

Changes in surface conditions east of the Reykjanes Ridge (North Atlantic) during the Late Pleistocene to Holocene cold events

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Abstract. The article presents data on the study of the AI-3359 marine sediment core recovered from the North Atlantic (east of the Reykjanes Ridge) during the Late Pleistocene to Holocene (the last 45,000 years). The data on ice-rafted debris (IRD) and *N. pachyderma* (s) distribution together with changes in the relative abundance of CaCO_3 enable assigning several cooling events during the investigated period. In the period of Late Pleistocene we found 4 cold events, which correspond to Heinrich events. However, ages of these cold events are slightly different from well-known ages of the Heinrich events. Six Holocene events in the study area centred at 10,800, 10,100, 6020, 2200, and 1200 years BP are the most pronounced cooling events with relatively intensive ice rafting in the study area. Cooling of the subsurface layer without intensive ice rafting is observed at 9300, 8300 and 4100 years BP. In the period of the

Little Ice Age, which is marked by cooling between 200 and 500 years BP, a late response of the subsurface layer on cooling on the surface is registered. During some warm intervals (800–1200 years BP, 3200–3900 years BP, 5300–5900 years BP, and 9600–10,000 years BP), ice rafting still occurred in the study area. Increase in the number of foraminiferal shells, calcium carbonate, and IRD during the last 230 years BP indicates a shift of the Arctic Front to the south resulting in intensive ice rafting.

Introduction

It is known that reconstruction of climate and oceanographic conditions is of great importance for our understanding and modelling of mechanisms of the current and future climate changes. Three different Atlantic Meridional Overturning Circulation (AMOC) states prevailed during interglacials, glacials, and short-term cold events, or stadials [e.g., *Rahmstorf*, 2002]. During interglacials, the circulation of deep water masses was in general similar to the modern state. Intensive advection of the warm Atlantic surface waters into the high latitudes occurred. This led to the active deep con-

vection with the North Atlantic Deep Water (NADW) formation in the Nordic Seas and stabilization of the AMOC system [*Rahmstorf*, 2006; *Wright and Flower*, 2002]. Glacial periods were characterized by suppressed NADW formation and migration of the North Atlantic Current (NAC) to the south. During this time, ice sheets were widespread in the Northern Hemisphere, and cold and freshened polar waters, as well as floating icebergs and sea ice, penetrated into the North Atlantic [e.g., *Barash*, 1988; *Eynaud et al.*, 2009; *Oppo and Lehman*, 1993; *Wright and Flower*, 2002].

Glaciers and ice sheets play an active role in the climate system and the global hydrological cycle. Overall iceberg fluxes increase in cold periods, peaking within a few centuries of climatic cooling [*Marshall and Koutnik*, 2006]. During the Late Pleistocene and Holocene short-term cold events, weakening of the AMOC occurred because of the influx of relatively cold and freshened polar water into the North Atlantic due to icebergs and sea ice melting [e.g., *Denton and Broecker*, 2008; *Eynaud et al.*, 2009; *Heinrich*, 1988; *Hemming*, 2004; *Matul*, 1994; *Wanner et al.*, 2011]. This caused instability of the AMOC system [*Vidal et al.*, 1997].

There are a lot of studies about origin and alternation mechanism of the Late Pleistocene and Holocene

short-term cold events [*Bond and Lotti*, 1995; *Bond et al.*, 1997, 2001; *Risebrobakken et al.*, 2011]. The Late Pleistocene cold events, or so-called Heinrich events, were discussed in many papers [*Bond et al.*, 1992, 1999; *Heinrich*, 1988; *Hemming*, 2004; *MacAyeal*, 1993; *Sarnthein et al.*, 2001]. However, some studies still raise a question about their origin [e.g., *Andrews and Voelker*, 2018; *MacAyeal*, 1993]. It is well-known that Holocene climatic conditions were also unstable (an alternation of warm and cold intervals). Study of cold Holocene intervals, or Bond events [e.g., *Bond et al.*, 1997], have shown that there is still no uniform theory describing their origin, and the mechanisms of their change [e.g., *Wang et al.*, 2013; *Wanner et al.*, 2011, 2014]. Bond events are defined as “a series of shifts in ocean surface hydrography during which drift ice and cooler surface waters in the Nordic and Labrador Seas were repeatedly advected southward and eastward, each time penetrating deep into the warmer strands of the subpolar circulation” [*Bond et al.*, 1997, 2001]. It is believed that meltwater flux into the North Atlantic, low solar activity, explosive volcanic eruptions, and fluctuations of the thermohaline circulation are closely interlinked with Bond events [*Wanner et al.*, 2011].

The aim of the present work is to trace changes

in the hydrological conditions of the sea surface to the east of the Reykjanes Ridge during the short-term cold events of the Late Pleistocene and Holocene. For this purpose, two paleohydrological proxies, ice-rafted debris (IRD) and relative abundance of the polar foraminifera *Neogloboquadrina pachyderma* (sinistral coiling) (Ehrenberg) in the AI-3359 marine sediment core were chosen. *N. pachyderma* (s) is a good indicator of the cold subsurface (70–130 m) waters [e.g. *Barash et al.*, 2002; *Kohfeld et al.*, 1996; *Simstich et al.*, 2003]. Data on IRD distribution could give information about the presence of seasonal sea ice and icebergs, their discharges and influx of the meltwater into the study area. Abrupt increase in IRD in the marine sediments indicates the short-term cold events within well-known ages [*Bond et al.*, 1992, 1999; *Heinrich*, 1988; *Hemming*, 2004; *MacAyeal*, 1993].

Study Area

Today, the sea surface hydrological conditions in the study area are controlled by the NAC. This surface current is one of the main elements of the AMOC which transfers relatively warm and saline water to the high

latitudes (Figure 1). While circulating to the northeast, NAC splits into several branches. One circulates along the Reykjanes Ridge to form the Irminger Current (IC). South of the Denmark Strait, a small branch of the IC separates to circulate along the west coast of Iceland. The remainder of the IC merges with the East Greenland Current (EGC) [*Bersch et al.*, 1999; *Brambilla et al.*, 2008; *Haine et al.*, 2008]. Another branch follows to the northeast along the coast of Norway and further north to the Arctic Oceans. In the Nordic Seas, this water cools down and sinks to a depth forming the NADW [*Broecker*, 1991; *Ganopolski and Rahmstorf*, 2001; *Rahmstorf*, 2006; *Sarafanov et al.*, 2012; *Wright and Flower*, 2002]. Today in the North Atlantic, the summer sea ice edge is located north of the studied core site, close to the Polar Front. The winter sea ice edge is located slightly west of the Arctic Front [*Alonso-Garcia et al.*, 2011].

From Holocene to modern, deposition in the study area was controlled mainly by two processes: current sorting and pelagic sedimentation. The sediments are carbonate-rich with the admixture of terrigenous material. Near-bottom contour current of the Iceland-Scotland Overflow Water (ISOW), which is the one of the main components of the NADW, reworks sedi-

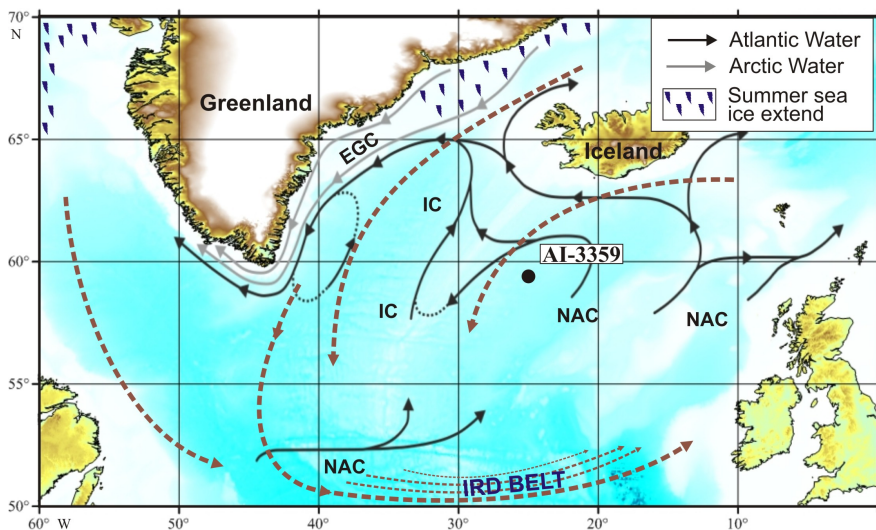


Figure 1. Studied core location and general circulation scheme in the study area: NAC – North Atlantic Current, IC – Irminger Current, EGC – East Greenland Current (after [Sarafanov *et al.*, 2012]). Brown arrows indicate inferred routes of icebergs during the last glacial (after [Peck *et al.*, 2006; Ruddiman, 1977]). Summer sea ice edge is marked by triangles (after [Alonso-Garcia *et al.*, 2011]).

ments and transports silt-size terrigenous material, as well as coccoliths and foraminiferal fragments to the study area [e.g., McCave *et al.*, 1995, 2017; Sivkov *et al.*, 2015]. Contour currents form sedimentary drifts which are good objects for detailed paleoceanographic reconstructions. The sedimentation rates on the drifts are increased and could be much more than 9 cm/ka

[e.g., *Kidd and Hill*, 1987]; whereas regional rates usually do not exceed 0.2–4 cm/ka [*Barash*, 1988; *Lisitzin*, 1978]. Foraminiferal shells which are sand-sized are deposited here mainly as a result of pelagic sedimentation.

The main source of sand-size terrigenous material is the ice rafting from the melting sea ice and icebergs [e.g. *Barash*, 1988]. Between 60° and 40°N locates a so-called IRD belt, which is the area of the highest concentration of lithic grains in the bottom sediments [*MacAyeal*, 1993; *Ruddiman*, 1977]. The accumulation and stability of the ice sheets during the last glacial period (reaching the critical mass during the cold intervals, active ice sheets melting during the warm intervals, ice shelves degradation, dynamics in sea level, etc.) influenced the iceberg discharges in the North Atlantic. These icebergs drifted to the south and discharged while melting, leading to IRD deposition.

Material and Methods

In the present study, the AI-3359 marine sediment core (59°29.885' N, 24°42.105'W, 2517 mbsl, 4.86 mbsf) recovered from the North Atlantic (east of the Reykjanes Ridge) during the 49th cruise of R/V *Akademik Ioffe* (2015) is investigated (Figure 1) [*Klyuvitkin et al.*,

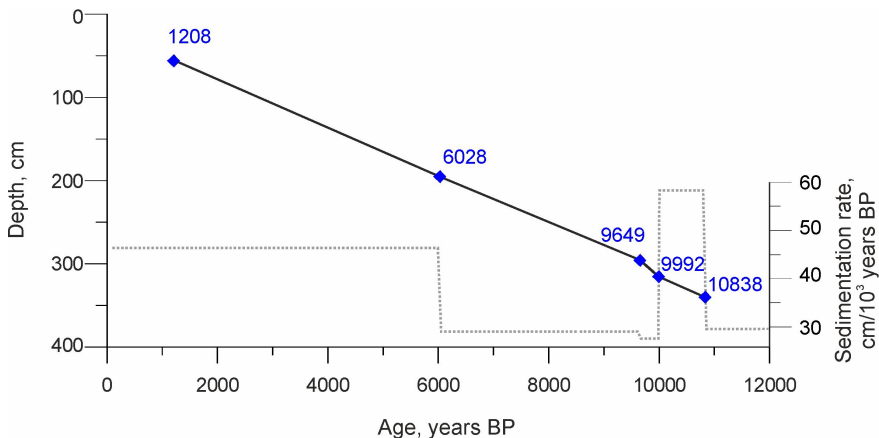


Figure 2. Age vs. depth profile of the AI-3359 core (upper part) based on AMS ^{14}C dates.

2016]. Lithological description of the core was carried out onboard.

The age model of the upper part of the core section (0–341 cm) is based on accelerator mass spectrometry (AMS) radiocarbon (^{14}C) dates. A total of 5 dates were obtained from planktonic foraminiferal shells of *Globigerina bulloides* (d'Orbigny) at the Poznan Radiocarbon Laboratory (Poznan, Poland). The standard radiocarbon age was calibrated using a Calib7.1 software [Stuiver and Reimer, 1993] (“Marine 13.14c” calibration curve, $\Delta R = 80 \pm 91$). The calendar age is presented as an average value within the $\pm 1\sigma$ confidence interval (Table 1, Figure 2).

Table 1. AMS Radiocarbon (^{14}C) Dates From the Studied AI-3359 core. BP = AD 1950

#	Depth, cm	Lab. Code	Dated material	^{14}C age, yr BP	Calibrated age BP (1σ ; $\Delta R = 80 \pm 91$)
1	55–56	Poz-95700	G. bulloides	1750 ± 90	1208
2	195–196	Poz-95695	G. bulloides	5700 ± 50	6028
3	295–296	Poz-95696	G. bulloides	9050 ± 50	9649
4	315–316	Poz-95698	G. bulloides	9270 ± 50	9992
5	340–341	Poz-95699	G. bulloides	9960 ± 80	10,838

The IRD counts, sand content, as well as changes in relative abundance of CaCO_3 and *N. pachyderma* (s) in the sediments were used for stratigraphic subdivision and age model of the lower part of the core section (341–486 cm). The relative abundance of CaCO_3 (every 10 cm; 1 cm thick slices) was obtained using an AN-7529 M express analyzer by means of the coulometric method. The carbonate content was calculated from the C_{carb} with a coefficient of 8.3. Lithic grains ($> 150 \mu\text{m}$ fraction; every 1 cm) were counted using MPSU-1 microscope. We also counted shells of the polar foraminifera *N. pachyderma* (s) in $> 150 \mu\text{m}$ fraction (every 5 cm in the upper part of the section (0–345 cm), and every 10 cm; in the lower part of the section (350–486 cm); 1 cm thick slices). Samples were splitted using a microsplitter, and no less than 300 individuals (or lithic grains) were examined. The IRD index is determined as the number of lithic grains per gram of dry sediment. Based on the IRD counts, cold Heinrich and Bond events with well-known ages were identified in the core section [*Bond et al.*, 1992, 1999; *Heinrich*, 1988; *Hemming*, 2004; *Sarnthein et al.*, 2001].

Additionally, the content of sand fraction (0.1–1 mm; every 10 cm; 1 cm thick slices) in the sediments was determined using a combined sieve and pipette method

[*Petelin*, 1967], with the additions from [*Alekseeva and Sval'nov*, 2005].

Marine isotope stage (MIS) boundary 2/1 was assigned based on the age model which was built using the AMS ^{14}C dates. MIS 3/2 boundary was allocated based on interpolation between the assigned reference points (IRD, sand content and *N. pachyderma* (s) peaks).

Results and Discussion

Stratigraphic Subdivision and Age Model of the AI-3359 Core Section

The core section is represented by calcareous silty clay. The upper part (0–15 cm) is enriched with a large number of foraminiferal shells. Fragments of foraminiferal shells are found throughout the core section. The IRD and content of sand fraction are in agreement with each other and mirror the relative abundance of CaCO_3 . All three parameters confirm the stratigraphic subdivision of the lower part of the core section (Figure 3).

In the AI-3359 core, 3 MIS covering the last 45,000 years are identified (Figure 3). The intervals 348–392 and 392–485 cm correspond to the cold MIS 2 (14,500–

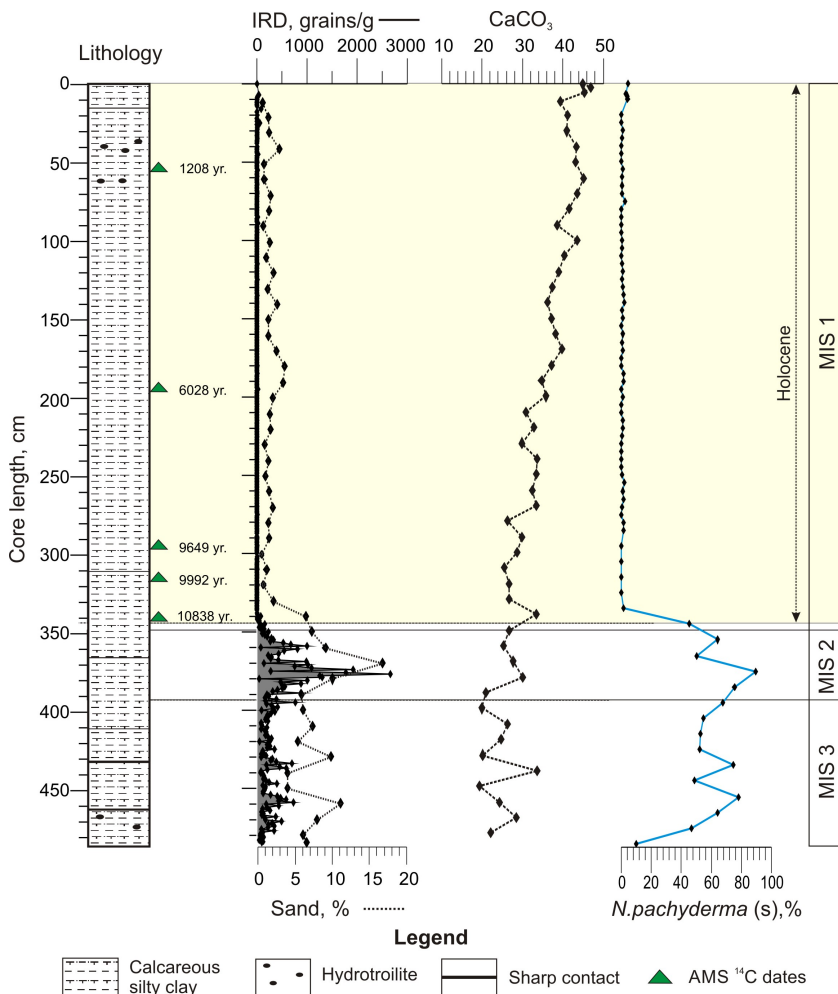


Figure 3. Stratigraphic subdivision of the AI-3359 core.

28,000 years BP) and relatively warm MIS 3 (28,000–45,000 years BP), respectively. MIS 2/1 boundary is allocated at the 348 cm. The interval 0–348 cm was accumulated during the MIS 1 (0–14,500 years BP) [*Lisiecki and Raymo*, 2005]. The Holocene boundary is at the 342 cm.

The average sedimentation rate of the upper part of the core section (0–341 cm) is about 29 cm/ka. The maximal sedimentation rate is observed between 9992 and 10,838 years BP (58.3 cm/ka). In the lower part of the core section (341–486 cm), the average sedimentation rate is 4.75 cm/ka (3.25 cm/ka for MIS 2 and 5.47 cm/ka for MIS 3).

The difference between sedimentation rates in the upper and lower parts of the core section could be explained by the changes in sedimentary conditions in the study area. After the glacial time, the relative abundance of the CaCO_3 increased indicating an increase in foraminiferal flux. Moreover, we suggest that an increase in the sedimentation rate in the study area could be a result of the intensive transport of silt-sized particles by the ISOW contour current at the onset of the

Holocene [*Bianchi and McCave*, 1999].

On the eastern flank of the Reykjanes Ridge, high Holocene sedimentation rates were registered by many researchers: up to 125 cm/ka [*Ruddiman and Bowles*, 1976]; 39 cm/ka in average [*Andersen et al.*, 2004], ~ 29 cm/ka in average [*Matul*, 1994], etc. *Giraudeau et al.* [2000] have registered maximal sedimentation rate (193 cm/ka) at the Reykjanes Ridge between 10,800 and 9000 years BP, as well as low sedimentation rate (no more 10 cm/ka) for the end of the Late Pleistocene. This coincides with our data about intervals of maximal and minimal sedimentation rates in the studied core site. However, there are differences between values of rates which could be interpreted as local changes in sedimentary conditions.

In the AI-3359 core, MIS 2 is marked by strong IRD and sand peaks. Glacial time (MIS 2 and 3) is characterized by the low relative abundance of CaCO_3 (no more than 33%), high IRD (up to 2662 grains/g) and sand (3.95–16.74%) values. MIS 1 is marked by the high content of CaCO_3 (28–46%), as well as low IRD (0–157 grains/g) and sand (0.45–3.51%) values (Figure 4).

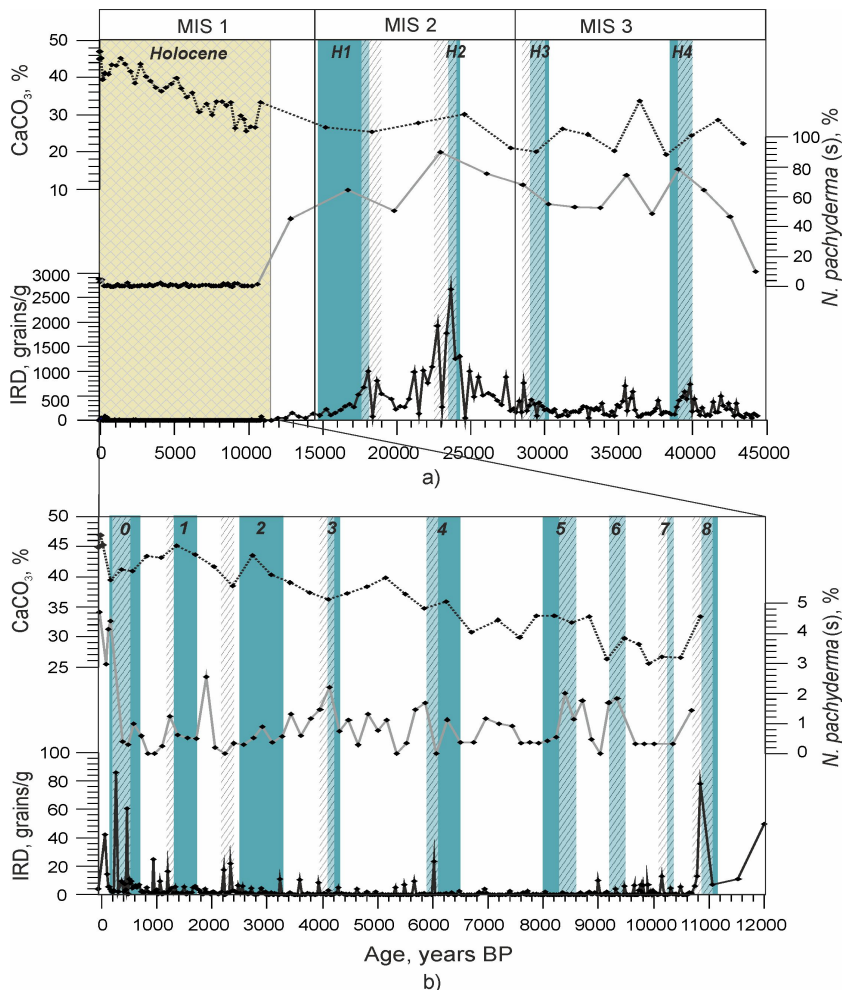


Figure 4. Distribution of CaCO_3 , *N. pachyderma* (s) and IRD in the studied core during the last 45,000 years (a), and during the Holocene (b). Heinrich (a) and Bond (b) events with well-known ages are marked by blue bars; cooling events observed in the AI-3359 core are marked by hatched bars: MIS – marine isotope stage.

All data obtained are compared with each other, and time intervals corresponding to the well-known short-term cold climatic events (Heinrich and Bond events) in the North Atlantic during the last 45,000 years are assigned.

Pleistocene Short-Term Cold Events

During the MIS 2 (28,000–145,000 years BP) and MIS 3 (45,000–28,000 years BP), IRD (47–2662 grains/g) and relative abundance of *N. pachyderma* (s) (10–89.4%) increased. It is also worth noting that in MIS 2 values of IRD reach its maximum – 2662 grains/g. At the same time, the relative abundance of CaCO_3 is in the range of 19–33%. During warm MIS 1, low IRD values are observed (usually no more 100 grains/g). This coincides with the low relative abundance of *N. pachyderma* (s) (usually no more than 2–3%), and high CaCO_3 content (25.5–46%).

In the AI-3359 core, four cold events are assigned. According to *Sarnthein et al.* [2001], Heinrich events have following ages: 1 – 14,670–18,100 years BP; 2 – 23,400–24,200 years BP; 3 – 29,000–30,200 years BP; 4 – 38,400–40,000 years BP. Clearly expressed IRD peaks between 17,500 and 19,000 years BP

(100–1001 grains/g) and between 22,500 and 24,000 years BP (1254–2662 grains/g) in the AI-3359 core are referred to Heinrich events 1 and 2, respectively. Relatively weak IRD peaks between 28,500 and 30,000 years BP and 39,000–40,000 years BP usually do not exceed 1000 grains/g and could be referred to Heinrich events 3 and 4, respectively (Figure 4). Our data show that in the area of the Reykjanes Ridge regional signals of ice rafting are somewhat different from the global. However, cold Pleistocene events, in general, coincide with Heinrich stadials. Assigned cold events correspond to increase in relative abundance of *N. pachyderma* (s) indicating cooling in the surface and subsurface water layer.

Holocene Short-Term Cold Events

Previous studies have registered nine Bond events (0–8) with well-known ages (Table 2). Using the data on IRD distribution, we tried to document well-known Bond events in the studied core. Additionally, data on changes in relative abundance of *N. pachyderma* (s) and CaCO_3 content were used.

In the AI-3359 core site, several pronounced IRD peaks are registered and could be referred to Bond

events 8, 7, 4, 2, 1 and 0.

Bond event 8 (11,100 years BP) [*Wanner et al.*, 2008] is recognized in our core between 10,700 and 11,000 years BP by a sharp increase in IRD (from 10 to 78 grains/g) centred at 10,800 years BP. Due to the low resolution of the data on the relative abundance of the *N. pachyderma* (s) and CaCO_3 we do not discuss these two parameters. As for IRD peak, most likely, increased sea ice formation occurred close to the study area. This resulted in intensive discharging and lithic grains accumulation (Figure 4).

A weak but recognizable IRD peak (12.9 grains/g), as well as decrease in relative abundance of calcium carbonate and *N. pachyderma* (s) between 10,100 and 10,400 years BP, could be referred to Bond event 7 (10,300 years BP) [*Wanner et al.*, 2008]. *Rashid et al.* [2014] have shown that Bond event 7 is associated with melting of the Laurentide Ice Sheet and the influx of meltwater into the Labrador Sea through the Hudson Strait. *Andersen et al.* [2004] have also registered cooling around 10,400 years BP at the Reykjanes Ridge. It is known that *N. pachyderma* (s) prefers a shallow mixed layer depth (upper 70–130 m) [*Simstich et al.*, 2003]. In the study area, the low relative abundance of this species could be related to the absence of response

Table 2. List of Well-Known Bond Events

Event (#)	Years BP	Name	References
Bond event 8	11,100 years BP	11.1 ka event	[<i>Wanner et al.</i> , 2008]
Bond event 7	10,300 years BP	10.3 ka event	[<i>Wanner et al.</i> , 2008]
Bond event 6	9200–9500 years BP	9.4 ka event	[<i>Rasmussen et al.</i> , 2000]
Bond event 5	8000–8600 years BP	8.2 ka event	[<i>Wanner et al.</i> , 2011]
Bond event 4	5900–6500 years BP	5.9 ka event	[<i>Wanner et al.</i> , 2011]
Bond event 3	4100–4300 years BP	4.2 ka event	[<i>Booth et al.</i> , 2005]
Bond event 2	2500–3300 years BP	2.8 ka event	[<i>Wanner et al.</i> , 2011]
Bond event 1	1350–1750 years BP	The Migration Period	[<i>Wanner et al.</i> , 2011]
Bond event 0	150–700 years BP	The Little Ice Age (LIA)	[<i>Wanner et al.</i> , 2011]

from the subsurface layer to the minor changes in the surface water layer.

A strong IRD peak (23 grains/g) at 6020 years BP, as well as increase in relative abundance of *N. pachyderma* (s) (up to 1.7%) and decrease in calcium carbonate at the 5800 years BP coincide with Bond event 4 (5900–6500 years BP) [Wanner et al., 2011]. We suggest that this cooling indicates a sea ice penetration in the study area followed by ice rafting. Cooling near the 5900 years BP was also observed further north, in the Fram Strait [Werner et al., 2016]. There is an evidence that after 6000 years BP, rainfall in the subtropics of the Northern hemisphere decreased resulting in drought [Brooks, 2006]. The event 5900 years BP also coincides with the end of the African wet period [Wang et al., 2013]. Our data together with previous studies allow suggesting that circulation of the NAC was slightly suppressed during this time. The summer sea ice edge could migrate south in comparison with its modern location.

Relatively high IRD values (20 grains/g) and a decrease in CaCO_3 content (39%) at 2200–2400 years BP, indicating a cooling in the AI-3359 core site, correspond to Bond event 2 (2500–3300 years BP) [Wanner et al., 2011]. This cooling could be an analog

of “2.7 ka cooling event” observed at the Reykjanes Ridge [*Moros et al.*, 2012]. However, increase in relative abundance of *N. pachyderma* (s) (up to 2.6%) was registered long after, between 1600 and 2000 years BP. We interpret this as a late response of the subsurface to the changes in the surface water layer. On the central East Greenland Shelf, increase in EGC flow was registered earlier, during the cold phase centred at 2400 years BP [*Perner et al.*, 2015]. This strengthening of the EGC led to increased sea ice formation, and, obviously, subsequent cooling in the study area via freshening of the surface water layer.

Cold interval which was observed in the studied core site between 1100 and 1300 years BP could be an analog of Bond event 1 (1350–1750 years BP) [*Wanner et al.*, 2011]. This Bond event is also known as the Migration Period. Relatively high values of IRD (18 grains/g) and *N. pachyderma* (s) (1.2%), as well as a slight decrease in CaCO₃ content, indicate increased sea ice formation and cooling of the surface and subsurface water layers during this interval. This is in agreement with the data from the Reykjanes Ridge about cooling at 1300 years BP [*Moros et al.*, 2012].

Two most pronounced IRD peaks between 200 and 500 years BP (up to 85 grains/g) are registered. This

interval is referred to Bond event 0 (150–700 years BP), or the Little Ice Age (LIA) [*Wanner et al.*, 2011]. A significant increase in IRD indicates the distribution of the sea ice south of the Iceland and cooling of the surface water layer. This coincides with data about maximal propagation of the sea ice in the North Atlantic during the last phase of the LIA (17th–early 19th century) [*Denton and Broecker*, 2008]. A high content of terrigenous grains in the sediments from the North Atlantic during the LIA was also registered by previous researchers [e.g. *Alonso-Garcia et al.*, 2017; *Moros et al.*, 2004]. The appearance of *N. pachyderma* (s) in the study area was registered after the Medieval Warm Period (c. 650–1150 years BP) [*Ljungqvist*, 2010]. A sharp increase in relative abundance of the polar species (up to 4.4%) only after 300 years BP with a simultaneous decrease in calcium carbonate content (from 46 to 39%) indicate the cooling of the subsurface water layer in the study area which occurred later than cooling of the surface (Figure 4).

We did not find a clear IRD signal of three Bond events (6, 5 and 3) in the studied core site. However, an abrupt increase in *N. pachyderma* (s) and a slight decrease in CaCO_3 are observed here. This allows us to use these parameters as indicators of the cooling events

in the study area.

Thus, there are no clearly pronounced IRD peaks during the Bond event 6 (9200–9500 years BP) [*Rasmussen et al.*, 2007]. However, a sharp increase in relative abundance of *N. pachyderma* (s) (up to 1.8%) and a decrease in relative abundance of CaCO_3 (up to 29%) are observed during this interval, indicating a slight cooling of the subsurface layer. This coincides with data about cooling at 9300 years BP and decrease in salinity of the surface waters in the North Atlantic [*Came et al.*, 2007; *Young et al.*, 2013]. Increase in IRD is observed later, at 8996 years BP, most likely marking sea ice melting because of warming.

A sharp increase in relative abundance of *N. pachyderma* (s) (up to 2%) between 8200 and 8670 years BP indicates cooling of the subsurface water layer in the study area. There are no changes in CaCO_3 relative abundance and no IRD peaks observed in our core section during this interval. However, we assign this interval to Bond event 5 (8000–8600 years BP; so-called 8.2 ka event) [*Wanner et al.*, 2011] only based on data on *N. pachyderma* (s) distribution, as this species a good indicator of cold subsurface waters and marks a decrease in sea surface temperature. It is well-known that a rapid release of a large amount of cold fresh

water from the Lake Agassiz preceded cooling at 8200 years BP [e.g. *Clarke et al.*, 2004]. *Andersen et al.* [2004] have registered decreased sea surface temperatures at the Reykjanes Ridge at 8300 years BP marking a cooling in this area. At the same time, in the studied core site, this event is not related to sea ice penetration and IRD deposition (Figure 4).

A decrease in CaCO_3 (from 40 to 34%) and increase in *N. pachyderma* (s) (from 0.9 to 2.2%) between 3900 and 4200 years BP could be an evidence of cooling of the subsurface water layer in the study area. This time interval coincides with Bond event 3 (4100–4300 years BP) [*Booth et al.*, 2005]. The sharp climate changes that occurred about 4200 years BP are recorded in different areas: from the North Atlantic to North Africa and South Asia [*Booth et al.*, 2005]. This event is considered to be one of the most pronounced Bond events: severe droughts affected the mid-continent of North America between 4100 and 4300 ka [*Booth et al.*, 2005]. However, in the studied core site, relatively low IRD values (8%) are registered at 3900 years BP. At the same time, in the Fram Strait slight increase of IRD was observed during the Bond event 3 indicating conditions cooler than those near the Reykjanes Ridge area surface. [*Werner et al.*,

2016].

Warm intervals are marked by increased CaCO_3 and decreased *N. pachyderma* (s) relative abundance. However, during some warm intervals (800–1200 years BP, 3200–3900 years BP, 5300–5900 years BP, and 9600–10,000 years BP), IRD peaks indicating sea ice melting are registered. This could be evidence of cooling of the surface water layer during these intervals. Despite the sea ice melting, warming of the subsurface water layer (decrease in *N. pachyderma* (s)) occurred during this time.

Increase in the number of foraminiferal shells (according to the lithological description of the studied core) during the last 230 years BP coincides with the abrupt increase in CaCO_3 , *N. pachyderma* (s) and IRD. It is known that Arctic Front is related to high planktonic foraminiferal flux, 20–40% carbonate, and high *N. pachyderma* (s) relative abundance, whereas Polar Front is characterized by low foraminiferal flux, less than 10% carbonate, and high *N. pachyderma* (s) relative abundance [Johannessen *et al.*, 1994]. Thus, our data indicate a shift of the Arctic Front to the south during this interval resulting in intensive ice rafting.

Conclusions

Our data have shown that AI-3359 core section was formed during the Late Pleistocene to Holocene (last 45,000 years). The temporal resolution of the Late Pleistocene does not allow us to discuss this interval in detail. In the Late Pleistocene, four cold events corresponding to the Heinrich events are assigned. However, the data obtained show that in the area of the Reykjanes Ridge regional signals of ice rafting are somewhat different from the global.

During the Holocene, the surface circulation that influenced sedimentary conditions in the study area varied considerably. Nine well-known Bond events are compared with assigned cooling events registered east of the Reykjanes Ridge. Six Holocene events centred at 10,800, 10,100, 6020, 2200, and 1200 years BP are the most pronounced cooling events with relatively intensive ice rafting in the study area. These events are referred to Bond events 8, 7, 4, 2, 1 and 0. We did not find a clear IRD signal of three Bond events (6, 5 and 3) in the studied core site. However, cooling of the subsurface water layer at 9300, 8300 and 4100 years BP is observed. This cooling is marked by the increase in relative abundance of polar species *N. pachyderma* (s).

LIA is marked by the cooling between 200 and 500 years BP. A late response of the subsurface layer to the cooling on the surface (sea ice melting) is registered.

During some warm intervals (800–1200 years BP, 3200–3900 years BP, 5300–5900 years BP, and 9600–10,000 years BP), ice rafting still occurred in the study area without cooling of the subsurface layer. Increase in the number of foraminiferal shells, calcium carbonate, and IRD during the last 230 years BP indicates a shift of the Arctic Front to the south resulted in intensive ice rafting.

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