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The ups and downs of the Holocene: exploring relationships between global CO_2 and climate variability in the North Atlantic region

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LUNDQUA Thesis 55
Quaternary Sciences
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LUNDQUA THESIS

LUNDQUA Thesis 55

The ups and downs of the Holocene: exploring relationships between global CO_2 and climate variability in the North Atlantic region

Catherine A. Jessen

Avhandling

att med tillstånd från Naturvetenskapliga Fakulteten vid Lunds Universitet för avläggande av filosofie doktorsexamen, offentligen försvaras i Geologiska institutionens föreläsningssal Pangea, Sölvegatan 12, Lund, fredagen den 3 marts 2006 kl. 13.15

Lund 2006
Lund University, Department of Geology, Quaternary Sciences

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This thesis is based on four papers listed below as Appendices I - IV. All the papers have been submitted to peer-reviewed international journals. Paper I is reprinted with the permission of John Wiley and Sons Ltd. Paper II is preliminarily accepted and Papers III and IV have been submitted to the journals indicated and are under consideration.

Appendix I: Jessen, C. A., Rundgren, M., Björck, S. and Hammarlund, D. 2005. Abrupt climatic changes and an unstable transition into a late Holocene Thermal Decline: a multiproxy lacustrine record from southern Sweden. *Journal of Quaternary Science* 20(4), 349-362.

Appendix II: Jessen, C. A., Rundgren, M., Björck, S. and Muscheler, R. Climate forced atmospheric CO_2 variability in the early Holocene: a stomatal frequency reconstruction. Submitted version of a preliminarily accepted manuscript. *Global and Planetary Change*.

Appendix III: Jessen, C. A., Rundgren, M., Björck, S., Andresen, C. S. and Conley, D. J. Variability and seasonality of North Atlantic climate during the early Holocene: evidence from Faroe Island lake sediments. Manuscript submitted to *Quaternary Research*.

Appendix IV: Andresen, C. S., Björck, S., Jessen, C. A. and Rundgren, M. Early Holocene terrestrial climatic variability along a North Atlantic island transect: palaeoceanographic implications. Manuscript submitted to *Quaternary Science Reviews*.

Contents

1. Introduction 1
- 1.1. Background 1
- 1.2. Project Objectives 3

2. Study areas and site selection 4
- 2.1. South-central Sweden (Paper I) 4
- 2.2. Faroe Islands (Papers II, III and IV) 6

3. Methods, materials and rationale 7
- 3.1. Fieldwork and sediment cores 7
- 3.2. Core correlation and sub-sampling 8
- 3.3. Radiocarbon dating and chronologies 9
- 3.4. Mineral magnetic analyses 9
- 3.5. Geochemical analyses 9
- 3.6. Pollen analyses 10
- 3.7. Stomatal index analysis 10

4. Summary of Papers 10
- 4.1. Paper I 10
- 4.2. Paper II 11
- 4.3. Paper III 12
- 4.4. Paper IV 14

5. Rapid climate change and atmospheric CO_2 concentrations 15
- 5.1. The nature of rapid climate change 15
- 5.2. Climate - carbon cycle connections 17
- 5.2.1. Dansgaard – Oeschger cycles of the last glacial period 17
- 5.2.2. Early Holocene dynamic climate (c. 11,650 – 10,000 cal. years BP) 17
- 5.2.3. The 8,200 cal. years BP event 19
- 5.2.4. The mid to late Holocene shift 20
- 5.2.5. The last 1,000 years 21

6. Comparison of ice core and stomatal frequency reconstructions 23

7. Conclusions 24

8. Acknowledgements 24

9. Svensk sammanfattning 25

10. References 27

Appendices

1. Introduction

1.1. Background

Over the last c. 150 years, CO_2 concentrations have risen well above the c. 280 ppmv average of the last three interglacials. This has raised concerns about anthropogenic effects on the natural carbon cycle and global warming via the greenhouse effect. Average concentrations in 2004 were 375 ppmv (Keeling and Whorf, 2005), well above natural levels, and continue the linear rise of at least the last 50 years. Little is known of the nature and causes of past non-anthropogenic variability in the carbon cycle and very little about how CO_2 concentrations respond to rapid climate changes such as those currently predicted, and possibly already occurring, in the next few hundred years. Climate and the carbon cycle are closely interrelated and investigating their responses to each other in a non-anthropogenic setting requires the study of palaeoclimatic archives.

The Vostok ice core indicates that global temperatures and atmospheric CO_2 concentrations have been tightly linked for at least the last 420,000 years (Figure 1.1) (Petit et al., 1999) and recent measurements from the Dome C ice core extend this relationship back to the last 650,000 years (Siegenthaler et al., 2005b). During the last three glacial-interglacial transitions, CO_2 increased between 600 and 1,000 years after Southern Hemisphere warming and c. 4,000 years before Northern Hemisphere warming (Caillon et al., 2003; Fischer et al., 1999). This time lag behind Southern Hemisphere warming suggests ocean circulation changes being crucial for at least the first 1,000 years of warming, but that the amplifying effects of increasing CO_2 concentrations may perpetuate the next c. 4,000 years of warming, and kick global climate out of its glacial mode. On shorter timescales, ice core measured atmospheric CO_2 and inferred global temperatures also show some similarities during the high magnitude variability within glacial stages and demonstrate a similar lead – lag relationship (c. 1,200 ± 700 year) to glacial terminations (Indermühle et al., 2000). The uncertainties are mainly due to the differences in the age of measured atmospheric gases and the age of the ice within which they are stored. Air bubbles are not closed off from the atmosphere

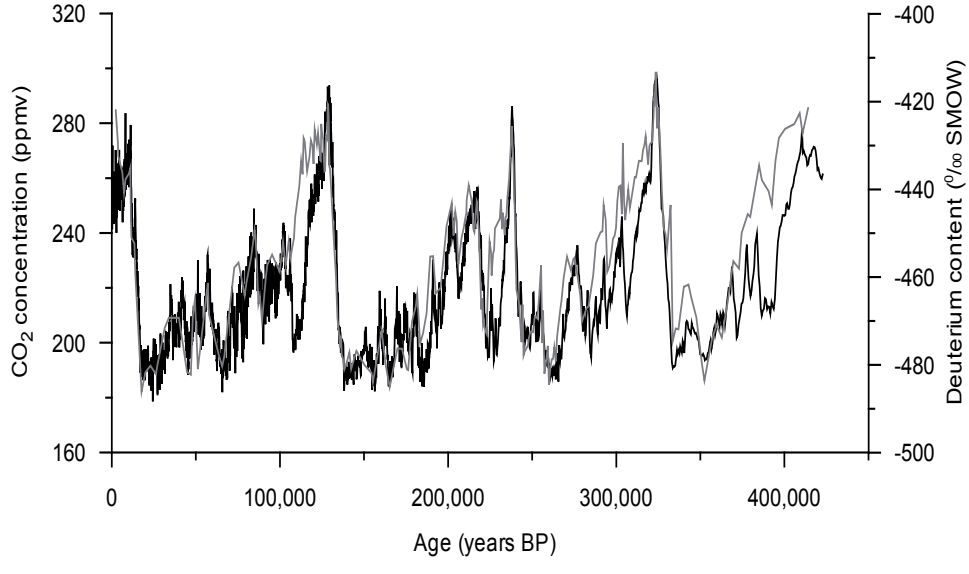

Figure 1.1. Black line: Deuterium content (‰ SMOW) and grey line: CO_2 concentration (ppmv) for the past 420,000 years in the Vostok ice core (Petit et al., 1999).

until they reach the base of the firn layer, prior to this air can either be freely moving or slowly diffusing through the firn column (Figure 1.2). Site-specific firn densification models are used to calculate the gas age – ice age difference (Δage) from which estimates of age distribution per sample can be obtained. At the Dome C coring site for example, Δage is estimated at c. 2,000 years in the last 10,000 years and c. 5,500 years at the last glacial maximum (± 10 %) (Monnin et al., 2001). Although potentially giving a higher resolution, the Greenland ice cores are not generally used due to possible dust related in situ production of CO_2 (Tschumi and Stauffer, 2000).

Rapid climatic changes in the Holocene have been demonstrated on local, regional and hemispheric scales, and over decadal timescales (e.g. Johnsen et al., 2001; von Grafenstein et al., 1999; O'Brien et al., 1995) but, except those of the about the last 1,000 years, these changes are not reflected in the ice core records of CO_2 concentrations. This limited variability is likely to partly reflect the relatively large age distribution per air sample. The Holocene part of the Dome C ice core CO_2 record, for example, has a sample age distribution of c. 10 % of Δage, i.e. each sample represents c. 200 years of CO_2 changes (Monnin et al., 2001). This means that any changes in CO_2 lasting less than one or two centuries are strongly muted in Antarctic ice core records and accordingly Holocene CO_2 records demonstrate little variability (Spahni et al., 2003).

It appears, therefore, that any possible sub-centennial scale atmospheric CO_2 changes associated with the known rapid climate changes are not likely to have been strongly registered in Antarctic ice cores. Because many Holocene climate reconstructions suggest changes on decadal timescales, there is a need for other, complementary, methods for the reconstruction of atmospheric CO_2. The relatively new method of stomatal frequency analysis applies the physiological response of certain C_3 plants to changing concentrations of CO_2 in the atmosphere (Woodward, 1987). These less direct proxy reconstructions may give larger uncertainties, but they can also provide an opportunity to reconstruct CO_2 concurrently with climatic conditions, giving a direct comparison of the two parameters independent of chronological uncertainties.

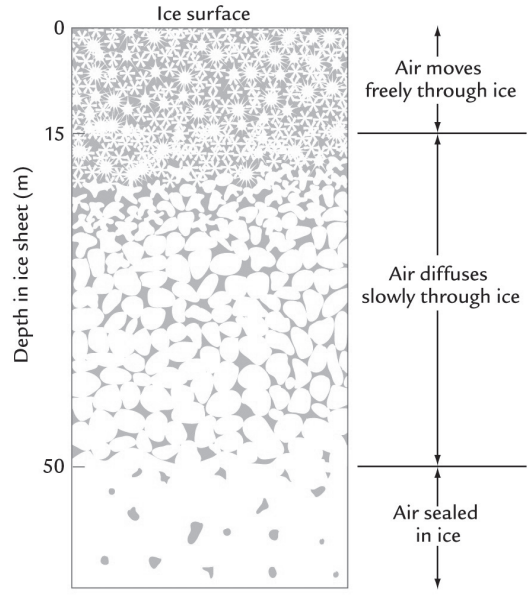

Figure 1.2. Processes of air bubble closure in ice showing arbitrary depths of air diffusion and the seal-off from the atmosphere of air bubbles in ice (from Raynaud, 1992; Ruddiman, 2001).

During bud-burst, C_3 plants can maximize their water retention capacity by regulating the proportion of stomata/epidermal leaf cells relative to the amount of CO_2 in the atmosphere. When atmospheric CO_2 concentrations are high, a plant can afford to reduce its number of stomata producing an inverse relationship of stomatal index to atmospheric CO_2. Stomatal frequencies can be calculated in two ways: by density or by index. It can be seen in Figure 1.3 that stomatal index (i.e. the proportion of the total number of stomata and epidermal cells over the leaf surface that are stomata) removes the effects of other environmental variables whereas stomatal density (i.e. the number of stomata per mm^2) may not be responding only to changes in atmospheric CO_2. The species-specific calibration of stomatal frequency applies measurements of archive herbarium material or recent well-dated leaves through the post-industrial CO_2 rise.

Carbon cycle – climate connections, over sub-centennial timescales, chiefly involve surface ocean conditions and the terrestrial biosphere. Any salinity/temperature changes in the upper ocean alter pCO_2 and therefore the drawdown of carbon

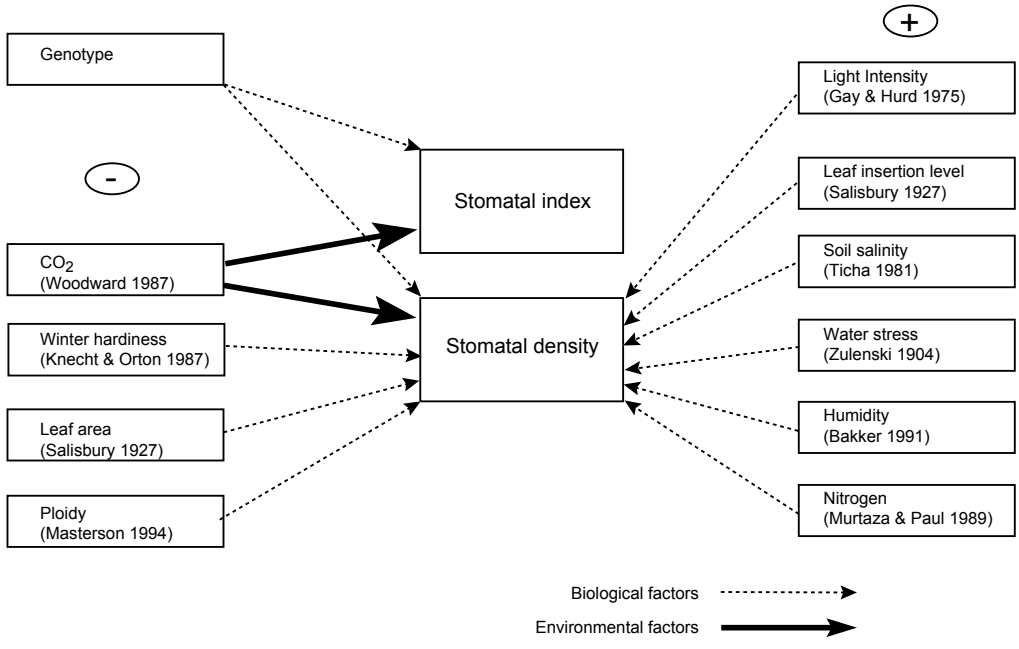

Figure 1.3. Flow chart illustrating the effects of both environmental and biological factors on stomatal density and index. + denotes a positive correlation and – denotes a negative correlation with stomatal density and/or index (From McElwain and Chaloner, 1996).

from the atmosphere. Changing temperatures and precipitation influence the photosynthesis/respiration balance in the terrestrial biosphere and therefore net carbon exchange with the atmosphere. This balance of fluxes between the different sources and sinks of carbon interchangeable on these relatively short timescales modifies the amount of carbon stored in the atmosphere.

The characteristics of rapid climate changes in the Holocene are not yet fully understood but are proving extremely complex on both temporal and spatial scales. Some have a wide spatial range and fairly short time window suggesting a fairly definitive forcing. Others, however, show time-transgressive features suggesting threshold responses more remote from the original forcing. Recent studies have also suggested an important role for seasonality in these abrupt changes (e.g. Denton et al., 2005; Moros et al., 2004; Meyers, 2002), and as many palaeoclimatic records mainly register summer conditions alone, further research is required in this area. Mechanisms through which climatic changes are communicated over wide geographical areas are also still being defined, but it is evident that the North Atlantic region, and possibly links involving sea ice may be important (Gildor and Tziperman, 2003).

1.2. Project Objectives

This project involves the use of rapidly accumulating lake sediments, from lakes and areas previously found to be sensitive to rapid climate change in the Holocene. Small, relatively shallow lakes were selected to maximise the supply of leaves and other macrofossils to the centre of the lake, and to allow the reconstruction of atmospheric CO_2 changes concurrent with rapid climate changes inferred from other proxies.

The project was instigated in order to focus, at high-resolution, on periods of rapid climate change in the Holocene, and to examine their relationship to atmospheric CO_2 concentrations. This kind of 'inside knowledge' into climate - carbon cycle on timescales longer than that of instrumental measurements, and within time periods of little or no significant human impact, is necessary in the

light of present day concerns of global warming and with CO_2 concentrations at levels unprecedented in the last 650, 000 years. More specifically the project aims were:

- To target lake records and areas known to have registered rapid climate changes during the Holocene.
- To focus in on these periods of rapid change and concurrently reconstruct climate and atmospheric CO_2 concentrations at high resolution.
- To compare the two records for leads and lags.
- To compare these records with existing palaeoclimatic records both from the North Atlantic region and at larger spatial scales.
- To infer causal relationships and processes involved.

2. Study areas and site selection

To compare atmospheric CO_2 concentrations and climatic conditions through periods of rapid climate change, certain criteria had to be met. Essentially the lakes had to have consistently preserved large numbers of leaf fragments for a suitable period of time, and to have a relatively high sedimentation rate to allow high-resolution analysis. Fairly small, shallow lakes are more likely to have higher concentrations of macrofossils in the centre where sediment focussing results in higher accumulation rates, and these types of lakes were therefore targeted. In the case of Lake Igelsjön, south-central Sweden, a high sedimentation rate and the presence of leaf macrofossils were already known from previous studies. In the search for a suitable site for study on the Faroe Islands however, these selection criteria were applied.

2.1. South-central Sweden (Paper I)

Lake Igelsjön is a shallow (1.5 to 2.5 m), small

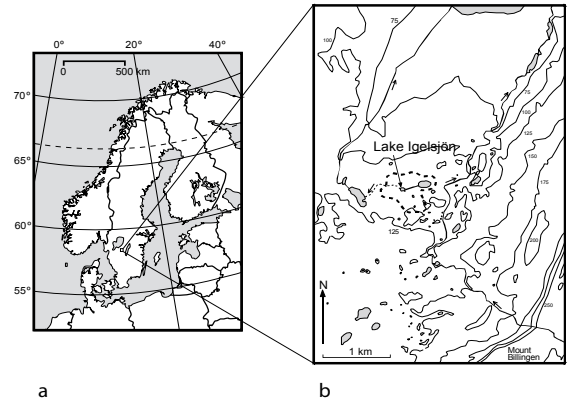

Figure 2.1. Location map for Lake Igelsjön, showing Scandinavia (a) and south-central Sweden (b). Dotted line indicates catchment area.

(c. 70 x 50 m) kettle hole lake situated immediately west of Mount Billingen, Västergötland, south central Sweden (58°28´N, 13°44´E) at 111 m. a.s.l. (Figures 2.1 and 2.2a). Local bedrock consists of sandstones, alum shales and limestones, producing highly calcareous lake sediments, with overlying glaciofluvial deposits of the Younger Dryas glacial readvance (Israelson et al., 1997; Björck and Digerfeldt, 1984). Stable isotope records of lacustrine carbonates of Lake Igelsjön, south-central Sweden recorded changes in regional temperature and precipitation for the whole Holocene period (Hammarlund et al., 2003). Two distinctive short-term changes are evident, suggesting the rapid decrease in summer temperatures and associated increase in net precipitation. The earliest cooling, 8,300 - 8,000 cal yr BP, is most likely to be associated with the large scale 8,200 cal yr BP event (Alley and Ágústsdóttir, 2005; Barber et al., 1999), which indicates that this lake is a sensitive recorder of climatic conditions. Analysis for stomatal frequency inferred CO_2 could not be undertaken in the sediments of this time period, as very few leaf macrofossils were available. A second rapid inferred cooling at c. 4,000 cal yr BP occurred early in a cooling trend that continues to the present day (most likely correlated to the 'Neoglacial' or the late Holocene Thermal Decline). Due to the relatively rapid sedimentation rate, the climatically sensitive nature of this lake, and large numbers of leaves and leaf fragments, it was selected to examine in detail,

Figure 2.2a. Photograph of Lake Igelsjön, south-central Sweden (Photo: D. Hammarlund).

Figure 2.2b. Photograph of Lykkjuvøtn, Sandoy, Faroe Islands (Photo: M. Rundgren).

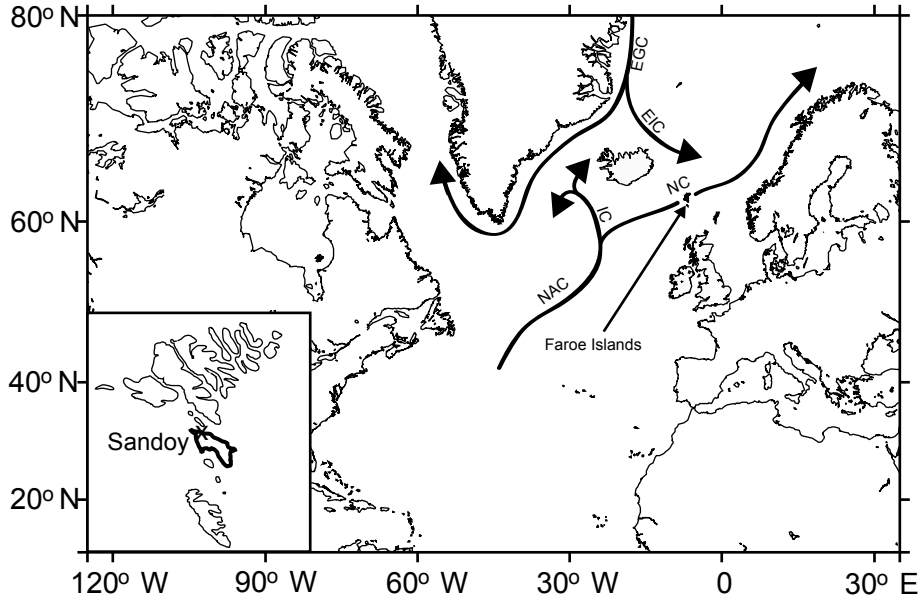

Figure 2.3. Location of the Faroe Islands and the major oceanic currents of the North Atlantic Ocean. NAC = North Atlantic Current, NC = Norwegian Current, IC = Irminger Current, EGC = East Greenland Current and EIC = East Icelandic Current. Inset shows map of the Faroe Islands with northern Sandoy highlighted.

the nature of the abrupt event at c. 4,000 cal yr BP and its relationship to global CO_2 levels.

The Holocene development of this area of south-central Sweden has been studied previously. A palynological reconstruction from Lake Flarken (Digerfeldt, 1977) situated c. 10 km north of Lake Igelsjön, indicates a fairly consistent *Betula-Quercus* dominated vegetation with 80-90 % tree pollen for most of the Holocene. The pollen profile from Lake Flarken has since been used in a pollen based temperature reconstruction and compared with the $\delta^{18}O$ record of Lake Igelsjön (Seppä et al., 2005). This study recorded a c. 1°C decrease in annual mean temperature correlative with the Igelsjön stable isotope record of cooler and/or wetter conditions at c. 4,000 cal yr BP. Human influence was not detected until c. 2,500 years ago in the Lake Flarken record (Digerfeldt, 1977) but as populations are known to have been expanding in the whole of Europe around 4,000 cal yr BP (Berglund, 2003), some human influence cannot be ruled out in the Igelsjön area around the time of this study.

2.2. Faroe Islands (Papers II, III and IV)

The present day climate of the Faroe Islands is strongly oceanic with average annual temperatures between 3.2°C and 10.5°C, high annual precipitation which increases during winter, and frequent winter storms from the north (Hansen, 1990). Located within the warm, saline North Atlantic Current/ Norwegian Current), the islands are occasionally influenced by cold polar air, due to a more southerly polar front or a tongue of polar water from the north west (Figure 2.3) (Humlum and Christiansen, 1998). Any changes in the strength or position of these major currents therefore affects the climate of the Faroe Islands. Their sensitivity to changes in the strength or position of the major currents in the North Atlantic was shown by Björck et al (2001). This work was focussed on a time period just prior to the deposition of the Saksunarvatn Ash at 10,240 cal yr BP (Björck et al., 2001; Johnsen et al., 1992), and revealed a climatic cooling c. 10,300 cal yr BP which probably lasted less than 200 years. Analysis of the Faroes data, and correlation with other records, suggested a large, hemispheric scale cooling. Due to

their documented sensitivity to climatic change, the Faroe Islands were selected for further detailed study as part of the present project. The early Holocene time period was also chosen because, in addition to the cooling at c. 10,300 cal yr BP, other rapid early Holoene climate changes have been documented in ice core, marine and terrestrial records (Bakke et al., 2005; NGRIP Members, 2004; Husum and Hald, 2002).

Lykkjuvøtn are two small, shallow lakes situated c. 1.5 km west of Skopun on Sandoy, Faroe Islands (61°54′37′′N, 6°54′30′′W) at 52 m. a.s.l. (Figures 2.2 and 2.4). The lakes are on the western edge of the gently undulating grasslands surrounding Skopun in the Middle Basalt Series but close to the steep sided slopes and rocky outcrops of the Upper Basalt Series to the south and west (Rasmussen and Noe-Nygaard, 1970). The southernmost lake has an inlet in the south with an outlet connecting to the northernmost lake which discharges via the coastal cliff into the sea. Modern vegetation is mostly heath with some small-scale grass farming and sheep grazing to the west of the southern lake.

Preliminary coring in the southernmost lake (Figure 2.4) indicated high concentrations of *Salix herbacea* leaves and due to the depth of the Saksunarvatn Ash relative to the base of the sequence, a high sedimentation rate was expected.

3. Methods, materials and rationale

Author contributions to these analyses and data interpretation are detailed in Table 1.

3.1. Fieldwork and sediment cores

At Lake Igelsjön, 6 parallel cores were extracted from the deepest part of the lake in January 2001 with a Russian corer. Previous studies indicated that an abrupt climate event was registered in the

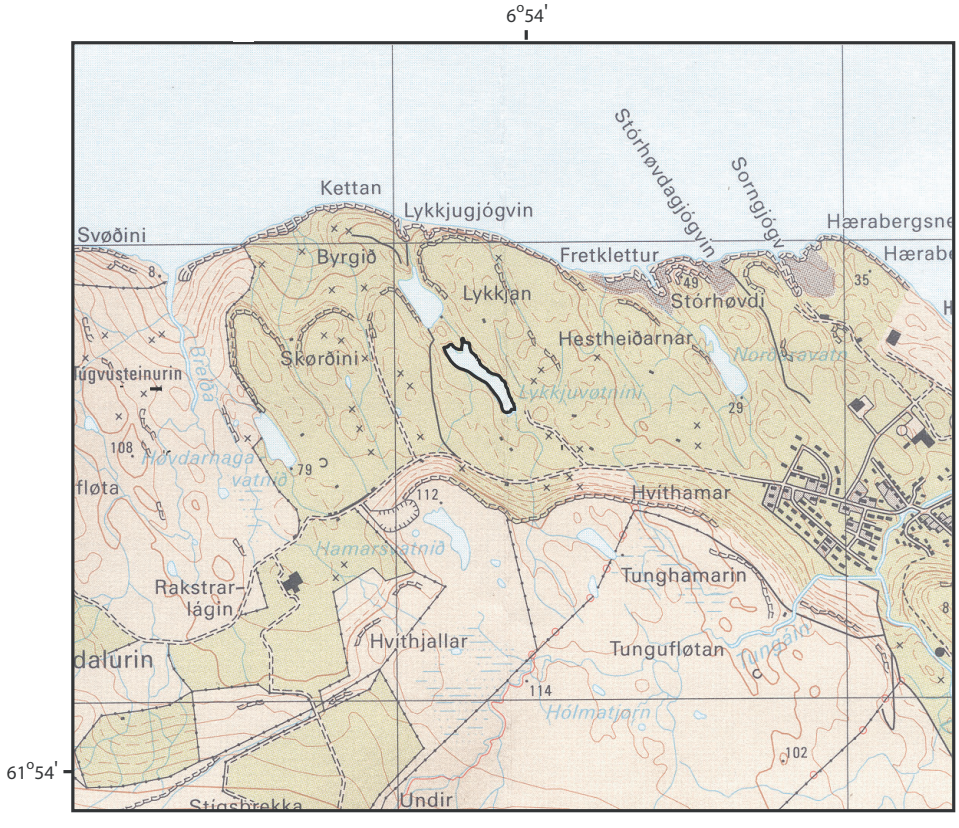

Figure 2.4. Topographic map of the study area in northern Sandoy, Faroe Islands. The lake investigated is highlighted. ©Kort og Matrikelstyrelsen (A.109/05)

Table 1. Author contributions to analyses and data interpretations in Appendices I - VI

	Appendix I	Appendix 2	Appendix III	Appendix IV (Faroe Islands)
Fieldwork	*Dan Hammarlund* *Mats Rundgren* *Anna Ericsson*	*Svante Björck* *Catherine Jessen* *Mats Rundgren*	*Svante Björck* *Catherine Jessen* *Mats Rundgren*	*Svante Björck* *Catherine Jessen* *Mats Rundgren*
Core correlation and sample preparation	*Catherine Jessen*	*Catherine Jessen*	*Catherine Jessen*	-
Magnetic susceptibility	*Catherine Jessen*	*Catherine Jessen*	*Catherine Jessen*	*Camilla Andresen* *Catherine Jessen* *Diana Serban* *Erika Suciu-Krausz*
Geochemistry	*Catherine Jessen*	*Catherine Jessen*	*Catherine Jessen*	*Catherine Jessen* *Diana Serban* *Erika Suciu-Krausz*
Pollen analysis	*Catherine Jessen*	-	-	-
Stomatal index analysis	*Catherine Jessen*	*Catherine Jessen*	-	-
Grain analysis	-	-	*Camilla Andresen*	*Camilla Andresen*
Age-model	*Svante Björck* *Dan Hammarlund* *Catherine Jessen* *Mats Rundgren*	*Svante Björck* *Catherine Jessen* *Mats Rundgren*	*Svante Björck* *Catherine Jessen* *Mats Rundgren*	*Camilla Andresen* *Svante Björck* *Catherine Jessen* *Mats Rundgren*
Data interpretation	*Svante Björck* *Dan Hammarlund* *Catherine Jessen* *Mats Rundgren*	*Svante Björck* *Catherine Jessen* *Raimund Muscheler* *Mats Rundgren*	*Camilla Andresen* *Svante Björck* *Daniel Conley* *Catherine Jessen* *Mats Rundgren*	*Camilla Andresen* *Svante Björck* *Catherine Jessen* *Mats Rundgren*

sediments at c. 5 m below water surface and the 1 m sediment cores were extracted from between 460 and 560 cm. The distinctly laminated sediments of calcareous-rich algal gyttja and algal-rich calcareous gyttja displayed abrupt colour changes with, of note, a marked greenish lamina between 503 and 504 cm, a dark, almost black organic lamina between 480 and 482 cm, and a sharp transition from light to dark sediments at 546.4 cm.

At Lykkjuvøtn, preliminary coring identified the distinct and recognizable Saksunarvatn Ash at 373 cm below water surface. Ten parallel cores were extracted from the deepest part of the lake to collect the ash layer and the sediments beneath. The deepest core recovered reached sediments at 459 cm below water surface. Sediments below the ash layer consisted of a fairly homogenous silt gyttja with abundant macrofossils. Some darker, more organic rich horizons were visible. A diffuse transition to gyttja clay and silty clay was observed at 441.5 cm.

3.2. Core correlation and sub-sampling

The combination of sediment samples from the parallel cores requires reliable correlation. The strongly laminated sediments from Lake Igelsjön allowed confident correlation using the marked colour changes. Sub-sampling intervals were defined within the lamination boundaries and mostly between 0.5 and 1.2 cm. Preservation of intact leaves occasionally produced slightly larger samples. One reference core was sub-sampled for magnetic susceptibility and loss-on-ignition analyses (108 samples). Identical sample levels were used in a focus zone between 478 and 530 cm for total carbon, total nitrogen, total sulphur and pollen analyses (44 samples). The same sample levels from the remaining 5 cores were combined and carefully

sieved through 500 and 250 µm mesh sizes to extract macrofossils. Terrestrial macrofossils were retrieved from 7 levels within the focus zone for radiocarbon dating. For stomatal frequency analysis, leaves from all levels in the focus zone were collected.

The Lykkjuvøtn sediments appear relatively homogenous and their correlation required estimates of volume specific magnetic susceptibility. Identical 1 cm sample intervals were assigned to each of the 10 Lake Lykkjuvøtn cores on the basis of magnetic susceptibility variations aided by several slightly enriched organic horizons. One reference core was used for geochemical analyses performed on all sample levels (72 samples). The remaining 9 cores were sub-sampled at identical 1 cm intervals, combined and sieved through 500 and 250 µm mesh sizes to extract macrofossils. Stomatal index was analysed on alternate samples with extra samples in periods of rapid change.

3.3. Radiocarbon dating and chronologies

The age models of both Lake Igelsjön and Lykkjuvøtn were based on AMS radiocarbon dates of terrestrial macrofossils and additionally, in the case of Lykkjuvøtn, on ash layer of known age.

Terrestrial macrofossils were extracted for dating by wet sieving and identified using a binocular microscope at 10 x magnifications. Radiocarbon ages were calibrated using IntCal98 (1998) and OxCal v.3.8 (Bronk Ramsey, 1995; Bronk Ramsey, 2001) (Lake Igelsjön) and IntCal04 (Reimer et al., 2004) and OxCal v.3.10 (Bronk Ramsey, 1995; Bronk Ramsey, 2001) (Lykkjuvøtn).

The Lake Igelsjön chronology was based on 7 dates and anchor points from 2 distinct lithological boundaries from a previously published age model (Hammarlund et al., 2003). Resultant sedimentation rates fluctuated between 0.18 and 1.35 mm/yr.

The Lykkjuvøtn chronology uses the Saksunarvatn Ash layer, 12 AMS radiocarbon ages based on terrestrial macrofossils and 4 AMS radiocarbon ages based on gyttja. The ash layer is dated to c. 10,240 cal yr BP in the GRIP ice core (Björck et al., 2001; Johnsen et al., 1992). Based on both the radiocarbon ages and magnetic susceptibility measurements, a change in sedimentation rate is suggested at 414 cm depth. The resultant age model therefore gives sedimentation rates of 0.47 mm/yr prior to the sedimentation rate change (at c. 10,680 cal yr BP) and 0.96 mm/yr subsequently.

3.4. Mineral magnetic analyses

Magnetic susceptibility (χ) analyses were performed using a Geofyzika Brno KLY-2 KAPPA bridge. The samples were then oven dried overnight at 105°C (Lake Igelsjön) or freeze dried (Lykkjuvøtn) and the results recalculated to mass specific (dry weight) magnetic susceptibility ($10^{-6}m^3kg^{-1}$).

3.5. Geochemical analyses

Determination of organic carbon content (OC) for Igelsjön was by loss-on-ignition (LOI) of the oven/freeze-dried samples by firing at 550°C for 2 hours and calculated as percentage weight loss at 550°C/2.5. After reweighing, they were fired for a further 4 hours at 925°C for calcium carbonate content ($CaCO_3$) and calculated as percentage weight loss at 925°C x 2.27. The estimation of $CaCO_3$ for the Lykkjuvøtn samples followed the same procedure.

Percentage Carbon – Nitrogen – Sulphur (CNS) analysis was measured for the focus zone from the Igelsjön core and the whole of the Lykkjuvøtn core. Igelsjön samples were measured on a CE Instruments CNS 2500 elemental analyser (Department of Geology and Geochemistry, Stockholm University). Conversion of the results to OC by total carbon – ($CaCO_3$/8.33) demonstrated excellent agreement between the two methods of OC estimation. For Lake Igelsjön the LOI percentage estimates of OC of the whole core were therefore deemed reliable.

CNS of all Lykkjuvøtn samples was measured on a Costech Instruments ECS 2010 elemetal analyser.

Biogenic silica percentage estimates (BSi) were obtained by the wet chemical analysis method as described by Conley and Schelske (2001). Sub-samples of 30 mg were freeze-dried, ground and homogenized prior to heating in a shaking bath with 40 ml of 1 % Na_2CO_3 for 5 hours. After 3, 4 and 5 hours digestion, a 1 ml aliquot was extracted and analysed for dissolved silica. Estimates of % BSi were obtained by performing a least-squares

regression on the measured increase of silica over time and extrapolating to the intercept.

3.6. Pollen analyses

Standard procedures were followed in the preparation of pollen slides (Berglund and Ralska-Jasiewiczowa, 1986) with the addition of Lycopodium spores for the calculation of pollen influx (Stockmarr, 1971). An average of over 700 grains per level and 22 levels were counted.

3.7. Stomatal index analysis

Leaf fragments and whole leaves were extracted using a binocular microscope at 10 x and 20 x magnifications. They were identified and analysed using an Olympus BX41 epifluorescence microscope (400 x magnification), Olympus C4040Z digital camera and DP-Soft imaging system. Care was taken to ensure that counted fragments were not parts of the same leaf. Counting was conducted as per Poole and Kürschner (1999), excluding leaf vein and marginal zones (Figure 3.1). Stomatal index (SI) was calculated as stomatal density/(stomatal density + epidermal cell density) x 100, and a species-specific average per level was used for CO_2 reconstruction. CO_2 concentrations were modelled as a function of SI by inverse (linear) regression (Draper and Smith, 1981). Modern training sets of *Quercus petraea* (Kürschner et al., 1996), *Betula pubescens/pendula* (Wagner et al., 2002) were applied for Lake Igelsjön and *Salix herbacea* (Rundgren and Beerling, 1999) for Lykkjuvøtn.

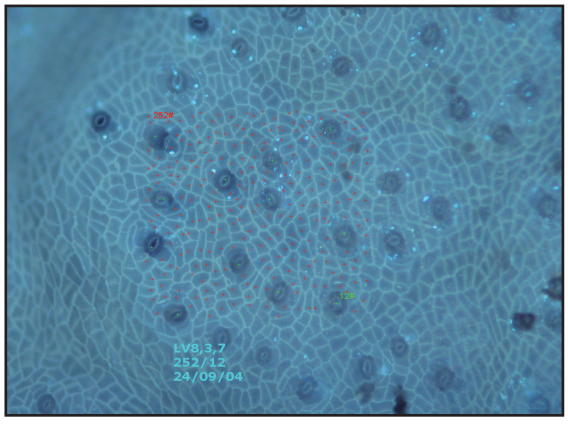

Figure 3.1. Image of a Salix herbacea leaf from the Lykkjuvøtn stomatal frequency analysis. Coloured marks indicate counted epidermal cells (red) and stomata (green). Count information was burnt on to the image prior to archiving. Photo: C. Jessen.

Mostly *Quercus robur* and *Betula pendula* and occasional *Q. petraea* and *B. pubescens* leaf fragments were identified in the Lake Igelsjön samples. Wherever possible, 7 field areas on 5 leaf fragments were counted per level in a total of 24 levels. A complete absence of well-preserved leaves of both genera was recorded in some consecutive sample levels in the lower section of the core and only one sample level contained sufficiently preserved leaves of both *Quercus* and *Betula*. However, insufficient preservation or absence of leaves caused some gaps in the record, especially in the lower part of the core, causing large uncertainties in the calibration. Comparable responses of both *Q. petraea* and *Q. robur* allow their combination for the purposes of this reconstruction (van Hoof, 2004). This comparable response is also the case for both *B. pendula* and *B. pubescens* allowing their combination into a single category (Wagner, 1998).

In the Lykkjuvøtn sediments, all the 1 cm sub-samples from the silt gyttja contained well-preserved whole or partial *Salix herbacea* leaves. In most levels, the optimal 5 individual leaves were counted per sub-sample with 5 fields from each of the abaxial and adaxial surfaces (maximum of 50 count fields per sub-sample level). A few small leaf fragments were observed in the basal clays but these were not sufficiently preserved to allow SI determination. In total, 42 levels were counted.

4. Summary of Papers

4.1. Paper I

Jessen, C. A., Rundgren, M., Björck, S. and Hammarlund, D. 2005. Abrupt climatic changes and an unstable transition into a late Holocene Thermal Decline: a multiproxy lacustrine record from southern Sweden. *Journal of Quaternary Science*, 20(4): 349-362.

This study focuses on a known abrupt climatic

change previously identified in the sediments of Lake Igelsjön in south central Sweden. Long-term Holocene palaeohydrological trends consistent with other Northern European studies had been reconstructed from this small lake by stable oxygen-isotope analyses (Hammarlund et al., 2003). Additionally, rapid changes were identified between c. 8,300 and 8,200 cal yr BP and around 4,000 cal yr BP. The earliest change could, within dating uncertainties, be correlated to the '8,200 event' found in Greenland ice cores and in many terrestrial records (Alley and Ágústsdóttir, 2005; Barber et al., 1999). The later event, at around 4,000 cal. yr BP, suggested changes predominantly in net precipitation and summer temperatures of a similar magnitude, but in contrast to that around 8,200 cal yr BP, lacked a subsequent full recovery and stabilised in cooler/wetter conditions. Because other records in the North Atlantic region also indicated a fairly major climatic change around this time period, and because relatively large concentrations of leaves were preserved in the sediments, this lake was selected for a high-resolution, multi-proxy study reconstructing changes in local lake conditions and terrestrial vegetation concurrently with global CO_2.

The highly laminated sediments cover a time period from c. 5,000 to 2,750 cal yr BP. The climate of the first c. 400 years is fairly stable but from c. 4,600 cal yr BP, a highly unstable period is identifiable in all proxy indicators. After an initial, sudden warming where temperatures, precipitation and pollen influx become comparatively high, all indicators show a dynamic cooling in a two-phase transitional shift. From c. 3,450 cal yr BP, all proxies once again indicate a stable climate, but conditions appear to be cooler than before the shift. The most extreme aquatic response occurs at c. 3,800 cal yr BP, broadly simultaneous with a change in local forest species composition. Other records in northern and southern Norway (Nesje et al., 2001; Lauritzen and Lundberg, 1999), and northern Sweden (Barnekow, 2000; Snowball et al., 1999) demonstrate climatic changes that could be associated with the period of instability at Lake Igelsjön. Further afield in the North Atlantic region, rapid climatic changes around this age have also been reconstructed (Barber and Charman, 2003; Macklin and Lewin, 2003; Anderson et al., 1998). If, as suggested by the Lake Igelsjön study, this time period is characterized by instability rather than by a single distinct event, all of these reconstructions from northern Europe could be correlative with the shift to cooler and wetter conditions sometimes known as the Neoglacial but here referred to as the Holocene Thermal Decline (HTD).

The reconstruction of atmospheric CO_2 by stomatal frequency analysis provided a basis for correlating the record with changes in the global carbon cycle. Leaf fragments were relatively abundant in Lake Igelsjön sediments in this time period but in some levels (especially in the less anoxic zones) they were either poorly preserved, too small or absent. Due to this, the inverse (linear) regression produces especially large confidence limits (95 %) in some levels. Both *Quercus* and *Betula* were recovered fom the sediments but only one sample level contained both genera. *Quercus* provides the most complete record over time and demonstrates a minimum in CO_2 concentrations for a few hundred years correlative with the end of the period of instability identified in the other proxies. The *Betula* reconstruction, although consisting of only 7 non-consecutive data points, does not reproduce the same trend. For these reasons the record of CO_2 concentration change is interpreted with great care, but it may reflect a response in the global carbon cycle to the instability caused by the shift to the Holocene Thermal Decline.

4.2. Paper II

Jessen, C. A., Rundgren, M., Björck, S. and Muscheler, R. submitted, Climate forced atmospheric CO_2 variability in the early Holocene: a stomatal frequency reconstruction. *Global and Planetary Change.*

The early Holocene is known to have been climatically dynamic due to readjustments after the Younger Dryas cold period (Björck et al., 2001; Sejrup et al., 2001; Hald and Hagen, 1998; Björck et al., 1997; O'Brien et al., 1995). Sea level changes, terrestrial colonization, soil formation, ocean circulation reorganizations and periodic meltwater pulses, together with associated climatic disturbances, may be expected to have had an effect on the global carbon cycle. Ice core gas measurements show little change in CO_2 concentration during this time

period (Monnin et al., 2001). This could imply that the climatic changes of the early Holocene had little effect on the global carbon cycle but, due to their limited time resolution, any variability on timescales less than a few centuries is not recorded in ice core records and their detection therefore requires a complementary method.

The higher resolution possible with stomatal frequency analysis allows the reconstruction of decadal to centennial scale changes in CO_2 concentrations. The aim of this study was to use an early Holocene leaf rich lacustrine record from the Faroe Islands, to complement the ice core record, and, additionally, examine the relationships between known regional climatic changes and the global carbon cycle.

When comparing diverse climate records on relatively short timescales, good chronological control is paramount. Here we constructed a well-constrained timescale based on a known volcanic ash layer and 16 AMS radiocarbon ages over less than 60 cm of sediment and over a time interval of less than 1,000 years (c. 11,230 - 10,330 cal yr BP). Sample levels analyzed for stomatal frequency were also densely spaced. Reconstructed concentrations, calibrated by inverse (linear) regression, indicated distinct trends and variability in atmospheric CO_2 concentrations. Biological systems are expected to include a certain amount of scatter in the resultant data, and this is particularly evident in high-resolution reconstructions, which are often smoothed to take account of this. Two methods of smoothing were applied to this data set, both of which represent the data but have opposing strengths and weaknesses. Firstly, a simple running mean was applied, which reduced biological scatter and demonstrated more realistic rates of change, but did not account for changing sedimentation rates, nor did it give errors for the reconstructed values. Secondly, we applied a low-pass filter (80 year cut-off) with uncertainties estimated by a Monte Carlo simulation (100 runs), which accounted for the change in sedimentation rate and gave errors on the reconstructed trend. This method does not however, reduce biological scatter and the amplitude of variability remains rather high. Accordingly, in the discussion relating to short-term trends and rates of change, the former method was utilised but when considering longer-term trends over the whole time period, the latter method was considered to best represent the data. As with many other stomatal frequency records this reconstruction produces both enhanced base line concentrations and greater amplitudes of variability relative to ice cores, but the rates of CO_2 decrease and increase are realistic when compared to those measured in the Law Dome ice core during the Little Ice Age (Etheridge et al., 1996).

The results suggest that for c. 150 years around 11,050 cal yr BP, atmospheric CO_2 concentrations decreased significantly. This decline is most likely associated with the Preboreal Oscillation (PBO), a probably meltwater forced cooling affecting a large area of the North Atlantic region (Björck et al., 1997).

A recovery was followed by a steady and consistent CO_2 decline over 300 years. In the absence of known global climatic instability during this time period (10,900 – 10,600 cal yr BP), we suggest that it is possibly due to expanding vegetation and soil formation in the Northern Hemisphere.

After 10,600 cal yr BP, stomatal frequency inferred CO_2 concentrations demonstrate increased instability correlative with a reoccurrence of meltwater influxes, increasing cooling of North Atlantic surface waters and increased variability in proxy climate indicators in the region (Teller et al., 2002; Sejrup et al., 2001; Hughen et al., 1996). These results suggest that climatic changes restricted to the North Atlantic region had a significant impact on the global carbon cycle.

There is however a striking similarity between this record of global atmospheric CO_2 and the record of solar activity as reconstructed by $\Delta^{14}C$ and ^{10}Be (Appendix 2, Figure 4). Recent studies have suggested that minor changes in solar activity may, via feedback mechanisms, have a larger effect on climate than previously thought during this period (for example Van der Plicht et al., 2004; Björck et al., 2001; Bond et al., 2001). The inferred CO_2 concentration changes reconstructed here may also suggest a rapid carbon cycle response to solar forced climate changes.

4.3. Paper III

Jessen, C. A., Rundgren, M., Björck, S., Andresen, C. S. and Conley, D., submitted, Variability and

seasonality of North Atlantic climate during the early Holocene: evidence from Faroe Island lake sediments, *Quaternary Research*.

Northward heat transport and the formation of North Atlantic Deep Water significantly affect the climates of the North Atlantic region. Reconstructing the changing climates of geographic areas sensitive to the velocity and position of the main surface currents can give information on larger, regional scale climate changes. The Faroe Islands are located within the Norwegian Current, a main branch of the North Atlantic Current. The sensitivity of lakes from these islands to register regional climatic change has been shown previously (Andresen et al., in press; Björck et al., 2001), and the aim of this study was to reconstruct the dynamic climate of the early Holocene and to correlate this with regional ice core, marine and terrestrial records. High-resolution sampling and radiocarbon dating generated multiproxy data for the period between 11,300 – 10,240 cal yr BP.

Many climate reconstructions are restricted to proxies primarily indicating summer conditions. As maximum Holocene Northern Hemisphere summer insolation occurred during this time period (Berger and Loutre, 1991), changes in winter conditions may therefore be underrepresented in the records from around the North Atlantic. In this study, we attempted to reconstruct both summer and winter conditions concurrently, by comparing the responses of 'winter' and 'summer' indicators. The production of organic carbon and biogenic silica in lake sediments is highly dependent upon temperature and is greatly enhanced during the warm summer months. Covariation of these two proxies is believed to broadly reflect summer climate conditions. After careful consideration of any other factors affecting the concentration of sulphur in lake sediments, variations were interpreted as reflecting external input via sea salt spray brought in by storms. The concentration of grains >255 µm is believed to relate to the amount of time that the lake was ice covered (Andresen et al., in press). Presently, lakes at sea level rarely freeze over on the Faroe Islands, and when they do, it is due to a tongue of polar water from the East Greenland Current reaching the islands (Humlum and Christiansen, 1998). In addition, as most storms on the Faroe Islands occur during the winter months, the covariance of sulphur and grains >255 µm is considered to indicate mainly winter conditions.

Distinct zones could be identified in the data on the basis of relative stability. In Zone 1 (11,300 – 11,000 cal yr BP) the summer indicators suggested stable and warm conditions. In contrast, the winter indicators suggested that a warming trend between 11,200 and 11,000 cal yr BP was interrupted by a fairly severe period of stormier winters, with increased periods of lake ice cover. It is possible that this episode relates to the Preboreal Oscillation (PBO), but due to radiocarbon plateaux we could not be certain (Björck et al., 1997). The PBO is however identified in many other records as having a major influence on summer temperatures, and their absence in Lykkjuvøtn may suggest that lacustrine sedimentation begins during the final phase of the PBO. The warmest winters of the whole time period are indicated around 11,000 cal yr BP, followed by a stable period (Zone 2) with rather cool winters and warm summers. This lasted until 10,680 cal yr BP and was followed by a period (c. 10,680 - 10,240 cal yr BP) which demonstrates much greater variability. Three cooling episodes were identified at c. 10,600 cal yr BP (predominantly winter), c. 10,450 cal yr BP (winter and summer), and c. 10,300 cal yr BP (winter and summer). Many other marine and terrestrial records from around the North Atlantic register increased cooling and instability at this time. Meltwater outbursts of fresh water into the North Atlantic are known to disrupt thermohaline circulation and disturb the climates of neighbouring regions. During the stable (Zone 2) period, no meltwater influxes are known, but they reoccur at c. 10,600 cal yr BP (Teller et al., 2002). This broadly correlates with the increased instability seen in the North Atlantic and Lykkjuvøtn records and with the identified cooling episodes. It is possible therefore that these influxes had a wide regional effect on climate and, significantly, the Lykkjuvøtn record of cooling episodes correlates with coolings in the $\delta^{18}O$ record of the GRIP ice core.

Although these correlations suggest meltwater influxes as a likely forcing factor, there are indications that they were not as effective on climate as slight changes in solar activity. Comparison between modelled and measured $\Delta^{14}C$ suggests

that carbon cycle changes at this time can be almost solely attributed to variations in solar activity and not to changes in thermohaline circulation (Muscheler et al., 2000). This implies that any repeated disturbances of thermohaline circulation were not strong enough to register as significant $\Delta^{14}C$ anomalies. Even so, there is evidence of a link between carbon cycle variability suggested in this study and inferred solar activity changes (see Paper II). This suggests a tight, complex, and as yet poorly understood, relationship between solar activity, meltwater pulses, thermohaline circulation changes and atmospheric CO_2 variability.

4.4. Paper IV

Andresen, C. S., Björck, S., Jessen, C. A. and Rundgren, M., submitted. Early Holocene terrestrial climatic variability along a North Atlantic island transect: palaeoceanographic implications. *Quaternary Science Reviews.*

This paper synthesizes the results of three early Holocene (11,500 – 8,500 cal yr BP) lacustrine studies along a North Atlantic transect. The oceans of this region are affected by the interaction of warm Atlantic waters and cold polar waters, and the aim was to use previously published and new Faroe data sets, to investigate the spatial pattern of early Holocene warming and their palaeoceanographic implications. The lakes are Lake N14, southern Greenland (Andresen and Björck, 2005; Andresen et al., 2004; Björck et al., 2002), Lake Torfadalsvatn, Iceland (Rundgren, 1999; Rundgren, 1998; Rundgren et al., 1997; Rundgren, 1995) and Lake Lykkjuvøtn, Faroe Islands (Jessen et al., submitted-a; Jessen et al., submitted-b). All these records have been shown to be representative of regional conditions and all are presently influenced by branches of the warm North Atlantic Current. The warm, saline ocean currents flow adjacent to the Faroe Islands (Norwegian Current), to the west of Iceland and on to the coast of southern Greenland (Irminger Current). The cold, fresher ocean currents flow south along the east coast of Greenland (East Greenland Current) with a branch veering off along the north of Iceland (East Icelandic current). The cold waters of this latter current can occasionally extend eastwards towards the Faroe Islands.

Five developmental phases were identified via a range of palaeoclimatic proxies generally indicating a stepwise warming pattern reflecting the development of North Atlantic oceanic currents. In the earliest phase, (Phase 1. 11,500 – 10,750 cal yr BP), the establishment of the North Atlantic Current and Norwegian Current aid the rapid early Holocene warming. This generally warm period is punctuated by a cooling believed to have been caused by a meltwater influx into the North Atlantic, and which is known as the Preboreal Oscillation (PBO). This cooling episode is probably absent in the Lykkjuvøtn record (see Paper III) but is clearly expressed in the Greenlandic and Icelandic records. Fresh meltwater influxes disturb the salt driven sinking of surface waters, impeding thermohaline circulation and reducing the northwards transportation of heat. Phase 2 (10,750 – 10,100 cal yr BP) indicates a period of cooling and reduced climatic stability on the Faroe Islands at the same time as a further warming step in southern Greenland and relative stability on Iceland. Cooling episodes at ca 10,600, 10,450 and 10,300 cal yr BP on the Faroe Islands broadly correlate with the reoccurrence of meltwater influxes after a c. 600 year absence. It is suggested that the repeated disturbances to the North Atlantic Current possibly resulted in an increase in warm southern waters reaching southern Greenland. The lack of evidence for the punctuated coolings on Iceland may be related to the resolution of the dataset being too low for these possibly short duration episodes. Phase 2 differs from both those before and after as it appears to be characterized by coolings mainly in the eastern sector of the North Atlantic Ocean. The western sector shows limited changes and, moreover, shows some indications of the Irminger Current absorbing some of the warmer waters rejected in the eastern sector. The Saksunarvatn Ash demarcates phases 2 and 3. Phase 3 (10,100 – 9,400 cal yr BP) is characterized by the expansion of warmth demanding plants in northern Iceland at 10,100 cal yr BP. Although this suggests that the Irminger Current increased in vigour, there is little evidence from the other two records of any correlative changes and this may indicate an excess of warmer waters transported from the south. Phases 4 (9,400 – 8,900 cal yr BP) and 5 (8,900 – 8,500 cal yr BP) are marked by warming steps in southern

Greenland and Iceland respectively. In southern Greenland, relatively stable climatic conditions are registered after 9,400 cal yr BP and this may indicate that a more stable ocean-surface circulation was established. At c. 8,900 cal yr BP, a warming recorded only in Iceland, along with additional local marine data (Castañeda et al., 2004), suggests the intensification of the Irminger Current.

This re-examination of previously published and new datasets has revealed clear patterns in the spatial and temporal development of North Atlantic currents during the early Holocene. The stepwise warming reflects the relative strengths of the northern branches of the North Atlantic and Irminger Currents, although not all the warming steps were synchronous and neither were all transitions seen at all sites.

5. Rapid climate change and atmospheric CO_2 concentrations

5.1. The nature of rapid climate change

Until fairly recently, climate change was generally believed to be a sluggish process, taking thousands of years in the shift from one stable state to another and having little affect on humankind. There were some indications of large shifts in the transitions between these states, but the overriding opinion was that nothing happened very quickly. This sense of non-urgency both in the palaeoclimatological community and in world politics changed markedly when the Greenland ice cores demonstrated that very fast climatic shifts (Dansgaard – Oeschger cycles), over centuries and possibly even decades, were not only possible but, in a geological timescale, relatively common during the last glaciation (Dansgaard et al., 1993; Grootes et al., 1993). Further recognition of these rapid switches in other long terrestrial and marine records supported the suggestion that global climate could make extremely fast switches between one mode of operation and another (Sachs and Lehman, 1999; Bond and Lotti, 1995; Taylor et al., 1993).

In contrast, ice core isotopic records indicate rather minor variability during the Holocene, although other ice core parameters, for example the glaciochemical signature (O'Brien et al., 1995), suggest fairly significant shifts in dominant cyclonic/anti-cyclonic circulation. Many terrestrial and marine records support this variability, seen often as abrupt climate changes, superimposed on fairly well understood long-term trends. The Holocene is not subject to such dramatic changes as those of the last glacial period, but these records suggest that the climate has not been stable and may have become more complex and regional, as time has progressed (O'Brien et al., 1995). Natural variability of the Holocene is influenced on millennial timescales by orbital variations. Insolation received at different latitudes and in different seasons can be detected in many long Holocene records (Berger and Loutre, 1991). Of the various sub-Milankovitch periodicities described, those of c. 2,500 and 1,500 years appear regularly in the literature (Chapman and Shackleton, 2000; Bianchi and McCave, 1999; Bond et al., 1997; Denton and O'Brien et al., 1995; Karlén, 1973). The 1,500 cycle in particular has been prominent in a range of records and associated with both D-O cycles and the Holocene record of North Atlantic IRD (Bond et al., 1997). The Holocene lacks the strong feedback mechanisms of glacial environments and displays relatively muted climatic responses but, nevertheless, the similar frequencies suggest that, the forcing of D-O cycles could still be active.

Causes of these rapid climate changes and their possible periodicities are still under discussion. Some forcings for rapid climate changes are fairly well understood. During the late glacial period and early Holocene the freshwater stored in ice sheets was both gradually but also catastrophically released into the oceans. Outbursts into the North Atlantic Ocean are believed to have disrupted thermohaline circulation and the formation of North Atlantic Deep Water, impacting on climates over wide areas (Barber et al., 1999; Klitgaard-Kristensen et al., 1998; Björck et al., 1996). In recent years evidence has also been growing for solar variability, as the most likely external primary forcing. Proxy signals of solar variability can be extracted from ^{10}Be and ^{14}C nuclide proxy records in ice cores and tree-rings, due to their increased production in the upper atmosphere when solar activity is lower. Increasingly climate records are suggesting that rapid changes,

and the '1,500 year cycle' in particular, correlate with inferred variations in solar activity (e.g. Jiang et al., 2005; van der Plicht et al., 2004; Björck et al., 2001; Shindell et al., 2001; Bond et al., 1997). In Papers II and III further links between solar activity variations and climate are found, but prior to Paper II, no rapid link between these solar variations and responses in the carbon cycle has been suggested. No solar cycle of c. 1,500 years is known, but model experiments suggest that climatic shifts on this frequency can be simulated by freshwater releases forced by the known c. 87 and 210 year solar cycles (Braun et al., 2005). This can explain the regularity of D-O cycles but not the associated non-glacial climate periodicity of the Holocene. Difficulties have arisen in formulating a mechanism, capable of enhancing the relatively small variations into detectable climatic changes. In an attempt to address this problem, a modelling experiment simulated the response to a c. 0.1% decrease in the 11 year sunspot cycle during the Maunder Minimum. The results reproduced a regional temperature decline similar to that of proxy reconstructions and identified dominant low-index states of the Arctic and North Atlantic Oscillations as the main amplifying mechanisms (Shindell et al., 2001). In addition, changes in sea ice extent have recently been suggested as important in the translation of small changes in thermohaline circulation to wider areas via a higher albedo, a reduction of heat flux to the atmosphere, and southward shifts in storm tracks (Alley and Ágústsdóttir, 2005; Gildor and Tziperman, 2003). The prominent correlation between winter indicators in the terrestrial sediments of the Faroe Islands and of atmospheric temperatures over Greenland shown in Appendix III supports the possibility of winter sea ice linking the climates of widely spaced geographic locations.

Whatever the primary or secondary forcings of Holocene rapid climate changes, it is clear that environmental responses and recovery rates are not only dependent upon forcing magnitude, but also on base conditions and threshold proximities whether it be, for example, in a bog or in a lacustrine environment. In recent years, a great deal of work has gone into their identification and temporal location, and this has provided a large amount of information about both local and regional changes in temperatures and precipitation. Synthesizing the available data to characterize their nature, identify patterns and define further their spatial scale is now receiving more attention. The responses of different proxy indicators to a known and well-defined episode such as the so-called '8,200 year event' can not only reveal changing oceanic and atmospheric circulation patterns, but also threshold conditions of different proxies and differences in the length of the anomalies in near-field and far-field sites (Rohling and Pälike, 2005). The Rohling and Pälike (2005) study, in particular, also highlights important differences between summer and winter responses during these periods of change, suggesting that a sharp winter cooling occurred within a period of general summer temperature decrease. Denton et al. (2005) also concentrated on the seasonality aspect of rapid climate change. They found that the annual mean temperature decrease during D-O cycles was mostly due to a fall in winter temperatures. This, it is suggested, was also a feature of the rapid climate changes of the early Holocene, but it may be part of a more general pattern. As many climate records are interpreted from summer-dominated indicators, the detection of comparable winter changes is required to gain further insight into these patterns. Paper III, shows that by concurrently reconstructing both winter and summer indicators, differences in their responses can give insight into links in regional climate and highlight aspects of seasonality.

There is, however, still a problem with collating all the available evidence during periods of time when climate changed abruptly. Proxy records can be of local, regional or global significance and may relate to one or more particular facets of climate. The difficult task of detecting large-scale changes in the myriad of threshold responses is, however, continuing. Recently a framework for Holocene climate variability was presented by Mayewski et al. (2004). They took a large number of records on a global scale and identified six time periods within which climate changes of global significance were concentrated (9,000 - 8,000, 6,000 - 5,000, 4,200 - 3,800, 3,500 - 2,500, 1,200 - 1,000 and 600 - 150 cal yr BP). These changes mostly involved cooler poles, drier tropics and major atmospheric circulation shifts. Paper I focuses on the period of climate change identified by Mayewski et al (2004) between 4,200 and 3,800 cal yr BP. It demonstrates that sensitive lakes and multi-proxy studies such as

these can provide evidence of longer time periods of instability, which may include more than one abrupt event. The many regional records, which identify single abrupt events within this time period, may be due to large-scale climatic instability promoting a variety of threshold based responses in other proxy records, all of which are essentially related.

5.2. Climate - carbon cycle connections

Large amounts of carbon transfer between different reservoirs during shifts between glacial and interglacial climate states. Over these long timescales, and by mechanisms not fully understood, the oceans are believed to have been the more efficient carbon sinks, removing carbon from the atmosphere as global climate enters a glacial period (Sigman and Boyle, 2000). Over sub-millennial timescales and over more minor climatic changes, a strong relationship between climate and the carbon cycle still exists (see Appendix II for further details), but the difficulties of defining their chronological relationship in ice cores has hampered the understanding of climate-carbon cycle interactions on these scales. On the very short timescales, i.e. the last few decades of instrumental measurements, carbon storage and the fluxes between reservoirs are fairly well understood. Unfortunately these records are short, extending back only half a century for atmospheric CO_2 and only a decade or two for detailed measurements of fluxes. Additionally, these measurements have been made during an anomalous period of time, when anthropogenic activities have released sources of carbon 'unnatural' to the climate system, and may not therefore be appropriate for the understanding of natural climate-carbon cycle connections.

Short summaries of the climate – carbon cycle relationships through the two time periods studied in Appendices I, II and III are described below. To put these changes into context, the longer scale Dansgaard - Oeschger cycles, the well-known '8,200 event' and the last 1,000 years are also summarised.

5.2.1. Dansgaard – Oeschger cycles of the last glacial period

Ice cores from GISP2, Greenland and Byrd Station, West Antarctica record the rapid climatic changes of the last glacial period (Blunier and Brook, 2001; Grootes et al., 1993; Johnsen et al., 1972). Synchronisation of the records using their methane (CH_4) profiles has revealed polar (and possibly also hemispheric) asynchrony of climate during these events (Blunier et al., 1998). Antarctic warming occurs between 1,500 and 3,000 years prior to Greenland warming (Blunier and Brook, 2001) and the end of Antarctic warming is coincident with the rapid warming in Greenland (the bipolar see-saw). Increases in atmospheric CO_2 concentrations are associated with Antarctic warming and simulations comparing the Vostok temperature and the Taylor Dome CO_2 records suggest a CO_2 delay of c. 1,200 ± 700 years, which is similar to the measured time delay at glacial – interglacial transitions (Fischer et al., 1999). Not every Antarctic climatic warming is associated with a CO_2 increase, but the largest increases (c. 20 ppmv) are related to those with Heinrich events and especially those preceded by longer D-O cycles (Indermühle et al., 2000; Stauffer et al., 1998). Mechanisms explaining this interhemispheric relationship with the global carbon cycle are still unclear, but present research is mostly concentrated on processes of changing oceanic pCO_2. A modelling experiment, which disrupted thermohaline circulation via a freshwater outburst, simulated an increase in CO_2 via a warming (i.e. a decrease in carbon uptake) in the Southern Ocean (Marchal et al., 1999). This mechanism may explain how climatic changes in the Southern Hemisphere appear to have a greater similarity to CO_2 concentrations than the Northern Hemisphere during D – O cycles. Similarities with the Southern Hemisphere are also evident during the last glacial termination although, via comparisons with CH_4, the Northern Hemisphere is believed to have some influence (Monnin et al., 2001). In Appendix II, $CO_{2(SI)}$ demonstrates a greater similarity to Northern Hemisphere climate during the early Holocene. This does not however, conflict with the bipolar relationship suggested during the last glacial period and termination, for during the early Holocene most records from the Southern Hemisphere indicate a greater degree of climate stability, while Northern Hemisphere climate is highly variable.

5.2.2. Early Holocene dynamic climate (c. 11,650 – 10,000 cal yr BP)

The high resolution Dome C and Dronning Maud Land ice cores drilled in Antarctica show minimal CO_2 variability during the early Holocene although, there may be a rising trend continuing until c. 10,000 years BP (Monnin et al., 2004). While evidence is sparse, Southern Hemisphere climate appears to have been relatively stable during the early Holocene (Bianchi and Gersonde, 2004; Masson et al., 2000) whereas Northern Hemisphere climate is extremely dynamic due, for example, to retreating ice sheets and frequent meltwater outbursts (Björck et al., 2001; Sejrup et al., 2001; Hald and Hagen, 1998; Björck et al., 1997). It may be expected that responses from these major Northern Hemisphere changes would have impacted on the carbon cycle and therefore be detectable in atmospheric CO_2 concentrations. To complement ice core measurements and add detail to their effectively smoothed record, stomatal frequency reconstructions from a variety of species have been produced (McElwain et al., 2002; Rundgren and Björck, 2003; Wagner et al., 1999). Each of these records indicates a decrease in atmospheric CO_2 between c. 11,250 and 11,150 cal yr BP and, within the uncertainties of radiocarbon dating at this time, these are likely to represent the same decrease event (Wagner et al., 2004). A few hundred years after the YD, between c. 11,300 and 11,150 cal yr BP, a well known cooling event recognized mainly in the North Atlantic region, the Preboreal Oscillation (PBO), occurs and has been associated with freshwater outbursts into the North Atlantic ocean (Fisher et al., 2002; Teller et al., 2002; Björck et al., 1997). The CO_2 decrease is probably due to the large-scale climate changes associated with this event and a disruption in the carbon cycle balance by changes in marine and terrestrial carbon sources and sinks. Further meltwater outbursts are known and assumed to have affected ocean circulation in the centuries after the PBO (Teller et al., 2002), but as few published high resolution records are available, climate variability in this time period is relatively unknown. The Faroe Islands climate is

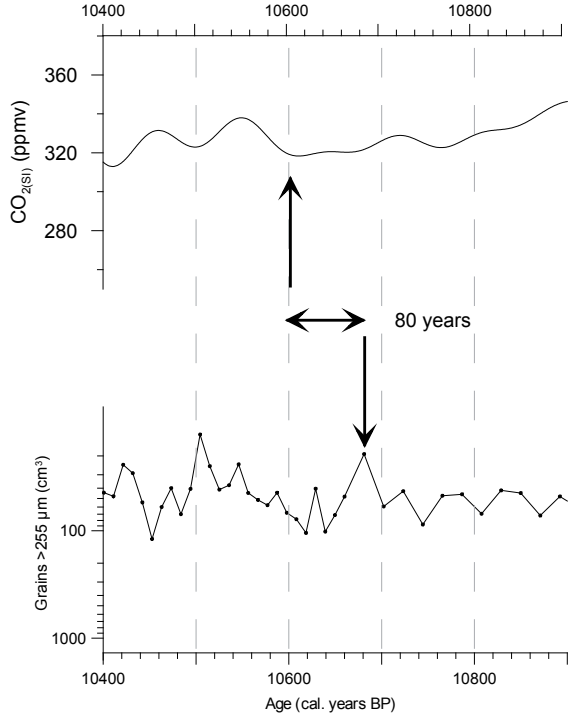

Figure 5.1. Grains (>255 µm) and $CO_{2(SI)}$ from Lykkjuvøtn for the period 10,900 to 10,400 cal. years BP indicating the time delay for the onset of instability in the two indicator proxies.

highly dependent upon oceanic conditions and the reconstruction of climate through this period shows variability consistent with the known freshwater outbursts (Appendix III). Additionally, the isolation of winter and summer indicators in the record has suggested previously undocumented links between winter conditions in the terrestrial North Atlantic and atmospheric temperatures above Greenland ice core sites. The similarity between the CO_2 reconstruction based on stomatal frequency and climatic changes based on independant proxy records also suggests that the climate of the Northern Hemisphere exerted a strong influence on global atmospheric CO_2 during a time period when the climate of the Southern Hemisphere was stable. The response time lag between these early Holocene climate indicators and CO_2 is difficult to ascertain due to the absence of a definite PBO climate anomaly in the Faroe Islands record. Although the time lag is unclear, it is almost certain that any CO_2 decrease occurred after the PBO climatic anomaly. Both the climatic and the CO_2 records however, register an onset of instability after a long period of stability. The increase in CO_2 variability occurs at c. 10,600 cal yr BP, whereas the climatic proxy responses register greater variability after c. 10,680 cal yr BP (Figure 5.1). This suggests that, if these Faroe lake sediment proxies are indeed representative of larger scale regional climatic changes, CO_2 concentrations respond to climate forced changes after a time delay of around 80 years. This time lag is similar to that predicted by model experiments simulating carbon cycle responses to freshwater forcing (Scholze et al., 2003). As mentioned previously, correlations of climatic variability with changes in solar activity are becoming more prevalent in the literature. In Paper II, a remarkable similarity between $CO_{2(SI)}$ and $^{10}Be/^{14}C$ inferred solar activity changes is described although the different chronologies mean their absolute time relationship cannot be determined. This suggests a rapid carbon cycle response to solar activity changes via climate (possibly linked through sea ice) to which the dynamic conditions of the Northern Hemisphere may have been particularly sensitive at this time. This suggested relationship has not been observed in proxy records previously.

5.2.3. The 8,200 cal yr BP event

The so-called 8,200 year BP event is one of the most distinct abrupt climate events in the Holocene record and is detectable in ice core, marine and terrestrial archives. For these reasons it is worth considering here in the context of the climatic changes reconstructed in Papers I, II, and III. Proxy records indicate that a catastrophic outburst of freshwater from glacial Lake Agassiz was the most likely cause of the widespread cooling and drying on an almost global scale (Alley and Ágústsdóttir, 2005; Rohling and Pälike, 2005; Barber et al., 1999; Klitgaard-Kristensen et al., 1998). Detailed syntheses of many records has recently indicated a possible sharp winter response of only a few decades within a longer, centennial scale, episode of cooler summers unrelated to the outburst trigger (Alley and Ágústsdóttir, 2005; Rohling and Pälike, 2005). Although Paper III only examines one palaeoclimatic record, the difference in summer and winter responses to abrupt climatic change, is clear and supports the enhanced effect of winter conditions suggested by 8,200 event studies. Although a CH_4 anomaly is detected in the atmospheric gases of ice cores around 8,000 years ago, none is detected in atmospheric CO_2 concentrations which are, at this time, in long term decline from the beginning of the Holocene (Indermühle et al., 1999; Monnin et al., 2004). In general, the stomatal frequency reconstructions over this time period, are at too low a resolution (Rundgren and Beerling, 1999), but a reconstruction using the stomatal index of *Betula* indicates a c. 25 ppmv decrease between c. 8,400 and 8,100 cal yr BP (Wagner et al., 2002). The extent of this decrease is more similar to the longer centennial summer changes than to the sharp winter decadal cold snap deduced from Rohling and Pälike's (2005) synthesis. It is proposed that evidence for terrestrial increased drawdown of carbon is insufficient to produce this response and the increased sink is most likely to have been due to lower sea surface temperatures and salinities associated with freshwater-forced weakened thermohaline circulation (Wagner et al., 2002). However a global atmospheric–sea–ice–ocean model simulated widespread changes in seasonal temperatures and precipitation due to weakened thermohaline circulation, which could not only

affect pCO_2 of surface ocean but also impact on terrestrial carbon exchange (Renssen et al., 2001). It has been suggested that compensatory Southern Ocean warming as found during the late glacial, may also have buffered the carbon cycle balance during the Holocene resulting in an absence of a measurable response to this event (Grootes et al., 2001). Climatic changes in the last 1,000 years were not as distinct, nor as large as those associated with the 8,200 year event. There are, however, carbon cycle balance changes detectable in Antarctic ice cores during this period, and a fall in CO_2 of c. 6 – 10 ppmv between c. 200 – 450 years ago is believed to be associated with the period known as the Little Ice Age (Etheridge et al., 1996) (see section 5,2,5). The disagreement between the ice core and stomatal frequency records around 8,000 cal yr BP may therefore be due to differing time resolution, but further confirmation of the $CO_{2(SI)}$ is necessary. In this context however, the c. 10 – 40 ppmv decreases found in the early Holocene (Appendix II) and possibly also associated with large freshwater outbursts appear realistic, as do the rates of change when compared to ice core measurements.

5.2.4. The mid to late Holocene shift

The longer-term climatic trends of warming winters and cooling summers in the northern latitudes are due to orbital variations and the changing receipt of insolation during the Holocene. Responses to this forcing in the Northern Hemisphere are evident in many records from the early to mid-Holocene, notably the Holocene Thermal Maximum, also known as the Hypsithermal, and the late Holocene Thermal Decline (HTD), also known as the Neoglacial. Some response can also be observed in the tropics, and although the Southern Hemisphere was subject to different orbital forcings, can also be detected towards the higher southern latitudes. The widespread response and the non-contemporary nature of the shift to the HTD is illustrated in Figure 5.2. The selection criteria for records in Figure 5.2, was that they were reconstructed at high-resolution and that they showed a distinct shift to the HTD, but it is not claimed that all available records meeting these criteria are included. In the North Atlantic region some climatic records show relatively linear responses to this long-term orbital trend (for example Koerner and Fisher, 1990) but many do not; instead they appear in sudden jumps or switches suggesting non-linear threshold responses (for example Smith et al., 2004). As changing atmospheric CO_2 concentrations indicate changes in the global carbon cycle, and therefore document the combined activity of many sources and sinks in order to produce a distinct CO_2 response, large scale and relatively synchronous changes may be required. This time period shows little large-scale spatial coherence, climate is regionally variable and complex, and responses in the carbon cycle may not be expected to clearly represent the climate record from any particular region. Ice core records do not indicate any CO_2 anomaly in this time period but, as mentioned above, these measurements may not necessarily produce the resolution required to detect any possible changes. In the time period covered by the Lake Igelsjön record (presented in Paper I), other abrupt climatic changes are documented in the North Atlantic region around 4,000 cal yr BP (Anderson et al., 1998; Laing et al., 1999; Lauritzen and Lundberg, 1999; Snowball et al., 1999). Reconstructing different aspects of climate from this sensitive lake has suggested that all these threshold responses may relate to a period of climatic instability. The concurrent reconstruction of stomatal frequency inferred atmospheric CO_2 concentrations ($CO_{2(SI)}$) also implied changes in the carbon cycle, but the large uncertainties and its short time range casts some doubt on the reliability of the reconstructed trend. The decrease in $CO_{2(SI)}$ occurs a few hundred years after lake proxy inferred responses, which could suggest a climate forced change in terrestrial carbon reservoirs. This may, however, require a broadly synchronous and large spatial scale for the shift to the HTD, and in Figure 5.2 it is clear that it was not globally synchronous. Moreover, the Igelsjön responses are relatively late, around 4,000 cal yr BP. Few records are available from the tropics and the southern hemisphere but most shift around, or prior to, 5,000 cal yr BP. North of c. 20°C, the time range stretches over 2,000 years (between c. 6,000 and 4,000 cal yr BP) and the Igelsjön shift is positioned between c. 4,600 and 3,400 cal yr BP. This wide time range and the complex nature of late Holocene responses, clearly indicates that a distinct response in atmospheric

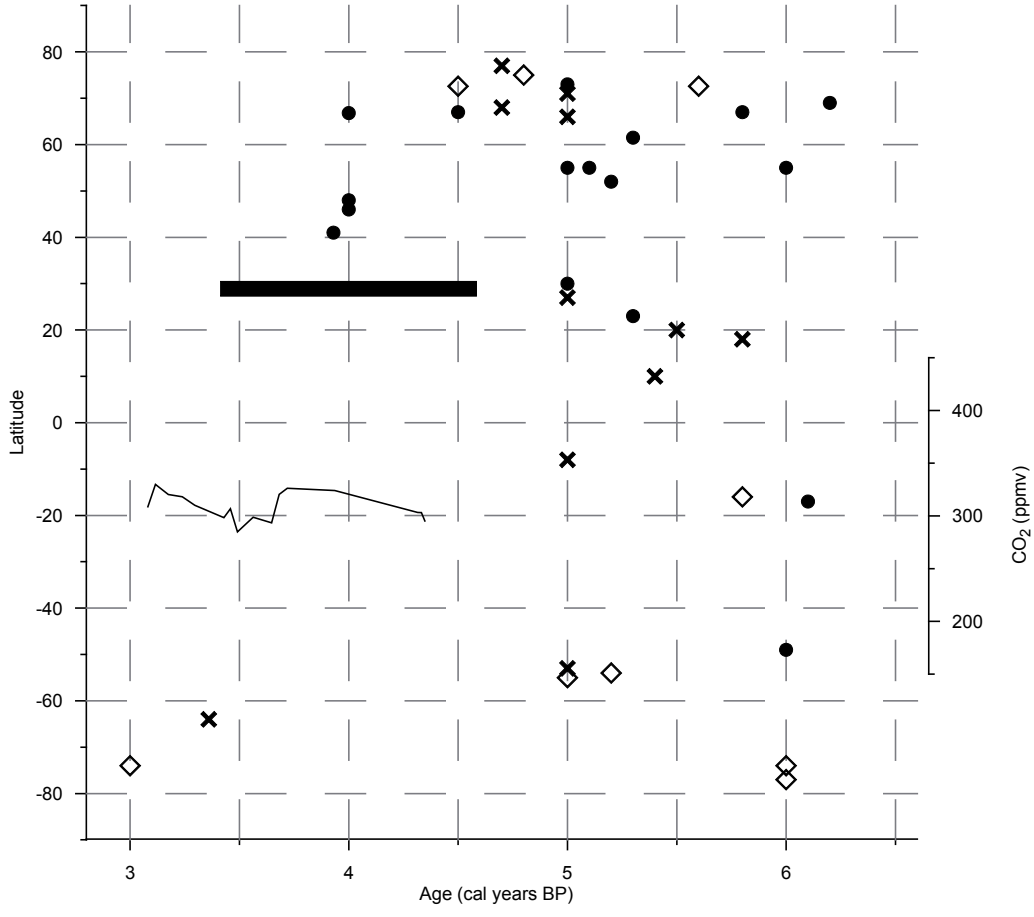

Figure 5.2. Age of a distinct shift to the late Holocene Thermal Decline (Neoglacial) detected in marine (crosses), terrestrial (filled circles) and ice core (open diamonds) records plotted against latitude. $CO_{2(SI)}$ based on Quercus stomatal frequency reconstruction from Igelsjön and filled bar indicates the period of instability detected in Igelsjön sediments (Appendix I). Reference sources:
Marine data: Andrews and Giraudeau, 2003; Andrus et al., 2002; de Menocal et al., 2000; Domack et al., 2001; Gupta et al., 2003; Haug et al., 2001; Hodell et al., 2001; Jennings et al., 2002; Keigwin, 1996; Koç and Jansen, 1994; Levac et al., 2001.
Ice core data: Dahl-Jensen et al., 1998; Heusser, 1998; Johnsen et al., 2001; Masson et al., 2000; O'Brien et al., 1995; Ramirez et al., 2003; Rosqvist and Schuber, 2003; Steig et al., 1998.
Terrestrial data: .Almquist-Jacobson, 1995; Barnekow, 2000; Bradbury et al., 1993; Enzel et al., 1999; Hassan et al., 1997; Heiri et al., 2003; Karlén and Kuylenstierna, 1996; Korhola et al., 2002; Korhola et al., 2000; Markgraf et al., 2003; Matthews et al., 2000; McDermott et al., 2001; McGowan et al., 2003; Morrill et al., 2003; Placzek et al., 2001; Wagner et al., 2000.

CO_2 may not be expected. A non-linear response of atmospheric CO_2 to the combined effect of these changes cannot however be ruled out. In addition to the changes in vegetation and soils, some indications of an increase in the production of North Atlantic Deep Water (NADW) have been found in marine records. Dated somewhere between 4,000 and 3,000 cal yr BP (Kuijpers et al., 2003), and possibly associated with a sea surface temperature decrease at c. 3,700 cal yr BP (Moros et al., 2004), the enhanced production of NADW could also contribute to any possible reduction of CO_2 concentrations. The period of instability in Igelsjön and its shift to the HTD is relatively late as compared to other records and the $CO_{2(SI)}$ decrease occurs some centuries after its onset in this record. If this response could be verified in further reconstructions, it may suggest that sudden, unexpected, threshold responses in

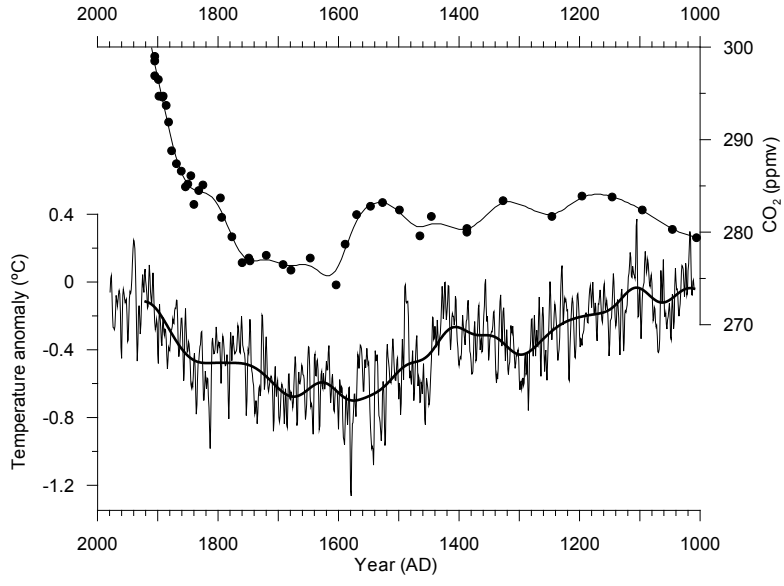

Figure 5.3. Temperature anomaly data (°C) for the last 1,000 years from Moberg et al. (2005) and Law Dome CO_2 measurements. Solid line indicates spline-fitted 20 year averages (Etheridge et al., 1996). Both data sets are shown on their published age scales.

atmospheric CO_2 are possible in the natural climate system which is of importance to the understanding of anthropogenic influences on present day climate.

5.2.5. The last 1,000 years

The last 1,000 years of climate variability, at least in the Northern Hemisphere, is fairly well known due to the availability of high-resolution palaeoclimatic records and historical sources. 'Little Ice Age' as a definition originally described the time period of glacier expansion between c. 1,300 – 1,950 AD but a large scale decrease in both summer and winter temperatures has been registered in many archives and supports the concept of a cooler climate in the period c. 1,570 – 1,900 AD (Matthews and Briffa, 2005). Previously, glaciers were not expanding and climate was warmer, a period often known as the Medieval Warm Period, although its geographic extent is less well defined. Importantly however, these time periods were not uniformly cold/warm but demonstrated a decadal average of cooler/warmer climates and historical sources suggest some instability in annual conditions. Two of the most recent (of several) syntheses of available data have shown not only higher than expected variability in temperatures (Moberg et al., 2005) and a hemispheric scale for the climatic changes (Matthews and Briffa, 2005), but also that this time period demonstrates a different global pattern from other episodes of abrupt climatic change during the Holocene (Mayewski et al., 2004). Temperature anomalies vary between geographic regions (northwest-central Asia recording a larger anomaly than Europe) but can be described as showing a decrease in summer temperatures of between 0.0 – 2.0°C (Matthews and Briffa, 2005).

This period is included here because it represents the only period in the Holocene in which ice core CO_2 records register variability believed to be related to centennial scale climatic changes, and hence is useful as a comparator with the reconstruction of early Holocene and mid-Holocene changes. Ice core CO_2 records are not fully in agreement, but generally show concentrations rising to c. 1,200 AD with values between c. 286 - 282 ppmv, and falling concentrations to c. 1,600 – 1,700 AD with values between c. 275 – 279 ppmv (Barnola et al., 1995; Etheridge et al., 1996; Monnin et al., 2004; Siegenthaler et al., 2005a). Figure 5.3 shows reconstructed temperature anomalies (Moberg et al., 2005) together with measured atmospheric CO_2

concentrations from Law Dome through the last 1,000 years (Etheridge et al., 1996). The Law Dome record of $\delta^{13}C$ and CO_2 for this period suggested an increased uptake by the terrestrial biosphere, probably due to the temperature sensitivity of heterotrophic respiration (Joos et al., 1999). A c. 50 year decrease in CO_2 begins at c. 1,550 AD and values remain low for c. 150 years. This could relate to the large-scale c. 100 year duration temperature decrease beginning at c. 1,420 AD and which was followed by lower temperature anomalies for 200 years. In this case carbon cycle responses are delayed by c. 100 years after temperature changes. This suggests that the c. 80 year delay detected between the lake palaeoclimatic proxies and $CO_{2(SI)}$ in the early Holocene record from the Faroe Islands is a realistic carbon cycle response to large-scale climatic cooling (Appendix II and Section 5.2.2).

6. Comparison of ice core and stomatal frequency reconstructions

Measurements of atmospheric CO_2 from trapped ancient air in ice cores are presently unrivalled in their ability to reconstruct past concentrations on multi-millennial timescales (Indermühle et al., 2000; Petit et al., 1997; Stauffer et al., 1998), but stomatal frequency reconstructions are perhaps more valuable on shorter timescales. Assessment of stomatal frequency reconstructions is often based on their ability to meet the standards of ice core records and are often criticized or even dismissed when they do not. Results have shown however, that the method can reliably reconstruct and reproduce trends in changing CO_2 concentrations on both multi-decadal and multi-centennial timescales (Wagner et al., 2004). Nevertheless, there is a difference in ice core and stomatal frequency baseline concentrations, in that stomatal frequency tends to produce comparatively elevated baseline values (Jessen et al., 2005; Rundgren and Beerling, 1999; Wagner et al., 2002; Wagner et al., 1999). This has been shown by a 9,000 year record based on *Salix herbacea,* where the main trends show a significant similarity to those of ice core records of the Holocene, but at values around 30 ppmv higher (Rundgren and Beerling, 1999). Baseline differences of this magnitude are found for many stomatal frequency reconstructions and this recurring inconsistency is difficult to explain. Some of the discrepancy may be due to certain species forming leaves in the spring or early summer, and therefore fixing the stomatal frequency at a relatively high point in the annual CO_2 seasonal variation. Ice cores, by contrast, record annual mean values. Larger scatter inherent in biological data may also contribute to the problem and improvement of the present calibration sets to further constrain predicted CO_2 concentrations would be of value. This clearly only explains some of the disagreement however, and this problem must be addressed as the method is further developed.

Another difference between stomatal data and ice core CO_2 records is the large (c. 10 – 50 ppmv) variability on decadal timescales detected in many studies (Jessen et al., 2005; Kouwenberg et al., 2005; McElwain et al., 2002; Wagner et al., 2002; Wagner et al., 1999). This cannot be validated by directly comparing the stomatal CO_2 trends with ice core amplitudes for, due to gas diffusion processes, the latter are effectively smoothed of any short term changes (Trudinger et al., 2003). Because of this absence, it is difficult to assess the ability of stomatal frequency to precisely capture CO_2 variability in earlier millennia. Where ice cores do record rapid CO_2 variability, for example in the last 1,000 years (Etheridge et al., 1996), changes of comparative magnitude have been detected together with the distinctive increase in concentrations within the last two centuries (Rundgren and Beerling, 1999). A study based on *Quercus* within the period 1,000 to 1,500 AD produced CO_2 trends similar to those of ice cores, but at an enhanced magnitude of variability (van Hoof et al., 2005). To address this apparent inconsistency, van Hoof et al. (2005) applied diffusional smoothing as constrained by the site-specific parameters for the D47 ice core to the data. This resulted in a reduction of $CO_{2(SI)}$ amplitudes of 25% and a variability which then more closely resembled the 12 ppmv range recorded in the D47 ice core. Further back in the Holocene, very little centennial scale variability in CO_2 is detected in ice cores, but gas diffusion and the time represented per sample could be masking any changes (Indermühle

et al., 1999; Spahni et al., 2003; Trudinger et al., 2003). Hence, ice cores cannot be used to verify any variability detected in stomatal frequency records. In Paper II, therefore, the rates of change were assessed and compared to the 1.5 ppmv per decade decrease observed at the end of the 16th century AD in the ice core records (Barnola et al., 1995; Etheridge et al., 1996; Indermühle et al., 1999; Monnin et al., 2004; Siegenthaler et al., 2005a). Accordingly, the decrease rates of 2.0, 1.5 and 0.7 ppmv per decade detected in the early Holocene were therefore found to be realistic. Overall, therefore, while the stomatal frequency method is still relatively new and still being developed, its potential value in complementing ice core CO_2 records with high resolution data should not be underestimated.

7. Conclusions

The objectives of this project involved the high-resolution comparison of climate records and atmospheric CO_2 concentrations during periods of natural rapid climate change. Detecting and understanding the background, non-anthropogenic, relationships is important in the context of the present anomalous concentrations of atmospheric CO_2 and the last few decades of climatic warming. This project has achieved the objectives of reconstructing climate from highly resolved and sensitive lake sediments during periods of rapid climate change, and concurrently reconstructing, at decadal resolution, changes in atmospheric CO_2. The appendices included here support the conclusions of previous studies of a lag of CO_2 behind climatic cooling. High resolution dating enabled the extent of the time lag to be determined, and this agrees with carbon cycle modelling after thermohaline circulation disruptions. Comparison with regional and global palaeoclimatic records has provided new insights into the causal relationships and processes involved in the connections between rapid climate change on a regional scale and global carbon cycle dynamics. Stomatal frequency analysis of sub-fossil leaves has been utilised to reconstruct atmospheric CO_2 variability. Ice core measurements of atmospheric CO_2 cannot easily resolve rapid changes on timescales of less than a few hundred years, but stomatal frequency analysis, albeit involving larger uncertainties and still under development, can complement ice core measurements by providing the high-resolution data necessary for understanding natural background climate – carbon cycle connections. Some specific novel observations have been made:

- During the period of early Holocene climatic stability in the Southern Hemisphere, Northern Hemisphere climatic changes display a relationship with changing atmospheric CO_2 concentrations.
- Distinctive climatic changes are identified in the winter indicators of Faroe Islands lake sediments during the early Holocene and correlate with freshwater pulses into the North Atlantic.
- A link between the palaeoclimatic winter indicators of Greenland and the Faroe Islands during the early Holocene suggests widespread and synchronous atmospheric changes, possibly connected via sea ice, which are not detected in the mostly summer based proxy reconstructions of the region.
- A previously unobserved similarity between changes in CO_2 and solar activity during the early Holocene suggests a rapid link via climate.
- The period of instability characterised by a series of abrupt events during the shift to the Holocene Thermal Decline was detected in lake sediments of south-central Sweden.

A large amount of information is now available from Holocene palaeoclimatic records. Synthesizing this information and increasing the knowledge of respective threshold responses is vital. Further understanding of the forcing of, and links between the different aspects of climate may help tease out any patterns presently masked by the complex nature of the data available.

One final point is perhaps worth making, periods of time during which climate changes rapidly often coincide with the collapse of some early human civilisations (deMenocal, 2001; Mayewski et al., 2004). Present day civilisation is characterised by dense populations, sometimes living in areas of high natural risk and any rapid changes in temperatures and precipitation patterns could have a great (and disruptive) effect on these societies. To understand how humans are impacting on the global climate system, the nature, regional scale and mechanisms of natural climate variability in the Holocene must

be established, and it is from palaeoclimatic studies, such as the one described here that further progress in this direction is likely to be made.

8. Acknowledgements

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9. Svensk sammanfattning

Jordens klimat har ändrats många gånger genom dess historia. Under de senaste 2,6 miljoner åren har de kontinentala landmassorna varit geografiskt fördelade på så sätt att relativt små skillnader i Jordens omloppsbana kring solen, s.k. orbitala förändringar, har givit upphov till övergångar mellan långvariga, kalla perioder (istider) och kortvariga, varma perioder (mellanistider). Det är dock viktigt att notera att dessa perioder inte har varit enhetligt kalla eller varma utan också har varierat på kortare tidsskalor. Orbitala förändringar är inte stora på dessa tidsskalor, men förstärkning genom interna återkopplingsmekanismer anses orsaka bl.a. de snabba klimatförändringar under istider som kallas Dansgaard-Oeshger-cykler. Den innevarande mellanistiden, holocen, började för omkring 11500 år sedan och ansågs, tills nyligen, ha varit klimatiskt stabil. Det är dock numera känt att klimatet har genomgått abrupta förändringar även under denna varma period, men p.g.a. begränsade förutsättningar för stark återkoppling i klimatsystemet, t.ex. till följd av att det finns få stora inlandsisar, är dessa klimatförändringar relativt småskaliga. Dessa snabba och kortvariga förändringar finns registrerade i paleoklimatiska arkiv såsom sediment i sjöar, i havet och på land, i torvmossar, inlandsisar och speleotem etc. och möjliggör rekonstruktion av klimatet under holocen. Mot bakgrund av dagens oro inför global uppvärmning och snabba klimatförändringar är det mycket angeläget att förstå hur, när och varför klimatet förändras.

Sambandet mellan klimatet och koldioxidkoncentrationen har varit viktigt genom Jordens historia. Positiva återkopplingsmekanismer tillser att atmosfärens CO_2-halt är relativt låg när Jordens klimat är kallt och att den är relativt hög när klimatet är varmt. Denna starka koppling illustreras väl av studier av isborrkärnor från inlandsisen i Antarktis. För de senaste 650000 åren visar mätningar som speglar den globala temperaturen och CO_2-analyser av luftbubblor i isen ett närmast identiskt mönster. Dessa förändringar inträffar dock inte exakt samtidigt. När temperaturen stiger i samband med att en istid tar slut vet vi att CO_2 ökar cirka 1200 år senare, men det anses att den stigande koldioxidkoncentrationen medverkar till

att höja temperaturen ytterligare. Att analaysera luftbubblor i inlandsisar är en utmärkt metod för att få information om CO_2-förändringar, men p.g.a. den fördröjning som sker i samband med att luften innesluts i isen kan det vara problematiskt att rekonstruera förändringar som äger rum under kortare tid än några århundraden. För att studera de samband som kan finnas mellan CO_2 och de snabba klimatförändringarna under holocen krävs kompletterande metoder. Analys av klyvöppningsfrekvens utnyttjar den fysiologiska responsen hos vissa arter av landväxter på förändringar i CO_2-koncentrationen. Även om metoden fortfarande är under utveckling, är den för närvarande den enda som kan användas för rekonstruktion av CO_2-förändringar på dessa korta tidsskalor. Före lövsprickningen utvecklas bladytans celler till antingen epidermisceller eller slutceller som omger en por. Dessa klyvöppningar möjliggör för växten att ta upp koldioxid ur luften, men de medger även vätskeförlust. Vid hög CO_2-koncentration kan växten tillåta sig att reducera antalet klyvöppningar på sina blad, och därigenom minimera vätskeförlusterna, utan att mängden koldioxid till fotosyntesen minskar. Genom att räkna antalet klyvöppningar per kvadratmillimeter (”stomatal density”), eller hellre proportionen celler som är klyvöppningar (”stomatal index”) kan man detektera förändringar i atmosfärens koldioxidhalt. Analyser av blad från de senaste 150 åren som hämtats från herbariesamlingar speglar den kända CO_2-ökning som skett till följd av industrialiseringen. Sjösediment har goda förutsättningar att bevara bladrester i tusentals år. Genom att analysera klyvöppningsfrekvensen hos sådana blad, och sedan kalibrera resultaten med hjälp av data från t.ex. herbarier, kan man erhålla en kvantifierad rekonstruktion av variationer i CO_2-koncentrationen.

Denna avhandling redovisar en undersökning av sambandet mellan förändringar i det regionala/lokala klimatet och den globala CO_2-koncentrationen under perioder av holocen då man känner till att snabba klimatförändringar ägde rum.

Omfattande klimatförändringar är kända från den tidig-holocena perioden (11500-8000 år sedan). Det dåtida klimatet påverkades starkt av efterdyningarna av den föregående istiden. Inlandsisar var fortfarande under reträtt i Skandinavien och Nordamerika, vilket kontinuerligt, och tidvis katastrofalt, frisläppte enorma mängder smältvatten till haven. Nordatlanten är särskilt känslig för sötvattenspulser eftersom dessa bromsar upp oceancirkulationen, vilket i sin tur leder till avkylning av hela Nordatlantregionen. Bland annat detta har föreslagits vara en orsak till de abrupta klimatförändringarna i början av holocen. En välkänd, kortvarig kallperiod inträffade mellan 11300 och 11150 år sedan och är känd som den preboreala oscillationen (PBO). Klimatet på Färöarna är starkt beroende av de oceaniska förhållandena, och det är känt att snabba klimatförändringar finns registrerade i sjöar där. Rekonstruktioner av klimatförhållandena vinter- och sommartid samt CO_2-koncentration under perioden 11300-10240 före nutid baserade på studier av sediment från sjön Lykkjuvøtn visade på ytterligare förändringar under perioden efter PBO. En period av låga temperaturer och ökad stormighet kunde detekteras för ca 11150 år sedan, och denna följdes av en mycket stabil period mellan 11000 och 10680 år före nutid som sammanfaller med en period utan smältvattentillförsel till Nordatlanten. Efter 10680 år sedan blev klimatet mycket mindre stabilt, och tre tydliga kallperioder kunde detekteras: en som kännetecknades främst av avkylning vintertid för omkring 10600 år sedan och två vinter/sommar-avkylningar för cirka 10450 och 10300 år sedan. Dessa perioder med låg vintertemperatur finns också registrerade i grönländska isborrkärnor (med hänsyn tagen till kronologiska osäkerheter), vilket indikerar regionala kopplingar i klimatet. CO_2-koncentrationen uppvisar en tydlig likhet, om än med en viss fördröjning, med klimatet med en minskning kring 10050 år sedan, vilket kan vara en försenad respons på PBO som nämndes tidigare. En enhetlig och stabil nedgång detekterades mellan 10900 och 10650 år sedan, liksom en ökad instabilitet efter 10550 år sedan. Genom direkt jämförelse av när återgången till instabilitet inträffar i de två rekonstruktionerna, vilka baseras på samma sedimentprover, kunde det konstateras att atmosfärens koldioxidhalt ändrades 80 år efter klimatet. Kronologisk jämförelse av de registrerade CO_2-nedgångarna med tidigare kända smältvattenpulser i Nordatlanten tyder på ett samband mellan dessa båda företeelser. Därutöver uppvisar CO_2-förändringarna likheter med variationer i solaktivitet. Detta indikerar

att CO_2 reagerar snabbt på minskad solaktivitet via förändringar i klimatet. En sådan likhet, och möjlig koppling, har inte tidigare detekterats i paleoklimatiska data.

Det holocena klimatet var generellt sett varmare i början av mellanistiden, medan klimatet har varit svalare och fuktigare under de senaste årtusendena. P.g.a. lokala skillnader och tröskeleffekter överensstämmer dock inte tidpunkten för denna förändring mellan olika arkiv. Tidigare studier av sediment från Igelsjön i södra, mellersta Sverige har visat på en snabb förändring till ett kallare och fuktigare klimat för omkring 4000 år sedan. En sjösedimentlagerföljd omfattande en period av några tusen år kring denna klimatförändring studerades i högre upplösning. Resultaten visade att såväl sjön som dess omgivning under denna övergång till ett svalare och fuktigare klimat under holocen reagerade med påtaglig instabilitet och genomgick en serie av snabba förändringar. Den koldioxidrekonstruktion som utfördes på samma prover, och baserades på bladfragment av både ek och björk, indikerade en tydlig nedgång under cirka 150 år mellan 3650 och 3500 år före nutid. Denna CO_2-rekonstruktion måste dock tolkas med mycket stor försiktighet p.g.a. de stora osäkerheter som hänger samman med den knappa tillgången till lämpliga bladfragment under vissa perioder.

De två ovan beskrivna studierna har visat att kombinationen av klimat- och CO_2-rekonstruktion med hög tidsupplösning kan bidra med ny kunskap om snabba, regionala klimatförändringar. Dessutom har de illustrerat klyvöppningsfrekvensmetodens potential att identifiera CO_2-förändringar över tidsskalor kortare än de som kan detekteras i iskärnor, även om kalibreringen av klyvöppningsdata ännu är förknippad med en del problem.

Här nedan specificeras några av de nya observationer som har gjorts inom ramen för detta doktorandprojekt:

- Medan klimatet var stabilt på södra hemisfären i tidig-holocen uppvisar klimatförändringar på norra halvklotet under samma tid ett samband med variationer i atmosfärens CO_2-koncentration.
- Distinkta klimatförändringar identifierades i vinterindikatorer i sjösediment från Färöarna i början av holocen, och dessa har ett tidsmässigt samband med sötvattenspulser till Nordatlanten.
- Likheter i responsen hos paleoklimatiska vinterindikatorer på Grönland och Färöarna under tidig-holocen indikerar att det förekom storskaliga och synkrona, atmosfäriska förändringar under denna tid. Dessa förändringar, vilka kan ha förmedlats via havsis, har inte detekterats i paleoklimatiska sommarindikatorer i regionen.
- En tidigare ej observerad likhet mellan förändringar av CO_2-koncentrationen och solaktiviteten under tidig-holocen indikerar en snabb koppling via klimatet.
- Övergången till den holocena temperaturnedgången är registrerad som en period av instabilitet, inklusive en serie abrupta skeenden, i sjösediment från södra, mellersta Sverige.

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