Holocene storminess and climate change in Lofoten and Vesterålen, northern Norway

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Bergen, February 2016 Pål Ringkjøb Nielsen

Abstract

This thesis investigates Holocene storminess and climate change reconstructed from lacustrine sediments from the Lofoten-Vesterålen archipelago in northern Norway (68–69°N, 12–16°E). The present thesis consists of an introduction and three individual papers in studying different perspectives of aeolian (wind) activity reconstructed from (I) glacier fluctuations, (II) coastal dunefield dynamics and (III) variations in aeolian sand influx from three different lake sediment basins.

Paper I presents the first high-resolution late-Holocene glacier record from Lofoten. The study is based on glacial geomorphological mapping and analyses of sediment cores from lake Kveitvikvatnet (30.1 m a.s.l.), which currently receives meltwater from three small cirque glaciers. By combining selected sediment proxies to glacier advances of known ages, a continuous curve of the glaciers equilibrium-line altitude (ELA) over the last 1200 years has been constructed. This has further been connected to an independent proxy for summer temperature using the well-known 'Liestøl-equation', as well as the D/A-ratio, resulting in winter precipitation estimates throughout the recorded period. The extremely high sedimentation rates measured in the sediment cores (0.15–0.45 cm/yr) allow us to draw an analogy to instrumental data from nearby meteorological stations, which strongly supports our approach. We have identified that both the Medieval Climate Anomaly (MCA) and the Little Ice Age (LIA) were periods of high glacier activity in Lofoten. It is proposed that the advancing glaciers during both periods were caused mainly by an increase in winter precipitation, in relation to an increase in the strength of the westerlies.

In Paper II we investigate the aeolian activity at a coastal dunefield on Andøya in Vesterålen. The study is based on a combination of geomorphological mapping, a lacustrine sediment record from the distal lake Latjønna (14.5 m a.s.l.) and a foredune stratigraphy. The lake sediment record was analysed by high-resolution measurements of sediment properties such as X-ray fluorescence (XRF), magnetic susceptibility (MS), grain size and loss-on-ignition (LOI). Aeolian activity was calculated based on the weight of sand grains >250 µm per cm recorded in Latjønna divided by the

sedimentation rate. The two investigated sites show quite contrasting chronologies, where high sedimentation rates in the lake record, associated with more aeolian influx, correspond to stability in the foredune stratigraphy reflected by the presence of palaeosols. Phases with high influx of sand to Latjønna are recorded around 4800, 4250, 3000–2000, 1850–1750, 1600–600, 450, 300 and 150 cal. yr BP. Based on the investigated sites, it is suggested that a falling sea level made sand available for deflation, and that increasing storminess was the main driver for increased aeolian activity. The influx of sand to Latjønna is concurrent with other reconstructions from the region, thus recording variations in past storminess occurring in the NE Atlantic region throughout the last 6200 years.

Paper III presents a reconstruction of aeolian activity (storminess) and mass-wasting events based on analysis of lacustrine sediment cores from lake Trehynnvatnet (33 m a.s.l.), which is located in a glacially carved valley at the outmost coast of western Langøya in Vesterålen, northern Norway. Sediment cores have been examined by use of various high-resolution proxies and firmly dated with ^{210}Pb and ^{14}C dating to detect changes in the depositional environment. In total, 35 event layers with a recurrence interval of ~300 years have been identified throughout the Holocene. The majority of these events are characterized as discrete coarse-grained sediment layers followed by normal grading and interpreted to be deposited by turbidity currents triggered by subaerial mass-wasting events. The continuous background sediments have been systematically investigated for the content of sand grains (>250 μm), which have been linked to catchment samples from a nearby beach located c. 750 m to the southwest. Based on the current wind regime and the local setting, the influx of wind-blown sand grains to Trehynnvatnet is suggested to reflect the strength, pattern and timing of storminess. The results show that storminess increased after 2800 cal. yr BP, with maximum influx of sand grains occurring during the Little Ice Age (LIA) period. The long-term trends shown in the influx of sand grains and mass-wasting events to Trehynnvatnet are similar to other reconstructions from nearby sites and from the NE Atlantic region. Hence, this record provides further knowledge about past regional scale changes in storminess and episodic extreme events throughout the Holocene.

List of publications

Paper I:

Nielsen, P.R., Balascio, N.L., Dahl, S.O., Jansen, H.L., Støren, E.W.N., Bradley, R.S. 2016: A high-resolution 1200-year lacustrine record of glacier and climate fluctuations in Lofoten, northern Norway. *The Holocene,* DOI: 10.1177/0959683615622551

Paper II:

Nielsen, P.R., Dahl, S.O., Jansen, H.L.: Mid- to late Holocene aeolian activity recorded in a coastal dunefield and lacustrine sediments on Andøya, northern Norway. Submitted to *The Holocene,* September 11, 2015.

Paper III:

Nielsen, P.R., Dahl, S.O., Jansen, H.L., Støren, E.W.N.: Holocene aeolian sedimentation and episodic events recorded in lacustrine sediments on Langøya in Vesterålen, northern Norway. Submitted to *Quaternary Science Reviews,* December 3, 2015.

Contents

Outline

This thesis consists of an introduction followed by three individual papers. The primary objective for the present thesis has been to improve the current understanding of past climate change in the Lofoten-Vesterålen archipelago, northern Norway, with special emphasis on past storminess and extreme weather events. The present study is based on sediment archives from key localities within a relatively small geographical area. The identification of catchment processes has been of utmost importance in understanding the lake sediments, as the different sedimentary regimes have to be separated in order to assess their relationship to climate. Paper I presents the first high-resolution continuous glacier reconstruction from Lofoten, spanning the last 1200 years. The study is based on a combination of glacial-geomorphological mapping and investigation of sediment cores from the distal glacier-fed lake Kveitvikvatnet. The studied glaciers are situated far below the regional equilibrium-line-altitude (ELA), implying that other factors such as avalanching and leeward accumulation of snow have a large influence in controlling the fluctuations in ELA. In Paper II we present a study of a coastal dunefield on Andøya to identify past variations in aeolian influx, as well as the relationship between dunefield alteration and sea level fluctuation. Two independent sites within the dunefield were studied; a lake sediment record from the distal lake Latjønna covering the last 6200 years and a foredune stratigraphy covering the last 3700 years. Paper III complements the study from Andøya, however spans the entire Holocene period (11500 years). The study is based on analyses of lake sediment cores from lake Trehynnvatnet on Langøya. Past episodic sedimentation from the adjacent valley slope, as well as the influx of aeolian sediments from the nearby beach were identified and separated, thereby providing a record of the frequency of mass-wasting events and aeolian sand influx (storminess).

Introduction

The climate of the North Atlantic region is influenced by large-scale atmospheric and oceanic circulation patterns. Because of their interactions, the area experiences one of the most frequent Northern Hemisphere storm tracks, resulting in high storm impact (e.g. Lamb and Frydendahl, 1991). The reason for this is the continuing passage of synoptic scale low-pressure systems (extratropical cyclones) following the North Atlantic storm track pattern. The system varies in intensity, frequency and position, and the most violent is regarded as extreme weather events causing widespread damages. The North Atlantic storms are usually most intense during late autumn and throughout the winter, when there is a large temperature- and pressure gradient between the air masses. The term *storminess* is much used in the literature, and is described as the ‘state of being stormy’ (Feser et al., 2014), expressed by direct observations of wind speed or mean sea level pressure (MSLP). Storminess can, in a broader sense, represent the trend in frequency and intensity of storms over a period (Carnell et al., 1996). The frequency of storms are of major concern, as a cluster of even low intensity storm events in rapid succession may cause high impact in terms of coastal erosion (e.g. Ferreira, 2005; 2006; Mailier et al., 2006).

Instrumental measurements provide key data in studying the inter-annual and decadal scale variability of North Atlantic storminess, giving a rather detailed picture from mid 19th century until present day (e.g. Carnell et al., 1996; Alexandersson et al., 2000; Dawson et al., 2002; Bärring and von Storch, 2004; Matulla et al., 2008; Pinto et al., 2009; Clemmensen et al., 2014). During the last 40 years there have been about 70 severe windstorms hitting Europe, resulting in losses of approximately 50 billion USD, as reported from insurance companies (Schwierz et al., 2010). In the last few years, three devastating windstorms have struck the Norwegian coastline, namely Dagmar (25th December 2011) and Nina (10th January, 2015). Both storms brought extremely high wind gusts (<65 m/s) and high storm surges, causing severe damage to infrastructure in the Nordic region (e.g. Kjølle et al., 2013). Such extraordinary storms are characterized by low probability and high impact, and further knowledge about past variability-, frequency- and intensity of such events are highly relevant in designing effective adaptation strategies for a changing climate.

The North Atlantic Oscillation (NAO) is thought to be the main pattern of weather and climate variability in NW Europe during winter (e.g., Hurrell, 1995; Thompson and Wallace, 1998; Wallace, 2000; Hurrell et al., 2003; Hurrell and Deser, 2010; Pinto and Raible, 2012). Positive NAO is associated with stronger westerly airflow (increased storminess) over Scandinavia, transporting moisture towards the westwards facing coastline. This is also reflected in the mass balance of maritime glaciers in southwestern Norway, which have been shown to expand during periods of positive NAO (e.g. Nesje et al., 2000a; Nordli et al., 2005; Imhof et al., 2012; Nesje and Matthews, 2012). Based on different storm indices from the North Atlantic region, the NAO has been positively correlated with periods of high storminess (Dawson et al., 2004a; Hanna et al., 2008; Matulla et al., 2008). However, there are some discrepancies as periods of negative NAO, such as during the Little Ice Age period (LIA), were probably affected by more intense storms rather than more frequent storms (e.g. Pinto et al., 2009; Trouet et al., 2012; Burningham and French, 2013; Clemmensen et al., 2014; Orme et al., 2016b). Hence, the variations in the NAO cannot be used directly as a measure of storminess.

Climate models predict higher temperatures worldwide for the future (e.g. IPCC, 2014). This is especially the case for the Arctic, which is visible in both the decline in arctic sea-ice cover and the increase in temperature, which greatly exceeds the global mean (Screen and Simmonds, 2010). This ‘polar amplification’ is modelled to continue into the future, with uncertain climatic consequences (e.g. Holland and Bitz, 2003). The increase in temperature will, consequently, lead to more evaporation and thus increased atmospheric moisture content (precipitation) (e.g. Bengtsson et al., 2009). Furthermore, it is likely that the North Atlantic extratropical cyclones are moving northwards in correspondence with the Northern Hemisphere jet streams and the position of the sea-ice edge in the Arctic Ocean (Archer and Caldeira, 2008; Bader et al., 2011; Bender et al., 2012). This may cause a shift in the present weather patterns with an unknown outcome.

Understanding past environmental change relies on investigations of natural archives that incorporate a climate-dependent signal. Lakes can store information about past environmental change based on sediments accumulating from the surrounding catchment. Selecting representative sites within the scope of the research objective is often difficult, and requires careful investigations (e.g. Dahl et al., 2003; DeVries-Zimmerman et al., 2014). Furthermore, to identify and convert certain sediment properties to proxy variables of past change, there is a need for a thorough analysis that encompasses both qualitative and quantitative high-resolution data, as well as a firm chronology based on ^{210}Pb and ^{14}C dating methods. By doing this, several studies have utilized lake sediments to reconstruct past variations in climate such as temperature (e.g. Bjune et al., 2004; Bjune and Birks, 2008; Aarnes et al., 2012; Birks et al., 2012; 2014), glacier fluctuations (e.g. Karlén, 1976; 1981; Leonard, 1986a; 1986b; Dahl and Nesje, 1994; Leonard, 1997; Leonard and Reasoner, 1999; Matthews et al., 2000; Nesje et al., 2000b; 2001a; Bakke et al., 2005a; 2005b; 2005c; 2010; 2013; Røthe et al., 2015; van der Bilt et al., 2015; Wittmeier et al., 2015; Gjerde et al., 2016; Jansen et al., 2016), mass-wasting events (e.g. Nesje et al., 2001b; Arnaud et al., 2002; Bøe et al., 2006; Nesje et al., 2007; Støren et al., 2008; 2010; Vasskog et al., 2011; Simonneau et al., 2013; Berntsson et al., 2015), and aeolian activity (e.g. Dean, 1997; Stanley and De Deckker, 2002; Lamoureux and Gilbert, 2004; Fisher and Loope, 2005; Timmons et al., 2007; Fisher et al., 2012; DeVries-Zimmerman et al., 2014; Orme et al., 2016a), making lake sediments one of the most valuable and important archives for palaeoclimatological investigations.

Coastal communities are especially vulnerable to increased storminess, and several documentary archives exist on sand drift and the associated burial of settlements, lighthouses and agricultural land, particular from the period between AD 1500 and 1850 (e.g Lamb and Frydendahl, 1991; Clarke and Rendell, 2009). Since sand is mobilised during stormy periods, it has been of great interest to find areas where aeolian sand is deposited and stored as a proxy of former wind-events (storminess) or progression of coastal environments. Based on this, dune stratigraphy and sediment cores from coastal areas have been investigated in an attempt to reconstruct past aeolian activity on the British Isles (e.g. Pye and Neal, 1993; Wilson and Braley, 1997; Wilson, 2002; Dawson et al., 2004b; Wilson et al., 2004; Orme et al., 2015; 2016b), in Denmark (e.g. Clemmensen et al., 1996; Dalsgaard and Odgaard, 2001; Clemmensen et al., 2006; Clemmensen and Murray, 2006; Aagaard et al., 2007; Clemmensen et al., 2009; 2015), in Sweden (e.g. Björck and Clemmensen, 2004; De Jong et al., 2006; 2007; Mellström et al., 2015), in Norway (e.g. Selsing and Mejdahl, 1994; Prøsch-Danielsen and Selsing, 2009; Sjögren, 2009), in France (e.g. Clarke et al., 2002; Billeaud et al., 2009; Sorrel et al., 2009; Van Vliet-Lanoë et al., 2014a; 2014b) and in Portugal (e.g. Clarke and Rendell, 2006; Costas et al., 2012). The causes for large-scale dune formation and sand drift are often difficult to identify, and several local factors such as distance from sediment source, volume and availability of sediment supply, sea level fluctuations, surface cover (vegetation/snow) and climate, alone or in combination, may be important for the establishment and progression of dune systems. There is, however, growing evidence suggesting that periods of sand drift can be linked to smaller-scale episodes of cooling and/or hydrological transitions in the North Atlantic region (De Jong et al., 2007; Clarke and Rendell, 2009; De Jong et al., 2009; Sorrel et al., 2012).

Research objectives

The main objective for the present thesis has been to improve and expand the knowledge about past storminess in northern Norway by use of geomorphological mapping and robustly dated lacustrine sediments from contrasting lake basins within wind-exposed settings. The study area is located at the northeasternmost tip of the North Atlantic storm tracks, and is therefore very sensitive to alterations in this important climate driver for the region. The following research objectives were focused on in this thesis:

1. Reconstruct past variations in storminess and winter precipitation from lake sediment records.
2. Investigate the relationship between past storminess and climate change in northern Norway and in the NE Atlantic region.

In an attempt to address these objectives, I will in the following provide an overview of the study area and an introduction to the approaches applied in Papers I-III.

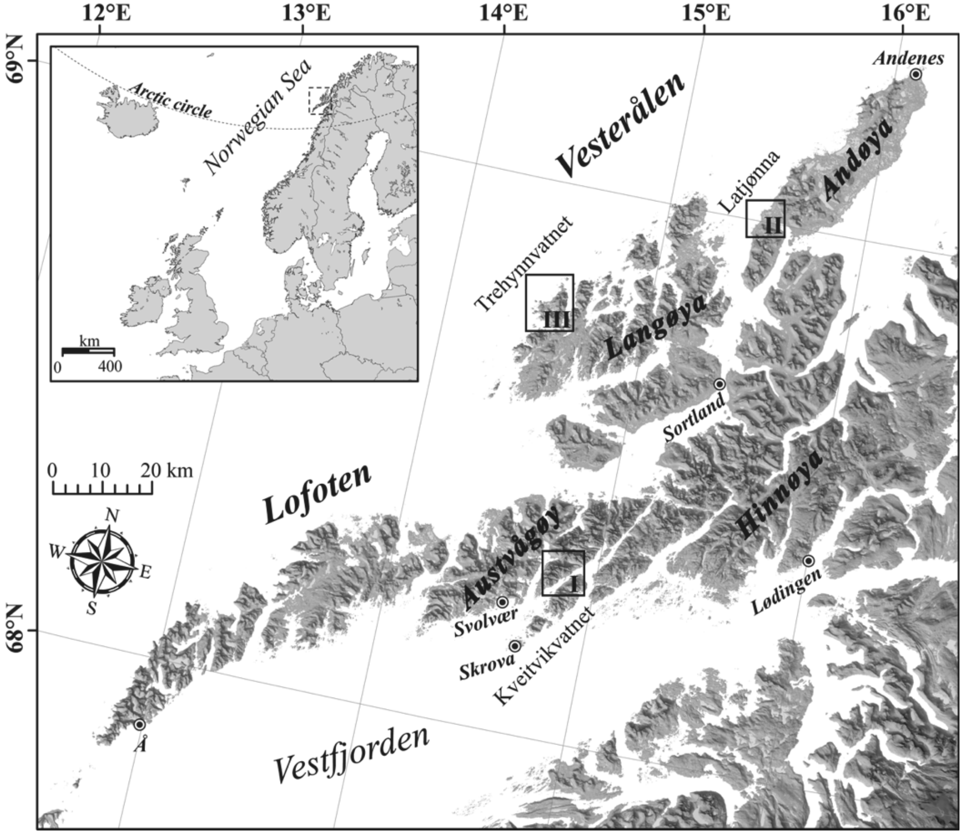


Figure 1: Map of the Lofoten-Vesterålen archipelago with the studied sites marked within the map (I, II and III). The inset figure places the study area (dashed square) in a regional context in northern Europe.

Study area

The investigated lakes are situated in the Lofoten-Vesterålen archipelago in northern Norway (Figure 1). The region has one of the largest latitudinal positive air-temperature anomalies in the world. This is caused by the constant influx of warm waters following the Norwegian Atlantic Current and the corresponding moist air of the westerlies. Because of these drivers, the area has a maritime climate. There is, however, a clear temperature and precipitation gradient from the southern coast of Lofoten to the inner coast of Vesterålen. This is here represented by climate data from Skrova/Kvitfossen and Andenes, respectively (DNMI, 2015). The southern part has a mean annual air-temperature of ~4.6°C and a mean annual precipitation exceeding 3000 mm in the alpine areas. In contrast, the northern part has a mean annual air-temperature and precipitation of ~3.6°C and ~1000 mm, respectively. Cirque glaciers are present on the leeward side of the precipitation bearing west-southwesterly winds on Austvågøy and Hinnøya at altitudes above 300 m (Andreassen and Winsvold, 2012).

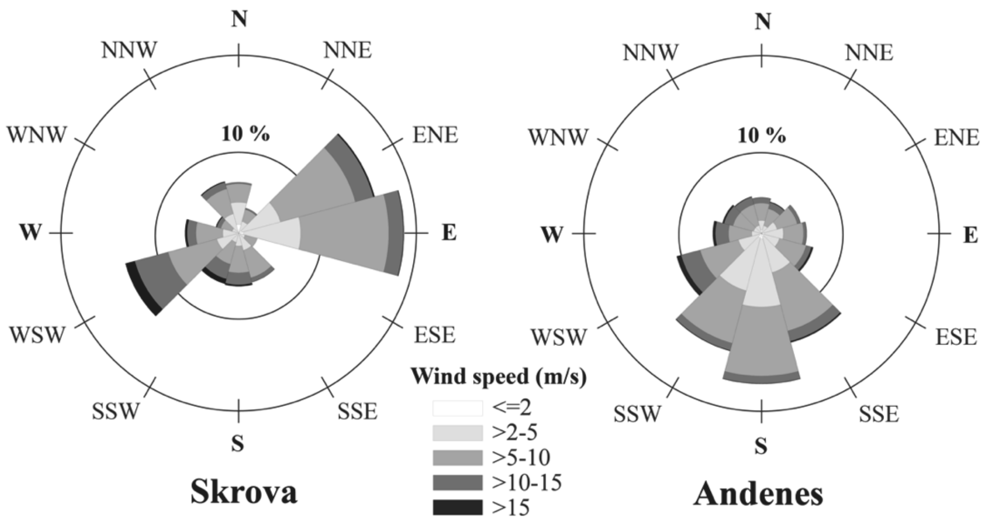


Figure 2: Wind roses showing modern average wintertime (Oct–Apr) wind speed and direction at Skrova (AD 1933–2014) and Andenes (AD 1930–2014) meteorological stations (DNMI, 2015).

The annual mean wind speed at Skrova (AD 1933–2014) is 6.2 m/s (7 m/s for wintertime and 5.2 m/s for summertime), and the annual mean wind speed at Andenes (AD 1930–2014) is 5.8 m/s (6.5 m/s for wintertime and 4.8 m/s for summertime) (DNMI, 2015). For both areas, the most intensive winds during all seasons come from a west-southwestern direction in relationship with the passage of extratropical cyclones following the North Atlantic storm track pattern (westerlies) (Figure 2). The two sites have, however, some variance in the general wind-pattern related to local topographic and climate variations.

The Lofoten-Vesterålen archipelago is of particular interest for studying the early deglaciation of Scandinavia, as the northernmost tip of Andøya was deglaciated during or soon after the last glacial maximum (LGM) (Møller and Sollid, 1972; Rasmussen, 1984; Vorren et al., 1988; 2013; 2015). The presence of several moraine systems on Andøya and in the nearby fjord-systems reflect readvances or standstills as the Scandinavian Ice Sheet retreated (e.g. Vorren and Plassen, 2002). Although several areas were influenced by cirque glaciation (e.g. Paasche et al., 2007; Aarnes et al., 2012), large parts of the islands in the Lofoten-Vesterålen archipelago were ice-free early and thereby susceptible to sub-aerial processes. Several prominent beach ridges, shorelines and abrasion terraces were formed during the deglaciation and throughout the Holocene, and establish the basis for reconstructing Late Weichselian and Holocene shore-level fluctuations (Marthinussen, 1962; Møller and Sollid, 1972; Møller, 1986; Vorren and Moe, 1986; Møller, 1987; 2003; Barnett et al., 2015). Based on these studies, the marine limit is varying from 15–40 m a.s.l. following a NW-SE transect from the outer Langøya (Paper III) to Austvågøy (Paper I). The beach ridge of the Tapes Transgression high stand (~6800 cal. yr BP) is present in the outermost study sites (Papers II and III) at altitudes between 5–8 m, and represent the highest sea level during the Holocene.

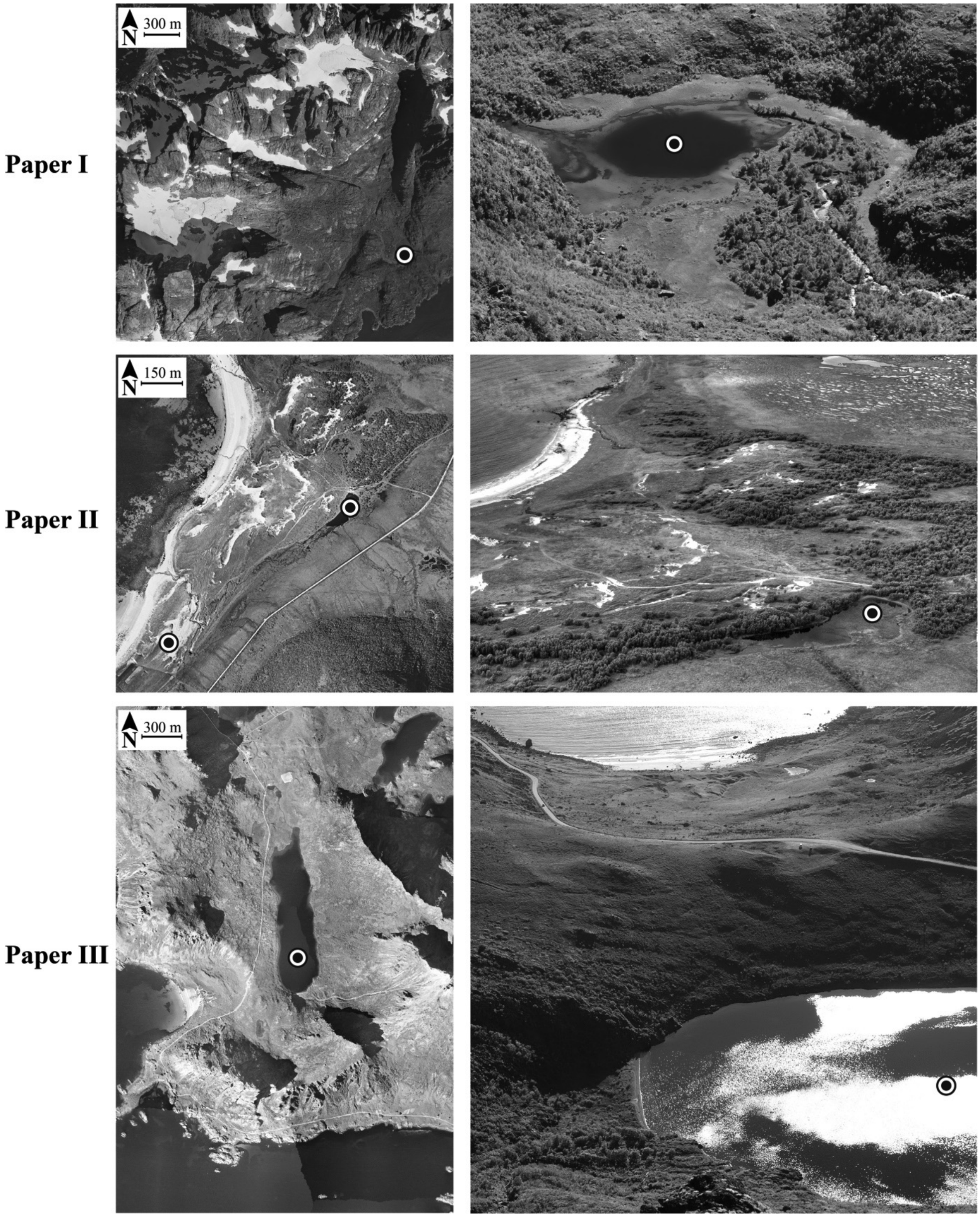


Figure 3: Aerial and terrestrial photographs of each study area (I, II and III) with coring/studied locations plotted. The aerial photographs were taken in AD 1952 (I), 1956 (II) and 1957 (III), all the terrestrial photographs were taken by the author during a field campaign in AD 2012.

Presentation of papers

The papers included in this thesis describe three different approaches in elucidating past aeolian (wind-) activity from sites that are very exposed to the prevailing west-southwesterly winds (Figure 3). In Paper I, lake sediments from the distal glacier-fed lake Kveitvikvatnet (30.1 m a.s.l.) were used to study glacier fluctuations of cirque glaciers that are affected by leeward accumulation of snow. In Paper II, a lake sediment record from Latjønna (14.5 m a.s.l.) and a foredune stratigraphy, both situated in close proximity to a dynamical coastal dune system on Andøya (Sandhaugan), were studied. The last study (Paper III) is based on lake sediment cores recovered from Trehynnvatnet (33 m a.s.l.), which is situated at the outmost coast of Langøya. Sand drift from the adjacent beach as well as episodic mass-wasting events from the nearby valley slopes are suggested to be important contributors to the sediment archive.

Paper I: Glacier and climate fluctuations on Austvågøy, Lofoten

Glaciers are amongst the best natural archives reflecting climate change (e.g. Oerlemans, 2005). Glaciers respond to the balance between accumulation of snow during winter and ablation during summer, giving valuable information on present and past climate conditions (e.g. Nesje et al., 2008; Winkler et al., 2009; Nussbaumer et al., 2011). Glaciers are also effective denudation agents, forming marginal moraines and producing glacier rock flour that is effectively transported in meltwater streams and deposited in distal lakes. A lowering of the equilibrium-line altitude (ELA) usually results in larger glaciers and increased amount of glacier-induced sediments being transported down-valley. Hence, former ELAs can be reconstructed based on regressions between known ELAs (former glacier positions) and distal lake sediment proxies (e.g. Dahl et al., 2003). Several studies have used similar approaches to reconstruct continuous records of past glacier fluctuations (e.g. Karlén, 1976; 1981; Leonard, 1985; Dahl and Nesje, 1994; 1996; Nesje et al., 2000b; 2001a; Bakke et al., 2005a; 2005b; Matthews et al., 2005; Bakke et al., 2010; Vasskog et al., 2012; Røthe et al., 2015; Wittmeier et al., 2015; Gjerde et al., 2016; Jansen et al., 2016).

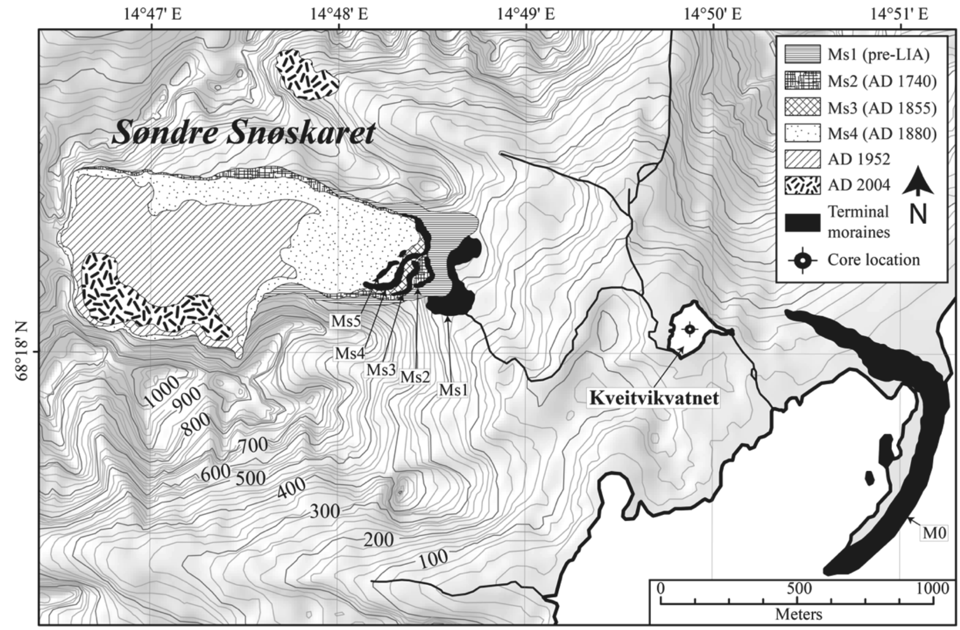


Figure 4: Map showing the southern part of the Kveitvikvatnet catchment displaying the reconstructed glaciers based on marginal moraines and aerial photography at Søndre Snøskaret.

Cirque glaciers situated leeward of the general precipitation-bearing winds may store valuable information on past atmospheric circulation, especially when they exist far below the regional temperature-precipitation ELA (TP-ELA), making them sensitive to variations in the prevailing wind pattern (TPW-ELA) (e.g Dahl and Nesje, 1992; Kuhn, 1995). The Langstrandtindan Mountains on Austvågøy provides such a site (Figure 4). In this location, three small cirque glaciers with aspect towards the NE are present within a relatively small catchment area (4.2 km^2) situated in a maritime setting. Historical maps, old aerial photography (Figure 3) and lichenometric measurements on marginal moraines in the glacier foreland depict that the largest glacier (Søndre Snøskaret) has retreated ~1.2 km, and decreased in area from 0.64 to 0.08 km^2, since the LIA-maximum (AD 1740) (Figure 4). To extend the record further back in time, several sediment cores from the distal glacier-fed lake Kveitvikvatnet (10 m deep) were retrieved and analysed for glaciofluvial input. Based on sediment parameters such as grain-size distribution, dry bulk density (DBD), loss-on-ignition (LOI) and magnetic susceptibility (MS), the sediments in the main core is interpreted to reflect high glaciofluvial input from 1200–650 and 500–70 cal. yr BP, separated by a short period with more fluvial sedimentation (coarse grained sorted sediments).

A continuous curve reflecting the fluctuation of the Søndre Snøskaret glacier has been produced based on linear regressions between dated glacier advances (marginal moraines) and well-dated glaciofluvial sedimentation to Kveitvikvatnet. The continuous TPW-ELA curve shows that the most extensive glacier activity was during the MCA between 940 and 850 cal. yr BP, with a TPW-ELA lowering of ~75 m, and during the LIA with several advances occurring at 450, 340, 270, 200 and 70 cal. yr BP, with maximum lowering of ~85 m at 200 cal. yr BP (Figure 5). This pattern resembles other reconstructions from the region, suggesting that the glacier responds to regional climate conditions (e.g. Dahl and Nesje, 1994; Matthews et al., 2000; Bakke et al., 2005a; 2005b; Matthews and Dresser, 2008; Bakke et al., 2010; 2013; Røthe et al., 2015). Because of the ultra-high resolution of this record, we sought to convert TPW-ELA to winter precipitation by use of the well-known Liestøl equation (1) (Liestøl, 1967; Liestøl in Sissons, 1979). The Liestøl equation is based on an exponential relationship between mean ablation-season temperature from 1 May to 30 September (t) and winter precipitation from 1 October to 30 April in metres water equivalent (A) at the ELA on 10 Norwegian glaciers (see Dahl and Nesje, 1996 and references therein):

$$A=0.915^{0.333t} \ (r^2 = 0.989, P < 0.0001) \quad (1)$$

Equation 1 implies that if the former ELA of the glacier and ablation temperature is known, it is possible to calculate winter precipitation, and vice versa. Several studies have successfully applied equation (1) to reconstruct former winter precipitation on Norwegian glaciers based on continuous ELA-reconstructions coupled with independent proxies for summer-temperature (Dahl and Nesje, 1996; Bakke et al., 2005b; Bjune et al., 2005; Matthews et al., 2005; Nesje et al., 2006; Gjerde et al., 2016; Jansen et al., 2016). The equation does not, however, separate the amount of leeward accumulation of snow deposited by wind from precipitation, thereby producing unreasonably high Pw estimates on cirque glaciers. To account for this effect, Dahl et al. (1997) introduced the D/A-ratio to estimate the potential for leeward accumulation in a cirque. The ratio is based on total drainage area (D) above TPW-ELA (the potential surface where snow can be deposited) and the reconstructed accumulation area of the glacier (A). To separate total winter accumulation into winter precipitation and leeward accumulation (including avalanches), the values obtained from the Liestøl-equation can be divided by a continuous curve reflecting the D/A-ratio (based on regressions with ELA). This means that if the D/A-ratio for a glacier is 2.0, the leeward accumulation of snow is assumed to equal the amount of winter precipitation. The Søndre Snøskaret glacier has D/A-ratios varying from 1.67 during the LIA-maximum to 4.39 in AD 2004, implying that the glacier gets increasingly more dependent on leeward accumulation of snow as it retreats. Applying this method using a tree-ring based proxy for summer temperature from Torneträsk (Grudd, 2008), past variations in winter precipitation for the Søndre Snøskaret glacier has been reconstructed (Figure 5).

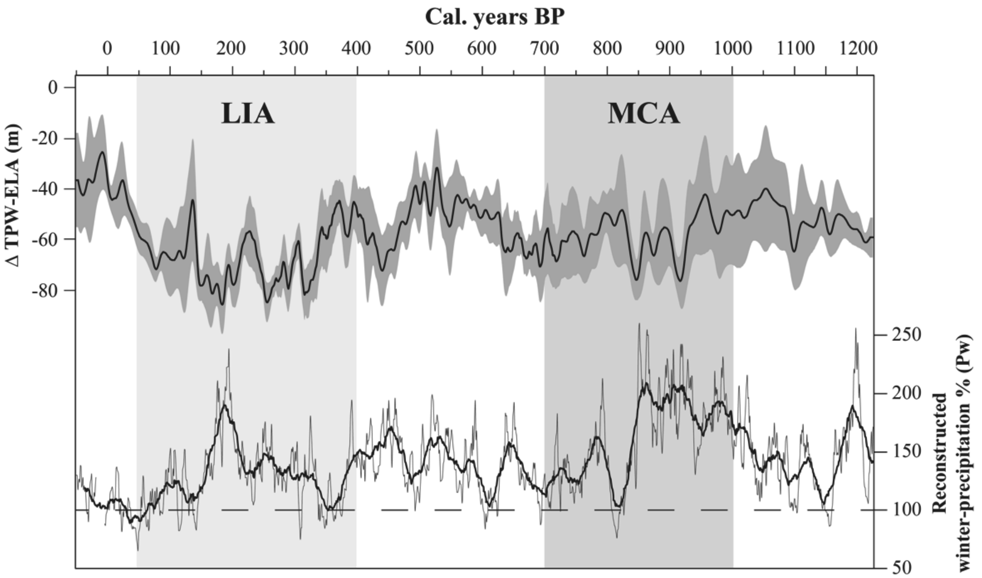


Figure 5: The upper curve shows the continuous TPW-ELA from Søndre Snøskaret with standard deviation (1σ) as confidence interval. In the lower curve, the reconstructed winter-precipitation based on the relationship between TPW-ELA and summer temperature from Torneträsk (using the Liestøl-equation) divided by the D/A-ratio is shown in % of mean winter precipitation at the ELA (~2900 mm).

Paper II: Aeolian activity on Andøya, Vesterålen

Coastal dunes are prominent landforms located along exposed windward coasts where sand is susceptible to deflation. Three components are key factors for the formation of coastal dunes; (1) supply of beach sand, (2) onshore winds with sufficient force capable of mobilising sand onshore from the beach, and (3) vegetation cover (Pye, 1983). Vegetation affects dune morphology, and is essential in the formation of for example foredunes where aeolian transportation competes with the growth of the vegetation (e.g. Arens, 1996; Hesp, 2002; Luna et al., 2011).

At present, there is growing evidence that periods of sand drift and dune building reflect phases of increased wind activity, thereby providing a proxy of past storminess (e.g. Clemmensen et al., 2001; Dawson et al., 2004b; Clemmensen et al., 2006; 2009; 2015). There are, however, several issues pertaining to the process of (re-) activation and stabilization when studying dune systems. Yizhaq et al. (2009) modelled dune reactivation processes to be almost irreversible. This implies that once a dune becomes active in response to an external forcing, it will stay active until a substantial adjustment occurs such as an increase in precipitation (vegetation cover), a decrease in wind-climate or human interference. This can possibly explain some of the long-term trends observed in the studies of dunefields, which to a greater extent limits the possibility of reconstructing smaller-scale events based on dune complexes. However, to compliment the dune records, Björck and Clemmensen (2004) developed a new proxy for storminess based on the identification of aeolian sand grains in raised bogs on the coastal plains in southwestern Sweden. They assumed, based on the localities being surrounded by wetland, that the content of silts and sands were brought into the bogs by aeolian processes. This was also verified by surface textures on single grains implying considerable aeolian reworking. Since coarse-grained particles (>0.2 mm) are usually transported as bed-load by saltation and surface creep (e.g. Tsoar and Pye, 1987), they argued that the content of sand grains in the cores represent periods when the irregular vegetation on the bog and the surrounding catchment were covered by snow and ice, making sand movement across the landscape less problematic (niveo-aeolian sand). Based on this, they suggested that the influx of sand grains larger than

0.2 mm (200 μm) constitute a proxy for winter storminess. Furthermore, they developed a parameter to quantify the aeolian sedimentation which they called Aeolian Sand Influx (ASI), involving total influx of quartz grains (>0.2 mm) per cm^2 per year. This method has been applied in similar studies from the region and provides strong support that the timing of dune activity reconstructed from nearby sites was driven by changes in storminess (De Jong et al., 2006; De Jong, 2007; Clemmensen et al., 2009). However, several studies also demonstrate that relative sea level (RSL) plays an important role in the development of dunefields and rate of aeolian influx, and is indeed a significant factor for the longer-term progression (e.g. Carter, 1991; Carter and Wilson, 1993; Provoost et al., 2011). The effect of RSL on dunefield development is especially prominent during the post-glacial stage and throughout the Holocene, when substantial changes in RSL occurred.

Coastal dunes are rather scarce in Norway. This is not a result of low wind activity, but mainly because of a lack of sediment sources (e.g. sand beaches) along the rugged coastline. Nevertheless, a few coastal dune systems are found along the coast from the Swedish border to the city of Haugesund in southern Norway, along the coast of Møre and Romsdal county in western Norway, and along the coast of Nordland and Troms counties in northern Norway (e.g. Klemsdal, 1969; Selsing and Mejdahl, 1994; Prøsch-Danielsen and Selsing, 2009; Sjögren, 2009). In Paper II, we focus on the island of Andøya in Vesterålen, northern Norway, where several small coastal dune systems are present (Figure 1, 3 and 6). Most of the dune systems are located in close proximity to sandy beaches along the westward facing shoreline. Sandhaugan is regarded as the largest and most developed dune systems on the island, and consists of a ~0.5 km^2 large sand sheet extending towards the northeast within the Sørmela nature reserve (Figure 6). Most of the study area is today vegetated and stable, however with a clear distinction between the southern and the northern part. The southern part is dominated by established foredunes and a large deflation surface, while the northern part contains several blowouts and parabolic dunes.

Resting on the assumption that periods with higher wind activity (more frequent high-energy wind events) cause increased deflation and sand drift further inland (e.g.

DeVries-Zimmerman et al., 2014), an adjacent lake, Latjønna, was cored and analysed in an effort to reconstruct the history of aeolian activity. In addition to this, the stratigraphy of a 10 m high foredune south in the dune system was investigated and dated (Figure 6).

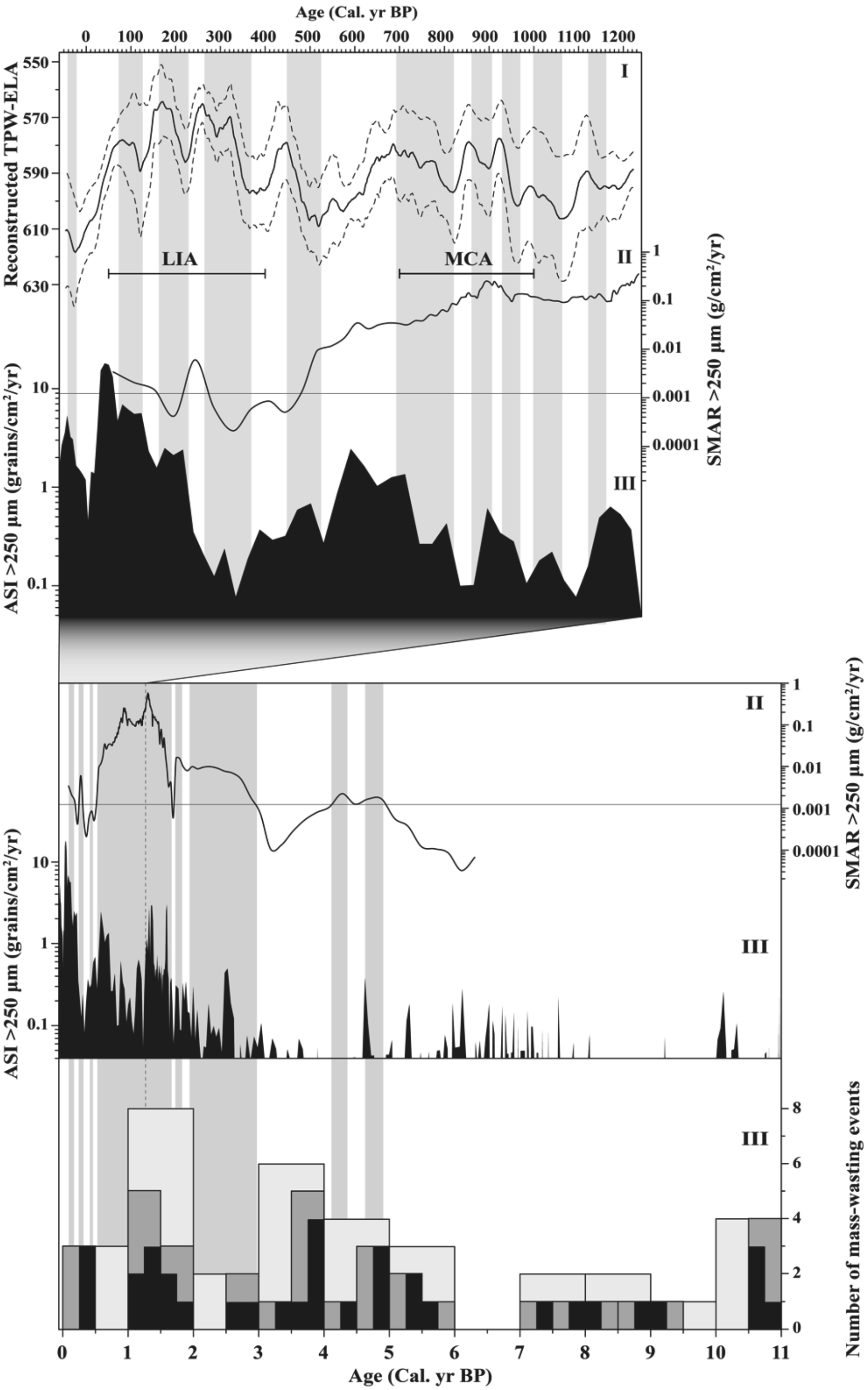
Figure 6: Photography of the Sandhaugan dunefield with view towards the northwest. Latjønna is located on the border between the dunefield and the adjacent bog (white arrow) and the foredune is located south in the dunefield marked with a black arrow.

The lake sediment core from Latjønna revealed a simple stratigraphy with several units containing laminated medium sand interspaced between organic-rich units. Based on the sediment analysis and geomorphological mapping, it is suggested that the sand units were deposited during periods of increased aeolian activity, and that the units containing organic-rich sediments reflect more stable periods with less deflation. To quantify the amount of aeolian activity, bulk sediments were sieved and the content of sand grains >250 µm were converted to sand mass accumulation rate (SMAR) based on the robust ^{14}C chronology following Sjögren (2009). The record shows high amplitude variations in sand influx during the last 6200 years, with a pronounced increase after 3000 cal. yr BP (Figure 7). The highest influx of sand is recorded between 1600 and 600 cal. yr BP. This is approximately at the same time as the studied foredune in the southern part indicate stable conditions as shown by the presence of palaeosols dated to between 1300 and 300 cal. yr BP.

The out-of-phase behaviour recognized between the lake record and the foredune stratigraphy suggests a rather complex relationship between local climate conditions, aeolian processes, RSL change and vegetation cover over a relatively small area. Foredunes are very dependent on the vegetation cover in trapping sand, as well as the distance from the sediment source (e.g. Hesp, 1988; 2002). Because of this, it is suggested that the short-term fluctuations in the influx of aeolian sand to the foredune is sensitive to changes in summer-climate (precipitation and storminess), and that the longer term changes in dune morphology is related to the trends in past RSL. For the lake record, it is assumed that the transportation of sand grains >250 μm was facilitated by snow and ice coating the irregular surface, in combination with periods of high wind activity. It is therefore suggested that the lake sediment archive (reflecting the parabolic dunes and blowouts) show changes in winter conditions, hence recording variations in past winter storminess (and snow cover).

To further extend the knowledge and establish a regional record of past aeolian activity, a comparable approach was applied at the outmost coast of Langøya some 50 km SW of Andøya.

Figure 7: A comparison between the results from the three papers in this thesis: Glacier fluctuations (TPW-ELA) in Lofoten (Paper I), aeolian influx (SMAR) to Latjønna on Andøya (Paper II), and aeolian sand influx (ASI) and frequency of mass-wasting events (plotted every 1000, 500 and 250 year) in Trehynnvatnet on Langøya (Paper III) during the last 11000 (bottom panel) and 1250 years (upper panel). The grey shading areas in the upper panel reflects periods with TPW-ELA lowering, and the grey shading areas in the lower panel indicate periods with high SMAR-values recorded on Andøya.


Age (Cal. yr BP)
0
100
200
300
400
500
600
700
800
900
1000
1100
1200
Reconstructed TPW-ELA
550
570
590
610
630
I
LIA
MCA
II
III
SMAR >250 µm (g/cm²/yr)
1
0.1
0.01
0.001
0.0001
ASI >250 µm (grains/cm²/yr)
10
1
0.1
Number of mass-wasting events
8
6
4
2
0
0
1
2
3
4
5
6
7
8
9
10
11
Age (Cal. yr BP)

Paper III: Aeolian activity and mass-wasting events on Langøya, Vesterålen

Inspired by the work of Björck and Clemmensen (2004), and with a desire to extend the record from Latjønna further back in time (Paper II), we were seeking a site with a less Holocene amplitude of regional RSL fluctuations and with a greater potential to reflect the occurrence of extreme wind events. This involved finding a site situated further northwest of the main shoreline isobases, and more distant from the coast to separate the impact of low-intensity storms from the more high-intensity storms. Such a setting was found at Nykvåg on western Langøya, at the outmost coast of Vesterålen (Figures 1, 3 and 8). At the site there is a small sand beach with an adjacent sheet of aeolian sand displaying several erosion scars (blowouts), being very exposed to the stormy conditions in the nearby Norwegian Sea. The beach is separated by a gap (Sandvikhalsen) at an altitude of 75 m, which funnels southwesterly winds towards lake Trehynnvatnet 750 m further inland. Lake Trehynnvatnet (33 m a.s.l.) is situated within a north-facing valley surrounded by steep mountains, covering a 2.8 km^2 drainage basin. In addition to the wind-component, debris-flows and avalanches occasionally follow an avalanche track towards the lake on the southeastern valley slope, which to a greater extent complicates the lake sediment record. Therefore, a detailed analysis of the lacustrine sediments was conducted in an attempt to separate the processes occurring within the catchment, and with an objective of reconstructing past aeolian activity (storminess) and the frequency of mass-wasting events.

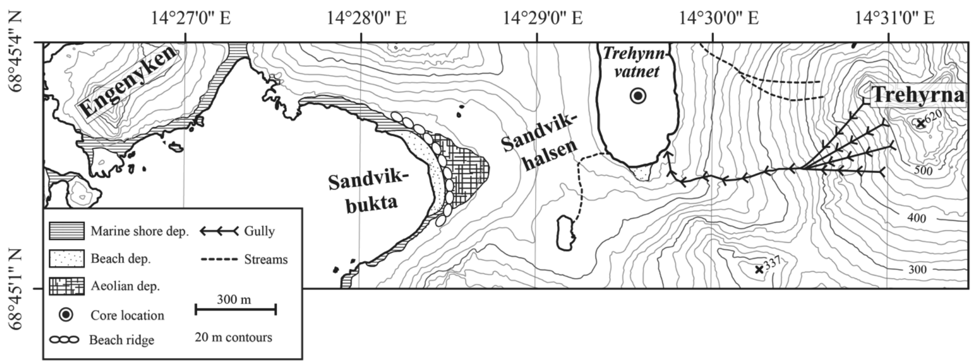


Figure 8: Map showing a subset of the field area on Nykvåg (Paper III).

The sediment cores from Trehynnvatnet consist of a light-brown fine-grained 'background' sediment, interrupted by several distinct, and up to 18.4 cm thick, coarse-grained dark-brown to grey event layers followed by normal grading. In order to investigate the characteristics of the sediments, the study focused on the sand fractions. The sand fractions was identified by wet-sieving the ignition residue (IR) from the loss-on-ignition procedure, dividing the samples into two grain-size fractions; 125–250 and >250 µm. The fractions between 125–250 µm were weighed and values transformed to percentage of IR (varying between 0–36%). Grain fractions >250 µm were counted under the microscope (varying between 0 and 750 grains per cm^3). Furthermore, in an attempt to distinguish the processes occurring within the catchment, selected samples from the background sediments and the event layers in the core, in addition to a catchment sample from the nearby beach, were scanned and analysed with Malvern Morphologi 3G particle characterizing tool. Using the mean value of selected shape factors (circularity, convexity and solidity), the results showed that the samples from the event layers in the core had different characteristics in relation to the samples from the beach and the background sediments, which were almost indistinguishable. Based on these measurements, it was suggested that the presence of sand grains >250 µm in the background (continuous) sediments represent periods with strong southwesterly winds, as they originate from the beach/aeolian deposit in Sandvikbukta. In order to reconstruct past storm frequency and intensity, ASI was calculated based on the number of grains >250 µm per 0.5 cm in the continuous sediments divided by sedimentation rate. Based on the sediment composition, the event layers were interpreted to represent the product of density currents triggered by subaerial mass-wasting events.

The recurrence interval for the mass-wasting events in Trehynnvatnet is ~300 years, with higher mass-wasting activity observed between 11000–10500, 5750–4750, 4000–3250, 2000–1000 and 500–250 cal. yr BP (Figure 7). In contrast, no mass-wasting events are registered between 10500–9250 and 7250–5750 cal. yr BP. The ASI is relatively low and stable from 11000 to 2800 cal. yr BP, with slightly higher activity between 7800 and 5800 cal. yr BP, which coincides with the Tapes Transgression high stand (~6800 cal. yr BP). After 2800 cal. yr BP the ASI displays high variability, with periods of high influx recorded around 2600–2400, 1600–1500 (AD 350–450), 1400–1250 (AD 550–700), 750–550 (AD 1200–1400) and 250–20 cal. yr BP (AD 1700–1930), with the latter period being the most intense (Figure 7). The frequency of mass-wasting events increases after 6000 cal. yr BP, coinciding with a decreasing trend in terrestrial and marine proxies for summer temperature, attributed to lower summer insolation (e.g. Seppä and Birks, 2001; Birks and Koç, 2002; Calvo et al., 2002; Bjune and Birks, 2008; Andersson et al., 2010). The increase in ASI following 2800 cal. yr BP is concurrent with low summer and sea-surface temperatures (Birks and Koç, 2002; Bjune and Birks, 2008), a shift towards a more positive NAO index (Olsen et al., 2012), and increasing winter precipitation along the western coast of Norway (Bakke et al., 2008) (Figure 9).

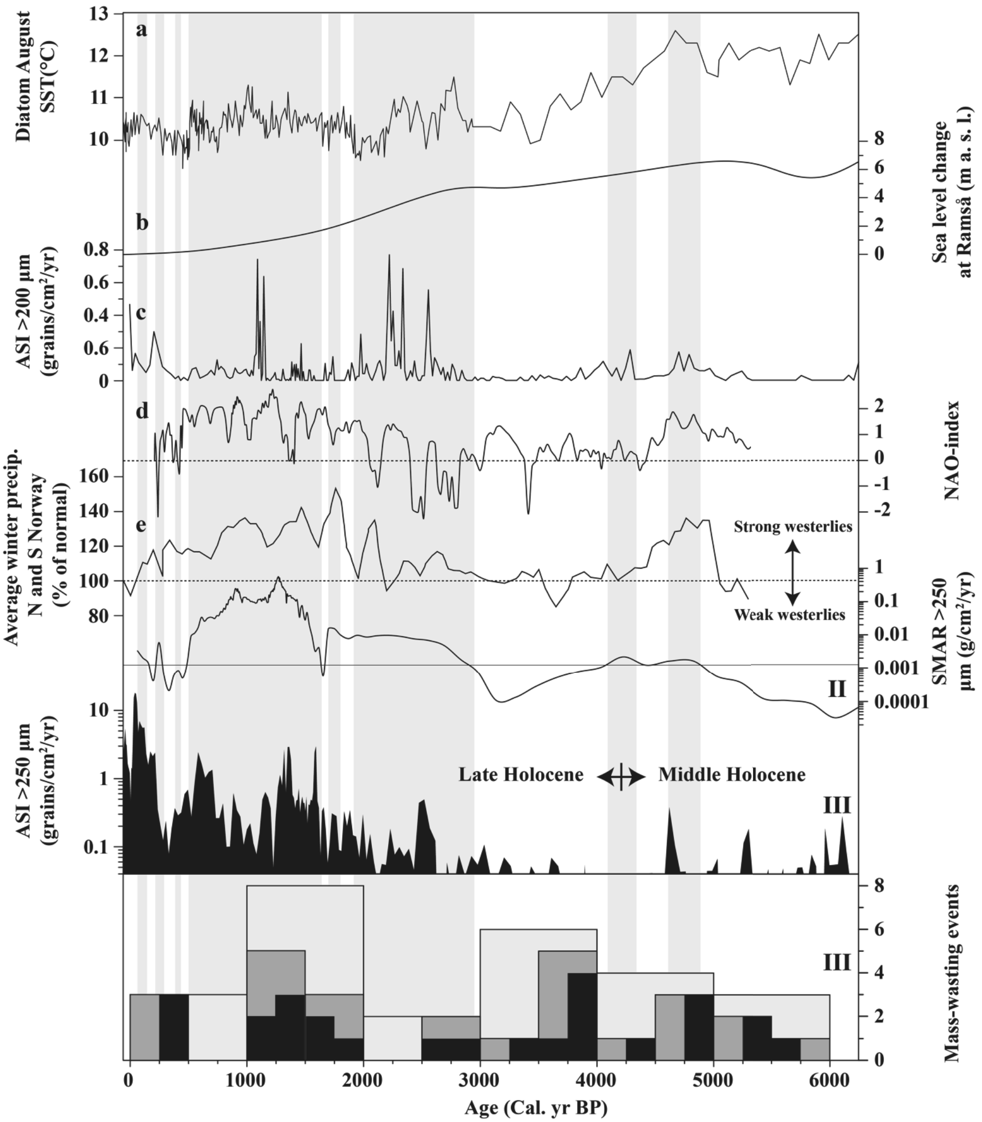


Figure 9: Comparison between selected proxy records from the surrounding region and the results from Paper II and III. (a) Reconstruction of August sea-surface temperatures from the Vøring plateau (Birks and Koç, 2002). (b) Relative sea level change at Ramså on Andøya (Marthinussen, 1962; Møller, 1986). (c) ASI-variations in southwest Sweden (De Jong et al., 2006). (d) Reconstructed NAO-index (Olsen et al., 2012). (e) Total winter precipitation reconstructed from distal glacier-fed lakes along the coast of western Norway, suggested to reflect the strength of the westerlies (Bakke et al., 2008). SMAR and ASI values from Andøya (II) and Langøya (III), respectively, plotted on a logarithmic scale. Mass-wasting events on Langøya (Paper III) plotted every 1000, 500 and 250 year. The grey shading areas indicate periods with peaks in SMAR on Andøya.

Synthesis and future perspectives

This thesis has provided three new records elucidating past aeolian activity and climate change from lacustrine archives in the Lofoten-Vesterålen archipelago, northern Norway. The investigated sites cover contrasting catchment basins within a relatively small geographical area. Climatically, the region is situated at the convergence between cold arctic and warm subtropic air masses, delineating the position of the arctic polar front, making the area highly sensitive to changes in the general atmospheric circulation patterns. Furthermore, warm northeast-moving ocean currents are influencing the area, providing a mild maritime climate at this latitude.

When comparing the results from the three investigated sites, a high degree of consistency in the long-term trends in aeolian and glacier activity is evident, with periods between 2600-500 and 250-20 cal. yr BP being the most intense (Figure 7). This is also recognizable in southwest Sweden and Denmark, where storminess was very high during this time span (Figure 9), indicating regional consistency in the long-term storminess records (De Jong et al., 2006; Clemmensen et al., 2009). However, this period is also concurrent with the onset of agricultural activity in arctic Norway and in Sweden, as well as a period of RSL lowering, which resulted in an opening of landscapes and changes in sediment availability (e.g. De Jong, 2007; Sjögren and Arntzen, 2013). Nevertheless, De Jong (2007) found that the ASI in Sweden was largely independent of these disturbances, and thus related to changes in storminess. When looking at the short-term trends, more complex patterns are revealed. It is difficult to find clear similarities between the decadal-scale fluctuation in TPW-ELA in Lofoten, SMAR in Latjønna and ASI to Trehynnvatnet. This is especially the case during the last 500 years on Andøya, which shows a substantial drop in SMAR throughout this period. This occurred approximately at the same time as the glaciers in Lofoten reached their LIA maximum, and ASI in Trehynnvatnet reached maximum values.

The rather short glacier-record from Lofoten (Paper I) does, unfortunately, reduce the possibility of comparing the continuous curve reflecting glacier fluctuations with the coastal sites. This underlines that a longer record of past TPW-ELA from the area is required in order to expand the knowledge on past aeolian activity in the region. This is particularly important since glacier-records are not usually influenced by the sources of error seen from coastal areas such as variations in sediment availability, RSL-fluctuation, vegetation changes and land-use.

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