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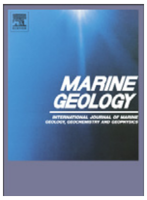

Continued meltwater influence on North Atlantic Deep Water instabilities during the early Holocene

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ABSTRACT

The transition into the Holocene marks the last large, orbitally derived climatic event and ultimately led to the onset of modern oceanic conditions. The influence of this climatic change on North Atlantic Deep Water (NADW) formation and circulation remains ambiguous. High-resolution records from southern Gardar Drift, south of Iceland, show abrupt decreases in benthic foraminiferal $\delta^{13}C$ values at discrete intervals during the early Holocene, suggesting that NADW shoaled episodically. Intervals of lower $\delta^{13}C$ values are coincident with higher $\Delta\delta^{18}O_{N.\ pachyderma\ (s)-G.\ bulloides}$ and high abundance of lithic grains/g, indicating that these periods also had enhanced surface water stratification, due to increased meltwater in the circum-North Atlantic region. Our new high-resolution planktonic and benthic foraminiferal stable isotopic data show that increased meltwater delivery led to brief reorganizations of deepwater currents. These southern Gardar surface and deep water records indicate that the early Holocene was a period of multiple abrupt climatic events that were propagated to the North Atlantic during the final break up of ice sheets in the Northern Hemisphere, and suggest that some component of the residual early Holocene sea level rise can be attributed to Northern Hemispheric sources.

1. Introduction

In the circum-North Atlantic region, the onset of the Holocene (~11.7 ka; Steffensen et al., 2008; Walker et al., 2009) marks the end of the transition from the last glacial period to current interglacial conditions (Broecker et al., 1989). Greenland ice core $\delta^{18}O$ records show that the Holocene was a warmer, less dusty period with decreased climatic variability, compared to the last glacial (Grootes et al., 1993; Alley et al., 1995). Similarly, geologic evidence from oceanic sediment cores (Broecker et al., 1989) and terrestrial records (Atkinson et al., 1987; Dansgaard et al., in press; Davis et al., 2003) from around the North Atlantic prescribe the Holocene as a period with warm temperatures and without large-scale climatic changes. The Holocene Thermal Maximum, caused by peak insolation ranged from 11 to 6 ka, depending on geographic location, and was less than 2 °C warmer than the Holocene baseline temperature in most locations (Kaufman et al., 2004; Renssen et al., 2012). Despite relative climatic stability, an estimated 30 m of lingering deglacial sea level rise occurred throughout the early Holocene, from 11.7 ka until at least ~8.0 ka (Fairbanks, 1989; Peltier and Fairbanks, 2006; Bard et al., 2010; Deschamps et al., 2012), attributed to freshwater delivery from the melting ice sheets (Andrews and Dunhill, 2004; Tornqvist and Hijma, 2012; Seidenkrantz et al., 2013). This evidence suggests that episodic or continual meltwater has been released from the Northern Hemisphere ice sheets, and may have affected North Atlantic ocean hydrography/circulation during the early Holocene.

Recent, higher-resolution examinations have demonstrated that Holocene climate is more variable than previously thought (e.g. Bond et al., 1997; Bianchi and McCave, 1999; Hoogakker et al., 2011; Larsen et al., 2012; Walker et al., 2012; Miller and Chapman, 2013), and have identified abrupt climate events within this purportedly stable interglacial period that have affected the deep ocean, as well as the more variable surface ocean (Alley et al., 1997; Marcott et al., 2013). Perhaps the most discussed of these is termed the ‘8.2 ka Event’ (Alley et al., 1997; Rohling and Pälike, 2005; Cronin et al., 2007; Born and Levermann, 2010; Young et al., 2012; Liu et al., 2013), a climatic cooling caused by North Atlantic surface water freshening (Ellison et al., 2006) that has been attributed to meltwater release from glacial Lake Aggasiz (Barber et al., 1999; Hillaire-Marcel et al., 2007; Tornqvist and Hijma, 2012). This meltwater event delivered freshwater into the North Atlantic region, and may have disrupted thermohaline circulation (Renssen et al., 2001) and decreased NADW formation (Ellison et al., 2006; Kleiven et al., 2008), despite some evidence for faster Iceland–Scotland Overflow (Bianchi and McCave, 1999). This proposed mechanism for the 8.2 ka Event is similar to a proposed mechanism for Younger Dryas cooling, wherein Broecker et al. (1989) suggested that a ‘fresh water

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cap' in the northern North Atlantic would have altered deepwater formation for the duration of the Younger Dryas (Clark et al., 2001; McManus et al., 2004; Tarasov and Peltier, 2005; Elmore and Wright, 2011) and during Heinrich Events (Vidal et al., 1997). However, other mechanisms have also been proposed to explain the Younger Dryas cold period, including changing atmospheric circulation (Wunsch, 2006; Brauer et al., 2008) and extraterrestrial impact (Firestone et al., 2007; Melott et al., 2010).

In addition to the 8.2 ka Event, other studies have presented evidence from oceanic sediment cores for meltwater-driven abrupt climatic events that may have perturbed deep ocean circulation patterns at 9.5 ka (Keigwin et al., 2004), 9.3 ka (Yu et al., 2010), 9.2 ka (Fleitmann et al., 2008, and references therein), 8.6 ka (Henderson, 2009), 8.4 ka (Kleiven et al., 2008), 4.2 ka (Booth et al., 2005; Menounos et al., 2008), 2.7 ka (Hall et al., 2004), and the Little Ice Age (1500–1900 AD; Bradley and Jones, 1993; Dahl-Jensen et al., 1998). While the evidence for these events has similarities in common with the sediment core records through the 8.2 ka Event and the Younger Dryas, they are less frequently observed in oceanic records and have yet to be directly tied to meltwater delivery routes.

Here, we present high-resolution proxy records of surface and deepwater environmental conditions from the northern North Atlantic to test the hypothesis that episodic surface water freshenings altered deepwater circulation patterns during the early Holocene. Records of proxies for surface water temperature (planktonic foraminiferal assemblage and $\delta^{18}O$ values), surface water stratification ($\Delta\delta^{18}O_{N.\ pachyderma\ (s)-G.\ bulloides}$, calculated from the difference between $\delta^{18}O_{G.\ bulloides}$ and $\delta^{18}O_{N.\ pachyderma\ (s)}$), ice rafted debris (IRD; quantity of lithic grains/g), bottom water temperature ($\delta^{18}O$ benthic foraminifera), and deep ocean circulation ($\delta^{13}C$ benthic foraminifera) are used to compare surface water hydrography with NADW variations during the critical Holocene interval.

2. Methods

2.1. Site information and sample processing

Surface ocean currents bring warm, salty surface water to the northeast North Atlantic via the North Atlantic Current, which bifurcates toward western Europe and the Nordic Seas, passing between the North Atlantic subpolar and subtropical gyres (Fig. 1; Hansen and Østerhus, 2000). The surface waters cool and sink in the Nordic Seas, returning to the North Atlantic as Iceland–Scotland Overflow Water (ISOW) and Denmark Strait Overflow Water (DSOW; Worthington, 1976; Fig. 1). The contributions of ISOW and DSOW are related to surface temperature and salinity in the Nordic Seas (Duplessy et al., 1988), as well as to surface inflow (Thornalley et al., 2009) controlled by the position and strength of North Atlantic gyres (Hansen and Østerhus, 2000), sill depth (Millo et al., 2006), sea ice cover (Prins et al., 2001; Raymo et al., 2004), and tectonics (Wright and Miller, 1996). Thus, researchers have suggested that overflow strength has varied on geologic, orbital, decadal and inter-annual timescales (Duplessy eat al., 1988; Oppo et al., 1995; Dokken and Hald, 1996; Wright and Miller, 1996; Bianchi and McCave, 1999; McManus et al., 1999; Turrell et al., 1999; Dickson et al., 2002; Raymo et al., 2004) Modern NADW is produced by the interplay between ISOW, DSOW, Antarctic Bottom Water (AABW), Labrador Sea Water, and Mediterranean Outflow Water (Mann, 1969; Worthington, 1976; Fig. 1). Due to their similar though complicated formation pathways, ISOW and DSOW export may co-vary or may have an inverse relationship (i.e. increased ISOW occurs at the expense of decreased DSOW); however this study has scope only to address the ISOW component.

Jumbo piston core 11JPC was collected by the *R/V Knorr* on cruise 166, leg 14, from 2707 m water depth on Gardar Drift (56°14′N, 27°39′W) in the eastern North Atlantic (Fig. 1; Table 1.). ISOW, the largest eastern source of modern North Atlantic Deepwater, bathes this site (Worthington, 1976; Bianchi and McCave, 1999). High sedimentation rates (~18 cm/kyr) offer high temporal resolution throughout the Holocene (Fig. 2).

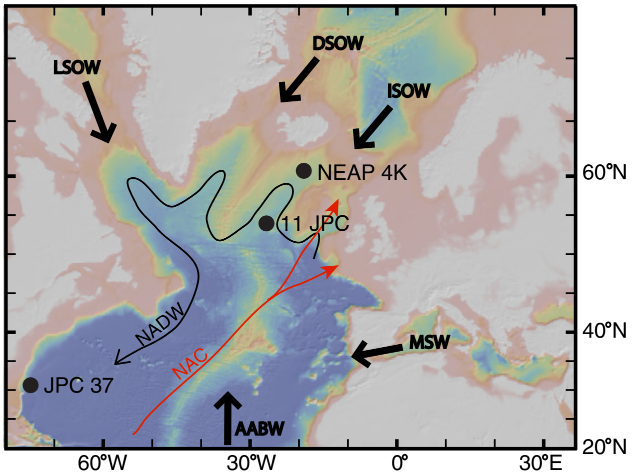

Fig. 1. Bathymetric map of the North Atlantic showing location of KN166-14 11JPC on Gardar Drift (this study), NEAP 4K (Hall et al., 2004), and KNR140-2 JPC 37 (Hagen and Keigwin, 2002). Generalized oceanographic currents are shown for surface flowing North Atlantic Current (NAC; red), and the five main contributors to North Atlantic Deep Water (NADW; black); Labrador Sea Overflow water (LSOW), Denmark Straits Overflow Water (DSOW), Iceland–Scotland Overflow Water (ISOW), Mediterranean Sea Water (MSW), and Antarctic Bottom Water (AABW).

The top 222 cm of core 11JPC was sampled at 1 cm intervals to study changes in surface water hydrography during the Holocene and Younger Dryas, yielding a sampling resolution of ~58 years per sample (Elmore and Wright, 2011). The >150 μm fraction of each sample was split using a microsplitter into an aliquot containing at least 300 planktonic foraminifera (Imbrie and Kipp, 1971). Abundances of the planktonic foraminiferal species were determined by manual counting. The three most common taxa were left-coiling *Neogloboquadrina pachyderma* (sinestral; s), right-coiling *N. pachyderma* (dextral; d), and *Globogerina bulloides*. Planktonic foraminiferal assemblage results are reported as percent, with respect to the total planktonic foraminiferal assemblage. The polar biogeographic region is dominated by *N. pachyderma* (s), thus % *N. pachyderma* (s) has been used as an indicator of relative temperature changes for polar to subpolar regions (Bé and Tolderlund, 1971; Bé, 1977).

Up to 15 tests of each of the planktonic foraminifera species *N. pachyderma* (s) and *G. bulloides* were selected using a binocular microscope from the 250 to 350 μm size fraction of each sample and analyzed for stable isotopic composition on an Optima Mass Spectrometer at Rutgers University (1-σ laboratory precision of an internal lab standard was 0.08‰ for $\delta^{18}O$ and 0.05‰ for $\delta^{13}C$). The differences ($\Delta\delta^{18}O_{N.\ pachyderma\ (s)-G.\ bulloides}$) between the $\delta^{18}O$ values of the surface-dwelling *G. bulloides* and thermocline-dwelling *N. pachyderma* (s) were then calculated for each sample to determine the differences in calcification environment driven by the depth habitat preference of each species, as defined by Lagerklint and Wright (1999). Since these two species have been selected out of the same samples, global changes in $\delta^{18}O$ driven by ice volume and/or any regional changes in $\delta^{18}O_{sea\ water}$ would not affect the $\Delta\delta^{18}O$ difference as both species would record these effects contemporaneously (Lagerklint and Wright,

Table 1
Locations of sediment cores used in this study.

Site	Water depth (m)	Latitude	Longitude
KN166-14 11JPC	2707	56°15′N	27°40′W
NEAP 4K	1627	61°29.91′N	24°10.33′W
KNR140-2 JPC 37	3000	31°41′N	75°29′W