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Link between European and North Atlantic abrupt climate changes over the last glaciation

Denis-Didier Rousseau,[1,2,3,4] Adriana Sima,[1] Pierre Antoine,[5] Christine Hatté,[6] Andreas Lang,[7] and Ludwig Zöller[3]

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[1] Sub-millennial timescale climate variations correlated with those in the North Atlantic area are identified in the loess sequence from Nussloch, Germany, exceptionally developed over the interval between about 38,000 and 18,000 years ago. The Dansgaard-Oeschger (DO) events 8 to 2, as well as some less pronounced warming episodes recorded in the Greenland ice have their counterpart in the Nussloch loess stratigraphy and in the variations of the loess grain-size index (GSI). The North Atlantic Heinrich events 3 and 2 are expressed at Nussloch as maxima of the GSI record. The similarity of the fine variations in the Nussloch loess and the Greenland ice records points to an intimate link of climate changes in Western Europe with those in the North Atlantic. **Citation:** Rousseau, D.-D., A. Sima, P. Antoine, C. Hatté, A. Lang, and L. Zöller (2007), Link between European and North Atlantic abrupt climate changes over the last glaciation, *Geophys. Res. Lett.*, *34*, L22713, doi:10.1029/2007GL031716.

1. Introduction

[2] Detailed evidence of rapid climate variations punctuating the last glaciation (between about 100,000 and 15,000 years ago) was found in the Greenland ice cores and in the North Atlantic marine sediments. Temperature oscillations over the Greenland (Dansgaard/Oeschger (DO) events [*Dansgaard et al.*, 1993] were correlated with the shifts of sea surface temperature (the Bond cycles [*Bond et al.*, 1993]) and with the episodes of massive iceberg discharge into the North Atlantic (Heinrich (H) events [*Bond et al.*, 1992]). Then, climate fluctuations correlated with those in the North Atlantic area have been identified in records at different locations worldwide [*Voelker*, 2002], suggesting that large areas responded to the coupled ocean-atmosphere signal, especially in the northern hemisphere. In Western Europe, even though it is adjacent to the North Atlantic and under direct influence of the westerlies, such information is scarce. This may be due not only to the different geographic settings, but also to the generally insufficient temporal resolution (or discontinuity) and reduced environmental sensitivity of the terrestrial archives. So far in this area only records of δ^{18}O in stalagmites [*Genty et al.*, 2003] and pollen assemblages in sediments [*Allen et al.*, 1999; *Sanchez-Goni et al.*, 2000; *Combourieu-Nebout et al.*, 2002; *Müller et al.*, 2003] show climate variations coeval to the DO or H events (Figure 1).

[3] Another source of information are the Western European loess deposits. Comparing the loess sequences from Northern France, Belgium and Germany, a stratigraphic pattern including pedological or sedimentlogical level marks was evidenced in the last glacial cycle [*Antoine et al.*, 2001], clearly resulting from a common climatic control. Most detailed investigations have been performed at Nussloch, Germany [*Antoine et al.*, 1999; *Hatté et al.*, 2001; *Rousseau et al.*, 2002; *Lang et al.*, 2003; *Moine*, 2003], where the loess deposits of the last glacial cycle are exceptionally well developed, compared to other European sites. Based on high-resolution stratigraphic and grain-size data from the last and most detailed of the four studied loess sequences from Nussloch, the P4, we show here that climate variability in the Western Europe appears correlated with that in the North Atlantic area at timescales at least as fine as centuries.

2. Material and Methods

[4] The Nussloch site (49°19′N, 8°43′E) is located south of Heidelberg, Germany, just south of the Odenwald Plateau, which dominate the right bank of the Rhine valley. Loess has accumulated in a series of large dune-like formations, oriented in a northwest to southeast direction, following the main direction of local wind at the time of peak deposition. The coarse material has been blown out from the wide alluvial plain nearby, whereas the fine material seems to have been brought not only from this local source, but also from the shelves of NW Europe continent which became exposed and dried out during glacial times, especially the English Channel and the southern part of the North Sea [*Lautridou*, 1985].

[5] The loess sequence P4, which covers the last glacial cycle, has a thickness of about 18 m. According to ^{14}C and luminescence dating [*Hatté et al.*, 2001; *Lang et al.*, 2003], the top approximately 13m were laid down between about 38,000 and 18,000 years ago. This corresponds closely with the interval of the North Atlantic DO events 8 to 2 and H events 3 and 2. In this portion, with sedimentation rates up to 1cm/yr, significantly more stratigraphic features were

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[1] Institut des Sciences de l'Evolution, CNRS-Université Montpellier II, Montpellier, France.

[2] Lamont-Doherty Earth Observatory of Columbia University, Palisades, New York, USA.

[3] Lehrstuhl Geomorphologie, Universität Bayreuth, Bayreuth, Germany.

[4] Now at Laboratoire de Meteorologie, UMR CNRS 8539, Ecole Normal Superieure, Paris, France.

[5] Laboratoire de Géographie physique, UMR CNRS 8591, Meudon, France.

[6] Laboratoire des Sciences du Climat et de l'Environnement, UMR CEA-CNRS 1572, Domaine du CNRS, Gif-sur-Yvette, France.

[7] Department of Geography, University of Liverpool, Liverpool, UK.

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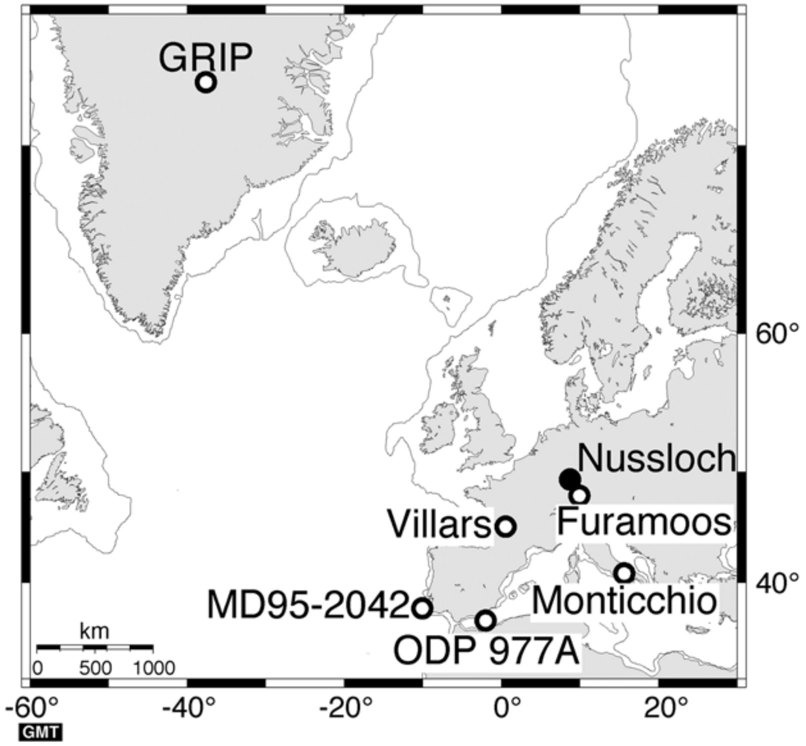

Figure 1. Location of the Nussloch site and of some other relevant records [*Dansgaard et al.*, 1993; *Allen et al.*, 1999; *Sanchez-Goni et al.*, 2000; *Combourieu-Nebout et al.*, 2002; *Müller et al.*, 2003; *Genty et al.*, 2003].

observed as in the previously described profiles P1 to P3. The fine pedostratigraphic analysis shows an alternation of loess layers, from cold and relatively dry climate conditions, with more or less developed paleosols, indicating periods of a relatively increased humidity (Figure 2). Some of the loess units show millimetric sandy laminations resembling those observed in other Western European loess sequences [*Antoine et al.*, 2001], pointing to episodes of a strong wind. The soil units are clearly expressed: a cambisol (LB) and tundra gley horizons (G1 to G7) already seen in the previous Nussloch profiles, as well as four new incipient gley layers (IG5b, IG6b, IG8a,b, IG9a,b). Some of the tundra gleys (i.e., soils formed under poor drainage), as G1 or G3&G4, show surface deformations due to freeze-thaw processes. This indicates that during their formation the climate was still cold, as confirmed by the malacological analysis [*Moine*, 2003].

[6] A grain-size index (GSI) was calculated as the ratio between the coarse grain fraction (26–52.6 microns) and fine silt and clay fraction (4–26 microns). High GSI values typically characterize loess units deposited at high sedimentation rates (probably due to increased frequency and strength of dust storms), whereas low values correspond to a decrease or even a stop of subaerial sedimentation, a stabilization of the top layer and soil development. The record of this index in the P4 sequence is similar to those in P2 and P3, but the time resolution is substantially higher (Figure 2). GSI variation reflects changes in the efficiency of the entrainment, the transport and the deposition of the coarse versus the fine dust grains, mainly due to the variation of wind speed [*Rousseau et al.*, 2002; *Nugteren and Vandenberghe*, 2004] and precipitation [*Ding et al.*, 1999].

3. Results and Discussion

[7] The high-resolution stratigraphy and dating, as well as the GSI data over the period between approximately 38,000 and 18,000 years ago allowed us to compare in detail the climate fluctuations recorded in the Nussloch loess with those from Greenland ice. For the latter we used the GRIP calcium (Ca, representing dust) concentration record [*Johnsen et al.*, 2001] instead of the classical ice-δ^{18}O variations, because the dust accumulation in Greenland ice is mainly influenced by wind and precipitation, same as the loess deposition, while the ice-δ^{18}O variations closely reflect the temperature change. Also, at timescales finer than a few hundred years the Ca (dust) records the switches in climate state much more distinctly than the δ^{18}O [*Fuhrer et al.*, 1999]. Stadial-to-interstadial transitions are abrupt in both the δ^{18}O and Ca, but then the two signals decouple: the δ^{18}O starts to decrease towards stadial values (slower in the beginning, then more abruptly), whereas the Ca concentration remains low and only towards the end of the warm phases of the DO cycles increases steeply (Figure 3). This facilitates the comparison to the loess sequence, with clear loess/paleosol boundaries.

[8] The following correlation rule [*Rousseau et al.*, 2002] is applied: the loess units at Nussloch, characterized by the high GSI values, are associated with intervals of high concentration of Ca (dust) in Greenland ice, and the paleosols, with low GSI values, are associated with intervals of low Ca (Figure 4). In terms of climate, this means that the

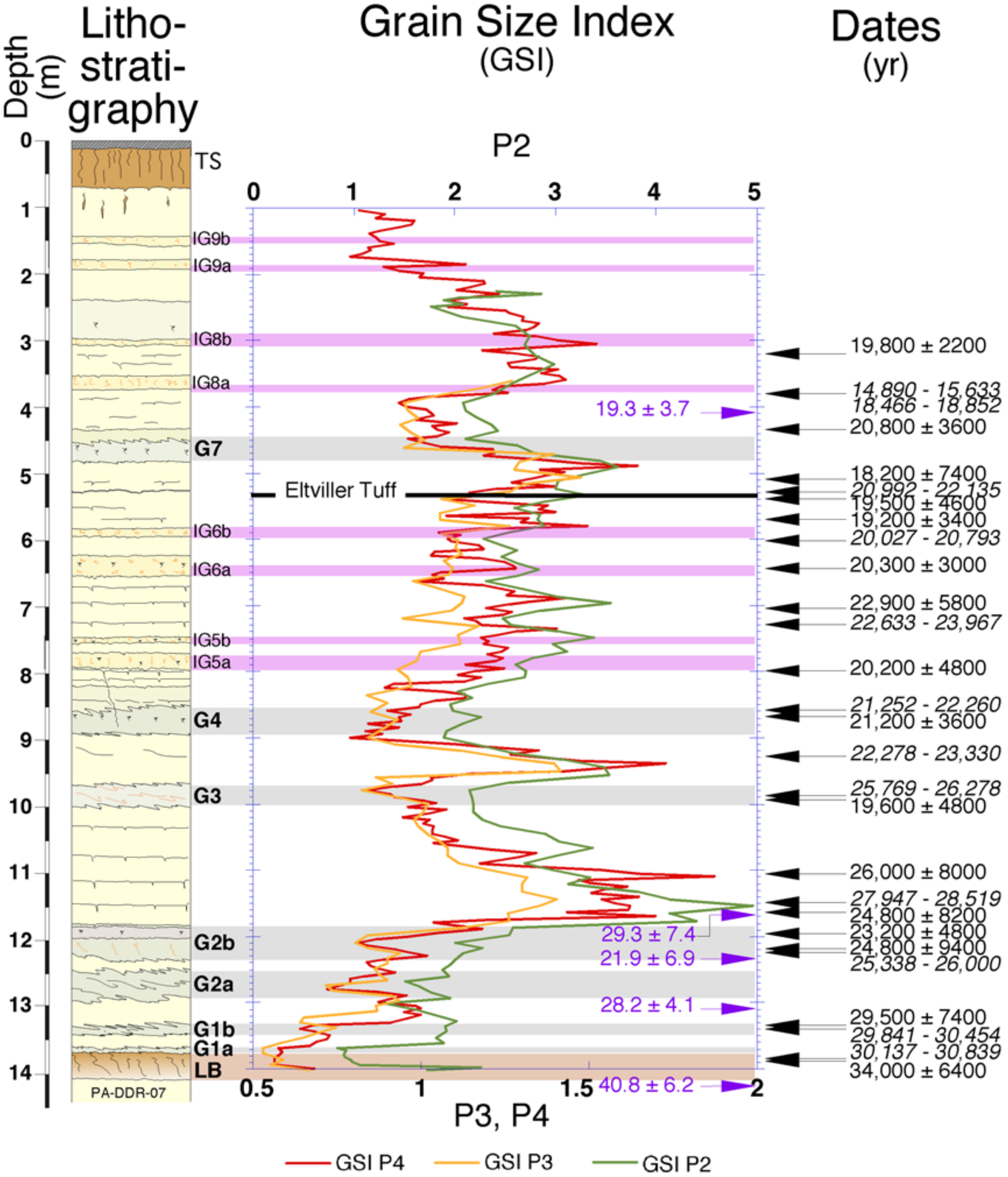

Figure 2. Nussloch P4 loess sequence. (left) Lithostratigraphy of the dilated part of the record (yellow, loess; brown-red, cambisol; light grey blue, tundra gley) [*Antoine et al.*, 2001, 2002]. (middle) Grain-size index (GSI) records from the P2, P3 and P4 profiles, showing a great similarity. GSI was calculated for P2 as (20–50 μm)/ <20 μm, based on sieve and pipette grain-size analyses, and for P3 and P4 as (52.6–26 μm)/ <26 μm, based on laser Coulter analyses. P2 and P3 depths were tuned to P4 by correlating the observed lithological units, except for the Eltviller tuff (ET, volcanic ash), which was used as an independent marker to test the tuning. Horizontal bands mark the cambisol (brown), the main gleys (green) and the less developed gleys or oxidized horizons (violet). (right) All available dates: ^{14}C (italic) and luminescence dates obtained on the P4 (in purple) and P2 (the rest). AMS dates, determined on preserved organic matter and indicating the plant degradation, have been converted to calendar years by using Calib05 [*Bard et al.*, 1998; *Reimer et al.*, 2004]. Only the luminescence dates, corresponding to the burial of dust grains in the sediment, are used to validate our age model.

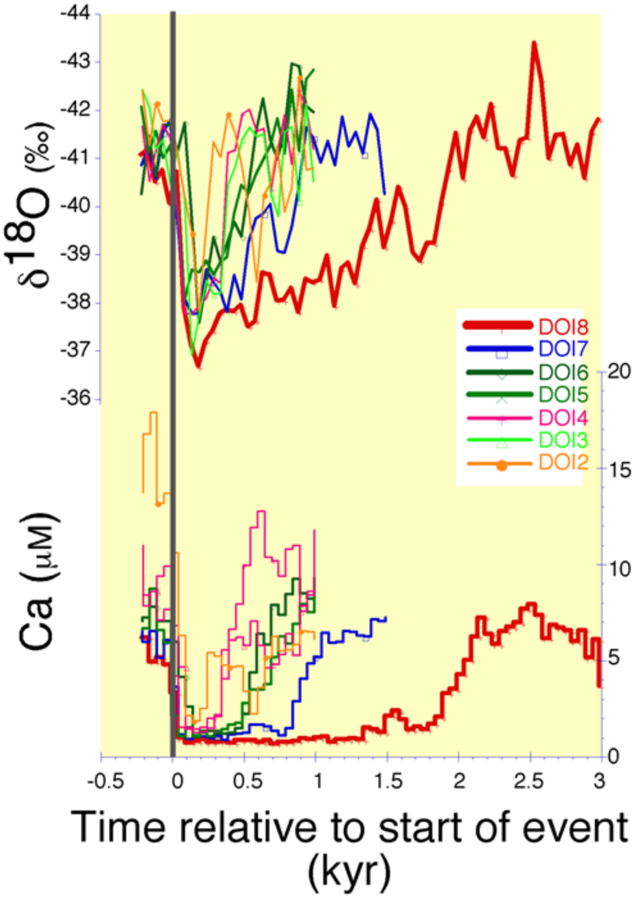

Figure 3. Temporal evolution of the DO events 8 to 2 as expressed in GRIP ice-core data: δ^{18}O (‰, top) and calcium (Ca, representing dust) concentration (μM, bottom) [*Johnsen et al.*, 2001]. The start of an event (time = 0 kyr) is given by the beginning of δ^{18}O enrichment in the ice core records (vertical black line) [cf. *Ganopolski and Rahmstorf*, 2001]. We note that the correct denomination of DO interstadials (DOI) is Greenland Interstadials [*Rousseau et al.*, 2006].

cold episodes in the North Atlantic area (DO stadials and H events) are supposed to correspond on the continent to the loess deposition intervals, in cold, dry and windy conditions (as also suggested by *Moine* [2003] and *Hatté and Guiot* [2005], while the warm phases (DO interstadials) are considered to correspond to milder and moister conditions, allowing the development of tundra gley horizons (increase in spring and summer permafrost thawing).

[9] By applying a threshold of approximately 2 micromols to the GRIP Ca data (T1 in Figure 4), the main intervals of low dust concentration in Greenland, corresponding to the DO interstadials, are delimited. We relate these intervals to periods of strong paleosol development at Nussloch. The longer the Greenland interstadial, the better developed the coeval soil. The DO interstadial 8 is associated with the unit LB in Nussloch, a gelic cambisol (arctic brown boreal soil) at the base of the studied sequence (Figure 2). The interstadials 7 to 2 are respectively correlated with tundra gleys G1a,b, G2a, G2b, G3, G4, and G7.

[10] Applying a second threshold (T2 in Figure 4), at approx. 6 micromols, to the GRIP Ca values, the main intervals of high dust concentration in Greenland are delimited, as well as a few less dusty intervals of short duration. The former, corresponding to Greenland stadials, are associated in the Nussloch stratigraphy with the well developed loess units, interpreted as episodes of cold, dry and windy climate in Western Europe. The less dusty intervals, characterized in Greenland by milder temperatures than during the DO stadials, but not as warm as in the DO interstadials, are related to the weakly developed gleys or oxidized horizons IG8 to IG9, which indicate moister and possibly also less windy conditions at Nussloch. Considering their weak development, these last intervals must have been marked in Europe, same as in Greenland, by only a short duration of no more than some 200 years and of a relative minor change of climate parameters. Thus, not only the main DO interstadials, but also less important warming events have their counterpart in Nussloch paleosol units. Moreover, considering the position in the stratigraphy of two specific units, marked by coarser, laminated loess, poor vegetation [*Hatté et al.*, 2001] and limited mollusc populations [*Moine*, 2003], these can be correlated with the Heinrich events 3 and 2.

[11] Further support for the presented correlation may come from data analysis on the one hand, and climate modelling on the other hand. Ongoing work is dedicated to the refinement of the Nussloch chronology and the more precise identification of dust sources. For Greenland, the NGRIP [*North Greenland Ice Core Project*, 2004] high-resolution chronology is now available [*Andersen et al.*, 2006], and a corresponding high-resolution dust record is expected. The modelling studies have generally focused on investigating the mechanism of the millennial-scale variability, widely thought to be related to changes in the Atlantic meridional overturning circulation [*Ganopolski and Rahmstorf*, 2001; *Wang and Mysak*, 2006]. Very few studies have addressed the impact of the North Atlantic abrupt climate changes on the continents. Numerical experiments with atmospheric general circulation models [*Hostetler et al.*, 1999; *Renssen and Bogaart*, 2003] or with an Earth system model of intermediate complexity [*Claussen et al.*, 2003] have indicated warmer and moister conditions in northwest Europe during the Greenland warm episodes (DO interstadials) than during the cold ones (DO stadials and H events). Also, a considerably reduced storm activity was simulated during the interstadials compared to the stadials [*Renssen and Bogaart*, 2003], due to the storm track relocation from northwest Europe in the cold phases towards the Nordic Seas in warm phases. This was a consequence of the northward retreat of the sea-ice margin [*Weinelt et al.*, 2003], and would imply decreased potential of eolian dust transport over our area of interest.

4. Conclusions

[12] The above modelling results support the correlation of climate indicators in the Nussloch loess and in the Greenland ice. This points to an intimate link of climate changes in Western Europe with those in the North Atlantic area. To further improve our understanding of the climate changes on the continent during the last glacial period, numerical experiments are needed with a resolution high enough to enable meaningful comparison to the data, and

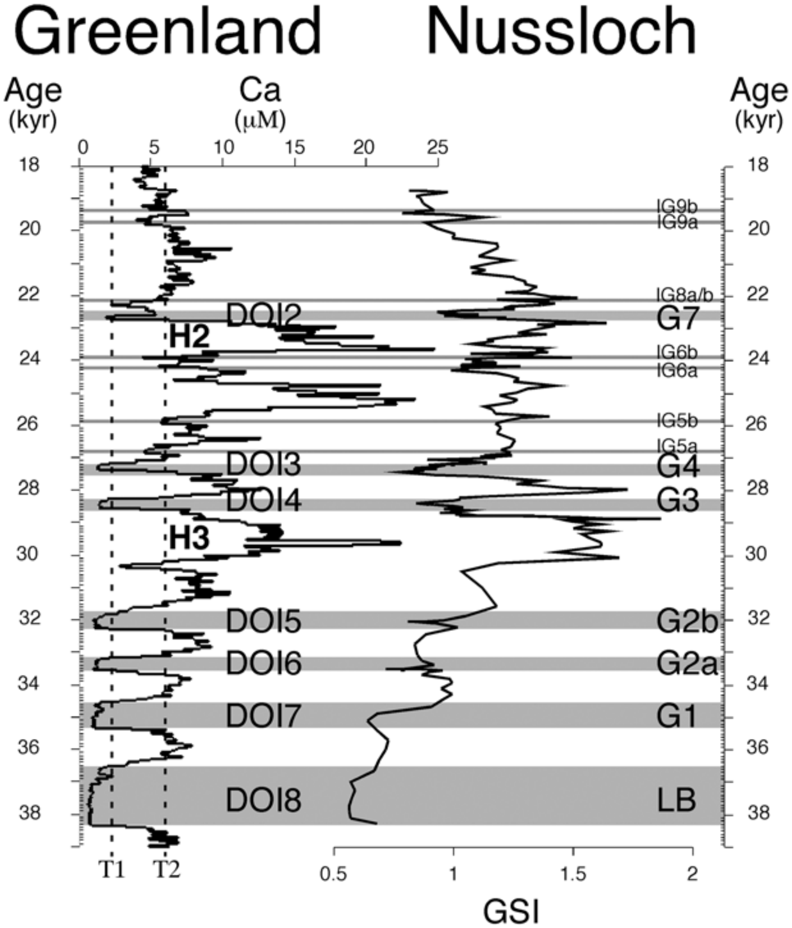

Figure 4. Correlation of the Nussloch GSI with the GRIP Ca (dust) record [*Johnsen et al.*, 2001]. The T1 threshold applied to Greenland data puts in evidence the main intervals of low dust concentration, corresponding to DO interstadials (DOI) 8 to 2. We associate them with intervals of low GSI values at Nussloch, corresponding to the brown boreal soil Lohne Boden (LB) and the well developed tundra gley units G1, G2a, G2b, G3, G4 and G7. The T2 threshold delimitates the dustiest intervals in Greenland, corresponding to DO stadials, as well as few less important dust peaks. We constructed our age model by associating the former with the main loess units at Nussloch, and the latter with the incipient gley horizons (IG5, 6, 8 and 9). The age model reasonably fits the available luminescence dates.

which will incorporate more recent information, especially the updates of sea-surface paleo-temperatures and sea-ice extent [*Sarnthein et al.*, 2003; *Kucera et al.*, 2005], both critical to the modelling results. Our high-resolution record fills a gap in the database of records of past climate changes on the continent.

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P. Antoine, Laboratoire de Géographie physique, UMR CNRS 8591, 1, Place Aristide Briand, 92 195 Meudon cedex, France.

C. Hatté, Laboratoire des Sciences du Climat et de l'Environnement, UMR CEA-CNRS 1572, Domaine du CNRS, bat 12, F-91198 Gif-sur-Yvette, France.

A. Lang, Department of Geography, University of Liverpool, Liverpool L69 7ZT, UK.

D.-D. Rousseau, Laboratoire de Meteorologie Dynamique, UMR CNRS 8539, Ecole Normal Superieure, 24 ru Lhomond, F-75231 Paris cedex 05, France. (denis.rousseau@lmd. ens.fr)

A. Sima, Institut des Sciences de l'Evolution, CNRS-Université Montpellier II, case 61, pl. E. Bataillon, 34095 Montpellier cedex 05, France.

L. Zöller, Lehrstuhl Geomorphologie, Universität Bayreuth, D-95440 Bayreuth, Germany.