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Trends and centennial-scale variability of surface water temperatures in the North Atlantic during the Holocene

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Abstract :

Two sediment cores retrieved off North Iceland (western Nordic Seas) and on the eastern flank of Reykjanes Ridge (Iceland Basin) were analyzed to generate high-resolution alkenone-derived sea surface temperature (SST) records to investigate North Atlantic Ocean circulation changes during the Holocene. Early Holocene SSTs off North Iceland were unstable (10 ± 1 °C) and 3 °C warmer than today reflecting active northward heat transport of the Atlantic Meridional Overturning Circulation (AMOC) interrupted by intermittent Polar Waters incursions onto the North Icelandic shelf. The Holocene thermal optimum occurred synchronously east of Reykjanes Ridge, with a mean value of 11.5 °C (±0.5 °C) similar to today, consistent with a sustained influence of AMOC. Both records indicate that the circulation across the North Atlantic intensified between 8000 and 7000 yr BP. Thereafter, SSTs in the two basin sites broadly depict opposing trends and centennial-scale oscillations and a notable cooling at ~5300 yr BP that coincides with Bond 4 event and the temporary collapse of the deep-water circulation. From 2500 yr BP onwards, SSTs in the Iceland Basin and the western Nordic Seas diverge leading to a marked cooling/warming dipole resulting in a temperature difference today of 4.5 °C. We show that SST trends and centennial-scale variability reflect variations of the subpolar gyre (SPG) circulation linked to drifting ice events and convection changes in the Labrador and Nordic Seas.

Highlights

► Early Holocene Thermal Optimum off North Iceland and East Reykjanes Ridge are synchronous with a 1.5 °C temperature difference. ► After 7000 yr BP surface temperatures show opposite trends due to different hydrological features in the two basins. ► Temperature difference between our western Nordic Seas and subpolar Atlantic sites reflects the subpolar gyre strength.

Keywords : Alkenones, SST, Holocene, North Atlantic, Subpolar gyre circulation

1. Introduction

The sensitivity of the Atlantic Meridional Overturning Circulation (AMOC) in the context of global warming is an area of active research (Yang et al., 2016; Chen and Tung, 2018). According to recent proxy reconstructions, enhanced freshwater export from the Arctic Ocean and Nordic Seas would be responsible for the reduction of the Labrador Sea deep-convection and the unprecedented AMOC decline since the end of the Little ice age (LIA) (Thornalley et al., 2018; Caesar et al., 2021). Indeed, after nearly 2000 yrs of relatively stable state, the AMOC started to weaken 150 years ago and more strongly since the mid-twentieth century to reach its lowest level in the last decades (Caesar et al., 2021). The Subpolar Gyre (SPG) cyclonic circulation is another important component of the AMOC linked to convection in the Labrador Sea (Hátún et al., 2005; Hátún and Chafik, 2018) that is also affected by freshwater inputs (Häkkinen and Rhines, 2004; Böning et al., 2006). Although model simulations have shown linkages between the deep-water formation rate, the strength of the SPG and the AMOC at decadal time-scales, long-term observations are still lacking to fully understand and quantify these relationships (Rhein et al., 2011; Bryden et al., 2005). Using altimetric and ocean temperature data, and a 1000-year control simulation performed on the fully coupled ocean-atmosphere GFDL CM2.1, Zhang (2008) showed that the strengthening of AMOC is associated with a weakening of the SPG and warmer sub-surface temperatures in the subpolar North Atlantic. This author further demonstrated an out-of-phase relationship between the AMOC and the SPG, with AMOC lagging deep convection in the Labrador Sea by several years, the time needed for advection of denser waters from convection sites (Labrador or Nordic Seas) to the ocean interior. The propagation of denser waters at depth by enhancing stratification would have limited convection and weakened the SPG. These results are consistent with time-series observations at 25°N (Bryden et al., 2005) but differ from the in-phase variation of AMOC and SPG (Böning et al., 2006). Finally, Chen and Tung (2018) recently showed that besides freshwater forcing, imbalance radiative forcing due to greenhouse gases would have contributed to the recent surface warming due to lower heat storage in the deep-ocean under a weak AMOC, highlighting the gaps in our understanding of the AMOC response to external forcing.

The East Greenland Current (EGC) flowing southwards along the East Greenland coast from Fram Strait and the Labrador Current (LC) exiting Arctic waters via the Canadian Archipelago are major conveyors of cold and freshwaters to the North Atlantic impacting on convective activity in the North Atlantic and subsequently on the AMOC (Figure 1) (Dickson et al., 1996). In the recent history, episodes of freshwater accumulation in the North Atlantic, known as the Great Salinity Anomalies (GSAs), have led to a significant reduction of convective mixing. While the GSA in the 60-70s was triggered by enhanced export of sea ice and melt water from the Arctic Ocean through Fram Strait, the GSA in the 1980s was likely caused by increase local sea ice formation due to severe winters in Baffin Bay (Belkin et al., 1998). These GSAs did not seem to have altered the AMOC (Böning et al., 2016), but convection shutdown of the Labrador Sea subsequent to the GSA in the 70s has been demonstrated (Gelderloos et al., 2012). Several centuries ago, during the LIA (1450-1850 yr AD) large surface temperature and salinity changes (Sicre et al., 2008; Moffa-Sánchez et al., 2014) associated with the expansion of sea ice (Massé et al., 2008) as far as the Faroe Islands have been documented (Denton and Broecker, 2008). This period of anomalous cold and icy surface waters would have been responsible for the severe climatic conditions in Western Europe (Denton and Broecker, 2008). Yet, according to Moreno-Chamarro et al. (2017) the cold LIA climate would not be linked to a reduction of AMOC or persistent negative NAO but rather explained by a leading role of a weak SPG.

The Holocene epoch provides an interesting time frame for investigating the impact of ice melt water on the North Atlantic Ocean circulation under different climate and forcing conditions. Indeed, at the time of high northern hemisphere summer insolation of the early Holocene, the subpolar North Atlantic experienced major surface temperature and salinity changes resulting from final melting of the Laurentide Ice Sheet (LIS) and Greenland Ice Sheet (GIS) (Thornalley et al., 2009; Solignac et al., 2004, 2006; Larsen et al., 2014; Ullman et al., 2016). Large freshwater release and sustained high buoyancy fluxes would have suppressed convection in the Labrador Sea (Hillaire-Marcel et al., 2001). It is not until 8000-7000 yrs ago that convection and SPG circulation would have re-established (Hillaire-Marcel et al., 2001). While early Holocene studies focused on the 8.2 ka event (Barber et al., 1999; Ellison et al., 2006), few have investigated the spatial and temporal evolution of the SPG circulation with decreasing boreal summer insolation (Thornalley et al., 2009; 2013; Moffa-Sanchez et al., 2014; Jalali et al., 2019), and even less have explored its links with the AMOC (Moreno-Chamarro et al., 2017; Thornalley et al., 2018).

Here, we present two Holocene high-resolution alkenone-derived Sea Surface Temperature (SST) reconstructions from off North Iceland in the western Nordic Seas (MD99-2275) and the eastern Reykjanes Ridge in the Iceland Basin (MD95-2015). These data extend the 0-4500 yr BP alkenone-SST record of the MD99-2275 core published by Sicre et al. (2008) and the 5500-2500 yr BP SST record of the MD95-2015 core of Jalali et al. (2019) to encompass the entire Holocene period and provide a description of SST variability at decadal to multidecadal-scales. Using published proxy records of surface and deep-water circulation, we investigate the development of ocean circulation in the two basins and discuss the links between SST and SPG changes triggered by insolation driven freshwater melting, ranging from a turn off-mode of the SPG circulation in the early Holocene to its resumption and further evolution with decreasing insolation and drifting ice episodes.

2. Material and methods

2.1. Oceanographic setting and core locations

The two study cores were retrieved using the Calypso corer during two cruises of the international IMAGES program aboard the French research vessel *Marion Dufresne* from two key areas of the North Atlantic. One is located in the western Nordic Seas off North Iceland (IMAGES V cruise, MD99-2275: 66°33.10N, 17°41.99W, 470 m water depth), the other in the Iceland Basin on the eastern flank of

Reykjanes Ridge (IMAGES MD101 cruise, MD95-2015: 58°76.22N, 25°95.88W, 2630 m water depth) (Figure 1). The MD99-2275 core is situated in the vicinity of the Polar Front today, where cold and low salinity waters of the EGC and East Icelandic Current (EIC) meet with the warmer and saltier waters of the North Icelandic Irminger Current (NIIC), a northern bifurcation of the Irminger Current (IC) flowing northwards across the Denmark Strait (Østerhus et al., 2005). SSTs off North Iceland are thus expected to reflect variations of the relative influence of the NIIC and EGC/EIC flows in relation to the position of the Polar Front. The MD95-2015 core is located on the path of the eastern branch of the SPG separating the relatively colder and fresher waters of IC from the saltier and warmer waters of the North Atlantic Current (NAC). This site is expected to provide information on the movements of the subpolar front and behavior of the SPG.

2.2. Age models

Both cores were continuously sub-sampled at a 1 cm step. The age model of the MD99-2275 core is based on 15 tephra layers (Table DR4 in Jiang et al., 2015) and the Bayesian calibration software OxcaCal4.2. The tephra-based age model was constructed to circumvent marine reservoir age problems. The uncertainties of the MD99-2275 age model has been estimated to be on the order of 10-20 years (Jiang et al., 2015). Because of the exceptional high sedimentation rate at this site (on average 250 cm/1000 yrs during the last 10000 yrs), the SST record achieves a mean temporal resolution of 4-5 yrs. For the MD95-2015 core, the age model is constructed with 21 AMS radiocarbon dates measured in the planktonic foraminifera on *Globigerina bulloides* converted to calendar ages using Oxcal4.3 (Ramsey, 2017) and the MARINE13 calibration data set (Reimer et al., 2013) using a ΔR = 73±69 yrs (Jalali et al., 2019). The MD95-2015 age model uncertainty is on the order of 100 yrs. The lower accumulation rate at this deeper site (on average 50 cm/1000 yrs) yields a mean temporal resolution of 20 yrs.

2.3. Alkenone derived Sea Surface Temperature

SSTs were estimated from the concentrations of the C_{37} alkenones. For both cores, lipids were extracted from freeze-dried sediments using a mixture of methylene chloride and methanol (2:1, v/v). Alkenones were isolated from the total lipid mixture by silicagel chromatography using the protocol adapted from Ternois et al. (1997). The fraction containing alkenones was analyzed by gas chromatography (GC) on an Agilent 6890 gas chromatograph equipped with an on-column injector. The GC oven was heated from 50°C to 300°C at a rate of 20°C/min and maintained at final temperature for 40 minutes. GC analyses were performed using a CP-Sil-5CB fused silica capillary column (50 m x 0.32 mm i.d., 0.25 µm film thickness, Chrompack) and helium as a carrier gas (25 ml min^{-1}). Individual compounds were detected with a flame ionization detector (FID). $U^{K'}_{37}$ index values were calculated from $C_{37:2}$ and $C_{37:3}$ using the following expression $(C_{37:2})/(C_{37:2} + C_{37:3})$. They were then converted into SSTs by applying the widely used calibration of Prahl et al. (1988), $T= (U^{K'}_{37} – 0.039)/0.034$). The internal analytical precision calculated from duplicate injections is estimated to 0.01 $U^{K'}_{37}$ ratio unit which converts to ±0.35°C (Sicre et al., 2011). The $C_{37:4}$ alkenone was not detected in the MD95-2015 and found in trace amounts in the upper part of the MD99-2275 core corresponding to coldest temperatures of the records, as expected from the location of the two cores on the path of the warm waters of the NAC.

Alkenones are primarily produced by the autotrophic coccolithophorid *Emiliana huxleyi*. In high-latitude regions, the main production season for phytoplankton is summer, when light and nutrient availability are favorable for photosynthesis (Sicre et al., 2002). In an earlier study, Sicre et al. (2011) demonstrated that in the MD99-2275 core the best correlation between the $U^{K'}_{37}$ index and gridded Hadley Center SST values was obtained for July temperatures (6-8°C) (Figure S1). Systematic warm offset of alkenone-SSTs during cold and icy years reflecting delayed coccolithophorid blooming due to sea ice melting (see Figure 3 in Sicre et al., 2011) was also observed and further corroborated in the Labrador Sea (Sicre et al., 2014). The remarkable agreement between $U^{K'}_{37}$- SSTs and instrumental data over the 20th century is not unexpected given that our shelf site off North Iceland is located on the path of the NIIC, where warm biases often found in the Nordic Seas are not observed (Bendle and Rosell-Melé, 2004). At MD95-2015, South of Iceland, direct comparison between proxy and instrumental data was not possible because the last 500 years of Holocene of the core are missing. Nevertheless, the uppermost core SST values (11-12°C) are also close to July-August surface temperatures measured at the core site (Figure S1) between 1955 and 2012, with summer values comprised between 11 and 12°C, i.e. 4 to 5°C warmer than off North Iceland (Figure S1). The earlier study of Giraudeau et al (2000) demonstrated that the coccolith record at this site primarily reflects the production and export from the upper ocean, precluding any dynamical processes induced by bottom flow.

3. Results

The Holocene SST records at MD99-2275 and MD95-2015 show strong multi-decadal to millennial-scale variations superimposed on long-term trends that are different at the two sites (Figure 2a,b). Off North Iceland (MD99-2275), early Holocene SSTs vary strongly around a mean of 10°C ($\pm$1°C) that exceeds modern values by 3°C. These fluctuations attenuate between 7000 and 5300 yr BP and amplify again after a stepwise decrease of 1.5°C around 5300 yr BP. The following 5300-2500 yr BP interval is characterized by 50 to 150 yr period SST oscillations superimposed on a broad increase from 8 to 10°C (Sicre et al., 2008). Over the last 2500 yrs, surface waters show a sharp cooling (from 10 to 7°C), which comprises a distinct three-century long warmer interval (1000 - 700 yr BP) known as the Medieval Climatic Anomaly (MCA). SSTs exhibit different features at the eastern Reykjanes Ridge site MD95-2015. The early Holocene part of the record indicates 1.5°C warmer values than off North Iceland with oscillations of lower magnitude (11.5$\pm$0.5°C). A remarkable difference between the two sites is the 3.5°C cooling between 7000 and 5300 yr BP recorded at the MD95-2015 core (from 11.5 to 8°C) while only of 1.5°C off North Iceland (Figure 2a,b). Thereafter, both records show opposite sign evolution with a temperature contrast between the two sites building-up over the last 2500 yrs to reach a value today of 4.5°C.

4. Discussion

4.1. Early Holocene till 8500 yr BP

High and unstable SSTs during the early Holocene off North Iceland suggest a generally strong inflow of warm NIIC with centennial-scale incursions of Polar Waters (Figure 2b). The range of variation of alkenone SSTs (7 - 13°C) is larger than that obtained in the same core from diatom assemblages (8 - 9°C), a result that essentially reflects higher alkenone maxima (13°C for alkenones vs 9°C for diatoms) (Jiang et al., 2015) (Figure S2). These warm extremes likely reflect time intervals of intensified NICC along the northern Icelandic coast as suggested by the coincidence of alkenone and diatom SST maxima. However, melt water transported by the EGC can cause a shift of coccolithophorid blooms towards warmer months (Sicre et al., 2011). Furthermore, under stratified conditions induced by freshwater, the near surface layer can rapidly warm, both effects conspiring towards warmer alkenones than diatom assemblage based SSTs (Andrews et al., 2021). Similar strong variability of early Holocene SSTs has been observed in the Denmark Strait region and attributed as well to varying contribution of warm and salty Atlantic waters and cold and fresher Polar Waters of the EGC (Andersen et al., 2004a; Justwan et al., 2008; Jennings et al., 2011). Likewise, at the even more distant site P-013 South of Greenland (Figure 1) dinoflagellate assemblages also revealed pronounced seasonal contrast and stratified conditions reflecting occurrences of ice and melt water from the GIS and the Arctic Ocean, further supporting our findings (Solignac et al., 2004).

Melting of the GIS and LIS reduced deep-water formation in the Labrador Sea thereby altering the SPG circulation and most probably the AMOC (Hillaire-Marcel et al., 2001). In order, to capture the SPG dynamical changes, Thornalley et al. (2009) generated surface and subsurface temperature and salinity records from paired δ^{18}O - Mg/Ca data measured in *Globigerina bulloides,* living in the surface mixed layer, and the thermocline dwelling *Globorotalia inflata* from the RAPiD-12-1K core located on the path of the NAC in the eastern subpolar Atlantic (Figure 1). The difference between the two foraminifera temperature and salinity values was then used to calculate a density difference interpreted as a proxy of upper ocean stratification and related to the intensity of the SPG (Thornalley et al., 2009). These records indicate stratified conditions until approximately 8500 yr BP reflecting the absence of winter convection in the Labrador Sea (see Figure 2 in Thornalley et al., 2009). The co-eval strong salinity contrast between the freshened Labrador Sea at P-013 (Solignac et al., 2004) and salty subsurface waters at RAPiD-12-1K (Figure 3b) is also in accordance with the shutdown of the SPG (Thornalley et al., 2009). Early Holocene warm alkenone SSTs at MD95-2015 evidence the dominant influence of the NAC at the eastern flank of Reykjanes Ridge despite the cold melt water outflow from the Labrador region, although SST cooled around 9300 and 8200 yr BP. This is confirmed by warm SSTs derived from Mg/Ca of G. *bulloides* in the RAPiD-12-1K core showing slightly colder values likely reflecting different season and depth habitat of G. *bulloides* and alkenone producers. At the western flank of Reykjanes Ridge, colder but rising SSTs in LO-09-14 core till 8200 yr BP indicate a weaker but increasing influence of the NAC and a strong imprint of Polar Waters (Figure 1 and 2d) (Andersen et al., 2004b; Berner et al., 2008). The presence of diatom *Thalassiosira gravida* indicates cold waters originated from the Davis Strait outflow, possibly explaining the late thermal optimum at this site (Andersen et al, 2004b). Based on sortable silt data, McCave and Andrews (2019) inferred that the NAC feeding the EGC at Fram Strait would have contributed to maintain a strong flow of Polar Waters along East Greenland thereby freshening the Labrador Sea. This is in contrast with the dominant influence of warm NAC waters in the eastern subpolar basin and North of Iceland nourished by a vigorous NIIC resulting in a temperature difference between our two sites of only 1.5°C. High Iceland-Scotland Overflow Water (ISOW) estimated from cores along Gardar Drift indicates active convection in the Nordic Seas while turned off in the Labrador Sea (Figure S3a,b) (Hoogakker et al., 2011; McCave and Andrews, 2019). These results suggest an active AMOC despite the shutdown of the SPG and convection in the Labrador Sea caused by large freshwater inputs advected by the EGC.

4.2. From 8200 to 7000 yr PB

With the demise of the LIS, salinity in the Labrador Sea gradually increased providing conditions for convection to resume (Hillaire-Marcel et al., 2001; Solignac et al., 2004). Active NAC circulation could have contributed to the salinity increase in the Labrador Sea through the EGC (McCave and Andrews, 2019) as well as the ISOW (Hall et al., 2004). After the steep freshening of subsurface waters in the RAPiD-12-1K core and surface waters in the P-013 core between 8500 and 8200 yr BP (Figure 3b), convection in the Labrador Sea and SPG circulation re-activated (Hillaire-Marcel et al., 2001; Thornalley et al., 2009). Indeed, salinity in the Labrador Sea and Iceland basin converge to a value of 34 reflecting intense mixing across the subpolar North Atlantic (Figure 3b). SSTs at MD95-2015 decrease slightly to come close to those found over the North Icelandic shelf (around 10°C; Figure 4c and Figure S5). Meanwhile, SSTs at LO-09-14 (Western Reykjanes Ridge) increase by about 1.5°C testifying active mixing with warm NAC waters and the retreat of the subpolar front. A vigorous ISOW flow reported in several studies (Bianchi and McCave, 1999; Hoogakker et al., 2011; Thornalley et al., 2013; Kissel et al., 2013; McCave and Andrews, 2019) (Figure S3a,b) and the occurrence of a thermal optimum along the Norwegian coast between 8900 and 7300 yr BP (Berner et al., 2011) add further support to intense northwards heat transport by a strong AMOC and SPG sustained by active convection both in the Nordic and Labrador seas.

4.3. From 7000 to 5300 yr BP

Around 7000 yr BP**,** surface waters at MD95-2015 begin a long-term cooling till the coldest value of the record (8°C) at ~5300 yr BP. This period coincides with the progressive invasion of drifting ice from Iceland across the subpolar North Atlantic as evidenced by the stacked record of % hematite grains in North Atlantic sediments of Bond et al. (2001) (Figure 4a,c). The concurrent decline of the ISOW flow along Gardar Drift (Figure S3) and the large decrease of the δ^{13}C of benthic foraminifera *Cibicidoides wuellerstorf*i at Feni Drift highlight a link between drifting ice, surface ocean cooling and deep-water circulation slowdown (Oppo et al., 2003). Widespread freshening caused by drifting ice is also indicated by the concomitant decrease of surface salinity in the Labrador Sea core P-013 (Figure 3b) and RAPiD-12-1K core. However, stable subsurface salinity at the later site suggests a strong upper ocean stratification and weakening of the SPG (Figure 4). On the contrary, surface warming at LO-09-14 (from 11 to 13°C) indicates limited advection of melt water to western Reykjanes and a lesser influence from the Canadian Archipelago as suggested by the absence of *Thalassiosira gravida* (Andersen et al., 2004b) (Figure 2d). Off North Iceland, SSTs slightly warmed before the stepwise cooling at 5300 yr BP also inferred from the abrupt increase of sea-ice diatom and the occurrence of the Arctic diatom species *Thalassiosira nitzschioides* in the MD99-2275 core, pointing towards Neoglacial conditions in the western Nordic Seas (Ran et al., 2008). Sortable silt at the nearby core MD99-2269 indicates a consistent sharp decline of the NIIC flow (see Figure 2 in McCave and Andrews, 2019). Increasing salinity difference between the Labrador Sea and the Iceland Basin since 7000 yr BP underpins the progressive weakening of the SPG, although the salinity contrast at 5300 yr BP did not reach that of the Early Holocene (Solignac et al., 2004; Thornalley et al., 2009) (Figure 3b). The SST decrease in the Norwegian Sea is also consistent with a reduced AMOC and northwards heat transport to the eastern Nordic Seas (Berner et al., 2011; Thornalley et al., 2013). These major hydrological changes of the surface and deep ocean circulation of the mid-Holocene took place at the time of the largest Holocene drift ice event and reduced solar irradiance, named Bond 4 event (Bond et al., 2001).

4.4. From 5300 to 2500 yr BP

Within this time interval, alkenone SSTs off North Iceland depict several marked cold events and an overall rise from 8 to 10°C while diatom SSTs do not show any clear trend and were less variable (Figure S2 and Fig 4c). This warming trend and superimposed cold episodes share resemblance with the NIIC flow reconstructed at MD99-2269, with speed minima being roughly co-eval with cold events at 4200, 3200 and 2700 yr BP (see Figure 2 in McCave and Andrews, 2019). This period is also characterized by large amplitude oscillations of the magnetite concentration (ARM) and magnetite grain-size (ARM/k) in the MD99-2275 core (Figure S4) that have been attributed to variations of the NIIC flow across the Denmark Strait (Rousse et al., 2006). SSTs in the MD95-2015 core rise again and depict larger amplitude centennial-scale oscillations till 4200 yr BP to then decrease towards the end of this interval marked by a cold spell nearly coincident with Bond event 2 (Figure 4a,c). This is paralleled by a reduction followed by an invigoration of the SPG as suggested by the density difference reflecting upper water stratification at RAPiD-12-1 core used as a proxy of SPG intensity (Figure 4b). SSTs off North Iceland show essentially opposite behavior leading to increasing ΔT between the two sites from 5300 to 4200 yr BP, and decreasing ΔT from 4200 to about 2500 yr BP (Figure 4c).

Contrary to East Reykjanes, SSTs at West Reykjanes LO-09-14 site show cooling over this interval with overlying fluctuations indicative of subpolar front excursions linked to drifting ice events (Figure 2d) (Andersen et al, 2004b). Note that surface waters at Greenland Rise (P-03) do not show freshening but instead a salinity increase towards 4200 yr BP (Figure 3b)(Solignac et al., 2004). Cold conditions would have been caused by local sea ice formation rather than Arctic influence as also shown by the drift-ice record of Bond 3 event (Jalali et al., 2019). Furthermore, incursions of warm IC water between 5200 and 4200 cal BP were reported at core site Fox05R/04G in the Denmark Strait (Andresen et al., 2012). While the EGC would be declining (McCave and Andrews, 2019), the LC flow reached its highest values around 3000 yr BP (Rashid et al., 2017) and might have been important in controlling SSTs in the southern subpolar North Atlantic. The importance of the LC in routing the cold and fresher Arctic originating waters into the SPG and eastern basin has been underlined by the recent study of Holliday et al. (2020).

4.5. From 2500 yr BP to Present Day

The last 2500 yrs period reveals the gradual establishment of a strong surface temperature contrast between the Nordic Seas and subpolar North Atlantic (Figure 4c). Surface ocean cooling at MD99-2275 and concomitant warming at MD99-2269 have led to the suggestion of a drastic reduction and subsequent limited eastward extent of the NIIC along the northern coast of Iceland (Ran et al., 2008; Jiang et al., 2015). Yet, SSTs in the two cores had already started to diverge around 5300 yr BP (Figure S2) (Justwan et al., 2008; Jiang et al., 2015). The presence of sea ice especially in the final stage of the LIA at MD99-2275 (Massé et al., 2008) contributed to steepened cooling in the region. As the Nordic Seas cooled, SSTs rose at the subpolar sites (MD95-2015, LO-09-14 and RAPiD-12-1) thereby generating a marked warm/cold dipole with a ΔT of about 4.5°C today (Figure 2a,d and 4c and Figure S5). Model simulations of the last millennium climate show a weakening of the SPG during the LIA as a result of surface freshening of the Labrador Sea and sea ice expansion which contributed to severe climate in western Europe (Moreno-Chamarro et al., 2017). However, these model results indicate no reduction of the AMOC and suggest a self-sustained weak SPG through the redistribution of salt and heat.

5. Conclusion

Our results highlight different Holocene hydrological developments in the western Nordic Seas and Iceland Basin and the role of the SPG in shaping centennial to millennial-scale variability across the North Atlantic. SST signals indicate synchronous Holocene thermal optimum in the western Nordic Seas and East of Reykjanes Ridge with a temperature difference between our two sites of only 1.5°C compared to 4.5°C today, reflecting the sustained influence of warm Atlantic waters. During this period of strong stratification caused by LIS and GIS melting, convection in the Labrador Sea was shut down and the SPG circulation turn-off despite an active AMOC and ISOW flow. With the demise of the LIS, convection in the Labrador Sea resumed and the SPG circulation established leading to a period of most intense AMOC between 8000 and 7000 yr BP sustained by convection both in the Nordic and

Labrador seas. Enhanced mixing and heat transport led to similar temperature between our two sites. The pronounced cooling at 5300 yr BP in both records is synchronous to the major drift ice known as Bond 4 event which would have caused the decay of the SPG, ISOW flow and AMOC, and the return of Neoglacial time in the Nordic Seas (Figure 4). Thereafter, the SPG alternated between weak and strong phases linked to the so-called quasi-periodic 1500 yr Bond cycles associated with shifts of the polar and subpolar fronts. Weak SPG phases occurred during major drift-ice events triggering stratified conditions. However, during prominent Bond events 4 and 2, surface cooling affected our two sites resulting in a reduced ΔT. In contrast, less prominent Bond events 3 and 1 led to increased ΔT reflecting warming of a weakened SPG due to limited spreading of cold and ice-bearing waters.

6. Data availability

The data presented are available on the NOAA database: (https://www.ncdc.noaa.gov/data-access).

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Figure captions

Figure 1. Map of annual mean SSTs (1955–2012) obtained from the World Ocean Atlas database (https://data.nodc.noaa.gov/las/getUI.do) in the North Atlantic. Locations of the cores discussed in the study are also indicated together with the major hydrological features. 2015: core MD95-2015 (Iceland Basin, this study); 2275: core MD99-2275 (NE Iceland, this study); 2269: core MD99-2269 (NW Iceland, Justwan et al., 2008); 9-14: core LO-09-14 (Reykjanes Ridge, Andersen et al., 2004b); P013: core P-013 (Greenland Rise, Solignac et al., 2004); 2251 and 76Cq: cores MD99-2251 and MD03-2676Cq, respectively (Gardar Drift, Hoogakker et al., 2011; Kissel et al., 2013); 980: core ODP 980 (Feni Drift, Oppo et al., 2003); 12-1k: core RADiP-12-1K (South Iceland rise, Thornalley et al., 2009); 2011: core MD95-2011 (Vøring Plateau, off Norway, Berner et al., 2011). STG: Subtropical Gyre; SPG: Subpolar Gyre; NAC: North Atlantic Current; IC: Irminger Current; NIIC: North Icelandic Irminger Current; EIC: East Icelandic Current; EGC: East Greenland Current; LC: Labrador Current; PF: Polar Front; SPF: Subpolar Front.

Figure 2. (a) Alkenone SST values from the MD95-2015 site (green curve), (b) and MD99-2275 site (blue curve) obtained using the calibration of Prahl et al. (1988). Thick lines in (a) and (b) represent 5 points adjacent-average smoothing. Green and blue bars next to the Y axis of (a) and (b) represent the range of modern summer SSTs at the two core sites. Diatom-based SST values from (c) the MD99-2269 site (Justwan et al., 2008) and (d) the LO-014-9 site (Andersen et al., 2004b; Berner et al., 2008).

Figure 3. (a) Alkenone-SST reconstruction at the MD95-2015 site (thick green line represents 5 points adjacent-average smoothing., this study). (b) Subsurface salinity reconstruction based on combined Mg/Ca and δ^{18}O in *Globorotalia inflata* in the RADiP-12-1K core (dark blue, from Thornalley et al., 2009) and sea surface salinity from the P-013 core Greenland Rise, Labrador Sea (orange curve) (from Solignac et al., 2004). The thick colored lines in (b) represent 3 points adjacent-average smoothing. The vertical bar highlights the period of SPG activation (8200-7000 yr BP).

Figure 4. (a) Stacked record of the percent hematite stained grains (red curve) and number of each Bond event from Bond et al. (2001). (b) Density difference between surface and subsurface waters obtained from paired Mg/Ca and δ^{18}O in *Globigerina bulloides* and *Globorotalia inflata* in core RAPiD-12-1K (Thornalley et al., 2009; Thick line represents 3 points adjacent-average smoothing). Blue and red arrows indicate decreasing and increasing of the SPG circulation, respectively. (c) Alkenone-based SST reconstruction at the MD95-2015 site, East Reykjanes Ridge (green curve) and MD99-2275 site off North Iceland (blue curve). Yellow and magenta arrows on the two curves indicate the trends calculated for selected time-intervals discussed in the text. Blue and green bars next to the Y axis represent the range of modern summer SSTs at the two core sites. The vertical bar highlights the 5.3 event.

Figure S1. Monthly sea surface temperature of MD95-2015 (green) and MD99-2275 (blue) core sites obtained from World Ocean Atlas database calculated between 1955 and 2012 (https://data.nodc.noaa.gov/las/getUI.do).

Figure S2. SST reconstruction of MD99-2275 based on alkenones (blue curve, this study; thick line represents 5 points adjacent-average smoothing) and diatom assemblages (orange curve) from Jiang et al. (2015). Diatom-based SST record from MD99-2269 site (purple curve) from Justwan et al. (2008) is also shown.

Figure S3. (a) Detrended low field susceptibility (K) measured in the MD03-2676Cq core (from Kissel et al., 2013), (b) Mean grain size of the sortable silt fraction (10-63 µm) measured in the MD99-2251 core (from Hoogakker et al., 2011; Kissel et al., 2013) and (c) Alkenone-derived SSTs of the MD95-2015 core (green curve, this study; thick line represents 5 points adjacent-average smoothing) all located in Southern Gardar.

Figure S4. Magnetic parameters and SSTs determined in core MD99-2275, off North Iceland. (a) Increase grain size ($\mathrm{ARM/k}$) and (b) decrease magnetic content (ARM) of the sediments are both indicative of strong circulation (from Rousse et al. 2006). (c) Alkenone-based SST reconstruction at MD99-2275 (this study; thick line represents 5 points adjacent-average smoothing). Vertical bars indicate periods of enhanced variability discussed in the text.

Figure S5. Temperature reconstructions obtained from the Mg/Ca ratio values measured in the calcite of the surface dwelling foraminifera *Globigerina bulloides* (light blue) and subsurface dwelling foraminifera *Globorotalia inflata* (dark blue) in the RADiP-12-1K core (from Thornalley et al., 2009). Alkenone-SSTs from the MD95-2015 core (green curve, this study; thick line represents 5 points adjacent-average smoothing). The vertical bar highlights the transition period of intense circulation (8500-7000 yr BP).

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