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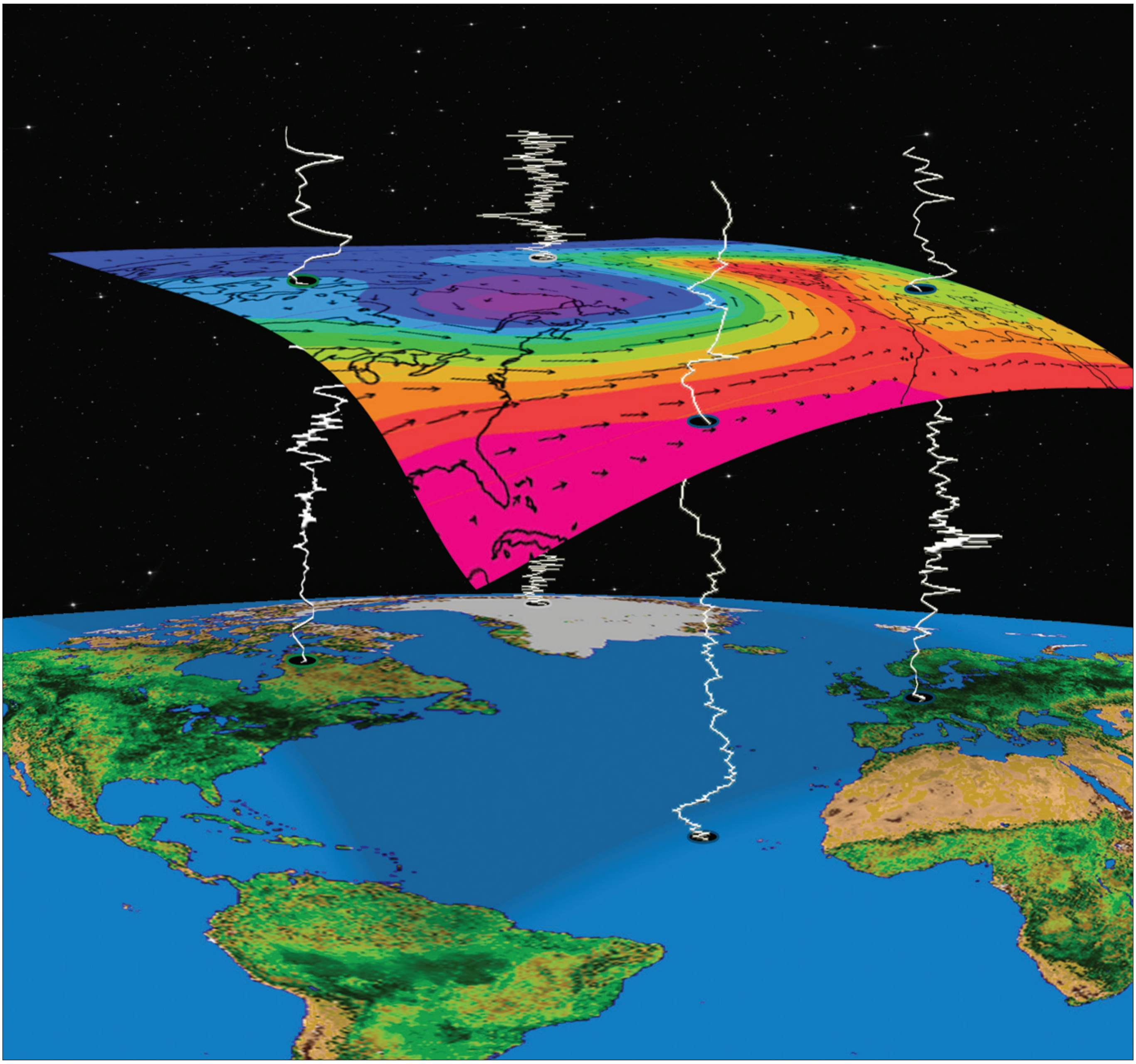
Data-Model Comparison

Editors:

Gerrit Lohmann, Louise Newman and Thorsten Kiefer



Paleodata and models have the potential for a truly symbiotic relationship but face various practical issues when it comes to their integration. The special section of this issue of PAGES News *highlights the importance of validating the results of individual reconstructions and simulations, and showcases a variety of methods that can be used for their comparison.*

Inside PAGES

From the PAGES Committees

Bette Otto-Bliesner and Ricardo Villalba were recently voted on to the PAGES Executive Committee (EXCOM), replacing Pinxian Wang and Rick Battarbee, who rotated off the Scientific Steering Committee (SSC) at the end of 2007. In addition, an organizational change in the SSC has resulted in Heinz Wanner, formerly PAGES Swiss Director, becoming PAGES Co-Chair and now sharing the leadership with Julie Brigham-Grette. Julie will rotate off the SSC at the end of 2008 and PAGES welcomes nominations for a new member before 27 April 2008. The SSC provides guidance for the PAGES project as a whole and oversees major scientific activities. In addition to scientific excellence and status in their communities, members are chosen to provide a balance of paleoscience expertise and national representation. A list of current SSC and EXCOM members, and details on the nomination procedure can be found at www.pages-igbp.org/people/sscleaders.html

PAGES Open Science Meeting & Young Scientists Meeting

The dates and location of PAGES 3rd Open Science Meeting (OSM) have been fixed! The OSM will be held from 8-11 July 2009 at Oregon State University in Corvallis, USA. In addition, a PAGES Young Scientists Meeting will be held for the first time alongside the OSM from 6-7 July 2009. The OSM Program Committee is currently working on the topics and structure of the meetings.

PAGES Info Sheets

Under the umbrella of Cross-Cutting Theme 4 (Dissemination and Outreach), PAGES is developing a series of information sheets that address key issues in climate and environmental science from a paleo-perspective. The issues will be addressed at a popular science level, targeted for early university-level students, and teachers of early- or pre-university courses. The first in the series, on "Earth System Models", has been launched to coincide with the special section of this newsletter issue. This, and other upcoming Info Sheets, can be downloaded for free from PAGES website (www.pages-igbp.org/science/infosheets).

PAGES Online Calendar

Following on from the successful redesign of the online paleo-jobs database (www.pages-igbp.org/services/jobs/), PAGES has recently updated the online calendar. You are now able to add paleoscience-related events directly to the database using the online form (www.pages-igbp.org/calendar/). Calendar entries will be posted within 24 hours of submission. This service is of course free.

LOTRED-SA Metadatabase

The LOTRED South America group has now been equipped with a database, where metadata of regional paleoclimate and paleoenvironmental data sets are collected and displayed (www.pages-igbp.org/cgi-bin/WebObjects/lotredsa). It is a simple tool intended to assist with data compilation by allowing for an overview of existing data. This type of database is available to all regional PAGES groups (contact Thorsten Kiefer; kiefer@pages.unibe.ch).

Next issue of PAGES newsletter

The next issue of *PAGES News* will contain a special section on speleothems, which will be guest edited by Dominik Fleitmann (University of Bern, Switzerland; fleitmann@geo.unibe.ch) and Christoph Spötl (University of Innsbruck, Austria; christoph.spoetl@uibk.ac.at). If you are interested in contributing a science highlight to this special section, please contact Dominik or Christoph directly. The next deadline for open manuscript submissions is 25 May 2008. Guidelines for contributions can be found at: www.pages-igbp.org/products/newsletters/instructions.html

PAGES Calendar 2008

23 - 27 June 2008 - Vancouver, Canada
1st American Dendrochronology Conference
www.treeringsociety.org/AmeriDendro2008/

29 June - 03 July 2008 - Fairbanks, USA
9th International Conference on Permafrost
www.nicop.org/

05 - 14 Aug 2008 - Oslo, Norway
33rd International Geological Congress: Earth System Science
www.33igc.org/coco/

11 - 13 Aug 2008 - Shanghai, China
Quaternary pollen database of China
www.pages-igbp.org/calendar/

14 - 16 Sep 2008 - Athens, Greece
Extreme climate events during recent millennia and their impact on Mediterranean societies
www.pages-igbp.org/calendar/

14 - 19 Sep 2008 - Colorado, USA
PMIP2 Workshop
www.pages-igbp.org/calendar/

29 - 31 Oct 2008 - Shanghai, China
PAGES Global Monsoon Symposium: Global Monsoon and Low-Latitude Processes
www.pages-igbp.org/calendar/

In memory of Professor Tungsheng Liu

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Tungsheng Liu, a former member of the PAGES SSC (1991 – 1995), died on 6 March 2008 in Beijing at the age of 91. His passing is a great loss to the PAGES community but his contributions will be remembered by all who study past global changes. Tungsheng was instrumental in the initiation and implementation of the PAGES Pole-Equator-Pole (PEP) projects, and was a co-leader of PEP II. One major component of the project was the extraction of paleoenvironmental information from the loess deposits in northern China.

It was in the spectacular Loess Plateau that his wisdom, scientific insight and vision were fully manifested. With over half a century of tireless and energetic endeavor, Tungsheng and his colleagues magically turned the successions of dust deposits on the apparently fragmented land into one of the biggest books on the history of Earth's environment. The widely accumulated loess deposit, with thicknesses of up to a few hundred meters, was a blessing of nature and its origin was hotly debated. From the 1950s, Tungsheng led numerous expeditions to the Loess Plateau. The unprecedentedly large volume of field and laboratory data, published in three monographs in 1960s, allowed him to demonstrate convincingly that loess was lain down by wind, which had changed over time. This opened an entirely new chapter in the study of past climate change in China. From the 1980s, Tungsheng led a number of major research projects that aimed to probe the pulses of past climate. These led to a series of new discoveries on the climatic history of East Asia on both glacial-interglacial and millennial scales, as evidenced in numerous publications in international journals. Hence, by the 1990s, the dust sequence in China was recognized as one of the three most important sources of past environmental information, alongside deep-sea sediments and polar ice sheets.

Two important contributions that Tungsheng made to the paleoscience community were the promotion of international collaboration and the training of new generations of scientists. With his support and encouragement, numerous scientific collaborations across many fields of past global change research, between China and other countries, were established. Many young scientists who interacted with him during the past decades are now becoming important players in PAGES activities. Tungsheng was also a strong advocate for interdisciplinary collaboration and the study of human impact on the environment. He was a "scientific magnet" and made an immense effort to bring together scientists from a wide range of scientific fields, with interests spanning many timescales.

Tungsheng Liu, a grand pioneer of loess paleoclimatology and a former member of the PAGES Scientific Steering Committee, will be greatly missed by the paleoscience community.

Tungsheng was probably the most internationally renowned Chinese Earth scientist of our time. He was elected as Vice President (1982-1991), and then President (1991-1995) of INQUA. His distinguished career also brought him many prestigious awards. In 2002, he was a Laureate of the Tyler Prize for Environmental Achievement, the premier award for "environmental science, energy and medicine conferring great benefit upon mankind". He won China's Supreme State Science and Technology Award in 2003. He was the EGU Alexander von Humboldt Medallist in 2007. He was a member of the Chinese Academy of Sciences and the Third World Academy of Sciences, and held Honorary Doctorates from the Australian National University and Lingnan University.

Tungsheng was one of the world's greatest geoscientists. He has left with us a solid foundation for a multidisciplinary approach to tackling issues related to past global change, and his pioneering work will allow us to continue our journey towards better understanding of the role of dust in climate change. We are greatly saddened by Tungsheng's passing but his spirit will live on as a source of inspiration for paleoscience.

Linking data and models

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Paleo-data and models have the potential for a truly symbiotic relationship. One application of paleoclimate data is to validate state-of-the-art coupled climate models for past time slices and specific climate transitions. Analyzing proxy-reconstructed paleoclimate records and models in tandem allows for the evaluation of climate transitions through the analysis of forcing and feedback mechanisms in past and future climate changes. In return, model simulations can aid in the interpretation of the causes of observed variations in paleoclimate data. Climate simulations enable a separation of the externally forced climate signal from internal variability (to the extent that the signal is distinguishable from the noise), something that cannot be achieved using proxy data alone. To become effective, these mechanisms require that data and model simulations can be compared in a meaningful way.

This special section of *PAGES News* highlights the importance of validating the results of individual reconstructions and simulations, and showcases a variety of methods that can be used for their comparison.

Spatial and temporal obstacles

Comparisons between paleoclimate and model data are hindered by the different characteristics of each data set. Model output is less reliable at small spatial scales, while some proxy data can be representative of only single sites. An important task is to develop methodologies for coping with these characteristics. This will allow subsequent, unbiased comparisons between simulations and proxy data that explicitly take into account the estimated errors in the proxy reconstructions and the small-scale resolution issues with models.

In general, proxy data are sampled at discrete spots in the areal dimensions of the Earth's surface and record the temporal dimension well. The vertical component of the environmental signal is only marginally captured, for example, by near-surface, thermocline, and near-bottom living marine organisms, or by sample transects across topographic gradients. While the reconstructions usually contain many points in time, the data will only be available at a limited number of discrete spatial locations. On the other hand, the spatial scale of recent global climate models (less than 300 km) enables the combined spatio-temporal domain to be explored.

Model-data advances

The comparison of paleoclimate and model data can be carried out in a number of ways. The simplest approach is to subsample the model output fields, picking out data only from those locations and seasons for which paleo-reconstructions exist for comparison. However, before a valid comparison can be made, it must be confirmed that the climate response is being compared on similar spatial and temporal scales.

There are two key statistical methods that synchronize the spatial scale of the model simulation and proxy reconstruction. The upscaling technique identifies the underlying large-scale processes, e.g., the teleconnections that control low-frequency variations observed in many proxy records. In this case, the statistical method brings the climate modes and shifts, such as those observed in the past 100 years, into a long-term context. The upscaling method can even be used to reconstruct synoptic conditions related to reconstructed ice core data (Rimbu et al., p. 5). The large-scale signal, which can be remote from the local proxy record, can then be compared with model simulations. In a similar direction, a variational approach can be used to connect the different scales of local paleo-information together with a dynamically consistent spatial smoothing (Kühl et al., p. 8). This is in contrast to the downscaling technique, where large-scale information obtained by a model simulation can be "zoomed in" to the smaller scale of proxy climate information (Raible et al., p. 10; Meyer and Wagner, p. 12).

Comparison of model simulations and data reconstructions can additionally aid in clarifying the true environmental signals recorded by proxies. It has been proposed that proxy parameters be included as tracers in models and create numerical simulations of proxy generation and burial in all available archives (i.e., synthetic marine, terrestrial and ice core), to compare them with real archives. This idea developed from the need for a mechanistic understanding of how environmental conditions are transferred to the archive. Proxy parameters that are found in a number of different archives, e.g., ^{18}O in foraminifera and ice cores, are particularly useful in this approach, as they provide information on how the climate signal is recorded within the one proxy in different climate components (ocean, ice). An example of modeling of marine $\Delta^{14}C$, and subsequent comparison with marine reservoir age, is presented by Butzin et al. (p. 13). The idea of generating pseudo-proxy records is also an important component of the new Paleo-Reconstruction Challenge (see Ammann, *PAGES News* 2008, 16(1): 4).

A variety of comparison techniques allow many additional objectives to be achieved through comparison of model simulations and proxy reconstructions. Identifying key regions where specific climate signals are likely to be recorded can optimize sampling efforts for future proxy reconstructions. It would be useful, for example, to explore targeted climate hot spots through a combined use of paleoclimate reconstructions and model-simulated climate data. Signal-to-noise ratios, or inverse methods, may be used to evaluate locations where climate phenomena can best be detected.

Comparison can also be made between different climate simulations, in order to assess whether additional forcings raise the levels of variability to a similar extent in both the simulated and reconstructed climates (Goosse et al., p. 15). Model results may also provide information on the onset, duration and magnitude of climate events, similar to how they may be expressed in proxy-based reconstructions (Wiersma et al., p. 16). Another approach is to test the robustness of model results through comparison of multiple model outputs with data (Otto-Bliesner and Brady, p. 18). Data-model comparisons can also enable the estimation of climate sensitivity (Schneider von Deimling et al., p. 20), which is important for predictions of future temperature rise based on current CO_2 projections.

Climate sensitivity estimates are reliant on estimates of past climate forcings. Data-model comparison can additionally be useful in reducing uncertainties in these past forcings (Crowley et al., p. 22). A slightly different approach is to run the model using the proxy data and to then use the model to obtain a dynamically consistent interpretation of the data. This approach has been used, for example, to clarify the temperature and ocean circulation regime during the Pliocene (Chandler

et al., p. 24). Models can also be tested against past and present scenarios (van Oldenborgh, p. 26; Mudelsee and Girardin, p. 28), which again helps to improve climate predictability.

Format and availability of data

For a data-model comparison, the proxy-reconstruction data needs first to be combined into one large data set with wide temporal and spatial coverage. This requires detailed information on sampling methods, age models and representativeness of proxy data. Fundamental to the continuation of the model-data comparison effort is the availability of and accessibility to data sets of proxy reconstructions and model output (Dittert et al., p. 30). Many recent data-modeling efforts have utilized proxy data sets made available in data archives.

Scientific education—bridging the gaps between disciplines

Earth System science is traditionally split into various disciplines and sub-disciplines. Overall, the diversity of expertise provides a solid base for interdisciplinary research. However, to gain holistic insights into the Earth System requires the integration of observations, paleoclimate data and climate modeling. These different approaches of Earth System science are rooted in the different disciplines (geology, physics, meteorology, oceanography, etc.), which cut across a broad range of timescales. It is therefore necessary to link these disciplines at a relatively early stage in MSc/PhD programs. The linking of data and modeling would enable graduate students from a variety of disciplines to cooperate and exchange views on the common theme of Earth System science, and lead to a better understanding of local processes within a global context.

Computational and conceptual models of the Earth System provide the ability to investigate different scenarios in biogeochemistry, such as the carbon cycle, the structure of marine sediments, and isotope distribution in climate components. Statistical analysis further provides a synthesis, comparison and interpretation of paleoclimate and simulated data. Training and education, particularly in time-series analysis, data exploration, process understanding and model interpretation, should all be key components of future education.

Northern hemisphere atmospheric blocking in ice core accumulation records from northern Greenland

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Atmospheric blocking is a large-scale, mid-latitude atmospheric phenomenon often associated with persistent quasi-stationary, synoptic-scale, high-pressure systems. The formation, maintenance and collapse of atmospheric blocking cause large-scale circulation anomalies and strongly impact weather patterns. Therefore, blocking regimes constitute a significant climatological feature.

Northern hemisphere blocking shows important variability at different timescales. Blocking frequencies have shown a downward (upward) trend over Atlantic and European (west Pacific) sectors. Superimposed on these linear trends, blocking frequencies show significant interannual and decadal variation (Barriopedro et al., 2006). However, in these studies, the blocking variability was derived over the relatively short time period covered by observational data with daily resolution. Here, we present the first attempt to directly relate interannual and decadal variability of several high-resolution snow accumulation records from northern Greenland with northern hemisphere atmospheric blocking. First, we investigate the relationship between atmospheric blocking and accumulation variability during the period covered by both accumulation and high-resolution (daily) observational data. Based on this relationship, we then discuss the blocking variability over the last 400 yr based only on the accumulation variability.

As an example of blocking circulation, we present in Figure 1a the 500-hPa geopotential height (shaded) and horizontal wind (vectors) during the mature phase (3 February 1975) of the blocking event that occurred in the North Atlantic sector from 28 January to 9 February 1975 (Diao et al., 2006). It can be seen that large-scale westerly flow, which is strongly blocked

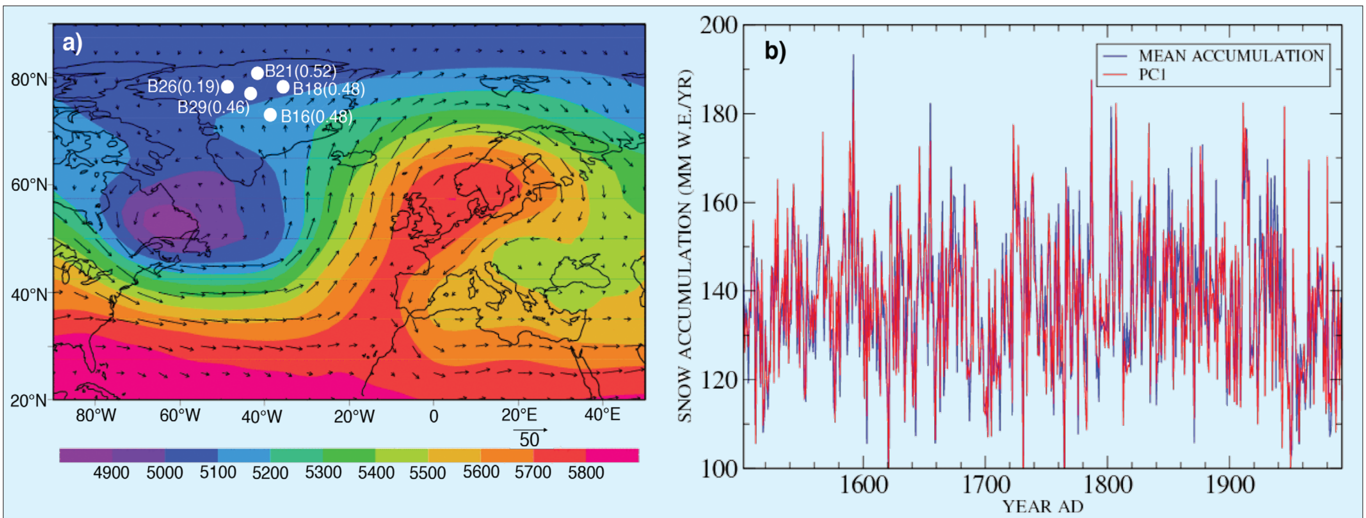

*Figure 1: **a**) The 500-hPa geopotential height (shaded; m) and horizontal wind (vector; m/s) during the mature stage (3 February 1975) of the 28 January to 9 February 1975 blocking event that occurred in the North Atlantic region. Location of core sites (filled white circles) and EOF1 values of snow accumulation records from Greenland are also indicated. **b**) The corresponding time coefficients (PC1) and the mean snow accumulation of the five records represented in a). The PC1 was scaled to have the same mean and variance as the mean accumulation time series (mm w.e./yr = mm water equivalent per year).*

over the northeast Atlantic, influences the Greenland region.

The Alfred Wegener Institute for Polar and Marine Research (AWI) in Bremerhaven, Germany performed a North Greenland Traverse (NGT) between 1993 and 1995 (Schwager, 2000). As a proxy for the blocking variability, we analyzed the yearly snow accumulation time series from five ice cores drilled during the NGT (Fig. 1a): B16 (73.9°N, 37.6°W; Miller and Schwager, 2004), B18 (76.6°N, 36.4°W; Miller and Schwager, 2000a), B21 (80.4°N, 41.1°W; Miller and Schwager, 2000b), B26 (77.3°N, 49.2°W; Miller and Schwager, 2000c) and B29 (76.0°N, 43.5°W; Miller and Schwager, 2000d). These shallow ice cores reach depths up to 150 m. Mean accumulation rates vary between 104 and 179 mm water equivalent/yr. The period covered by all five annual resolution records is 1502 to 1992 (or 491 years). These accumulation records are available through the PANGAEA online environmental database (www.pangaea.de).

Accumulation records from Greenland are affected by both meteorological and glaciological noise (Crüger et al., 2004). To filter out this noise and to obtain the dominant patterns of accumulation variability, an Empirical Orthogonal Function (EOF) is applied to normalized accumulation anomalies over the entire 1502 to 1992 period. The first EOF (Fig. 1a), which describes about 24% of variance, captures in-phase variability of all accumulation records. Its associated time coefficients (PC1) show variations very similar to the mean accumulation of the five records (Fig. 1b).

Since blocking heights affect the middle and upper troposphere, the 500 hPa geopotential anomaly field is widely used to identify blocking events. A popular algorithm to identify blocking events in this field, also used in our study, was developed by Tibaldi and Molteni (1990). For each longitude, the northern (southern) meridional 500 hPa geopotential height gradients are calculated between three base latitudes, 55°N, 60°N and 65°N and the corresponding 20°N (S) latitudes. A given longitude is defined as blocked at a specific instant in time if at least one gradient between the base and southern latitudes is greater than zero, and at least one gradient between northern latitudes and the corresponding basic latitudes is smaller than -10 m/degree latitude (Tibaldi and Molteni, 1990). The frequency of blocking (with neither time persistence or spatial criteria yet imposed) at a certain longitude is defined as the ratio between the number of days when that longitude was blocked to the total number of days of the analyzed period.

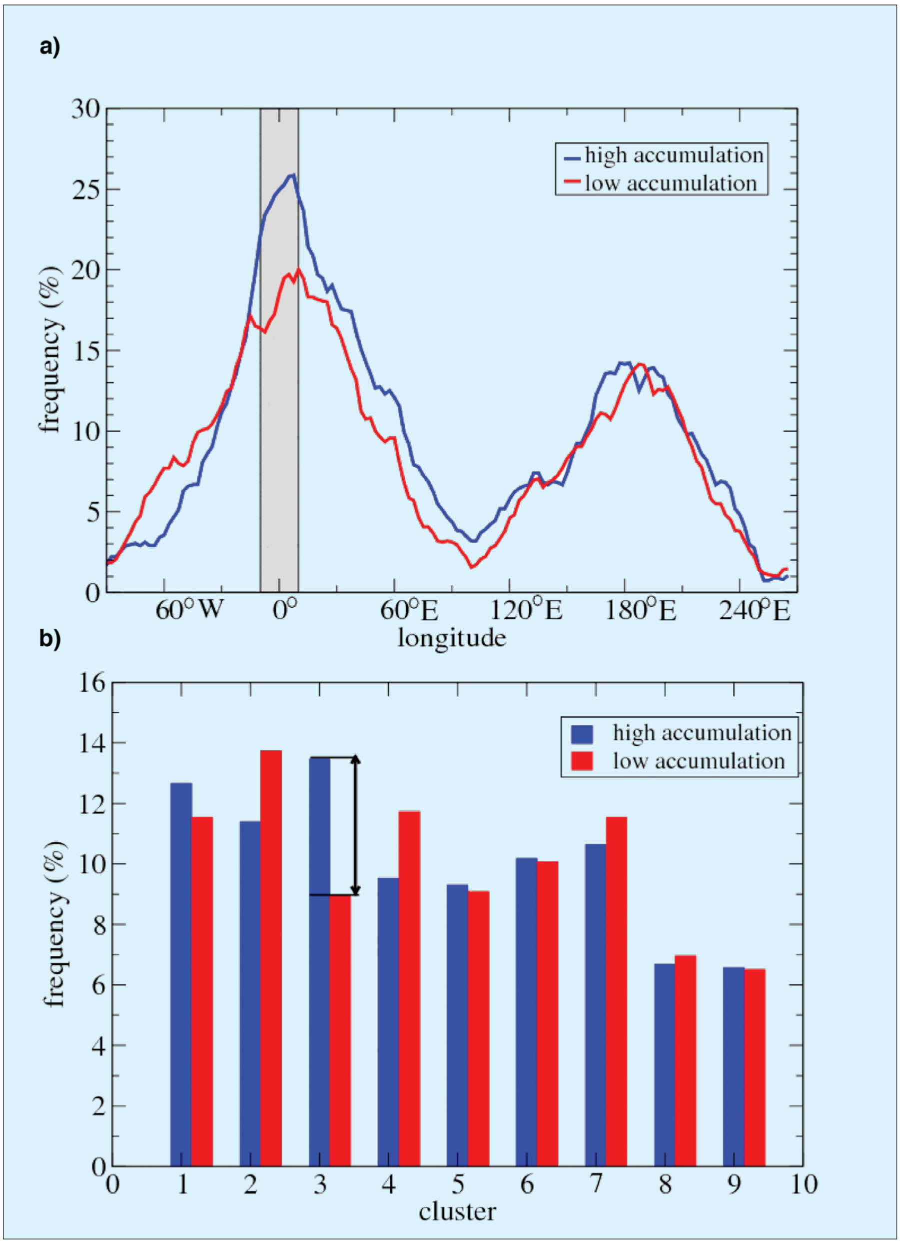

*Figure 2: **a**) Blocking-like frequency as a function of longitude for years of high and low snow accumulation on Greenland during the 1948-1992 period. Shaded area outlines the 5°W-5°E area discussed in the text. **b**) Frequency of daily atmospheric patterns during high and low accumulation years during the period 1850-1992 grouped in 9 clusters according to Philipp et al. (2007). The arrow indicates the difference between frequency of cluster 3 for high and low accumulation years.*

The frequency of blocking events during high accumulation years (PC1 higher than 0.75 standard deviation) is significantly higher in the Atlantic-European sector (20°W-100°E) than the corresponding frequency during low accumulation years (PC1 lower than -0.75 standard deviation). A reverse situation is found for the sector 80°W-20°W (Fig. 2a). No significant differences between the frequencies of blocking events during high and low accumulation years were detected outside the Atlantic and European sectors (Rimbu et al., 2007). A cluster analysis of a daily-reconstructed atmospheric circulation since 1850 revealed that winter atmospheric circulation in the Atlantic-European region is optimally represented by 9 clusters (Philipp et al., 2007). To better assess the relationship between the snow accumulation variability on Greenland and Atlantic-European atmospheric circulation, we compared the frequency of these clusters during high and low accumulation years for the period 1850-1992 (Fig. 2b). Significantly higher frequency of cluster 3 is recorded during high relative to low accumulation years. Cluster 3 represents a blocking high centered near the UK (Philipp et al., 2007).

A blocking-like circulation is associated with a blocking event if it is persistent in time and extends over several longitudes. The typical duration of blocking episodes varies between 5 and 30 days (Tibaldi and Molteni, 1990). Based on the frequency distribution of blocking-like circulation states, as represented in Figure 2a, we define a blocking index as the num-

ber of days in a winter when in sector 5°W-5°E (Fig. 2a, shaded region) at least three consecutive longitudes are blocked for at least four consecutive days. The blocking index is significantly correlated with accumulation PC1 over the period 1948-1992. This result is confirmed by a composite analysis. It reveals that this sector was blocked on average 13.6 days per winter during high accumulation years, which is significantly more frequent than the 8.6 days per winter during low accumulation years.

To identify the physical mechanism responsible for the relationship between blocking activity and the dominant pattern of accumulation variability, we investigated the moisture transport (Peixoto and Oort, 1992) in the Atlantic European region during years characterized by high and low values of the above-defined blocking index. The axis of maximum moisture transport, defined as vertically integrated water vapor transport (vectors), shifts to a more northeast-directed orientation across the Atlantic and extends northward to Greenland during years of high blocking index values (Fig. 3a) relative to the times of low blocking index (Fig. 3b). A significant reduction in the magnitude of atmospheric moisture transport (contour lines) over Greenland during periods of less frequent blocking relative to periods of frequent blocking is also evident.

We have shown that over periods covered by observed and reconstructed daily atmospheric circulation data, high accumulation in our Greenland ice cores is associated with high blocking frequency in the Atlantic-European region. Assuming that this relationship is stable in time, the periods of relatively high (low) accumulation during the last 400 years are characterized by high (low) blocking activity in the Euro-Atlantic region. We detected significant peaks at bi-decadal (~20 yr) and multi-decadal (~70 yr) timescales in the PC1 of accumulation records, which may also characterize the blocking activity in the Atlantic region. Our analysis should be extended to other proxy data, as well as to climate model experiments, for a better understanding of blocking variability during past periods.

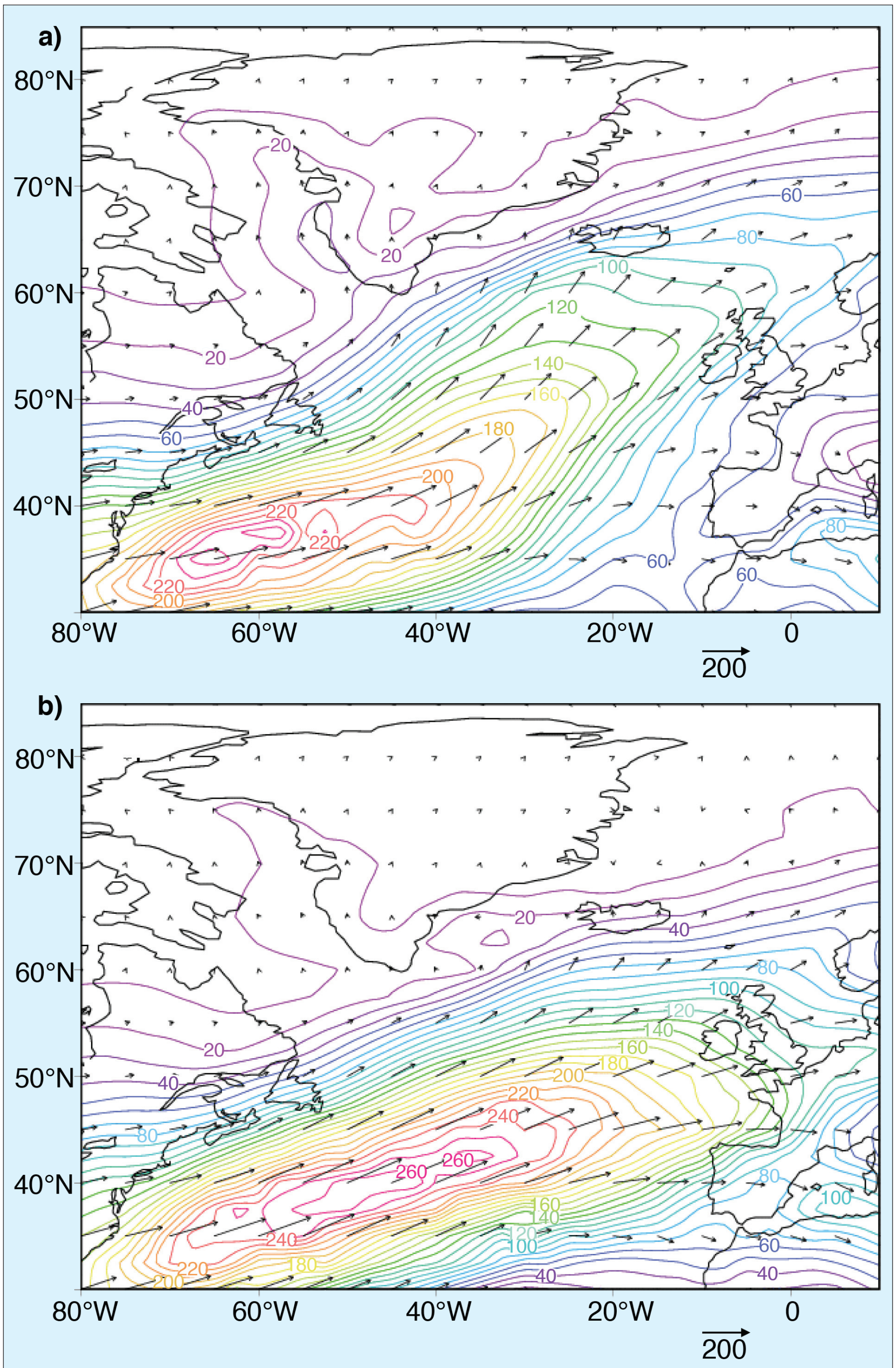

*Figure 3: Water vapor transport (vector) during **a**) high and **b**) low values of blocking index (see text for definition). The magnitude of the water vapor transport (kg/ms) is indicated by both contour lines and length of vectors.*

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For full references please consult:
www.pages-igbp.org/products/newsletter/ref2008_2.html

Reconstruction of Quaternary temperature fields and model-data comparison

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Model-data comparisons for paleoclimatic periods are one way to increase the confidence in climate system models, which are, for example, used to simulate projections of future climate change. The last interglacial, the Eemian (~127-116 kyr BP), is an example of a warm period that came to a natural end and a period in which human influence was literally absent. The fact that many sites exist in Europe, where the Eemian has been well investigated, adds to the attractiveness of this period for spatial reconstructions and for model-data comparisons. Model-data comparisons, however, are challenged by the use of data on different spatial scales. Conventional reconstruction methods provide local reconstructions for individual sites, although these results may be biased by characteristics of the local environment. This often hampers a proper comparison with climate models, and hence their validation, because these local effects are mostly attributable to scales too small to be resolved by climate models. A variational approach (Gebhardt et al., 2008) connects the different scales by an upscaling of the local paleoinformation, together with a dynamically consistent spatial smoothing.

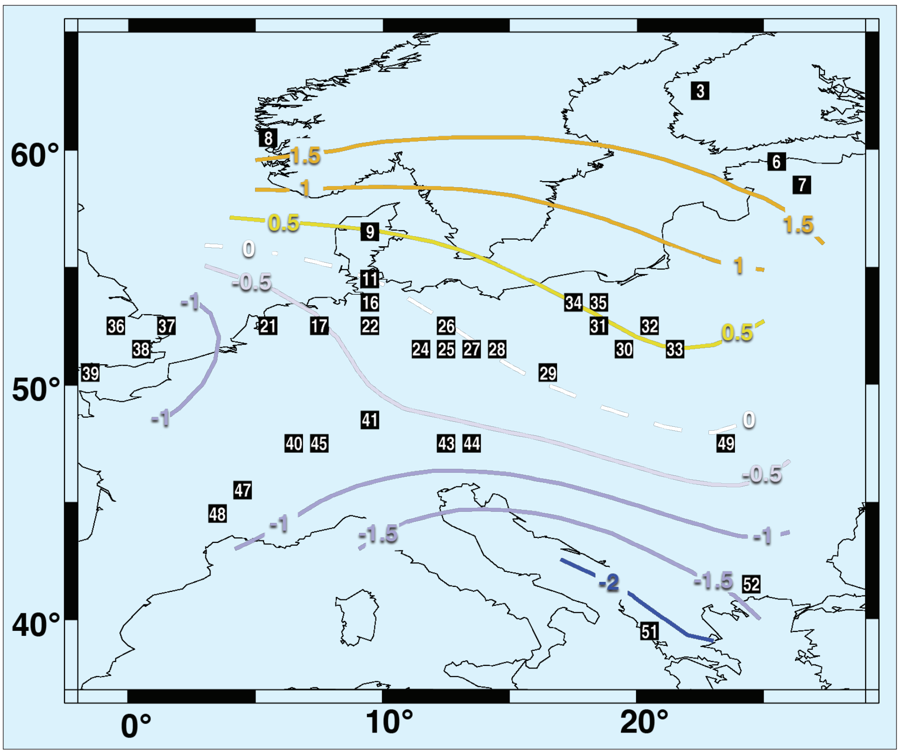

Figure 1: January temperature anomalies between the modern climate (1961–1990, New et al., 2000) and those reconstructed for the Corylus-phase (Pollen Assemblage Zone 4a) of the Eemian interglacial (Gebhardt et al., 2008). The contour interval is 0.5°C. The numbers in black boxes refer to site locations for which detailed information can be found in Gebhardt et al. (2008).

Probabilistic reconstruction and variational approach

Paleobotanical fossils (such as pollen and plant macrofossils) provide well-established terrestrial proxies used for quantitative climate reconstructions. Various approaches exist to transfer the paleobotanical data into reconstructed climate (e.g., Birks and Birks, 2003). Probabilistic reconstruction methods can take into account the uncertainties inherent in the fossil record and enable clarification of the relationship between climate and individual taxa. They potentially include all taxa, can be multivariate, and allow for an estimation of the reconstruction error. The relationship between climate and individual taxa can be described by probability density functions. For example, combining transfer functions of several co-occurring taxa provides the most probable climate reconstruction and its range of uncertainty (Kühl et al., 2002).

An approach that accounts for the difference in local proxy-reconstructions and large-scale climate simulations is the reconstruction of climate parameters as spatially coherent fields on scales comparable to those resolved by typical climate system models (Gebhardt et al., 2008). The variational analysis by Gebhardt et al. (2008) combines the probabilistic reconstruction method of Kühl et al. (2002) with a dynamical constraint (with a simple yet efficient model of the underlying climate physics) on the reconstructed climate parameter. The core of such a variational method is a cost function (Le Dimet and Talagrand, 1986), which mathematically takes into account all paleobotanical information, and climate physics information, in the reconstruction.

Our cost function for the reconstruction of temperature fields consists of two parts. The aim is to minimize the sum of these parts, i.e. the "costs" of the reconstruction. Both parts are a function of the deviation of the Eemian temperature field from the 1961–1990 climatology developed by New et al. (2000). The proxy data, in this case botanical fossil remains, form the basis of the vegetational part of the cost function. Statistical transfer functions translate the potential Eemian temperature field at a fossil site to a probability of the paleo-occurrence of the observed fossil record. The higher this probability, the lower the costs of this vegetational part in the cost function.

The second part quantifies the deviation of the potential Eemian temperature field from a simple dynamical constraint, which serves to capture the main climatological characteristics of large-scale temperature anomalies (Klaßen et al., 1994; Hense et al., 1990). The main purpose of this constraint is to stabilize the reconstruction by constraining the spatial structures of the Eemian temperature anomalies to climatologically relevant scales but not their amplitudes.

The temperature field for which the cost function is minimized, i.e., for which the cost function calculates lowest costs, is the one that is most consistent with all available information (Fig. 1) and is interpreted as the most likely Eemian temperature field. All mathematical details of the cost function are described in Gebhardt et al. (2008).

Data-model comparison

Reconstructed January and July mean temperatures of the early Eemian (~125 kyr BP) have errors with a median value of about

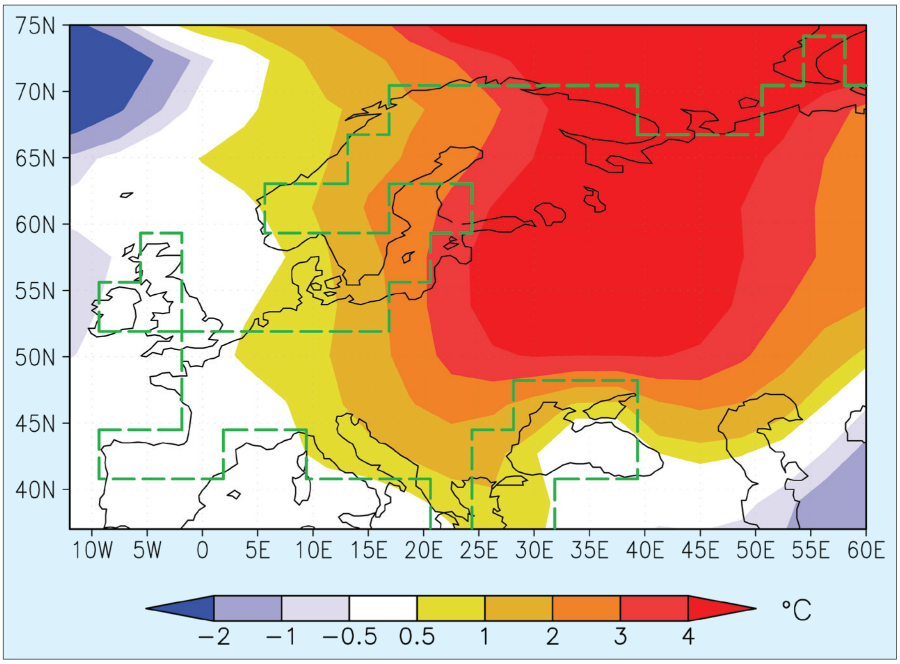

Figure 2: January temperature anomalies as simulated by the coupled ocean atmosphere general circulation model ECHO-G for the Eemian at 125 kyr BP minus preindustrial, averaged over a 50-year interval. The land mask of the model is shown with green dashed lines to illustrate the spatial resolution of the model (Kaspar et al., 2005).

1.8°C in January and about 1.1°C in July. Reconstructions across Europe show positive temperature anomalies for Scandinavia and near the east coast of the Baltic Sea. In contrast, early Eemian temperatures in Central Europe were apparently quite similar to those found today, as no drastic differences were reconstructed between the Eemian and modern (1961–1990) climate. This implies somewhat stronger temperature gradients across Europe in the Eemian than are observed today (Fig. 1) (Gebhardt, 2003; Kühl, 2003).

A gradient in simulated January temperature anomalies is also visible for that region in a climate simulation (Kaspar et al., 2005) using the coupled climate model ECHO-G (Min et al., 2005), which was driven by orbitally-induced changes in insolation (Fig. 2). The model consists of the ECHAM4 atmosphere model at a horizontal resolution of ~3.75° and 19 vertical levels, coupled with the HOPE-G ocean model at ~2.8° and a gradual meridional refinement toward the equator to 0.5°.

The temperatures in Western Europe (Spain, France) are similar in the simulation of the Eemian interglacial and of the preindustrial period. Increasing temperature differences between both simulations occur in the northeast direction toward Scandinavia. In the region of Finland, the temperature anomalies are in the order of +3°C. The general pattern is consistent with the results of the reconstruction, and model and reconstructions only differ in the magnitude of deviation between Eemian and today's climate.

The overall similarity in the pattern supports the conclusion drawn in Kaspar et al. (2005) that the same processes are responsible for the spatial distribution in the simulation and in the estimates from the paleoecological data. The winter temperature anomalies cannot be explained by insolation change directly because the winter insolation in the high northern latitudes was lower in the Eemian than today. Therefore, it can only explain the Western European temperature differences.

Two effects contribute to the increasingly positive differences toward Scandinavia: First, increased westerly winds at around 55°N transport more oceanic heat into this region. Second, the winter sea ice in the Arctic is significantly reduced, especially in the Barents Sea. This causes a strong reduction in the surface albedo, resulting in significantly increased regional temperatures. The decreased sea ice coverage is mainly a result of the distinct increase in northern hemispheric summer insolation, which is not compensated for by reduced winter insolation. These results illustrate that changes in insolation and the reaction of the atmosphere-ocean system, as simulated by the climate model, are sufficient to explain the reconstructed European temperature patterns.

Although it has to be noted that the reference period for calculating anomalies for the reconstruction (1961-90) and the ECHO-G simulation (1871-1900) are different, the offset due to climate change is small in winter and with weak gradients in summer (Min and Hense, 2007). Thus, there is no effect on the conclusion about orbitally induced influence. The results are in line with previous modeling studies (e.g., Felis et al., 2004). More results of the ECHO-G simulations and comparisons with other studies can be found in Kaspar and Cubasch (2007).

Even though there are model-data comparisons that show good correspondence between local reconstructions and model simulations (e.g., Kaspar et al., 2005), the large-scale properties of the reconstructed anomaly fields is certainly more suitable for comparisons of proxy-based reconstructions with simulated paleoclimates because their spatial resolution and consistency are closer to the properties of the model simulations.

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Maunder Minimum climate variability from wind and moisture-sensitive proxies and model simulations

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To assess ongoing and potential future climate change with confidence, it is necessary to put such changes into a long-term perspective. The only accessible information beyond instrumental records is proxy data. However, proxy data suffer from three shortcomings: (i) they are indirect measures of climate variability, (ii) they could represent a mixture of different signals (e.g., temperature and precipitation), and (iii) they are often sparsely resolved in time and space. Alternatively, climate models can be used. However, such models are afflicted with uncertainties related to their formulation and the processes they include. Moreover, the credibility of model simulations crucially depends on the availability and quality of forcing data (Rind et al., 2004), which is estimated from proxy data. Thus, a deeper insight into past climate changes can only be gained by an interdisciplinary effort.

The Maunder Minimum (MM; ca. 1645 – 1715) was a period of reduced solar irradiance and was characterized by prolonged cold conditions (Luterbacher et al., 2001). Therefore, it serves as an example period and enables understanding of forcing-induced variations on the climate, in particular atmospheric circulation and the hydrological cycle. For example, in ensemble simulations of the MM, Yoshimori et al. (2005) showed that natural forcing signals, like volcanic eruptions, are clearly represented in the modeled temperature, and partly in precipitation, on hemispheric scales. On regional scales, natural forcing signals could be masked by the unforced atmosphere-ocean variability. These regional results have important implications in identifying suitable locations to reconstruct climatic responses to external forcing functions.

Thus, the ensemble simulations of the MM provide a beneficial test-bed, which could improve our understanding of what is recorded in proxy data. Here, we aim to compare results obtained from these ensemble simulations of the MM and a present-day control simulation, with wind- and moisture-sensitive proxy data in order to show the model's ability to clarify discrepancies between proxy records and to help in the interpretation of proxy data.

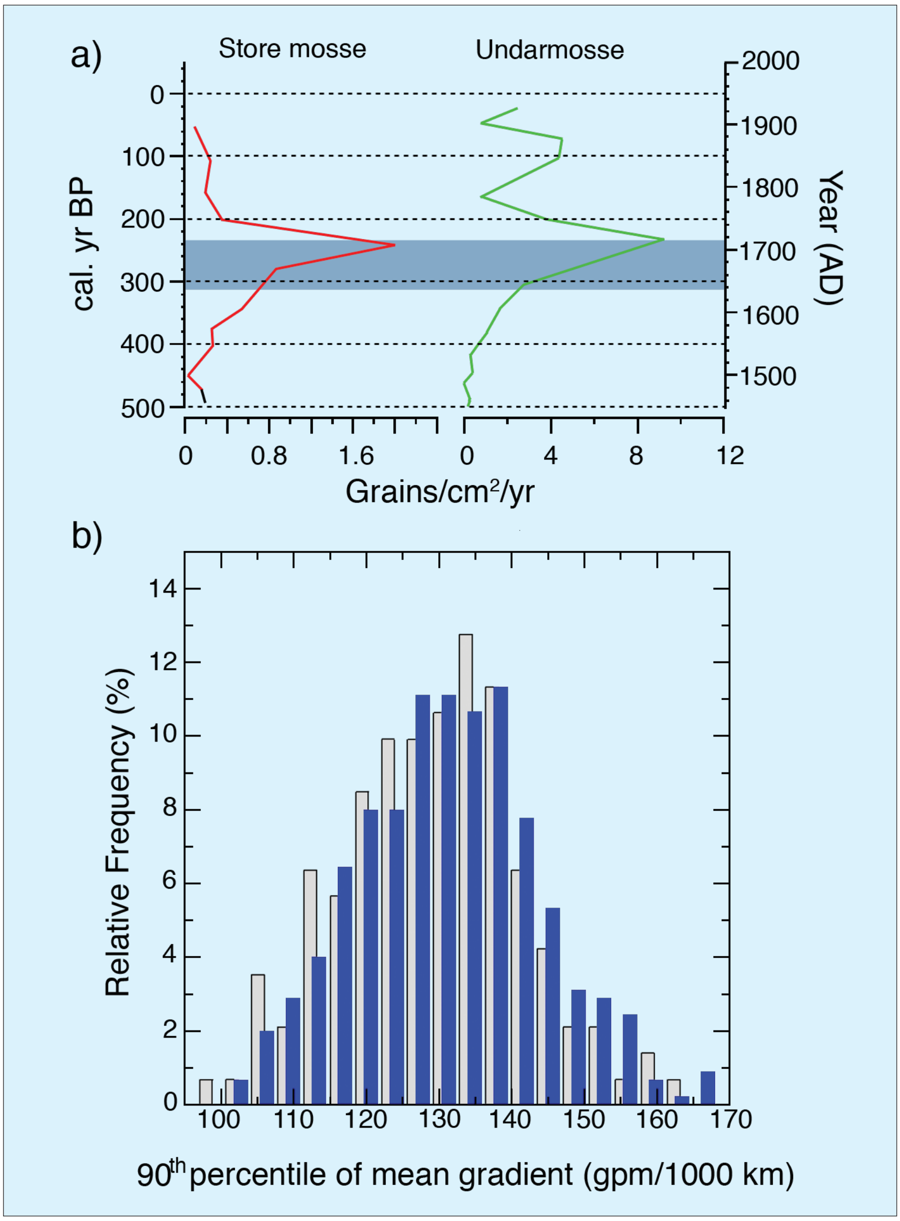

*Figure 1: **a**) Annual influx of sand grains (>200 µm) into the ombrotrophic peat bogs Store mosse and Undarmosse, southwest Sweden (De Jong et al., 2006; 2007) with shaded area indicating duration of the MM; **b**) Simulated distributions of extreme cyclone intensity in northern Europe (Raible et al., 2007) for the MM (blue) and present-day control simulations (grey) (gpm = geopotential meter).*

Wind sensitive proxies

Two ombrotrophic peat bogs in southwest Sweden were studied for the content of wind-transported sand grains (De Jong et al., 2006; 2007). High abundances of medium-large sand grains are related to winter storminess, thus the abundance of medium-large sand grains was used as a proxy for storm frequency and intensity (Fig. 1a). These studies provided strong indications that storminess substantially increased around the MM, compared with both earlier and later time periods. De Jong et al. (2006; 2007) also showed that increased storminess recorded at the two sites apparently coincided with storm events recorded at other sites in southwest Scandinavia, suggesting that these records reflect a regional-scale climatic signal. However, an independent climate field reconstruction of sea surface pressure (Luterbacher et al., 2001) shows a negative phase of the North Atlantic Oscillation (NAO), which implies on average weaker winds over Northern Europe.

At first glance, this is in contrast to the proxy data from southwest Sweden. To clarify the reasons for this discrepancy, the

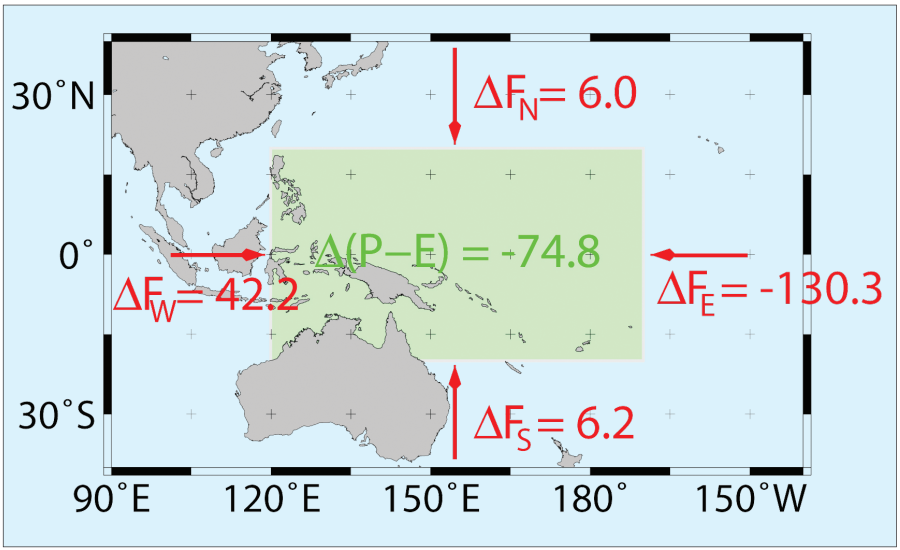

Figure 2: Annually vertically integrated moisture budget between MM simulations and the 1990 control simulation: ΔF are the moisture flux changes integrated over the corresponding boundaries (west, north, east, south) and Δ(P-E) is the change in the difference precipitation minus evaporation (Yoshimori et al., 2006). The unit is 10^6kg/s.

proxy results were compared to modeling results obtained from a comparison of the ensemble simulations of the MM with a present-day control simulation (Raible et al., 2007). Initial results suggested that during MM, winter cyclones traveled more zonally and shifted southward relative to today. This means that the number of cyclones was, on average, decreased over northern Europe, leading to a simulated pressure difference between the MM and today, which represents the negative phase of the NAO (similar to Luterbacher et al., 2001).

To gain further insight, cyclones and their characteristics, such as extremes in cyclone intensity, were investigated in the ensemble simulations of the MM and compared with the present-day control simulation (Raible et al., 2007). The results show that even in areas where the number of cyclones is lower during the MM, such as in northern Europe, the extreme cyclone intensity is significantly higher in winter (Fig. 1b), compared to today. Raible et al. (2007) provided a hypothesis for the processes underlying this cyclone intensification. The meridional temperature gradient plays a key role in intensifying these extreme cyclones, as well as the increase of lower-level baroclinicity (a measure of stratification) in the North Atlantic, when comparing the MM with today.

Thus, the modeling results help to overcome this apparent contradiction, showing that a decrease in the number of storms in northern Europe during the MM was accompanied by an intensity increase. This suggests that the sand-grain proxy records (De Jong et al., 2006; 2007) are strongly influenced by extreme events rather than the pure number of storms. However, one should mention that these results are obtained from a single model and that the difference is only statistically significant between MM versus today, and not between MM versus a control simulation for 1640 AD conditions; the latter shows the influence of solar and volcanic forcing only during the years of the MM period.

Concept to interpret hydrological proxies

The interpretation of hydrological proxies provides another challenge, as such proxies can be sensitive to dynamic and/or thermodynamic effects. To overcome these difficulties, an analysis, which allowed the separation of the two effects, was applied to the same ensemble simulations of MM in Yoshimori et al. (2006).

The analysis of Yoshimori et al. (2006) focused on the western tropical Pacific, where coral proxy data (Hendy et al., 2002) indicated salinity changes in this region during the MM. Hendy et al. (2002) showed that the reconstructed salinity was increased during the MM, compared to today. They further hypothesized that these salinity changes were associated with changes in the Hadley circulation.

In Yoshimori et al. (2006) this hypothesis was investigated. The ensemble simulations of the MM show a salinity anomaly of the same positive sign in the western tropical Pacific as the coral proxy data. Moisture fluxes of these ensemble simulations of the MM are compared with a present-day control simulation. As shown in Figure 2, the salinity anomaly is primarily generated by an atmospheric moisture transport anomaly through the eastern boundary of the region. The humidity-change-related part of this flux dominates over the circulation-related part. The humidity change is generated by a temperature decrease due to a lower saturation pressure of water vapor, as the cold atmosphere of the MM held less moisture than the warm atmosphere of today.

From the study of Yoshimori et al. (2006) alone, the interpretation of the coral proxy record is inconclusive because of uncertainties in the model simulations and the coarse model grid, as discussed in detail in their paper. Nevertheless, the model output provides a consistent but different interpretation of the coral proxy data, i.e., thermodynamic vs. dynamic effects. It is clear that further studies and improved models are needed to further clarify these discrepancies.

Outlook

Bringing together proxy data and modeling results will help to overcome their individual caveats and obstacles. Studies presented here show that carefully interpreting such simulations can help to increase the understanding of wind and hydrologically sensitive proxy data and to put them into a dynamical context. The strength of modeling studies also lies in providing mechanisms that explain changes in proxy data. Moreover, a coordinated effort for multi-model ensemble simulations for the last millennium would be useful to highlight robust results. The steadily growing proxy data offers future opportunities for interdisciplinary collaborations, e.g., in South America (e.g., LOTRED-SA;www.pages-igbp.org/science/lotred-sa/) and the Mediterranean Basin (e.g., MedCLIVAR; www.medclivar.eu/); the latter is thought to be highly sensitive, particularly with regards to the hydrological cycle (IPCC, 2007).

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The Little Ice Age in southern Patagonia: Comparison between paleoecological reconstructions and downscaled model output of a GCM simulation

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The “Little Ice Age” (LIA) usually refers to climatic anomalies over the northern hemisphere between the 13th and mid-19th century. The LIA is well documented in northern Europe and America, where a huge variety of chronicles, historical documents, proxy-based reconstructions and also temperature measurements indicate cooler and wetter conditions. Within the LIA, a period with even lower temperatures was the Maunder Minimum (MM; ~1645–1715). Proxy and modeling studies point to a prominent influence of solar forcing causing the MM (Eddy, 1976; Zorita et al., 2004). At the beginning of the last millennium, a period of warmer conditions, especially over Europe, has been documented; the so-called Medieval Warm Period (MWP; ca. 9th–13th centuries) (Jones et al., 2001; Osborn and Briffa, 2006).

For the southern hemisphere, especially for the mid- and high-latitudes, no documentary evidence of these climatic events is available due to the large oceanic areas and the sparse settlement of the continental regions during these periods. Additionally, the number of proxy-based reconstructions is fragmentary.

Here, results of a simulation with a general circulation model (GCM) with varying forcing factors (solar, volcanic, greenhouse gases) of the last 1000 years are compared to proxy data for southern South America. The main goal was to examine if, and to what extent, the LIA could be identified in paleohydrological proxies in southeastern Patagonia. In the GCM simulation the LIA is indicated by a pronounced decline in northern hemispheric temperatures in the period between 1500 and 1900 (cf., von Storch et al., 2004).

The GCM used had quite a coarse resolution (ca. 300 x 300 km). Small-scale processes, specifically those related to hydrological variables, are not realistically reproduced. To overcome this, an additional statistical downscaling technique was implemented, relating the large-scale circulation of the GCM, which is more realistically reproduced than hydrological variables, with local precipitation over South America. The downscaling model is based on principal component regression analysis (Luterbacher et al., 2002). To set up the downscaling models, the leading five sea level pressure (SLP) principal components of the National Centers for Environmental Prediction (NCEP)-reanalysis (Kistler et al., 2001) over southern South America were linked to precipitation over southeastern Patagonia (Beck et al., 2004) for the period 1951–2000 by means of multiple linear regression. (Principal components reflect the temporal evolution of eigenvectors (=Empirical Orthogonal Functions, EOFs) of the covariance-matrix, e.g., from SLP anomaly fields.) Although the downscaling models describe only part of the observed precipitation variability, their performance is still high enough to be used for downscaling the large-scale circulation of the GCM. To obtain the simulated SLP principal components of the last thousand years, the observed NCEP-EOFs were projected onto the simulated SLP anomaly fields. In the last step, these simulated SLP-principal components were used to reconstruct precipitation over southeastern Patagonia. Downscaling models also allow investigation of the physical mechanisms that explain precipitation changes related to changes in the Southern Hemispheric Westerlies (SHWs). For southeastern Patagonia, the downscaling models show that stronger SHWs are linked to higher precipitation and vice versa (Wagner et al., 2007).

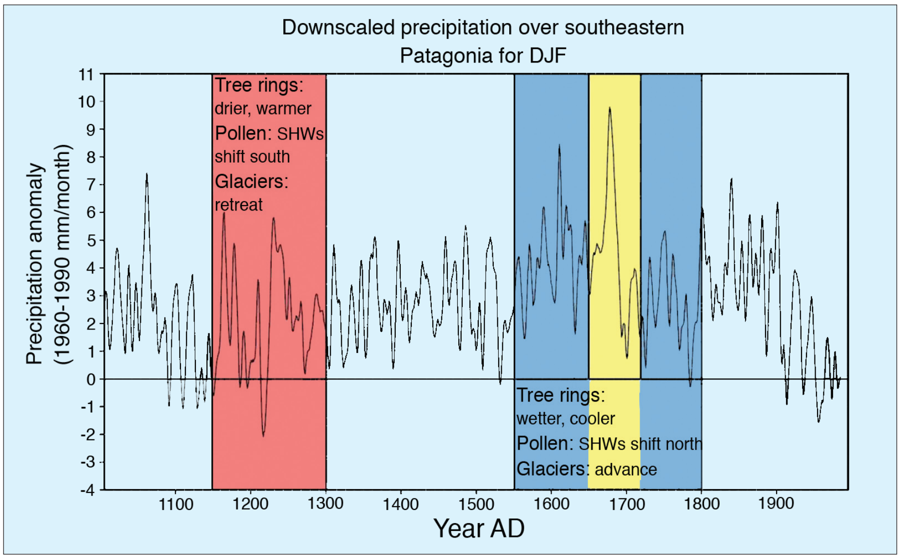

*Figure 1: Downscaled precipitation for south-eastern Patagonia for austral summer (DJF) (MWP = **red**, LIA = **blue**, MM = **yellow**). Note the wetter conditions during the LIA, especially the MM compared to the most recent period 1960–1990 indicated by the zero line. Climatic information derived from proxy data is given for the respective anomalous periods.*

The downscaled precipitation for southeastern Patagonia for austral summer (DJF) is shown in Figure 1. Results for the different historical periods are compared with the most recent period (REC), i.e., 1960–1990. According to Figure 1, the LIA, and here especially the MM, is a time of wetter conditions in Patagonia compared to REC, with precipitation anomalies of +4.1 and +3.4 mm/month for the MM and the LIA, respectively. Precipitation differences are statistically different at the 5% level. Conversely, most periods during the MWP show conditions that are only slightly higher compared with REC (+1.7 mm/month). Here precipitation differences are not statistically significant at the 5% level.

These precipitation fluctuations can be attributed to latitudinal shifts of the SHWs. A mechanism that possibly explains changes in SHWs relates to the extension of the sea ice south of South America (not shown): During the MWP, the SHWs shifted further to the south due to a decrease in sea ice cover. As a consequence, the SHWs were located over southern Patagonia. The volume of sea ice increased during the LIA, especially around the MM and the SHWs shifted further northward again.

Downscaled results of the GCM simulation are also in accordance with results from dendroclimatological investigations (Villalba, 1990; Lara and Villalba, 1993) that show wetter conditions in Patagonia

during the LIA. Again, these changes can be attributed to shifts of the SHWs. Additionally, lacustrine investigations (Haberzettl, 2006; Stine and Stine, 1990) indicate lower temperatures and wetter conditions in Patagonia during the LIA. Pollen-based results point to vegetation-type changes from dry to wet species. The latter can also be attributed to shifts in the SHWs (Mayr et al., 2007). Further, the analysis of glaciers and moraines in Patagonia show extensive glaciation during the LIA (Harrison et al., 2006, Koch and Kilian, 2005, Thompson et al., 1986).

Therefore, the comparison between proxy-based reconstructions and results from the GCM simulation show that both, model and proxy data indicate a climatically anomalous period between the mid-16th and 19th century over southern South America. This suppors the hypothesis that the LIA, as indicated in proxy based and modeled northern hemispheric temperatures, is also reflected in hydrological variables over parts of the southern hemisphere.

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Three-dimensional radiocarbon modeling: A tool to assess the last glacial ocean circulation and radiocarbon chronologies

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At the Last Glacial Maximum (LGM), the overturning circulation of the ocean was probably quite different from today. The changes are still debated, as the current generation of coupled climate models arrive at contradictory results (e.g., Otto-Bliesner et al., 2007), and paleoceanographers face the problem of extracting robust and unambiguous information from proxy data.

In an attempt to reconcile observations with modeling, we simulated the distribution of marine radiocarbon (^{14}C) at the LGM, using a three-dimensional ocean general circulation model connected with an atmospheric radiocarbon reservoir (Butzin et al., 2005). The ocean model has an effective horizontal resolution of 3.5°, with a vertical resolution of 22 depth levels, and it is forced with atmospheric fields, which were derived in previous glacial climate simulations (as described by Prange et al., 2004). In a series of sensitivity studies with constant boundary conditions, we explored the influence of sea surface temperatures, sea ice extent, wind stress, and Antarctic sea ice formation on the glacial ^{14}C distribution and on the meridional overturning circulation (MOC).

Our simulations reveal a crucial influence of the background climate conditions on the results. The best agreement of modeled ^{14}C distributions with glacial ^{14}C observations is for a model run with significant MOC changes in the Atlantic, where the North Atlantic Deep Water (NADW) shallows to a depth above about 2 km and weakens by about 40% compared to the present day. Conversely, Antarctic Bottom Water flow intensifies and compensates for the weakened NADW transport into the South Atlantic. As a consequence, the modeled abyssal glacial Atlantic is depleted in ^{14}C (Fig. 1), very cold and very saline. These results are in line with proxy data evidence (see Lynch-Stieglitz et al., 2007, for a review).

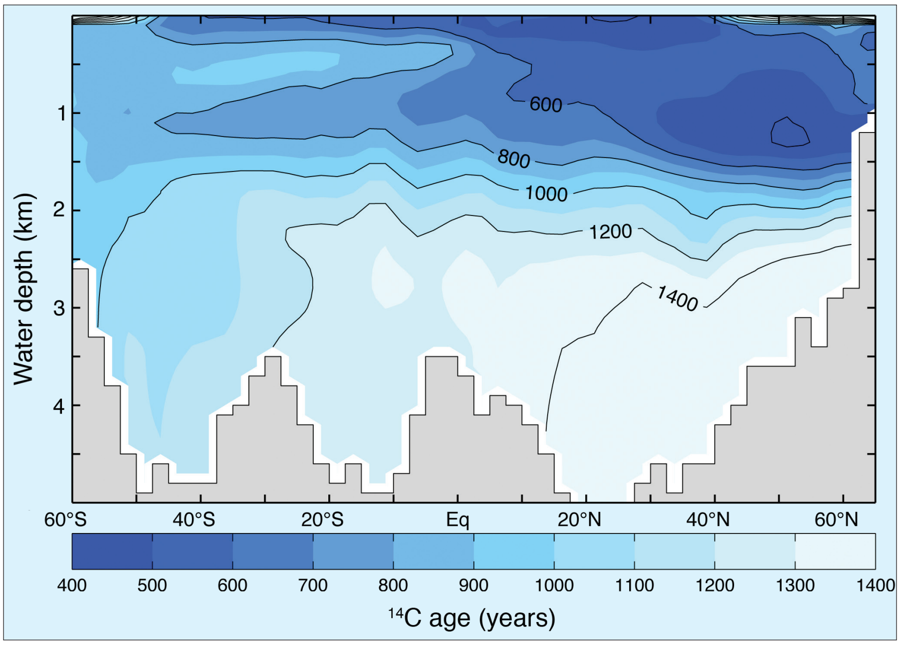

Figure 1: Radiocarbon age in the western Atlantic (along the GEOSECS track) according to simulations for the Last Glacial Maximum (Butzin et al., 2005).

Radiocarbon concentrations in environmental samples are frequently quoted in the form of ages relative to atmospheric ^{14}C values. Applying the law of radioactive decay, high ^{14}C concentrations translate into low ^{14}C ages, and vice versa. Radiocarbon concentrations of the present-day surface ocean correspond to an apparent marine reservoir ^{14}C age (MRA) of about 400 yr in the global mean, and range from about 300 yr in the subtropics to 1000 yr at high latitudes (e.g., Key et al., 2004). Our simulations indicate generally higher MRAs for the LGM (Fig. 2). This reflects slower uptake of ^{14}C by the glacial ocean, which is predominantly due to the reduced partial pressure of atmospheric CO_2

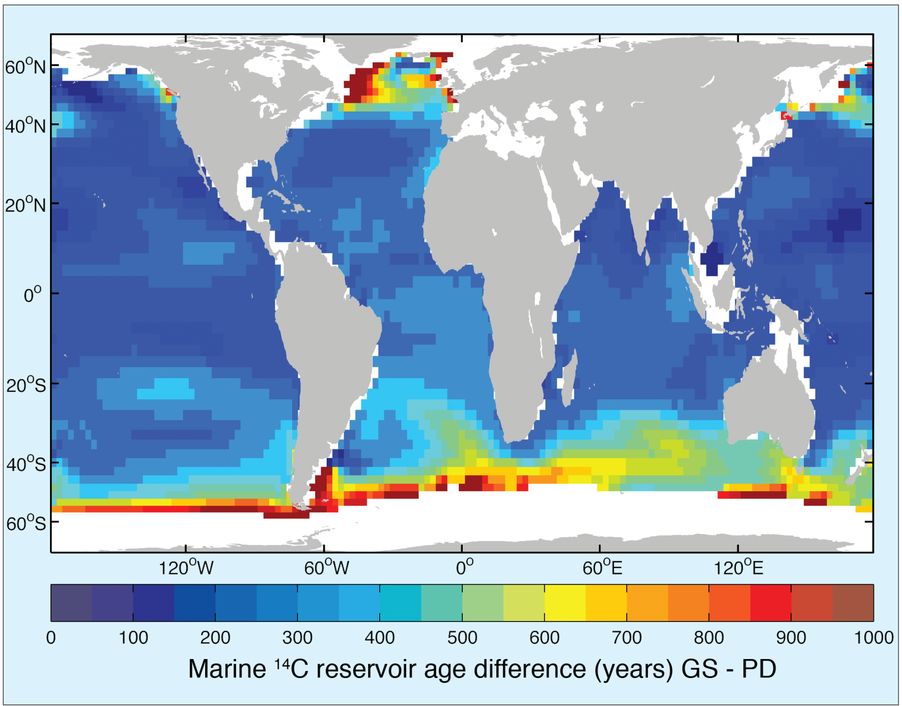

Figure 2: Marine reservoir age difference between the glacial (GS) and the present-day (PD) ocean, based on model calculations (Butzin et al., 2005).

and weakened MOC at the LGM. The spatial and temporal variability of MRAs is a critical factor in ^{14}C dating. Beyond the tree ring record (i.e., before ca. 12.4 cal kyr BP), atmospheric chronologies for ^{14}C dating rely to a large extent on cross-dated marine archives such as laminated sediments or corals. Although there is observational evidence for considerable MRA changes during the last deglaciation (e.g., see Cao et al., 2007, and references therein), most ^{14}C chronologies have not included this effect but assume time-invariant MRA values.

For this reason, we devised a self-consistent iteration scheme in which existing radiocarbon chronologies for the last deglaciation can be readjusted by transient, three-dimensional simulations of marine and atmospheric $\Delta^{14}C$ (Butzin et al., 2008). The idea is to infer atmospheric $\Delta^{14}C$ from marine reconstructions by back and forth model calculations. The iteration scheme starts with a prescribed atmospheric $\Delta^{14}C$ chronology (derived from marine data assuming a certain inverse MRA correction), and uses an ocean model to diagnose the corresponding evolution of marine $\Delta^{14}C$. If there are differences between model results and reconstructions, the atmospheric chronology has to be adjusted by applying a modified MRA correction, and the ocean model is rerun using this new atmospheric ^{14}C input curve. The procedure is repeated until model results and reconstructions converge, which implies that atmospheric $\Delta^{14}C$ values and MRAs are consistent with marine reconstructions.

To estimate the uncertainties associated with the intensity of ocean ventilation during the last deglaciation, we examined the effect of different climatic background states (ranging from a Heinrich meltwater event-type state with substantially reduced MOC to a present-day state with strong MOC), and thus obtained upper and lower bounds for the deglacial MRA evolution. As an example, we considered a ^{14}C chronology from the Caribbean, which originally assumed a time-invariant MRA value of 420 yr (Hughen et al. 2006; see Fig. 3). Our simulations started from steady-state conditions at 25 cal kyr BP assuming atmospheric $\Delta^{14}C$ = 530‰. We focused on the period 20–14 cal kyr BP, as the first millennia of the simulations may be biased by the model's adaptation to the transient ^{14}C input history. The readjustment points to MRAs of 100–850 yr in the Cariaco Basin during the last deglaciation. Correspondingly, the variability of re-adjusted atmospheric $\Delta^{14}C$ increases by –50 to +100‰, and increases the mysterious drop of atmospheric concentrations between 17.5 and 14.5 cal kyr BP discussed by Broecker and Barker (2007).

Our readjustment approach is complementary to statistical methods devised for the estimation of ^{14}C chronologies (such as devised by Buck and Blackwell, 2004). Uncertainties of this approach due to potential model deficiencies could be narrowed down by ensemble and intercomparison runs.

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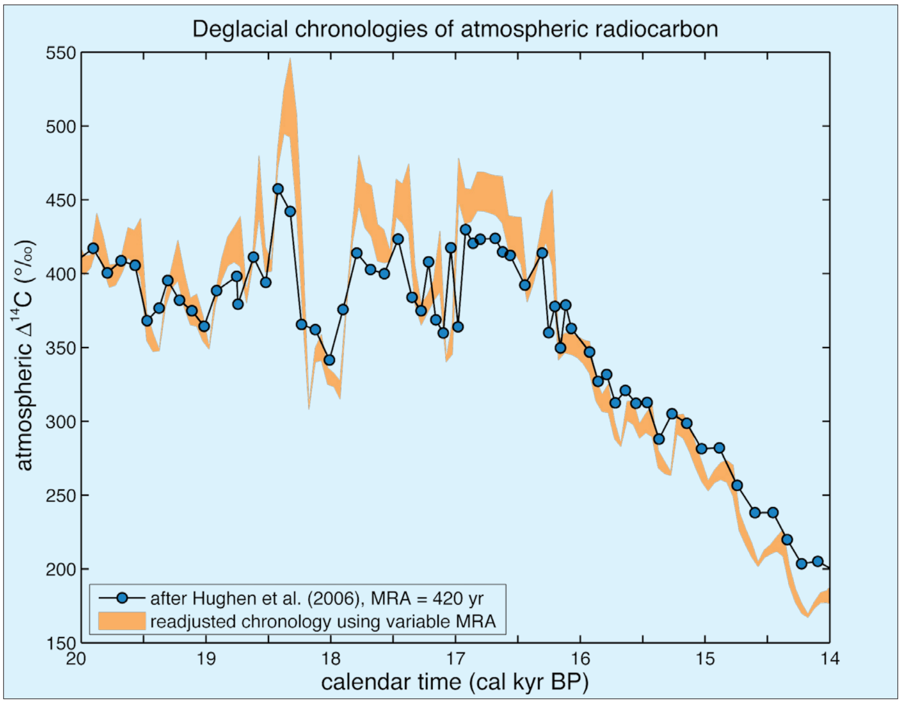

Figure 3: Readjustment of an atmospheric ^{14}C chronology (Hughen et al., 2006, originally assuming a time-invariant marine reservoir age correction of 420 yr) by self-consistent modeling. Different climatic forcing scenarios yield upper and lower bounds spanning the uncertainty range of the readjustment approach (Butzin et al., 2008).

Data assimilation over the last millennium using ensemble techniques

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Over the last few years, a large number of new proxies, new large-scale reconstructions and model simulations covering the last millennium have become available (e.g., Mann and Jones, 2003; Jansen et al., 2007). They consistently show that at the hemispheric (or quasi-hemispheric) scale, the most recent decades are likely the warmest of at least the past millennium. Moreover, the recent warming can only be simulated in models if the effect of the increase in greenhouse gases concentration in the atmosphere due to human activities is taken into account.

However, our understanding of climate change in the period before this clear anthropogenic influence is still fragmentary. One reason for this is the relatively small magnitude of the signal recorded over this period, compared with, for instance, the changes observed during the Last Glacial Maximum. A second element is the spatial heterogeneity of the signal, with climates in disparate regions evolving very differently over time. Part of this regional variability could be related to changes in atmospheric and oceanic circulation. For instance, it has been proposed that the North Atlantic Oscillation or the El Niño Southern Oscillation may be influenced by solar and volcanic forcing, leading to a spatial response of the system similar to the characteristic patterns associated with those modes of variability (e.g., Robock, 2000; Shindell et al., 2001, 2003; Mann et al., 2005). On the other hand, a significant part of the variability is purely related to the internal dynamics of the climate system and could not be linked to any modification in the external forcing. At the regional scale, particularly in mid and high latitudes, this internal variability is generally the dominant cause of the observed temperature changes before the 20th century (e.g., Goosse et al., 2005; Tett et al., 2007).

As long as a model contains the correct basic atmospheric and oceanic physics, it can simulate the forced variability. In this framework, models can produce patterns similar to those observed when averaged over a relatively large number of events or years. This could then be tested by comparing simulated and observed changes during the years following several major volcanic eruptions, or on average over long periods characterized by high (or low) total solar irradiance.

Models cannot be expected to precisely reproduce the time evolution of the true climate due to the large and potentially chaotic internal variability. Comparing regional details between model and observations for a single simulation is thus unlikely to yield meaningful insights, even if averaged over multiple decades before the anthropogenic warming of the late 20th century. One solution is to perform an ensemble of simulations over the last millennium in order to provide a reasonable estimate of the range of anomalies potentially associated with internal variability. The consistency between model results and proxy records can then be established by verifying that the observed evolution is well within the range obtained from the ensemble of simulations.

An alternative is to use data assimilation to optimally combine information from proxy data and model simulations, and obtain a consistent picture of past climate changes. Such an approach coerces the model towards agreement with the proxy records, taking into account the potential uncertainties in both model results and proxy data. In this approach, a realization of the model's internal variability is selected that is closest to the actual climate state, as inferred from the proxy data. The result of the data assimilation exercise over the last millennium is then a reconstruction of past changes, taking into account all the information available from proxy-data, model results and reconstructions of the changes in external forcings.

Despite the potential merit of this approach, only a few attempts at such data assimilation have thus far been made, perhaps because of the technical challenges involved. Simulations have been performed in which the model state is nudged, using a sophisticated statistical approach, to a pattern reconstructed from available observations (e.g., Jones and Widmann, 2003; van der Schrier and Barkmeijer, 2005). One advantage to such a technique is its computational efficiency. Furthermore, the spatial pattern of climate change is constrained at all locations of the model's domain. On the other hand, this approach requires one to have first statistically reconstructed from proxy data the pattern toward which the model state will be nudged.

Another option is to use ensemble techniques, where the information provided by the ensemble of simulations is combined with the one provided by the proxies at the time considered. In this framework, the simplest method is probably to first perform a large ensemble of simulations (of the order of 100 or more) over a particular year or period. The dis-

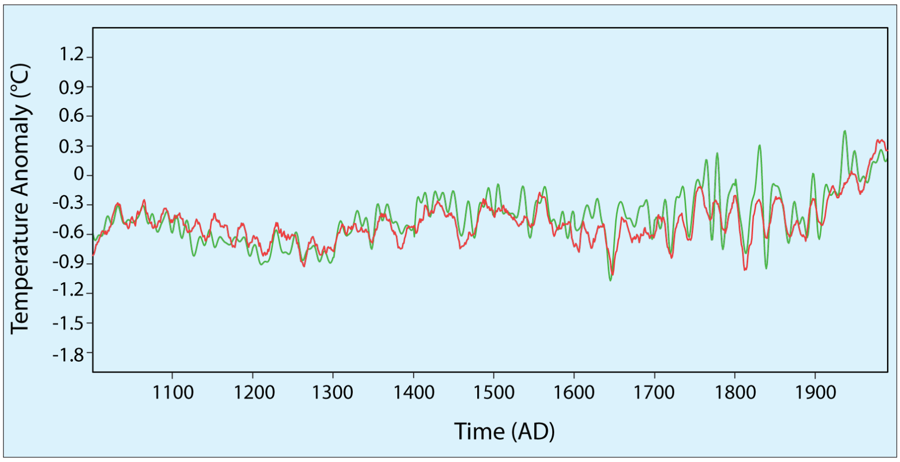

*Figure 1: Anomaly of annual mean temperature averaged over the area 0-30°E, 55-65°N, corresponding to northern Europe, from 1100 to 1900 AD. The **green line** is the average of several proxy records in this area (Mann et al., in prep.) and the **red line** is the result of a simulation with data assimilation using ensemble technique in the LOVECLIM model (www.astr.ucl.ac.be/index.php?page=LOVECLIM%40Description). An 11-year running mean has been applied to both time series. At this scale, the agreement between proxy record and the simulation using data assimilation is very good. For comparison, the range associated with internal variability in this area in the model, as measured by the standard deviation of an ensemble, is larger than 0.4 °C (Goosse et al., 2005), i.e., of the same order of magnitude as the difference between the warmest and coldest period during the pre-industrial period.*

tance between each member of the ensemble and the proxy record is measured by a cost function using reconstructed and simulated variables at the locations where the proxies are available. The best simulation, defined as the one that minimizes this cost function, is then selected as representative for this particular year or period, and used as the initial condition for the subsequent year. The procedure is repeated as many times as required in order to provide a reconstruction for the whole millennium (e.g., Collins, 2003; Goosse et al., 2006; Figure 1).

In this technique, the model is only constrained locally, at the locations where the proxy records are available. This is a clear advantage, compared to the nudging techniques, as the reconstructed spatial pattern is the result of the data assimilation procedure itself and is thus independent of any statistical method used to reconstruct patterns. A downside of the approach is the potential systematic error incurred if the model is not able to reproduce observed teleconnections between different regions.

Preliminary proofs of concept using this ensemble method have demonstrated that it can efficiently yield a plausible large-scale reconstruction if only a small number of proxies are available, and yet can also reconstruct regional detail where the number of available proxy data are sufficiently large (e.g., Goosse et al., 2006).

On the basis of these successful preliminary results, ongoing work is underway to investigate in greater detail the mechanisms that may be responsible for the climate changes of the past millennium. Potential refinements of the approach include a more sophisticated treatment of the uncertainties in both the proxy data and simulation results. This is a challenging issue for a number of reasons. For example, the nature of the uncertainties in proxy-derived climate records are complex, involving complicated physical or biological responses, which may yield frequency-dependent loss of climate information. Further work is necessary to characterize these uncertainties and biases more fully. Furthermore, classical assimilation methods used in meteorology and oceanography cannot be transferred directly to the analysis of the past millennium. Fortunately, focused efforts in this area are now underway, as discussed at one recent workshop on "Data assimilation to study the climate of the past millennium" (www.astr.ucl.ac.be/index.php?page=Wokshop_assim). It is reasonable to expect that significant improvements in the techniques used for data assimilation over the last millennium will be achieved in the years ahead, yielding significantly refined estimates of past changes and a better understanding of the causes of those changes.

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Facilitating proxy-data interpretation of abrupt climate events using model simulations

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Climate model results vs. proxy-based climate reconstructions

Comparing climate model results for abrupt climate events with proxy-based climate reconstructions is often hampered by the difference in spatial and temporal characteristics. Proxy-based climate reconstructions present a climate signal over a long period of time at a specific location. Due to bioturbation, sample size, aquifer buffering, diffusion, etc., the climate signal recorded at an arbitrary point in time is often the integrated climate signal over several decades. This produces a time series of the climate signal smoothed by a decadal-scale filter. Modeling results, on the other hand, are often visualized as the spatial distribution of the average temperature or precipitation over a decadal- or centennial-scale time-window (averaging time-window) relative to a control climate.

This way of visualizing climate-model results generally gives a good indication of the geographical distribution of the event and the relative magnitude in differ-

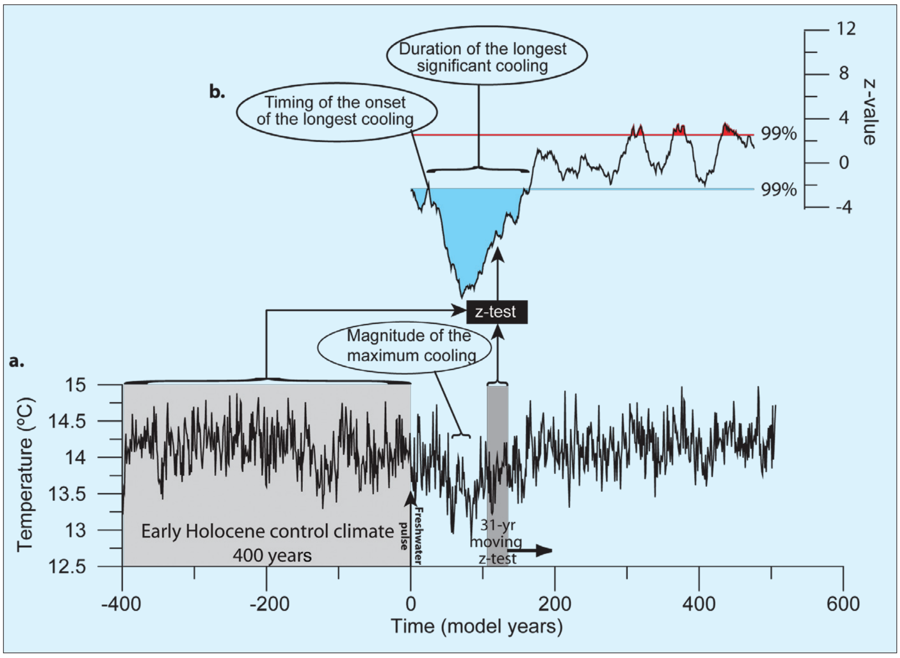

*Figure 1: Moving z-test. **a**) Surface temperature output from a grid-cell in the climate model. The arrow at t = 0 indicates the introduction of the freshwater pulse. By way of a moving z-test, we assess if the mean of the 31-year moving window is statistically different from the mean of the early Holocene control climate. **b**) the z-test values are separated into significant and non-significant values. Also indicated are the variables plotted in Figure 2: Timing of the longest anomalous cooling, duration of the longest anomalous cooling and the maximum 31-year cooling.*

ent areas. However, the method ignores the fact that the climate response in certain areas may have varied on timescales smaller than the applied averaging time-window, especially when considering relatively short-lived climate anomalies. For instance, areas may have undergone climate changes that were shorter than the averaging time-window, or variability may have occurred within the period, such as a warming preceding a cooling. In these cases, the climate anomaly of a centennial-scale time-window is not a good indication of the climate response in the model. Using shorter averages (e.g., 10-year means) can be misleading, as climate on such a short timescale is influenced by decadal-scale internal variability. Another shortcoming of the use of averaging time-windows is that valuable information present in climate model results is ignored, such as differences in timing and duration of a climate response in different areas.

Here, we propose a novel method for the analysis and presentation of simulation results of anomalous centennial- to millennial-scale climate warming or cooling events. The method provides information on the timing (onset), duration and magnitude of climate events for every spatial grid-cell (5.625 x 5.625 deg. longitude and latitude), similar to the way they could be expressed in proxy-based reconstructions. Information on these factors provides insight into the spatial and temporal evolution of a climate event, and should facilitate a direct comparison between climate models and proxy-based reconstructions. As an illustrative example, we apply the method to climate model results of the 8.2 kyr climate event.

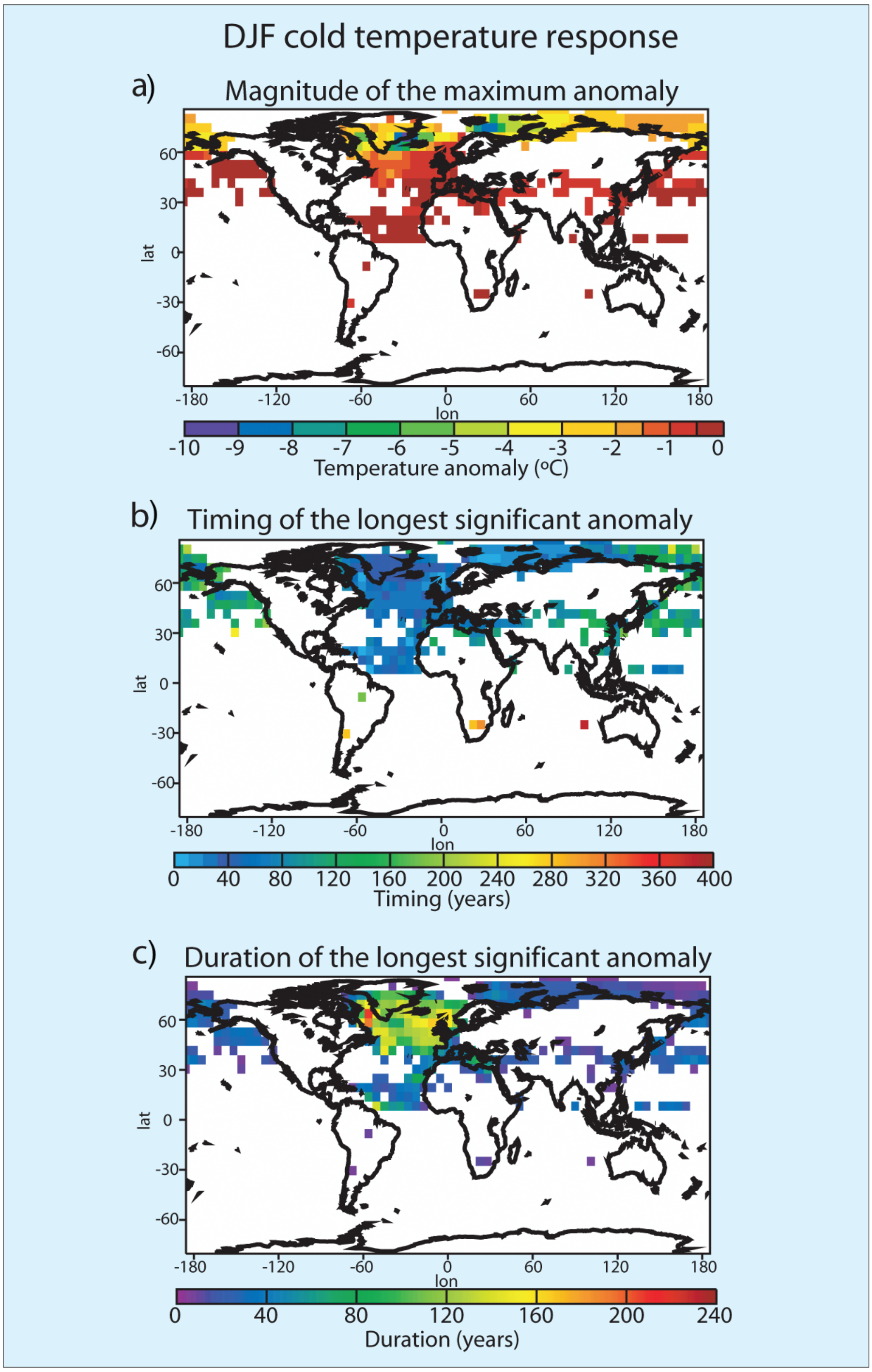

Figure 2: Modeled spatial and temporal characteristics of the significant DJF surface cooling anomaly of the 8.2 kyr event from averaging the results of the 10 ensemble members: ***a****) maximum 31-year average cooling;* ***b****) timing of the longest significant cooling;* ***c****) duration of the longest significant cooling. Notice that the magnitude plot shows the maximum temperature anomaly of the 31-year moving window for every grid-cell that is asynchronous.*

The 8.2 kyr climate event

The 8.2 kyr event is the most pronounced Holocene climate event in the North Atlantic area (Alley et al., 1997). The event is widely regarded to have been caused by the catastrophic outflow of the proglacial lakes Agassiz and Ojibway, causing weakening of the ocean thermohaline circulation (Barber et al., 1999). In an earlier study, we performed multiple simulations of the 8.2 kyr event in the ECBilt-CLIO-VECODE coupled climate model (Opsteegh et al., 1998; Goosse and Fichefet, 1999; Brovkin et al., 1992) by introducing various volumes of freshwater into the Labrador Sea in a stable early Holocene climate state (Wiersma et al., 2006). One particular experiment, in which we introduced 3.26 x 10^{14} m^3 of freshwater, produced a cooling in Greenland that compared well with the 8.2 kyr event of ~160 years duration (Thomas et al., 2007) and ~3.3 °C (Kobashi et al., 2007) transient cooling, recorded in Greenland ice cores. This modeling experiment consisted of 10 model runs (ensemble members), each starting from a slightly different climate state. Although the perturbation is applied from different initial conditions, the modeled climate event was similar in each of the different ensemble members.

Analyzing the model results

We used the surface temperature results of this experiment to analyze the timing, duration and magnitude of the modeled 8.2 kyr event for each model grid-cell. Our atmospheric model contains a surface grid of 64 by 32 cells for longitude and latitude, respectively. In this example (Wiersma et al., 2008), we used the yearly December-January-February (DJF) surface temperature output (Fig. 1a).

We are interested in finding the temperature response of the 8.2 kyr event in the model results, as could be expressed in common proxy-based reconstructions. Therefore, in each of the ensemble members we applied a moving z-test to the time-series of surface temperature of every grid-cell. This test assesses whether the mean of a sample (here a 31-year centered moving-window; Fig. 1a) and the popula-

tion (here the 400 year early Holocene control climate before the perturbation; Fig. 1a) are statistically different, by comparing the variance and average. Subsequently, we separated cold and warm anomalies that are significant at the 99% level (Fig. 1b). For the grid-cells with significant cold and/or warm temperature anomalies, we calculated the following properties: the duration of the longest anomaly, the maximum 31-year mean temperature anomaly and the timing of the onset of the longest anomaly relative to the freshwater forcing (Fig. 1).

Applying this method on the separate ensemble members generates a climate response that also includes anomalous data points resulting from natural climate variability. Since we are interested in the temperature anomaly that is forced by the lake drainage, we average the output properties (magnitude, timing and duration) of the 10 ensemble members and mask grid-cells that do not show a significant anomalous response in each ensemble member. Subsequently, we generate anomaly maps for each of the properties. In contrast to many studies that aim to derive the externally forced climate signal (e.g., Stott et al., 2000), we do not first average the ensemble members and then perform the statistical test. The reasoning behind this is that we are interested in the signal that could be registered in climate proxy archives. This signal is comparable to the climate signal of a single ensemble member and different from the artificially enhanced signal of the ensemble average. We then average the properties in the ensemble members and filter out grid-cells that do not show a climate response in each of the ensemble members to obtain the robust response. This step is reasonable because all ensemble members showed a similar climate evolution.

Timing, duration and magnitude

Figure 2 shows the results of this analysis for the cold response in the DJF season. The first striking feature is that the cold anomaly is concentrated in the northern hemisphere, especially Greenland, the North Atlantic area and its eastern coastline. The Arctic Ocean and the Mediterranean Sea area are affected. A robust cooling response is also present in the Asian subtropical regions around 30°N. Large variations in magnitude are evident, and the largest anomalies are north of Iceland and near Spitsbergen (Fig. 2a). Furthermore, time-lags in the onset of the event are present in the order of decades (Fig. 2b). Interestingly, the cold response in Greenland emerges ca. 40 years after the freshwater forcing. The duration of the event exhibits geographical variation as well, with the longest duration in the North Atlantic area and gradually decreasing towards the limits of the impact (Fig. 2c). In the remaining areas where a response is simulated, the duration is in the order of decades, which strongly reduces the probability of being recorded. Moreover, applying the same analysis on the cold response in the June-July-August season provides insight into seasonal differences in the response. Focusing on the warm response provides information on the behavior of the bipolar seesaw and possible warm overshoots following an initial cooling (Wiersma et al., 2008).

To summarize, the method presented here is an improvement on the traditional analysis of climate modeling results and facilitates model-data comparison for several reasons. First, the method provides information on geographical variation in timing, duration and magnitude of abrupt climate events, which can serve as a framework for proxy-data interpretation. Second, proxy-based climate reconstructions can be compared directly to the modeling output, since the latter contains decadal-scale information comparable to proxy records. Third, the results can be used to indicate areas where the event is expected to be registered in proxy records, providing clues about where to look for a specific climate response.

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PMIP2 climate model-proxy data intercomparisons for the LGM

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Climate models may perform equally well for simulating the present-day and 20th century climates, yet produce very different responses to likely changes in forcing (such as greenhouse gases and insolation) in the future. Therefore, it is important to compare current state-of-the-art climate model simulations of past climates against the benchmarks of paleo-observations. The Paleoclimate Modelling Intercomparison Project (PMIP) is a long-standing initiative endorsed by PAGES and the World Climate Research Programme JSC/CLIVAR Working Group on Coupled Models (WGCM). It provides for coordination of paleoclimate modeling activities on the mechanisms of climate change, the identification of key feedbacks operating in the climate system, and on the capability of climate models to reproduce climates that are different from modern.

PMIP initially focused on two periods, the Last Glacial Maximum (LGM; ca. 21 cal kyr BP) and the mid-Holocene (MH; ca. 6 cal kyr BP). The experiments were designed to examine the climate response to Milankovitch orbital forcings for the MH and the presence of large ice sheets and low greenhouse gas (GHG) concentrations for the LGM. Seventeen modeling groups participated in simulations of these time periods with atmosphere-only models (PMIP1), and twelve groups in the second phase of the project (PMIP2) using ocean-atmosphere or ocean-atmosphere-vegetation models. With the incorporation of coupled atmosphere-ocean-sea ice models into PMIP2, new comparisons to proxy data can now be used in evaluating the capabilities of current climate models to simulate climate conditions different than present. Here, we describe two such comparisons of the PMIP2 LGM simulations to glacial proxy data: deep-ocean tempera-

tures and salinities in the Atlantic Ocean, and sea ice extent around Antarctica.

PMIP2 LGM simulations

Six international modeling groups have contributed PMIP2 simulations for the LGM: CCSM (the National Center for Atmospheric Research CCSM3 model), HadCM (the UK Met Office HadCM3M2 model), FGOALS (the LASG/Institute of Atmospheric Physics FGOALs-g1.0 model), IPSL (the Institut Pierre Simon Laplace IPSL-CM4-V1-MR model), MIROC (the CCSR/NIES/FRCGC MIROC3.2.2 medres model), and ECBilt-CLIO (the KNMI ECBilt/Louvain-la-Neuve CLIO intermediate complexity model)—models also used for the IPCC AR4 simulations of future climate change. For the PMIP2 LGM simulations (Braconnot et al., 2007), all of the models used the ICE-5G reconstruction of LGM continental ice sheets (Peltier, 2004), the same change from pre-industrial levels of atmospheric concentrations of carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) based on the ice core records (Fluckiger et al., 1999; Dallenbach et al., 2000; Monnin et al., 2001), the specification of additional land due to a lowering of sea level, and the change to insolation resulting from a slightly different orbit of the Earth. The presence of extensive glacial ice sheets accounts for over half of the total radiative forcing of the troposphere (Hewitt and Mitchell, 1997), and the lowering of GHG concentrations (primarily the CO_2) accounts for most of the remaining radiative forcing (Otto-Bliesner et al., 2006), with small contributions from the additional land and insolation changes.

Atlantic deep-ocean temperatures and salinities

Pore fluid measurements of the chloride concentration and the oxygen isotopic composition from Ocean Drilling Program (ODP) cores in the Atlantic have allowed the simultaneous reconstruction of salinity and temperature of the deep ocean for the LGM (Fig. 1) (Adkins et al., 2002). For modern, the core top samples indicate the presence of warm, salty North Atlantic Deep Water at great depths for latitudes north of ~40°N, with the colder and somewhat fresher Antarctic Bottom Water dominating south of this latitude. For LGM, these cores indicate that the Southern Ocean deep water extended its influence far into the North Atlantic. LGM Atlantic deep waters were much colder and saltier than modern day. Additionally, deep ocean potential temperatures (θ) were relatively homogenous over the north-south extent of the Atlantic, compared to modern data. The data also suggest a significant north-south deep ocean salinity gradient during the LGM in the Atlantic, with the deep Southern Ocean much saltier than the North Atlantic.

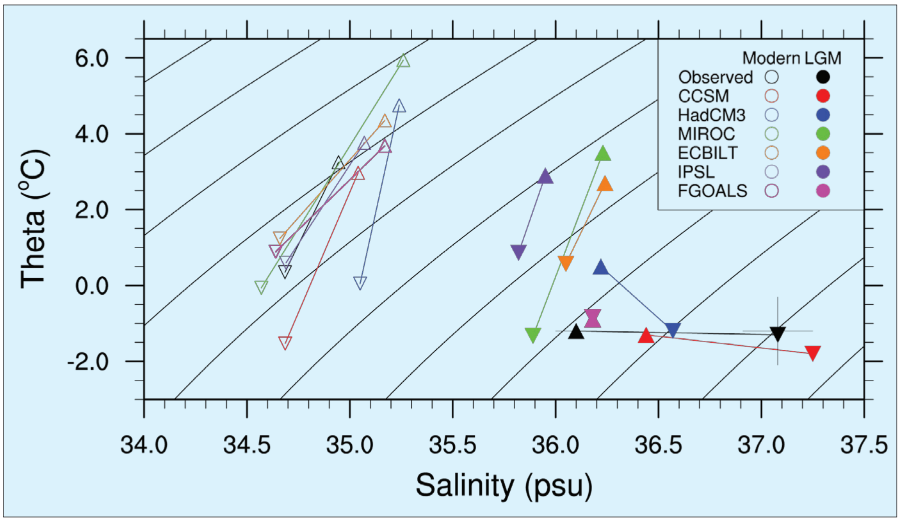

Figure 1: Theta (potential temperature) and salinity for modern (open symbols) and LGM (filled symbols) estimated from data (black symbols with error bars) at ODP sites (Adkins et al., 2002) and predicted by PMIP2 models. Site 981 (Δ) is located in the North Atlantic (Feni Drift, 55°N, 15°W, 2184 m). Site 1093 (∇) is located in the South Atlantic (Shona Rise, 50°S, 6°E, 3626 m). Only CCSM included a 1 psu adjustment of ocean salinity at initialization to account for fresh water frozen into LGM ice sheets; predicted salinities for the other models have been adjusted to allow comparison.

The PMIP2 models can be used to simulate the three-dimensional temperature and salinity structure of the oceans. Model-ODP comparisons show that the models reproduce the modern deep ocean temperature-salinity structure in the Atlantic basin relatively well (Fig. 1). They simulate warmer and saltier deep waters at Feni Drift in the North Atlantic than at Shona Rise in the Atlantic sector of the Southern Ocean, with deep ocean density gradients mainly due to the temperature difference. Greater differences between models occur for the LGM simulations. Three of the models simulate a very cold and relatively homogeneous temperature structure from north to south in the Atlantic basin, with CCSM also simulating the observed large north-south salinity differences during the LGM. The other three models also simulate colder LGM deep waters and somewhat greater salinity increases in the Southern Ocean than the North Atlantic as compared to modern but retain the temperature-salinity structure of the modern simulation.

Southern hemisphere sea ice

Planktic foraminiferal estimates of sea surface temperature and abundances of diatoms and radiolarians preserved in deep-sea sediments in the Southern Ocean have been utilized for reconstructing LGM sea ice extent around Antarctica. Increasing abundances of taxa that show a strong correspondence to sea ice or open ocean have been used to estimate statistically the number of months per year of sea ice cover (Gersonde et al., 2005; Crosta, 2007). The diatom records confirm the presence of extensive sea ice around Antarctica during LGM winters, similar to the reconstruction of CLIMAP (CLIMAP project members, 1981) but argue for a more restricted extent during LGM summers (Fig. 2). The diatom-reconstructed LGM summer sea-ice margin around Antarctica extended far northward to ~55-60°S in the Atlantic, while in the Indian Ocean sector, the extent was similar to modern.

The climate models used for PMIP2 predict the thermodynamics and dynamics of sea ice with sea ice models of varying complexities. All the models simulate an expansion of sea ice at LGM compared to modern, with greater expansion in the Atlantic sector than the Pacific sector. Overall, the models agree with the data on winter LGM sea ice extent in the Pacific sector but only two models extend the sea ice as far northward as the data in the Atlantic sector. The model simulations of summer sea ice extent are much less consistent. Three of the models simulate LGM summer sea ice extent comparable to modern extent in the Southern Ocean, while the other three models simulate much more expansion of LGM summer sea ice. The asymmetry of LGM summer sea ice extent between the Atlantic and Indian Ocean sectors, as indicated by the data, is simulated poorly by all the models. The FGOALS model simulates the greatest sea ice extent during the LGM, with relatively small seasonal variation.

Implications

It has been shown that the response of the coupled climate system to changes in GHG forcing is dependent on the simulation of sea ice physics and strong sea ice

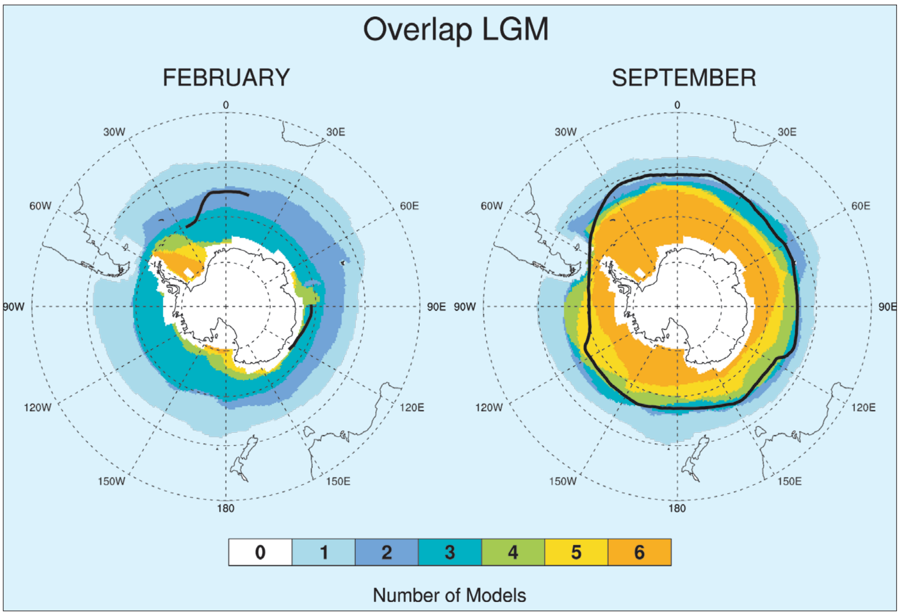

Figure 2: LGM sea ice distribution in the southern hemisphere simulated by PMIP2 models for February and September. For each grid cell, the figure indicates the number of models that simulate at least 15% of the area covered by sea ice. The proxy reconstructions of sea-ice edge (black lines) are from Gersonde et al. (2005).

feedbacks (Holland et al., 2001). This complexity is also highlighted by these PMIP2 results, where models show a large range of sea ice and associated ocean circulation responses to LGM forcing. Climate model simulations combined with proxy reconstructions have shown that LGM sea ice and ocean stratification can provide additional constraints on interpretation of the LGM Atlantic meridional overturning (Shin et al., 2003; Otto-Bliesner et al., 2007). LGM sea ice extent has been shown to be important in modulating the atmosphere-ocean interactions and water mass formation in the subpolar North Atlantic. The cold, salty Antarctic bottom waters at LGM form in coastal leads and just equatorward of permanent sea ice cover, due to brine rejection during sea ice production. Additionally, the suppression of air-sea gas exchange due to glacial sea ice expansion in the Southern Ocean has been suggested to play a possible role in regulating past atmospheric CO_2 (Morales Maqueda and Rahmstorf, 2002; Stephens and Keeling, 2000).

Further information on the models discussed can be found at www.pages-igbp.org/products/newsletter/ref2008_2.html. Details on PMIP2 can be found at http://pmip2.lsce.ipsl.fr

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Are paleo-proxy data helpful for constraining future climate change?

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How sensitive is our climate system to CO_2? This is a key issue in a world of rising greenhouse gas concentrations. Estimating the temperature sensitivity of the Earth to changes in atmospheric CO_2 has therefore been the subject of intensive research. Yet, uncertainty in our knowledge of this sensitivity is still large—as expressed by the broad 2-4.5°C range of climate sensitivity (ΔT_{2x}) estimates (Meehl et al., 2007). Commonly ΔT_{2x} is defined as the equilibrium global-mean temperature change for doubling the pre-industrial CO_2 concentration. The direct radiative effect is a warming by 1°C but what makes the total warming uncertain is the strength of the fast climatic feedbacks—mainly ice-albedo, water vapor, lapse rate and cloud feedback. Here, we discuss how paleo-data can be used to reduce uncertainty in the range of ΔT_{2x}.

One way to compute climate sensitivity is to use climate models that calculate the feedbacks and thus ΔT_{2x}. Another approach is to use the observed response of the climate system to constrain climate sensitivity. Studies using the climate signal provided by the instrumental record of the past 100-150 years were unable to rule out ΔT_{2x} values above the IPCC range (Meehl et al., 2007). Unless we wait for the climate change signal to become much stronger, it will not be possible to greatly reduce uncertainty in ΔT_{2x} in this way. A way out of this dilemma may be the use of paleo-data, which contain information on how sensitively the climate system has responded in the past to a radiative perturbation.

The three critical conditions for the success of this approach are: (1) a sufficiently large climate response in order to separate the signal from climatic noise, and sufficiently accurate data describing both (2) the climate change and (3) the forcing of this climate change. A promising candidate is the climate of the Last Glacial Maximum (LGM; 21 kyr BP), a time period that was on global average 4-7 °C colder than today (Schneider von Deimling et al., 2006a) with an abundance of good data on the forcing and the temperature distribution.

The observed response, seen through past climate changes, can be used in two ways for inferring ΔT_{2x}:

(1) The ratio of past temperature change to forcing is estimated based on data and is then taken as a measure for the temperature response to doubling of CO_2 (paleo-calibration, Covey et al., 1996). This approach assumes that the strength of the climate feedbacks inferred from the past can be taken as a direct measure for ΔT_{2x}. As the past is not a perfect analog for the future (e.g., the spatially inhomogeneous glacial forcing differs from the homogeneous 2xCO_2 forcing), this assumption may be questionable.

(2) Using paleo-data in conjunction with climate models to constrain model

parameters. We will refer to this approach, which estimates ΔT_{2x} without assuming a perfect past-future analog, as the CMD (Constraining Models by Data) approach. Required for this are models able to simulate paleoclimates and present climate based on different boundary conditions without altering model parameters. Such models are used to simulate the temperature response of the climate system following a large radiative perturbation (e.g., as caused by prescribing LGM boundary conditions). The paleo-data are used to sort out those models that are overly sensitive or not sensitive enough. We can then base our estimate of ΔT_{2x} on those models that have successfully simulated the LGM cooling (or other paleoclimates).

Constraining climate sensitivity by LGM ensemble simulations

We tested the CMD approach for estimating ΔT_{2x} using a fully-coupled model of intermediate complexity (CLIMBER-2, Petoukhov et al., 2000). With an ensemble of 1000 model versions we calculated the present-day climate state, LGM cooling and $2xCO_2$ warming for all model versions (Schneider von Deimling et al., 2006b). A clear link between simulated $2xCO_2$ warming and LGM cooling emerged in our model-ensemble: models with a high ΔT_{2x} also revealed a pronounced glacial cooling. By comparing the simulated present-day climate to data, we could discard a set of model versions, as they were inconsistent with the data, but the model versions that survived this test of model performance still showed a rather large range of ΔT_{2x}. However, using LGM data from tropical sea surface temperature regions and Antarctica, high sensitivity models could be rejected as being unrealistic (they simulated a LGM climate too cold). Accounting for uncertainty in the model parameters and in the paleo-proxies, the CMD approach allowed us to reject model versions with ΔT_{2x} values above about 4°C (Fig. 1).

A crucial issue regarding the robustness of such an estimate is whether we have underestimated structural model uncertainty: what would have been the outcome of this analysis using a set of structurally different climate models? Applying somewhat different boundary conditions, Annan et al. (2005) performed a similar experiment based on a GCM ensemble (neglecting ocean dynamics and the forcing by glacial dust and vegetation) and inferred a weaker link between past cooling and future warming, resulting in a larger uncertainty estimate of ΔT_{2x}. The impact of model structure on estimating ΔT_{2x} is the most difficult type of uncertainty to quantify. More model studies that have performed comparable experiments would be helpful in this regard.

Climate state dependency of climate feedbacks

The strength of climate feedbacks (Λ) depends, to a certain extent, on the climate state (e.g., a larger sea-ice and snow albedo feedback might operate in a colder climate than in a warmer one). As a consequence, linear extrapolation on ΔT_{2x} from the LGM may be unreliable and the CMD approach should be used because climate models allow for the explicit simulation of the dependency of Λ on the climate state.

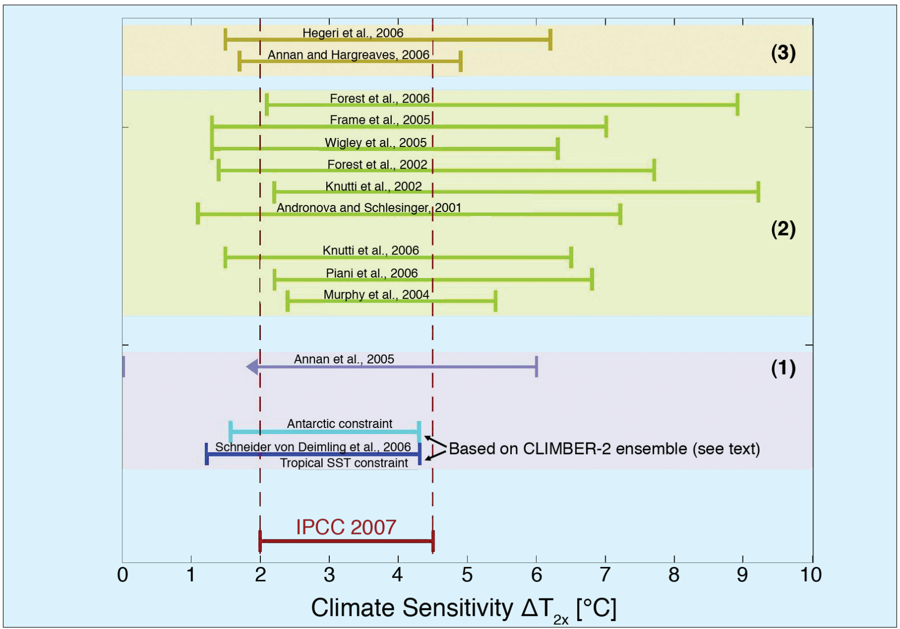

*Figure 1: Model-based estimates of climate sensitivity (most intervals represent 90% confidence levels, IPCC estimate is based on individual AR4 model results, Annan et al. (2005) do not provide a lower bound). ΔT_{2x} ranges were constrained using (**1**) LGM proxy-data, (**2**) instrumental data, and (**3**) by combining paleo and instrumental data. A more extensive overview of studies having constrained the range of ΔT_{2x} by paleo or instrumental data is presented by Edwards et al. (2007).*

Yet, so far this state dependency of Λ between the LGM and $2xCO_2$ climate has not been captured consistently among climate models (Crucifix, 2006; Hargreaves et al., 2007) and ΔT_{2x} estimates inferred by such an approach depend to a certain extent on the model used. This is an uncomfortable situation for the prospect of using paleo-data from a colder climate for constraining future warming. Further analyses are needed to better understand to what extent the current model discrepancy in the simulated feedback characteristics stems from different model physics, and to what extent from the method of analyzing the feedbacks. One explanation for discrepancies of simulated LGM characteristics could be that some models have not been run long enough to reach full equilibrium.

So far only a few state-of-the-art climate models have performed an LGM simulation experiment. It remains to be seen whether climate models with a ΔT_{2x} well outside the IPCC range can simulate a LGM cooling consistently with paleo-evidence. The LGM climate provides a promising test of model sensitivity that is worth applying to a much larger set of climate models.

Further progress in narrowing the range of ΔT_{2x} might also come from using paleo-constraints from warm periods. This could be valuable additional information, as a warmer climate can be considered a better analog for future climate change. One problem with paleo-data from a warmer world, however, is that they range farther back in time and uncertainties both in forcing and climate response are large. Reducing those uncertainties is especially promising for inferring better-constrained estimates of ΔT_{2x} using the CMD approach as outlined here.

Acknowledgements

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Volcanism and the Little Ice Age

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The Little Ice Age (LIA; ca. 1250-1850) has long been considered the coldest interval of the Holocene. Because of its proximity to the present, there are many types of valuable resources for reconstructing temperatures from this time interval. Although reconstructions differ in the amplitude of cooling during the LIA, they almost all agree that maximum cooling occurred in the mid-15th, 17th and early 19th centuries.

The LIA period also provides climate scientists with an opportunity to test their models against a time interval that experienced both significant volcanism and (perhaps) solar insolation variations. Such studies provide information on the ability of models to simulate climates and also provide a valuable backdrop to the subsequent 20th century warming that was driven primarily from anthropogenic greenhouse gas increases.

Although solar variability has often been considered the primary agent for LIA cooling, the most comprehensive test of this explanation (Hegerl et al., 2003) points instead to volcanism being substantially more important, explaining as much as 40% of the decadal-scale variance during the LIA. Yet, one problem that has continually plagued climate researchers is that the paleo-volcanic record, reconstructed from Antarctic and Greenland ice cores, cannot be well calibrated against the instrumental record. This is because the primary instrumental volcano reconstruction used by the climate community is that of Sato et al. (1993), which is relatively poorly constrained by observations prior to 1960 (especially in the southern hemisphere).

Here, we report on a new study that has successfully calibrated the Antarctic sulfate record of volcanism from the 1991 eruptions of Pinatubo (Philippines) and Hudson (Chile) against satellite aerosol optical depth (AOD) data (AOD is a measure of stratospheric transparency to incoming solar radiation). A total of 22 cores yield an area-weighted sulfate accumulation rate of 10.5 kg/km^2, which translates into a conversion rate for AOD of 0.011 AOD/kg/km^2 sulfate. We validated our time series by comparing a canonical growth and decay curve for eruptions for Krakatau (1883), the 1902 Caribbean eruptions (primarily Santa Maria), and the 1912 eruption of Novarupta/Katmai (Alaska) against a reanalysis (Stothers, 1996) of the original AOD data and lunar eclipse estimates of AOD for Krakatau (Keen, 1983). The agreement (Fig. 1) is very good—essentially within the uncertainty of the independent data. Our new ice core reconstruction shows several significant disagreements with the Sato et al. (1993) reconstruction in the late 19th and early 20th centuries. As we have essentially the same number of records over the entire interval of the Sato et al. reconstruction, and their database decreases significantly prior to 1960, we contend that our reconstruction for the earlier intervals is at least as good as that of Sato et al. It is, at the very least, a legitimate alternate reconstruction to use for this earlier time interval.

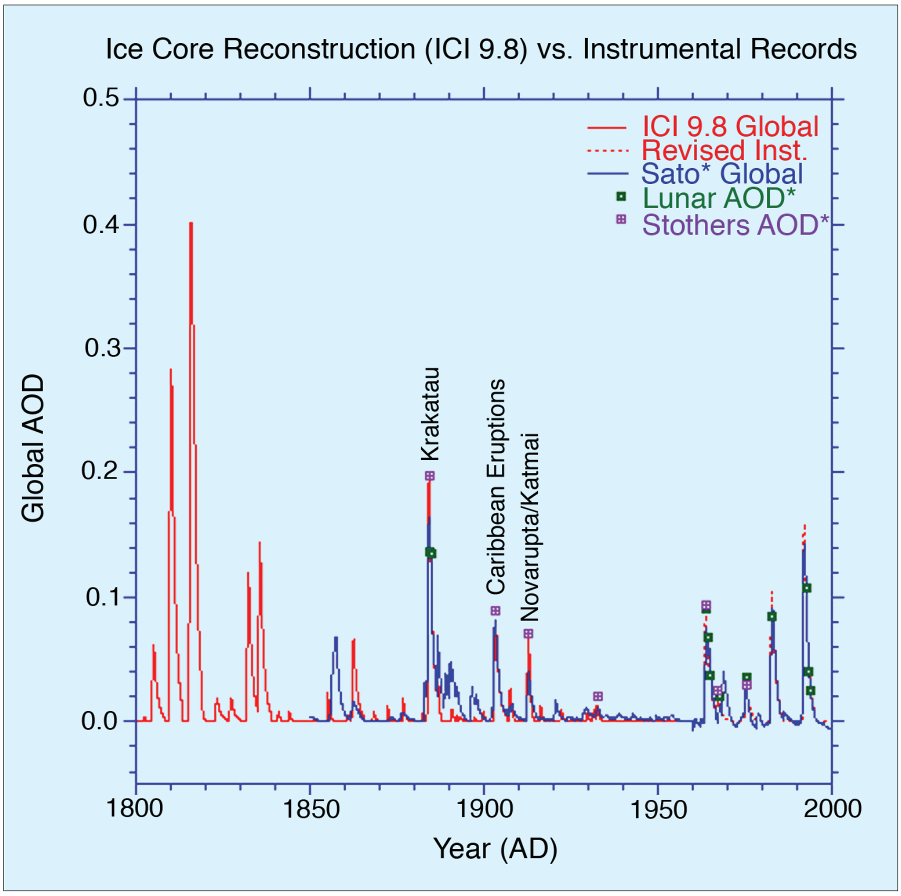

Figure 1: Comparison of new ice core reconstruction with various instrumental-based reconstructions of stratospheric aerosol forcing. The asterisks refer to some modification to the instrumental data; for Sato et al. (1993) and the Lunar AOD, the asterisk refers to the background AOD being removed for the last 40 years. For Stothers (1996), it refers to the fact that instrumental observations for Krakatau (1883) and the 1902 Caribbean eruptions were only for the northern hemisphere. To obtain a global AOD for these estimates we used Stothers (1996) data for the northern hemisphere and our data for the southern hemisphere. The recon,struction for Agung eruption (1963) employed Stothers (1996) results from 90°N-30°S and the Antarctic ice core data for 30-90°S.

Although the above analysis may not permanently put to rest uncertainties about calibration of ice core sulfate data, it does represent an encouraging advance over present reconstructions. We therefore applied the methodology to part of the LIA record that had some of the largest temperature changes over the last millennium. A total of 13 Greenland and Antarctic ice cores were used as the main database, with spot data included from other cores. The ice core reconstruction was then compared (Fig. 2) against the temperature reconstruction of Jones et al. (1998), which indicates the standard cooling patterns discussed above, including the well known very severe cooling of the mid-1690s in western Europe.

The ice core chronology of volcanoes is completely independent of the (pri-

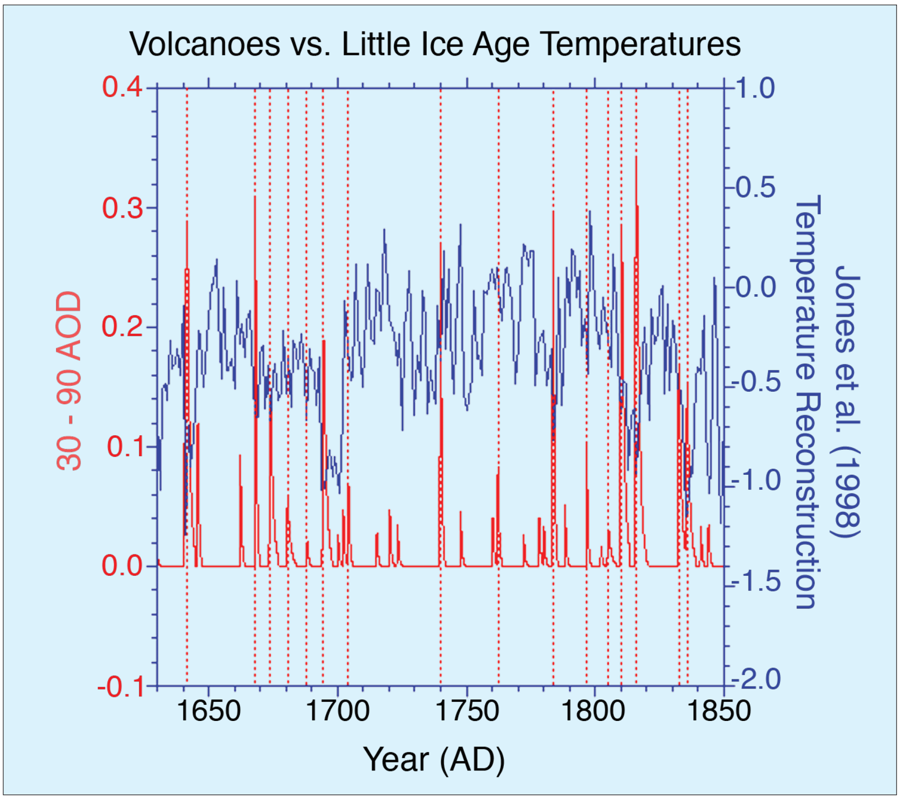

Figure 2: Comparison of 30-90°N version of ice core reconstruction with Jones et al. (1998) temperature reconstruction over the interval 1630-1850. Vertical dashed lines denote levels of coincidence between eruptions and reconstructed cooling. AOD = Aerosol Optical Depth.

marily) tree ring based temperature reconstruction. The volcano reconstruction is deemed accurate to within 0 ± 1 years over this interval. There is a striking agreement between 16 eruptions and cooling events over the interval 1630-1850. Of particular note is the very large cooling in 1641-1642, due to the concatenation of sulfate plumes from two eruptions (one in Japan and one in the Philippines), and a string of eruptions starting in 1667 and culminating in a large tropical eruption in 1694 (tentatively attributed to Long Island, off New Guinea). This large tropical eruption (inferred from ice core sulfate peaks in both hemispheres) occurred almost exactly at the beginning of the coldest phase of the LIA in Europe and represents a strong argument against the implicit link of Late Maunder Minimum (1640-1710) cooling to solar irradiance changes.

During the 18th century lull in eruptions, temperatures recovered somewhat but then cooled early in the 19th century. The sequence begins with a newly postulated unknown tropical eruption in mid-late 1804, which deposited sulfate in both Greenland and Antarctica. Then, there are four well-documented eruptions—an unknown tropical eruption in 1809, Tambora (1815) and a second doublet tentatively attributed in part to Babuyan (Philippines) in 1831 and Cosiguina (Nicaragua) in 1835. These closely spaced eruptions are not only large but have a temporally extended effect on climate, due to the fact that they reoccur within the 10-year recovery timescale of the ocean mixed layer; i.e., the ocean has not recovered from the first eruption so the second eruption drives the temperatures to an even lower state.

The new reconstruction also predicts higher AOD levels for Krakatau than Sato et al. (1993). This has important implications for prior paleo-reconstructions, as the Sato et al. (1993) estimate has been a key calibration point for absolute scaling of the entire paleo-volcanic reconstruction. The new result implies that methods using the Sato et al. (1993) approach could underestimate the true magnitude of earlier eruptions by ca. 20%. This conclusion represents just one of the many of the benefits of the new reconstruction.

A final benefit of the new reconstruction is that the uncertainty in the absolute magnitude of past volcanic forcing may be reduced by about one-half, to (tentatively) 10-15% (1 σ). This reduction may have significant implications for estimating climate sensitivity from the record of the last 1000 years. For example, Hegerl et al. (2006) estimate that the range of climate sensitivity for the LIA was approx. the same as for the instrumental record. Climate sensitivity is a measure of the magnitude of the system response to a particular forcing, such as CO_2 changes; it is essentially the Holy Grail of greenhouse gas climate studies. However, the largest uncertainty in the sensitivity estimate of Hegerl et al. (2006) was due to the magnitude of volcanic eruptions. If this uncertainty can be significantly reduced, which now seems to be the case, it will significantly narrow the range of uncertainty in the paleoclimate sensitivity estimate—a prospect we plan to explore after the initial paper has been written.

Full documentation of the scaling and time series is now being prepared for publication. The database for the reconstruction plus the volcano time series of forcing, interpolated to ca. 10 day intervals for the purpose of use in climate model simulations, will be released upon publication.

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The PRISM Model/Data Cooperative: Mid-Pliocene data-model comparisons

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The mid-Pliocene (~3.3 to 3.0 Myr) has become an attractive target for climate modeling studies, as the dynamics of past warm climates provide a potential guide to understanding future climate change. This interval was selected for detailed study because it spans the transition from relatively warm global climates of the Early Pliocene, when glaciers were greatly reduced in the northern hemisphere, to the generally cooler climates of the Pleistocene, with expanded northern hemisphere ice sheets and prominent glacial–interglacial cycles. The US Geological Survey (USGS) Pliocene Research, Interpretation and Synoptic Mapping (PRISM) Project has documented the characteristics of mid-Pliocene climate on a global scale, and several model-data studies based on PRISM data have been funded by the National Science Foundation (NSF), the National Environmental Research Council (NERC), and NASA.

Initial paleoenvironmental reconstruction

Four generations of PRISM paleoclimate reconstructions (PRISM0–PRISM3) have evolved from studies summarizing conditions at a large number of marine and terrestrial sites (e.g., Cronin and Dowsett, 1991; Poore and Sloan, 1996). Prior to PRISM0, Dowsett and Poore (1991) analyzed microfossil data from a series of North Atlantic cores and concluded that although the modern North Atlantic differs little from the Last Interglacial, it is cooler than the mid-Pliocene. Middle and high latitudes were warmer during the mid-Pliocene than either the Last Interglacial or the present day (Dowsett et al., 1992). However, low latitudes showed no change during climate extremes (Last Glacial Maximum, Last Interglacial and mid-Pliocene), favoring increased meridional ocean heat transport over increased CO_2 as the primary forcing behind mid-Pliocene warming.

Iterative data–model approach

As the USGS expanded its data sets beyond the North Atlantic and beyond the marine realm, mid-Pliocene northern hemisphere boundary conditions began to take shape. It was a significant, multi-year effort to bring together formerly disparate research projects and construct full global data sets, so the first mid-Pliocene climate simulations were run (with the NASA/GISS atmospheric GCM) using only the completed northern hemisphere data (Chandler et al., 1994). Data from the Pacific and circum-Arctic regions (Barron, 1992a, b; Ikeya and Cronin, 1993; Cronin et al., 1993) were used to produce the first northern hemisphere SST analysis for the mid-Pliocene (Dowsett et al., 1994). Much of the design and production techniques for these digital data sets were developed at this time, leading to the framework for our long-term, iterative, data/modeling approach.

These early simulations were justified on the basis that: 1) they employed only specified surface conditions, 2) the available mid-Pliocene tropical data showed little change from modern, and 3) our focus was on northern hemisphere high-latitude effects. The simulations showed global mid-Pliocene warmth, similar to temperatures forecast for the mid-21st century.

The first global reconstruction, PRISM1, was based on 64 marine and 74 terrestrial sites; it included annual vegetation, land-ice, monthly SSTs and sea-ice, sea level, and topography (Dowsett et al., 1996; Thompson and Fleming, 1996). Warming was greatest at high latitudes and during winter, with meridional temperature gradients decreased by 10°C and driven largely by decreased ice and snow cover (Sloan et al., 1996). Low latitudes were largely unchanged, though significant cool and wet anomalies over Africa made it clear that details of regional climate were significant for comparisons to both local proxy studies and to future climate change. The hydrological cycle intensified over the continents but actually weakened, on average, over the oceans. This feature distinguished the mid-Pliocene from future global warming simulations, and emphasized the importance of proxy temperature data (e.g., Wara et al., 2005) that suggest warmer eastern equatorial Pacific temperatures. However, PRISM1 data-modeling comparisons have supported independent proxy data that show increased mid-Pliocene meridional ocean circulation (MOC) and associated heat fluxes.

PRISM2 (Fig. 1) incorporated additional marine sites, re-calibration to a common modern SST climatology, new sea level estimates, and a new land-ice configuration (Dowsett et al., 1999; Dowsett, 2007). Model simulations using specified surface conditions from PRISM2 data have largely confirmed results from studies using PRISM1. However, more significantly, the PRISM2 data set provides initial conditions for a series of fully coupled ocean-atmosphere model (OAGCM) simulations. The use of coupled OAGCMs is essential to the exploration of mechanisms for mid-Pliocene warmth, such as the possible role

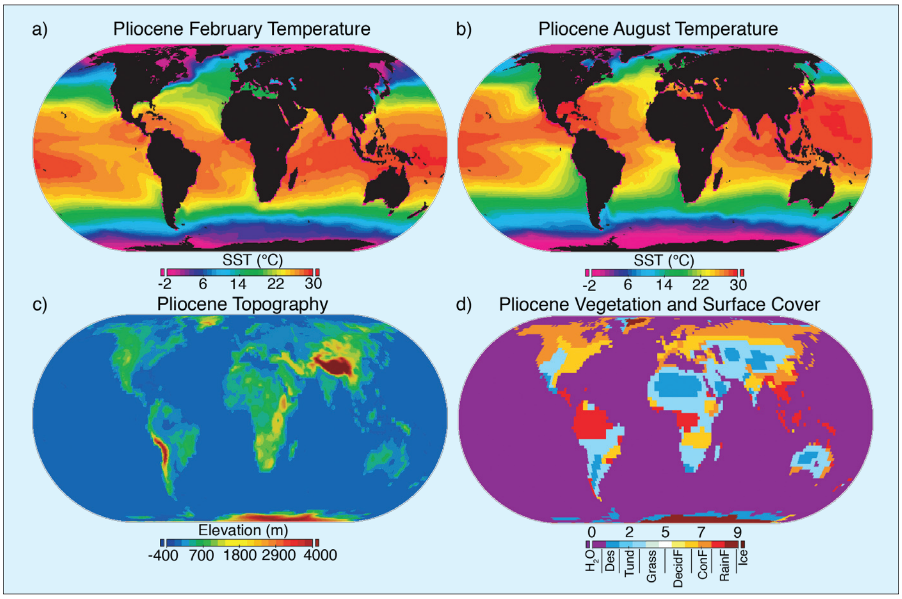

*Figure 1: Summary of the PRISM2 paleoenvironmental reconstruction (modified from Dowsett, 2007); **a)** Pliocene February SST; **b)** Pliocene August SST; **c)** Pliocene topography; **d)** Pliocene vegetation/land cover.*

of enhanced thermohaline circulation (THC), and to model evaluation. Haywood and Valdes (2004) presented the first fully coupled ocean-atmosphere mid-Pliocene simulation, which showed global surface temperature warming of 3°C over pre-industrial values. In contrast to previous modeling experiments, surface temperatures warmed in most areas, including the tropics (1-5°C). The model predicted a general pattern of ocean warming (1-5°C) in both hemispheres to a depth of 2000 m, below which no significant differences were noted. Analysis of the model-predicted MOC indicated a weaker THC. Diagnostics for heat transport indicated that neither the oceans nor the atmosphere transported significantly more heat in the mid-Pliocene. Rather, the major contributing mechanism to mid-Pliocene warmth was the reduced extent of high-latitude terrestrial ice sheets (50% reduction on Greenland, 33% reduction on Antarctica) and sea-ice cover, specified by the PRISM2 data set, resulting in a strong ice-albedo feedback (Haywood and Valdes, 2004). The model-predicted response of the THC is opposite to that interpreted from the mid-Pliocene SST reconstruction (e.g., Dowsett et al., 1992; Dowsett et al., 1996). While simulating increased SSTs in many regions, the model appears to underestimate the change at mid-latitudes (Fig 2a). This apparent data-model mismatch is an important issue to examine in terms of model dependency, model initialization, length of model run, uncertainty in paleoceanographic reconstruction, and the internal consistency of the PRISM data set as a whole.

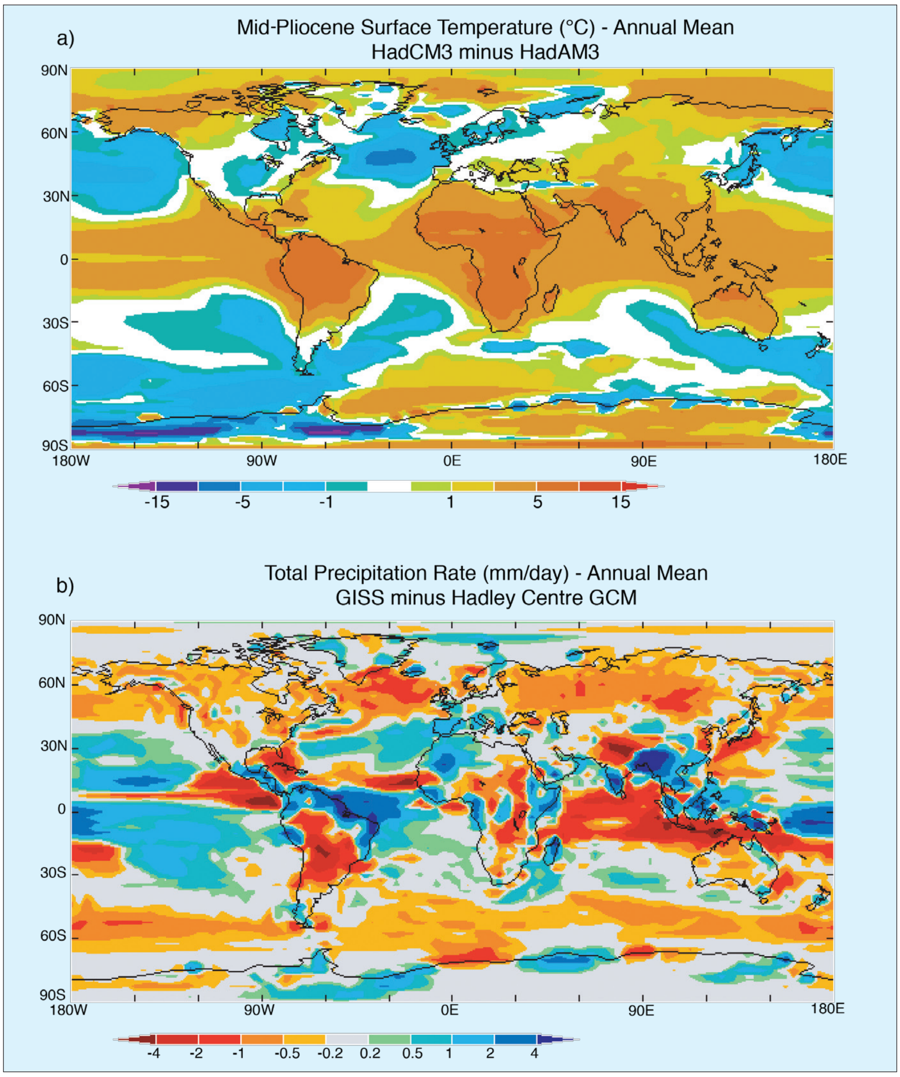

Figure 2: ***a****) Difference in mid-Pliocene annual mean surface temperature (°C) between a fully coupled ocean atmosphere GCM simulation using HadCM3 and an atmospheric general circulation model simulation using fixed PRISM2 SSTs and the HadAM3 GCM. Note the coupled ocean atmosphere model HadCM3 predicts higher surface temperature in the tropics and relatively cool conditions in parts of the mid-latitudes, particularly over the North Atlantic and Pacific Oceans (modified from Haywood and Valdes, 2004);* ***b****) Difference in annual mean total precipitation rate (mm/day) between the GISS and the Hadley Centre GCMs for the mid-Pliocene. Note the reduction is precipitation in storm track regions in the GISS GCM and the shift in location of the Indian Monsoon.*

Future of the PRISM Model/Data Cooperative

PRISM3, still in development, incorporates multiproxy re-examinations of SST (with maximum and minimum peak SSTs providing a climatological error bar), revised land-ice and vegetation schemes based on independent vegetation and ice models, and deep-ocean temperature (DOT) reconstructions based on Mg/Ca paleothermometry (Cronin et al., 2005; Dowsett et al., 2005, 2006; Hill et al., 2007; Salzmann et al., 2008). Nearly all of the coupled GCMs used in the IPCC multi-model ensembles for future climate change show a temperature rise in the North Atlantic lagging other high- and mid-latitude regions. These results do not rule out an eventual equilibrium state similar to the warm North Atlantic of the Pliocene but some of the same coupled-GCMs find a similar cool anomaly in mid-Pliocene simulations, at odds with proxy data. Initial experiments using beta versions of the PRISM3 DOT data to initiate simulations show an increase in MOC compared to simulations that are initiated with PRISM2 SSTs and modern deep ocean temperatures.

A pilot intercomparison is already underway between the GISS and Hadley Centre GCMs using prescribed boundary conditions from the PRISM2 data set, with a simulation using the CCSM to follow shortly (Fig. 2b). The first planning meeting for a mid-Pliocene model intercomparison project, part of PMIP, has been arranged for early June 2008 at the NASA Goddard Institute for Space Studies in New York. Further announcements will be made through PMIP and PAGES. More information on the PRISM reconstruction can be found at http://geology.er.usgs.gov/eespteam/prism/prism3main.html

Acknowledgements

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How unusual was autumn 2006 in Europe?

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Meteorologically, the autumn of 2006 was an extraordinary season in Europe (van Oldenborgh, 2007). In the Netherlands, the 2-meter temperature at De Bilt averaged over September–November was 1.6°C higher than the previous record since regular observations began in the Netherlands in 1706, which was a tie between 1731 and 2005 (Fig. 1a). Figure 1b shows that the area with 3°C anomalies stretches from the Alps to Denmark and from Belgium to Poland. This made it by far the warmest autumn on record in the UK, Belgium, the Netherlands, Denmark, Germany and Switzerland. Pre-instrumental reconstructions indicate that September-November 2006 was very likely the warmest autumn since 1500 in a large part of Europe (Luterbacher et al., 2007).

The impacts of the high temperatures on society and nature were not very strong because a higher temperature in autumn corresponds to a phase lag of the seasonal cycle. However, a similar anomaly in summer would have given rise to a heat wave analogous to the summer of 2003, which caused severe problems (e.g., Schär and Jendritzky, 2004).

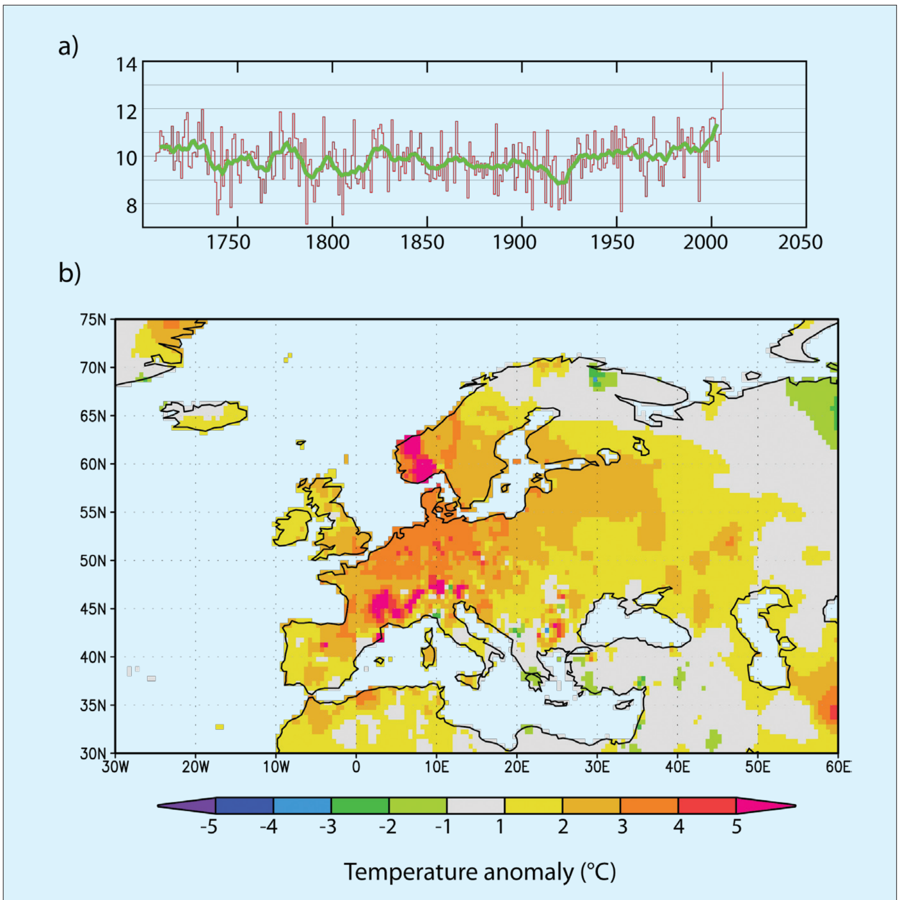

*Figure 1: **a**) Autumn 2-meter temperatures (red) at De Bilt, the Netherlands with a 10-yr running mean (green) 1706-2006 (van Engelen and Nellestijn, 1996). **b**) The temperature anomaly (°C) (relative to 1961-1990) of Sep-Nov 2006 in the GHCN/CAMS dataset (Fan and van den Dool, 2007).*

Return times

Figure 1a shows that the autumn temperature at De Bilt for 2006 is well above the values observed previously. How rare the event was can be quantified by computing its return time. A return time of 100 years means that the probability of the event happening is 1% every year. As the autumn 2006 temperature is unprecedented, the return time is computed by extrapolation of a fit to the other observations. In autumn, a normal distribution fits the data quite well. The position of the 2006 temperature in the tail of this distribution then gives the return time.

First, we compute the return time of autumn 2006 in the Netherlands under the assumption that there are no long-term climate variations, only interannual variability. This gives a return time of 10,000 years. The high value implies that the assumption is false: climate does change on longer timescales. Global warming has made high temperature anomalies much more likely in the last decades, and this decreases the return times of recent high extremes.

Global warming

The effect of global warming on monthly mean local temperature can be described well by a linear relationship:

$$T'(t) = AT'_{global}(t) + \varepsilon(t),$$

where A indicates how much faster (or slower) the local temperature trend is than the trend in global mean temperature anomalies $T'_{global}(t)$. The remainder $\varepsilon(t)$ represents the weather noise. In practice, $T'_{global}(t)$ is smoothed to remove the influences of El Niño and La Niña.

For De Bilt, the factor A is 1.7±0.4 in autumn over 1901-2005 (before 1901 both the observations at De Bilt and the global mean temperature have much larger uncertainties). Subtracting the trend $AT'_{global}(t)$ from the observed temperature we obtain the random fluctuations due to the weather, $\varepsilon(t)$. These are plotted in Figure 2a as red crosses. The horizontal scale is chosen in such a way that a normal distribution tends to a straight line. The normal distribution that has been fitted to the data is indicated by the central green line in Figure 2a. The upper and lower green lines denote the 95% confidence interval of the return times derived from the fit. Extrapolation is always a risky exercise and should not be performed without an estimate of the error margins.

The temperature of autumn 2006 above the trend is depicted in Figure 2a by the horizontal purple line. Even after subtracting the trend, it still is the warmest autumn since 1901, with an anomaly of 2.6 K above the trend, and a best estimate of the return time of 650 years (the intersection of the central green and purple lines). The 95% confidence interval is 125 to 10,000 years in De Bilt.

A map of the return times for Europe is shown in Figure 2b. Over a large part of Europe, the weather was much warmer than expected from the trend. Estimates of the return times of the weather are longer than 200 years over most of the area where the anomaly was largest, reaching 2000 years in northern Germany and Denmark.

Climate model simulations

Observed 2006 autumn temperatures greatly exceed the range observed so far, even after accounting for the rise in temperature due to global warming. Do current climate models predict that this type

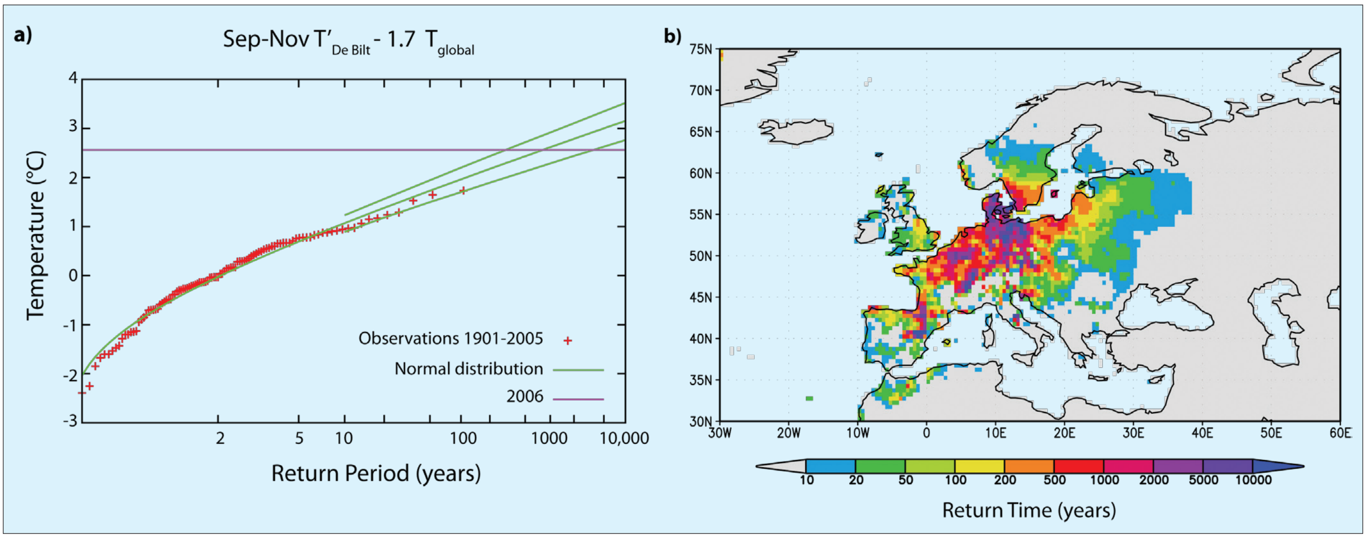

*Figure 2: **a**) Probability distribution of homogenized De Bilt temperatures 1901-2005 (Brandsma et al., 2003) with the linear regression against the global mean temperature anomalies (with a 3-yr running mean) subtracted (red). The intersection of the fit to a normal distribution (green) and the value observed in 2006 (purple) gives the return time of autumn 2006 in De Bilt. **b**) Return time of autumn 2006 in the context of the years 1948-2005 in Europe.*

of extreme events will happen more frequently as Europe heats up?

We investigated the changes in the distribution of autumn temperatures using data from the ESSENCE project: 17 runs with a state-of-the-art climate model (ECHAM5/MPI-OM, Jungclaus et al., 2006) over 1950-2100. These use observed concentrations of greenhouse gases and aerosols up to the year 2000 and the A1b scenario afterwards, which reaches twice the pre-industrial CO_2 concentrations in 2100. This model has the most realistic circulation over Europe of all the models used for the IPCC Fourth Assessment Report (van Ulden and van Oldenborgh, 2006; van den Hurk et al., 2006). Results from this model have been checked against the next four climate models ranked by the realism of the simulated mean circulation over Europe.

There are two ways in which a climate model can simulate lower return times than an extrapolation based on past observations. The first would be that the model indicates that the true, long-term trends are higher than observed so far. The uncertainties in the observations are still large; if, due to natural variability, the trends have been underestimated the fluctuations would not have been as extreme as they appeared. This shows up as a vertical shift in an extreme value graph, like Figure 2a. A second possibility would be that the variability increases, making large fluctuations more likely. This has been shown to occur in summer due to soil moisture effects (e.g., Schär and Jendritzky, 2004; Seneviratne et al., 2006; Fischer et al., 2007). In an extreme value graph, this shows up as steeper lines.

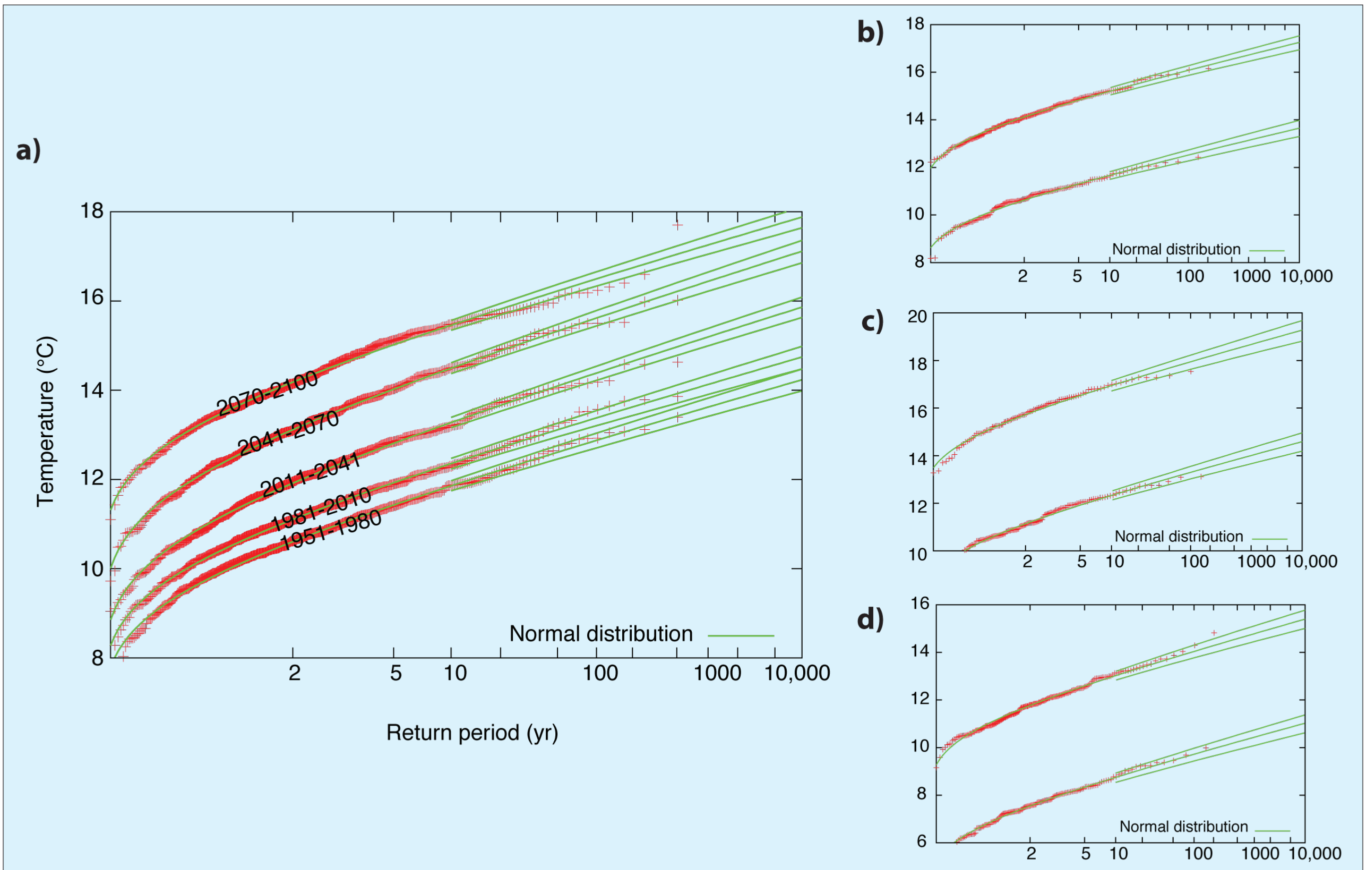

*Figure 3: **a**) Extreme autumn temperatures at 52°N, 5°E in 17 ESSENCE runs in 1951-1980, 1981-2010, 2011-2041, 2041-2070 and 2070-2100; in the 20th and 22nd century runs in the **b**) GFDL CM2.1, **c**) UKMO HadGEM1, and **d**) CCCMA CGCM 3.2 T63 models. Green lines indicate fits to normal distributions (with uncertainties).*

However, the ESSENCE ensemble simulates lower warming trends than the observations in the area where the return times of autumn 2006 are high. The other four models that we considered also show lower than observed trends. If we believe the model trends rather than the observed ones, the return times would be increased to thousands of years.

The 17 ensemble members in ESSENCE enable us to investigate the changes in variability as a function of time. The extreme value distributions of the model surface air temperature at De Bilt have been computed for 30-year intervals, each of which contains 510 years of data. These five curves are shown in Figure 3. There is a clear vertical shift over time: the warming trend. However, there is no indication of an increase in the slopes that would make extremely warm autumn temperatures more likely. This result was confirmed using three other climate models, for which a comparison between the 20th and 22nd centuries could be made. None of these show an increase in the tail of the distribution at the grid point corresponding to De Bilt.

We conclude that current climate models show neither a faster increase in the mean temperature nor an increase in variability that would reduce the return times of autumn 2006.

Conclusions

The autumn of 2006 was extraordinarily warm in large parts of Europe, with temperatures up to 4°C above the 1961-1990 norms. Assuming an unchanging climate, this would correspond to return times of 10,000 years and more.

Global warming has made a warm autumn like the one observed in 2006 much more likely by shifting the temperature distribution to higher values. Taking only this mean warming into account, the best estimate of the return time of the observed temperatures in 2006 is still in excess of 200 years over large parts of Europe.

Current climate models already underestimate the observed mean warming in Europe relative to global warming before 2006. They also do not show an additional increase of the warm tail of the distribution as the climate warms. Either the autumn of 2006 was a very rare event, or these climate models do not give the correct change in temperature distribution as the temperature rises, due to missing feedbacks.

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Risk prediction of Canadian wildfires

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Wildfires in Canada burn on average more than 2 x 10^4 km^2 of forest per year (Fig. 1) (Stocks et al., 2003), with accompanying economic losses. In years of high fire activity in Canada, the amount of carbon released into the atmosphere by wildfires approaches levels comparable to industrial carbon emissions (Amiro et al., 2001). Predicting the risk (probability) of such extreme events in the regional domain and on mid-term timescales (decades) can serve forest managers, climate and carbon modelers, and the insurance industry. Several requirements have to be met to achieve prediction skill and reliability: data records of sufficient length, climate models able to reproduce observed data properties, and a robust statistical risk estimation method. Results from wildfire records (observed, proxy, and models) analyzed with kernel estimation (a nonparametric smoothing approach), reveal that by the end of the 21st century, wildfire risk for Canada may rise and eventually exceed the high levels observed in the previous two centuries.

Data: Wildfire proxy records

Records of directly observed wildfire events are sparse and cover too short a time frame for risk analysis of extreme (i.e., rare) events. This study considered only large (> 200 ha) fires, from the Large Fire Data Base (Stocks et al., 2003) to achieve a high degree of data homogeneity over the observation period, 1959 to 1998. These large fires account for 97% of the total area burnt in Canada. The variable "FireOcc" represents the number of large fires per year. To broaden the temporal coverage of the study, we extended the FireOcc period

Figure 1: Red Lake forest fire, Ontario (photo by Brian Stocks, Canadian Forest Service).

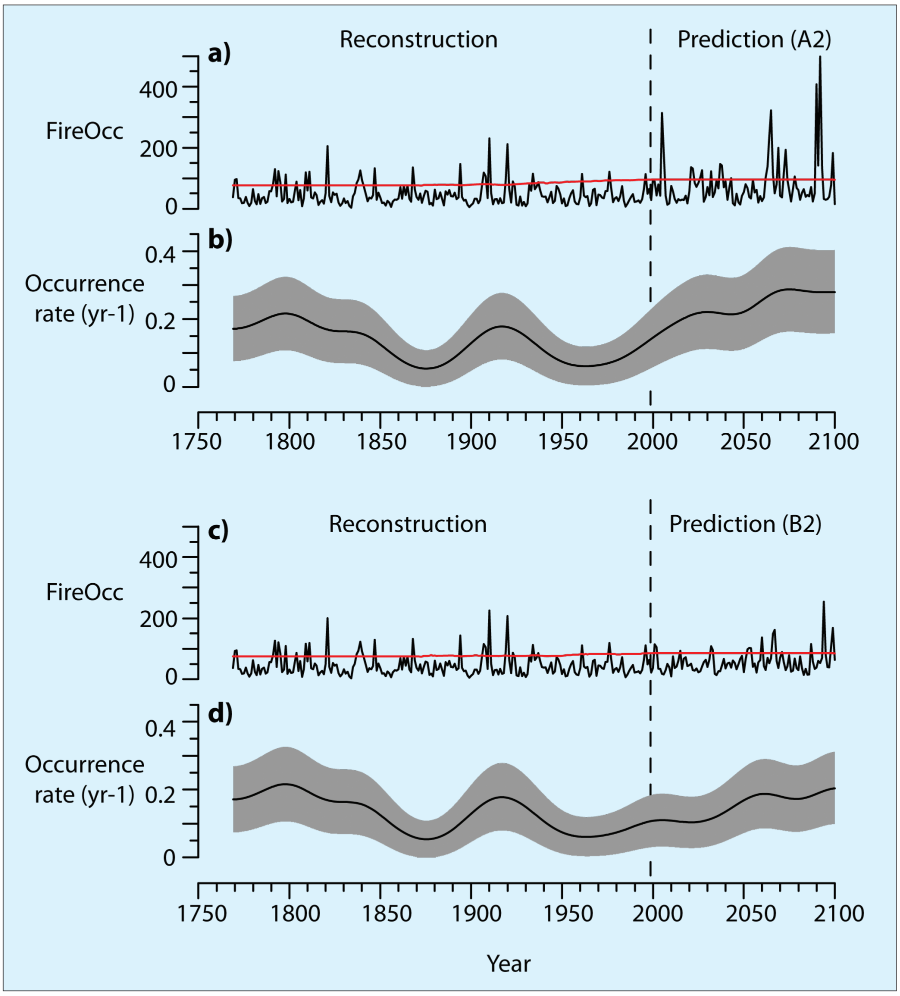

*Figure 2: Past and future wildfire risk in Canada. (**a, c**) FireOcc – number of large (> 200 ha) forest fires per year, reconstructed (1769–1998) from tree ring measurements via the Drought Code, or modeled for greenhouse gas emission scenarios A2 and B2. Red line indicates threshold for extreme fire years and is defined by robust measures of trend and variability (CLIM-X-DETECT software with parameters z = 2.5 and k = 100, Mudelsee (2006)). (**b, d**) Wildfire risk estimated as rate of occurrence (solid black line) of extreme fire years via a kernel approach (CALIZA software with bandwidth parameter h = 15 a, developed after Mudelsee et al. (2003, 2004)). Bootstrap simulations (nsim = 10000) yield 90% confidence bands (grey shading) for risk estimates.*

back to 1769 using a two-stage proxy approach based on the Canadian Drought Code (DC). This index (Turner, 1972) is the daily moisture content of organic matter (bulk density 138.9 kg/m^3) for an average organic matter thickness of 18 cm.

In the first stage of analysis, measured records of tree ring thickness were used to infer DC. The tree ring database (126 replicated records) covered the Canadian Boreal Shield (Girardin et al., 2006). The rationale was that the assimilation of carbohydrates and optimal tree growth occur only if soil moisture is sufficient to maintain foliage water potential and minimize vapor water deficits (Girardin and Tardif, 2005). The relation was expressed as a linear model and estimation of the model parameters allowed inference of records of mean July DC for six regions (Boreal Plains, Lake Seul, Lake Nipigon, Abitibi Plains west, Abitibi Plains east, and Central Laurentians) of the Boreal Shield in the period from 1769 to 1998. Additionally, the mean July and August temperature for a seventh region, Southern Laurentians (SL) was estimated.

In the second stage, the inferred proxy DC (and temperature) records were transformed into a single FireOcc record for Canadian boreal forests east of 100°W. The transformation model is a stepwise multiple linear regression of 14 predictor variables (6 proxy mean July DC records, 6 one-year lagged proxy mean July DC records, 1 proxy temperature record from SL, 1 one-year lagged proxy temperature record from SL) on the FireOcc response variable. The regression parameters were estimated for the observation interval (1959–1998). This calibration was in turn applied to the data for the period from 1769 to 1958. The success of this approach rests on: (1) the stability of the regression relation over time, and (2) the accuracy of the relation. The first criterion may be well fulfilled because dividing the calibration interval (1959–1978 and 1979–1998) does not lead to significant changes in regression parameters. The accuracy can be tested by several techniques of data–model comparison, such as reduction of error or the product means test. Such methods are detailed elsewhere in this issue. See also Girardin and Mudelsee (in press), who assessed the calibration accuracy, with positive results.

Models: Wildfire proxy scenarios

The General Circulation Model ECHAM4 was used for independently simulating temperature and precipitation over 1850 to 2100. Analyzed were the IPCC's greenhouse gas emission scenarios A2 and B2 (Solomon et al., 2007). The gridded daily temperature and precipitation data (about 2.8 deg. spatial resolution) were further transformed into simulated DC by an empirical soil-evapotranspiration model (Girardin et al., 2004). These values were projected in the spatial and temporal domains to yield mean July DC for the seven regions. Feeding DC into the calibrated multiple linear regression model produced FireOcc forecasts. The quality of this model–proxy approach was assessed elsewhere (Girardin and Mudelsee, in press) by means of comparison with other model simulations (e.g., CGCM3). In general, the increase in regional precipitation projected toward the end of the 21st century will be insufficient to compensate for increasing temperatures, and insufficient to maintain potential evapotranspiration at current levels, no matter which scenario is considered. Here, we focus on the wildfire risk by statistically analyzing the indirect proxy FireOcc record, which we inferred from the DC reconstructions (1769–1998) and the climate modeling (1999–2100).

Results and conclusions

Setting a robust threshold to FireOcc (Fig. 2a,c) allows for the identification of extreme fire years. We were interested in how often such years occur. The rate of occurrence was analyzed using kernel functions and mathematical bootstrap simulations (Fig. 2c,d). First, risk of extreme wildfire years was not constant over time but displayed lows and highs (values up to 0.22 yr^{-1} at around 1800 or 0.18 yr^{-1} during the first half of the 20th century). The average risk of extreme wildfire years through the instrumental period (to 1998) was 0.13 yr^{-1}, which means every 7th to 8th year is an extreme year. Predicted future increases depend on the selected emission scenario. Under the "moderate" B2 scenario, risk values for the end of the 21st century are around 0.20 yr^{-1} (Fig. 2d), under A2 they may be as high as 0.28 yr^{-1}. Although the statistical uncertainty (confidence band) is substantial, the amount of data (number of extreme years) allows us to conclude that these changes are statistically significant.

A number of critical points were addressed (see Girardin and Mudelsee, in press) to evaluate the robustness of these findings. First, proxy representativeness is not perfect. For example, influences of spring and autumn DC values have been ignored. Tree ring series pre-processing (removal of long-term physiological growth signals) may also hide long-term climate trends. Second, feedbacks from vegetation, regional climate systems or other forest disturbances, were not accounted for. Third, emission scenarios are technically "guesses" with unquantified, presumably large, error bars. Fourth, extrapolation errors may have affected the FireOcc calibration as well as the climate model. The confidence bands should capture a portion of these uncertainties. On the other hand, selection of statistical parameters in figure 2 is rather uncritical, as a sensitivity analysis showed.

We deliberately use the word "prediction" instead of "projection" because the latter's connotation of an assumption-free analysis is misleading. Every analysis of future situations necessarily makes assumptions (actualism). The task is rather to quantify and include the error sources into the analyses. In this regard, it is important to evaluate climate model uncertainties. For this objective, the ensemble method is insufficient because it ignores parameterization uncertainties (e.g., hydrological cycle). The bootstrap simulation method (Challenor, 2004) has the potential to include parameterization and also emission uncertainties but its full implementation requires a leap in computing power.

The predicted increases in fire risk may lead to considerable increases in wildfire management costs, offset the influences of elevated temperatures and atmospheric CO_2 concentrations on forest and tree productivity, and affect the availability of harvestable trees (Girardin and Mudelsee, in press). More frequent, large wildfires may also become a major factor in our changing climate, owing to greater carbon losses that could feed the warming (Kurz et al., 1995; Flannigan et al., 2006).

Acknowledgements

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What can data tell us about past climate that is useful for the future? Data management in paleoclimatology

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During the last decades, the number of scientific publications has increased exponentially, as has the number of scientific data sets. No end to the increase is in sight. Under the constraints of an efficient cost-benefit publication system, editors have had to tighten the measures for acceptance of manuscripts (e.g., maximum number of pages, and rigorous selection criteria). Data tables have often been relegated to appendices or supplementary material. With increasing availability of publications through the internet, unique and persistent digital object identifiers (DOIs) have been invented to keep up with the flood of publications. For a long time, scientific data have not been considered within this design strategy. However, the increasing amount of scientific data calls for appropriate archiving and international availability.

Today, this concept is forcefully supported by the Recommendations of the Commission on Professional Self Regulation in Science (1998), the Berlin Declaration on Open Access to Knowledge in the Sciences and Humanities (2003), the white paper on the free access to scientific data by the Association of Learned and Professional Society Publishers (ALPSP, 2006), and the OECD Principles and Guidelines for Access to Research Data from Public Funding (2007). The vision of the World Data Centre system is the optimized exchange of scientific information leading towards significant and sustainable support of future scientific achievements, as scientific data are perceived as the backbone of discovery. Combined with methods, results, interpretation, and discussion, data sets create a useful scientific publication. However, data have standalone value, and the unconfined availability of (and access to) the data allows for broader use and novel scientific debate.

The value of paleoclimate data to societally relevant problems in climate and environmental change is now well known. To make these data widely available, two remarkable archives have been developed: (1) the PANGAEA® Publishing Network for Geoscientific and Environmental Data (Bremerhaven, Germany), which serves as the technical archive for the World Data Center for Marine Environmental Sciences (WDC-MARE), and (2) the NCDC World Data Center for Paleoclimatology WDC-Paleoclimatology in Boulder, USA. WDC-Paleoclimatology describes its mission as providing "the paleoclimate data and information needed to understand and model inter-annual to centennial-scale environmental variability" PANGAEA® campaigns with its long-term and secured archiving structure, highly efficient editorial system, and extensive interoperability with other international data centers and portals. WDC-Paleocli-

matology evolved to become a source of data and information for specific themes, such as drought and abrupt climate change PANGAEA® has "special emphasis on environmental, marine and geological basic research", with the potent notion of being an exemplary publication and library system for scientific, geo-referenced data. Whether you prefer the one or the other World Data Centre may depend on your personal needs, or your fondness for (1) more focused data collections (WDC-Paleoclimatology), or (2) data mining in a billion data points warehouse (PANGAEA®/WDC-MARE).

To realize the digital library-of-data concept, data sets are perceived as data entities. A data entity consists of meta-information and data. Meta-information is any information describing a data set. Data is the pure, primary scientific information, which can be numbers, text, graphics, logging, audio and video recording and reproduction, etc. Where a dendrochronological record provides a few bytes of data only, CTD profiles can deliver some kilobytes of data, and satellite information measure beyond the megabyte border. Whether a single data point is recorded or a gigabyte mass data stream, it is not size that matters. It is rather the data set's scientific value and its unconfined availability (cf., panFMP, Schindler and Diepenbroek, 2008), and the standard assignment of one unique persistent, bibliographic identifier per data set to turn a plain data set into an autonomous data publication, cross-referenced with its original scientific paper. Data archiving is carried out in close co-ordination with the principal investigator. Owing to networking with other systems, database contents can be tracked down by means of search engines, portals, and online library catalogs. The technique of data citation gives a strong motivation for scientists to publish their data, which in the long range will improve data quality and availability.

Some data publications relate to individual papers or studies, while others are vast compilations and syntheses that receive periodic updates. For example, the Climatological Database for the World´s Oceans (CLIWOC; Gallego et al., 2005) with climatological and meteorological observations from ship logbooks between 1750 and 1854, contains some 5000 data sets. Based on 36 original scientific papers, Anderson and Mulitza (2001) compiled a 7791 digit set of $\delta^{18}O$ data from planktic foraminifers in surface sediments. As part of the Paleoclimate Database of the Quaternary (PKDB), Frenzel et al. (2001) document the atlas of paleoclimates and paleoenvironments of the northern hemisphere. The International Tree Ring Databank is continually updated, and provides the field with not only ten thousand raw ring-width measurements but also standardized chronologies and data quality statistics. Some data publications are remarkable for their unusual content. Müller et al. (2005) have archived harmonic tremor signals of the so-called "singing iceberg".

Paleo data give us the window on the past. Beyond their presentation in individual publications, paleo data form a rich tapestry of the four-dimensions we inhabit (time, latitude, longitude, and elevation). They tell us when, for how long, and for what reasons, the climate has changed. Digital data libraries make it all possible.

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PMIP (Paleoclimate Modelling Intercomparison Project)

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The Paleoclimate Modelling Intercomparison Project (PMIP) is a long-standing initiative endorsed by both the WCRP/CLIVAR (World Climate Research Programme/Climate Variability and Predictability) Working Group on Coupled Modelling (WGCM) and PAGES. It has provided an efficient mechanism for coordinating paleoclimate modeling activities, which provide valuable information on the mechanisms of climate change, the identification of key feedbacks operating in the climate system, and the capability of climate models to reproduce climates different from today. Thanks to the production of data syntheses and to rigorous model-data comparisons, the mid-Holocene (ca. 6 kyr BP) and the Last Glacial Maximum (LGM; ca. 21 kyr BP) are now recognized as benchmark periods for climate models. Although the main focus is on model-model intercomparison and evaluation, PMIP has acted as an important discussion forum, promoting the understanding of past climate changes as a necessary basis for confidence in future predictions. As a result, PMIP has contributed significantly to the last two IPCC assessments.

In the last 10 years, climate models have moved from atmosphere-only to coupled ocean-atmosphere models and ocean-atmosphere-vegetation models. Models that include the coupling between the physical climate and biogeochemical cycles, such as the carbon cycle, have also been developed. These couplings, and the corresponding feedbacks, shape the response of the climate system to external variations. They are required to enable understanding of how climate has evolved through time and how it will evolve in the future in response to human activities. The second phase of PMIP (PMIP2) was launched in 2002 and addresses the role of the different feedbacks using these coupled models (Harrison et al., 2002; Crucifix et al., 2005).

All the information to run a PMIP2 simulation is available on the PMIP2 website (http://pmip2.lsce.ipsl.fr/; see Braconnot et al., 2007 for an overview). Model results are stored in a common database hosted at LSCE on raid disks and the data is distributed through a Linux file server. Guidelines, file format convention, variable names and structures, and utilities follow the requirements of the WCRP CMIP3 multi-model dataset. Participation in PMIP analyses is an open process. About 80 sub-projects are now registered and most of them have already produced publications in high-level international journals (see, e.g., Fig. 1, and Otto-Bliesner and Brady, p. 18-20 this issue). Several data syntheses have also been released through the website, as well as a subset of maps showing

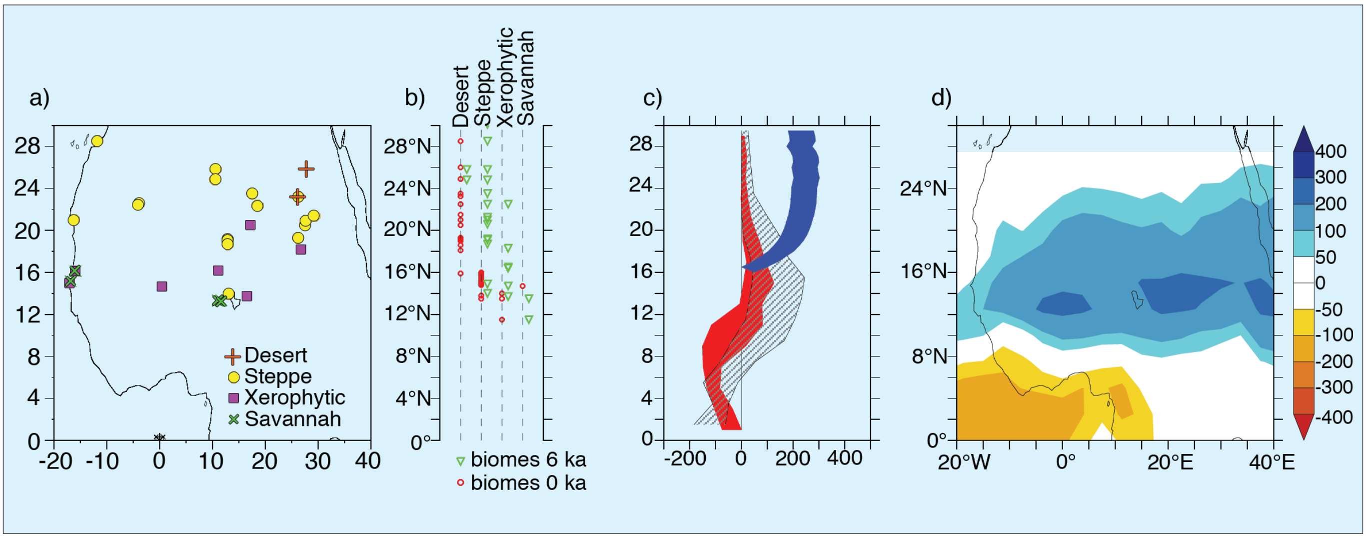

*Figure 1: Biome and precipitation changes in Africa for the mid-Holocene. **a**) Biome distribution during the mid-Holocene. **b**) Zonal mean biome distribution for mid-Holocene (6kyr) and pre-industrial (0kyr) periods, and **c**) change in annual mean precipitation (mm/yr) as simulated by the PMIP1 atmosphere alone models (red) and the PMIP2 coupled ocean-atmosphere models (black dashed). The model envelope is the range of precipitation covering 50% of the simulations around the median simulation. Blue band indicates the amount of precipitation that would be needed to replace modern desert by steppe. **d**) Ensemble mean change of annual mean precipitation (mm/yr) estimated from PMIP2 coupled ocean-atmosphere simulations. These figures show that PMIP2 coupled simulations are in better agreement with data than PMIP1 atmosphere alone simulations but that they still fail to produce enough precipitation to sustain steppe as far as 23°N, as suggested by pollen data. These figures are adapted from Jolly et al., 1998, Joussaume et al., 1999 and Braconnot et al., 2007.*

results of the different models. Systematic model-data comparisons are a key element of the program. PMIP will continue to foster the development of improved methods of reconstructing climate parameters from paleo-observations, and of rigorous statistical approaches for comparing simulated and observed climates. This will ensure that these comparisons focus on appropriate variables and scales.

PMIP is now also interested in new periods, such as the early Holocene and the last glacial inception, and in new topics, such as "water-hosing experiments" (testing the sensitivity of the Atlantic meridional overturning to surface water flux forcing). State-of-the-art models can now be used to examine changes in short-term climate variability and in climate extremes, such as droughts or storms. PMIP has also started to promote the development of "forward models" for use in model evaluation and, increasingly, for coupling directly within a climate-model framework. These new challenges will require new data syntheses, including syntheses of high-resolution indicators.

PMIP has developed a new Science and Implementation Plan to help prepare for the next IPCC assessment. The plan (available from the PMIP2 website) is structured around four themes: 1) evaluation of Earth System models for 6 kyr BP and LGM, 2) interglacials and warm periods, 3) abrupt climate change, and 4) measures of model skill in simulating paleoclimate conditions. Details will be discussed at the next PMIP2 workshop (14-19 Sept 2008, Colorado, USA). This workshop will also showcase ongoing sub-projects and explore linkages between climate and environmental studies.

*World Climate Research Programme/Climate Variability and Predictability

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An overview of some current CLIVAR modeling activities

Howard Cattle

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Modeling activities form a key component of CLIVAR, the World Climate Research Programme's Climate Variability and Predictability Project. From the global modeling perspective, these activities are carried out and coordinated through the joint WCRP/CLIVAR Working Group on Coupled Modelling (WGCM) and the CLIVAR Working Groups on Ocean Model Development (WGOMD) and on Seasonal to Interannual prediction (WGSIP). A key task for all of these groups is to maintain an oversight, and encourage developments in the component and coupled models needed for climate prediction (e.g., see Fig. 1). CLIVAR's regional monsoon and ocean basin panels also have modeling foci, often linked to results from CLIVAR-sponsored field programs such as the North American Monsoon Experiment (2004) or the current Tropical Atlantic Climate Experiment (2006-10), which has brought improved coverage of surface and subsurface data and dedicated process studies in the eastern tropical Atlantic. In addition, CLIVAR's Global Synthesis and Observation Panel (GSOP) has a key activity to inter-compare the outputs of current global ocean synthesis efforts that use data assimilation of the historical dataset of ocean observations to produce consistent ocean analyses.

An important activity for the WGCM has been the coordination, under the Coupled Model Intercomparison project (CMIP-3), of the global coupled climate

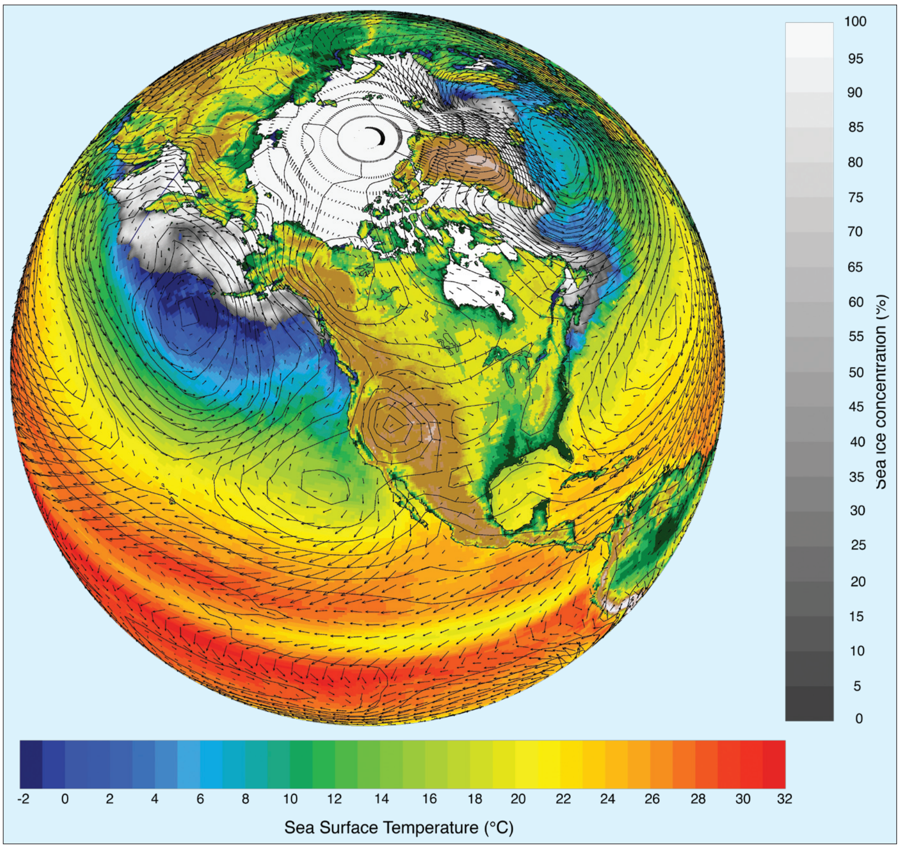

Figure 1: This figure shows, for the atmosphere, vectors depicting the winds in the lowest model layer, and the sea level pressure, shown as lines of constant pressure. The ocean model surface temperatures are shown in blue to red colors and the sea ice concentration is shown in gray. This simulation is from the Department of Energy-sponsored Parallel Climate Model (PCM). This coupled model consists of the NCAR Community Climate Model (CCM) for the atmospheric component, the Los Alamos National Laboratory Parallel Ocean Program (POP) for the ocean component, and the Naval Postgraduate School sea ice model. The PCM was specifically designed to execute on parallel supercomputers. (Figure designed by Gary Strand of NCAR, using FERRET, from PMEL).

model runs carried out in support of the IPCC AR4 WG-1 and their archiving and dissemination for the worldwide research community by the Program for Climate Model Diagnosis and Intercomparison (PCMDI) (www-pcmdi.llnl.gov/projects/cmip/index.php). Community access and analysis of this +35 Tb data archive, from 15 modeling groups across 11 countries, continues unabated. As of November 2007, more than 1000 registered users had downloaded data (over 300 Tb in total), and over 300 related journal articles had been published. With IGBP-AIMES, WGCM is now working to set the strategy for the next generation climate simulations that:

1. Identify new components in preparation for inclusion in atmosphere-ocean general circulation models (e.g., chemistry, aerosols, carbon cycle, dynamic vegetation).
2. Establish communication for coordination through the WCRP (WGCM and WGSIP in particular) and IGBP (AIMES in particular) and the Integrated Assessment (IA) modeling teams (the recently formed "Scenarios Consortium").
3. Propose an experimental design for 21st century climate change experiments involving initialized short-term (decadal prediction) experiments to ca. 2030, and long-term mitigation/adaptation experiments to 2300.
4. Specify the requirements for new stabilization scenarios (with regard to impacts, mitigation, and adaptation).

Both WGCM and WGSIP are engaged in developing the protocol for the proposed near-term decadal simulations out to ca. 2030 (point 3 above). WGSIP is also coordinating the pan-WCRP Climate system Historical Forecast Project (CHFP; www.clivar.org/organization/wgsip/chfp/chfp.php). The experiment is aimed at testing the hypothesis that there is currently untapped seasonal predictability due to interactions (and memory) among all the elements of the climate system (Atmosphere-Ocean-Land-Ice). It therefore calls for runs of seasonal prediction models that include the relevant interactions among land-ocean-atmosphere-ice. A data management plan for the project has been formulated and a call has been put out encouraging proposals for diagnostic sub-projects from the community. The CHFP was launched at the WCRP Seasonal Prediction Workshop in Barcelona in June 2007, another outcome of which was a consensus statement on the current status of seasonal prediction, available from: www.clivar.org/organization/wgsip/spw/spw_position.php

WGOMD activities have been focused on the completion of an intercomparison of 7 global ocean ice models run for 500 years using a fixed seasonal cycle of inputs to derive the atmospheric forcing. A joint paper for the peer-reviewed literature that documents the experimental design and simulation results of these CORE-I (Coordinated Ocean-ice Reference Experiment-I) integrations is in preparation. During 2008-9, WGOMD will explore the CORE-II experimental protocol, which focuses on inter-annually varying forcing based on reanalysis and observational products, aiming for a peer-reviewed paper in late 2009. CORE-III activities encompass exploration of the impact on the ocean of enhanced freshwater perturbations around the region of the Greenland ice cap. During 2008, WGOMD also plan to develop the concept of a repository for evaluating ocean simulations, giving web-based guidance on ocean model evaluation. Further information on the CORE activity can be found at www.clivar.org/organization/wgomd/core/core.php and more information on CLIVAR in general at www.clivar.org.

Towards an Australasian climate reconstruction for the past two millennia

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[2]Landcare Research, Lincoln, New Zealand; [3]School of Geography and Environmental Science, Monash University, Australia; [4]Department of Physical Geography and Quaternary Geology, Stockholm University, Sweden; [5]Department of Geological Sciences, University of Michigan, USA
Other collaborators are listed on the PAGES website at www.pages-igbp.org/products/newsletter/ref2008_2.html

In 1988, the World Meteorological Organization and the United Nations Environment Program established the Intergovernmental Panel on Climate Change (IPCC) to assess our understanding of the scientific basis of risk of climate change and opportunities for adaptation and mitigation. Unfortunately, relatively widespread instrumental measurements only extend back to the mid-19th century. In spite of this, there exists a wealth of indicators of past climate that show that rapid changes have taken place. Annually resolved climate proxies, such as tree rings, corals, lake sediments and historical climate datasets have been major contributors to such studies; typically, past surface temperatures have been inferred by calibrating to instrumental temperature data using statistical relationships.

A suite of global, hemispheric and continent-wide reconstructions have emerged during the last decade (e.g., Mann et al., 1998, 1999; Jones et al., 2001; Cook et al., 2004; Moberg et al., 2005; Hegerl et al., 2006) and were prominently synthesized in the IPCC AR4 (Jansen et al., 2007). Reconstructions generally agree that present-day northern hemisphere temperatures exceed those of the last 2 millennia. On the other hand, they differ considerably in details of climate history and sensitivity.

Although some criticism has been leveled at the reconstructions, the essential results have also recently been supported by a panel of the US National Academy of Sciences (National Research Council, 2006). It was noted, however, that more must be done to reduce uncertainties in periods before 400 years ago and in the southern hemisphere. Furthermore, the NRC report and the IPCC AR4 alike demand regional-scale reconstructions of climate variables other than temperature. Some attempts to increase the representativeness of paleoclimate reconstructions have been made. For instance, the dependence on annually and decadally resolved datasets has not always captured variability on multi-centennial timescales. By combining low- and high-resolution proxies (which capture long- and short-term change, respectively) and using a wavelet transform technique, Moberg et al. (2005) demonstrated relatively large multi-centennial variability. Pollack et al. (2006) also reported a borehole temperature reconstruction for the Australian regions (Fig. 1). Although this shows the same broad pattern observed in the northern hemisphere, the precise timing and detail of change was not possible to resolve with this method.

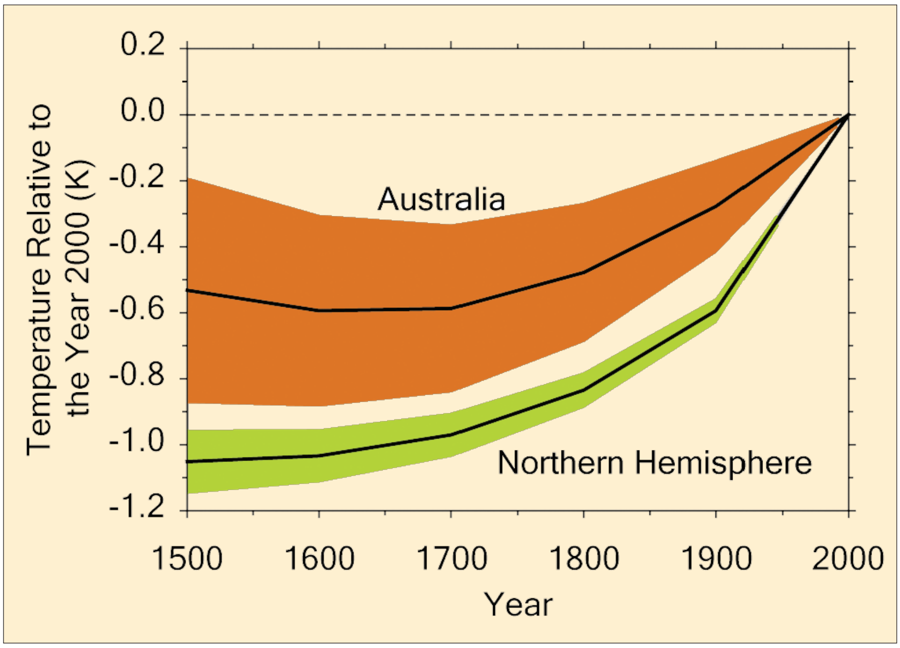

Figure 1: Comparison of Australian borehole temperature reconstruction to northern hemisphere borehole reconstruction (modified from Pollack et al., 2006).

The Australasian region straddles several major atmospheric and oceanic boundaries (many of which are interconnected), which have the potential to be highly sensitive under a variety of future climate change scenarios. These include the Australian Monsoon, the Interdecadal Pacific Oscillation, El Niño-Southern Oscillation (ENSO), and the East Australian Current. In some Australian locations, meteorological records extend back to AD 1840 but are most common only from the beginning of the 20th century (Nicholls et al., 2006). In an attempt to extend the climate record beyond the historical period, we have established a PAGES-endorsed Working Group to develop a reconstruction for the past two millennia in Australia.

20 published datasets have now been identified, including coral calcification, $\delta^{18}O$ and $\delta^{13}C$, tree-ring widths and ice core $\delta^{18}O$. Due to the limited number of sites and their variable length, it has so far proved problematic to integrate the reconstructed temperature series into a robust Australasian average. As an alternative, we are following the approach recently reported by Osborn and Briffa (2006), whereby proxies with positive correlations to temperature are compared to identify hemispheric-scale climate anomalies. Of the 20 datasets, only 10 have proved to have a significant positive correlation with temperature. The results are currently being prepared for publication but suggest that temperatures over Australasia at the end of the 20th century were unusually high compared to the past 550 years. Future work is now focusing on expanding the network of temperature datasets, extending the records further back in time and developing a comprehensive series of quantified moisture-sensitive proxies.

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For full references please consult:
www.pages-igbp.org/products/newsletter/ref2008_2.html

Improving our understanding of the marine biotic response to anthropogenic CO_2 emissions

ESF-PAGES Workshop, Barcelona, Spain, 26-28 September 2007

Thorsten Kiefer[1], S. Barker[2], D. Schmidt[3] and P. Ziveri[4]

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During recent years, ocean acidification (OA) has rushed onto the global change agenda as a global-scale consequence of rising atmospheric CO_2 levels. Biotic responses to changing ocean carbonate chemistry are expected to impact ecosystems, feedback on global climate, and eventually affect socioeconomies. However, our knowledge about the nature of biotic responses to OA is still too limited to quantify their impacts (see also report on IGBP-SCOR Fast Track Initiative workshop in Lamont, 2006; *PAGES News*, 14:3, 29-30). Therefore, the European Science Foundation (ESF) EuroCLIMATE program, with co-sponsoring from PAGES, organized the Barcelona workshop to bring together a diverse range of experts to review knowledge of the likely effects of OA on planktonic calcifying organisms and marine biogeochemistry. Five sessions addressed 1) Biocalcification mechanisms, 2) Genetics and physiology, 3) Ecology and biogeography, 4) Lessons from the fossil record, and 5) OA in the Mediterranean.

Here, we focus on the fossil record and what can be learned from it about responses and effects of marine biota and ecological systems. More comprehensive reports are published in The Eggs (Ziveri et al., 2007) and Eos (Ziveri et al., 2008). Case studies, ranging from the onset of the Cenozoic era to the recent past, featured a range of perturbations of the carbon system:

Daniela Schmidt (University of Bristol) presented data from the Cretaceous/Paleogene (K-Pg) Boundary (~65 Myr ago), and suggested that the major environmental and climatic changes included abrupt OA (Fig. 1). A drop in average foraminiferal test size and a shift of the carbonate production from coccolithophore- to foraminifera-domination demonstrate profound changes in plankton composition. A decrease in carbonate accumulation at this time is related to a reduction in calcification rather than increased dissolution at the sea floor. Recovery of the carbonate production took several million years.

The Paleocene-Eocene Thermal Maximum (PETM), a rapid OA event ~55 Myr ago, was the subject of presentations by Jim Zachos (University of Santa Cruz) in a public lecture and by Heather Stoll (University of Oviedo). Stoll showed new evidence from the Southern Ocean (a region particularly sensitive to the effects of OA) of distinct shifts in plankton assemblage at the PETM, with an increase in the presence of species generally more suited to warmer conditions and less susceptible to dissolution (Fig. 2). Furthermore, coccolith Sr/Ca data provide some evidence that coccolithophore production may have peaked during the PETM in the Southern Ocean.

Significant deepening of the calcite lysocline and carbonate compensation depth during the Eocene-Oligocene (E-O) boundary (~34 Myr) reveals a whole ocean 'reverse' acidification event associated with the first major growth of ice sheets on Antarctica. Based on tests with a biogeochemical ocean box model, Toby Tyrell (University of Southampton) discussed sea-level fall due to the ice sheet growth and a consequent shift of carbonate deposition from shallow shelf reef areas to the deep sea as the favored explanation of these changes in carbonate chemistry.

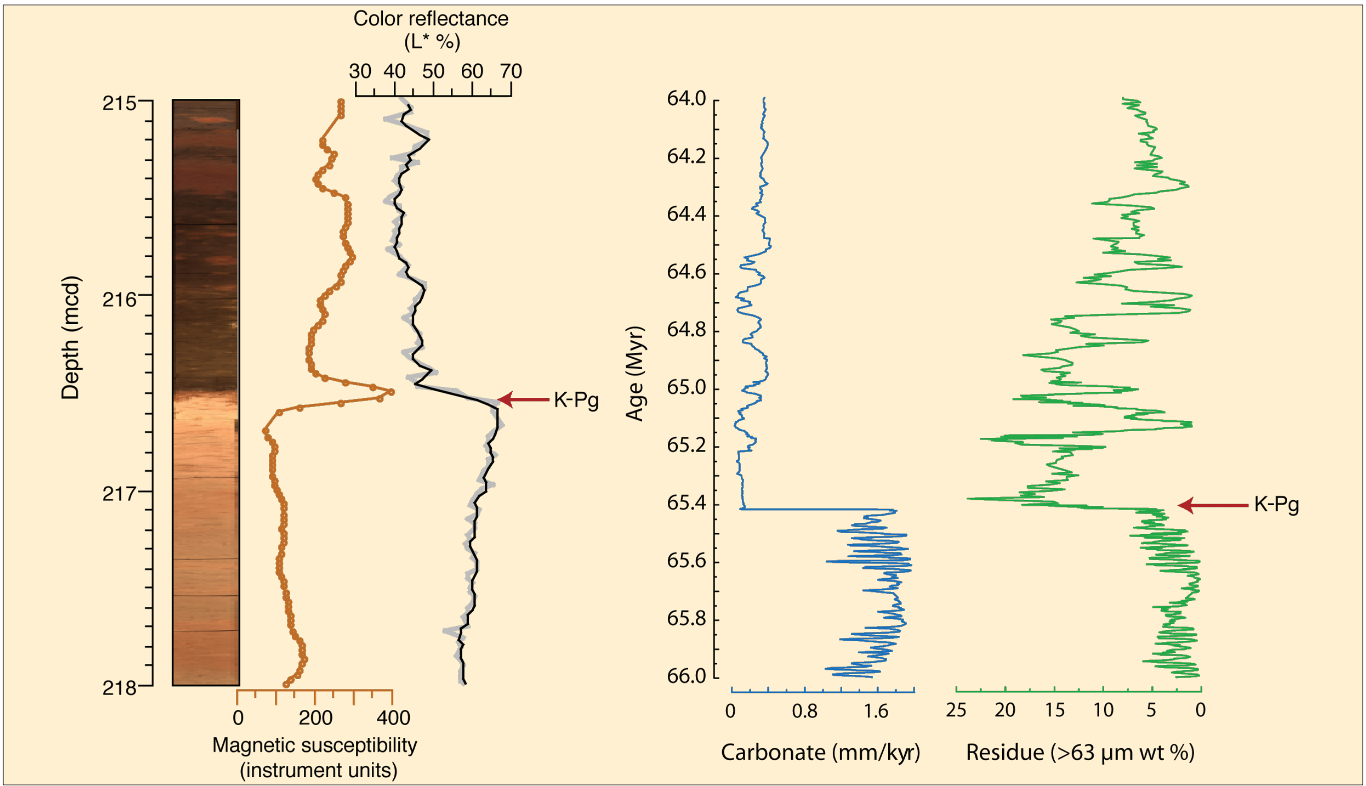

Figure 1: The Cretaceous/Paleogene (K-Pg) boundary at Walvis Ridge Ocean Drilling Paogram Site 1262. The boundary is characterized by a drop in carbonate accumulation and an increase in clay, iron oxide and volcanic ash accumulation, which produced distinctive increases in magnetic susceptibility and color reflectance (lightness L). A percentage increase of the coarse fraction relects the shift in dominant carbonate producers from coccolithophores to foraminifera. Figures after Kroon et al., 2007.*

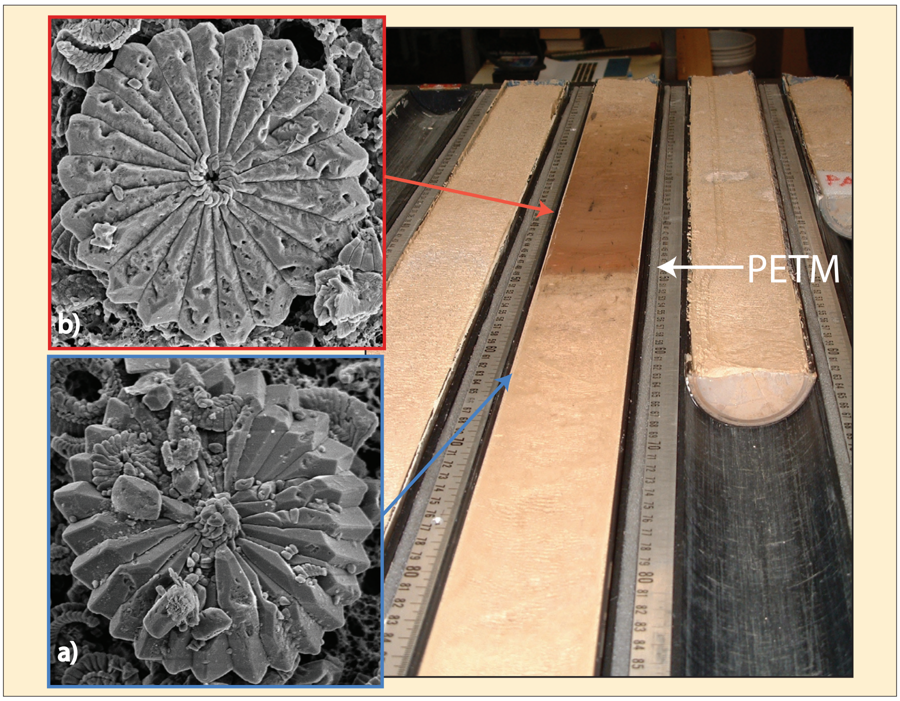

Figure 2: Core photo from Walvis Ridge (Ocean Drilling Program ODP Leg 208) with dark sediment representing the PETM, and calcareous nannofossils of Discoaster multiradiatus *(Site 1263). (**a**) a relatively well-preserved, pre-PETM specimen; (**b**) a corroded specimen from the acidification event during PETM. Scanning electron microscope (SEM) images from Mascha Dedert, Vrije Universiteit Amsterdam.*

Stephen Barker (Cardiff University) illustrated widespread deep ocean acidification and resulting dissolution of carbonate sediments during the Mid-Brunhes interval (~0.6-0.2 Myr ago). This global change in ocean carbonate chemistry may have been driven by an increase in pelagic carbonate production caused by the proliferation of the calcifying *Gephyrocapsa* coccolithophore. This example provides a case for: (1) how profound changes in biology can drive (or feedback on) OA, and (2) how changes in the calcifying planktonic ecosystem can influence the balance between the organic and inorganic carbon pumps and hence ocean-atmospheric CO_2 exchange and global climate.

Carles Pelejero (CMIMA-CSIC Barcelona) gave an example of an OA study from the historical past. A 300-year reconstruction of pH from boron isotopes in corals from Flinders Reef (NE Australia) shows a strong (~0.2 pH units) multi-decadal oscillation with ~50 yr cyclicity, rather than the monotonic decrease expected as a consequence of anthropogenic CO_2 release. While the oscillating pH may be a local phenomenon in the reef environment associated with the Interdecadal Pacific Oscillation, an interesting key finding was that the measured coral calcification rate did not apparently respond to the pH changes.

Andy Ridgwell (University of Bristol) stressed a general point arising from attempts to model the sediment response to changes in OA: Although it is relatively straightforward to predict the inorganic response of carbonate sediments to changes in ocean acidity, it is extremely important that we are able to constrain the associated changes in atmospheric CO_2 and possible biological calcification responses before we will be able to reduce the uncertainties in our models.

According to Richard Zeebe (University of Hawaii) none of the past OA scenarios will be able to depict the true extent of future acidification. The injection of carbon into the ocean–atmosphere system, even during the PETM, was most likely not as rapid and intense as the modern situation. A more gradual release of carbon would have been more efficiently buffered by deep sea carbonate dissolution, resulting in a reduced effect on surface ocean pH. A noteworthy implication of this is that any effect on marine biocalcification during past OA events, including the PETM, may represent the very minimum response that might be expected in the future.

Particular emphasis was given to considering the geographical distribution of any event in terms of response in the system. For example, the extent of carbonate dissolution during the PETM was not equal globally. Although none of the past OA analogs seem to be able to depict the true extent of future acidification, they all provide important constraints on the nature of the threat for the near and distant future. These constraints are also critical in order to assess planktonic species adaptation rates to such perturbations, putting our ability to understand the future on firmer ground.

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Oceanography and Climate Change: Past, present and future scenarios

Austral Summer Institute VIII, Dichato, Chile, 7-14 January 2008

Sergio Contreras Quintana (Workshop Participant)
Department of Biogeochemistry, Max Planck Institute for Marine Microbiology, Bremen, Germany; scontrer@mpi-bremen.de

The Austral Summer Institute VIII on “Oceanography and Climate Change: Past, present and future scenarios” was held in Dichato, Chile, from 7 – 14th January 2008. Twenty students were selected from 92 applicants to participate in the workshop, which also involved the participation of word-class lecturers.

The first week focused on two key topics:

1) El Niño Southern Oscillation, theory, observations and predictions was lectured by Dr. Axel Timmerman, from the University of Hawaii. Lectures were complemented with computer-based exercises and homework, including ocean and atmosphere data analyses and simple model runs for ENSO predictions.
2) The role of the thermohaline circulation on the Earth’s climate was lectured by Dr. Andrey Ganopolsky from the Potsdam Institute for Climate Impact Research. This included a discussion of climate consequences in modern times

Students and lecturers of the Austral Summer Institute VIII

and in future climate scenarios, and was complemented by student discussion sessions on predefined topics.

On the last day, the team project "Congress hearings on thermohaline ocean circulation" was organized. Students prepared independent arguments for and against the importance of the ocean thermohaline circulation and made presentations to argue their cases.

The second week focused on the theory of the Milankovitch cycle as the main driver of past and future climate variability. This theme was lectured by Prof. André Berger from the Université Catholique de Louvain, Belgium. Based on Prof. Berger's model, we calculated orbital parameters and solar forcing for different periods of the year and different geological periods in the past and future. During this week, Prof. Jorge Sarmiento also lectured on the main biogeochemical cycles in the modern ocean and how they can affect the climate system. Most of these lectures were also complemented with exercises.

The course included "Distinguished Lectures on Climate Variability" delivered at the main campus of the University of Concepcion. The purpose of this was to offer these presentations to a wider audience. In addition to listening to Dr. Sarmiento and Dr. Berger, we were able to learn from Chilean experts about the analysis of the biological and societal consequences of global change. This proved to be a good experience for class participants, as well as for the other professionals and students who were able to attend.

I would like to thank the University of Concepción and PAGES for providing me with the opportunity to attend this workshop. I feel that attending the course gave me a broader perspective on climate change, which has strengthened my background in paleoceanography. In my opinion, this type of activity, in which students and professors interact in a friendly, informal environment outside the classroom, facilitates communication, and results in professional development and joint research enterprises.

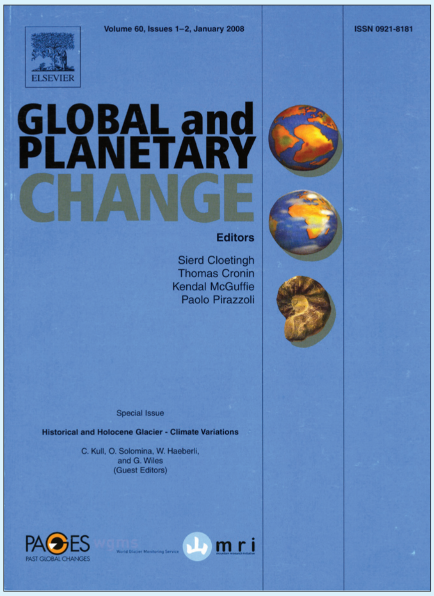
New on the PAGES bookshelf

Historical and Holocene glacier-climate variations

Editors: C. Kull, O. Solomina, W. Haeberli and G. Wiles

ELSEVIER Press

This special issue of Global and Planetary Change provides an overview of recent research activities concerning changes in the timing of glacier changes and their linkages to climate. The contributions are based on presentations from two glacier–climate–cryosphere sessions co-organized by the EU-funded GLOCHAMORE project (Global Change in Mountain Regions), PAGES and the WGMS (World Glacier Monitoring Service) at the Open Science Conference on "Global Change in Mountain Regions" organized by the MRI (Mountain Research Initiative) and held in Perth, Scotland, 2-6 October, 2005.



Summary of Contents:

- Historical and Holocene glacier–climate variations; *O. Solomina et al.*
- Norwegian mountain glaciers in the past, present and future; *A. Nesje et al.*
- Strength and spatial patterns of the Holocene wintertime westerlies in the NE Atlantic region; *J. Bakke et al.*
- 19th century glacier representations and fluctuations in the central and western European Alps; *H.J. Zumbühl et al.*
- Palaeoclimate from glaciers: Examples from the Eastern Alps during the Alpine Lateglacial and early Holocene; *H. Kerschner and S. Ivy-Ochs*
- Recent glacier changes and climate trends on South Georgia; *J.E. Gordon et al.*
- 20th-century glacier recession and regional hydroclimatic changes in northwestern Patagonia; *M.H. Masiokas et al.*
- Tracing tropical Andean glaciers over space and time; *B.G. Mark*
- Century to millennial-scale temperature variations for the last 2000 yrs from glacial geologic records of Southern Alaska; *G.C. Wiles et al.*
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- A brief consideration of climate forcing factors in view of the Holocene glacier record; *A.T. Grove*
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John P. Smol

Blackwell Publishing, ISBN: 978-1-405-15913-5; ISBN -10: 1-405-15913-8

The pollution of lakes and rivers has become an international problem, reaching crisis proportions in many regions. The second edition of "Pollution of Lakes and Rivers" addresses many of the present-day water quality problems. It demonstrates how paleolimnological approaches can be used to interpret the physical, chemical, and biological information stored in lake and river sediments, and how this information is integral to identifying key environmental stressors and setting targets for mitigation purposes.

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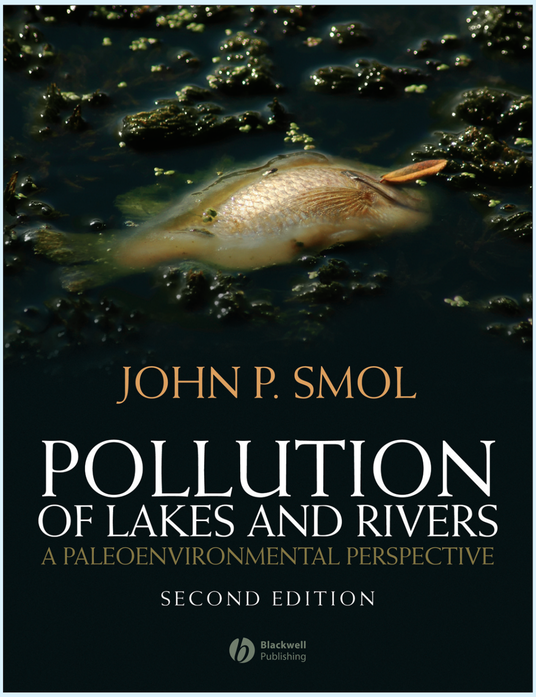

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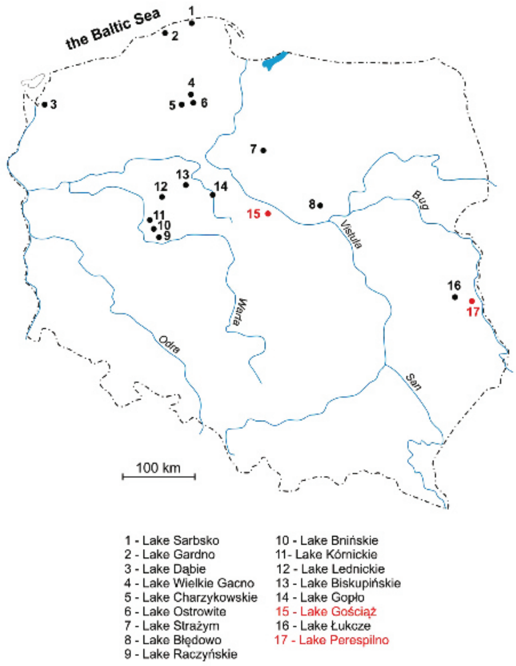
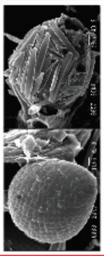
POLAND

Poland lies in the Central European Pleistocene periglacial and glacial zone, and sits in a transitional zone between continental and maritime climatic influences. Paleolakes, modern lakes, peats, coastal sediments and fossil soils provide many opportunities for paleoclimate and environmental reconstructions. There is a long tradition of Quaternary and Late-Pliocene continental paleoenvironmental studies in this region. More recently, classic disciplines such as geomorphology, sedimentology, paleogeography, geoarcheology, paleolimnology and paleoecology have been applied in multi-proxy reconstructions of the Holocene. The results of many paleoresearch projects, from the Baltic Sea to the Tatra Mountains, have been recorded at KBN (State Committee for Scientific Research), the primary funding source in Poland.



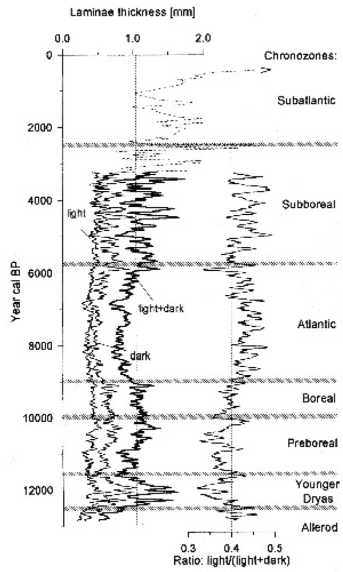
The location of Polish lakes used in multiproxy environmental reconstructions

Paleo-peat archives possess a valuable record of paleoenvironments in Poland. Fossil testate amoebae in these peatlands are used to reconstruct past hydrological changes in the region.



RESEARCH INSTITUTIONS

There are more than 15 departments within research institutes in Poland that conduct paleoresearch. For a full list, with links to their websites, visit the Polish National PAGES website.



Lake Gościąż, Central Poland, contains laminated sediments composed of light and dark colored bands of calcareous gyttja (calcareous, organic sediment). Each consecutive pair of light-dark laminae reflect the fluctuation of the climate during one year. This figure shows the variations in thickness of these laminae throughout the last ca. 12,000 years (Goslar, 1998; see the webpage for more details).

FUNDING

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