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Notes

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ABSTRACT

The Younger Dryas stadial (Greenland Stadial 1) has long been recognized in proxy records throughout the North Atlantic region as a stable, cool period that started and ended abruptly. However, modeling experiments in which the Younger Dryas cooling was forced by meltwater predict much more unstable climatic conditions compared to the proxy records. Here we present evidence of a climatically unstable Younger Dryas based on a decadal-resolution marine proxy record from the Norwegian continental shelf. This record shows that the North Atlantic was characterized in the early Younger Dryas by Arctic Water and an increasing accumulation of fresh surface water that peaked at 12,500 calendar yr B.P. For ~300 yr during the late Younger Dryas, the sea-surface temperatures fluctuated between glacial values (~2 °C) and interglacial values (~10 °C) on a subdecadal to multidecadal time scale. This period of extreme instability preceded the more stable and warm Holocene, starting ca. 11,500 calendar yr B.P. These results are consistent with modeling experiments that link the Younger Dryas climate changes to fluctuations of the North Atlantic thermohaline circulation.

Keywords: North Atlantic, Younger Dryas, stable isotopes, sea-surface temperatures, planktic foraminifera.

INTRODUCTION

Both the mechanisms and the climatic implications of the Younger Dryas stadial have drawn much attention during the last decades (e.g., Alley and Clark, 1999). Data from the Greenland Ice Core Project (GRIP) ice core at Summit have allowed this cool event, defined as the Greenland Stadial 1 (GS-1) (Björck et al., 1998), to be dated to 12,650–11,500 calendar (cal.) yr B.P. The general view of the GS-1 is that it was a stable, cool period that started and ended very abruptly (within decades), as documented in a number of records throughout the North Atlantic region (Johnsen et al., 2001; Klitgaard-Kristensen et al., 2001).

Modeling experiments simulating a GS-1 cooling with meltwater in the northern North Atlantic (Broecker et al., 1990) result in a major weakening of the North Atlantic thermohaline circulation (Manabe and Stouffer, 1997, 2000). These experiments have shown that the transitions into, or from, the cool stadial were unstable for >100 yr. Here we present a high-resolution marine proxy record from the Norwegian continental shelf that appears to confirm the high climatic instability suggested by modeling experiments. Stratigraphic records of subdecadal to decadal resolution are required to establish the degree of climate variability characteristic of a transition between glacial and interglacial climate modes. The purpose of this paper is to investigate climate variability in the oceans during the Younger Dryas stadial at the required temporal resolution and to consider the possible driving mechanisms for the degree of climate variability inferred.

The investigated sediment core was retrieved in Andfjorden off northern Norway (Fig. 1). The site is located in a climatically sensitive area. Today it is influenced by warm, saline Atlantic Water transported in the Norwegian Current and by the less saline coastal water in the Norwegian Coastal Current (Fig. 1). Cooler and less saline Arctic Water dominates in the open ocean north and west of the site. High-resolution acoustic surveys at the core site reveal a low-relief, almost flat bathymetry, and ~25 ms (two-way traveltime) of acoustically laminated sedimentary deposits with no sign of mass movements (Plassen and Vorren, 2002). The lithology of the sediments in this area has been described and interpreted in detail in a number of studies (cf. Plassen and Vorren, 2002, and references therein). X-rays of the investigated unit show undisturbed glaciomarine sediment that contains bivalves in live position and only rare bioturbation. Detailed stratigraphic analyses were performed on the glaciomarine unit between 250 and 700 cm depth in the core, including classification of planktic foraminifera (100–1000 μm fraction) (Figs. 2A–2D), identification of ice-rafted debris (IRD, >2 mm) from X-ray radiographs (Fig. 2E), counts of rhyolitic ash grains (>63 μm), and determination of $\delta^{18}O$ and $\delta^{13}C$ values measured on the planktic foraminifer *Neogloboquadrina pachyderma* (sinistral) (Figs. 3A, 3D). *N. pachyderma* lives in the upper 200 m of the water column, and its $\delta^{18}O$ value is an indicator of both global changes in ice volume and local variations in sea-surface temperature (SST) and sea-surface salinity (SSS) (cf. Weinelt et al., 2001, for a review). The corresponding $\delta^{13}C$ is an indicator for the nutrient and ventilation conditions of the surface waters (e.g., Berger and Vincent, 1986). The SST, based on the planktic foraminiferal fauna, has been estimated using both the programs C2 (Juggins, 2002) and SIMMAX (Pflaumann et al., 1996) for modern analogue techniques (Figs. 3F–3H). The SSS was estimated according to the method of Duplessy et al. (1991) (Fig. 3F). Geochemical analyses were performed on both basaltic and rhyolitic ash grains by using a JEOL 840 scanning electron microscope equipped with an EDAX energy-dispersive spectrometer analyzer using ZAF corrections.

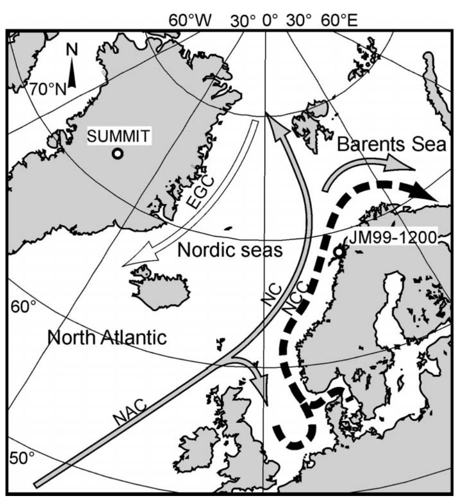

Figure 1. Location map of North Atlantic region, showing positions of marine sediment core used in present study (JM99-1200; 69°15.95′N, 16°25.09′E; 476 m water depth) and SUMMIT ice cores used for correlation. NAC—North Atlantic Current; NC—Norwegian Current; NCC—Norwegian Coastal Current; EGC—East Greenland Current.

AGE MODEL AND TIME RESOLUTION

We obtained 10 accelerator mass spectrometry ^{14}C dates (Table 1) in order to construct an age model. In addition, the counts of rhyolitic grains, identified on the basis of geochemical analysis to represent the Vedde Ash, depict a marked spike at 435.5 cm in the core (Fig. 2F). The lower slope of this spike, at a core level of 436.5 cm, was used as a time marker of 10,310 ^{14}C yr (Birks et al., 1996), corresponding to 11,980 ice-core yr (Grönvold et al., 1995). We used a total reservoir correction of 700 yr (including difference between marine reservoir age of local region and model ocean, $\Delta R = 200$ yr) for the ^{14}C dates between 11,165 and 10,130 ^{14}C yr in accordance

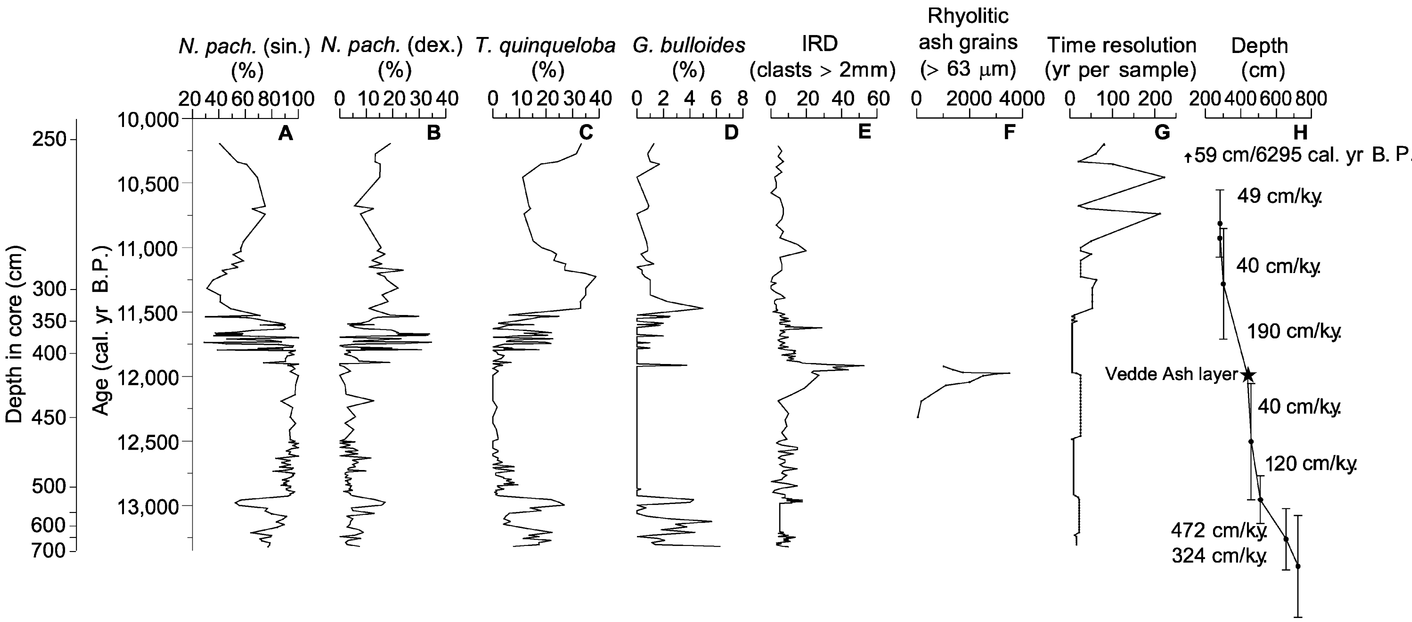

Figure 2. Proxies analyzed from core JM99-1200. A–D: Planktic foraminifera. *N. pach.—Neogloboquadrina pachyderma* (sin.—sinistral; dex.—dextral). *T.—Turborotalita. G.—Globigerina*. E: IRD—Ice-rafted debris. F: Rhyolitic ash grains. Geochemical analysis of rhyolitic grains indicates that they could be correlated to Vedde Ash (cf. Grönvold et al., 1995). Grains have been counted statistically between 425 and 450 cm. Above and below these levels, samples have been inspected for ash grains. G: Time resolution. H: Age model (tephra chronology (Vedde Ash) and accelerator mass spectrometry ^{14}C dates used). Sedimentation rate was calculated by linear interpolation.

with Bondevik et al. (1999) and Waelbroeck et al. (2001). For all older and younger dates, a total reservoir correction of 464 yr (including $\Delta R = 64$ yr) was used (Table 1). These corrections also give the best fit of the ^{14}C dates relative to the Vedde Ash date. The ^{14}C dates were converted to calendar years by using the INTCAL database (Stuiver et al., 1998). Use of this conversion shows that one of the dates (TUa 3728) is too old compared with both the Vedde Ash and the nearby date (KIA 11165, Table 1); this date was therefore rejected. An age model has been constructed by linear interpolation between the dates. The ages used for the calibrated dates (Table 1) represent the mean for the 2σ age interval of highest probability.

The age model in our record shows a very good match with the GRIP and Greenland Ice Sheet Project (GISP) ice cores δ^{18}O values (Johnsen et al., 2001; Grootes et al., 1993) and

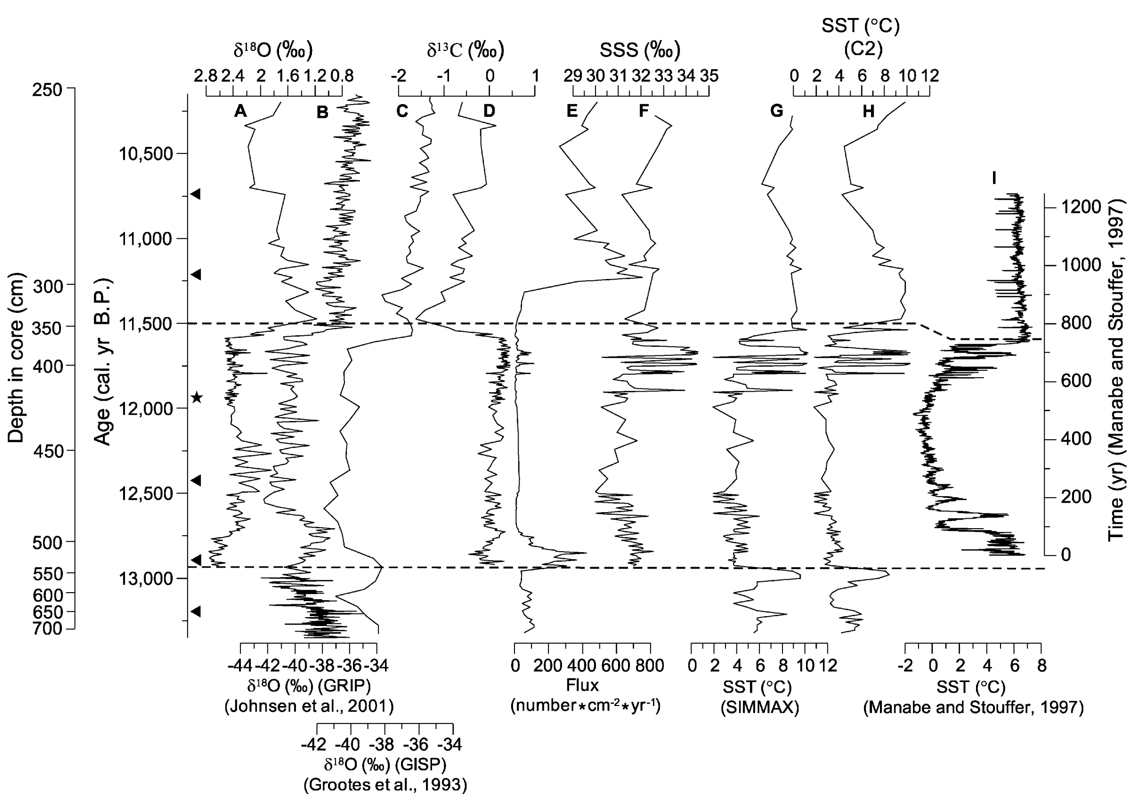

Figure 3. A, D–H: Proxy data from core JM99-1200. B: δ^{18}O values from Greenland Ice Core Project (GRIP) ice core. C: δ^{18}O values from Greenland Ice Sheet Project (GISP) ice core. Isotopic measurements—δ^{18}O (A) and δ^{13}C (D)—δ^{18}O values were corrected for ice-volume effect (Fairbanks, 1989). E: Flux of planktic foraminifera. F: Sea-surface salinity (SSS) with error of 0.5‰ (Duplessy et al., 1991). G and H: Sea-surface temperature (SST). General deviation of SST is ~ ±0.96 °C. Temperatures <3 °C are estimated too warm (Pflaumann et al., 1996). I: SST model results from Manabe and Stouffer (1997). Arrows at left axis show dating points used in age model. Asterisk shows Vedde Ash position. Dashed lines illustrate beginning and end of cold period (GS-1—Younger Dryas).

TABLE 1. RADIOCARBON DATES AND CALIBRATED AGES IN CORE JM99-1200

Core depth (cm)	Lab. ref.	^{14}C age (B.P.)	Reservoir correction (yr)	95.4% (2σ) cal. age ranges†	Age used (cal. yr B.P.)	Local corrected (ΔR)
59	TUa-2921	5965 ± 60	400	6429–6161	6295	64+/−35
280.5	TUa-3728	10,350 ± 85	500	11,352–10,604	*	200+/−50
281.8	KIA-11165	10,130 ± 50	500	11,058–10,538	10,798	200+/−50
300.5	TUa-3729	10,510 ± 85	500	11,697–10,838	11,267	200+/−50
436.5		Vedde Ash			11,980	
457.5	TUa-3730	11,165 ± 90	500	12,939–12,039	12,489	200+/−50
511	TUa-2922	11,460 ± 85	400	13,124–12,754	12,939	64+/−35
655.5	TUa-2923	11,830 ± 85	400	13,484–13,007	13,245	64+/−35
723.5	TUa-2924	12,160 ± 80	400	13,850–13,060	13,455	64+/−35
788	KIA-11109	12,425 ± 55	400	14,292–13,432	13,862	64+/−35
855	TUa-3030	12,575 ± 100	400	15,133–13,450	14,292	64+/−35

Note: The dates (performed on bivalves and shell fragments) were converted into calendar years by using INTCAL 98 (Stuiver et al., 1998) with a selected ΔR (the difference between marine reservoir age of local region and model ocean) for each date. The ΔR value was selected on the assumption that ΔR in northern Norway was higher during Younger Dryas (GS-1) than it was during Allerød (GI-1a) and early Holocene (Bondevik et al., 1999; Waelbroeck et al., 2001). The position of Vedde Ash layer supported the use of ΔR value of 200 yr during GS-1.

*Dating excluded from the age model.

†Calibration data (Stuiver et al., 1998).

requires an offset of only +5 and +49 yr, respectively, at the end of the characteristic temperature step at the GS-1–Holocene boundary shown in both records (Figs. 3B, 3C, 3G, and 3H). The δ^{18}O and δ^{13}C records (Figs. 3A, 3D) from the sediment core depict very significant depletions close to the SST step at the GS-1–Holocene transition, supporting the age model. Further, the SST of the reported record (Figs. 3G, 3H) shows a very good fit to the GISP chronology of the Allerød interstadial (GI-1a–GS-1 transition, with an offset of ~45 yr at the beginning of the decrease in temperature into GS-1 (Fig. 3C).

RESULTS AND DISCUSSION

The GI-1a–GS-1 transition is characterized by a marked drop in SST from values close to modern temperatures in the area (~9–10 °C) to <3 °C. This SST drop indicates increased dominance of Arctic Water relative to Atlantic Water. The SST drop was followed by a peak in foraminiferal flux (Fig. 3D) that may reflect increased production in an oceanic frontal zone area, e.g., the Arctic Front, between Arctic and Atlantic Water.

The period 12,800–12,500 cal. yr B.P. was characterized by a polar planktic foraminiferal fauna (Fig. 2A) and low SSTs, between 2 and 4 °C (Figs. 3G, 3H), suggesting low influx of Atlantic Water and increasing influence of Arctic Water (cf. Hopkins, 1991). These relatively stable, cool conditions were accompanied by a decrease in δ^{18}O (Fig. 3A) supporting a gradual decrease in SSS (Fig. 3F). The decreasing trend is interpreted to reflect a gradual accumulation of fresh surface water. The SSS values were low (average SSS 31.4‰) compared with modern values (~33‰). We consider these SSS values, associated with low SSTs, to be conservative, following Simstich et al. (2002). They showed that δ^{18}O values measured on *N. pachyderma* (sinistral) do not reflect the total freshwater proportion of the surface water owing to the water depth position (70–250 m) of this species in the water column. They found that SSS estimates based on this isotopic signature are overestimated by as much as 2.5‰. However, SSS values for the warmer events (>7 °C) are less reliable (Duplessy et al., 1991).

The lowest time resolution during GS-1 was found between 12,500 and 11,900 cal. yr B.P. (Fig. 2G). This is considered to be the coldest interval based on minima in SSTs (Figs. 3G, 3H), low foraminiferal flux (Fig. 3E), and reduced sedimentation rates (Fig. 2H). Intervals of low SSSs and SSTs ca. 12,500 and 12,000 cal. yr B.P. (Figs. 3E, 3F) indicate a possible increased influence of Arctic Water. An IRD peak occurred at the end of this cold interval. The age of the IRD peak (Fig. 2E) matches well with the age of the onset of deglaciation in the Malangen fjord (Hald et al., 2003), farther inland in the study area.

This coldest interval was succeeded by a period from 11,800 cal. yr B.P. to 11,500 cal. yr B.P. characterized by extreme instability in SSTs. The temperatures oscillated between cold (minimum 2 °C) and warm (maximum 10 °C) on a subdecadal to multidecadal time scale (Figs. 3G, 3H). A total of five SST maxima and 5 minima have been identified during a period of 300 yr. The warming peaks are synchronous with increases in SSS, and the cooling peaks coincide with decreases in SSS (Fig. 3F). The warm peaks are characterized by a higher diversity of subpolar species (Figs. 2B–2D) and a higher flux of planktic foraminifera (Fig. 3E). These fluctuations appear to reflect rapid shifts in the position of an oceanic front separating cool, less saline, and sea-ice–covered water from relatively warm, saline Atlantic Water. A possible source for the cold water is probably Arctic Water in the Norwegian Sea, rather than coastal water influenced by freshwater from the waning Fennoscandian Ice Sheet. The latter would likely have been reflected by extreme depletions in ^{18}O, and fresh meltwater does not support a planktic foraminiferal fauna. The modern planktic foraminiferal fauna in this shelf area is strongly reduced and dominated by juveniles and ''kummer-forms'' because of increasing influence of fresh coastal water (Hald and Vorren, 1984). Such forms are very rare in the reported record. The marine δ^{18}O measurements in the reported proxy record (Fig. 3A) show mainly small variations during the large SST and SSS fluctuations. In general, δ^{18}O values are high, indicating cool SSTs. A possible explanation for this discrepancy between SST, SSS, and δ^{18}O values could be that the isotopic measurements are from the single planktic polar species *N. pachyderma* (sinistral), which reflect mainly the colder end member of the water masses present in the area (Hald and Hagen, 1998). The SSTs, however, are based on integrations of the whole planktic fauna.

PROXY RECORD COMPARED TO MODELING EXPERIMENTS

A simulation of Younger Dryas climate was based on an ocean-atmosphere modeling experiment conducted by Manabe and Stouffer (1997, 2000). The model estimates changes in SSSs, SSTs (Fig. 3I), and thermohaline circulation (THC) forced by a freshwater discharge of 0.1 Sv at 50°–70°N in the North Atlantic Ocean during a 500 yr period. The model is idealized in space and time, but it clearly shows a weakening of the THC at the beginning of the cooling that induces almost synchronous, significant fluctuations in SST and SSS values for ~250 yr until a more stable period becomes established. Rahmstorf (1995) also modeled the sensitivity of the North Atlantic region to an input of freshwater and showed a short period with fluctuating THC at the beginning of such a discharge, followed by a rapid decrease in the vigor of the THC. The model results are in agreement with the declining SSS and SST values suggested by our data between 12,800 and 12,500 cal. yr B.P. (Figs. 3E–3H).

The extreme SST fluctuations identified in the reported proxy record (Figs. 3G, 3H) are also recognizable in model experiments by Manabe and Stouffer (1997, 2000). The Manabe and Stouffer model predicts high-amplitude fluctuations in SST (Fig. 3I) and SSS values for ~150 yr at the end of the cooling period. These fluctuations are in phase with small-scale THC changes superimposed on a gradual increase of the strengthening of the THC. The difference in time scale between the idealized model (Fig. 3I) and the proxy record (Figs. 2 and 3) can be explained by differences in natural vs. modeled freshwater forcing. Goldstein et al. (2003) used a climate and biochemical model to simulate North Atlantic air temperatures for a freshwater discharge simulating a cooling. The model results depict increased air-temperature fluctuations between 11,900 and 11,600 cal. yr B.P. However, the amplitude of the model fluctuations in the atmosphere is not as large as the amplitudes of the SSTs inferred from the proxy record. This model is supported by the ice-core $\delta^{18}O$ record, which shows relatively small fluctuations throughout the GS-1 event (Fig. 3C). Taylor et al. (1997) argued that most of the GS-1–Holocene transition in the GISP-2 ice core occurred over a 40 yr period. This transition included small-scale changes in various atmospheric proxies, e.g., dust concentrations. However, the duration of this unstable period is significantly shorter compared to the extreme SST fluctuations in the reported proxy record.

The extreme temperature fluctuations are reflected only in the reported marine record, not in the ice-core record. The reason for this difference may be that the ice-core proxy record represents a more integrated, regional temperature signature compared to the reported marine record. Alternatively, a lack of snow accumulation at Summit during warm summers could be causing these differences. The good correlation between the reported record and the modeled THC, SST, and SSS fluctuations of the North Atlantic (Manabe and Stouffer, 1997, 2000) suggest that the SST fluctuations in the reported record could be a result of fluctuations of the North Atlantic THC. The extreme fluctuations in SST and SSS values could be magnified due to alternate weakening and strengthening of the convective exchange of cold, less saline surface water with warm, saline subsurface water. Between 11,800 and 11,500 cal. yr B.P., the present proxy record was located in a sensitive boundary area close to oceanic fronts. The results suggest that high-resolution proxy records from this setting allow detection of the rapid shifts between cold and warm climate and major climatic changes in the North Atlantic region.

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