Early Holocene terrestrial climatic variability along a North Atlantic Island transect: palaeoceanographic implications

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Abstract

A synthesis of the early Holocene climatic development in the North Atlantic region is presented, based on three previously published lake records from southern Greenland (Lake N14), Iceland (Lake Torfadalsvatn) and the Faroe Islands (Lake Lykkjuvøtn). The interval 11 500–8500 cal BP has been divided into five phases with respect to the inferred strength of the North Atlantic Current (NAC) and Irminger Currents (IC). Phase 1 (11 500–10 750 cal BP) was characterised by the first establishment of the NAC and IC in the vicinity of the studied sites, interrupted by the Preboreal Oscillation around 11 200 cal BP. Phase 2 (10 750–10 100 cal BP) was marked by a further warming step in southern Greenland rather concordant with a change into colder and more variable winters on the Faroe Islands. It is proposed that this could partly be related to a series of melt water outbursts disturbing the thermohaline circulation in the eastern Atlantic Ocean, resulting in a warming trend in the western region. During Phase 3 (10 100–9400 cal BP) the strength of the IC reaching northwestern Iceland intensified. A more stable regime in surface circulation was established at the onset of Phase 4 (9400–8900 cal BP) in southern Greenland and was followed by a change towards further warm conditions on Iceland at the onset of Phase 5 (8900–8500 cal BP).

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1. Introduction

The North Atlantic region’s response in environmental systems during the early Holocene warming was complicated and does not show a common pattern over large areas. Often the warming phase occurred stepwise, interrupted by occasional returns to cooler conditions rather than a uniform warming. This probably relates to the varying influences of melting ice sheets, the timing of establishment of interglacial surface current systems and atmospheric trajectories at different places, combined with local thresholds in the interaction between climate and the biosphere, hydrosphere and cryosphere at the investigated localities.

The aim of this paper is to investigate the pattern of early Holocene warming in an east–west transect across the North Atlantic Ocean. This is done by comparing three well dated and regionally representative lake records from southern Greenland, Iceland and the Faroe Islands. The three were chosen on the basis of their near-coastal position in regions presently influenced by branches of the warm North Atlantic Current (NAC).

Lake N14 was previously studied by Björck et al. (2002), Andresen et al. (2004) and Andresen and Björck (2005) and was chosen to represent the early Holocene climatic development in southern Greenland. Lake Torfadalsvatn represents the early Holocene climatic development on northern Iceland. Lake Torfadalsvatn was previously studied in detail by Björck et al. (1992), Rundgren (1995, 1998, 1999) and Rundgren et al. (1997). On the Faroe Islands, Lake Lykkjuvøtn was chosen to represent the early Holocene climatic development and was previously studied by Andresen et al. (2006), Jessen et al. (2007) and Jessen et al. (accepted).

2. Setting

The subarctic region of the North Atlantic Ocean is characterised by interaction of warm Atlantic and cold Polar water masses. The warm NAC is directed straight
across the Faroe Islands whereas its western branch—the Irminger Current (IC)—flows along the southern and western coast of Iceland and southern Greenland (Fig. 1). The cold and less saline waters of the East Greenland Current (EGC) and East Icelandic Current (EIC) adjoin the IC in the relatively narrow oceanographic Polar Front that fluctuates at the northern entrance of the Denmark Strait (Dietrich et al., 1980). The EIC may occasionally have a branch directed towards the northern regions of the Faroe Islands. Furthermore, low-pressure systems frequently move from positions south of Greenland in a northeasterly direction across Iceland and the Faroe Islands resulting in highly variable weather conditions.

Lake N14 is situated on Angissoq Island (59°59’N and 44°11’W) 15 km south of southern Greenland at 33 m a.s.l. and has an area of 628 m². Mean summer temperature at Qaqortoq is 6.5°C and mean winter temperature is −5°C. Annual precipitation varies and increases from 858 mm just west of Angissoq Island to 2000–3000 mm east of the site.

Lake Torfadalsvatn (66°04’N, 20°23’W, Fig. 1) has an area of ca 370 000 m² and is situated at 47 m a.s.l. on the northwestern part of the Skagi Peninsula in Northern Iceland. Mean July temperature at Hraun in the northeastern corner of Skagi is 8.2°C and mean January temperature is −1.8°C. Annual precipitation is around 475 mm.

Lake Lykkjuvøtn is situated in the northwestern part of the island of Sandøy (61°54’N, 6°54’W), in the southwestern part of the Faroe Islands archipelago. It has an area of ca 1250 m² and is situated at 52 m a.s.l. Mean August temperature at Torshavn is 10.5°C with a mean January temperature of 3.2°C. Annual precipitation increases from 850 mm in the west to 2750 mm in the mountainous northern and eastern part.

Lake coring was carried out in the distal parts of the three lake basins in order to avoid local influence from streams.

3. Summary of earlier results

3.1. Chronologies

Radiocarbon dates and the age model for Lake N14 were previously published in Andresen et al. (2004). The period 11 550–8500 cal BP is represented by 15 radiocarbon dates (Fig. 2A). The early Holocene part of the chronology of Lake Torfadalsvatn was previously presented in Rundgren et al. (1997) and Rundgren (1998). It is based on 5 radiocarbon dates and the identification of the Saksunarvatn tephra as a 12 cm thick ash layer, which has been dated to 10 240 cal BP in the GRIP ice core record (Björck et al., 2001). This 12 cm interval is displayed as isochronous in the age model (Fig. 2B). In addition the age model of the lake sediment was constrained by identification of a series of local pollen assemblage zones correlated to regional pollen assemblage zones (Rundgren, 1995; Rundgren, 1998; Rundgren et al., 1997).

Age models and radiocarbon dates from Lake Lykkjuvøtn were previously published in Andresen et al., (2006) and Jessen et al. (2007) (Fig. 2C). The age model in the investigated interval is based on 18 radiocarbon dates and
the recognition of the Saksunarvatn tephra as a 1 cm thick ash layer. Andresen et al. (2006) and Jessen et al. (2007) set the age of the Saksunarvatn tephra to 10,240 cal BP in accordance with Björck et al. (2001).

3.2. Southern Greenland—Lake N14

The early Holocene environmental development as documented in Lake N14 is summarised on the basis of moss occurrence and biogenic silica content (%) (Fig. 3). Increasing content of biogenic silica reflects increasing precipitation and temperature as diatom production is favoured by increased wash-out of silica-rich silt and clay. In contrast, aquatic moss occurrence increases in response to more arid climatic conditions as clearer lake water (limited by in-wash of clastic material) favours growth of aquatic mosses (see Andresen et al., 2004 for further discussion of interpretation of proxies).

The early Holocene increasing biogenic silica content is interpreted as the response to increased humidity and warming conditions. This assumption concurs well with other records from the region; i.e. ice cores which document rapidly increasing warming and precipitation during the earliest two to three millennia of the Holocene (Alley et al., 1997; Dansgaard et al., 1993; Johnsen et al., 2001) and marine (Koc et al., 1993) and lacustrine records (Wooller et al., 2004) which also document rapid warming. Therefore the Lake N14 record is interpreted to be regionally representative of climatic changes in the southern Greenland region.

The onset of the Holocene at 11,550 cal BP is characterised by aquatic moss occurrence. At 11,125 cal BP intermittent layers of algal-rich gyttja become increasingly common, which was interpreted as a response to increased run-off suppressing moss growth. A northward movement of the low pressure tracks, in relation to the situation during deglaciation, may explain the increased precipitation. Between 11,100 and 10,800 cal BP the content of moss is relatively high and variable, suggesting periodic returns to more arid and colder conditions at around 11,075–11,000, 10,975–10,900 and 10,860–10,800 cal BP. Björck et al. (2002) investigated the diatom flora at this level and suggested a correlation to the Preboreal Oscillation (PBO) for the moss deposited between 11,075 and 11,000 cal BP. The younger age of the PBO (dated to 11,200 cal BP in Björck et al., 1997, 2002) in the Holocene age model of Lake N14 was explained by a less reliable age model in this interval (Fig. 2A).

Around 10,750 cal BP a marked increase in biogenic silica production indicates a rapid transition towards a warmer and more humid climate. At the same time the moss occurrence decreases, supporting the idea that climate became less arid. However, three short-lived episodes of a return to colder conditions are evidenced by moss peaks and minor decreases in biogenic silica centred at 10,600, at 9,550 and at 9,375 cal BP.

Another rapid transition towards more warm and humid conditions is observed after 9,400 cal BP where biogenic silica production increases stepwise towards still higher values. At the same time mosses reappear and remain an important component of the sediment throughout the rest of the Holocene (Andresen et al., 2004). The reappearance of moss most likely marks a transition towards a more stable Holocene climatic regime; this is also corroborated by a relatively marked decrease in sedimentation rate (Fig. 2A).

In summary, the biogenic silica and aquatic moss variability and their inferred climatic changes document a gradual warming during the early Holocene occurring in a number of steps at 11,550, 11,125, 10,750 and 9,400 cal BP. Marked short-lived coolings are documented around 11,050, 10,950, 10,850, 10,600, 9,550 and 9,375 cal BP.

3.3. Iceland—Lake Torfadalsvatn

The early Holocene environmental development as documented in Lake Torfadalsvatn is summarised on the basis of the organic carbon content (%), the concentration of Pediastrum and shrubs, dwarf shrubs and terrestrial pollen (Fig. 4). In addition a number of local pollen zones were established (Rundgren, 1997) and these are illustrated by concentration values for selected pollen taxa. The sediment record has been studied in detail by Björck et al. (1992) and Rundgren (1995, 1998, 1999). Based on a similar vegetational development to that recorded at a
Fig. 4. Geochemical and palynological analyses from Lake Torfadalsvatn on Iceland. Dashed lines indicate increased warming. Solid boxes indicate short-lived coolings.
number of other terrestrial sites in this region (Rundgren et al., 1997), it was concluded that the observed changes in Lake Torfadalsvatn were forced by broad-scale climatic changes.

The earliest Holocene from 11 500 to 11 000 cal BP is represented by Local Pollen Assemblage Zone (LPAZ) T6. The pollen spectra document herb tundra and is characterised by increased *Oxyria+ Rumex acetosa/acetosella* values (most likely reflecting an expansion of *Oxyria digyna*, Rundgren, 1998) indicating a change towards milder and more humid conditions at the onset of this zone. Limnic productivity in Lake Torfadalsvatn was relatively high as seen by high values of organic carbon and *Pediastrum*. Within this zone there is evidence of a short-lived cooling event, the PBO (Björck et al., 1997) registered as a decrease in organic carbon content and *Pediastrum* concentration at 11 200 cal BP. The pollen spectra show a coincident decrease in Caryophyllaceae and *Betula nana* concentrations showing that the impact of this cooling was not limited to the limnic system, but also affected the terrestrial system. At the end of the event, the LPAZ 6 terrestrial pollen concentration and in particular *O. digyna* increased, suggesting a change towards milder conditions. At 11 000 cal BP the pollen spectra (LPAZ T7) show a large expansion of dwarf shrubs such as *B. nana, Salix* and *Emetrum nigrum* indicating a closing of the vegetation cover. High limnic production as indicated by increased *Pediastrum* concentration and organic carbon content suggest a further amelioration in climate.

At 10 100 cal BP (onset of LPAZ T8) *E. nigrum, Juniperus communis* and *B. nana* expanded rather abruptly at the expense of *Salix*. This has been interpreted as a response to a sudden change to drier summer conditions and warmer winters (Rundgren, 1998). At the same time organic carbon content and *Pediastrum* concentration in the lake decreased markedly. This is most likely a dilution effect of the high tephra content of the sediment following the deposition of the Saksunarvatn Ash at 10 240 cal BP and increased winter precipitation caused by increased precipitation in Atlantic waters on the northern coast of Iceland (Hallsdóttir, 1995). In Lake Torfadalsvatn, organic carbon content and *Pediastrum* concentration increase at the same time also documenting a further step in the early Holocene warming.

In summary, the vegetation, limnic and inferred climatic changes document a gradual warming during the early Holocene occurring in a number of steps at 11 500, 11 000, 10 100 and 8900 cal BP. A marked short-lived cooling is documented at 11 200 cal BP (PBO).

3.4. Faroe Islands—Lake Lykkjuvøtn

The early Holocene environmental development as documented in Lake Lykkjuvøtn is summarised on the basis of content of biogenic silica, clastic and organic material (%), flux of grains larger than 255 μm and sulphur content (%) (Fig. 5). The regional significance of the climatic variability as interpreted from Lake Lykkjuvøtn was discussed in Andresen et al. (2006) who showed a fairly good correlation to marine records both north and south of the Faroe Islands and in both long- and short-term variability. The time period 11 300–10 300 cal BP was described in detail by Jessen et al. (2007) and Jessen et al. (accepted) and the time period 10 300–2000 cal BP is described in detail by Andresen et al. (2006). The latter presented the flux of grains larger than 255 μm as a new combined proxy for lake ice occurrence and wind activity; i.e. a proxy for winter cooling.

Early Holocene aquatic production in Lake Lykkjuvøtn commenced around 11 240 cal BP as evidenced from rapidly increasing values of biogenic silica and organic material. The relatively late onset of Holocene limnic production is probably related to late dead ice melt-out (Jessen et al., accepted). The biogenic silica and organic material proxies show no clear traces of the PBO. The proxies independent of lake sediment development do, however, suggest a recovery from a period of cooler conditions (grain flux). This recovery is interrupted however, for a period of ca 100 years, and is synchronous with a major increase in sea salt spray inferred windiness (% sulphur) prior to 11 100 cal BP. It is difficult to assign a precise age to the PBO due to the Δ14C plateau but it is possible that these changes relate to this event.

Except for the suggested winter cooling prior to 11 100 mentioned above, the interval 11 200–10 680 was characterised by relatively low content of sulphur and grain flux and high and stable organic and biogenic silica content. This suggested a period characterised by warm summers and relatively stable but fairly cool winters (Jessen et al., accepted). A short-lived return to slightly cooler summers centred at 10 900 cal BP was suggested on the basis of lowered values of biogenic silica and organic material with an absence of any marked response in sulphur content and grain flux. Around 10 680 cal BP sedimentation rate and the flux of sand grains larger than 255 μm increase and display a marked variability. At the same time the content of sulphur, probably originating from sea salt spray increases, which supports the idea that the grain flux is also controlled by wind activity. Apparently winters became harsher and more variable with increased wind activity. In particular, three events of winter cooling are evident; these are centred at 10 600, 10 450 and 10 300 cal BP. As they are accompanied by more variable organic matter and more variable and slightly decreased biogenic silica production in the lake, summer temperatures may also have slightly decreased, at least episodically, after 10 680 cal BP.
Around 10 240 cal BP the Saksunarvatn tephra was deposited as a 1 cm thick layer in Lykkjuvøtn. Andresen et al. (2006) describe the period after deposition of the Saksunarvatn ash until 9500 cal BP as characterised by a change of landscape and sediment processes caused by the ash deposits unrelated to climatic change. Following the eruption, tephra deposited in the catchment would have been transported with surface run-off (and wind) into the lake. This would result in continued dilution of the sediments with mineral material, evidenced as lowered organic material and biogenic silica content, whereas the clastic material content increases. At the same time the flux of sand grains other than tephra particles is still high suggesting either winter temperatures were still lowered at this time or that the tephra temporarily decreased the vegetation cover exposing mineral material to wind. This so-called post-Saksunarvatn phase has also been observed in the Faroese Lake Starvatn (Andresen et al., 2006) where it only lasted for 50–100 years after the volcanic eruption. This discrepancy in duration could be related to the different geomorphologic setting around Lake Lykkjuvøtn with steep slopes; however, it could also be related to a less reliable age model for Lake Starvatn at this time (see Andresen et al., 2006). Around 9525 cal BP biogenic silica and organic material increase. At the same time the flux of sand grains larger than 255 μm decreases markedly, suggesting either a return to relatively warm summers and mild winters or that the influence from tephra on the sediment composition decreased. These climatic conditions persist until 8500 cal BP and it was suggested by Andresen et al. (2006) that this may represent early Holocene Optimum conditions on the Faroe Islands.

In summary, the limnic and inferred climatic changes document a period around 11 200–11 000 cal BP of stable summers but variable winters and 11 200–10 680 cal BP with stable warm summers and relatively cool winters. After 10 680 cal BP and until deposition of the Saksunarvatn tephra, winters—and possibly also summers—became colder episodically. After deposition of the Saksunarvatn tephra and until 9525 cal BP it is difficult to estimate if sedimentologic changes are solely related to the impact of the tephra particles on the landscape (and thereby blurring any signals in the sediment from climatic change) or if the high flux of grains larger than 255 μm could indicate still relatively cold winters. Between 9525 and 8500 cal BP the climate became warm and stable again. Short-lived cooling episodes are documented around 10 900, 10 600, 10 450 and 10 300 cal BP.

4. Early Holocene shifts in the strength of warm surface currents across the North Atlantic Ocean

Based on the summary for the early Holocene climatic development inferred from the three lakes (Fig. 6) we have
attempted to reconstruct the development in relative strength of the NAC and IC by dividing the interval 11 500–8500 cal BP into five phases (Fig. 7).

4.1. Phase 1 (11 500–10 750 cal BP)

In Southern Greenland, on Iceland and on the Faroe Islands, early Holocene climatic warming is rapid—although on the Faroe Islands limnic production in Lake Lykkjuvøtn is slightly delayed at 11 240 cal BP. For this reason the signal of a PBO is not as clear, in contrast to Lake Torfadalsvatn (Björck et al., 1992) and Lake N14 (Andresen et al., 2004; Björck et al., 2002).

Fisher et al. (2002) have proposed that the PBO could be related to a relative large melt water discharge event from glacial Lake Agassiz to the Arctic Ocean via the Mackenzie River. They propose that freezing of flood water into sea ice in the Beaufort region, coupled with increased river ice production during winter, resulted in a thick and extensive pack ice flowing through the Fram Strait. Upon melting in the North Atlantic the freshwater anomaly could have decreased NADW formation which would have led to cooling over large areas.

The PBO is rapidly followed by a return to warm conditions in southern Greenland and on Iceland around 11 000 cal BP and on the Faroe Island around 11 100 cal BP. Whereas conditions are increasingly warmer after the PBO on Iceland, warming in southern Greenland and on the Faroe Islands was punctuated by a minor cooling between 11 000 and 10 800 cal BP.

The earliest Holocene warming phase (11 500–11 200 cal BP) probably reflects the first establishment of the NAC and IC in the vicinity of the studied sites (Fig. 7) and there might have been a further increase in the strength of the current right after the PBO at 11 000 cal BP around Iceland. The latter suggestion of increased Atlantic water flow to Iceland is supported by diatom data from the North Icelandic shelf indicating a climatic amelioration at or slightly before 11 000 cal BP (Andersen et al., 2004; Knudsen et al., 2004).

4.2. Phase 2 (10 750–10 100 cal BP)

The onset of this phase is characterised by a further warming step in southern Greenland. On Iceland there are no major changes whereas winters suddenly became colder and more variable on the Faroe Islands after 10 680 cal BP. Jessen et al. (accepted) have suggested that this setback in climate on the Faroe Islands could be related to an increased frequency of freshwater outbursts from the disintegrating Laurentide ice sheet, which would interrupt the thermohaline circulation. Melt water outbursts to the North Atlantic Ocean at 10 600, 10 400 and 10 300 cal BP (Teller et al., 2002) are broadly coeval with the short-lived coolings on the Faroe Islands at 10 600, 10 450 and 10 300 cal BP, respectively (Jessen et al., accepted). These relatively minor melt water fluxes may have followed the track of the warm subtropical gyre waters and further north via the NAC and the IC. However, southern Greenland was relatively unaffected by this series of melt water outbursts, except for a short-lived cooling around 10 600 cal BP and it may be hypothesised that it was a mostly eastern Atlantic phenomenon which is also corroborated by a concurrent change towards colder winter conditions in waters off western Norway (Sejrup et al., 2001). Usually Holocene cooling episodes on centennial to millennial timescales in the North Atlantic Ocean are in-phase with southern Greenland (Andresen et al., 2004; Andresen and Björck, 2005), but it could be suggested that the melt water episodes at 10 400 and 10 300 cal BP were too small to be manifested all the way to southern Greenland. Teller et al. (2002) has estimated the flux of the 10 400 and 10 300 cal BP outbursts to only 0.12 and 0.07 Sverdrup, respectively. In comparison the PBO and the 10 600 cal BP outbursts were much larger, with fluxes of 0.19 and 0.22 Sverdrup, respectively. The reason for varying sensitivity for freshwater input between the NAC and the IC may be related to the former being driven by deep convection and partly brine formation in the GIN Seas, whereas convection in the Labrador Sea is intermediate (Dickson and Brown, 1994). Indeed, the rather synchronous warming in southern Greenland could perhaps suggest that repeated slow-downs of the NAC to the eastern Atlantic Ocean may even have resulted in a redirection/intensification of warm subtropically originated waters to the western region of the North Atlantic with the IC. This suggestion is further supported by marine records.
from the Labrador Sea documenting increased warming between 11 500 and 10 000 cal BP (Solignac et al., 2004). Such a scenario is supported by recent computer simulations emphasizing the influence by the subpolar gyre on inflow of saline water to the eastern North Atlantic (Hátún et al., 2005).

The lack of evidence for short-lived coolings on Iceland at this time suggests that it was either unaffected by these melt water events or that data resolution is too low to trace short-lived episodes of cooling. The latter could be the case as a short lived cooling has been observed on the basis of diatom data from the North Icelandic shelf around 10 700 cal BP (Knudsen et al., 2004), possibly coeval with the 10 600 cal BP melt water outburst.

4.3. Phase 3 (10 100–9400 cal BP)

The period after deposition of the Saksunarvatn tephra is rather complicated to evaluate on the basis of Lake Lykkjuvøtn on the Faroe Islands, but we speculate (see above) that there may have been a period of continued colder winters on the Faroe Islands. In northern Iceland the IC became more vigorous as evidenced from the sudden expansion of warmth demanding plant communities at 10 100 cal BP. In the marine record a transition into warmer conditions is observed as a change in diatom and foraminifera records on the northern Iceland shelf along with a decrease in the flux of ice rafted debris—although just before the deposition of the Saksunarvatn ash (Knudsen et al., 2004). There are no traces of a further intensification of the IC to southern Greenland at this time.

4.4. Phase 4 (9400–8900 cal BP)

Based on a relative strengthening of the warm currents directed towards southern Greenland we suggest that a more stable regime in surface circulation was established here around 9300 cal BP. On the Faroe Islands climatic conditions reached a Holocene maximum although the exact onset of this stage is difficult to determine due to the
blurring effect from the post-Saksunarvatn phase. On Iceland there are no indications of a change towards warmer conditions as evidenced from the terrestrial archive (Lake Torfadalsvatn). However, the marine record north of Iceland indicates a step towards an intensified IC around 9300 cal BP (Castañeda et al., 2004).

4.5. Phase 5 (8900–8500 cal BP)

The onset of phase 5 is related to a warming step on terrestrial Iceland around 8900 cal BP. This is supported by increased warming as evidenced from the marine archive north of Iceland (Castañeda et al., 2004—core B997-324) suggesting an intensification of the IC. However, there are no traces of an increase in warming in southern Greenland or on the Faroe Islands at this time, indicating that this was more of an Icelandic phenomenon.

5. Conclusions

Based on the observed pattern of early Holocene warming in the North Atlantic region we conclude that it occurred in a number of steps between 11 500 and 8500 cal BP and propose that it reflects the development of the relative strength of the northern branches of the Gulf Stream: the NAC and IC. These warming steps were at times synchronous between southern Greenland, Iceland and the Faroe Island and at times not all transitions to warming phases could be tracked at all three locations at the same time.

Phase 2 (10 750–10 100 cal BP) differs from the other phases in that it was characterised by coolings in the eastern sector of the North Atlantic Ocean. We relate these often short events to episodic melt water outbursts from the eastern sector of the North Atlantic Ocean—rather it may be suggested that this region accumulated the warm waters rejected in the eastern sector of the North Atlantic Ocean and at times not all transitions to warming phases could be tracked at all three locations at the same time.

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