North Atlantic Deep Water and climate variability during the Younger Dryas cold period

Aurora C. Elmore* and James D. Wright
Department of Earth and Planetary Sciences, Rutgers University, 610 Taylor Road, Piscataway, New Jersey 08854, USA

ABSTRACT

The Younger Dryas, the last large millennial-scale climate oscillation (12.9–11.6 ka), has been widely attributed to a massive meltwater discharge event that disrupted ocean circulation and plunged the circum–North Atlantic back into a near-glacial state. Low-resolution deep-water reconstructions indicate lower North Atlantic Deep Water (NADW) production during the Younger Dryas, though the $\Delta^{14}C$ record requires some deep-water production. Herein, we reconstruct deep-water mass variations using a southern Gardar Drift sediment core with an expanded Younger Dryas section. We show that southern-sourced water invaded the deep North Atlantic to start the Younger Dryas, but was replaced by NADW within 500 yr. Southern-sourced waters briefly reappeared at the end of the Younger Dryas. These deep-water reorganizations to start and end the Younger Dryas suggest that increased meltwater fluxes were limited temporally and focused on regions where deep-water convection occurred during the deglaciation.

INTRODUCTION

Broecker et al. (1989) proposed that abrupt Younger Dryas cooling was caused by the addition of meltwater to the northern North Atlantic, when the Laurentide drainage was rerouted from the Mississippi River to the St. Lawrence River. A "fresh-water cap" thus reduced deep-water production in the northern North Atlantic (Broecker et al., 1989). This meltwater hypothesis, with the associated surface-water cooling, sea-ice expansion, and deep-water reorganization, is still the preferred explanation for the Younger Dryas (Broecker et al., 2010), although other mechanisms have been proposed (e.g., Bradley and England, 2008; Brauer et al., 2008; Kennett et al., 2009). Younger Dryas–like events have occurred during previous deglaciations, emphasizing the importance of understanding these events as an integral part of glacial terminations (Broecker et al., 2010).

Decreased North Atlantic Deep Water (NADW) formation during the Younger Dryas is inferred from low benthic foraminiferal $\delta^{13}C$ values (Boyle and Keigwin, 1987) and increased Pa/Th ratios (McManus et al., 2004) on the Bermuda Rise; increased ε_{Nd} values in the South Atlantic (Piotrowski et al., 2005) and Bermuda Rise (Roberts et al., 2010); $\Delta^{14}C$ perturbations in the Cariaco Basin (Hughen et al., 1998); and decreased sortable silt size on the Bjorn Drift (Praetorius et al., 2008) and Blake Outer Ridge (Evans and Hall, 2008). Higher resolution records indicate some variability in NADW circulation within the Younger Dryas (McManus et al., 2004; Praetorius et al., 2008; Thornalley et al., 2010a), but a coherent pattern has not yet been established.

We used a jumbo piston core, KN166–14 11JPC (11JPC herein), to address the finer scale variations in deep-water circulation during the Younger Dryas. Core 11JPC was collected by the R/V *Knorr* on cruise 166, leg 14, from 2707 m water depth on the Gardar Drift (56°14′N, 27°39′W) in the eastern North Atlantic (Fig. 1A). Iceland-Scotland Overflow Water, the largest eastern source of modern NADW, bathes this site (Worthington, 1979). High sedimentation rates (~25 cm/k.y.) offer the requisite temporal resolution to reconstruct intra-Younger Dryas variability. Benthic foraminiferal $\delta^{13}C$ records are used herein to track changes in the bottom-water masses at this southern Gardar location. Previous studies have established that NADW retained high $\delta^{13}C$ values (~1‰) throughout the deglacial to the Holocene (e.g., Praetorius et al., 2008), while Antarctic Bottom Water values were <0‰ (e.g., Piotrowski et al., 2005). The age model for this core is based on 15 accelerator mass spectrometry ^{14}C dates (Fig. 1A; see the GSA Data Repository[1]).

BOTTOM-WATER PROXY RESULTS AND INTERPRETATIONS

Benthic foraminiferal $\delta^{13}C$ values from core 11JPC were 1‰ during the Bølling-Allerød, and decreased to 0.4‰ at the start of the Younger Dryas (ca. 12.9 ka; Fig. 2). Following this initial excursion, benthic foraminiferal $\delta^{13}C$ values increased, reaching 1‰ by 12.5 ka. Bottom-water $\delta^{13}C$ values remained high for 500–700 yr. A second decrease in $\delta^{13}C$ values to 0.5‰ centered ca. 11.8 ka lasted <300 yr, but quickly rebounded as the Younger Dryas ended and the Holocene began. Thus, the pattern of benthic foraminiferal $\delta^{13}C$ changes during the Younger Dryas mimics a W, recording decreasing values going into the Younger Dryas, recovery to moderate values in the mid-Younger Dryas, a second decrease at the end of the Younger Dryas, and a final recovery into the early Holocene.

We interpret this W pattern in the benthic foraminiferal $\delta^{13}C$ record as primarily reflecting changes in the deep-water masses at the southern Gardar Drift, such that NADW was partially replaced by southern-sourced waters to start and end the Younger Dryas (Fig. 2). This interpretation is supported by records from other deep-water proxies (e.g., McManus et al., 2004; Piotrowski et al., 2005; Praetorius et al., 2008), which indicate that the $\delta^{13}C$ decreases reflect a reduction in northern-sourced deep water at the onset and termination of the Younger Dryas.

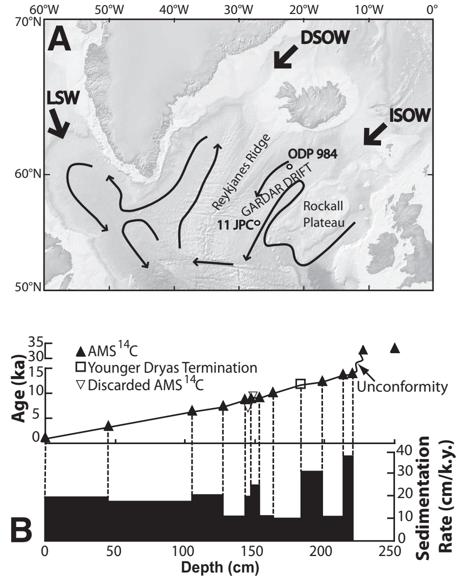

Figure 1. A: Bathymetric map of North Atlantic showing generalized bottom-water currents (LSW— Labrador Sea Water; DSOW—Denmark Strait Overflow Water; ISOW—Iceland Scotland Overflow Water; after Worthington, 1979). Locations of core 11JPC on southern Gardar Drift (this study) and Ocean Drilling Program (ODP) Site 984 (Praetorius et al., 2008) are shown. B: Age model (AMS—accelerator mass spectrometry) and 341 sedimentation rates for 11JPC (Table DR1 [see footnote 1]).

*Current address: Marine Science Center, University of New England, 11 Hills Beach Road, Biddeford, Maine 04005, USA; E-mail: aelmore@une.edu.

[1]GSA Data Repository item 2011052, methods and table of age model tie points, is available online at www.geosociety.org/pubs/ft2011.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

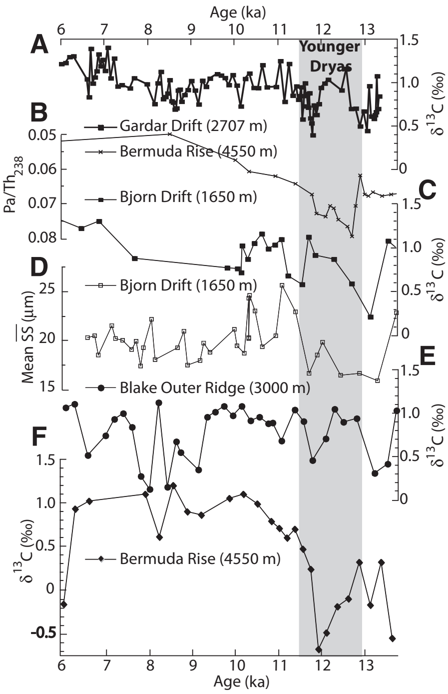

Figure 2. Paleoceanographic records of North Atlantic deep-water masses from 6 to 13.5 ka, highlighting Younger Dryas. A: Core 11JPC *Planulina wuellerstorfi* $\delta^{13}C$ shown versus age, showing W pattern of inter-Younger Dryas circulation changes. Supporting evidence for inter-Younger Dryas circulation variability is also shown. B: Pa/Th from Bermuda Rise (McManus et al., 2004). C: *P. wuellerstorfi* $\delta^{13}C$ from Bjorn Drift (Praetorius et al., 2008). D: Mean sortable silt ($\overline{SS}$) from Bjorn Drift (Praetorius et al., 2008). E: *P. wuellerstorfi* $\delta^{13}C$ from Blake Bahama Ridge (Hagen and Keigwin, 2002).

We note, however, that bottom-water $\delta^{13}C$ values may be influenced by factors other than the relative mixing between water masses, including air-sea exchange (Charles et al., 1994), brine formation (Meland et al., 2008; Thornalley et al., 2010a), and changing surface-water productivity (Mackensen et al., 1994; Hoogakker et al., 2007). We rule out the air-sea exchange processes as an explanation for the $\delta^{13}C$ decreases because Younger Dryas surface cooling would tend to increase the $\delta^{13}C$ of dissolved inorganic carbon. Additionally, while brine formation in the Nordic Seas imparts a low $\delta^{13}C$ signal, and has been demonstrated to be an important process during the deglaciation in locations proximal to the Nordic Seas (Meland et al., 2008; Thornalley et al., 2010a), brine formation is volumetrically too small to be the primary source of deep water at 2700 m, at this distal location on the southern end of Gardar Drift. Benthic foraminiferal taxa indicative of increased phytodetritus (Smart et al., 1994) were not found in the sections with low benthic foraminiferal $\delta^{13}C$, giving no evidence for productivity-induced alteration of $\delta^{13}C$.

While Younger Dryas climate change hypotheses often invoke deep-water reorganization in the North Atlantic, the southern Gardar Drift $\delta^{13}C$ record indicates that the initial decrease in NADW was followed by the return of a moderate NADW flux during the mid-Younger Dryas. Both McManus et al. (2004) and Thornalley et al. (2010a) noted a similar change in North Atlantic circulation from deeper or shallower sites, suggesting that the observed $\delta^{13}C$ records largely reflect deep-water circulation changes (Fig. 2). The interpretation of a second NADW decrease at the end of the Younger Dryas has received little attention, but is also evident in the benthic foraminiferal $\delta^{13}C$ records on the Bjorn Drift (Praetorius et al., 2008), Blake Outer Ridge (Hagen and Keigwin, 2002), and Bahama Bank (McManus et al., 2004; Roberts et al., 2010), and in sortable silt records from Bjorn Drift (Praetorius et al., 2008) and the Pa/Th record from the Bermuda Rise (Fig. 2; McManus et al., 2004).

Differences in the magnitude of NADW reductions and recoveries recorded in various proxy records during the Younger Dryas result from differences in location, proxy biases, and age control. North Atlantic sediment drifts develop from the interplay between bathymetry and deep-water currents; therefore, climate states that produce less-dense deep-water masses will not produce rapid sediment accumulation on the deepest sediment drift sites (>4000 m; e.g., Bermuda Rise). Thus, the low-resolution benthic foraminiferal $\delta^{13}C$ and Cd/Ca records from Bermuda Rise record a greater invasion of southern-sourced water during the Younger Dryas, but do not have the requisite temporal resolution to see intra-Younger Dryas variability (Fig. 2; Boyle and Keigwin, 1987). It is also important to note that the $^{231}Pa/^{230}Th$ and sortable silt proxies respond to the physical flux of water, whereas benthic foraminiferal $\delta^{13}C$ values reflect the relative contributions between the northern- and southern-sourced water masses.

The initial reduction in NADW production at the start of the Younger Dryas is more pronounced at deep and distal sites. Benthic foraminiferal $\delta^{13}C$ values from the Bermuda Rise (4550 m) approach −0.5‰ (Boyle and Keigwin, 1987), indicating that southern-sourced deep water fully replaced NADW in the deepest Atlantic basins (Fig. 2). High Cd/Ca values from the same core also denote a deep-water mass of southern origin (Boyle and Keigwin, 1987). In contrast, most mid-depth North Atlantic records (~2000–3000 m) indicate a partial, but not full collapse of NADW to begin the Younger Dryas, evidenced by benthic foraminiferal $\delta^{13}C$ values of ~0.3‰ (Fig. 2).

The extent of NADW recovery during the mid-Younger Dryas also varies based on position and proxy. Benthic foraminiferal $\delta^{13}C$ values reach 1‰ on the Bjorn (Praetorius et al., 2008) and Gardar Drifts, as well as on the Blake Outer Ridge (Hagen and Keigwin, 2002), indicating that NADW was the dominant water mass at these depths in the northern North Atlantic during the mid-Younger Dryas (Fig. 2). In contrast, benthic foraminiferal $\delta^{13}C$ values from the deepest North Atlantic cores remained low during the mid-Younger Dryas (Boyle and Keigwin, 1987), showing that NADW did not penetrate as deeply as it did during the Bölling-Alleröd or Holocene. Likewise, $^{231}Pa/^{230}Th$ and sortable silt proxies indicate only a small increase in the bottom-water current velocity from the early to mid-Younger Dryas (Fig. 2). Therefore, the overall flux of NADW increased from the early to mid-Younger Dryas, but did not reach Bölling-Alleröd or Holocene strength.

SURFACE-WATER PROXY RESULTS AND INTERPRETATIONS

Differences in $\delta^{18}O$ values ($\Delta\delta^{18}O$) recorded by surface-dwelling *Globigerina bulliodes* and thermocline-dwelling *Neogloboquadrina pachyderma* (sinistral, s) provide a measure of surface-water conditions (Lagerklint and Wright, 1999). The $\Delta\delta^{18}O$ record from 11JPC increased during the Younger Dryas, indicating that the habitats of *G. bulliodes* and *N. pachyderma* (s) diverged significantly (Fig. 3D). Stratification in temperature and/or salinity, common in modern polar environments (Kohfeld et al., 1996), or differing seasons of calcification for subpolar regions will produce differing $\delta^{18}O$ values among the planktonic foraminiferal species (Lagerklint and Wright, 1999). We suspect that both increased surface stratification and a shift to colder temperatures produced the large (>1‰) $\Delta\delta^{18}O$ values during the Younger Dryas. The absence of peaks in the $\Delta\delta^{18}O$ record that would correlate with the $\delta^{13}C$ decreases at the start and end the Younger Dryas suggests that large meltwater spikes were distal to our site.

Our reconstruction of NADW variability on the Gardar Drift requires lower surface-water salinities during the Younger Dryas compared to the Bolling-Allerod and Holocene because surface-water salinity dictates the density of NADW, controlling whether upper or lower NADW is formed. Otherwise, the mid-Younger Dryas recovery should have been recorded in the deepest North Atlantic cores. Evidence for increased meltwater from both the Fenno-Scandinavian and Laurentide ice sheets is found at locations proximal to the waning continental ice sheets (Bodén et al., 1997; Carlson et al., 2007; Thornalley et al., 2010b). We propose that persistent glacial meltwater input from both ice sheets lowered surface salinities to produce a sufficiently less-dense, more glacial-like variety of NADW during the Younger Dryas.

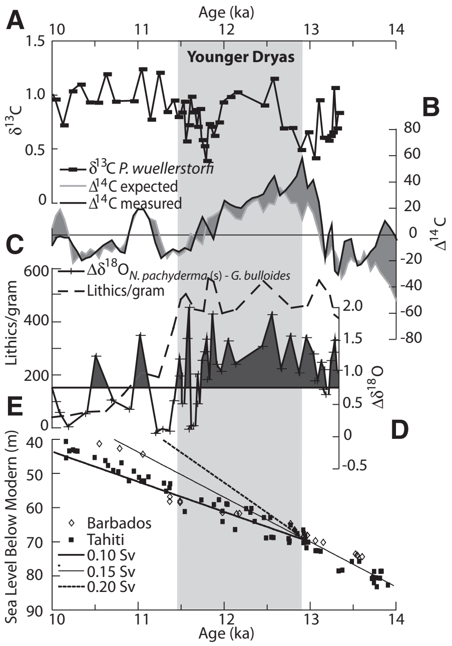

Figure 3. Surface-water and deep-water records for the North Atlantic from 14 to 10 ka. A: Core 11JPC *Planulina wuellerstorfi* $\delta^{13}C$ versus age, showing W pattern of inter-Younger Dryas circulation changes. B: Detrended records of estimated $\Delta^{14}C$ production and measured $\Delta^{14}C$ (Muscheler et al., 2000); difference between records is highlighted in gray. C: Core 11JPC lithics/gram, showing higher ice-rafted debris throughout Younger Dryas. D: Core 11JPC $\Delta\delta^{18}O_{N.\ pachyderma–G.\ bulloides}$ indicating increased surface stratification and thus more meltwater during Younger Dryas. E: Modeled sea-level reconstructions under various meltwater scenarios shown with sea-level data from Barbados (Peltier and Fairbanks, 2006) and Tahiti (Bard et al., 2010). *G. bulliodes—Globigerina bulliodes*; *N. pachyderma—Neogloboquadrina pachyderma* (s).

SEA-LEVEL CONSTRAINTS ON MELTWATER

Ocean circulation models require continuous and volumetrically large fresh-water inputs to produce a sustained shutdown of NADW throughout the Younger Dryas (Clark et al., 2001; Rahmstorf et al., 2005). Model estimates of fresh-water fluxes required to stop NADW during the Younger Dryas range from 0.1 to 0.5 Sv (Ganopolski and Rahmstorf, 2001; Rahmstorf et al., 2005) with many flux estimates between 0.15 and 0.175 Sv (Clark et al., 2001). Fresh-water inputs of 0.15–0.175 Sv sustained throughout the Younger Dryas would raise sea level 15–20 m (Fig. 3D), yet coral-based records indicate that sea level rose by <10 m during the Younger Dryas (Fig. 3D; Peltier and Fairbanks, 2006; Bard et al., 2010). In light of the deep-water circulation reconstruction presented herein and limitations of total fresh-water volume imposed by sea-level records, we propose that a volumetrically small supply of meltwater resulted in less-dense NADW during the Younger Dryas, and that any large meltwater events were confined to a few centuries, and did not persist throughout the Younger Dryas.

Consistent with model studies that suggest that the location, rather than volume, of meltwater is the most important factor in determining whether a meltwater injection will affect deep-water circulation (Fanning and Weaver, 1997; Tarasov and Peltier, 2005), Bodén et al. (1997) reported that the drainage of the Baltic Ice Lake occurred in two steps; these two drainage events correlate with the large circulation reorganization at the onset of the Younger Dryas, as well as the brief NADW decrease at the end of the Younger Dryas. We suggest that the proximity of the Fenno-Scandinavian meltwater to the region of deep convection primarily controlled NADW buoyancy during the Younger Dryas.

ATMOSPHERIC $\Delta^{14}C$

We concur with McManus et al. (2004), who noted that a complete cessation of NADW during the Younger Dryas is incompatible with the atmospheric $\Delta^{14}C$ record (Stocker and Wright, 1998; Muscheler et al., 2000), requiring not only a decrease in NADW production at the start of the Younger Dryas, but also its reestablishment soon thereafter (McManus et al., 2004; Meissner, 2007). According to Muscheler et al. (2000), the only significant difference between atmospheric $\Delta^{14}C$ production and measured $\Delta^{14}C$ records occurred during the early part of the Younger Dryas (Fig. 3B), corresponding to the initial low benthic foraminiferal $\delta^{13}C$ values on the southern Gardar Drift. The convergence of the ^{14}C production and measured $\Delta^{14}C$ records by ca. 12.5 ka corresponds to increased benthic foraminiferal $\delta^{13}C$ values in 11JPC (Fig. 3). The deep-water event that ended the Younger Dryas is not evident in the $\Delta^{14}C$ record, possibly owing to its brevity. Our deep-water reconstruction is consistent with the assertions of Muscheler et al. (2000) and McManus et al. (2004), that most of the $\Delta^{14}C$ excursion in the Younger Dryas is accounted for by changing atmospheric ^{14}C production. However, the discrepancy in the early Younger Dryas requires a slow down in NADW formation, followed by a mid–Younger Dryas recovery.

CONCLUSIONS

Many studies now show a more dynamic circulation system for the last glacial interval, with nearly complete shutdowns associated with intermittent meltwater and iceberg discharge events (McManus et al., 2004) and the formation of intermediate water at the expense of deep water (Roberts et al., 2010). We consider that the W pattern for deep-water circulation observed during the Younger Dryas may be an extension of this pattern, albeit on a shorter time scale. We propose that the beginning and end of the Younger Dryas were characterized by meltwater injections directly to the site of deep-water formation, which generated a weakened NADW, and allowed for the formation of intermediate water and the intrusion of southern-sourced water into the deep North Atlantic. During the mid-Younger Dryas, NADW production continued with a less-dense variety.

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