Late Glacial and Holocene Glacier Activity in Arctic Norway

Reconstruction of glacier fluctuations using surface exposure dating of moraines and multi-proxy analysis of sediments deposited in distal glacier-fed lakes

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Scientific environment

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Abstract

Late Glacial and Holocene glacier activity in Arctic Norway was reconstructed based on high-sensitivity ^{10}Be dating of a moraine sequence deposited by the mountain glacier Rødhetta on the island of Arnøya, and a study of sediments deposited in several distal glacier-fed lakes located down the valley from the northern outlet of the Langfjordjøkelen ice cap on the Bergfjord Peninsula.

In Paper I, we present the first comprehensive Late Glacial through Holocene ^{10}Be dated mountain glacier moraine chronology in Arctic Norway. We show that temperature-sensitive mountain glaciers in Arctic Norway reached their maximum Late Glacial extent about 1000 years prior to the onset of the Younger Dryas. Following considerable retreat, glaciers re-stabilized about 12.3 ka ago, showing oscillatory retreat through the rest of the Younger Dryas stadial with the final culmination about 11.5 ka ago. The Younger Dryas glacier advances were significantly smaller in amplitude than the earlier Late Glacial culmination. No subsequent culminations took place during the Holocene until the Little Ice Age. The presented chronology of the Arctic mountain glacier is complemented by the glacier modeling results. The Equilibrium Line Altitude (ELA) lowerings compared to present day related to each moraine are as follows: Late Glacial ~220 m, Younger Dryas ~130 m, and Little Ice Age ~80 m. The most likely climate conditions during the moraine formation periods are represented by summer temperature cooling compared to present-day by ~3.2 °C during the Late Glacial culmination, by ~1.9 °C during the Younger Dryas, and by ~0.8 °C during the Little Ice Age. We show that this pattern is consistent with updated glacier records in the North Atlantic region, with suggested peak Late Glacial ice during the Bølling-Allerød/Antarctic Cold Reversal interval, a considerably smaller culmination early in the Younger Dryas stadial, and slight glacier retreat throughout the Younger Dryas. To explain this Late Glacial pattern and its similarity to southern mid-latitude glacier records, we propose that the Late Glacial bipolar seesaw mechanism was primarily a (northern) winter phenomenon, while summer temperatures were synchronized between the

hemispheres by atmospheric CO_2 forcing, as documented by the inter-hemispherically consistent Late Glacial mountain glacier records.

In Paper II, we present a high-resolution relative glacier activity record covering the past ~10,000 cal. a BP from the northern outlet of the Langfjordjøkelen ice cap in Arctic Norway, reconstructed from detailed geomorphic mapping, multi-proxy analyses of distal glacier-fed lake sediments, and sedimentary fingerprinting. Principal Component Analysis was used to characterize sediments of glacial origin and trace them in a chain of lakes located down the valley. Of the variations in the sediment record of the uppermost Lake Jøkelvatnet, 73% can be explained by the first Principal Component axis and tied directly to upstream glacier erosion, while the glacial signal becomes weaker in the more distal lakes Store Rundvatnet and Storvatnet. Magnetic susceptibility and titanium count rates were found to be the most suitable indicators of Holocene glacier activity in the distal glacier-fed lakes. The complete deglaciation of the valley of Sør-Tverrfjorddalen occurred ~10,000 cal. a BP, followed by a reduced or absent glacier during the Holocene Thermal Optimum. The Langfjordjøkelen ice cap reformed with the onset of the Neoglacial ~4100 cal. a BP, and a gradually increasing glacier activity culminated during the Little Ice Age in the early 20th century. Over the past 2000 cal. a BP, periods of decreased glacier activity were centered around 1880, 1600, 1250 and 950 cal. a BP, while intervals of increased glacier activity occurred around 1680, 1090, 440 and 25 cal. a BP. The reconstructed Holocene glacier activity at the Langfjordjøkelen ice cap is consistent with regional temperature proxy records and glacier variability reconstructions across Norway. Long-term changes in the extent of the northern outlet of the Langfjordjøkelen ice cap largely followed trends in regional summer temperature, while winter season atmospheric variability may have triggered multi-decadal glacier fluctuations and generally affected the amplitude of glacier events.

List of publications

Paper I

Wittmeier, H.E., Schaefer, J.M., Bakke, J., Rupper, S., Paasche, Ø., Schwartz, R. and Finkel, R.C. (in review): Late Glacial Mountain Glacier culmination in Arctic Norway 14,000 years ago consistent to southern mid-latitudes. *Nature Geoscience*.

Paper II

Wittmeier, H.E., Bakke, J., Vasskog, K. and Trachsel, M. (in review): Holocene glacier activity in Arctic Norway reconstructed using multi-proxy fingerprinting in distal glacier-fed lake sediments. *Quaternary Science Reviews*.

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Outline

The first chapter of my Ph.D. thesis is divided into two main parts. The first part contains an introduction which gives an overview of the objectives of the thesis, the study area, and the methods applied. A novel methodological approach for future studies is outlined, combining geomorphic mapping, surface exposure-dated moraine sequences and distal glacier-fed lake sediment analyses. Through a robust description of the morphostratigraphy of the major moraine sequences as observed in the study areas, the results of this thesis can be scaled to a larger region of Arctic Norway. A quantification of corresponding Equilibrium Line Altitude fluctuations would allow robust large-scale paleoclimatic analyses. This is a suggestion for further work, building on the findings of my Ph.D. thesis.

The second part contains a presentation of the two papers that form my Ph.D. thesis. In Paper I, we study Late Glacial and Holocene culminations of the mountain glacier Rødhetta on the island of Arnøya in Arctic Norway. We compare the timing and amplitude of the glacier culminations in Arctic Norway to glacier evolution in the southern mid-latitudes in order to test the bipolar connectivity which is recorded in ice core temperature proxy records from Greenland and Antarctica. We connect mapped shorelines to our surface exposure-dated moraine chronology in order to constrain the early part of the regional sea level history. In Paper II, we use multi-proxy analyses of sediments deposited in distal glacier-fed lakes to reconstruct a robustly dated, continuous high-resolution record of Holocene glacier activity of the northern outlet of the Langfjordjøkelen ice cap in Arctic Norway. We discuss the history of glacier advances and retreats during the Late Glacial and Holocene in relation to past atmospheric and oceanic variability in the North Atlantic region.

Introduction

Since the end of the Last Glacial Maximum (LGM) (~22 ka ago), the climate at high-northern and high-southern latitudes has been subject to major changes during the transition from glacial to interglacial conditions, defined as the Late Glacial (LG) period (16-11 ka). The bipolar seesaw (Broecker, 1998) has become the dominant mechanism for explaining anti-phased millennial-scale temperature changes between the Northern and Southern Hemispheres during the last glacial cycle (Stenni et al., 2011). The LG period displays a particularly clear and well-established bipolar seesaw signature of ice core temperature proxy records from Greenland and Antarctica (Fig. 1) (Jouzel et al., 2007; Rasmussen et al., 2006). The Northern Hemisphere experienced the warm Bølling/Allerød interval (14.7-12.9 ka) and a subsequent abrupt climate shift to the colder climate conditions of the Younger Dryas (YD) stadial (12.9-11.7 ka) (Rasmussen et al., 2006), which were characterized by large-scale re-organizations of atmospheric and oceanic circulation patterns (Bakke et al., 2009) before the transition to interglacial conditions at the onset of the Holocene period. The Southern Hemisphere records show an opposing pattern with a cooling during the Antarctic Cold Reversal (ACR) (14.7-12.8 ka) (Jouzel et al., 2007) followed by post-ACR warming in step with the global rise in atmospheric CO_2 (12.8-11.7 ka) (Monnin et al., 2004).

The glacial-interglacial cycles of the Earth's climate were driven by orbital forcing, and orbital influence has also been linked to the major, millennial-scale LG and Holocene climate changes (Berger and Loutre, 1991; Berger, 1978; Milankovitch, 1941), whereas underlying, smaller-scale atmospheric and oceanic variability might be related to sunspot occurrence (Eddy et al., 1976; Lean et al., 1995), volcanic activity (Otterå et al., 2010; Robock, 2000), and meltwater pulses into the North Atlantic Ocean (Clark et al., 2001; Thornalley et al., 2010) (see chapter Paleoclimatic Implications).

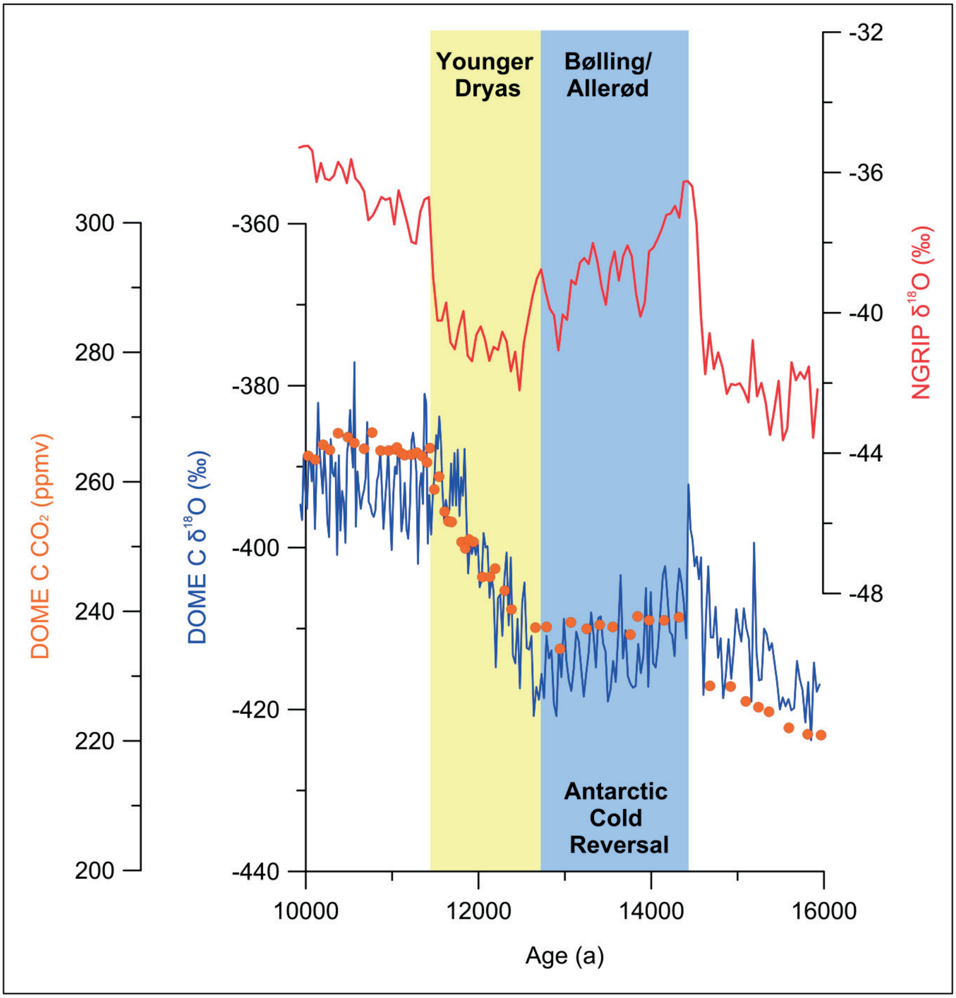

Figure 1 The Late Glacial period, 16-11 ka ago, displays a particularly clear and well-established bipolar seesaw signature of ice core temperature proxy records from the NGRIP in Greenland (Rasmussen et al., 2006) and DOME C in Antarctica (Jouzel et al., 2007; Lemieux-Dudon et al., 2010). While the Northern Hemisphere experienced the warm Bølling/Allerød interval and a subsequent abrupt shift to the Younger Dryas stadial, the southern records show an opposing pattern with the Antarctic Cold Reversal followed by post-ACR warming in step with the global rise in atmospheric CO_2 (Lemieux-Dudon et al., 2010; Monnin et al., 2004).

The Early to Middle Holocene was dominated by the warm period of the Holocene Thermal Optimum (HTO) (~9-6 ka), when temperatures in the Northern Hemisphere were higher than today (Birks et al., 2014; Bjune et al., 2005; Bjune et al., 2004; Kaufman et al., 2004; Marcott et al., 2013; Nesje, 2009; Rasmussen et al., 2007; Seppä and Birks, 2001). A major exception is the '8.2 event', an about 150-year-long cold pulse triggered by a North Atlantic meltwater event (Alley and Ágústsdóttir, 2005; Kleiven et al., 2008; Rasmussen et al., 2006). Subsequent to the HTO, temperatures gradually cooled during the Middle to Late Holocene (Bjune et al., 2004; Marcott et al., 2013; Seppä and Birks, 2001), leading to the transition into the Neoglacial, which varied regionally in its timing (Nesje, 2009; Wanner et al., 2011). The overall climate cooling of the Neoglacial culminated during the Little Ice Age (LIA) (~1300-1850 CE) climate anomaly (Grove, 1988, 2004). During recent decades, anthropogenic forcing such as greenhouse gas emissions and land cover changes have been adding up to a reversal of the long-term cooling, especially pronounced in the Arctic region (Kaufman et al., 2004; Kaufman et al., 2009; Wanner et al., 2008; Wanner et al., 2011).

The knowledge about past natural climate variability is of major importance to understand present climate conditions independently of anthropogenic forcing, and necessary to be able to predict the future evolution of the Earth's climate on regional and global scales (Jansen et al., 2007). Due to the fact that the temporal extent of instrumental records is limited to less than a few centuries, paleoclimate archives of multiple proxy indicators are invaluable for reconstructing past climate variability on a regional, hemispheric and even inter-hemispheric scale. The North Atlantic region, and especially the maritime Norwegian west coast, with its strategic location with respect to major oceanic and atmospheric circulation patterns, is a key area of focus for LG and Holocene paleoclimate research. The major, millennial-scale climate trends of the LG and Holocene outlined above, as well as shorter, centennial to multi-decadal scale fluctuations are reflected in various proxy records from this region, which have contributed to a better understanding of the mechanisms and the effects of changes in external forcing involved in large-scale climate variability.

Proxy records from Greenland ice cores can span back in time as far as the full last glacial-interglacial cycle (Bond et al., 1993; Dahl-Jensen et al., 1998; Dansgaard et al., 1993; Johnsen et al., 1992), and, especially for the LG time period, ice core temperature proxies from Greenland and Antarctica have widely been used as important archives for comparison of climate variability on an inter-hemispheric scale

(Barbante et al., 2006; Blunier and Brook, 2001; Buizert et al., 2014; Fudge et al., 2013; Jouzel et al., 2007; Lemieux-Dudon et al., 2010; Mayewski et al., 1997; Monnin et al., 2004; Rasmussen et al., 2006; Rasmussen et al., 2007; Stenni et al., 2011; Stocker and Johnsen, 2003). Marine records from the North Atlantic and the Nordic Seas allow for reconstructions of past oceanic circulation patterns and sea surface temperatures (Andersen et al., 2004a; Andersen et al., 2004b; Andersson et al., 2010; Andersson et al., 2003; Andrews et al., 2009; Berner et al., 2010; Bond et al., 2001; Cabedo-Sanz et al., 2013; Calvo et al., 2002; Hald et al., 2007; Kleiven et al., 2008; Klitgaard-Kristensen et al., 2001; Klitgaard-Kristensen et al., 1998; Koç et al., 1993; Marchal et al., 2002; Risebrobakken et al., 2003; Sejrup et al., 2011). Holocene terrestrial records from Scandinavia include pollen, chironomids, biomarkers and diatoms from lake sediments (Balascio et al., 2011; Birks et al., 2014; Birks et al., 2005; Bjune et al., 2005; Bjune et al., 2010; Bjune et al., 2004; Rosén et al., 2001; Seppä and Birks, 2001; Seppä et al., 2009), oxygen isotope records from lake sediments (Hammarlund et al., 2002; Hammarlund et al., 2003; Rosqvist et al., 2013; Rosqvist et al., 2007; Shemesh et al., 2001), tree rings (Briffa et al., 1998; Briffa et al., 2002; Esper et al., 2012; Grudd et al., 2002; Loader et al., 2013; Melvin et al., 2013; Young et al., 2012), speleothems (Lauritzen and Lundberg, 1999; Linge et al., 2001; Sundqvist et al., 2007), and past variations in glacier activity as reconstructed from historical sources (Grove, 1988, 2004), from moraine records dated by lichenometry (Matthews, 2005; Winkler, 2003) and high-sensitivity ^{10}Be (Briner et al., 2014; Goehring et al., 2008; Mangerud et al., 2013), and from a variety of physical proxies from glacier-fed lake sediments (Bakke et al., 2010; Bakke et al., 2009; Bakke et al., 2005; Bakke et al., 2013; Karlén, 1976, 1981; Lie et al., 2004; Matthews et al., 2000; Nesje et al., 2014; Nesje et al., 2000; Nesje et al., 2001; Rosqvist et al., 2004; Vasskog et al., 2012) dated by radiocarbon dating of macrofossils (Reimer et al., 2013) and ^{210}Pb records (Appleby, 2008), and from a combination of glacier-fed lake sediments with tree-limit records (Dahl and Nesje, 1996; Karlén, 1976).

In Arctic Norway, inferences on the LG and Holocene glacial and sea level history have always been hampered by poor chronological control. The approach of radiocarbon dating of shells from marine deposits (Andersen, 1968; Kverndal and Sollid, 1993; Marthinussen, 1962; Sollid et al., 1973; Vorren and Elvsborg, 1979) and organic material from isolation basins (Corner and Haugane, 1993; Romundset et al., 2011) to constrain absolute age control of the deglaciation and sea level history in Arctic Norway is challenged by reservoir-age uncertainties of marine samples (Lohne et al., 2012), sparse availability of organic material in the northern high latitudes (Romundset et al., 2011) and the fact that radiocarbon dates only give relative ages of glacier advance and retreat if not sampled directly from incorporated material within the moraine deposit.

The main goal of this thesis was to improve the understanding of LG and Holocene climate variability in the northern high latitudes and thereby test the bipolar seesaw hypothesis on an inter-hemispheric scale. Based on the fact that glaciers are sensitive climate indicators, two independent, robustly dated reconstructions of past mountain glacier/ice cap outlet glacier activity in Arctic Norway are presented to address this underlying key task. The two methodological approaches of this thesis are (i) geomorphic mapping, high-sensitivity ^{10}Be dating of a moraine sequence and robust first-order modeling of a mountain glacier and (ii) sedimentary fingerprinting of glacier indicators and high-resolution analyses of distal glacier-fed lake sediments in a chain of lakes downstream from an ice cap outlet glacier. Applying these two methodological tools within one study frame is a novel approach in the northern high latitudes with a great potential to increase the understanding of the drivers of multi-decadal to millennial-scale climate variability in the northern polar region, identifying patterns and modes and their inter-hemispheric connectivity during the LG and Holocene. The produced data sets are robustly dated, improving the spatial coverage of terrestrial paleoclimate proxy data in Arctic Norway, and adding valuable knowledge of natural climate variability in a bipolar context.

Mountain glaciers are particularly sensitive indicators of past climate conditions (Denton and Karlén, 1973; Porter, 1975) as their fluctuations in size are mainly controlled by ablation season temperature, the amount of snow accumulation during the accumulation season and, to some extent, the prevailing wind direction (wind drift of dry snow). Moraine records in glacier forelands can provide climate event records spanning thousands of years, and glacier-fed lake sediments can contain continuous records of upstream glacier fluctuations since the time of deglaciation of the basin. First-order glacier modeling is a robust approach to quantify the underlying climate drivers of glacier activity.

Many glaciers in Scandinavia had LIA maximum advances that surpassed previous Holocene extents, erasing earlier deposited moraine sequences and, hence, limiting direct dating as the single approach of glacier reconstruction at such sites. The combination of a high-sensitivity ^{10}Be dated moraine chronology and a continuous high-resolution distal glacier-fed lake sediment record at one site could produce robust and continuous chronologies of past glacier activity in future studies, and, if applied over a larger spatial scale, open up for a more detailed understanding of past climate on a regional scale (see chapters Methodological Approach and Regional Morphostratigraphy).

Research Objectives

The main research objectives of this thesis are twofold, divided into (i) methodological and (ii) paleoclimatic objectives.

i) Methodological objectives

- Utilize detailed geomorphic mapping and high-sensitivity ^{10}Be dating on a well-resolved moraine sequence fronting a small mountain glacier, and quantify the underlying climate drivers of glacier activity using a first-order glacier modeling approach (Paper I)
- Use the relationship between physical sediment proxies and geochemical variability to define the sedimentary fingerprints of glaciers in lake sedimentary records along a chain of lakes down-valley of an outlet glacier, to resolve the glacial vs. non-glacial signal, and to identify the most suitable lake basin to be used to reconstruct past glacier activity (Paper II)
- Develop a novel approach that will provide continuous LG and Holocene data sets with high temporal resolution using sedimentary records from distal glacier-fed lakes, analysing these with a suite of multi-proxy methods, and integrating the results with independent glacier chronologies using state-of-the-art methodology combined with novel dating techniques

ii) Paleoclimatic objectives

- Use reconstructions of small mountain- and outlet glaciers and model the underlying climate drivers to enhance our understanding of the controls on decadal- to centennial-scale climate variability in Arctic Norway, identifying patterns and modes and their inter-hemispheric connectivity during the LG and Holocene.
- Contribute to the age constraint of the LG deglaciation and sea level history in Arctic Norway.

Study Area

The study sites in Arctic Norway are located at the west coast about fifty kilometers apart from each other (Fig. 2).

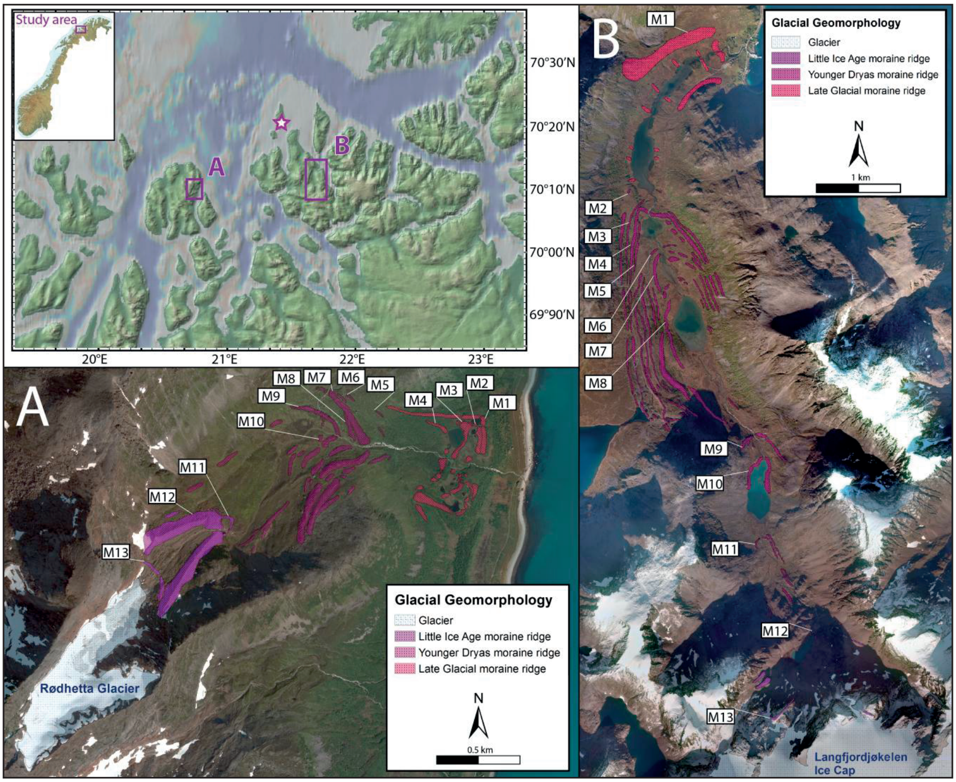

Figure 2 Regional setting of the study sites in coastal Arctic Norway (purple squares). A) Rødhetta Glacier on the island of Arnøya (Paper I). B) The northern outlet of the Langfjordjøkelen ice cap on the Bergfjord Peninsula (Paper II). For a more detailed close-up of the study sites, see geomorphic maps in Paper I and Paper II. The star indicates the location of the climate station 92700 Loppa.

The climate conditions in the northern North Atlantic region are characterized by the major atmospheric and oceanic circulation patterns in the area, their interactions and phase relationships. Any change in the northward transport of heat from the mid-latitudes through water and air masses can have enormous effects on regional, hemispheric and even inter-hemispheric climate conditions. Due to its preeminent location at the center of interaction, the northern North Atlantic region is a key area for studying northern hemispheric LG and Holocene glacier activity with the aim of improving the understanding of past climate variability.

In Arctic Norway, the Scandinavian Ice Sheet (SIS) started its dynamic retreat around 15.7 ka (Stokes et al., 2014) or even a few centuries earlier (Laberg et al., 2007), and made way for the formation of local mountain glaciers and ice caps in the recently deglaciated mountain areas (Fig. 3). In contrast to the rather large ice masses of ice sheets, small ice caps and alpine mountain glaciers have short response times and react sensitively to even small changes in climate conditions, which makes them excellent climate indicators (Denton and Karlén, 1973; Porter, 1975).

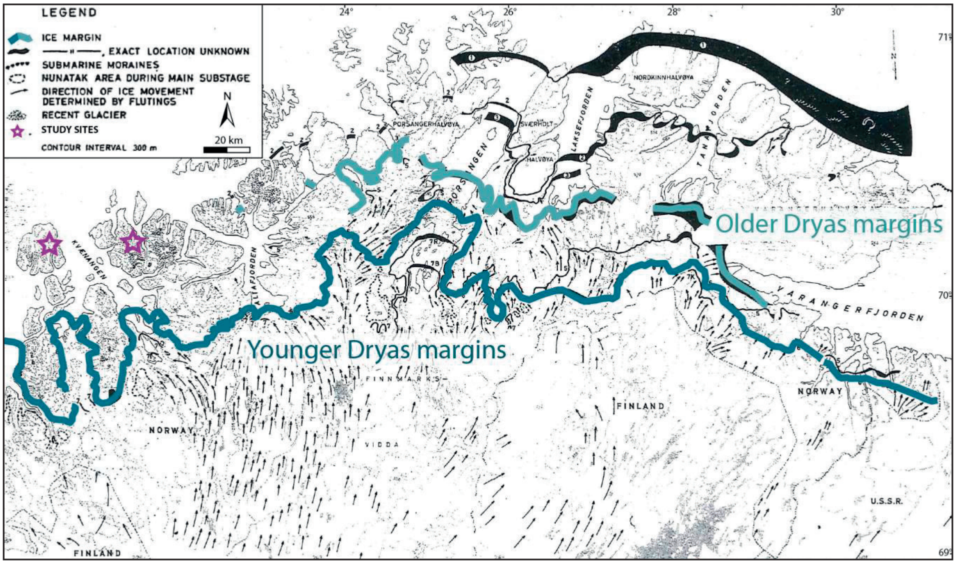

Figure 3 Map of northern Arctic Norway (modified from Sollid et al., 1973) showing the northern margins of the Scandinavian Ice Sheet (SIS) during the Younger Dryas (dark blue) and the Older Dryas (turquoise), based on marginal moraine deposits. Sollid et al. (1973) linked SIS moraines to raised shorelines in Finnmark County by tracing and dating distinct halts of ice sheet retreat in reference to seven post-LGM sub-stages (black and turquoise/blue lines). The study sites of this thesis (purple stars) are located beyond the ice sheet margins, where local glaciation could take place.

Local glaciation and periglacial processes have shaped the landscape of Arctic Norway since deglaciation (Andersen, 1968; Bakke et al., 2005; Kverndal and Sollid, 1993; Møller and Sollid, 1972) and have left spectacular landforms such as rock glaciers and terminal moraine systems. Former shorelines can be traced on different levels along the coast, reflecting postglacial sea level variations with the highest former shoreline more than 60 m higher than present-day beaches (Corner and Haugane, 1993; Marthinussen, 1962; Romundset et al., 2011; Sollid et al., 1973; Vorren and Elvsborg, 1979).

The study sites are located on the island of Arnøya (70°08’N 20°35’E) in Troms County (Paper I) and on the Bergfjord Peninsula (70°8’N 21°43’E) in Finnmark County (Paper II). Both sites have a maritime climate, with relatively small diurnal and seasonal temperature variations, due to the location at the eastern rim of the northern North Atlantic Ocean and close to the Norwegian Atlantic Current. Mean (1961-1990) summer (May to September) temperature of 8.7 °C and mean winter (October to April) precipitation of 563 mm were measured at the climate station No. 92700 Loppa (10 m a.s.l.) (Fig. 2) (DNMI, 2012).

Arnøya displays summits up to 1150m a.s.l. and hosts several small (< 1 km^2) alpine mountain glaciers located in lee-warded valley sites facing northeast. Rødhetta Glacier (920-450 m a.s.l) is a northeast-directed mountain glacier of 0.3 km^2. The drainage valley of Rødhetta Glacier, the valley of Storelvdalen, displays a highly resolved and well-preserved moraine sequence with quartz-containing boulders embedded on the crests of the ridges (Paper I).

The Bergfjord Peninsula contains three ice caps, Øksfjordjøkelen, Langfjordjøkelen and Svartfjelljøkelen. Our study site is located in the valley of Sør-Tverrfjorddalen, which drains the northern outlet of the Langfjordjøkelen ice cap (1045-820 m a.s.l.). The valley of Sør-Tverrfjorddalen is surrounded by mountain ridges of 400-900 m a.s.l. and features steep valley sides in the southern part and gentler slopes in the northern part. The sediment-laden meltwater river drains northwards through six lakes before it enters the fjord. The fine-grained clay and silt fractions are partly deposited and partly transported further by the meltwater through the chain of lakes. While glacial sediments typically dominate in such glaciofluvial systems, other processes such as rapid mass-movement, outwash of old basal till from the valley sides and re-sedimentation of earlier glacial deposits (Jansson et al., 2005) also contribute to the sedimentary budget of the lakes with material of non-glacial origin (Paper II).

Mapping of former shorelines at both sites revealed a consistent pattern of the relative sea level history in the area, with distinct beach ridges and abrasion terraces reflecting the Marine Limit, the Main shoreline and the Tapes transgression. The Marine Limit is unambiguously linked to the outermost moraine sequence deposited by Rødhetta Glacier, dated to 14.1 ± 0.8 ka, displaying an absolute minimum age for the LG sea level high-stand in Arctic Norway (Paper I).

Methodological Approach

Two different approaches were utilized to reconstruct past glacier activity in Arctic Norway, (i) detailed geomorphic mapping combined with high-sensitivity surface ^{10}Be exposure dating (Paper I) and (ii) high-resolution multi-proxy analyses of distal glacier-fed lake sediments and catchment samples (Paper II). In the following, the two methodological approaches are outlined, and combined into one approach as the suggested optimal strategy for future studies of regional LG and Holocene glacier and climate variability in Arctic Norway.

Geomorphic mapping

Detailed geomorphic mapping is a major prerequisite for the successful application of the methodological approaches in this thesis. Surface exposure dating (SED) (Paper I) requires an accurate knowledge of the moraine stratigraphy in the glacier foreland since the moraine ridges with the dated boulders embedded on their crests have to be put in spatial relation to each other. For distal glacier-fed lake sediment studies (Paper II) the superficial deposits covering the surrounding lake catchments play a major role for the choice of adequate coring locations and for interpreting the source of the sedimentary deposits (glacial vs. non-glacial) in the core records.

The more detailed and accurate the geomorphic maps are, the more confidently a comparison can be made between sites or larger regions. Based on the correlation to the shoreline mapping and maximum dates in the lake sediment records of the valley of Sør-Tverrfjorddalen, the terminal moraines fronting the northern outlet of the Langfjordjøkelen ice cap on the Bergfjord Peninsula have been color-coded according to age (Geomorphic Map, Paper II), as have the terminal moraines of the Rødhetta Glacier directly dated by SED (Geomorphic Map, Paper I). A comparison of the geomorphic maps reveals a high similarity in number and appearance of the moraine ridges and their respective distance relative to the adjacent glacier. The consistency of the moraine records found through observation is supported by the relative and absolute age control obtained for the two sites by the different methodological approaches.

Surface exposure dating

SED is a comparably novel method used to obtain accurate age control of rock surfaces (Balco, 2011; Gosse and Phillips, 2001). Applied directly to terrestrial surface rocks, SED is independent of organic material, as opposed to radiocarbon (^{14}C) dating, which has been the most widely applied approach to establish age control of proxy records during the past decades. In the northern high latitudes, the availability of organic matter is restricted, likely due to unfavorable climate conditions and preservation issues, and even though recent studies on isolation basins have provided chronologies of Holocene sea level curves in Arctic Norway based on radiocarbon dating (Romundset et al., 2011), finding reliable proxy archives for LG and Holocene glacier and sea level changes remains challenging. SED as a direct dating method turns out to be an invaluable approach for terrestrial paleoclimate research in the polar regions because it enables accurate age control of glacier culminations which, if determined with the same methodological approach, can be directly compared with other glacier records on a regional and global scale (Paper I). Methodological improvements allow high-sensitivity ^{10}Be dating since recently to be used to date rock surfaces of the entire Holocene age up to present day (Schaefer et al., 2009). In that respect, the term ‘high-sensitivity’ combines (i) the capability to measure small amounts of ^{10}Be (on the order of 100 atoms/g), and (ii) low blanks indicating high signal/noise ratios even for those low-level samples. The methodological application in this thesis shows that such high-sensitivity ^{10}Be analytics can be performed in a semi-clean laboratory led by more than one Principal Investigator (Cosmogenic Dating Group, Lamont-Doherty Earth Observatory). The fact that the geochemical method does not require an ultra-clean laboratory makes this technique applicable for the wider geologist community.

The in-situ production of cosmogenic nuclides (stable nuclides ^{3}He, ^{21}Ne; radionuclides ^{10}Be, ^{14}C, ^{26}Al and ^{36}Cl) in rock surfaces occurs through interaction of secondary cosmic neutrons reaching the Earth’s surface with target atoms in the exposed terrestrial surface (Davis and Schaeffer, 1955; Lal, 1991). The use of ^{10}Be has recently achieved accurate results in terms of moraine chronologies and reconstruction of punctual glacier records in the southern mid-latitudes (Schaefer et al., 2009), and was followed by numerous ^{10}Be SED studies in both hemispheres (Briner et al., 2014; García et al., 2012; Jomelli et al., 2014; Kaplan et al., 2010; Licciardi et al., 2009; Mangerud et al., 2013; Putnam et al., 2010). The knowledge of the ^{10}Be production rate is of critical importance with respect to accuracy and precision of ^{10}Be chronologies. For calculating the ^{10}Be ages of the Rødhetta moraine sequence, we are in the fortunate position to be able to use the precise local Arctic Production Rate presented by Young et al. (2013) which was established based on high-quality data sets in Arctic Canada and Greenland from landforms of similar age than the ones studied here, and integrated with the key datasets available from the northern high latitudes. The ^{10}Be surface exposure age of the moraines is interpreted to represent the termination of a glacier culmination because the ^{10}Be moraine age closely corresponds to the completion of sediment deposition with the onset of glacier retreat (Paper I). Geologic factors that potentially could impair the simple surface exposure dating approach include inherited ^{10}Be of the boulder surface, moraine formation related to more than one depositional event, movement of the boulder subsequent to glacial deposition, and boulder deposition through non-glaciogenic processes such as rapid mass-movements.

Analyses of distal glacier-fed lake sediments and catchment samples

Changes in sediment output from alpine glaciers are mainly related to the size of the glacier in the catchment (Fig. 4) and the mass turnover gradient of the glacier, which are driven by accumulation rates in winter and ablation-season temperatures (Dahl et al., 2003). The subsequent meltwater transport and the final deposition of the sediments in downstream distal glacier-fed lake basins reflect past glacier activity (Karlén, 1981; Leemann and Niessen, 1994). In Scandinavia, distal glacier-fed lake sediments have a prominent history as proxy records in paleoclimate research (e.g. Bakke et al., 2009; Bakke et al., 2005; Karlén, 1976; Lie et al., 2004; Nesje et al., 2001; Rosqvist et al., 2004). Paper II gives an overview of the development and application of lake sediment analyses in glacier reconstructions. To capture the glacial signal, and to distinguish between sediments of glacial and non-glacial origin, the following parameters are widely used: loss-on-ignition (LOI) as an inverse indicator of minerogenic sediment content (Karlén, 1976), dry bulk density (DBD) as a proxy for particle size and sediment porosity (Bakke et al., 2005), magnetic susceptibility (MS) as an indicator of changes in minerogenic sediment input (Matthews et al., 2005; Thompson et al., 1975), grain size distribution (GS) as an indicator of changes in (melt)water run-off (Bakke et al., 2010; Lie et al., 2004), and more recent X-ray fluorescence (XRF) scanning techniques (Guyard et al., 2007; Kylander et al., 2011) that are able to produce high-resolution records. Statistical methods for proxy record interpretation, such as the Principal Component Analysis (PCA), are necessary tools to explore multivariate datasets that commonly consist of large amounts of quantitative data (Bakke et al., 2013; Vasskog et al., 2012).

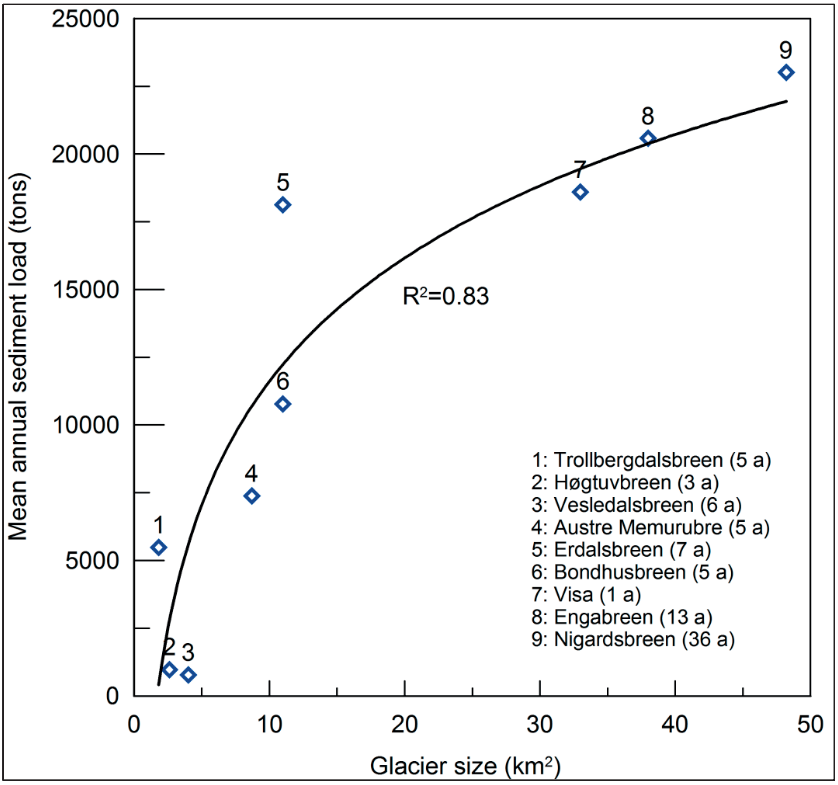

Figure 4 Glacier size in relation to the mean annual sediment load for nine Norwegian glaciers over the indicated time periods. Plotted after Diodato et al. (2013) based on data from Roland and Haakensen (1985) and Østrem et al. (2005).

We measured the sediment parameters mentioned above on multiple cores from several distal glacier-fed lake basins retrieved from the chain of lakes in the valley of Sør-Tverrfjorddalen, and used PCA on the data sets obtained from the multi-proxy analyses of the lake sediments. We collected soil samples from superficial deposits representing various earth surface processes in the individual lake catchments and subjected them to multi-proxy fingerprinting in order to recognize sediments in the lake basins that originate from up-valley glacier activity (Paper II).

Glaciological modeling of Equilibrium Line Altitudes and underlying climate changes

The Equilibrium Line Altitude (ELA) of a glacier is very closely related to the local climate, particularly summer air temperature and winter precipitation (Dahl et al., 2003). Variations in the ELA can therefore be commonly attributed to changes in these two variables. This can be best illustrated by its relationship to the annual (net) mass balance, which describes the net gain or loss of ice and snow per year. The mass balance is highly dependent on the climate conditions. If the annual mass balance of a glacier as a whole is negative, the ELA rises, and when the balance is positive, the ELA lowers. The ELA of a glacier, hence, marks the boundary between the accumulation area and the ablation area, where the net mass balance equals zero (Paterson, 1994). The steady-state ELA is defined as the altitude where the annual (net) mass balance must be zero for the glacier to remain in its present size. A glacier on which the average snowline corresponds to the steady-state ELA therefore is in balance with the climate.

The concept is very useful because it provides a measure of the climatic means related to certain glacier positions and geometries. Reconstructed ELA records over a larger region can provide an important proxy for implications on past climate variability (Balascio et al., 2005). There is a variety of methods and modeling approaches available to reconstruct former ELAs based on mapped moraines (e.g. Oerlemans, 2001, 2011; Osmaston, 2005; Porter, 1975; Rupper et al., 2009).

In Paper I, we applied a robust first-order glacier model on a detailed mapped mountain glacier moraine sequence in order to quantify the changes in ELA along with the changes in temperature and precipitation necessary to trigger glacier events able to deposit these moraine ridges. An ELA depression of simple mountain glaciers is defined by a lowering of the ELA, and hence, glacier expansion triggered by climate deterioration. We derived a simple model that estimates the ELA for glacier valley widths and slopes, glacier length, and glacier thickness (Oerlemans, 2001, 2011; Rupper et al., 2009). We calculated the change in ELA (relative to present day), accounting for hypsometry of the glacier valley, feedbacks associated with glacier thickness and bed topography. The mass balance changes required to the changes in ELA were calculated using mass balance gradients. The winter precipitation changes required are simply equal to the derived mass balance changes, assuming all of the precipitation change occurs as snow. We reconstructed the summer temperature changes required to explain the ELA and mass balance changes using a positive degree-day approach (Paper I).

Combined methodological approach – a proposal for future studies

While robust where moraines are available, glacier reconstructions based on moraine chronologies rely on a selective preservation of moraine ridges, and therefore do not exclude the possibility of multiple Holocene glacier advances. Many Norwegian mountain glaciers experienced their maximum Holocene advances during the LIA (Nesje et al., 2008), potentially overriding previous Holocene moraine deposits. This remains a challenge regardless if the moraines have been dated directly using cosmogenic nuclides or lichenometry, or indirectly through radiocarbon dating of mega-fossils buried in till or underneath the moraines themselves. To overcome the issue of incomplete reconstructions, Karlén (1976) suggested that glacial erosion and the associated production of rock flour, which is transported to and deposited in downstream lakes, could provide a continuous record of glacier fluctuations. Reading the glacial signal as preserved in the lake sediments has proven to be an important tool in Scandinavia, extending and filling the gaps given by dated moraine chronologies that record snapshots of the history of glacier advance and retreat

(Bakke et al., 2010; Bakke et al., 2009; Bakke et al., 2005; Bakke et al., 2013; Karlén, 1976, 1981; Lie et al., 2004; Matthews et al., 2000; Nesje et al., 2014; Nesje et al., 2000; Nesje et al., 2001; Rosqvist et al., 2004; Vasskog et al., 2012). The lake sediments are dated using mainly the ^{14}C and ^{210}Pb dating methods; the age uncertainty depends on the number and accuracy of the dates. The use of distal glacier-fed lake sediments to reconstruct continuous ELA variations enables to infer high-resolution paleoclimatic implications. The quantification of sediment variability and better dating techniques open up to infer detailed information about the climatic factors affecting the ELA (accumulation and ablation). In that respect, reliable quantification of the glacial sediments in a lake is of critical importance, and minerogenic sediment input of non-glacial origin needs to be eliminated from the record in order to minimize any noise in the reconstruction.

A simple regression model can be used to calculate continuous ELA fluctuations, when a distal glacier-fed lake sediment record can be tied to the adjacent moraine chronology at a sufficient number of points for the time interval covered by both records (Bakke et al., 2010; Bakke et al., 2005). A challenge remains, however, in sufficiently minimizing the uncertainty of this approach due to the fact that the number of data points from the respective moraine chronology is limited and must be covered for by interpolation.

Robust and accurate age control of the moraines in a glacier foreland is commonly restricted to the most recent centuries, and the applied dating methods tend to depend on site-specific conditions, such as (micro)climate, hydrology or substrate. Lichenometry is a widely used method that can be applied on surfaces up to 500 years in age (Innes, 1985; Matthews, 2005). Historical documents, paintings and pictures can give indications of earlier glacier extents, yet are seldom available for time periods earlier than the LIA (Grove, 1988). Radiocarbon dating, though covering a much longer dating range, depends on the availability of incorporated organic material, which is usually sparse in high latitudes and high altitudes. SED has the potential to date moraines of significantly higher ages (up to 4 million years using ^{10}Be), and the method is independent of site-specific conditions that may be difficult to account for since nuclide production rates are based on physical principles (Lal, 1991). High-sensitivity ^{10}Be dating can give robust and accurate moraine ages covering the whole time range of the LG and Holocene (Schaefer et al., 2009).

Based on the findings of this thesis we propose we propose a novel, complementary methodological approach for future studies in the northern high latitudes (Fig. 5): the combination of high-sensitivity ^{10}Be SED of moraines and high-resolution distal glacier-fed lake sediment records at one single site. This approach bears great potential to obtain continuous ELA records covering multi-millennial timescales.

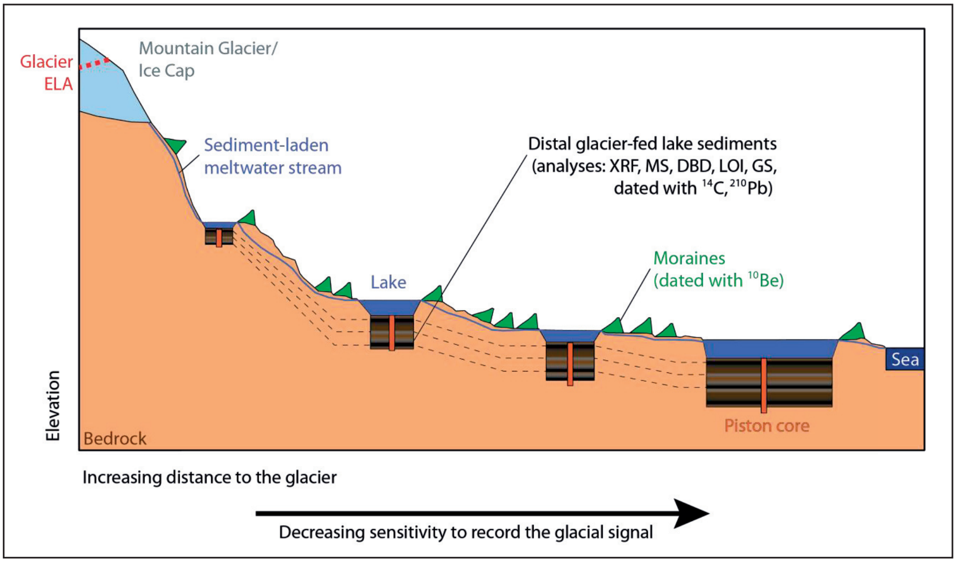

Figure 5 Schematic profile view of the novel complementary methodological approach as proposed in this thesis. Mountain glaciers/outlet glaciers of ice caps erode their beds, and the eroded material is deposited as till and moraines or transported away by meltwater. The moraines reflect a close to steady-state position of the respective glacier. The obtained ^{10}Be age dates the onset of glacier retreat after this quasi steady-state period, i.e. the onset of warming after a cool period. The former glacier ELA can be modeled from the mapped moraine ridges. Lakes located downstream of the glacier act as sediment traps. The distal glacier-fed lake sediments reflect the glacier activity during the time of sedimentation; the signal-to-noise ratio increases with distance to the glacier. If the two methodological approaches of high-sensitivity ^{10}Be dated moraines and high-resolution analyses of distal glacier-fed lake sediments are combined, a continuous past ELA record can be obtained for this site, with robust age control for the time periods of the Late Glacial and Holocene.

Regional Morphostratigraphy

The field survey at the two study sites, on the island of Arnøya and the Bergfjord Peninsula, showed that the LG and YD moraine records display similar geomorphological characteristics.

The Rødhetta Glacier and the northern outlet of the Langfjordjøkelen ice cap are facing towards the sea, and the outermost moraine sequences at both sites feature abrasion terraces from postglacial sea level variations. The LG moraines at both sites are prominent, distinctive moraines that require substantial time to evolve (Fig. 6). The glacier settings at the study sites in this thesis do not support the formation of prominent, even multi-ridged, moraine sequences, such as these LG moraines, within short timescales such as decades. In theory, cooler conditions might reduce ice velocities and the mass turnover gradient of glaciers, which for instance has been shown for present-day sub-polar/polar glaciers (Fitzsimons, 2003; Fitzsimons et al., 1999). Low angle beds and and wide ablation zones give rise to lower ice velocities in the respective ablation zones. The only moderately steep valley walls at the Rødhetta and Langfjordjøkelen settings make considerable sediment supply via landslides unlikely, indicating that most of the sediments were produced by glacial erosion. The resulting sediment flux towards the terminus has probably been relatively low, implying a rather slow build-up of the LG moraine sequences.

At Rødhetta Glacier (Fig. 2A), the LG moraine sequence (M1 to M4) is ~80 m high (230-70 m a.s.l.) and consists of four elongated push moraines that can be followed ~500-800 m alongside. The sequence consists of unsorted sediments of all grain sizes and contains rounded boulders up to several meters in diameter. The moraines have similar proximal and distal slope angles of 35-40°, and the crests are rounded. Several former meltwater channels cut through the terminal moraines. The individual moraine ridges are interpreted to represent oscillatory glacier advances interrupting the overall retreat of Rødhetta Glacier. The partly hummocky structure including some relict dead ice topography indicates stagnant ice and vertical melt down of the glacier terminus in periods. Shoreline mapping of the Rødhetta moraine system revealed that the glacier was land-based when it deposited the LG moraine sequence (Paper I).

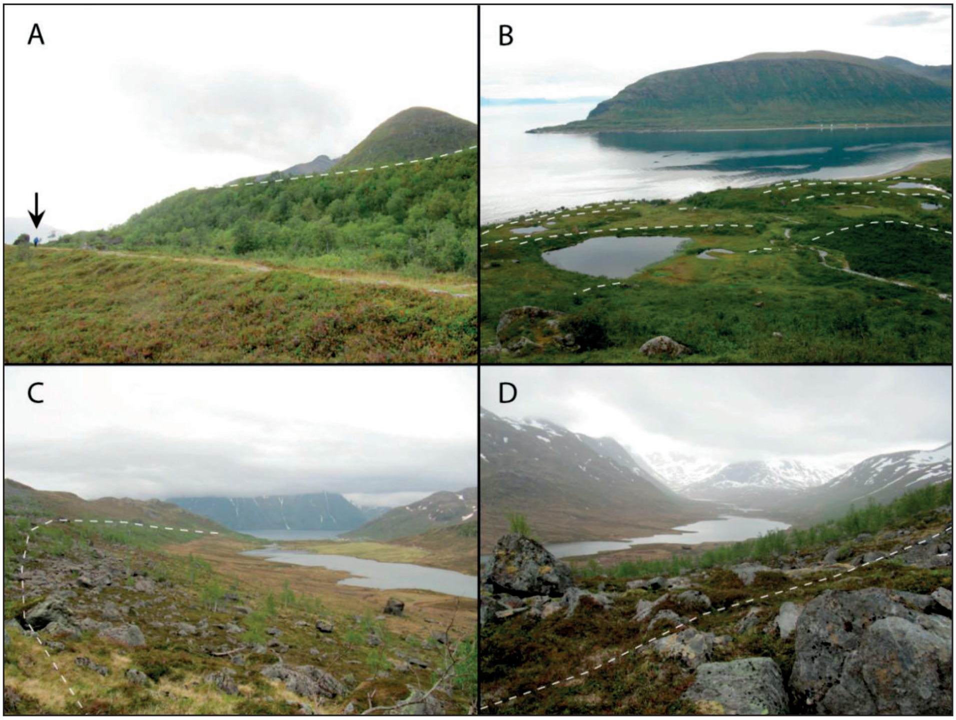

Figure 6 The prominent Late Glacial (LG) moraines observed in the field. A) The Rødhetta LG moraine with a person for scale (arrow); the moraine edge is indicated by the dashed line. B) The Rødhetta LG moraine photographed from above; the individual moraine ridges M1 to M4 (Fig. 2) are indicated by the dashed lines. C) The left-lateral part of the Langfjordjøkelen LG moraine photographed looking to the north; the moraine top is indicated by the dashed line. D) The left-lateral part of the Langfjordjøkelen LG moraine photographed looking to the south.

At the northern outlet of the Langfjordjøkelen ice cap (Fig. 2B) the LG moraine (M1) is ~40 m high (~45-85 m a.s.l.) and consists of a ~1200 m long ridge on the western valley side where it is much more pronounced and well-preserved than on the eastern flank. The moraine consists of unsorted sediments of all grain sizes and displays numerous boulders of 0.5-5 meters in diameter on the surface. Based on its characteristics as a bouldery three-part terrace set > 20 m above the local Marine Limit, and the lack of wave-washing impact, Evans et al. (2002) classified the LG moraine as ice-shelf moraine. Proximal to the moraine, several ~50-150 m long and up to 10 m high cross-valley De Geer moraines are located on each side, supporting the interpretation that the LG moraine was marine-based and the glacier calving into the sea.

The YD moraine sequences consist of individual ridges or composite moraines that are clustered in comparably close spatial proximity to each other, deposited by a glacier in general retreat-mode (Fig. 7).

At Rødhetta Glacier (Fig. 2A) the YD moraine sequence (M5 to M10) consists of six partly continuous, broadly arcuate elongated ridges (330-160 m a.s.l.). The ridges are ~70-1200 m long and ~5-50 m high, with proximal and distal slope angles that are similar on individual ridges, ranging from 20° to 40°; the crests are rounded. We ascribe the rather symmetric cross profiles to the erosional impact over the long period of time since deposition. They consist of unsorted sediments of all grain sizes and most of them contain rounded boulders up to several meters in diameter. The valley topography is unfavorable to supplying sufficient supraglacial debris to create dumped moraines, also indicated by the lack of coarse, angular blocks in the moraine material.

At the northern outlet of the Langfjordjøkelen ice cap (Fig. 2B), the YD moraine sequence (M2 to M11) consists of prominent, elongated and arcuate shaped moraine ridges. In the northern half of the valley, the ridges (M2 to M8) form up to ~20-40 m high and 4000 m long near-continuous moraine loops running across the whole valley, divided only by narrow stream incisions. In the southern part, where the valley floor narrows, the ridges (M9 to M11) are ~750-900 m long, and 1-10 m high. The moraine sides have proximal and distal slope angles that are similar on individual ridges, ranging from 30° to 40°, and the crests are rounded. The ridges consist of unsorted sediments of all grain sizes and display boulders up to several meters in diameter on the surface.

We interpret the YD moraines at both sites as push moraines representing oscillatory glacier advances interrupting the general retreat of Rødhetta Glacier and the northern outlet of the Langfjordjøkelen ice cap.

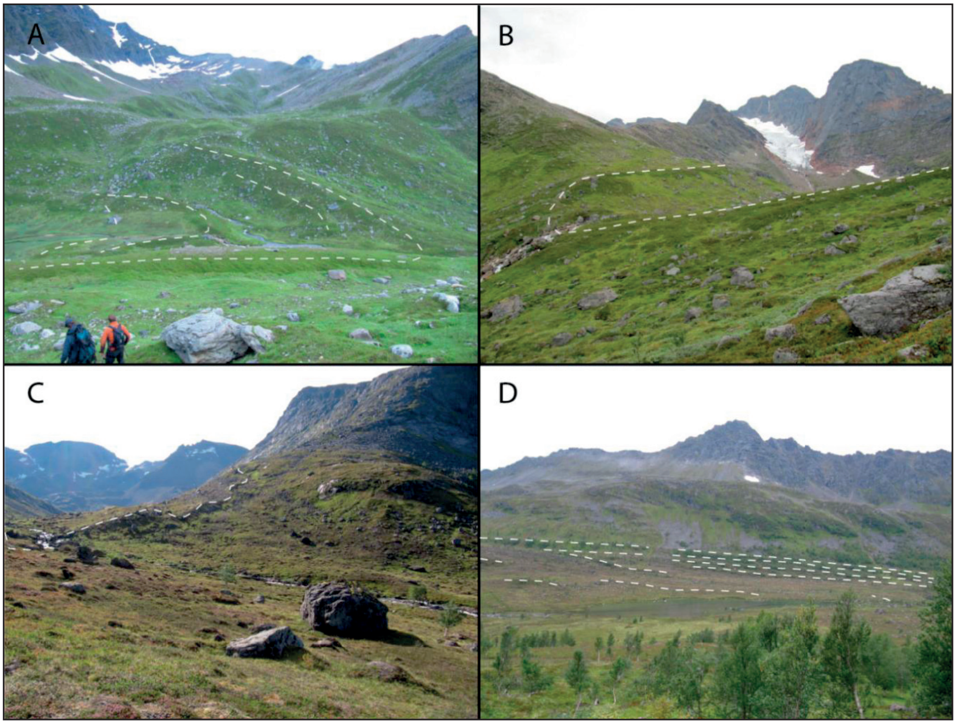

Figure 7 The Younger Dryas (YD) moraine sequence consists of several individual moraine ridges deposited in short distance to each other as observed in the field. Rødhetta moraines (crests indicated by dashed lines): A) Moraines M7 to M10. B) Moraine M9, photographed from the distal side. Langfjordjøkelen moraines (crests indicated by dashed lines): C) Moraine M9. D) Moraines M2 to M7 on the western valley side (Fig. 2).

In regard to the spatial proximity of the study sites, the striking similarity of the main characteristics of the LG and YD moraine stratigraphy in the two glacier forelands studied in this thesis may not be surprising. In Arctic Norway, however, there are numerous sites containing similar moraine sequences, which seem suitable to apply the methodological approach outlined above. Sites displaying moraine ridges of presumably LG/YD age can be observed all along the coastal parts of Arctic Norway, from the island of Andøya in Nordland County in the south, through the Lyngen Peninsula in Troms County, to the island of Arnøya and the Bergfjord Peninsula in Finnmark County in the north (Fig. 8). The moraine type localities observed in our study sites seem to be part of a consistent pattern of moraine stratigraphy in Artic Norway.

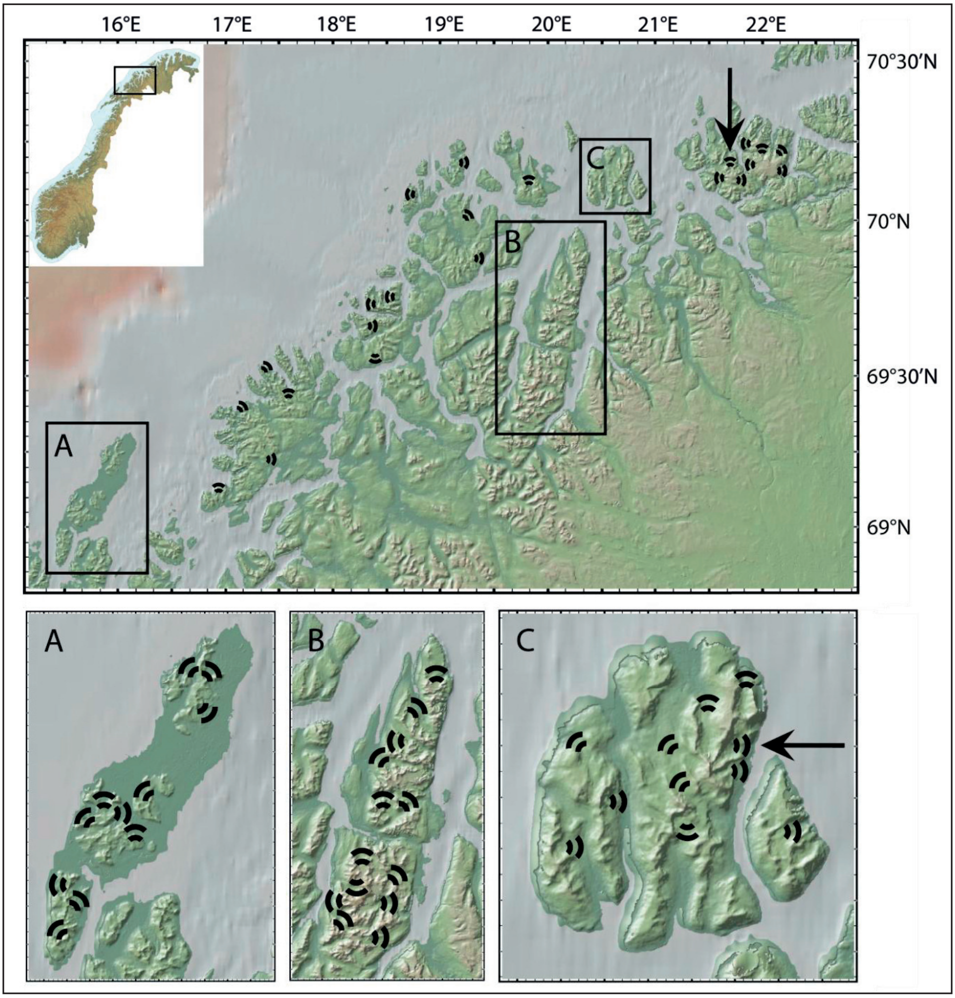

Figure 8 Regional map of coastal Arctic Norway. Moraine localities of presumably Late Glacial and Younger Dryas age are schematically mapped from aerial photographs (NPRA et al., 2014) with black double-arcs. The characteristic signature of the LG/YD moraines displayed at our type localities on the island of Arnøya and Bergfjord Peninsula (indicated by arrows) can be observed all along the coastal parts of Arctic Norway, including the island of Andøya (A), the Lyngen Peninsula (B) and the island of Arnøya (C).

If robustly reconstructed ELA records of LG and YD glaciers can be up-scaled to a region as large as coastal Arctic Norway (outlined in Fig. 8), this would allow for robust implications on the regional paleoclimate history. A recently developed GIS tool (Pellitero et al., submitted) could be applied to automatically calculate ELAs of the glacier systems with moraine stratigraphies of the same character as our type localities. The resulting data set of LG and YD ELA variations of glacier fluctuations in the region of Arctic Norway would allow for (i) large-scale climatic analyses and compilation with models in a region were paleoclimate proxy data is sparse and often lacks accurate chronologic constraint, and (ii) studying the slope of the regional ELA trends at the two time periods in question, with the potential to study the effect of a vast ice sheet to the east of the study sites. Even though the glaciers in coastal Arctic Norway are most sensitive to variations in summer temperature on millennial to multi-centennial timescales (Paper I), the maritime setting implies that these glaciers also are important indicators of winter precipitation (snow) and prevailing wind direction during the accumulation season. Winter season influence on glacier activity can amplify, or weaken, a major glacier response on centennial-scale trends in ablation season temperature, and induce minor responses of the glacier on a multi-decadal scale (Paper II). LG and YD ELA changes reconstructed on a regional level would enable distinctive inferences about the impact of atmospheric versus oceanic circulation modes on the evolution of the glaciers during the respective time intervals of moraine formation. Different aspects of the reconstructed mountain glacier/ice cap outlet glacier ELAs during the LG and YD would indicate differences in the prevailing wind direction of the respective time period. For instance, an overall ELA slope tilting towards the northeast would imply a prevailing southwesterly wind direction. An extended ELA study as outlined here, hence, might convey paleoclimatic information about circulation patterns in the northern North Atlantic region that no other proxy archives could reveal.

Paleoclimatic Implications

The reconstructed LG and Holocene decadal- to millennial-scale variations in glacier activity in Arctic Norway are presumably the result of a sum of long- and short-term forcing factors that drive natural climate fluctuations in the North Atlantic region. The share of the individual factors in the overall regional forcing varied constantly during the LG and Holocene (Wanner et al., 2008). In the following, some aspects of these forcing factors are discussed in the light of the new results gained in this thesis.

Long-term changes in northern high-latitude climate

Orbital forcing is suggested to be a dominating driver of major long-term LG and Holocene climate changes (Berger, 1978; Mayewski et al., 2004), based on its impact on the amount and latitudinal distribution of solar radiation reaching the Earth's atmosphere as the position and the orientation of the Earth relative to the Sun undergo changes over time. In that respect, orbital forcing is potentially able to drive millennial-scale changes in glacier activity in Arctic Norway, including the deglaciation following the LGM, the transition into the Holocene, and the Neoglacial time period. Changes in the eccentricity of the Earth's orbit (on 100,000 to 400,000 year cycles), changes in obliquity, which is in the tilt of the Earth's spin axis (on 41,000 year cycles) and changes in the precession of the Earth's axis (on 23,000 year cycles) are assumed to affect the insolation differently at different latitudes, and may induce changes in atmospheric and oceanic circulation patterns and seasonality in the hemispheres over time (Berger, 1978; Laskar et al., 2004; Mayewski et al., 1997; Milankovitch, 1941).

During the YD, the precession cycle of the equinoxes was different compared to the present-day situation. The Earth reached perihelion during the Northern Hemisphere summer, implying northern hemispheric winter minimum, and summer maximum insolation (Berger and Loutre, 1991; Raymo and Huybers, 2008). Subsequent to the maximum around 12-10 ka, Northern Hemisphere summer insolation declined throughout the Holocene (Berger and Loutre, 1991). This development can have caused a general summer cooling trend, which may explain the gradually increasing glacier activity in the course of the Holocene as reflected in various proxies from the northern high latitudes, resulting in the onset of the Neoglacial 4-6 ka ago.

Short-term changes in northern high-latitude climate

Underlying the long-term climatic trends induced by millennial-scale orbital forcing, there is shorter-amplitude climate variability, and a number of rapid multi-decadal to centennial-scale climate anomalies are seen during the LG and Holocene in Arctic Norway. First, variations in sunspot occurrence can cause differences in the radiation emitted by the Sun, which in turn impacts the energy input to global climate (Eddy et al., 1976; Lean et al., 1995). In particular, changes in the total and spectral solar irradiance reaching the Earth have shown to be correlated with solar activity and have been linked to changes in global temperatures on centennial timescales (Bard et al., 2000; Bond et al., 2001; Vonmoos et al., 2006). Second, volcanic activity can affect the global climate because volcanic aerosols in the atmosphere can absorb solar radiation and that way induce climate cooling at the surface of the Earth (Miller et al., 2012; Otterå et al., 2010; Robock, 2000). Third, meltwater pulses, rapidly released into the North Atlantic, can be able to alternate oceanic circulation patterns, with the potential of major impact on the regional climate conditions in the surrounding regions (Clark et al., 2001; Kleiven et al., 2008; McManus et al., 2004; Thornalley et al., 2010). During the LG period, declining ice sheets covered vast mainland areas of the Northern Hemisphere and constituted significant freshwater sources, which indicates that this time span might have been particularly prone to meltwater forcing of abrupt short-term climate changes.

Late Glacial and Holocene climate changes in Arctic Norway

The transition from glacial to interglacial conditions during the LG was characterized by rapid alternations between different dominating oceanic and atmospheric circulation patterns, and the gradual warming was interrupted by cold periods on millennial to decadal timescales (Broecker et al., 2010; Denton et al., 2010; Heinrich, 1988; Mayewski et al., 1993; Rasmussen et al., 2006). The bipolar seesaw concept (Broecker, 1998), based on the anti-phased millennial-scale climate records from

Greenland and Antarctic ice core temperature proxies (Jouzel et al., 2007; Rasmussen et al., 2006), shows a particularly clear signature during the LG (Fig. 1). In terms of abrupt hemispheric climate change, Heinrich Stadials (HS) supposedly display key periods of the bipolar seesaw mechanism. HS, including the YD stadial (HS-0), were periods of catastrophic discharge of icebergs and freshwater input into the North Atlantic Ocean sourced from Northern Hemisphere ice sheets that led to extreme North Atlantic stadial (cold) conditions (Heinrich, 1988). The iceberg pulses released during HS supplied freshwater to the North Atlantic, which in turn could have slowed the Atlantic meridional overturning circulation (AMOC) and related heat transport towards the northern high latitudes (Clark et al., 2001; McManus et al., 2004). During the YD stadial/HS-0, one potentially immediate consequence were the large seasonal changes in Arctic sea ice extending south towards the mid-latitudes during winters (Koç et al., 1993). Dominated by extremely cold winters, the Arctic seasonality was arguably greatly enhanced during the YD stadial (Denton et al., 2005). The extensive North Atlantic winter sea ice cover could have shifted the Westerlies southward and create an extreme polar climate in the northern North Atlantic region during YD winters (Bakke et al., 2009; Broecker, 2006; Denton et al., 2005), reducing the moisture source of Arctic glaciers during the YD stadial (Alley, 2000).

Simplified, the LG regional climate conditions of the greater North Atlantic region were mainly determined by the interaction of three dominating factors. First, a high-pressure field located above the SIS could form a substantial part in the atmospheric circulation system of the region. Second, the Westerlies were carrying warm and moist air masses to the Norwegian coast, coming from the North Atlantic where the Norwegian Atlantic Current (NwAC) as part of the AMOC supplied the region with warmer waters from the mid-latitudes. Third, the sea ice extent of the Nordic Seas was a factor that could have had major impact on both the manifestation of the ice sheet high-pressure field and the location and strength of the Westerlies. During the YD stadial/HS-0, enhanced sea ice presumably could change the large-scale atmospheric and oceanic conditions in the northern high latitudes by cutting off the SIS high pressure field and the influx of the NwAC. Limited influx of warm water masses from the south, a southward shift of the Westerlies, and increased seasonality might then have been able to create Arctic desert conditions with a strong high pressure system located above the North Pole (Fig. 9).

North Atlantic meltwater events, inducing cooling oceanic conditions related to periods of cold atmospheric conditions such as HS and the YD/HS-0 (Broecker, 2003), have also been linked to multi-decadal cold spells such as the Older Dryas and the 8.2 event of climate deterioration (Kleiven et al., 2008; Thornalley et al., 2010). Vice versa, North Atlantic sea ice was supposedly small during the abrupt Bølling warm peak, when the AMOC reinvigorated strongly at the end of HS-1 (McManus et al., 2004). During the latter part of the YD, sea ice conditions possibly were more variable (Cabedo-Sanz et al., 2013), as were glacier conditions in western Norway, which may indicate that rapidly alternating atmospheric and oceanic conditions might have characterized the termination of the YD and led to the transition into the interglacial conditions of the Holocene (Bakke et al., 2009).

The striking similarity of LG glacier culminations of Rødhetta Glacier in Arctic Norway and glaciers in the southern mid-latitudes (Paper I) could point to CO_2 as the major driver of summer temperature on an inter-hemispheric scale, imprinting a steady warming trend (as reflected in Greenland and Antarctic ice core records, Fig. 1) on a global scale. CO_2 forcing is of global nature and has been suggested to be particularly important for the temperature during summers, when the Arctic sea-ice forcing is small and thus does not overpower radiative forcing (Broecker, 2013). Under this scenario, the bipolar seesaw mechanism was primarily a (northern) winter phenomenon during the LG, whereas CO_2 slowly forced the global climate into synchronicity between the two hemispheres. The solar forcing of the precession cycle likely added to the increased seasonality during the YD, when aphelion occurred during the Northern Hemisphere winter (Berger and Loutre, 1991), causing shorter and warmer summers compared to present day.

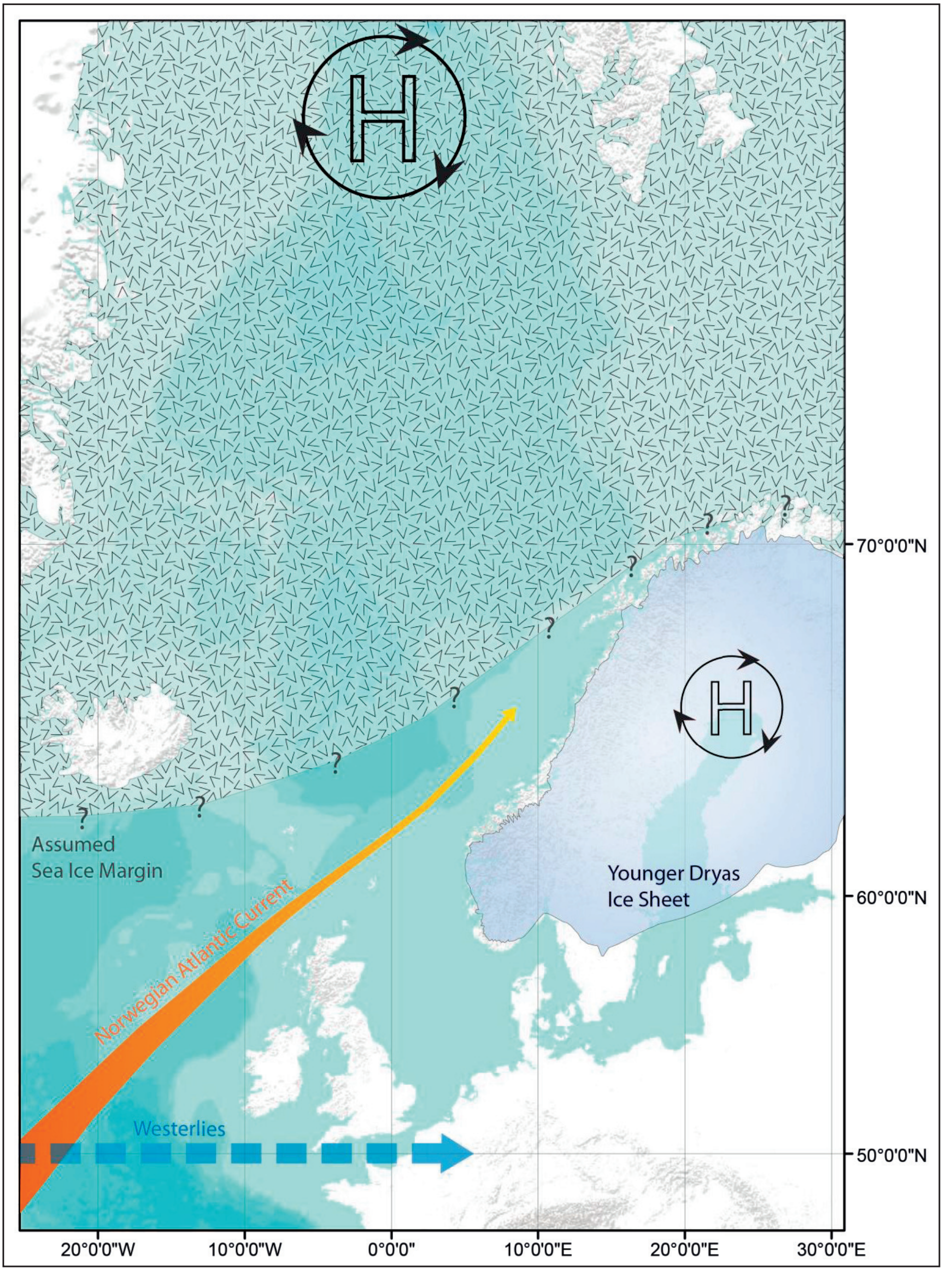

Figure 9 Schematic map of the North Atlantic region and the main factors that may have dominated the regional climate conditions during the Younger Dryas. Enhanced sea ice extent during the Younger Dryas could potentially cut off the high-pressure system over the Scandinavian Ice Sheet and shift the Westerlies southward in dependence of the Norwegian Atlantic Current in the North Atlantic region, leading to extreme polar climate conditions in Arctic Norway with a high-pressure field located above the North Pole. The Younger Dryas extent of the Scandinavian Ice Sheet is outlined as in Andersen et al. (1995).

The climate deterioration of the LIA is the most prominent Holocene climate anomaly and is reflected with overall low temperatures in various terrestrial and marine proxy records from the Northern Hemisphere (Ahmed et al., 2013; Andersen et al., 2004b; Kaufman et al., 2009; Massé et al., 2008; Seppä et al., 2009; Sicre et al., 2008). The LIA has been attributed to short-term changes in the northern mid- to high latitudes linked to reduced sunspot occurrence (Spörer and Maunder Minima) (Bard et al., 2000; Bond et al., 2001; Eddy et al., 1976) and increased volcanic activity (Miller et al., 2012; Robock, 2000). Despite summer temperatures reaching the lowest level of the past two millennia, the glacier activity at the northern outlet of the Langfjordjøkelen ice cap (Paper II) was lower than at the present day over a period of two centuries prior to the local Neoglacial culmination in the early 20th century. Low sea surface temperatures (SSTs) along with increased drift ice appearances (Andersen et al., 2004a; Andrews et al., 2009; Mann et al., 2009; Sicre et al., 2008), a predominantly negative mode of the NAO index (Luterbacher et al., 2001) and increased sea ice extent (Lamb, 1979; Massé et al., 2008; Ogilvie, 1994; Ogilvie, 1984, 1992; Ogilvie and Jónsson, 2001) during this period point to reduced moisture supply in Arctic Norway during wintertime, which might have limited glacier growth. A reduction of accumulation-season precipitation due to less winter cyclonic activity has also been related to a southward displacement of the oceanic polar front (Ballantyne, 1990; Lamb, 1979). The LIA response of the Langfjordjøkelen ice cap ~1925 CE is contemporary to a strong positive signal of the NAO index (Luterbacher et al., 2001), which indicates warm and moist winter season conditions along the Norwegian coast in addition to lower summer temperatures.

During the past two millennia, the glacier activity of the Langfjordjøkelen ice cap seems to have been dominated by changes in summer temperature, while winter season atmospheric variability has triggered high-frequent (decadal to multi-decadal) glacier fluctuations and generally impacted the amplitude of glacier events. Forced by a combination of long- and short-term factors driving natural climate fluctuations, the glacier outlet has been very dynamic with rapid variations in size. A strikingly similar pattern of retreating glaciers around 1600 years ago and advancing glaciers during the

LIA is reflected in reconstructions from cirque glaciers in Svalbard (Reusche et al., 2014 and references therein), pointing to a regional climate forcing of solar-induced changes in summer temperatures dominating the glacier response in the northern North Atlantic realm, potentially weakened/amplified by related changes in oceanic circulation and sea ice.

Final Remarks

- In this thesis, a novel methodological approach for future studies is outlined, combining detailed geomorphic mapping, high-sensitivity ^{10}Be dating, first-order glacier modeling and high-resolution distal glacier-fed lake sediment analyses. If scaled to a larger region, a quantification of corresponding Equilibrium Line Altitude fluctuations in Arctic Norway would allow large-scale paleoclimatic analyses.
- The data in this thesis are retrieved from the northern North Atlantic region, a sensitive region located in the center of interaction of major atmospheric and oceanic circulation patterns, mirroring changes in the heat transport towards northern high latitudes during the Late Glacial until today.
- Robust chronologies of proxy data based on different dating methods as presented in this thesis open up to gaining important insight into past sensitivity of glaciers to different climatic forcing mechanisms on a regional, hemispheric and even inter-hemispheric scale.
- A first-order glaciological model applied on a detailed mapped mountain glacier moraine sequence as in this thesis can provide robust reconstructions of past ELAs and quantify the underlying climate changes.
- The Late Glacial mountain glacier record from Arctic Norway presented here is consistent to the southern mid-latitudes, pointing towards a scenario where the Late Glacial bipolar seesaw mechanism was primarily a (northern) winter phenomenon, while summer temperatures were synchronized between the hemispheres by atmospheric CO_2 forcing.
- Based on the work carried out in this thesis, recommendations for further work include the collection of similar robustly dated records from other mountain glacier sites and potentially ice sheet deposits in the greater North Atlantic region, in order to substantiate the findings of this thesis and build a robust proxy archive of consistent glacier reconstructions for comparison on hemispheric and inter-hemispheric scales.

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