

Anomalously mild Younger Dryas summer conditions in southern Greenland

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ABSTRACT

The first late-glacial lake sediments found in Greenland were analyzed with respect to a variety of environmental variables. The analyzed sequence covers the time span between 14 400 and 10 500 calendar yr B.P., and the data imply that the conditions in southernmost Greenland during the Younger Dryas stadial, 12 800–11 550 calendar yr B.P., were characterized by an arid climate with cold winters and mild summers, preceded by humid conditions with cooler summers. Climate models imply that such an anomaly may be explained by local climatic phenomenon caused by high insolation and Föhn effects. It shows that regional and local variations of Younger Dryas summer conditions in the North Atlantic region may have been larger than previously found from proxy data and modeling experiments.

Keywords: Southern Greenland, lake sediments, paleoclimatic proxy records, Younger Dryas.

INTRODUCTION

The interest in the so-called Younger Dryas stadial—which terminates the last glacial stage and precedes the present interglacial, the Holocene—has grown strong during the last few decades of the twentieth century, and the general implications of this climatic event have also been avidly discussed (e.g., Alley and Clark, 1999).

Although originally discovered and described in detail for a century from Scandinavian lacustrine sediments (Hartz and Milthers, 1901), the records from the deep Greenland Summit ice cores have become a template of this cool event, defined as the Greenland stadial 1 (GS-1) event (Björck et al., 1998) and dated to 12 650–11 500 calendar (cal.) yr B.P. in the GRIP (Greenland Ice Core Project) ice core. The $\delta^{18}\text{O}$ values of the ice as well as other techniques imply that central Greenland was subject to mean annual temperature drops and rises at the beginning and end of the GS-1 event on the order of 10–20 °C (Cuffey et al., 1995; Severinghaus et al., 1998).

LATE-GLACIAL LACUSTRINE RECORD FROM SOUTHERN GREENLAND

Five lakes with pre-Holocene records were cored on islands south and southeast of Nanortalik, southwesternmost Greenland. The oldest of these records was found on the island

of Angissoq (Fig. 1), and was retrieved with a Russian corer (chamber 1 m long, 7.5 cm diameter) from a lake named N14 (59°58.99'N, 44°10.81'W, 33 m above sea level, 3.3 m water depth). Because of glacial unloading, crustal rebound exceeded the global sea-level rise following the deglaciation, and the island rose above sea level. This process turned former marine basins into lakes, and

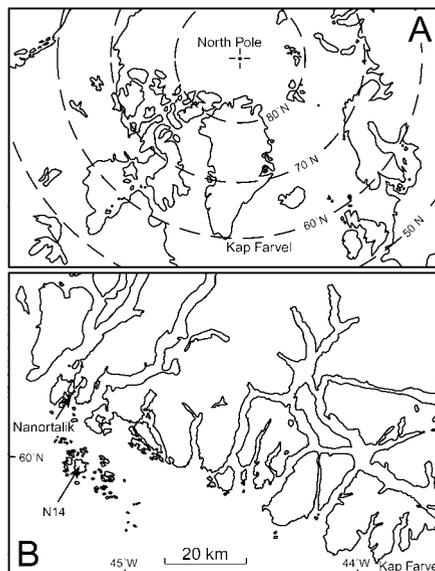


Figure 1. Location map. A: Greenland's central position within North Atlantic region. B: Nanortalik–Kap Farvel area in southernmost Greenland with N14 site indicated.

the ^{14}C age of the isolation of N14 from the sea was calibrated to 13 800 cal. yr B.P. (Bennike and Björck, 2000). At the Younger Dryas onset, the lake had thus been a proper lake for ~1000 yr, but the seashore was only a few hundred meters away and the Greenland ice-sheet margin was possibly situated <20 km from the site.

The sediments were analyzed with a multi-stratigraphic-data approach (organic and mineral matter; biogenic silica [bioSi], sulfur content; magnetic susceptibility; diatom, pollen, and macrofossil content; and annual dry-mass accumulation rate [DMAR] of organic and mineral matter and of bioSi), including high-resolution ^{14}C dating. Here we report from the lower part of the sequence, which begins at 780 cm below the lake surface with a marine silty clay and gyttja clay (Fig. 2). At 771 cm, the sediments become lacustrine, owing to the isolation from the sea. Clay gyttjas alternating with moss gyttjas thereafter dominate the sequence (Fig. 2).

The 18 ^{14}C dates of this soft-water lake were calibrated (Table 1) to create a calendar year-based time scale. Apart from the well-known ^{14}C plateau at 9900–10 100 ^{14}C yr B.P., where calibration is almost meaningless, the calibrated ages display two main sedimentation rates, one below and one above the plateau. If the two sedimentation rates are extrapolated over the plateau, the two curves meet at 742 cm. Because accumulation rates usually alter in connection with sedimentary changes and the only such change during the time of the plateau occurs at 741.5 cm, this is most likely the point at which the sedimentation rate changed markedly. This results in an age of 11 550 cal. yr B.P. for the 741.5 cm level and produces the proper time span, 700 yr, for the plateau (Stuiver et al., 1998). Because of the well-established chronology, all data presented here are related to time (Figs. 2–4).

The boundary between the Allerød interstadial (GI-1a) and the onset of the Younger Dryas stadial (GS-1) is characterized by a distinct shift in ^{14}C ages (e.g., Björck et al., 1996; Hughen et al., 1998); ages of 11 000–

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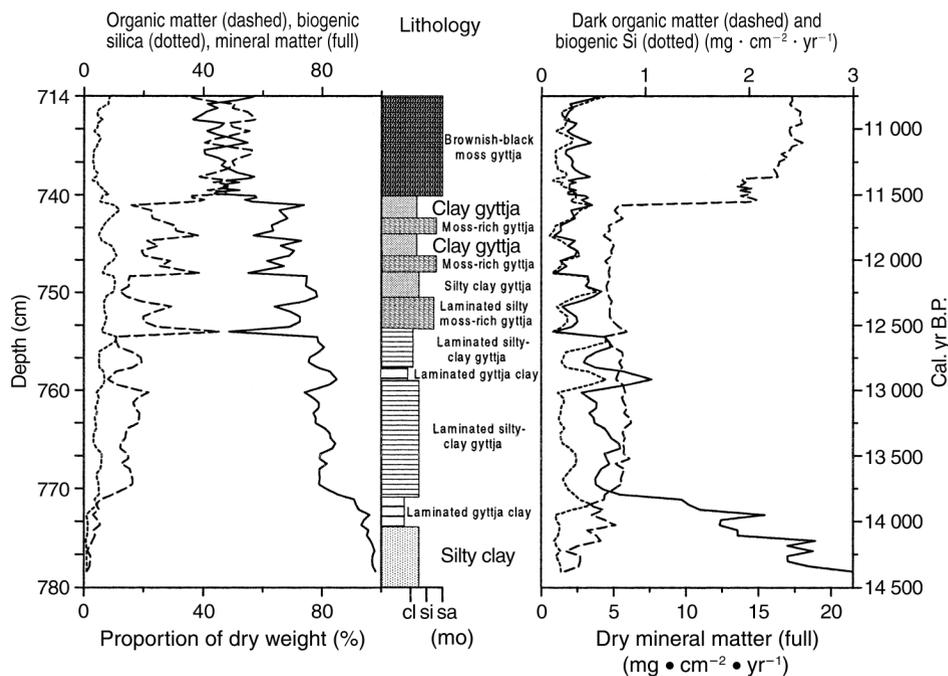


Figure 2. Left diagram shows dry weight percentage of three main sediment components. Sediment lithology is displayed in center; abbreviations: cl—clay, si—silt, sa (mo)—sand and mosses. Gyttja is organic sediment consisting of plant and animal remains (detritus) and with >30% organic material by dry weight. Clay gyttja contains 6%–30% and gyttja clay contains 3%–6% organic material. Right diagram shows annual influx of three components per square centimeter. Note that age scale to right is linear, whereas depth scale to left changes as consequence of changing sedimentation rate at 741.5 cm (see text).

10 900 ¹⁴C yr B.P. below the boundary suddenly shift to ages of 10 700 ¹⁴C yr B.P. This shift is situated at 758 cm (Table 1), corresponding to 12 800 cal. yr B.P. in our age model, and is between the two established Greenland Summit ice-core ages (Johnsen et al., 1992; Alley et al., 1993) for the onset of the Younger Dryas cooling.

Apart from the lithologic change at the isolation of the lake from the sea, the clearest sedimentary change occurs at 11 550 cal. yr

B.P. (Fig. 2), which possibly constitutes a response to altered limnic conditions at the onset of the Holocene. The sedimentary changes between the isolation at 13 800 cal. yr B.P. and 11 550 cal. yr B.P. are, however, very subtle, and the clear lithologic shift at the start of the Younger Dryas cooling, usually seen in north-west European lake records, is clearly lacking.

By plotting the main sediment components as a percentage of dry weight (Fig. 2), a decreasing trend in mineral matter is seen be-

tween 14 400 and 11 550 cal. yr B.P. (Fig. 2). This trend is partly balanced by increasing organic matter, especially from 12 600 cal. yr B.P. onward, and by bioSi percentages, especially between 12 700 and 11 600 cal. yr B.P. If, however, these components are expressed as annual DMAR (expressed as $\text{mg}\cdot\text{yr}^{-1}\cdot\text{cm}^{-2}$), a somewhat different picture emerges. The DMAR of organic matter is stable after isolation, followed by an abrupt rise at 11 550 cal. yr B.P., whereas the DMAR of mineral matter shows a decreasing trend, but with no distinct change in connection with the lithologic shift at 11 550 cal. yr B.P. The DMAR of bioSi reaches a peak during the isolation phase, followed by fairly stable values until 13 000 cal. yr B.P. Between 13 000 and 12 200 cal. yr B.P., higher values are attained, followed by slightly lower but varying values. It is noteworthy that higher bioSi values are usually found in connection with the moss-barren sediments (Fig. 2), i.e., the clay gyttjas, and that these sediments after 13 000 cal. yr B.P. have considerably higher contents and DMARs of bioSi than corresponding sediments before 13 000 cal. yr B.P.

We conclude that pre-Holocene lake productivity was fairly constant, but with possibly higher productivity and less surface runoff (decreased DMAR of mineral matter), after 13 000 cal. yr B.P., i.e., during Younger Dryas time. The increase in DMAR of organic matter at 11 550 cal. yr B.P. is explained by the sudden moss dominance. This implies better light conditions at the lake bottom due to, e.g., decreased phytoplankton biomass in the upper water column, but possibly not because of a decreased amount of suspended mineral matter; the previously decreasing trend of DMAR of mineral matter is interrupted by slightly increasing values after 11 600 cal. yr B.P. (Fig. 2). Instead, the latter implies increased surface runoff.

The sediments are extremely poor in pollen grains. With the exception of the 13 150 cal. yr B.P. level, pollen concentrations vary between 0 and 5700 grains per cubic centimeter. Because of the low pollen sums, we only present concentration and influx curves (Fig. 3). Apart from the 13 150 cal. yr B.P. level, pollen concentrations and influx values are very low until 11 400 cal. yr B.P., followed by a gradual rise. This occurs a few hundred years into the Holocene, beginning at 11 550 cal. yr B.P., implying a gradual establishment of higher vegetation. The appearance of, e.g., *Empetrum nigrum* and *Vaccinium* pollen types in the core at 11 500 cal. yr B.P. suggests that these plants were present on the island already during the Younger Dryas. Other types present between 12 900 and 11 500 cal. yr B.P. are, e.g., Poaceae, Caryophyllaceae of *Sagina* type, Chenopodiaceae, and *Saxifraga caespitosa* type. The latter may suggest arid conditions, partly in contrast to the more wet-demanding *Saxi-*

TABLE 1. THE RADIOCARBON DATING SERIES FROM N14

Depth (cm)	Dated material*	$\delta^{13}\text{C}$ (‰)	¹⁴ C age (¹⁴ C yr B.P.)	Calibrated age (cal. yr B.P.)	Lab no.
708.75–708.25	Aqm	-20.4	9335 ± 60	10 600–10 420	AAR-5805
712.75–712.25	Aqm	-19.6	9445 ± 55	10 750–10 560	AAR-5804
719.25–718.75	Aqm	-18.9	9690 ± 70	11 200–10 860	AAR-5803
727.25–726.75	Aqm	-17.5	9810 ± 60	11 235–11 170	AAR-5801
730.2–729.8	Aqm	-20.2	10 025 ± 80	11 650–11 290	Ua-15411
736.2–735.8	Aqm	-21.1	10 005 ± 95	11 640–11 250	Ua-15410
738.1–737.9	Aqm	-22.3	9955 ± 85	11 450–11 220	Ua-15409
740.1–739.9	Aqm	-22.7	10 100 ± 100	11 950–11 300	Ua-14925
747.1–746.9	Aqm	-22.0	10 040 ± 95	11 700–11 290	Ua-15407
748.9–748.7	Aqm	-22.6	10 330 ± 90	12 350–11 900	Ua-15406
751.2–750.8	Aqm	-23.5	10 430 ± 85	12 650–12 100	Ua-15405
754.1–753.9	Aqm	-23.9	10 585 ± 85	12 860–12 350	Ua-15404
757.25–756.75	Bulk	-19.9	10 780 ± 95	12 980–12 800	Ua-15883
759.75–759.25	Bulk	-22.0	11 030 ± 95	13 150–12 940	Ua-15884
761.25–760.75	Bulk	-20.7	11 355 ± 95	13 430–13 170	Ua-15885
762.75–762.25	Bulk	-20.7	11 510 ± 100	13 550–13 150	Ua-15886
764.25–763.75	Bulk	-18.3	11 600 ± 95	13 700–13 430	Ua-15887
771–765	Tem	-22.3	11 665 ± 125	13 830–13 450	Ua-14844

Note: Calibrated ages are shown with age ranges of more than 50% probability according to Oxcal 3.5 (Bronk Ramsey, 1998), based on the INTCAL98 calibration data set (Stuiver et al., 1998). Datings were performed at the AMS laboratories in Århus and Uppsala.

*Abbreviations: Aqm = aquatic mosses, Bulk = bulk sediment, Tem = terrestrial mosses.

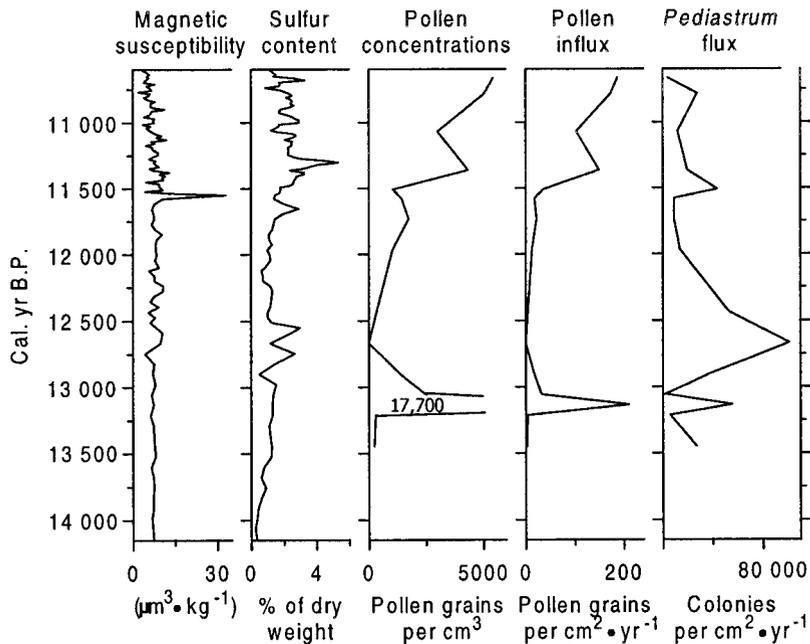


Figure 3. Magnetic susceptibility and sulfur content of sediments, as well as total pollen concentrations, pollen influx values, and flux of *Pediastrum* (green algae) colonies related to calendar years before present.

fraga stellaris found before 12 800 and after 11 550 cal. yr B.P. More than half of the pollen grains at 13 150 cal. yr B.P. are of the Caryophyllaceae *Sagina* type, which indicates that the plant must have grown close to the lake. The only macroscopic remains of vas-

cular plants were a few seeds of *Minuartia* sp. (Caryophyllaceae) and *Saxifraga* cf. *oppositifolia* in a sample between 13 800 and 13 400 cal. yr B.P., and the former was also found between 12 800 and 12 600 cal. yr B.P.

The sediments are rich in colonies of green

alga *Pediastrum*. The *Pediastrum* flux curve shows a maximum between 12 900 and 12 500 cal. yr B.P., followed by lower, but still high values (Fig. 3). The lower frequencies after 11 500 cal. yr B.P., causing better light conditions at the bottom of the lake, can partly explain the abundance of aquatic mosses during the early Holocene.

The diatom flora, with 53 different species, is dominated by a few pioneer species (Fig. 4). The lower part of the sequence is dominated by *Achnanthes conspicua* and *Fragilaria virescens* var. *exigua*. The former is a brackish-water-tolerant species, indicating, e.g., influence from sea spray, whereas the latter often occurs early in lake successions. At 12 800 cal. yr B.P., the flora became dominated by *Achnanthes* [*minutissima* agg.] and *Achnanthes pusilla*, but *F. virescens* var. *exigua* was still common. The two former taxa are cosmopolitan, and especially *A. [minutissima* agg.] is common in early Holocene profiles (Bradshaw et al., 2000; Rosén et al., 2001), following disturbances of different types. The lake was thus dominated by three pioneer species during the Younger Dryas stadial, but the increasing dominance of the two *Achnanthes* taxa is best explained by increased pH; *A. [minutissima* agg.] often occurs after liming (Rhodes, 1991). The pH reached a maximum between 12 500 and 11 500 cal. yr B.P. (Fig. 4), indicating increased weathering and leakage of base cations from the drainage area or

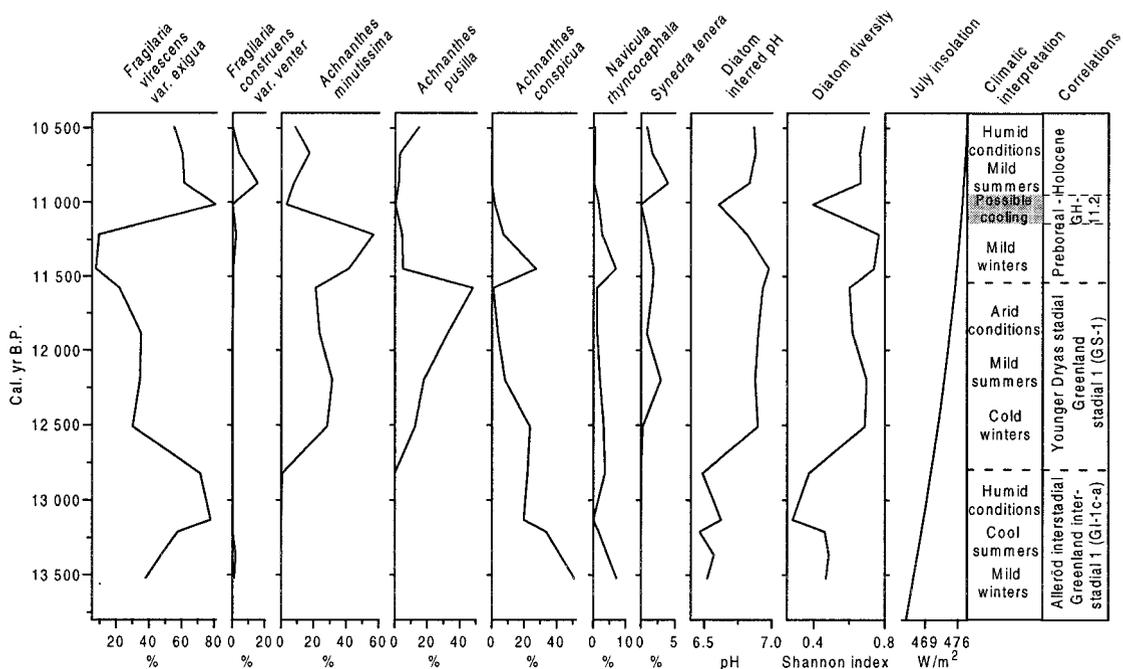


Figure 4. Most abundant diatom species, related to calendar years B.P., as well as diatom-inferred pH and diatom diversity. Between 330 and 400 diatom valves per sample were counted; methods followed Rosén et al. (2000). For pH reconstruction, weighted-average model was employed with inverse deshinking (Birks et al., 1990) used on 50-lake training set from northern Sweden (Rosén et al., 2000), where $R^2_{\text{jack}} = 0.61$ and root-mean-squared error of prediction (RMSEP) = 0.30 units. R^2 and RMSEP are based on jackknifing. Diatom diversity was calculated as Shannon index (Zar, 1996). To right is shown July insolation curve for 60°N (Berger, 1978) and inferred local climatic development and correlations to North Atlantic climatic events, with both traditional terminology and new event stratigraphy (Björck et al., 1998; Walker et al., 1999).

increased concentration of nutrients. The simultaneous decreasing flux of mineral matter (Fig. 2) implies that the latter explanation is the most likely one. This is also supported by high *Pediastrum* fluxes (Fig. 3), the maximum in diatom diversity (Fig. 4), and the fairly high content and fluxes of bioSi (Fig. 2).

LATE-GLACIAL PALEOCLIMATIC SCENARIO

Our data suggest that the time period for the Younger Dryas stadial was preceded and followed by more unstable and humid conditions. They also imply that lake productivity during the Younger Dryas was high and that the pH of the lake water increased, possibly because of an increased nutrient load during the growing seasons. This suggests that Younger Dryas summers, with high insolation, were fairly warm and dry, causing lake levels to drop, concentrating the nutrients, and increasing lake-water temperatures. The presence of the diatom *Synedra tenera*, with an abundance optimum at temperatures of 14 °C (Rosén et al., 2000), during the Younger Dryas and after 11 000 cal. yr B.P. (Fig. 4) also implies fairly warm lake temperatures. The seemingly stable conditions and the lack of vegetation succession imply that winters were cold and dry. A thin snow cover reduced spring melt effects and the possibility for most plants to survive harsh winter conditions.

Our data therefore suggest that the Younger Dryas climate in southernmost Greenland was characterized by fairly arid conditions. Furthermore, the Younger Dryas minimum of the sea-spray—indicating diatom *Achnanthes conspicua* (Fig. 4), together with the sulfur minimum (Fig. 3), suggests that the surrounding ocean was ice covered during most of the year, preventing a wind- and wave-induced sea-spray influence.

At 11 550 cal. yr B.P., the conditions rapidly changed into a humid climate with significantly warmer winters, and the previously ice-covered sea opened. However, a period of less favorable conditions occurred a few hundred years into the Holocene (Figs. 3 and 4), which may correspond to the Preboreal oscillation (Björck et al., 1996) or the GH-11.2 event (Walker et al., 1999).

DISCUSSION

A reduction of the Atlantic thermohaline circulation, triggered by increased freshwater fluxes, is an important hypothesis to explain the Younger Dryas cooling. We therefore compare our results with the output from global coupled atmosphere ocean models forced to simulate the consequences of such a process. Schiller et al. (1997) forced the ECHAM3/LSG coupled general circulation model (GCM) with increased meltwater discharge into the North Atlantic to directly simulate the isolated effect of a reduction in the

North Atlantic deepwater formation. Aiming at simulating the rapid warming terminating the Younger Dryas, Fawcett et al. (1997) used the GENESIS model—an atmospheric GCM coupled to a mixed-layer ocean model with specified meridional heat transport—and indirectly specified a change in the deep-water formation by varying the heat convergence in the Nordic Seas. The simulation responses are consistent with our reconstruction: a south-eastward extension of the North Atlantic sea-ice margin with an associated winter cooling spreading over most of the northern North Atlantic region, resulting in winter temperature drops between 20 °C (Schiller et al., 1997) and 15 °C (Fawcett et al., 1997) in southern Greenland. Both models show reduced Younger Dryas precipitation as compared to the situation with nonreduced deep-water formation. Regarding seasonality, both models (although not shown in Schiller et al., 1997) show by far the largest anomalies in winter, in contrast to small or even close to zero temperature and precipitation anomalies in summer. None of the simulations, however, indicate anomalously warm summers as suggested by our data set. This discrepancy could be attributed to local weather conditions, which cannot be captured at the coarse horizontal resolution of the two models. In particular, this may relate to locally very dry lee conditions with high insolation, i.e., a so-called Föhn effect, developing in southernmost Greenland if the anomalous wind has a northerly direction. It is likely that such local phenomena could offset larger scale patterns and lead to anomalous local energy inputs during summer—an effect that, compared to present day, could be enhanced by the high summer insolation during the Younger Dryas.

The study demonstrates the necessity of a dense network of paleoclimatic sites in combination with fine-resolution modeling, to advance our knowledge about the complexities of seemingly stable climatic scenarios, e.g., the Younger Dryas cooling in the North Atlantic region.

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