GEOPHYSICAL RESEARCH LETTERS, VOL. 37, L03501, doi:10.1029/2009GL041013, 2010

Permafrost evidence for severe winter cooling during the Younger Dryas in northern Alaska

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Received 18 September 2009; revised 30 November 2009; accepted 5 January 2010; published 4 February 2010.

[1] The Younger Dryas cold event, a rapid reversion to glacial climate conditions at the Pleistocene-Holocene transition, has generally been attributed to the release of meltwater from the Laurentide Ice Sheet to the North Atlantic or Arctic oceans. The reaction of the North Pacific region to this "shutdown" of the thermohaline circulation in the North Atlantic during Younger Dryas is little understood. In this paper, we present the first radiocarbon-dated centennial-scale stable water isotope record from permafrost in northern Alaska. This Late Glacial winter climate reconstruction from Barrow ice wedges demonstrates the existence of a Younger Dryas cold event, formerly believed to be reduced or absent in this area. Our stable isotope data display a gradual change of the atmospheric moisture source conditions during the Younger Dryas, likely associated with the successive opening of the Bering Strait. **Citation:** Meyer, H., L. Schirrmeister, K. Yoshikawa, T. Opel, S. Wetterich, H.-W. Hubberten, and J. Brown (2010), Permafrost evidence for severe winter cooling during the Younger Dryas in northern Alaska, *Geophys. Res. Lett.*, *37*, L03501, doi:10.1029/2009GL041013.

1. Introduction

[2] The Younger Dryas (YD) interval, from approximately 12.9 to 11.5 kyr cal BP, is of great interest for understanding rapid natural climate change, especially with regard to recent global warming scenarios. Various archives such as glacier ice [e.g., *Dansgaard et al.*, 1989; *Alley*, 2000; *Steffensen et al.*, 2008], tree rings [*Muscheler et al.*, 2008], lacustrine [*Kokorowski et al.*, 2008] and marine sediments [*McManus et al.*, 2004; *Broecker*, 2006] provide evidence for strong climate variability during the Late Glacial-Holocene transition. However, between these archives there is still major disagreement on timing, length, seasonality and spatial extent of the YD cold event [*Muscheler et al.*, 2008]. The consequences of abrupt climate change have been dramatic for both, paleo fauna and human population during the YD [*Firestone et al.*, 2007]. As permafrost regions are known to be susceptible to recent climate warming [*Osterkamp*, 2005; *Lemke et al.*, 2007; *Romanovsky et al.*, 2007], particularly with regard to feedback mechanisms of a potential release of stored carbon from permafrost [*Walter et al.*, 2006; *Zimov et al.*, 2006], they should also store evidence of these changes. However, little is known about the potential of permafrost as paleoclimate archive, which can be studied by stable water isotopes analogously to glacier ice [*Mackay*, 1983; *Meyer et al.*, 2002]. In this paper, we present a winter climate record from ground ice in permafrost of northern Alaska, a region, where paleoclimate records extending beyond the Late Glacial-Holocene transition are rather sparse, often restricted to lake sediments and rely mostly on summer indicators such as pollen [*Kokorowski et al.*, 2008].

[3] In permafrost science, ground ice is defined as all types of ice contained in frozen or freezing ground [*van Everdingen*, 1998] including ice wedges. Ice wedges are widely distributed in non-glaciated high northern latitudes, are diagnostic of permafrost and, in general, indicative of periods of cold and stable climate conditions. They are found in both continuous and discontinuous permafrost zones and may also have formed during and survived interglacials [*Froese et al.*, 2008]. Ice wedges are distinctive due to their vertically-oriented foliations and air bubbles. They form as winter thermal contraction cracks are periodically filled by surface water (mainly from snow melt), which quickly (re)freezes at negative ground temperatures forming ice veins [*Lachenbruch*, 1962]. The seasonality of thermal contraction cracking and of the infill of frost cracks are generally related to winter and spring, respectively. Ice wedges are, thus, indicative of winter climate conditions.

[4] We investigated a relict, buried ice-wedge system within the continuous permafrost zone near Barrow, northern Alaska (71°18′N, 156°40′W; Figure 1). The Barrow ice-wedge system (BIWS) is buried under about three meters of Late Glacial/early Holocene ice-rich sediments. Permafrost in this area is cold (about −9°C) and extends to over 300 meters in depth. The section, situated a few hundred meters to the East of the Barrow village, was excavated and first described in the early 1960s [*Brown*, 1965]. The BIWS consists of two intersecting ice wedges, which were sampled at a depth of 4.5 m below the surface, perpendicular to its growth structures, covering the complete time interval of ice wedge formation. In total, 131 samples were taken for stable isotope analyses from ice wedges in five sampling transects, which were sampled with an electric chain saw (1.5 cm slices in 10 cm intervals). All ice samples were transported frozen to the cold laboratory at Alfred Wegener Institute for Polar and Marine Research (Bremerhaven, Germany), where they were cut for stable isotope and radiocarbon analyses. Ages of organic remains in the buried ice-wedge system were determined by Accelerator Mass Spectrometry (AMS) ^{14}C-dating of plant remains (mainly lemming pellets, small roots, leaves or twigs) picked

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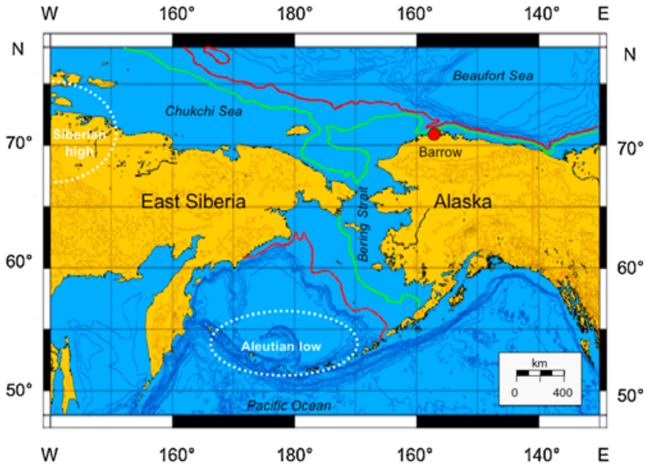

Figure 1. Location of the Barrow ice-wedge system (BIWS) in northern Alaska (red dot). Red and green contours indicate the −100 m and −50 m isobaths, respectively. The −100 m isobath corresponds widely to the position of the shoreline at 18 kyr cal BP [*The PALE Beringian Working Group*, 1999]. White dotted lines give the approximate positions of the modern dominant atmospheric pressure centers (Aleutian low and Siberian high) according to *Mock et al.* [1998].

under light microscope. The measurements were carried out in the AMS facility of the Leibniz Laboratory in Kiel, Germany [*Nadeau et al.*, 1997, 1998]. In order to eliminate contamination by younger organic acids only the leached residues were used for dating. AMS ^{14}C-ages were calibrated using the CALIB rev. 5.02 Software, Calibration dataset: intcal04.14c [*Reimer et al.*, 2004]. Mean calibrated ages were calculated from the minimum and maximum values (2σ range). Stable water isotopes were measured with a Finnigan MAT Delta-S mass spectrometer at the Alfred Wegener Institute, Research Unit Potsdam using equilibration techniques. Hydrogen and oxygen isotope ratios are given as per mil difference relative to V-SMOW (‰, Vienna Standard Mean Ocean Water), with internal 1σ errors better than 0.8‰ and 0.1‰ for δD and δ^{18}O, respectively [*Meyer et al.*, 2000].

2. Results and Discussion

[5] In this paper, we present the stable oxygen (δ^{18}O, ‰ V-SMOW) and deuterium excess records (d excess = δD − 8* δ^{18}O [*Dansgaard*, 1964]) from the BIWS (Figure 2). The δ^{18}O values are interpreted as a proxy for air temperatures in the region of precipitation, whereas the d excess characterizes sea surface conditions (i.e., relative humidity, temperature, wind speed) in the moisture source region [*Merlivat and Jouzel*, 1979]. The chronology of the BIWS stable isotope record is based upon mean calibrated AMS ^{14}C-ages. AMS ^{14}C-dates of organic matter enclosed in the BIWS suggest continuous ice-wedge formation for about 3000 years duration between 14.4 and 11.3 kyr cal BP (before present = before 1950; Table 1, comprising the Bølling-Allerød Interstadial (BA), the Younger Dryas Stadial (YD) as well as the onset of the Preboreal warming (PB). Regular ice wedge growth is supported by continuously decreasing ^{14}C-ages from the lateral contact towards the center of the ice wedges. We interpolated linearly between each two neighboring ^{14}C-dated samples in order to generate a stacked BIWS stable isotope record. The enhancement of the stable isotope record of the BIWS is based on the assumption of regular ice-wedge growth (as supported by the sequence of AMS ^{14}C-dates in the BIWS) as well as on constant horizontal growth rates between two ^{14}C-dated samples. Further details about the sampling locality and the paleoenvironmental context are given by H. Meyer et al. (Late Glacial and Holocene isotopic and environmental history of northern coastal Alaska: Results from a buried ice-wedge system at Barrow, submitted to Quaternary Science Reviews, 2009).

[6] The BIWS stable isotope data is compared to the N-GRIP (North Greenland Ice Core Project) δ^{18}O and d excess records [*Steffensen et al.*, 2008] (Figure 2) for the time interval between 15 and 10 kyr cal BP. N-GRIP is the most recently published Greenland ice-core record with

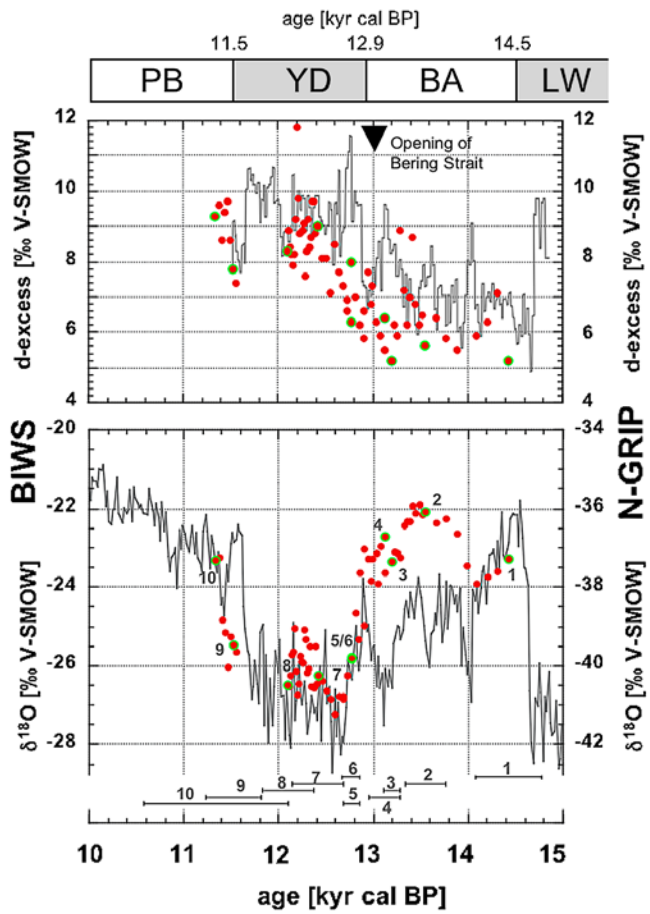

Figure 2. Stable isotope record (top; d excess, and bottom; δ^{18}O) of the Barrow ice-wedge system (BIWS, red dots) in comparison with the N-GRIP ice core [*Steffensen et al.*, 2008] in 20-yr resolution (grey lines) for the time interval between 10 and 15 kyr cal BP. Green circles indicate directly AMS ^{14}C-dated samples (mean calibrated ages), which are numbered as in Table 1. In Figure 2 (bottom), 2σ error bars of each date are displayed. Main chronological units are given: LW, Late Wisconsin; BA, Bølling-Allerød; YD, Younger Dryas; and PB, Preboreal.

Table 1. Radiocarbon Dates of Organic Remains in Ice Wedges of the Barrow Ice-Wedge System

	Sample ID	Radiocarbon Age (yr BP)	Calibrated Age 2σ Range (yr cal BP)	Mean Calibrated Age (yr cal BP)	Lab ID
1	BAR-IW-^{14}C-1	12,370 ± 60	14,770–14,082	14,426	KIA 25339
2	BAR-IW-^{14}C-3	11,700 ± 100	13,761–13,338	13,550	KIA 33159
3	BAR-IW-^{14}C-5	11,310 ± 45	13,275–13,107	13,191	KIA 25656
4	BR06-IW-4.1	11,250 ± 90	13,284–12,956	13,120	KIA 33157
5	BAR-IW-^{14}C-7	10,740 ± 60	12,861–12,681	12,771	KIA 25657
6	BR06-IW-4.9	10,730 ± 60	12,857–12,674	12,766	KIA 33158
7	BAR-IW-^{14}C-11	10,480 ± 65	12,690–12,141	12,416	KIA 25658
8	BAR-IW-^{14}C-22	10,290 ± 45	12,367–11,830	12,099	KIA 25659
9	BR06-IW-3.11	9990 ± 80	11,811–11,238	11,525	KIA 33156
10	BR06-IW-3.5	9850 + 230 / − 220	12,098–10,585	11,342	KIA 33155

highest resolution and dating accuracy for the Late Glacial-Holocene transition. The similarity between N-GRIP and BIWS δ^{18}O records is striking with a prominent decrease in δ^{18}O at 12.9 kyr cal BP and subsequent increase at around 11.5 kyr cal BP bracketing the YD cold stadial. Although the absolute N-GRIP δ^{18}O values are lower reflecting colder mean annual air temperatures at the Greenland drill site, both N-GRIP and BIWS records display δ^{18}O variations of the same order of magnitude (6‰ in BIWS; 7‰ in N-GRIP ice core). The decrease in δ^{18}O reflecting colder temperatures at around 12.9 kyr cal BP occurs nearly contemporaneously both in N-GRIP and BIWS records, whereas the increase in δ^{18}O at 11.5 kyr cal BP is interpreted as early PB warming pulse, which is recorded first in the N-GRIP ice core, followed by a more gradual change in the BIWS δ^{18}O record with a lag of 100 to 200 years. The contemporaneous cooling of N-GRIP and BIWS records at the onset of the YD is supported by two directly AMS ^{14}C-dated samples (Table 1 and Figure 2; samples N° 5 and 6) in the BIWS sequence. However, the gradual warming around 11.5 kyr cal BP towards the beginning of the PB has the largest dating uncertainty (Table 1 and Figure 2) and should therefore be interpreted with more caution. The coldest phase in both records is around 12.5 kyr cal BP. These observations contrast with re-evaluation of paleoclimate (mostly palynological) data from Alaska, which suggest that the YD cold event has been absent or reduced in northern Alaska [*Kokorowski et al.*, 2008]. Therefore, using the modern synoptic climatology [*Mock et al.*, 1998] provides further insight to the interpretation of regional paleoclimate records. During the second half of the 20th century, atmospheric circulation patterns were seasonally and spatially heterogeneous. Changes in position and intensity of the Aleutian low as well as of the Siberian high (Figure 1) are responsible for large parts of the climate variability in this region [*Mock et al.*, 1998]. Accordingly, the cold season during the YD was associated with a stronger and more pronounced Aleutian low [*Kokorowski et al.*, 2008]. The evidence of a YD cold event in the BIWS δ^{18}O record emphasizes that the YD in northern Alaska was related to the winter season. This is supported by prominent YD evidence in southern Alaskan coastal regions [*Kokorowski et al.*, 2008], which are presently characterized by winter precipitation maxima [*Mock et al.*, 1998].

[7] Both, N-GRIP ice core and BIWS data have a tendency for relatively low δ^{18}O values in their records at about 14.0 to 14.2 kyr cal BP, but at higher temperature level than in YD. A cold phase between Bølling and Allerød stages is known from the Greenland ice cores as Older Dryas event and could also be detected in the BIWS δ^{18}O record. The major discrepancy between both records is a well-defined maximum in the BIWS δ^{18}O dataset during the BA period (at about 13.5 kyr cal BP), as compared to the N-GRIP ice core δ^{18}O maximum at 14.5 kyr cal BP. The BIWS δ^{18}O maximum is contemporaneous to other regional records such as the initial establishment of Betula shrub tundra in western Alaska [*Hu et al.*, 2002]. This suggests that in Alaska not only the ecological response but also the BA winter climatic optimum differs by about 800–1000 years from the Greenland temperature maximum.

[8] It is generally agreed that oceanographic changes in the North Atlantic region (e.g., of the meridional overturning circulation) are responsible for the sudden Northern Hemispheric climate deterioration [*McManus et al.*, 2004; *Broecker*, 2006]. The YD cooling has been attributed to the release of meltwater from the Laurentide Ice Sheet to the North Atlantic or Arctic oceans [*Tarasov and Peltier*, 2005], which stopped or weakened North Atlantic deep water (NADW) formation and, thus, the thermohaline conveyor belt. The "shutdown" of the meridional overturning circulation and the subsequent lack of heat transport to the Arctic during YD led to a rapid temperature drop in the entire Northern Hemisphere. This was connected with altered atmospheric circulation patterns and the southward extension of the Arctic sea ice cover. Global circulation model simulations suggest lower sea surface temperatures (SST) during the YD [*Mikolajewicz et al.*, 1997], both in the North Atlantic (about 4 K) and North Pacific (about 2.5 K) regions. Combining the δ^{18}O records from N-GRIP ice core and BIWS, we assume that the YD cooling occurred nearly contemporaneously at both sites, whereas warming pulses might occur by centuries later in northern Alaska. Despite the mentioned dating uncertainties in the BIWS record, the PB warming at about 11.5 kyr cal BP could have originated in the North Atlantic likely due to the re-initiation of NADW formation [*McManus et al.*, 2004].

[9] The d excess records from both BIWS and N-GRIP ice core coincide in general trends and absolute values (Figure 2). The BIWS varies from low d excess (of about 6‰) during BA to higher d excess (of about 9‰) in YD. A similar trend in the N-GRIP d excess record from 6–7‰ in BA to about 9–10‰ in YD has been observed between 13.5 and 12.8 kyr cal BP [*Steffensen et al.*, 2008]. An abrupt shift in the N-GRIP d excess record at 12.9 kyr cal BP has been precisely dated and reaches maximum d excess values of 11.5‰. This has been interpreted as rapid reorganization

of the Arctic atmospheric circulation and was accompanied by low precipitation rates in Greenland [*Dansgaard et al.*, 1989; *Alley*, 2000]. The shift in the BIWS d excess record illustrates that Alaskan atmospheric circulation patterns were part of this reorganization process, but more smoothly and, with a lag of about 500–600 years, later than in Greenland. A rise in d excess is indicative of a different (e.g., southward shifted) moisture source (or changing conditions within a stationary moisture source) characterized by lower relative humidities and/or higher SSTs. However, for both North Pacific and North Atlantic, lower SSTs were modeled [*Mikolajewicz et al.*, 1997]. A similar counter-intuitive shift in d excess has been described for Greenland high elevation sites with low d excess in mild phases and high d excess in cold phases [*Johnsen et al.*, 1989]. This has been explained by a southward shift of the polar front and a more southern sea-ice limit leading to higher latitudinal temperature gradients and stronger zonal wind patterns. Therefore, a shift to a different (warmer or less humid) moisture source for winter precipitation in northern Alaska is likely. We suggest that the lag of this shift behind the Greenland record and the gradual increase of BIWS d excess is related to oceanographic changes such as the opening of the Bering Strait between about 12 and 11 kyr ^{14}C BP [*Elias et al.*, 1996; *Keigwin et al.*, 2006]. *Bradley and England* [2008] refined this estimate to about 13 kyr cal BP, when inflow of Pacific water through the Bering Strait brought first Pacific bivalves to the Arctic Ocean. The breaching of the Bering Strait initialized a northward flow of large amounts of low-saline Pacific water to the Arctic Ocean. A local cold-SST moisture source for winter precipitation in northern Alaska, however, can be excluded according to our d excess data. Additionally, the Bering Strait was frozen in winter and low temperatures imply a low moisture-carrying capacity of air masses. Therefore, we hypothesize that the general change of oceanographic circulation patterns in the North Pacific region, especially of the sea surface water, might have caused this gradual change of the BIWS moisture source region.

3. Conclusions

[10] Our findings highlight the potential of permafrost, especially ice wedges, as centennial-scale, winter season paleoclimate archives, which expand the spatially-restricted glacier ice records to larger continental areas of the Northern Hemisphere. The BIWS record represents the first isotope-based permafrost climate record of the Late Glacial-Holocene transition including first well-documented evidence for the YD cold stadial. A similar d excess record from the Greenland ice sheet and its permafrost “analogue” in Alaska underline the atmospheric-oceanographic linkage between both regions.

[11] **Acknowledgments.** Field logistics was provided by the Barrow Arctic Science Consortium (BASC) in support of the U.S. National Science Foundation Project OPP-0327664, Barrow Permafrost Observatory. The site is owned by the Ukpeagvik Iñupiat Corporation (UIC), the Barrow Village Corporation.

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