although some climate-related trends are found in the discharge of the Nordic countries (e.g. Hisdal *et al.*, 2006; Wilson *et al.*, 2010), instrumental records are in most cases too short to properly assess the relative role of such mechanisms. In Norway the instrumental river discharge record dates back 170 years (river Glomma). Continuous time series do, however, not commonly exceed more than 30–40 years. Historical records report single extreme events as early as in the fourteenth century and may provide some additional information (e.g. Roald, 2002; Furseth, 2006).

Palaeorecords, covering thousands of years and thus also climate change during the Holocene, may, however, add insight to the changing frequency of extreme events during climate change that is not covered by the instrumental or historical records. Regionally, the early to mid-Holocene climate was, during certain periods, up to several degrees warmer than during the last few decades (Jansen *et al.*, 2007) concerning the range of predicted global change for the coming century (Meehl *et al.*, 2007) and predicted local (Norway) change for the coming 50 years (Hanssen-Bauer *et al.*, 2009). Such changes may cause a shift in the mean state that affects the likeliness of what was previously defined as *extreme* to occur (Figure 1b). Examination of how event frequency has responded to large changes in climate forcing in the past may thus be useful in assessing how the same processes will respond to the large climate change anticipated for the future.

"Last week it rained for a few days: At the same time rivers and creeks grew and flooded land, fields and meadows, took away farms, houses, bridges, roads, timber, and wooden stables, on which occasion a few people where killed. It caused great damage everywhere."

Media coverage of the Stor-Ofsen flood event in 1789 printed in *Trondheims Adresse Contoirs Efterretninger*, 31 July 1789 (Translated from Norwegian by the author). The Stor-Ofsen is the most damaging natural disaster in Norway during historic times. More than 70 people were killed and 120 large landslides are associated with the event. Large parts of southern and central Norway was affected and many people migrated from the most severely hit areas (Furseth, 2006).

Research objectives

The following main research objectives were focused on:

1- Utilize and develop methodologies to identify the sedimentary imprint of extreme events such as floods and debris flows in lake sediments.

2- Develop process-specific records of Holocene floods and debris flows, and investigate the possible impact of climate change on the frequency of such events.

In the following I present and discuss the approaches used in Papers I-III to address these objectives.

Identifying floods and mass-wasting events using lake sediments

The science of palaeohydrology and the study of palaeofloods is a relatively young discipline, emerging during the 1950s (see e.g. Baker, 2008). It is truly an interdisciplinary field of research as it encompasses the movement of water in continental areas, its geomorphologic influence on the landscape and its interaction with the atmosphere.

Traditionally the identification of extreme events such as floods and debris-flows in sedimentary archives is simply based on a visual examination of colour, textural and/or quantifiable sedimentological characteristics. Such more or less qualitative identification may provide in-depth knowledge of single events, but may contain a subjective element that may form a source of uncertainty regarding consistency of the identification criteria. In order to study large datasets or do comparative studies, a quantitative approach is, therefore, more suitable (Papers II and III). In this thesis, both approaches are explored in order to gain knowledge on the evolution of extreme events during the Holocene period.

Relative to normal flow conditions, floods and debris flows increase erosion via remobilisation and transport of materials along ravines, river channels, floodplains or bedrock-canyon marginal zones. Based on such associated changes, section studies of alluvial fans (Matthews *et al.*, 2009), floodplains and slack-water flood-deposit stratigraphy (Baker, 1987; Knox, 2000; Benito *et al.*, 2003; Baker, 2008) and discrete sharp-bounded minerogenic horizons in lake sediments (Thorndycraft *et al.*, 1998; Brown *et al.*, 2000; Nesje *et al.*, 2001a; Bøe *et al.*, 2006; Moreno *et al.*, 2008) have been used in order to reconstruct records of Holocene river floods and debris flows. The main challenge in utilising sedimentary archives in order to reconstruct palaeorecords of such events has, however, been to obtain continuous records that are able to record information about high-frequency sedimentary changes without, at the same time, being disturbed or eroded by the events themselves. Continuous lake-sediment archives are well suited for the purpose of identifying decadal to centennial changes in event frequency as lake basins of a certain depth easily trap material and are resilient to erosion. The application of methods that are capable of distinguishing sedimentary bands on a millimetre or even sub-millimetre scale (see e.g. CT-scanning in Paper II) allows for the detection of subtle sedimentary changes in lake-sediment cores. Radiocarbon (^{14}C) dates obtained from macrofossils commonly return age estimates within uncertainties of ± 20–50 years depending on the specific archive in question. Lead (^{210}Pb) dates usually cover the last 150–200 years with very high precision, returning age estimates within ranges of ±10–20 years. Thus, by using suitable lake-sediment archives, it is possible to track continuous changes in event frequency on a decadal–centennial time scale over several thousands of years.

Using sedimentary archives for palaeoclimatic reconstructions, event layers are commonly regarded as noise and may cause a substantial source of error if interpreted as continuous sedimentation (Paper I). Arnaud *et al.* (2002) introduced a methodology using the grain-size distribution in a sediment core to differentiate between discrete rapid-event layers and continuous sedimentation. In Paper I we utilize this concept, and based on grain-size grading and degree of sorting we investigate the possibility of separating the dominant processes of the complex multi-process sedimentary system of Lake Russvatnet (Figure 2). River floods, or high surface runoff, are recognized by an increase in the mean grain size and an increased degree of sorting. These parameters are calculated using Gradistat software and the Folk and Ward (1957) method defining the mean grain size M (Eq. 1) and sorting as the spread around this mean expressed in standard deviations (σ) (Eq. 2). P_x is the grain diameter at the cumulative percentile value of x (Blott and Pye, 2001).

$$M = \exp\frac{\ln P_{16} + \ln P_{50} + \ln P_{84}}{3} \qquad \textit{(Eq. 1)}$$

$$\sigma = \exp\left(\frac{\ln P_{16} - \ln P_{84}}{4} + \frac{\ln P_5 - \ln P_{95}}{6.6}\right) \qquad \textit{(Eq. 2)}$$

Mass-wasting deposits are recognized by their increased mean grain size (M), and by a decrease in the degree of sorting (increase in σ) compared to the continuous sedimentation or background signal.

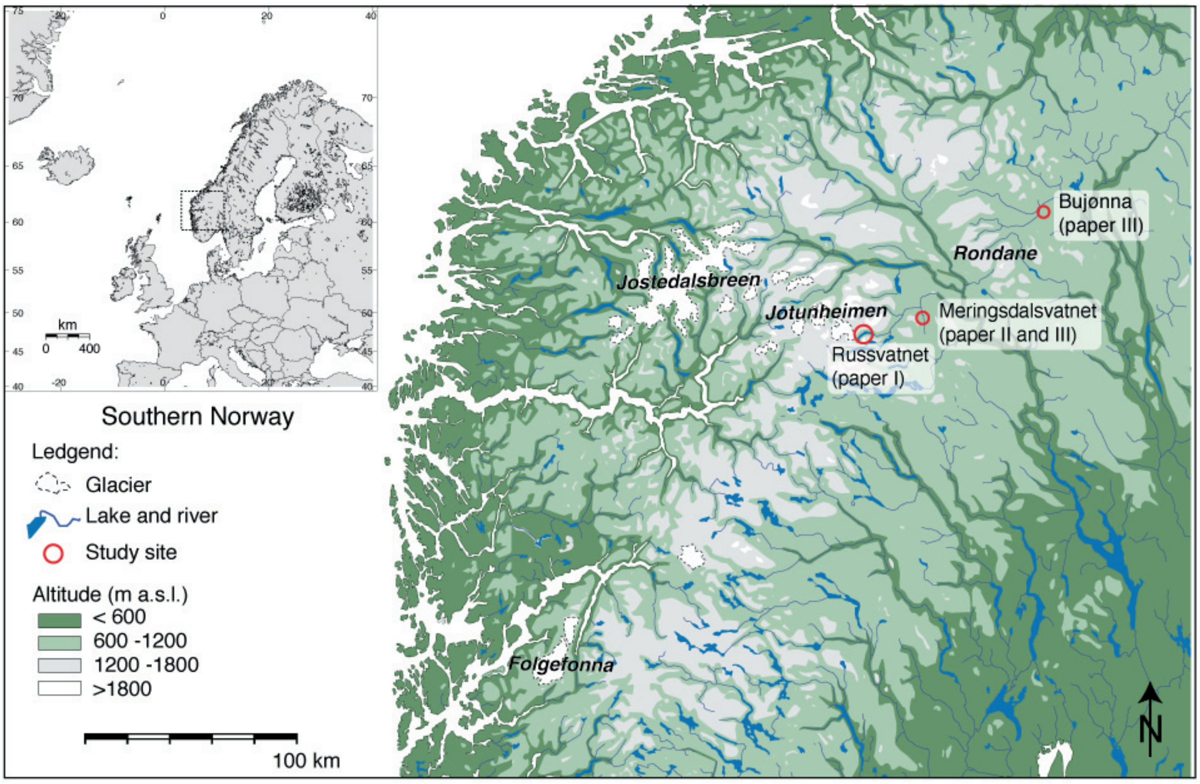


Figure 2: Topographic map of southern Norway. The location of the studied Lakes Russvatnet (Paper I), Meringsdalsvatnet (MER) (Papers II and III) and Butjønna (BUTJ) (Paper III) are marked on the map.

Learning from findings in Russvatnet (Paper I), where floods and debris flows dominated the sedimentary succession, and inspired by Bøe *et al.* (2006), who recorded more than 100 flood events in Butjønna in the Østerdalen region (Figure 2), we were seeking a "single-process" archive recording river-flood activity in the Jotunheimen region. In Lake Meringsdalsvatnet (Figure 2) we found such a sedimentary environment consisting of a background signal of organic gyttja and distinct light-grey silty layers representing individual flood layers (Paper II, Figure 3). The study site at a former delta surface ensures an abundant source of fine-grained material and a flat area around the lake preventing the direct influence of slope processes. There is no glacial input to the lake and no gravely layers, such as the debris-flow units found in Lake Russvatnet. Due to the thin laminations (cm–mm scale) and the high-frequency of events, a quantitative approach to determine the Holocene flood frequency was aimed for. Our objective criterion for the identification of flood events rests on the assumption that flood events remobilize minerogenic catchment material at a rate significantly higher than for normal flow conditions and transport it to the lake basin. The rates of change (RoC) in high-resolution parameters sensitive to the influx of such minerogenic content is used as a diagnostic tool to constrain sedimentary intervals consisting of remobilised catchment material, by marking the onset of individual floods (Figures 3 and 4).

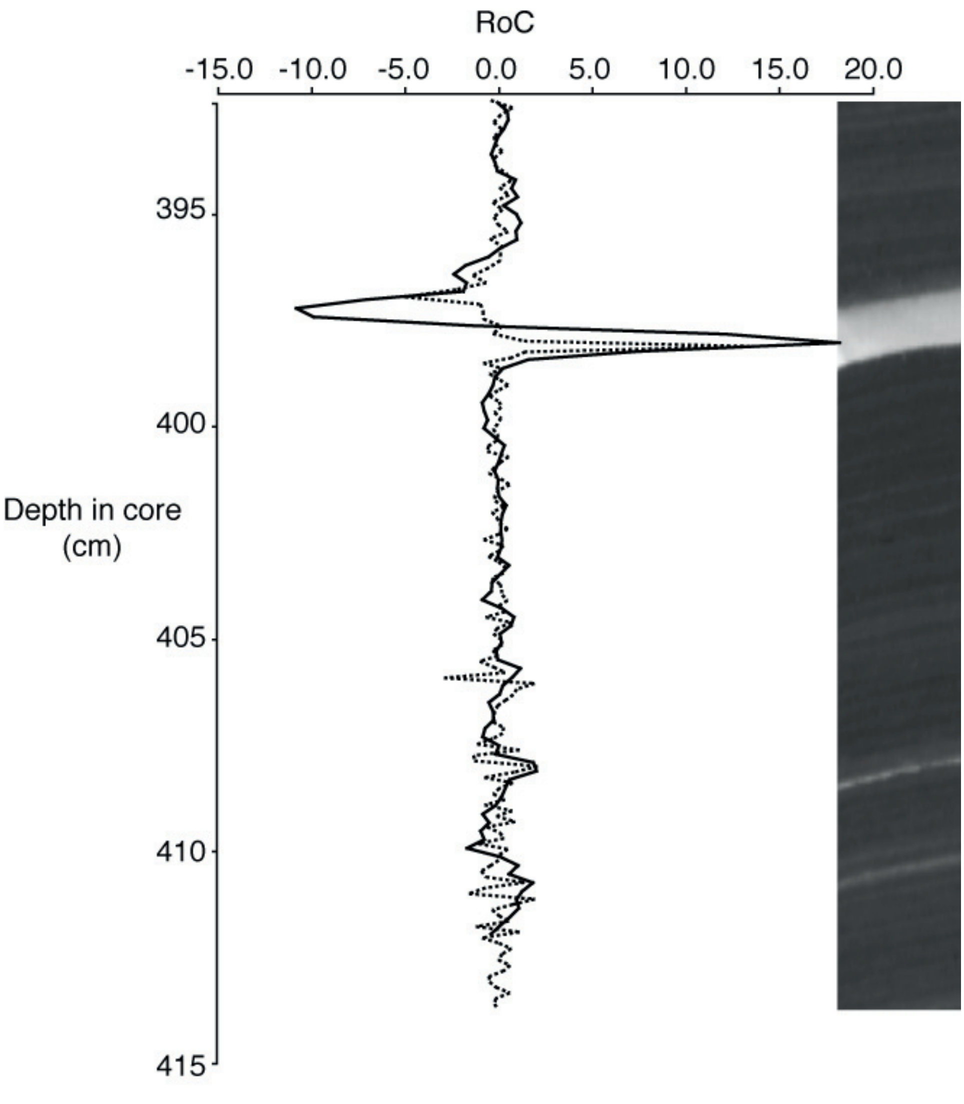


Figure 3: Example of how a flood layer in the core (MERP-207, Paper II) is detected by rate of change in magnetic susceptibility (full line) and CT-number (dotted line). A CT X-ray image (right) of the core section shows dense (light) layers deposited by floods.

The sensitivity of the approach is determined by the RoC value regarded as sufficient to represent a flood event. Figure 5 show cumulative distributions of RoC values in two records used in Papers II and III, and the corresponding number of recorded events by using an increasing level of determination. In Papers II and III we used a threshold level of one standard deviation. This level corresponds to the 94th (MER) and 89th (BUTJ) percentile (records are not strictly normally distributed), and indicates that RoC values above this threshold level are truly extreme values in the datasets, marking significant changes in the input of minerogenic material. A less conservative identification threshold results in a larger number of recorded floods (Figure 5), and would strengthen the statistical basis for further analysis. This would, however, decrease the robustness of the results as well. Positive identification of several known regional historic floods (Figure 4) indicate that the utilized RoC threshold is a reasonable estimate and that the approach to record these events, indirectly through the sediments they carry and subsequently deposit as lake sediments, is reliable.

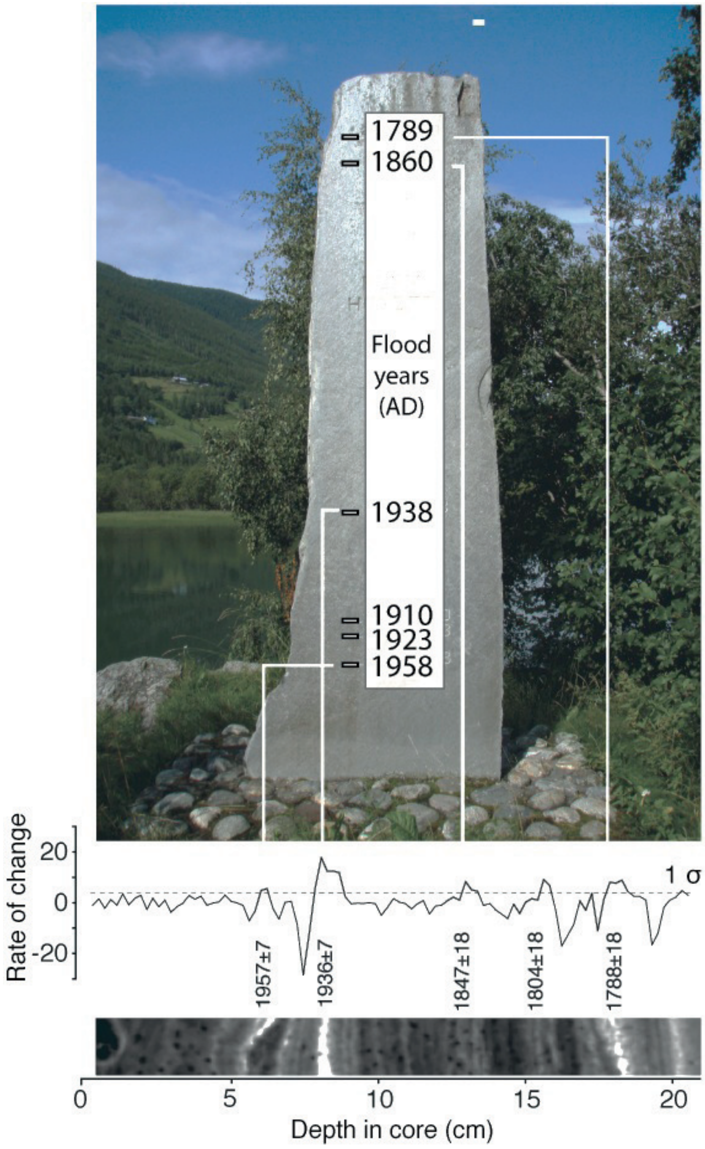
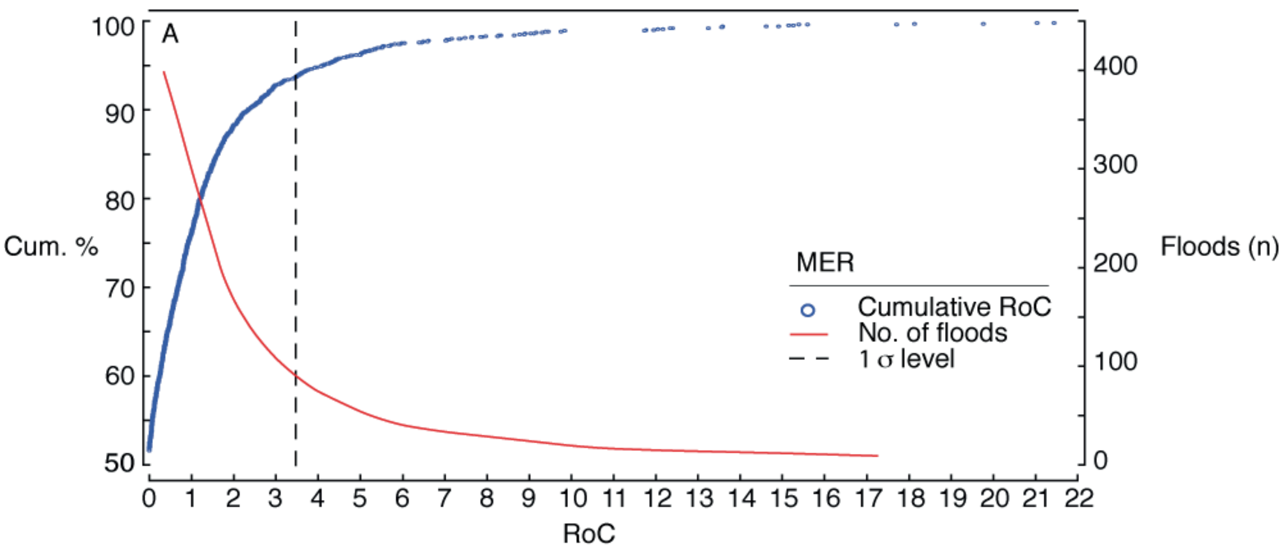


Figure 4: Flood marker at Lalm (c. 20 km east of Meringsdalsvatnet) indicating large historical floods in the area. The highest recorded level was during Stor-Ofsen on June 22 1789. Flood layers identified in MERP-207 (Paper II) by rate of change in magnetic susceptibility exceeding one standard deviation (1σ) are indicated below the picture. Dates on the identified layers correspond to the age depth model of the sediment core (see Paper II).



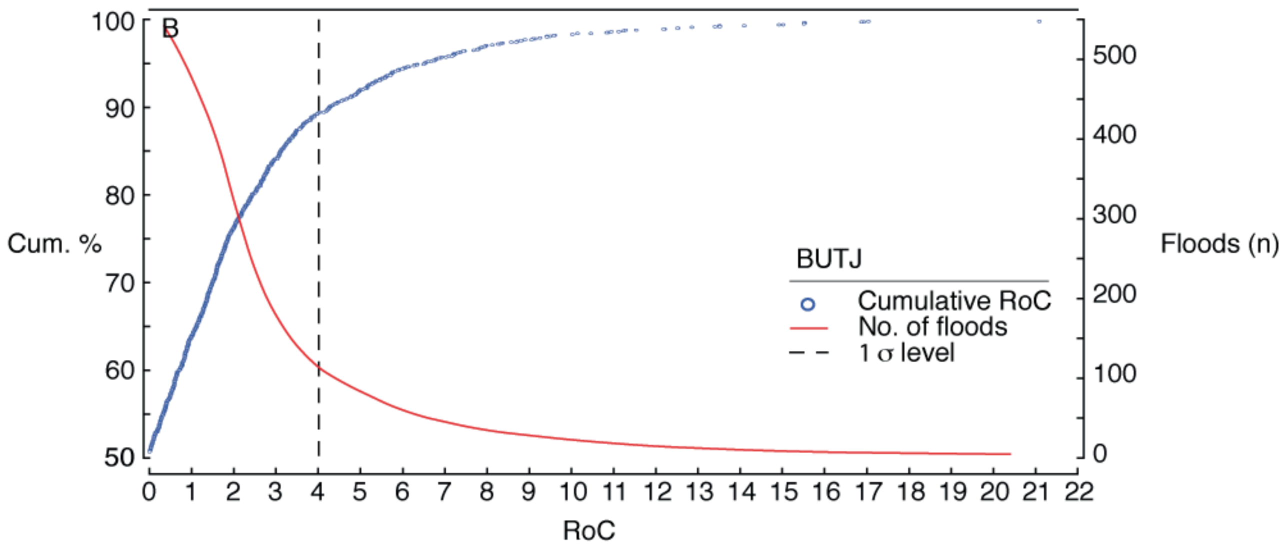


Figure 5: A) Cumulative distribution of positive RoC in magnetic susceptibility values in the MER record (blue dots) and the number of flood events recorded using different levels of RoC for positive identification (red line). The dotted line indicates the one standard deviation level of RoC=3.4 (94th percentile) resulting in 92 flood events (Papers II and III). B) The same as A, but for the BUTJ record. The dotted line indicates the one standard deviation level of RoC=4.1 (89th percentile) resulting in 112 flood events (Paper III).

Extreme events in a long-term climatic perspective

Reconstructions of past climate change are commonly based on biological or glaciological proxies that typically record seasonal or mean annual variations averaging over several years, decades or centuries. Extreme events such as debris flows and floods, commonly triggered by weather fluctuations with a duration of hours to months, are fundamentally different from these averaging variables. Palaeorecords of extreme events may therefore provide insight to the variation of short-lived events over long time scales. Modern process-form relationships are widely used in palaeo-sciences to reconstruct past environments. For reconstruction of the complex relationship between climate change, atmospheric variability and the frequency of debris-flows and floods we have, however, to be aware of some limitations to this approach.

(i) Extreme events commonly result from short-term, local weather events such as extreme precipitation or rapid snowmelt interacting with local site conditions. Event records, therefore, tend to have a stochastic element not easily related to climatic variables, and a precise correspondence between transient climatic changes and single events is thus not expected.

(ii) During the relatively short period of detailed instrumental observations, only a very limited number of extreme events have occurred, and the modern analogue is therefore based on a limited set of criteria.

These limitations are, however, the main motivations for doing this kind of study as well. Long-term records are needed in order to assess the long-term relationship between climate change and event frequency.

A general trend in a changing climate – changing the mean state (cf. Figure 1b) – may move the limits for triggering extreme events and dominate over the local site conditions (e.g. Matthews *et al.*, 2009). In the reconstructed flood records (Papers II and III), significant changes have been found over the last 10,000 years. Figure 6 shows the different frequency distributions in RoC values in the BUTJ record between the Holocene thermal maximum (HTM) and the Neoglacial period.

Following the above discussion, the RoC indicates an influx of flood-transported sediments, and the shift towards higher variability in the Neoglacial period is thus indicative of increased flood frequency, possibly caused by a shift in the boundary conditions (cf. Figure 1b).

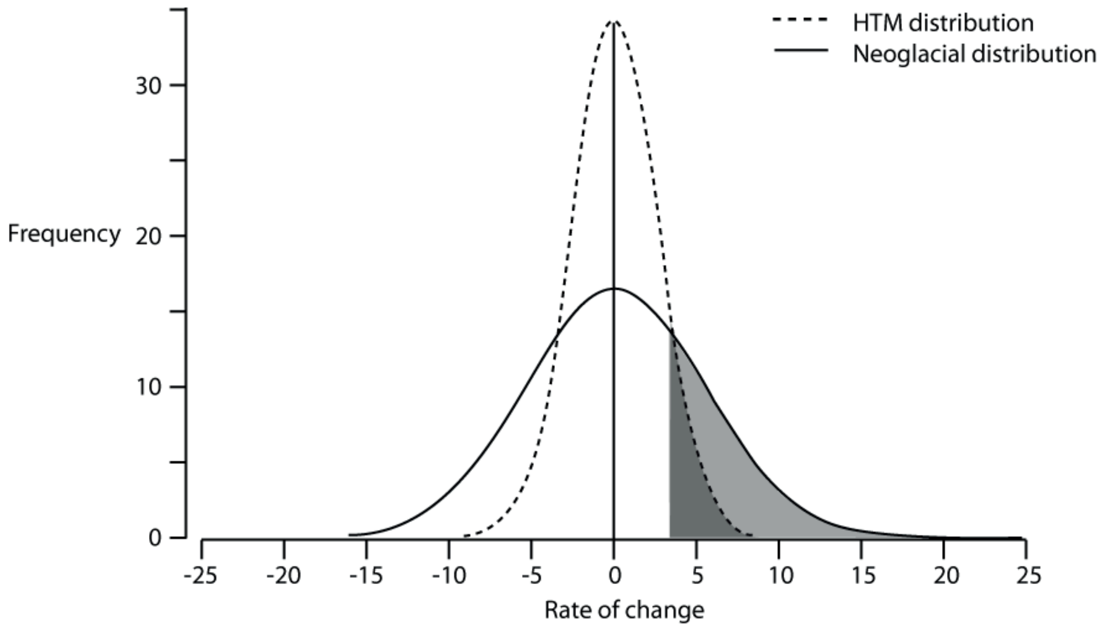


Figure 6: Frequency distributions of rate of change (RoC) values from HTM and the Neoglacial period in the BUTJ core (Paper III). Distributions are based on selections of 230 vales from 6000–7000 cal. yr BP and 500–1500 cal. yr BP, respectively. The shaded areas indicate values above the threshold for positive flood identification (1σ). Compared to HTM, the Neoglacial distribution indicates an increased RoC variability, arguably caused by an increase in flood frequency.

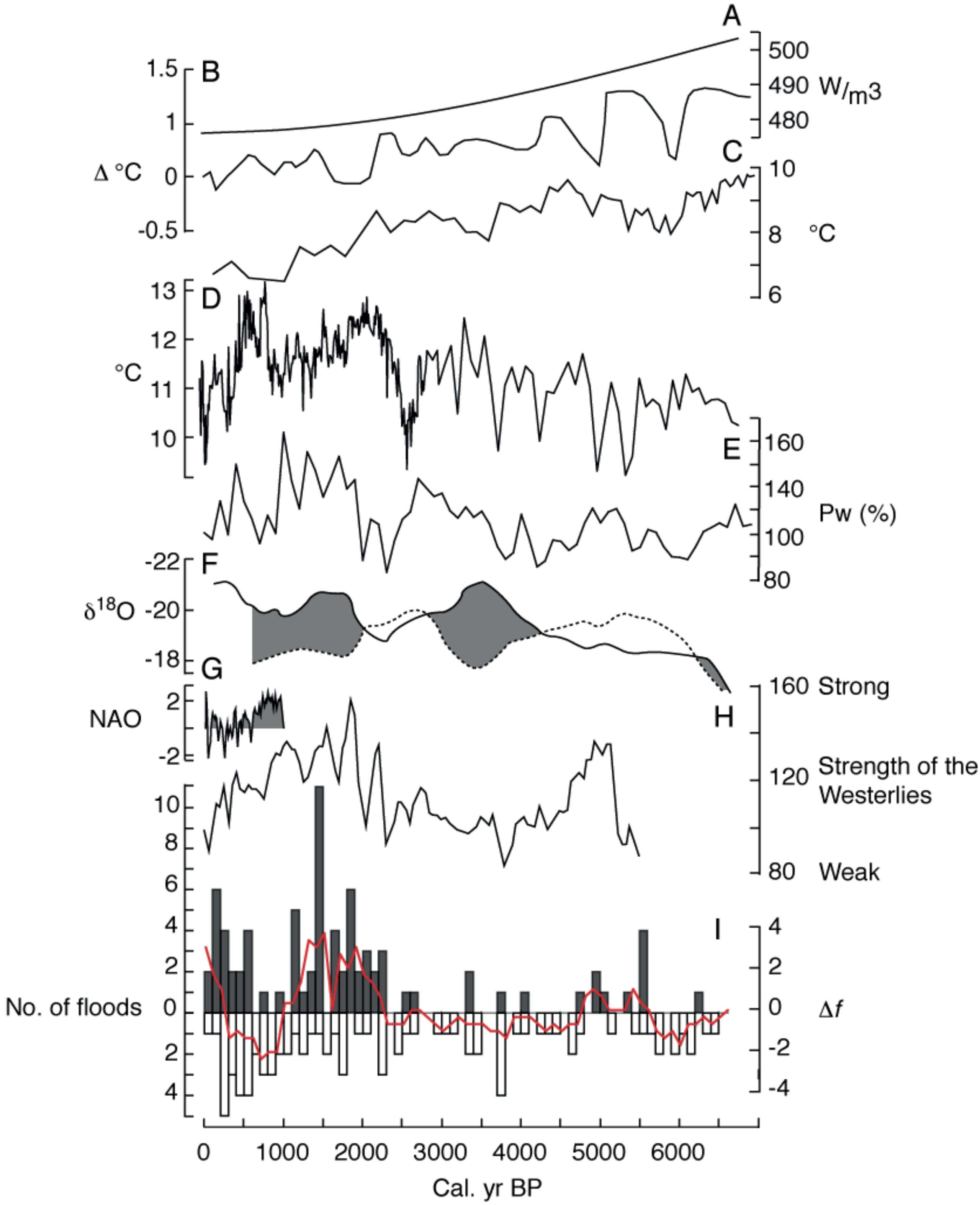
Rapid snowmelt and heavy summer precipitation are the most common triggering mechanisms of both river floods and debris flows in eastern Norway (Sandersen, 1997). The amount of water stored as snow during the winter accounts for about half the annual precipitation in southern Norway, and in the mountains it account for even more (Wold, 1992). Snowmelt is thus the major contributor to river discharge (Gottschalk *et al.*, 1979) and rapid snowmelt is argued to be the dominating triggering mechanism behind river floods (Papers II and III and discussions therein). From historical records we also find that the majority of floods in eastern Norway have occurred during the spring-snowmelt season, unlike in western Norway, where floods are triggered directly by heavy autumn/winter rainstorms (Roald, 2002). The period of 1840–1870 was, for example, dominated by large amounts of snow in the Norwegian mountains, and several major floods were recorded in eastern and southern Norway during this period (Roald, 2003). A changing amount of snow available for melting is therefore considered the most likely cause of the long-term changes in flood frequencies during the Holocene.

Although snowmelt is the most important floodwater contributor, the largest and most damaging events often occur in combination with intense precipitation. The most severe event during historic times, the Stor-Ofsen in July 1789, was triggered by an unfortunate combination of rapid snowmelt, long-lasting heavy precipitation and deep ground frost causing overland flow (Østmoe, 1985). Similarly, over the spring in 1860 the snow melting occurred simultaneously with heavy precipitation, causing huge floods in eastern Norway, and Gudbrandsdalen had its highest flood level since the Stor-Ofsen (Roald, 2002). More recently, in June 1995, a combination of unusually large amounts of snow, rapid snowmelt and precipitation caused the most damaging flood in eastern Norway since the Stor-Ofsen (Lundquist 1996).

The climate in southern Norway, and in particular the winter situation, is at present highly influenced by North Atlantic atmospheric circulation, and changes in this have a decisive influence on regional climate even over relatively short distances (Hanssen-Bauer and Førland, 2000; Hanssen-Bauer *et al.*, 2009). Thus, reconstructions of past winter precipitation and gradients across Norway have been suggested as a possible palaeo-indicator for low-frequency variations in the North Atlantic atmospheric-circulation patterns (Nesje *et al.*, 2000; Bakke *et al.*, 2008). Operating on centennial time scales, we compare our reconstructed flood records with palaeoclimatic records from southern Norway, and relate the internal variability to long-term prevailing tendencies in the North Atlantic climate.

The general Holocene multi-millennial-scale trend in the reconstructed flood records from Butjønna and Meringsdalsvetnet (Papers II and III), and also other extreme event records (see e.g. Vasskog *et al.,* 2011), is increasing from a low frequency during the HTM to a high frequency and a late Holocene maximum during the Neoglacial period. Summer temperature reconstructions indicate a cooling trend over the same period, ultimately in terms of orbital forcing (Figures 7 A, B and C). Rimbu *et al.* (2003) relate a decreasing Holocene trend in alkenone-derived North Atlantic sea-surface temperature (SST) to a general weakening of North Atlantic atmospheric circulation from the early to late Holocene – a trend that is supported by coupled climate models (Gladstone *et al.*, 2005). Recent studies indicate, however, that alkenone-based proxies are mainly related to summer-season temperatures (Jansen *et al.,* 2008; Leduc *et al.,* 2010). Thus, the winter-season significance of such reconstructions is questionable. Foraminifera-based North Atlantic SST reconstructions are, although influenced by several mechanisms (Andersson *et al.*, 2010), argued to closer reflect the winter-season temperature (Jansen *et al.*, 2008), and such records indicate an opposite trend with warming towards the late Holocene (Figure 7D). Glacier reconstructions also indicate a late Holocene maximum (e.g. Nesje *et al.,* 2008), and based on reconstructed winter precipitation from glaciers on the west coast of Norway Bakke *et al.* (2008) record an increase in the variability of the westerlies at *c*. 2500 cal. years BP and a pronounced late Holocene peak at *c*. 1800 cal. years BP (Figure 7H). This may indicate that increased wintertime temperatures in the North Atlantic coincide with an intensification of the atmospheric circulation and a general increase in moisture transport over Scandinavia. The general correspondence of increasing flood frequency with an increase in winter precipitation during the Holocene lends credibility to the ability of snowmelt flood records to detect changes in past wintertime climate.

Figure 7: A) Summer (JJA) insolation at 65 °N (Laskar et al., 2004) B) Summer temperature variations inferred from megafossils (Pine) in the Scandes mountains (Dahl and Nesje 1996) C) Mean annual temperature based on pollen-temperature transfer functions (Seppä et al 2005) D) Foraminifera-based North Atlantic SST reconstruction (MD95-2011) (Andersson et al., 2010) E) Winter precipitation (Pw%) reconstructed from Jostedalsbreen western Norway (Nesje et al., 2001b). F) Variations in lakewater $\delta^{18}O$ at Lake Spåime (full line) and Lake Svartkälstjärn (dotted line) indicating positive (shaded) and negative (open) NAO (St.Amour et al., 2010). G) Reconstructed NAO (Trouet et al., 2009). H) Strength of the westerlies reconstructed from glacier-derived winter precipitation along the west coat of Norway (Bakke et al., 2008). H) Flood frequency (n/100 years) reconstructed from Meringsdalsvatnet (black) and Butjønna (white) identified by using rate of change in magnetic susceptibility exceeding 1σ. The Δf (MER – BUTJ) is plotted as a three-hundred-year running average, and indicates the relative geographical distribution of floods between the sites.


A
500
490 W/m3
480
1.5 B
1
Δ °C 0
-0.5
C
10
8 °C
6
13 D
12
°C
11
10
E
160
140
Pw (%)
100
80
-22 F
δ18O -20
-18
G
NAO 2
-2
160 Strong
H
120 Strength of the Westerlies
80 Weak
10
8
6
4
2
No. of floods 0
2
4
I
4
2
0 Δf
-2
-4
0 1000 2000 3000 4000 5000 6000
Cal. yr BP

Superimposed on the long-term Holocene trend is the multi-decadal- to millennial-scale variability. Modeling experiments indicate that such variability in the North Atlantic region is forced by solar and volcanic activity, internally modulated by atmospheric and ocean circulation (Cassou, 2008; Otterå *et al.*, 2010). At present, the wintertime atmospheric circulation has two leading flow regimes: the zonal westerly airflow and the meridional airflow. The permanence of these regimes over long timescales is, however, not fully understood. Observational and historical (Hurrell, 1995; Luterbacher *et al.*, 2002), and proxy data (Appenzeller *et al.*, 1998; Cook *et al.*, 2002; Meeker and Mayewski, 2002; Trouet *et al.*, 2009) indicate that the North Atlantic Oscillation (NAO) is detectable and dominating on inter-annual to millennial time scales. The occurrence of multiple atmospheric-circulation modes in the North Atlantic region (Barnston and Livezey, 1987) have, however, recently regained attention (e.g. Hurrell *et al.*, 2003; Cassou, 2008), and Jacobeit *et al.* (2003), for instance, demonstrate that the dominance of the NAO has changed over historic times.

In Paper III we relate the variability in snowmelt floods in southern Norway to regional atmospheric-circulation anomalies. During historic times none of the major flood events occur simultaneously in eastern and western Norway (Roald, 2003), and similarly we find that our palaeoflood records reveal significant differences (Δf) over a short distance. Using instrumental data as a modern analogue we suggest that these differences are associated with wintertime atmospheric-circulation anomalies (Figure 8) and that similar mechanisms have dominated the shifting flood frequencies during the Holocene as well. In accordance with reconstructed records of winter precipitation from southern Norway (Figure 7E), we find increasing variability over the late Holocene and major shifts in the flood frequency at about 2300, 1200 and 200 cal. years BP (Figure 7I) that arguably reflect shifts in the dominating atmospheric circulation – distinctly different from the NAO – causing changes in the regional weather patterns (Figure 8). Comparing cellulose $\delta^{18}O$ from two lakes in western and eastern central Sweden that is sensitive to the distribution of wintertime precipitation, St.Amour *et al.* (2010) found a systematic reversed gradient between the two study sites, arguably related to the changing modes of North Atlantic atmospheric circulation. Records indicate a prolonged interval of climatic stability in the mid-Holocene (*c.* 6300–4200 cal. years BP) and an increase in variability over the late Holocene with major shifts at *c.* 4200, 3000, 2000 and 800 cal. years BP (Figure 7F). Over the last *c.* 2500 years this variability corresponds broadly with the distribution of floods (Δf) across southern Norway and this indicates large-scale transitions in the distribution of winter precipitation during this period. Over the last *c.* 1000 years the Δf decreased until *c.* 600 cal. years BP, and subsequently increased towards the present, shifting from negative to positive values 200 years ago (AD 1750). Trouet *et al.* (2009) indicate a persisting positive NAO from *c.* 1000 to 600 years ago and increased variability over the last 600 years (Figure 7G). Meeker and Mayewski (2002) found that the winter-season Siberian High, Icelandic Low and Azores High shifted from weak to strong entering the Little Ice Age (LIA) (*c.* AD 1400), implying a more intense winter circulation over the North Atlantic during the LIA. The variability in the distribution of floods across southern Norway thus coincides with major shifts in the wintertime North Atlantic atmospheric circulation, particularly over the last 2300 years.

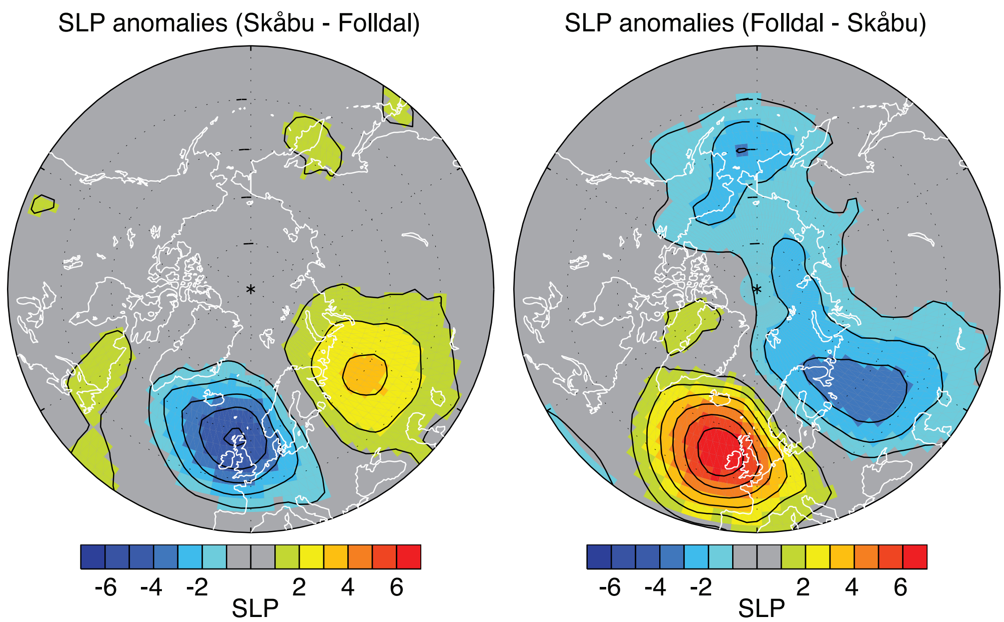


Figure 8: Sea level pressure (SLP) associated with periods of large precipitation gradients between the two catchments compared in PAPER III (cf. figure 1). Standardized winter precipitation (Nov. – Mar.) from Skåbu (MER) and Folldal (BUTJ), and gridded SLP from the NCEP/NCAR reanalysis (Kalnay et al., 1996) were used to calculate the SLP anomalies associated with significant difference (>1 standard dev.) between the two areas.

The general similarity with reconstructed glacier activity and winter precipitation suggest that this variability is dependent on variations in the intensity of the wintertime circulation that transports moist air from the North Atlantic, and that the distribution of this moisture (as snow) is the dominant factor controlling the frequency of snowmelt floods over this period.

Scenarios for future frequency of large floods (50-year floods) in Norway indicate a general increase of about 7% over the next 50 years. Comparing different models, however, predictions of the geographic distribution of discharge in southern Norway differ significantly with respect to the models` sensitivity to different modes of circulation (Hanssen-Bauer *et al.*, 2009). Our findings from eastern Norway show that shifts in the wintertime atmospheric circulation may indeed modulate the regional distribution of floods, and support the general tendency of increasing flood activity if predictions for wetter future winter conditions come true. Increased vegetation cover, less snow compared to rain and several melting periods during the winter may, however, counteract this trend and cause less snowmelt-flood activity.

Future perspectives

Findings presented in this thesis indicate that palaeoflood records may, in relation to snowmelt, contain a reliable signal of regional winter-precipitation variations (Papers II and III). This, however, relies on an improved understanding of the mechanisms behind the flood events. The two main mechanisms behind the floods are spring snowmelt and late-summer rainstorms. Indications of two subdivisions in the properties of the flood layers (Figure 8 in Paper II) may reflect these different flood types. Further studies on this, for example, by high-resolution geochemical analysis such as X-Ray Fluorecence (XRF), or high-sensitivity magnetic analysis such as First-order Reversal Curves (FORCs), may improve the ability to differentiate between summer- and winter-season related events. Such differentiation may further clarify the climatic influence on flood frequency and magnitude, and is needed in order to make robust flood-record-based paleoclimatic reconstructions.

The continental eastern part of southern Norway has an intriguing climatic setting. The climatic gradient across southern Norway, and the strong relationship with the North Atlantic atmospheric circulation makes Scandinavia suitable for studies of dominating patterns of palaeopressure in the North Atlantic region. Despite being a relatively short distance from the west coast, the winter climate in eastern Norway is dominated by completely different circulation patterns than the NAO pattern that dominates the west coast climate (Paper III). On-going and future work on glacier reconstructions from Russvatnet compared to well-studied glaciers on the west coast may add insight to the changing dominance of the leading modes of atmospheric circulation during the Holocene. Extension of the gradient towards eastern continental Europe, as well as a north–south gradient between Scandinavia and southern Europe, could further clarify some unsolved elements of Holocene climate fluctuations.

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