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

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**Key points:** Holocene, Sea Surface Temperature, subpolar gyre, North Atlantic

## 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 ( $10 \pm 1^\circ\text{C}$ ) and  $3^\circ\text{C}$  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  $11.5^\circ\text{C}$  ( $\pm 0.5^\circ\text{C}$ ) 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  $\sim 5300$  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  $4.5^\circ\text{C}$ . 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.

**Key words:** 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

55 of denser waters at depth by enhancing stratification would have limited convection and weakened  
56 the SPG. These results are consistent with time-series observations at 25°N (Bryden et al., 2005) but  
57 differ from the in-phase variation of AMOC and SPG (Böning et al., 2006). Finally, Chen and Tung (2018)  
58 recently showed that besides freshwater forcing, imbalance radiative forcing due to greenhouse gases  
59 would have contributed to the recent surface warming due to lower heat storage in the deep-ocean  
60 under a weak AMOC, highlighting the gaps in our understanding of the AMOC response to external  
61 forcing.

62 The East Greenland Current (EGC) flowing southwards along the East Greenland coast from Fram Strait  
63 and the Labrador Current (LC) exiting Arctic waters via the Canadian Archipelago are major conveyors  
64 of cold and freshwaters to the North Atlantic impacting on convective activity in the North Atlantic and  
65 subsequently on the AMOC (Figure 1) (Dickson et al., 1996). In the recent history, episodes of  
66 freshwater accumulation in the North Atlantic, known as the Great Salinity Anomalies (GSAs), have led  
67 to a significant reduction of convective mixing. While the GSA in the 60-70s was triggered by enhanced  
68 export of sea ice and melt water from the Arctic Ocean through Fram Strait, the GSA in the 1980s was  
69 likely caused by increase local sea ice formation due to severe winters in Baffin Bay (Belkin et al., 1998).  
70 These GSAs did not seem to have altered the AMOC (Böning et al., 2016), but convection shutdown of  
71 the Labrador Sea subsequent to the GSA in the 70s has been demonstrated (Gelderloos et al., 2012).  
72 Several centuries ago, during the LIA (1450-1850 yr AD) large surface temperature and salinity changes  
73 (Sicre et al., 2008; Moffa-Sánchez et al., 2014) associated with the expansion of sea ice (Massé et al.,  
74 2008) as far as the Faroe Islands have been documented (Denton and Broecker, 2008). This period of  
75 anomalous cold and icy surface waters would have been responsible for the severe climatic conditions  
76 in Western Europe (Denton and Broecker, 2008). Yet, according to Moreno-Chamarro et al. (2017) the  
77 cold LIA climate would not be linked to a reduction of AMOC or persistent negative NAO but rather  
78 explained by a leading role of a weak SPG.

79 The Holocene epoch provides an interesting time frame for investigating the impact of ice melt water  
80 on the North Atlantic Ocean circulation under different climate and forcing conditions. Indeed, at the  
81 time of high northern hemisphere summer insolation of the early Holocene, the subpolar North  
82 Atlantic experienced major surface temperature and salinity changes resulting from final melting of  
83 the Laurentide Ice Sheet (LIS) and Greenland Ice Sheet (GIS) (Thornalley et al., 2009; Solignac et al.,  
84 2004, 2006; Larsen et al., 2014; Ullman et al., 2016). Large freshwater release and sustained high  
85 buoyancy fluxes would have suppressed convection in the Labrador Sea (Hillaire-Marcel et al., 2001).  
86 It is not until 8000-7000 yrs ago that convection and SPG circulation would have re-established  
87 (Hillaire-Marcel et al., 2001). While early Holocene studies focused on the 8.2 ka event (Barber et al.,  
88 1999; Ellison et al., 2006), few have investigated the spatial and temporal evolution of the SPG  
89 circulation with decreasing boreal summer insolation (Thornalley et al., 2009; 2013; Moffa-Sanchez et  
90 al., 2014; Jalali et al., 2019), and even less have explored its links with the AMOC (Moreno-Chamarro  
91 et al., 2017; Thornalley et al., 2018).

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

102

## 103 **2. Material and methods**

### 104 *2.1. Oceanographic setting and core locations*

105 The two study cores were retrieved using the Calypso corer during two cruises of the international  
106 IMAGES program aboard the French research vessel *Marion Dufresne* from two key areas of the North  
107 Atlantic. One is located in the western Nordic Seas off North Iceland (IMAGES V cruise, MD99-2275:  
108 66°33.10N, 17°41.99W, 470 m water depth), the other in the Iceland Basin on the eastern flank of

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

## 119 2.2. Age models

120 Both cores were continuously sub-sampled at a 1 cm step. The age model of the MD99-2275 core is  
121 based on 15 tephra layers (Table DR4 in Jiang et al., 2015) and the Bayesian calibration software  
122 Oxcal4.2. The tephra-based age model was constructed to circumvent marine reservoir age  
123 problems. The uncertainties of the MD99-2275 age model has been estimated to be on the order of  
124 10-20 years (Jiang et al., 2015). Because of the exceptional high sedimentation rate at this site (on  
125 average 250 cm/1000 yrs during the last 10000 yrs), the SST record achieves a mean temporal  
126 resolution of 4-5 yrs. For the MD95-2015 core, the age model is constructed with 21 AMS radiocarbon  
127 dates measured in the planktonic foraminifera on *Globigerina bulloides* converted to calendar ages  
128 using Oxcal4.3 (Ramsey, 2017) and the MARINE13 calibration data set (Reimer et al., 2013) using a  $\Delta R$   
129 = 73±69 yrs (Jalali et al., 2019). The MD95-2015 age model uncertainty is on the order of 100 yrs. The  
130 lower accumulation rate at this deeper site (on average 50 cm/1000 yrs) yields a mean temporal  
131 resolution of 20 yrs.

## 132 2.3. Alkenone derived Sea Surface Temperature

133 SSTs were estimated from the concentrations of the C<sub>37</sub> alkenones. For both cores, lipids were  
134 extracted from freeze-dried sediments using a mixture of methylene chloride and methanol (2:1, v/v).  
135 Alkenones were isolated from the total lipid mixture by silicagel chromatography using the protocol  
136 adapted from Ternois et al. (1997). The fraction containing alkenones was analyzed by gas  
137 chromatography (GC) on an Agilent 6890 gas chromatograph equipped with an on-column injector.  
138 The GC oven was heated from 50°C to 300°C at a rate of 20°C/min and maintained at final temperature  
139 for 40 minutes. GC analyses were performed using a CP-Sil-5CB fused silica capillary column (50 m x  
140 0.32 mm i.d., 0.25 µm film thickness, Chrompack) and helium as a carrier gas (25 ml min<sup>-1</sup>). Individual  
141 compounds were detected with a flame ionization detector (FID). U<sup>K37</sup> index values were calculated  
142 from C<sub>37:2</sub> and C<sub>37:3</sub> using the following expression (C<sub>37:2</sub>)/(C<sub>37:2</sub> + C<sub>37:3</sub>). They were then converted into  
143 SSTs by applying the widely used calibration of Prahl et al. (1988),  $T = (U^{K37} - 0.039)/0.034$ . The internal  
144 analytical precision calculated from duplicate injections is estimated to 0.01 U<sup>K37</sup> ratio unit which  
145 converts to ±0.35°C (Sicre et al., 2011). The C<sub>37:4</sub> alkenone was not detected in the MD95-2015 and  
146 found in trace amounts in the upper part of the MD99-2275 core corresponding to coldest  
147 temperatures of the records, as expected from the location of the two cores on the path of the warm  
148 waters of the NAC.

149 Alkenones are primarily produced by the autotrophic coccolithophorid *Emiliana huxleyi*. In high-  
150 latitude regions, the main production season for phytoplankton is summer, when light and nutrient  
151 availability are favorable for photosynthesis (Sicre et al., 2002). In an earlier study, Sicre et al. (2011)  
152 demonstrated that in the MD99-2275 core the best correlation between the U<sup>K37</sup> index and gridded  
153 Hadley Center SST values was obtained for July temperatures (6-8°C) (Figure S1). Systematic warm  
154 offset of alkenone-SSTs during cold and icy years reflecting delayed coccolithophorid blooming due to  
155 sea ice melting (see Figure 3 in Sicre et al., 2011) was also observed and further corroborated in the  
156 Labrador Sea (Sicre et al., 2014). The remarkable agreement between U<sup>K37</sup> - SSTs and instrumental data  
157 over the 20<sup>th</sup> century is not unexpected given that our shelf site off North Iceland is located on the  
158 path of the NIIC, where warm biases often found in the Nordic Seas are not observed (Bendle and  
159 Rosell-Melé, 2004). At MD95-2015, South of Iceland, direct comparison between proxy and  
160 instrumental data was not possible because the last 500 years of Holocene of the core are missing.  
161 Nevertheless, the uppermost core SST values (11-12°C) are also close to July-August surface  
162 temperatures measured at the core site (Figure S1) between 1955 and 2012, with summer values  
163 comprised between 11 and 12°C, i.e. 4 to 5°C warmer than off North Iceland (Figure S1). The earlier  
164 study of Giraudeau et al (2000) demonstrated that the coccolith record at this site primarily reflects

165 the production and export from the upper ocean, precluding any dynamical processes induced by  
166 bottom flow.

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169

### 3. Results

170 The Holocene SST records at MD99-2275 and MD95-2015 show strong multi-decadal to millennial-  
171 scale variations superimposed on long-term trends that are different at the two sites (Figure 2a,b). Off  
172 North Iceland (MD99-2275), early Holocene SSTs vary strongly around a mean of 10°C ( $\pm 1^\circ\text{C}$ ) that  
173 exceeds modern values by 3°C. These fluctuations attenuate between 7000 and 5300 yr BP and amplify  
174 again after a stepwise decrease of 1.5°C around 5300 yr BP. The following 5300-2500 yr BP interval is  
175 characterized by 50 to 150 yr period SST oscillations superimposed on a broad increase from 8 to 10°C  
176 (Sicre et al., 2008). Over the last 2500 yrs, surface waters show a sharp cooling (from 10 to 7°C), which  
177 comprises a distinct three-century long warmer interval (1000 - 700 yr BP) known as the Medieval  
178 Climatic Anomaly (MCA). SSTs exhibit different features at the eastern Reykjanes Ridge site MD95-  
179 2015. The early Holocene part of the record indicates 1.5°C warmer values than off North Iceland with  
180 oscillations of lower magnitude ( $11.5 \pm 0.5^\circ\text{C}$ ). A remarkable difference between the two sites is the  
181 3.5°C cooling between 7000 and 5300 yr BP recorded at the MD95-2015 core (from 11.5 to 8°C) while  
182 only of 1.5°C off North Iceland (Figure 2a,b). Thereafter, both records show opposite sign evolution  
183 with a temperature contrast between the two sites building-up over the last 2500 yrs to reach a value  
184 today of 4.5°C.

### 185 4. Discussion

#### 186 4.1. Early Holocene till 8500 yr BP

187 High and unstable SSTs during the early Holocene off North Iceland suggest a generally strong inflow  
188 of warm NIIC with centennial-scale incursions of Polar Waters (Figure 2b). The range of variation of  
189 alkenone SSTs (7 - 13°C) is larger than that obtained in the same core from diatom assemblages (8 -  
190 9°C), a result that essentially reflects higher alkenone maxima (13°C for alkenones vs 9°C for diatoms)  
191 (Jiang et al., 2015) (Figure S2). These warm extremes likely reflect time intervals of intensified NICC  
192 along the northern Icelandic coast as suggested by the coincidence of alkenone and diatom SST  
193 maxima. However, melt water transported by the EGC can cause a shift of coccolithophorid blooms  
194 towards warmer months (Sicre et al., 2011). Furthermore, under stratified conditions induced by  
195 freshwater, the near surface layer can rapidly warm, both effects conspiring towards warmer  
196 alkenones than diatom assemblage based SSTs (Andrews et al., 2021). Similar strong variability of early  
197 Holocene SSTs has been observed in the Denmark Strait region and attributed as well to varying  
198 contribution of warm and salty Atlantic waters and cold and fresher Polar Waters of the EGC (Andersen  
199 et al., 2004a; Justwan et al., 2008; Jennings et al., 2011). Likewise, at the even more distant site P-013  
200 South of Greenland (Figure 1) dinoflagellate assemblages also revealed pronounced seasonal contrast  
201 and stratified conditions reflecting occurrences of ice and melt water from the GIS and the Arctic  
202 Ocean, further supporting our findings (Solignac et al., 2004).

203 Melting of the GIS and LIS reduced deep-water formation in the Labrador Sea thereby altering the SPG  
204 circulation and most probably the AMOC (Hillaire-Marcel et al., 2001). In order, to capture the SPG  
205 dynamical changes, Thornalley et al. (2009) generated surface and subsurface temperature and salinity  
206 records from paired  $\delta^{18}\text{O}$  - Mg/Ca data measured in *Globigerina bulloides*, living in the surface mixed  
207 layer, and the thermocline dwelling *Globorotalia inflata* from the RAPiD-12-1K core located on the  
208 path of the NAC in the eastern subpolar Atlantic (Figure 1). The difference between the two  
209 foraminifera temperature and salinity values was then used to calculate a density difference  
210 interpreted as a proxy of upper ocean stratification and related to the intensity of the SPG (Thornalley  
211 et al., 2009). These records indicate stratified conditions until approximately 8500 yr BP reflecting the  
212 absence of winter convection in the Labrador Sea (see Figure 2 in Thornalley et al., 2009). The co-eval  
213 strong salinity contrast between the freshened Labrador Sea at P-013 (Solignac et al., 2004) and salty  
214 subsurface waters at RAPiD-12-1K (Figure 3b) is also in accordance with the shutdown of the SPG  
215 (Thornalley et al., 2009). Early Holocene warm alkenone SSTs at MD95-2015 evidence the dominant  
216 influence of the NAC at the eastern flank of Reykjanes Ridge despite the cold melt water outflow from  
217 the Labrador region, although SST cooled around 9300 and 8200 yr BP. This is confirmed by warm SSTs  
218 derived from Mg/Ca of *G. bulloides* in the RAPiD-12-1K core showing slightly colder values likely  
219 reflecting different season and depth habitat of *G. bulloides* and alkenone producers. At the western

220 flank of Reykjanes Ridge, colder but rising SSTs in LO-09-14 core till 8200 yr BP indicate a weaker but  
221 increasing influence of the NAC and a strong imprint of Polar Waters (Figure 1 and 2d) (Andersen et  
222 al., 2004b; Berner et al., 2008). The presence of diatom *Thalassiosira gravida* indicates cold waters  
223 originated from the Davis Strait outflow, possibly explaining the late thermal optimum at this site  
224 (Andersen et al., 2004b). Based on sortable silt data, McCave and Andrews (2019) inferred that the NAC  
225 feeding the EGC at Fram Strait would have contributed to maintain a strong flow of Polar Waters along  
226 East Greenland thereby freshening the Labrador Sea. This is in contrast with the dominant influence  
227 of warm NAC waters in the eastern subpolar basin and North of Iceland nourished by a vigorous NIIC  
228 resulting in a temperature difference between our two sites of only 1.5°C. High Iceland-Scotland  
229 Overflow Water (ISOW) estimated from cores along Gardar Drift indicates active convection in the  
230 Nordic Seas while turned off in the Labrador Sea (Figure S3a,b) (Hoogakker et al., 2011; McCave and  
231 Andrews, 2019). These results suggest an active AMOC despite the shutdown of the SPG and  
232 convection in the Labrador Sea caused by large freshwater inputs advected by the EGC.

#### 233 4.2. From 8200 to 7000 yr PB

234 With the demise of the LIS, salinity in the Labrador Sea gradually increased providing conditions for  
235 convection to resume (Hillaire-Marcel et al., 2001; Solignac et al., 2004). Active NAC circulation could  
236 have contributed to the salinity increase in the Labrador Sea through the EGC (McCave and Andrews,  
237 2019) as well as the ISOW (Hall et al., 2004). After the steep freshening of subsurface waters in the  
238 RAPiD-12-1K core and surface waters in the P-013 core between 8500 and 8200 yr BP (Figure 3b),  
239 convection in the Labrador Sea and SPG circulation re-activated (Hillaire-Marcel et al., 2001; Thornalley  
240 et al., 2009). Indeed, salinity in the Labrador Sea and Iceland basin converge to a value of 34 reflecting  
241 intense mixing across the subpolar North Atlantic (Figure 3b). SSTs at MD95-2015 decrease slightly to  
242 come close to those found over the North Icelandic shelf (around 10°C; Figure 4c and Figure S5).  
243 Meanwhile, SSTs at LO-09-14 (Western Reykjanes Ridge) increase by about 1.5°C testifying active  
244 mixing with warm NAC waters and the retreat of the subpolar front. A vigorous ISOW flow reported in  
245 several studies (Bianchi and McCave, 1999; Hoogakker et al., 2011; Thornalley et al., 2013; Kissel et al.,  
246 2013; McCave and Andrews, 2019) (Figure S3a,b) and the occurrence of a thermal optimum along the  
247 Norwegian coast between 8900 and 7300 yr BP (Berner et al., 2011) add further support to intense  
248 northwards heat transport by a strong AMOC and SPG sustained by active convection both in the  
249 Nordic and Labrador seas.

#### 250 4.3. From 7000 to 5300 yr BP

251 Around 7000 yr BP, surface waters at MD95-2015 begin a long-term cooling till the coldest value of  
252 the record (8°C) at ~5300 yr BP. This period coincides with the progressive invasion of drifting ice from  
253 Iceland across the subpolar North Atlantic as evidenced by the stacked record of % hematite grains in  
254 North Atlantic sediments of Bond et al. (2001) (Figure 4a,c). The concurrent decline of the ISOW flow  
255 along Gardar Drift (Figure S3) and the large decrease of the  $\delta^{13}\text{C}$  of benthic foraminifera *Cibicidoides*  
256 *wuellerstorfi* at Feni Drift highlight a link between drifting ice, surface ocean cooling and deep-water  
257 circulation slowdown (Oppo et al., 2003). Widespread freshening caused by drifting ice is also indicated  
258 by the concomitant decrease of surface salinity in the Labrador Sea core P-013 (Figure 3b) and RAPiD-  
259 12-1K core. However, stable subsurface salinity at the later site suggests a strong upper ocean  
260 stratification and weakening of the SPG (Figure 4). On the contrary, surface warming at LO-09-14 (from  
261 11 to 13°C) indicates limited advection of melt water to western Reykjanes and a lesser influence from  
262 the Canadian Archipelago as suggested by the absence of *Thalassiosira gravida* (Andersen et al.,  
263 2004b) (Figure 2d). Off North Iceland, SSTs slightly warmed before the stepwise cooling at 5300 yr BP  
264 also inferred from the abrupt increase of sea-ice diatom and the occurrence of the Arctic diatom  
265 species *Thalassiosira nitzschioides* in the MD99-2275 core, pointing towards Neoglacial conditions in  
266 the western Nordic Seas (Ran et al., 2008). Sortable silt at the nearby core MD99-2269 indicates a  
267 consistent sharp decline of the NIIC flow (see Figure 2 in McCave and Andrews, 2019). Increasing  
268 salinity difference between the Labrador Sea and the Iceland Basin since 7000 yr BP underpins the  
269 progressive weakening of the SPG, although the salinity contrast at 5300 yr BP did not reach that of  
270 the Early Holocene (Solignac et al., 2004; Thornalley et al., 2009) (Figure 3b). The SST decrease in the  
271 Norwegian Sea is also consistent with a reduced AMOC and northwards heat transport to the eastern  
272 Nordic Seas (Berner et al., 2011; Thornalley et al., 2013). These major hydrological changes of the  
273 surface and deep ocean circulation of the mid-Holocene took place at the time of the largest Holocene  
274 drift ice event and reduced solar irradiance, named Bond 4 event (Bond et al., 2001).

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#### 4.4. From 5300 to 2500 yr BP

277 Within this time interval, alkenone SSTs off North Iceland depict several marked cold events and an  
278 overall rise from 8 to 10°C while diatom SSTs do not show any clear trend and were less variable (Figure  
279 S2 and Fig 4c). This warming trend and superimposed cold episodes share resemblance with the NIIC  
280 flow reconstructed at MD99-2269, with speed minima being roughly co-eval with cold events at 4200,  
281 3200 and 2700 yr BP (see Figure 2 in McCave and Andrews, 2019). This period is also characterized by  
282 large amplitude oscillations of the magnetite concentration (ARM) and magnetite grain-size (ARM/k)  
283 in the MD99-2275 core (Figure S4) that have been attributed to variations of the NIIC flow across the  
284 Denmark Strait (Rousse et al., 2006). SSTs in the MD95-2015 core rise again and depict larger  
285 amplitude centennial-scale oscillations till 4200 yr BP to then decrease towards the end of this interval  
286 marked by a cold spell nearly coincident with Bond event 2 (Figure 4a,c). This is paralleled by a  
287 reduction followed by an invigoration of the SPG as suggested by the density difference reflecting  
288 upper water stratification at RAPiD-12-1 core used as a proxy of SPG intensity (Figure 4b). SSTs off  
289 North Iceland show essentially opposite behavior leading to increasing  $\Delta T$  between the two sites from  
290 5300 to 4200 yr BP, and decreasing  $\Delta T$  from 4200 to about 2500 yr BP (Figure 4c).

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

#### 303 4.5. From 2500 yr BP to Present Day

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

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### 319 5. Conclusion

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

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

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## 339 **6. Data availability**

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

341

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347 R/V *Marion Dufresne* in the framework of the International Marine Past Global Change Study (IMAGES)  
348 program. The authors thank the crew and scientists of the R/V *Marion Dufresne* involved in the coring  
349 operations.

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## Figure captions

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**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 Prah 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  $\delta^{18}\text{O}$  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  $\delta^{18}\text{O}$  in *Globigerina bulloides* and *Globorotalia inflata* in core RADiP-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.

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

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

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

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

409 **Figure S5.** Temperature reconstructions obtained from the Mg/Ca ratio values measured in the calcite  
410 of the surface dwelling foraminifera *Globigerina bulloides* (light blue) and subsurface dwelling  
411 foraminifera *Globorotalia inflata* (dark blue) in the RADiP-12-1K core (from Thornalley et al., 2009).  
412 Alkenone-SSTs from the MD95-2015 core (green curve, this study; thick line represents 5 points  
413 adjacent-average smoothing). The vertical bar highlights the transition period of intense circulation  
414 (8500-7000 yr BP).

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