An abrupt wind shift in western Europe at the onset of the Younger Dryas cold period

ACHIM BRAUER[1]*, GERALD H. HAUG[2,3], PETER DULSKI[1], DANIEL M. SIGMAN[4] AND JÖRG F. W. NEGENDANK[1]

[1]GFZ German Research Centre for Geosciences, Telegrafenberg, D-14473 Potsdam, Germany
[2]Geological Institute, Department of Earth Sciences, ETH Zürich, 8092 Zürich, Switzerland
[3]DFG-Leibniz Center for Surface Process and Climate Studies, Institute for Geosciences, Potsdam University, 14476 Potsdam, Germany
[4]Department of Geosciences, Princeton University, Princeton, New Jersey 08544, USA
*e-mail: brau@gfz-potsdam.de

Published online: 1 August 2008; doi:10.1038/ngeo263

The Younger Dryas cooling 12,700 years ago is one of the most abrupt climate changes observed in Northern Hemisphere palaeoclimate records[1–4]. Annually laminated lake sediments are ideally suited to record the dynamics of such abrupt changes, as the seasonal deposition responds immediately to climate, and the varve counts provide an accurate estimate of the timing of the change. Here, we present sub-annual records of varve microfacies and geochemistry from Lake Meerfelder Maar in western Germany, providing one of the best dated records of this climate transition[5]. Our data indicate an abrupt increase in storminess during the autumn to spring seasons, occurring from one year to the next at 12,679 yr BP, broadly coincident with other changes in this region. We suggest that this shift in wind strength represents an abrupt change in the North Atlantic westerlies towards a stronger and more zonal jet. Changes in meridional overturning circulation alone cannot fully explain the changes in European climate[6,7]; we suggest the observed wind shift provides the mechanism for the strong temporal link between North Atlantic Ocean overturning circulation and European climate during deglaciation.

The Younger Dryas cold period, the last major cold phase before the Holocene warming, had an extensive impact on terrestrial environments, in western Europe in particular. Indeed, its first description arose from vegetation changes. Despite the detailed record of the Younger Dryas cooling from the Greenland ice cores[1,2], and from marine and lake sediments[3,4], the cause of the Younger Dryas remains a matter of debate including even a major meteorite impact[8]. The Younger Dryas climate change coincided with a marked reduction in the North Atlantic meridional overturning circulation[3] (MOC), and a shutdown[9,10] or weakening[3] of the MOC is the preferred explanation for the Younger Dryas cooling. This shutdown, in turn, is typically explained as the result of a major release of meltwater into the North Atlantic[9,10].

However, the periods of highest meltwater rates during the last glacial–interglacial transition, labelled as Meltwater Peaks 1A and 1B, occurred several hundred years before and after the Younger Dryas, respectively[11]. This has led to speculation regarding specific possible source regions for a catastrophic release of freshwater, including both the Laurentide[12] and Fennoscandian[13] ice shields. Likewise, several different paths for the meltwater have been proposed[12–14]. The failure of palaeoclimatologists to find evidence for the proposed source and path of the freshwater, even after an intensive search[15], is remarkable.

A further weakness in the 'MOC shutdown' hypothesis involves the role of the MOC in circum-Atlantic climate. A premise behind this hypothesis has been that the warm subtropical water flowing northeastward into the high-latitude North Atlantic to feed the formation of North Atlantic Deep Water is a major heat source for the mild winters of western Europe. However, a compelling case has been made that this northeastward flow of warm water is, in itself, not responsible for the equable climate of modern Europe[6,7]. Rather, the standing wave associated with the Icelandic Low and the accompanying northward trajectory of the westerly winds over the North Atlantic is a major source of wintertime heat, as is the simple heat capacity of the ocean[7]. Thus, there is something of a paradox with regard to MOC shutdown and cold conditions over Greenland and Europe: a remarkable correlation is observed between these two phenomena in the case of the Younger Dryas and the cold phases of Dansgaard–Oeschger cycles[16], yet shutdown of the MOC cannot, in itself, explain the observed cooling. This situation has led to new proposals for the cause of the Younger Dryas and the cold phases of Dansgaard–Oeschger cycles, involving the winds[6] and sea ice[17], with the MOC change potentially being a feedback or response to these changes.

Here, we report a sedimentary record of wintertime wind strength over a German maar lake in the Eifel region (Fig. 1), spanning a 230-year time window of the late Allerød and transition into the Younger Dryas (12.8–12.5 kyr). The present-day climate is dominated by the prevailing westerly winds (Fig. 1). The sediment record from Lake Meerfelder Maar (MFM) contains a succession of 12,000 varves yielding a temporal resolution that allows insight into even seasonal changes[5]. MFM is the only lake record in western Europe that contains a continuous sequence of annual layers throughout the Younger Dryas. This is probably due to the exceptional situation of this lake: deep in a maar crater, with steep crater walls attenuating wind stress over the lake surface. Earlier studies have demonstrated the sensitivity of this lake to Younger Dryas climate change[18] and have shown that the environmental shift at the beginning of the Younger Dryas occurred faster than suggested by oxygen isotope and other records from the Greenland ice cores[2] (see the Supplementary Information). Here, we present new geochemical major element micro-X-ray fluorescence scanner

© 2008 Macmillan Publishers Limited. All rights reserved.

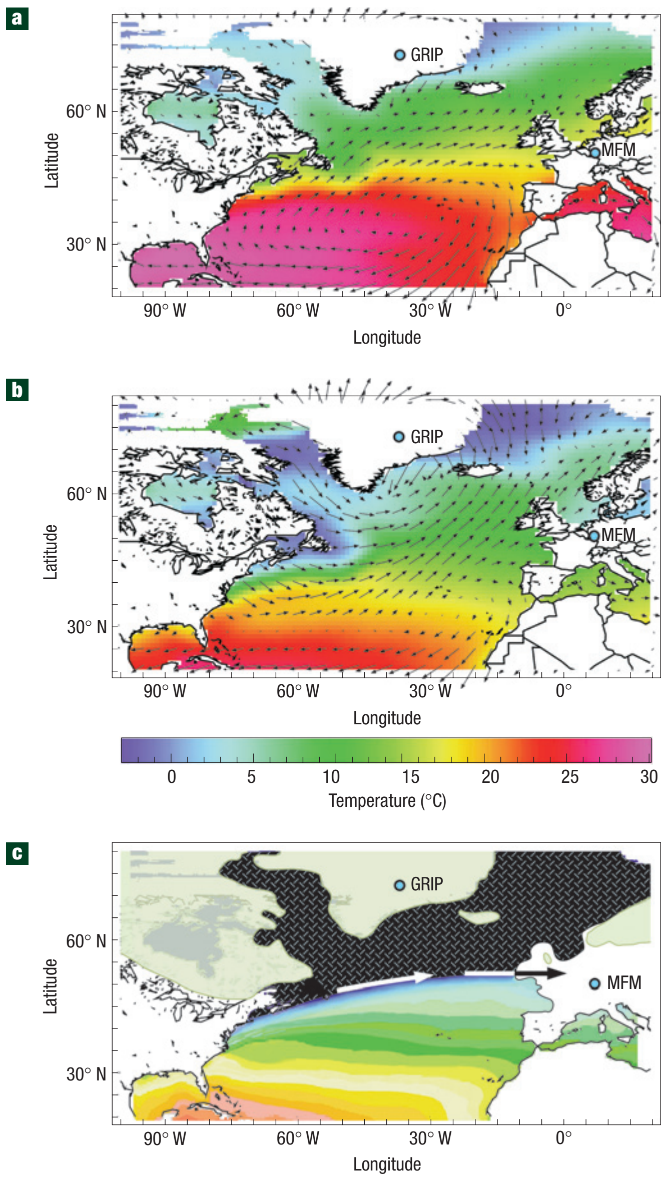

Figure 1 North Atlantic sea surface temperature (colours)[29] and surface wind fields (vectors)[30] in the circum-North Atlantic region. a,**b**, Winds 10 m above ground for the present-day months of August (**a**) and February (**b**). During the winter today, the winds approach northern Europe from a southwesterly direction, as part of the large-scale standing wave pattern of the westerlies[23]. **c**, Hypothesized patterns of North Atlantic sea surface temperature and winds during the Younger Dryas winter season. Winter sea ice cover (hatched area) is adopted from ref. 23. Locations of Lake Meerfelder Maar (MFM) and the Greenland Ice Core Project ice core are indicated.

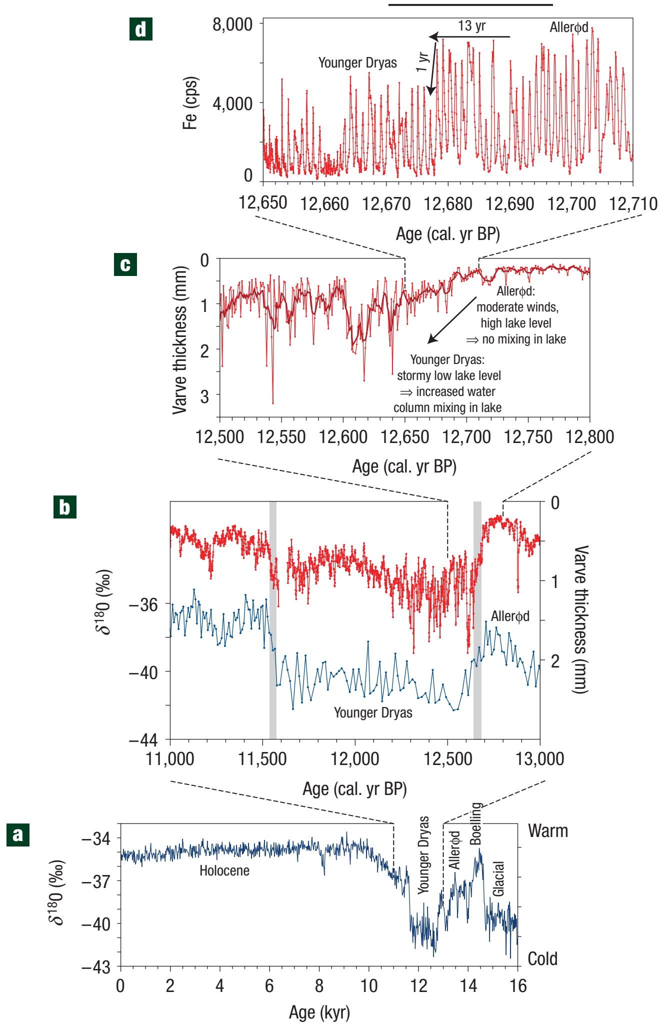

Figure 2 MFM sediment changes and their relationship to the Greenland ice core record. a, Greenland Ice Core Project oxygen isotopes[1]. **b**, Five-point running mean varve thickness[5] compared with Greenland Ice Core Project oxygen isotopes[1], each on its own independent chronology based on layer counting. **c**, Varve thickness record for the Allerød–Younger Dryas transition. **d**, Scanner Fe-counts for the Allerød–Younger Dryas transition at 50 μm resolution. The decreased amplitude of the wintertime Fe maxima coincides with the cessation of siderite formation. From about 12,700 varve yr BP, individual varves with low siderite appeared sporadically, indicating years with stronger winds. At 12,679 varve yr, the system switched irreversibly to the high-wind state.

data, with up to 30 measurements per varve, in combination with seasonal sedimentation data that address conditions in the lake most strongly affected by winter wind strength. Precision varve counting of the entire record, 69 accelerator mass spectrometry ^{14}C dates, and tephrochronological control allow the onset of the Younger Dryas to be placed on a calendar timescale with great accuracy (see the Supplementary Information).

The composition of seasonal sublayers and their succession within the MFM varves is determined by climatically controlled environmental processes[5]. At the onset of the Younger Dryas, the seasonal layer formation underwent a dramatic change, with a 4–5-fold increase in annual sedimentation rate (Fig. 2) and a change in varve composition (Fig. 3). Varve couplets of the Allerød consist of spring/summer sublayers composed of amorphous organic matter and few diatom frustules and autumn/winter sublayers composed of authigenic siderite, the last indicating stable anoxic bottom water conditions[19]. Detrital components are almost absent in both sublayers. At the onset of the Younger Dryas, siderite formation abruptly ceased, and autumn/winter layers became composed of siliciclastic and organic detrital matter from the catchment, with additions of reworked shallow-water sediments. The reworked sediments are indicated by abundant

© 2008 Macmillan Publishers Limited. All rights reserved.

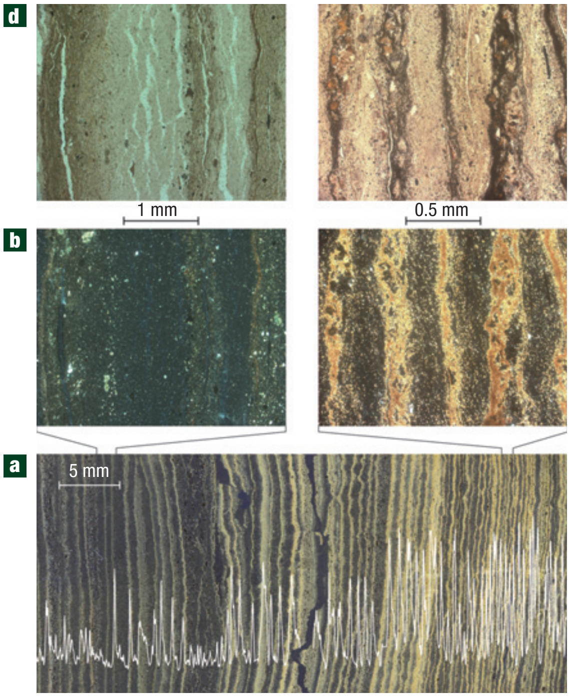

Figure 3 Photomicrographs of varves before and after the onset of the Younger Dryas event. a, Scanned thin section image (polarized light) of the Allerød–Younger Dryas transition. Siderite layers are coloured light yellow; the white line indicates micro-X-ray fluorescence scanner Fe data. **b–e**, Enlarged microscopic images of early Younger Dryas and late Allerød under polarized (**b**,**c**) and plane parallel light (**d**,**e**): Younger Dryas varves (**b**, **d**) are thick and composed of spring/summer diatom layers and autumn/winter layers of reworked minerogenic and organic matter. Thin Allerød-type varves (**c**,**e**) are characterized by spring/summer layers of amorphous organic matter and autumn/winter layers consisting mainly of siderite.

periphytic diatoms that grow on submerged substrates in the littoral zone. During spring/summer, thick monospecific diatom layers (*Stephanodiscus* sp.) formed. Pollen changes indicate that climate degradation ensued essentially immediately, given an inherent timescale for biotic response of about 20 years (ref. 5).

The siderite varves that formed under anoxic bottom water conditions during the Allerød indicate minimal seasonal (winter) mixing of the water body, which is best explained by low wind stress on the lake surface and a high lake level. With the onset of the Younger Dryas cold period, the formation of thick monospecific diatom layers (*Stephanodiscus* sp.) during spring/summer is explained by an increase in the wind-driven upward mixing of nutrient-rich bottom water. The reworked sediments argue for a major fall in lake level and an increase in wave activity at the shoreline due to windy conditions. Particularly striking are the pronounced inter-annual to decadal oscillations before the final shift, which occurred within one year (Fig. 2d). These short-term fluctuations indicate that the change from calm and wet to windy and dry conditions began with a period of individual extreme years with Younger Dryas-like conditions. However, the depositional system in the lake switched back after these extreme years to Allerød-like conditions until the permanent shift at 12,679 varve yr BP. The wind effects must have been very strong because, in all other lakes in western Europe with annually laminated sediments in the Allerød, varve formation ceased at the onset of the Younger Dryas (see the Supplementary Information).

One previously uncovered clue regarding the mechanism for the Younger Dryas cooling in northern Europe is that the cooling was distinctly more pronounced during autumn, winter and spring[20,21]. Today, inter-annual variation in winter climate in western Europe is to a large degree controlled by the North Atlantic Oscillation (NAO) through changes in atmospheric circulation[22]. Cold and dry winters are characteristic for the negative mode of the NAO and a weakened zonal flow, whereas stronger westerly winds are typical of the positive NAO mode and cause warm and wet winters in western Europe. However, the MFM record indicates a clear link between the Younger Dryas cooling in western Europe and a strengthening of the westerly winds over this region. Therefore, our observations call for a shift in atmospheric and ocean conditions that are different from the changes associated with the NAO.

Indications of cold and dry Younger Dryas winters associated with strong westerly winds[23] provide the first hint of the atmospheric mechanism by which the cooling of Greenland and the open North Atlantic might be imprinted on central Europe. Today, the westerlies are a source of warmth to Europe, largely owing to the prevailing southwesterly track of the winds as they approach the continent[24]. To associate stronger westerlies with cooling requires cooling and/or sea ice cover of the Atlantic waters over which the westerlies passed. This could have been caused by a more zonal or northwesterly (less southerly) path of storm tracks following the southward shift of sea ice[25], or by an equatorward shift in the isotherms of the North Atlantic surface, or both. Assuming a constant track for the westerlies, cooling of the subpolar North Atlantic would have worked to reduce the heat transport to Europe. Perhaps more importantly, this cooling would have made the North Atlantic sea surface temperature gradient more zonal and potentially stronger. These changes would have converted the westerlies into a stronger and more zonal jet, which would also have worked to cool Europe, especially during winter (Fig. 1c). Similarly, the dry conditions in western Europe during the early Younger Dryas are the expected result of a shift in the prevailing winds to a trajectory that passed over colder and potentially ice-covered North Atlantic waters, thus accumulating less latent heat[26].

An oceanic trigger for this change is possible, perhaps through a southward advance in sea ice, but an atmospheric trigger cannot be ruled out. In either case, positive feedbacks exist that would support the new Younger Dryas steady-state configuration, with cool polar surface waters maintaining strong and zonal westerlies, and with this state for the westerlies reducing the northward incursion of warm waters from the Gulf Stream extension into the subpolar North Atlantic (Fig. 1c). The abruptness of the changes noted at MFM suggests a role for sea ice in these positive feedbacks, as sea ice is a rapid and strong climate amplifier[27]. Given the currently available records of the Younger Dryas reduction in North Atlantic overturning, it is not yet possible to distinguish whether this overturning change was the driver of the subpolar North Atlantic cooling or a product of it. The latter possibility is not unreasonable, in that the northward penetration of water from the lower latitude Atlantic seems to be an important prerequisite for convection in the Greenland–Iceland–Norwegian Sea[28]. In either case, reduction in North Atlantic overturning is energetically consistent with subpolar North Atlantic cooling and more zonal patterns for both sea surface temperature gradients and the westerlies.

These results help to reconcile the tight observed connection between North Atlantic overturning reductions and cooling in Europe[4,16] with the evidence that the ocean heat transport associated with this overturning is not a major source of heat to Europe[7]. Our data show that a cooling of the subpolar North Atlantic affected atmospheric circulation over the Atlantic sector so as to reduce the transport of heat to western Europe. Regardless of whether North Atlantic overturning reduction was the cause

© 2008 Macmillan Publishers Limited. All rights reserved.

or effect of this North Atlantic cooling, its coincidence with this cooling leads to a temporal link among reduced North Atlantic overturning, North Atlantic cooling and reduced wind-driven heating of Europe.

METHODS

This study was carried out on composite profile MFM-6 derived from five individual cores that were precisely correlated on the basis of microscopic laminae identification. Previous studies of more than 20 cores from all parts of the lake basin provide a good spatial knowledge of the sedimentation and have demonstrated that all cores from the deepest part of the basin can be correlated on a varve-to-varve base (see the Supplementary Information). Varve structure and seasonal layer composition have been investigated on overlapping series of large-scale thin sections. These data have been complemented with geochemical major element micro-X-ray fluorescence scanner data at 50 μm resolution providing geochemical information for individual seasonal layers (5–8 data points/varve for the Allerød; 20–30 data points/varve for Younger Dryas). These geochemical data could be directly assigned to micro-facies data because XRF scanning has been carried out on the same impregnated sediment blocks from which the thin sections have been prepared. A detailed chronology for the MFM sediment record has been obtained from microscopic varve counts and 69 accelerator mass spectrometry ^{14}C dates on terrestrial macro-remains (see the Supplementary Information). The Younger Dryas cooling is biostratigraphically defined and dated from 12,680–11,590 varve yr BP thus comprising 1,090 varves[5]. A prominent time marker at the base of this section is the Laacher See tephra, which has been dated at 12,880 varve yr BP and was deposited 200 varve years before the onset of the Younger Dryas[5].

Received 14 September 2007; accepted 30 May 2008; published 1 August 2008.

References

1. Johnsen, S. J. *et al*. Irregular glacial interstadials record in a new Greenland ice core. *Nature* **359**, 311–313 (1992).
2. Alley, R. B. *et al*. Abrupt increase in Greenland snow accumulation at the end of the Younger Dryas event. *Nature* **362**, 527–529 (1993).
3. McManus, J. F., Francois, R., Gherardi, J.-M., Keigwin, L. D. & Brown-Leger, S. Collapse and rapid resumption of Atlantic meridional circulation linked to deglacial climate changes. *Nature* **428**, 834–837 (2004).
4. von Grafenstein, U., Erlenkeuser, H., Brauer, A., Jouzel, J. & Johnsen, S. J. A mid-European decadal isotope-climate record from 15,500 to 5,000 years B.P. *Science* **284**, 1654–1657 (1999).
5. Brauer, A. *et al*. High resolution sediment and vegetation responses to Younger Dryas climate change in varved lake sediments from Meerfelder Maar, Germany. *Quat. Sci. Rev.* **18/3**, 321–329 (1999).
6. Wunsch, C. Abrupt climate change: An alternative view. *Quat. Res.* **65/2**, 191–203 (2006).
7. Seager, R. *et al*. Is the Gulf Stream responsible for Europe's mild winters?. *Q. J. R. Metereol. Soc.* **128**, 2563–2586 (2002).
8. Firestone, R. B. *et al*. Evidence for an extraterrestrial impact 12,900 years ago that contributed to the megafaunal extinctions and the Younger Dryas cooling. *Proc. Natl Acad. Sci.* **104**, 16016–16021 (2007).
9. Broecker, W. S. Does the trigger for abrupt climate change reside in the ocean or in the atmosphere? *Science* **300**, 1519–1522 (2003).
10. Broecker, W. S., Peteet, D. M. & Rind, D. Does the ocean–atmosphere system have more than one stable mode of operation? *Nature* **315**, 21–26 (1985).
11. Fairbanks, R. G. A 17,000-year glacio-eustatic sea level record: Influence of glacial melting rates on the Younger Dryas event and deep-ocean circulation. *Nature* **342**, 637–642 (1989).
12. Teller, J. T., Leverington, D. W. & Mann, J. D. Freshwater outbursts to the oceans from glacial Lake Agassiz and their role in climate change during the last deglaciation. *Quat. Sci. Rev.* **21/8-9**, 879–887 (2002).
13. Björck, S. *et al*. Synchronised terrestrial-atmospheric deglacial records around the North Atlantic. *Science* **274**, 1155–1160 (1996).
14. Tarasov, L & Peltier, W. R. Arctic freshwater forcing of the Younger Dryas cold reversal. *Nature* **435**, 662–665 (2005).
15. Broecker, W. S. Was the Younger Dryas triggered by a flood? *Science* **312**, 1146–1148 (2006).
16. Allen, J. R. M. *et al*. Rapid environmental changes in southern Europe during the last glacial period. *Nature* **400**, 740–743 (1999).
17. Li, C., Battisti, D. S., Schrag, D. P. & Tziperman, E. Abrupt climate shifts in Greenland due to displacements of the sea ice edge. *Geophys. Res. Lett.* **32**, doi:10.1029/2005GL023492 (2005).
18. Brauer, A., Günter, C., Johnsen, S. J. & Negendank, J. F. W. Land-ice teleconnections of cold climatic periods during the last glacial/interglacial transition. *Clim. Dyn.* **16/2-3**, 229–239 (2000).
19. Berner, R. A. A new geochemical classification of sedimentary environments. *J. Sedim. Petrol.* **51/2**, 359–365 (1981).
20. Lücke, A. & Brauer, A. Biogeochemical and micro-facial fingerprints of ecosystem response to rapid Late Glacial climatic changes in varved sediments of Meerfelder Maar (Germany). *Palaeogeogr. Palaeoclimatol. Palaeoecol.* **211/1-2**, 139–155 (2004).
21. Denton, G. H., Alley, R. B., Comer, G. C. & Broecker, W. S. The role of seasonality in abrupt climate change. *Quat. Sci. Rev.* **24/10-11**, 1159–1182 (2005).
22. Hurrell, J. W., Kushnir, Y. & Visbeck, M. The North Atlantic Oscillation. *Science* **291**, 603–605 (2001).
23. Isarin, R. F. B., Renssen, H. & Vandenberghe, J. The impact of the North Atlantic Ocean on the Younger Dryas climate in northwestern and central Europe. *J. Quat. Sci.* **13/5**, 447–453 (1998).
24. Thompson, D. W. J. & Wallace, J. M. Regional climate impacts of the northern hemisphere annular mode. *Science* **293**, 85–89 (2001).
25. Kageyama, M., Valdes, P. J., Ramstein, G., Hewitt, C. & Wyputta, U. Northern Hemisphere storm tracks in present day and Last Glacial Maximum climate simulations: A comparison of the European PMIP models. *J. Clim.* **12/3**, 742–760 (1999).
26. Braconnot, P. *et al*. Results of PMIP2 coupled simulations of the Mid-Holocene and Last Glacial Maximum—Part 1: Experiments and large-scale features. *Clim. Past* **3**, 261–277 (2007).
27. Visbeck, M. The Ocean's role in Atlantic climate variability. *Science* **297**, 2223–2224 (2002).
28. Broecker, W. S. Thermohaline circulation, the Achilles heel of our climate system: Will man-made CO_2 upset the current balance? *Science* **278**, 1582–1588 (1997).
29. Reynolds, M. R. W., Rayner, N. A., Smith, T. M., Stokes, D. C. & Wang, W. An improved in situ and satellite SST analysis for climate. *J. Clim.* **15**, 1609–1625 (2002).
30. Kalnay, M. E. *et al*. The NCEP/NCAR 40-year reanalysis project. *Bull. Am. Meteorol. Soc.* **77/3**, 437–471 (1996).

Supplementary Information accompanies this paper on www.nature.com/naturegeoscience.

Acknowledgements

The work was supported by the Deutsche Forschungsgemeinschaft (DFG). M. Köhler and D. Berger participated in the coring campaign and prepared petrographic thin sections. A. Hendrich helped with the layout of the figures.

Author information

Reprints and permission information is available online at http://npg.nature.com/reprintsandpermissions. Correspondence and requests for materials should be addressed to A.B.

© 2008 Macmillan Publishers Limited. All rights reserved.