

February 2003

## PAGES - Past Global Changes Magazine formerly PAGES news

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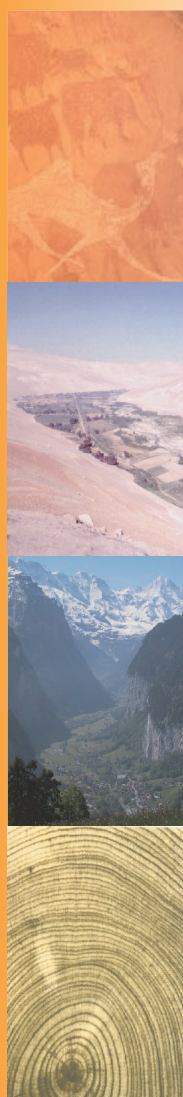
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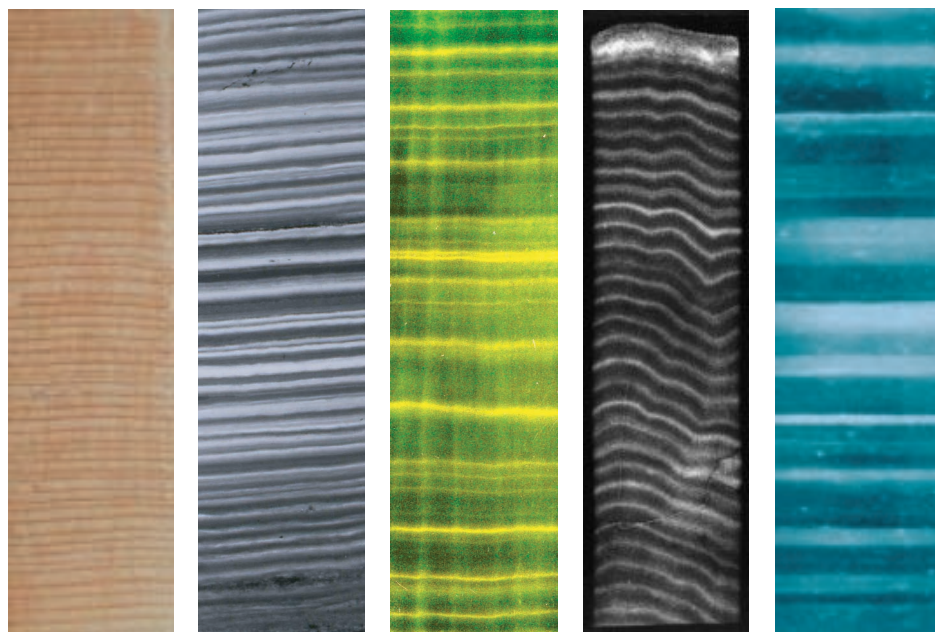
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## **HOLIVAR** **Holocene Research**



[www.pages-igbp.org](http://www.pages-igbp.org)



Annually banded archives: (from left to right) tree rings of Huon pine from Tasmania (Edward Cook); varves from Lake Holzmaar, Germany (Bernd Zolitschka); speleothems from Rana, Norway (J. Kihle); coral from Papua New Guinea (Sandy Tudhope); ice from GISP2, Greenland (Anthony Gow)

### **Contents**

#### **2 Announcements**

- Editorial: *HOLIVAR*
- PAGES Session at the Fall AGU 2003
- Inside PAGES
- Tales From the Field: We Need Your Input
- Newsletters: Do You Need a Hardcopy?
- New on the Bookshelf
- Marie Curie International Fellowships

#### **4 Program News**

- The *HOLIVAR* Programme

#### **6 National Page**

- Russia

#### **7 Science Highlights**

- Developments in Age-Depth Modeling
- Instrumental Climate Data
- Varved Lake Sediments in Scandinavia
- $^{14}\text{C}$  as an Indicator of Solar Variability

- Climate and Fennoscandian Tree-Rings
- Climate Reconstruction from Peatlands
- Climate Forcing During the Holocene
- Tephra, a Tool for Dating and Correlation
- Simulating the Last Millenium Climate
- Holocene Climate in the Tien Shan Region
- Climate Variations in the Gulf of California
- Climate and the Maya

#### **31 Workshop Reports**

- 2<sup>nd</sup> *HOLIVAR* Workshop, Belgium:  
Climate Modeling  
Holocene Climate Variability
- Environmental Magnetism, India

#### **35 Epilogue**

- Holocene Research: Past Present Future

#### **36 Last Page**

- Calendar
- A New Paleofire Database



## Editorial

HOLIVAR (Holocene Climate Variability) is a new ESF (European Science Foundation) scientific program that seeks to bring together researchers interested in short- and long-term climate variability over the Holocene period. HOLIVAR is concerned with scientific issues identified as being of international importance for climate change studies by the PEPiII research community in IGBP-PAGES. It is also a contribution to the PAGES/CLIVAR intersection, which is a shared research agenda between WCRP and IGBP. The central questions addressed by the HOLIVAR program concern how climate has varied naturally on annual to centennial time-scales and determining the cause of Holocene climate variability. The main natural forcing factors under discussion are solar irradiance and volcanic activity, and a key focus of the HOLIVAR program is to determine how the various natural archives (e.g. tree rings, speleothems, lake and marine sediments, mires, and glaciers) can be used together to reconstruct past climate on these time-scales and in relation to these forcings. Archives with visible annual resolution are of special importance because they provide a precise chronology and offer the best resolution as climate proxies. The relationship between climate proxies and climate variables—temperature and rainfall—is more often indirect and complex than linear over time. One of the main tasks of HOLIVAR is to combine natural proxies with instrumental records and documentary data in order to understand past natural climate variability more fully and to calibrate and test paleoclimate reconstruction methodologies. Holocene climate modeling is also of particular interest within the HOLIVAR community. Combined paleoclimate data can be used to test and improve the performance of climate models, whereas model experiments can help in the understanding of the causes of past climate variability. The papers presented in the science highlights section of this PAGES Newsletter are based on the extended abstracts volumes and the many fruitful discussions that took place during the first and second ESF-HOLIVAR workshops “Combining climate proxies” and “Investigating Holocene climate variability using data-model comparisons” held at Lammi Biological Station, Finland in April 2002 ([http://www.gsf.fi/esf\\_holivar/](http://www.gsf.fi/esf_holivar/)) and Louvain-la-Neuve, Belgium in June 2002 (<http://www.cru.uea.ac.uk/~timo/holivar/>), respectively.

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## AGU Meeting, 8 - 12 Dec. 2003, San Francisco, USA Special PAGES Session: Rates of Change in the Earth System

**Convenors:** *Keith Alverson*, PAGES IPO, Bern, Switzerland; [alverson@pages.unibe.ch](mailto:alverson@pages.unibe.ch)  
*Julie Brigham-Grette*, University of Massachusetts, USA; [juliebg@geo.umass.edu](mailto:juliebg@geo.umass.edu)  
*Thomas Stocker*, University of Bern, Switzerland; [stocker@climate.unibe.ch](mailto:stocker@climate.unibe.ch)

### Description:

Much of paleoenvironmental research has focused on (quasi-) equilibrium climate states of the past, such as the Eemian (roughly between 140,000 and 117,000 years before present) or the Last Glacial Maximum (21,000 years before present). Here the terms "climate state" and "climate system" include the whole Earth system as inferred by climatologists, geologists and ecologists, among others. By making comparisons with the present-day climate state, we have been able to infer the magnitude of climate-sensitivity parameters. However only non-equilibrium or transient climate states, such as the last deglaciation, allow us to assess the magnitude of the inertia in the Earth system. Areas of interest include, but are not limited to, forcing factors (greenhouse gas concentrations), climatic variables (temperature, hydrological balance, glacier mass balance, sea level) and the biosphere (biodiversity, alpine timberline, landcover change). Estimates of past rates of change can provide us with a long-term perspective on recent changes and help us to appreciate their magnitude. Furthermore, they give us a taste of how rapid climate change may operate in the future. State-of-the-art earth system models require a variety of field-based estimates for the inertia of the climate system in order to make reliable predictions for the future.

Further information: <http://www.agu.org/meetings/fm03/>

## Inside PAGES

After several months of disruption to office routine due to changes in personnel, the IPO is running smoothly again.

The Executive Director **Keith Alverson**, is now supported by four part-time office staff: Office Manager (**Selma Ghoneim**), Web-Database Coordinator (**Kaspar Grathwohl**), Project Officer (**Leah Christen**), and Science Officer (**Christoph Kull**). More information about the role of these people in the day-to-day running of PAGES, along with their contact details, can be found on our website at <http://www.pages.unibe.ch/ppeople/staff.html>.

### New PAGES Office Location

In September, another major office change took place when we moved from our current location in the center of the city to an office near the main train station. This move was necessary because of modifications to our current office building. The new address is Sulgeneckstrasse

38, 3007 Bern, Switzerland. Phone, fax and email remain the same.

### PAGES SSC Meeting 2003

The PAGES Science Steering Committee (SSC) recently held its annual meeting in Banff, Canada. The minutes of the meeting are available on our website at <http://www.pages.unibe.ch/ppeople/sscleaders.html>.

**Julie Brigham-Grette**, former Vice-Chair, has taken over the role of SSC Chair from **Vera Markgraf**. After serving two terms, **Vera Markgraf**, **Matti Saarnisto** and **José Boninsegna** will be leaving the SSC. The IPO thanks them for all their hard work. **Riuji Tada** and **Carole Crumley** were nominated to serve for another three-year term. There are currently several committee positions vacant.

The IPO would like to encourage nominations from developing countries and from scientists from the southern hemisphere—two areas that are currently underrepresented on the SSC.

Please contact **Keith Alverson** ([alverson@pages.unibe.ch](mailto:alverson@pages.unibe.ch)) for further information.

### 2004 Newsletters

The next Newsletter is open to science highlights from all PAGES-relevant research. Scientific contributions as well as workshop reports and program news are welcome.

If you are interested in contributing, contact **Christoph Kull** ([kull@pages.unibe.ch](mailto:kull@pages.unibe.ch)). All submissions should follow the instructions for authors on our website at <http://www.pages.unibe.ch/products/newsletters.html> and be submitted by 31 December 2003.

In the interest of saving paper and postage, we are asking all members if they would like to receive 'virtual' PAGES Newsletters. These newsletters would be sent by email as pdf file attachments. Please contact **Leah Christen** ([leah.christen@pages.unibe.ch](mailto:leah.christen@pages.unibe.ch)) if you would like to have the Newsletter emailed to you rather than posted. Back issues are always available as pdf files to download from our website at <http://www.pages.unibe.ch/products/newsletters.html>.

## Tales from the Field: We need your Input!

Do you have an interesting and humorous story from your paleoenvironmental fieldwork? If you write it down in 500 words or less and send it to us, we will put it in PAGES news!

## PAGES Newsletters: Do you need a hardcopy?

The PAGES IPO sends out about 3500 Newsletters three times a year. If you would like to receive the PAGES Newsletter as a downloadable pdf file only, please inform [leah.christen@pages.unibe.ch](mailto:leah.christen@pages.unibe.ch)

Thanks a lot!





## New on the PAGES bookshelf:

### Paleolimnology - The History and Evolution of Lake Systems

Andrew S. Cohen, Professor of Geosciences, University of Arizona

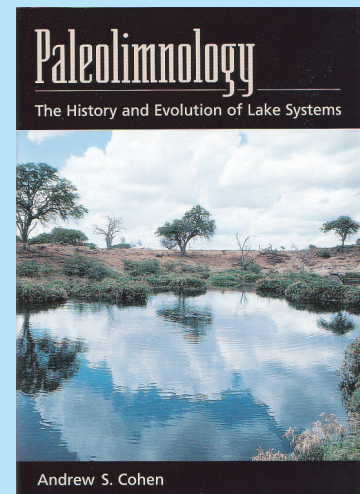
ISBN: 0-19-513353-6

Publication date: 8 May 2003, Price: £74.50 (Hardback)

OUP USA 528 pages, 204 line illus & 28 halftones,

<http://www.oup.co.uk/isbn/0-19-513353-6>

This text, written by a leading researcher in the field, describes the origin and formation of lakes in order to give context to the question of how lacustrine deposits form. It explains the process of sedimentation in lakes and the chemistry of those deposits and describes how the age of lake deposits is determined. Additionally, this book shows how different groups of fossils are used in interpreting the paleontological record of lakes. In order to illustrate the more synthetic approaches to interpreting the history of lakes, the author also discusses such special topics as lake-level history, lake evolution, and the impact of environmental change on lakes.



## Marie Curie Incoming International Fellowships (IIF)

The European Commission's Sixth Framework Programme includes the introduction of Marie Curie Incoming International Fellowships. These Fellowships are available to fund top-class researchers from countries outside the 15 European Union Member and Associated States to support research visits of one to two years in a host research organization within one of the EU States. Support for fellows to return to their country of origin may be included for developing countries, emerging and transition economies. EUR11 million has been allocated to a 12 February 2004 deadline.

PAGES would be happy to act as host organization for a researcher interested in applying for a Fellowship to conduct research in Switzerland. Such a fellowship would be mutually beneficial and would enable you to take advantage of PAGES' international connections. We invite you to contact us with a short research proposal by 31 December 2003. Please note: You would need to apply for the Fellowship yourself but we could provide assistance, if necessary.

Further information about the Fellowship is available at:  
[http://fp6.cordis.lu/fp6/call\\_details.cfm?CALL\\_ID=30](http://fp6.cordis.lu/fp6/call_details.cfm?CALL_ID=30)

Please send proposals to:  
 Christoph Kull ([kull@pages.unibe.ch](mailto:kull@pages.unibe.ch))

## HOLIVAR (Holocene Climate Variability)

**RICK BATTARBEE**

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HOLIVAR (<http://www.esf.org/holivar>) is an ESF scientific program in the life and environmental sciences. It seeks to bring together European scientists interested in climate variability over the Holocene period—broadly the last 11,500 years of Earth history. Scientists involved in the program are paleoclimatologists, climate histori-

ans and climate modelers, and the program aims to stimulate research on a number of key questions:

- How and why has climate varied naturally on different time-scales (annual, centennial and millennial) over the Holocene period?
- How can an understanding of past variability improve the performance of climate models, leading to an improved prediction of future climate change?
- How can climate models help to explain past climate change?

- How has climate variability and the nature of human society interacted during the Holocene?

Although these are questions of global relevance, HOLIVAR focuses mainly on research in Europe and Africa, and is allied closely to the aims and objectives of the Past Global Changes (PAGES) PEP-III project, which is concerned with climate change along a pole-to-pole transect through Europe and Africa. It is also a contribution to the PAGES/CLIVAR Intersection, which is a shared research agenda between WCRP and IGBP.

## Scientific Rationale

The latest research on recent climate variability is tending increasingly to the view that greenhouse-gas forcing is becoming the dominant, though not the only, process driving global warming. Consequently, future climate change will be the result of interactions between the effects of human-induced changes and the effects of natural variability. There is therefore an urgent need to understand these interactions and to document and identify the characteristics of natural climate variability.

Natural variability, whether associated with mechanisms external or internal to the earth system, is expressed on inter-annual, decadal, and century time-scales, and it is variability on these time-scales that climate and earth system modelers are seeking to simulate. Data for only the most recent part of the historical record can be derived from instrumental measurements and, therefore, there is a need to extend the instrumental record backwards in time using proxy records of climate change contained in naturally occurring archives, such as lake and marine sediments, peat bogs, tree rings, speleothems, and ice cores.

However, none of these archives alone is adequate to capture the temporal- and spatial-scale variability needed for regional comparisons with climate model output. Consequently, the prime objectives of HOLIVAR are to encourage the

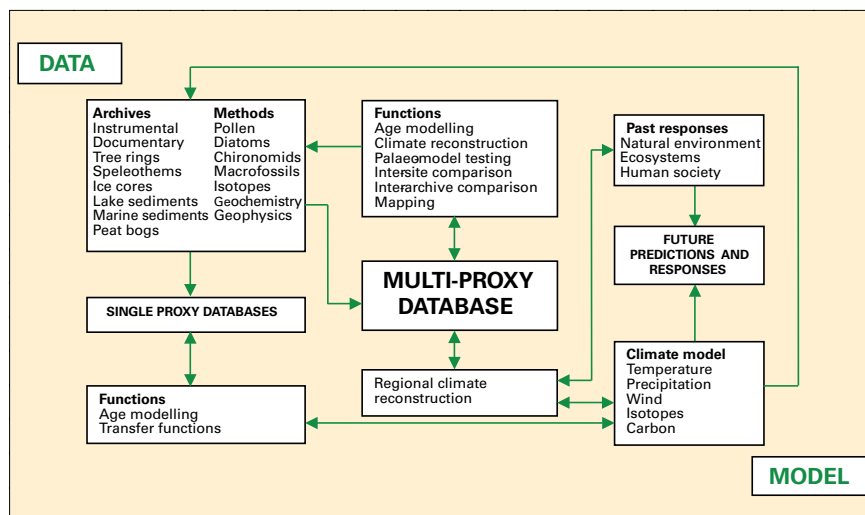


Figure 1: The HOLIVAR concept

harmonization of paleoclimate data from the different archives, to encourage the use of multi-proxy databases that can be used to combine data of different types at the regional scale, and to encourage and facilitate comparisons between data and model output (Fig. 1).

## Work Timetable

The program objectives are being met over a five-year period (2001-2005) by a series of meetings, workshops, and training courses, which will culminate in an open science meeting in September 2005.

- 2001 International conference (co-sponsored by IGBP-PAGES) on *"Past Climate Variability through Europe and Africa"*, Aix-en-Provence, France.
- 2002 Research workshop on *"Combining proxies"*, Lammi, Finland.
- 2002 Research workshop on *"Data-model comparisons"*, Louvain-la-Neuve, Belgium.
- 2003 Research workshop on *"Holocene dating, chronologies, and age modelling"*, Utrecht, the Netherlands.
- 2003 Training course 1 on *"Quantitative Holocene climate reconstruction and data-model comparisons"*, London, UK.
- 2004 Research workshop on *"Databases and data analysis"*, Bremerhaven, Germany.
- 2004 Training course 2 on *"Quantitative Holocene climate reconstruction and data-model comparisons"*, location to be decided.

2004 Research workshop on *"Holocene climate forcing"*, Zurich, Switzerland.

2004 Research workshop on *"Climate-human society interactions during the Holocene"*, location to be decided.

2006 Open Science Meeting on *"Holocene climate variability"*, London, UK

## Steering Committee and Funding

HOLIVAR is financed on an *à la carte* basis by ESF member organizations in Austria, Belgium, Finland, France, Germany, the Netherlands, Norway, Sweden, Switzerland, and the United Kingdom. The program steering committee meets annually and comprises:

Rick Battarbee, Chair (UK), André Berger (BE), Keith Briffa (UK), Françoise Gasse (FR), Eystein Jansen (NO), Ingemar Renberg (SE), Matti Saarnisto (FI), Christoph Spötl (AT), Jurg Beer (CH), Bas van Geel (NL), Dirk Verschuren (BE), Bernd Zolitschka (DE), Svenje Mehlert (ESF) and Joanne Dalton Goetz (ESF).

Further information is available on the program web site at (<http://www.esf.org/holivar>) or by contacting Joanne Dalton Goetz, ESF ([jdalton@esf.org](mailto:jdalton@esf.org)); Heather Binney, ECRC-UCL, UK ([h.binney@ucl.ac.uk](mailto:h.binney@ucl.ac.uk)); or Rick Battarbee, ECRC-UCL, UK ([r.battarbee@ucl.ac.uk](mailto:r.battarbee@ucl.ac.uk)).





# Russia

A broad variety of landscapes from the Arctic in the North to the Subtropics in the South, from very continental to marine provides great opportunities for diverse paleoenvironmental studies in Russia. Traditional fields of Russian paleoenvironmental research are marine and terrestrial sediments, pollens, DIATOMS, plant macrofossils, permafrost, glacier variations and ice-cores, tree-rings and documentary records.

## National PAGES contact:

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## High Latitude Paleoenvironments, 2002

The first conference organized and supported by PAGES in Moscow «High Latitude Paleoenvironments» in May, 2002, brought together more than a hundred research scientists from Russia, Ukraine, Belorussia, Estonia, Kirgizstan, Uzbekistan, and Georgia (see map).



In addition to the 21 PAGES SSC members from 14 countries, scientists from USA, Germany, Netherlands, Finland, Sweden, Spain, Italy, and Israel attended the conference. 82 posters and 15 oral papers were presented and discussed. A special issue of Palaeo3 presenting a selection of papers from the conference is in preparation.

## Other related contacts:

IGBP: Constantine Lutaenko ([lutaenko@mail.primorye.ru](mailto:lutaenko@mail.primorye.ru))

Glaciological Society: Vladimir Mikhaleiko ([mikhaleiko@hotmail.com](mailto:mikhaleiko@hotmail.com))



## Funding Agency:

Russian Foundation for  
Basic Research ([www.rfbr.ru](http://www.rfbr.ru))

**Journals:** Papers of Academy of Sciences (Doklady Akademii Nauk); Proceedings of Russian Academy of Sciences; Geographical series (Izvestiya Akademii Nauk; Seriya geograficheskaya); Proceedings of Russian Geographical Society (Izvestiya Russkogo Geograficheskogo Obchestva); Arctic and Antarctic (Arktika i Antarktika); Ecology (Ekologiya); Bulletin of Quaternary Commission (Bulletin' Komissii po izucheniyu chetvertichnogo perioda); Volcanology and Seismology (Vulkanologiya i Seismologiya)



## upcoming conferences related to PAGES activities:

World Climate Change Conference. Moscow. September 29-October 3, 2003 ([www.wccc2003.org](http://www.wccc2003.org))

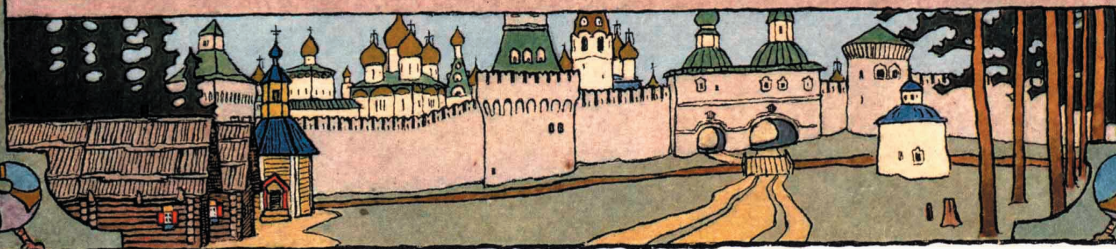
Dendrochronology: achievements and prospects. Krasnoyarsk, October 23-30, 2003 ([ovsidorova@forest.akadem.ru](mailto:ovsidorova@forest.akadem.ru))

Arctic Climate System Study Final Conference. St. Petersburg, November 11-14, 2003 (<http://acsys.npolar.no>)

Shrinkage of Cryosphere: Facts and Analyses. St. Petersburg, May 24-28. ([glazovsk@gol.ru](mailto:glazovsk@gol.ru))

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on September 4, 2003: 132

И. БИЛИБИНЪ. 1900.





## Developments in Age-Depth Modelling of Holocene Stratigraphical Sequences

H.J.B. BIRKS AND EINAR HEEGAARD

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Absolute chronology is the basis for all comparisons and correlations of Holocene stratigraphical proxy records. It is essential to develop independent absolute chronologies for such stratigraphic sequences before attempting comparisons, correlations, and syntheses, so as to avoid the well-known problems of visual "curve-matching" and associated dangers of the "reinforcement syndrome" and the "suck-in" phenomenon (Bennett, 2002a). A statistical approach for developing age-depth models is desirable so that the uncertainties in the radiometric age determinations can be taken into account and confidence intervals for the resulting models estimated and displayed.

As almost all Holocene stratigraphic sequences (e.g. peats, lake sediments) are from non-laminated sediments, an absolute chronology must be based on radiometric dating ( $^{14}\text{C}$ , also  $^{210}\text{Pb}$  for the very recent past) and, if available, volcanic tephras of known age. Radiocarbon years do not equal calendar years. It is, however, possible to calibrate radiocarbon dates (with their associated uncertainties) for the Holocene into calibrated ages, thanks to the development of the internationally adopted INTCAL98 radiocarbon calibration data-set and the availability of calibration software such as CALIB, OXCAL, and BCAL. Age-depth modelling using calibrated ages is essential if correlations and comparisons are to be made with proxy records based on an absolute chronology, such as ice-cores or tree-rings. Such modelling using calibrated ages has, however, several statistical problems.

### Developing a Chronology

The stages in developing an absolute chronology for a Holocene sequence based on a series of  $^{14}\text{C}$  dates are (1) calibration of the  $^{14}\text{C}$  dates, (2) statistical age-depth modelling using calibrated dates, and

(3) model selection and evaluation. Assuming that the  $^{14}\text{C}$  dates are reliable, are not subject to problems of hard-water effects and incorporation of "old" carbon from other sources and, in the case of marine sequences, that the marine reservoir effect is known, the first step is calibration of the radiocarbon dates. Different calibration procedures can give different calibrated ages and very different ranges and probability distributions, especially if Bayesian approaches are adopted. In the Bayesian approach, it is possible to take account of other dates from the same sequence during the calibration of individual radiocarbon dates. If it is known that one date is younger than another because of their known stratigraphical relationship, it is possible to use this information to reduce the range of uncertainties for the calibrated ages of both dates (Bennett, 2002b). The irregular probability distribution functions of calibrated dates can be summarized in many ways (e.g. intercept, mode, median, weighted average) and the resulting summaries can have important influences on the final age-depth models. An additional potentially critical question is whether the radiocarbon calibration curve should be smoothed to match the potential resolution of the stratigraphical sequence of interest. The effect of such smoothing is usually to alter the uncertainties in the resulting calibrated ages.

Given a set of calibrated ages (and associated uncertainties) for a stratigraphical sequence, the next step is to convert the sample depths into estimated calibrated ages prior to comparison with other proxy records. This can readily be done by simple linear interpolation with confidence intervals estimated for the resulting age estimates (Bennett, 1994, 2002b). However, it is often also necessary to estimate sediment deposition times, fossil accumulation rates ("influx"), or

rates of biotic change. Here one needs to develop a statistical model for estimating calibrated ages for each sample based on a geologically realistic model of sediment accumulation. Linear interpolation between dated horizons is not appropriate here. Age-depth models are required that (1) are statistically reliable and robust, (2) provide estimates of the uncertainties of the calibrated age estimates for each sample, (3) take account of the uncertainties in the datings, radiocarbon calibrations, and sampling, (4) are geologically realistic, and (5) are easy to implement. Various methods such as linear interpolation, cubic splines, and regression models (e.g. polynomial least-squares regression) in the framework of generalized linear models (GLM) have been used (see Bennett, 1994, 2002b). The approach we have adopted (Heegaard and Birks, 2003) is weighted, non-parametric regression in the framework of generalized additive models (GAM) (Yee and Mitchell, 1991). In contrast to GLM, GAM models are driven primarily by the data themselves rather than by fitting prespecified GLM regression models to the data. Smoother functions are fitted to the data with appropriate prespecified link and error functions. Weightings can be introduced for all dated samples, with weights inversely proportional to the uncertainties in the calibrated ages. Well-dated horizons (e.g. tephra layers) or the lake-sediment core-top receive high weights in the regression, whereas calibrated ages within a radiocarbon plateau, and hence with a large calibration uncertainty, receive low weights.

### Choosing the Model

After fitting a series of GAM models with different error specifications and smoothers using different degrees of freedom to the available calibrated ages and their associ-

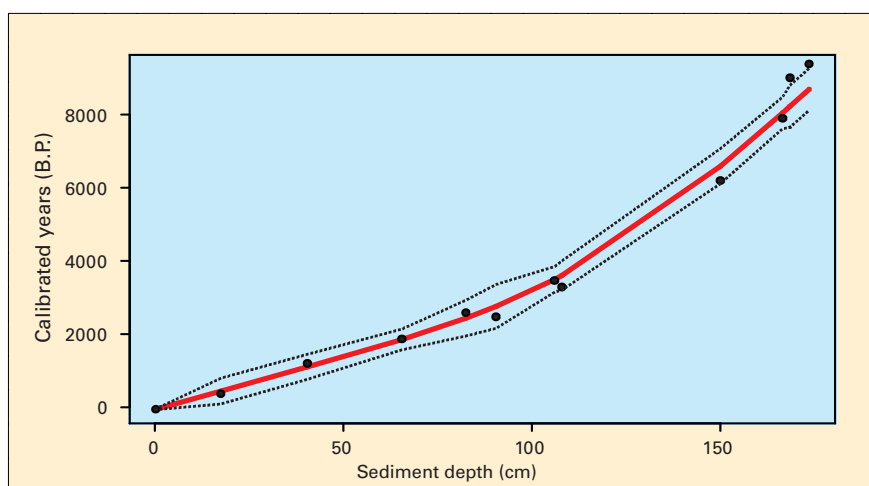


Figure 1: The relationship between sediment depth and calibrated years B.P. for Gåvåli lake, Dovre, Norway (data are kindly lent to us by Wenche Eide). The red line is the expected calibrated year for a particular sediment layer. The dotted lines represent the 95% confidence interval based on the insecurity of the observed calibrated dates and the regression line in combination. Here we used a constant variance in the regression.

ated uncertainties, the next step is to select the simplest parsimonious model (called the “minimal adequate model” in statistical model building), namely the simplest statistically significant solution that uses the fewest terms in the model and the fewest numbers of degrees of freedom in the fitted smoother. Model selection is done by examining regression diagnostic plots and PRESS statistics. The point-wise standard errors for the mean regression response are added to the standard error of the individual age estimates to calculate 95% confidence intervals for the entire age-depth model. All these analyses are implemented as a S-PLUS macro (Heegaard and Birks, 2003). The resulting age-depth model and associated age estimates and 95% confidence intervals should be critically evaluated by comparison with independently derived age estimates from the same geographic region. This GAM approach allows the use of calibrated  $^{14}\text{C}$  dates,  $^{210}\text{Pb}$  dates, tephra, and other independently dated horizons in one age-depth model and has been found to produce realistic age-depth relationships for a range of lake-sediment sequences in Norway, Sweden, Finland, Austria, Switzerland, Greenland and the UK.

An age-depth model is statistically based and as such includes various assumptions: (1) the datings used are reliable, (2) the radiocarbon calibrations are reliable and

the weighting functions used are realistic, (3) sample age is known with a larger error than sample depth, so we are justified in regressing age on depth rather than depth on age, (4) the principle of parsimony, (5) there are no sedimentary disturbances in the sequence and there are no gaps due to coring artifacts or errors, and (6) the mean radiocarbon date is independent of its variance. The final choice is the simplest adequate model possible statistically and has the largest degrees of freedom. It should therefore be relatively robust and have good predictive power. However, the model is a working hypothesis to be tested by independent criteria. Being a statistical model, it has uncertainties and all Holocene age estimates generally have associated 95% confidence intervals of between 50-200 calibrated years. Such intervals can easily encompass rapid events of short duration (Bennett, 2002a). If age-depth modelling is applied consistently to different proxy records at different sites, this should provide a robust basis for comparing and correlating many Holocene proxy records. Future developments should be directed at trying to reduce the uncertainties of the resulting age estimates. Decomposition of the total model variance suggests that to reduce the model uncertainties from 100-200 to 25-50 years, uncertainties in the radiocarbon calibration need to be reduced by 75%, assuming

that other sources of uncertainty (sampling, radiocarbon assay, etc.) remain the same.

## Conclusion and Outlook

In comparing and interpreting Holocene stratigraphical records, more attention needs to be paid to the uncertainties associated with the age-depth models. The uncertainties provide a guide for the basis of any correlation (Bennett, 2002a). In the correlation of an “event” between sequences, the 95% confidence intervals of the age estimates should consistently overlap but as Bennett (2002a) notes, the correlation may still be valid even if a 1 in 20 confidence interval fails to overlap. However, when most or all of the confidence intervals do not overlap, the proposed correlation should be rejected. Comparison and correlation of stratigraphical sequences are, in reality, hypotheses that should be tested and falsified using statistical criteria (Bennett, 2002a). Statistically based age-depth models are valuable because they force the researcher to be explicit about the assumptions of the model and the quality of the data used. How much confidence do we really have in the basic radiocarbon age determinations and in the subsequent calibrations? Age-depth modelling is perhaps one of the weakest areas in Holocene research at present and it is an area that urgently requires further attention. Such work is currently in progress at the Bjerknes Centre for Climate Research in Bergen.

## REFERENCES

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## Instrumental Climate Data

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Instrumental data form the necessary basis for climate reconstructions. The data are used for calibration in proxy reconstructions and are usually considered to be “true” climate information by proxy specialists. However, before applying instrumental data to proxy climate reconstructions, a number of questions should be addressed: To what extent do instrumental data reflect real climate? For which regions of Europe does well-tested and homogenized instrumental climate information exist? How long are the existing instrumental series and what is their spatial density? Last but not least, coverage by different climate parameters should also be taken into account. That is, “climate” reconstructions should be more than single-variable analyses. In most cases, climate is represented by temperature alone. Precipitation is sometimes also included but very rarely is the whole climate system analyzed.

Experience with instrumental climate reconstruction in Alpine areas shows that homogenization is indispensable for extracting the real climate signal from non-climatic noise. Non-climatic noise is caused by a number of factors, such as relocation, and changes in measuring technology, instrument installation and observation time, among others. The uncertainty

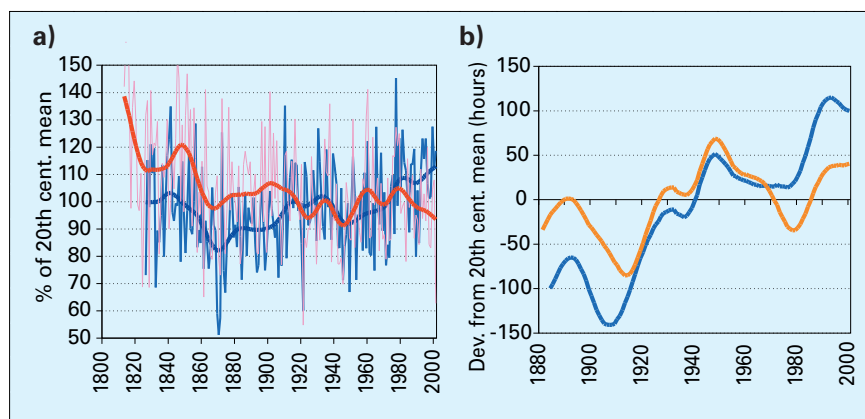


Figure 2: Two examples of the spatial variability of long-term climate trends.

(a) Long-term annual precipitation totals (single years and 30 years smoothed) for a grid point in SE-France (4E-46N, blue) and one in N-Italy (10E-46N), both relative to the 20th century mean. (b) Long-term annual sunshine duration in the Eastern Alps (30 years smoothed) for high (>2000m, blue) and low (<600m, yellow) elevation sites.

is not made random simply by combining a large number of series together, since in many cases there are systematic biases in the original series. Figure 1 shows two examples of such systematic offsets in climatic time series—one typical of recent decades, one of the 19th century. While homogenization is valuable, poor quality homogenization can erroneously import climate information from remote regions. It should therefore be undertaken with care, using mathematical tests together with information about station history (meta-data) and be carried out in smaller sub-regions with a dense network of highly correlated series. For an overview on homogenization see Peterson et al. (1998).

Two European sub-regions serve to illustrate “close to ideal” instrumental climate variability datasets. They show the number of inhomogeneities that are detectable and removable, the average length of homogeneous sub-intervals for the different climate parameters, and to what extent such high-density regional datasets differ from existing large-scale datasets. These sub-regions are the “Larger Fennoscandian Region” (NACD dataset, e.g. Moberg and Alexandersson, 1997; Hanssen-Bauer and Nordli, 1998) and the “Greater Alpine Region” (ALOCCLIM and ALPCLIM datasets, e.g. Auer et al., 2001; Böhm et al., 2001). Both are “multiple”, “long-term” and “dense”; much time has been invested in homogenization of both instrumental series, and both regions are rich in proxy data sources for paleo-climate reconstructions. Studies of these regional high-density datasets (typical mean site distances of 30 to 100 km) show that existing global-scale datasets (e.g. Jones, 1994; Vose et al., 1993) are deficient when resolving meso-scale variability patterns. Paleo-climatologists should pay attention to this fact since most of the proxy sources react to local to meso-scale climate and not to continental to global-scale changes. Two examples from the European Alps illustrate that there is not only variability in time

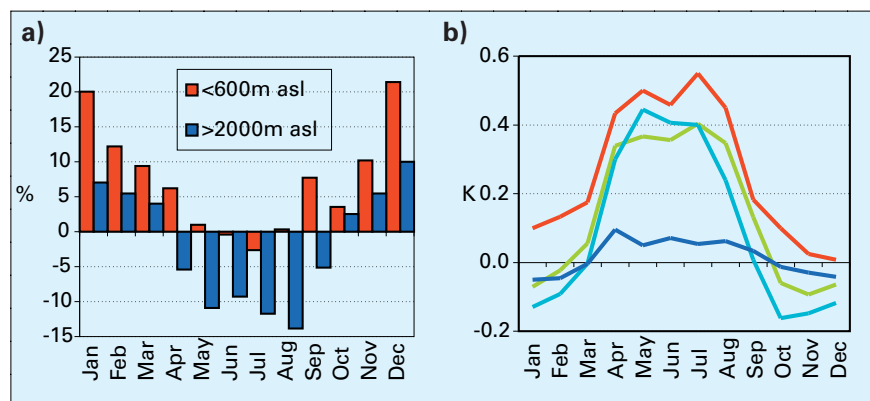


Figure 1: Two examples of systematic offsets in instrumental climatic time series in Central Europe. (a) Sunshine duration offset (new minus old in percent of monthly totals) in the 1980s due to automation in the Austrian network (red: low elevation sites, blue: high elevation sites). (b) Temperature offset (new minus old in °C) in the late 19th century for four typical surroundings due to changes in observation time (red: urban, green: extra-alpine rural, light blue: inner-alpine <1000m asl., dark blue: inner-alpine >2000m asl.).



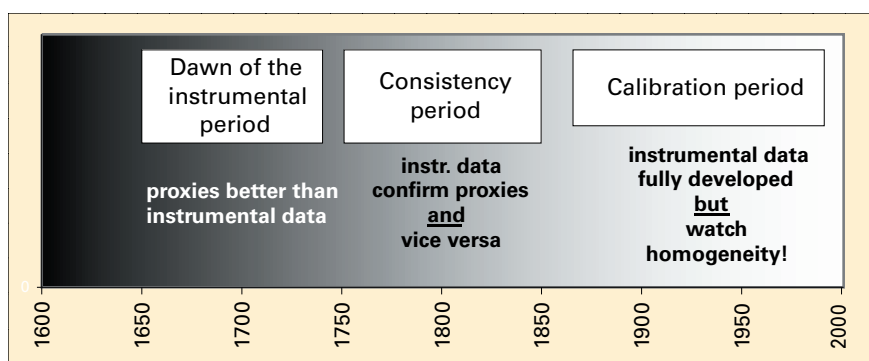


Figure 3: Development of the potential of instrumental climate data for paleo-climate reconstructions.

but also considerable variability in space—horizontally (Fig. 2 left) and vertically (Fig. 2 right).

Figure 3 presents a timeline that summarizes our conclusions on the quality, availability and potential of instrumental data for the reconstruction of climate. There is no question that before the mid-18<sup>th</sup> century the very rare instrumental information that existed is inferior to high-quality reconstructions based on proxies. The real calibration period started as late as

the second half of the 19<sup>th</sup> century. Since then, well-homogenized and spatially dense instrumental information has been available to calibrate proxy data. For the one hundred years in between, both sources (instrumental and proxy) are reliant on each other, with only a combination of different sources providing reasonable information about past climate variability. That period may therefore best be called the “consistency period”

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## Climate and Environmental Reconstructions from Scandinavian Varved Lake Sediments

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### Introduction

Annually resolved proxy records, such as varved lake sediments, are important archives of past climate variability and environmental change. The primary strength of any varved archive is that it contains a continuous and inherent calendar year timescale that forms a temporal framework for paleoenvironmental reconstruction. In addition, many physical, chemical and biological parameters can be used to accurately infer fluxes. The structure and composition of varves are governed by a multitude of interacting factors in different sedimentary environments that, in the best cases, can be related to external forcing factors and subsequently interpreted as records of regional climate change (e.g. Hughen et al., 2000).

The contemporary annual climate in Fennoscandia has strong

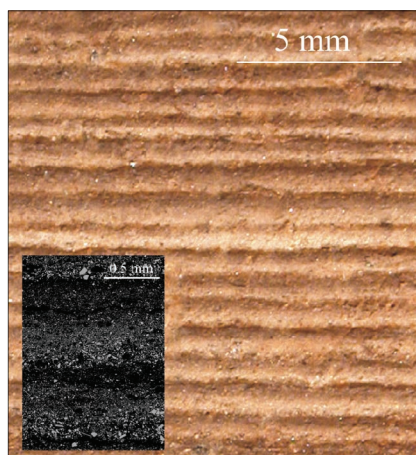


Figure 1: Images of Lake Nautajärvi (central Finland) clastic-organic nonglacial varves at AD 200 taken from the fresh sediment surface (left) and thin-section, using a back-scattered mode of surface scanning electron microscope (right).

seasonality, which causes several months of ice cover on lakes, peak floods during the spring snowmelt, summer (and winter) stratification of the water column, algal blooms and occasional autumn storms.

This myriad of factors is the principal cause of distinct rhythmic sedimentation and of the formation and preservation of varves in lakes (Renberg, 1982; Ojala et al., 2000, Zillén et al., in press). Varves in small to mid-sized lakes in Finland and Sweden typically appear as clastic-biogenic couplets (Fig. 1) (Pettersson, 1996; Ojala et al., 2000), which sometimes cover the entire past glacial history of the basin, up to 10,000 years or more. A typical Fennoscandian lake varve is composed of an allochthonous fine-grained minerogenic layer deposited as a result of the spring snowmelt, grading into an organic summer layer formed by primary productivity and a thin dark-colored layer composed of fine-grained organic matter that settles during the winter when the lake is ice-covered (Renberg, 1982). In many cases, the varves are best seen after oxidation

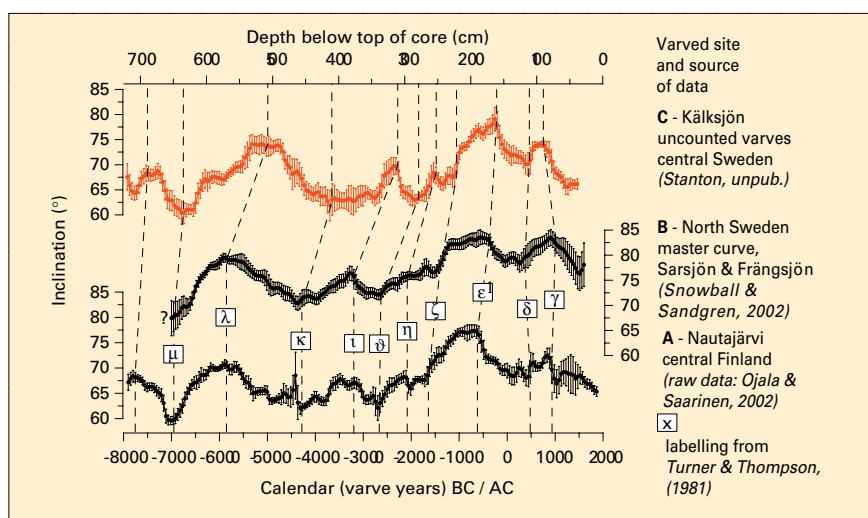


Figure 2: Precisely dated high-resolution reconstructions of geomagnetic field secular variations for the last 10,000 years, based on a network of varved lake sediments in Finland and Sweden, has resulted from cooperation between the Geological Survey of Finland and the Geological Institute at the University of Lund in Sweden. The example shows a varve dated inclination master curve for Nautajärvi in central Finland (a) and a stacked inclination master curve from Sarsjön and Frängsjön in northern Sweden (b). Both curves are based on the spherical smoothing of data with a moving time-window of 150 years (Snowball and Sandgren, 2002). The potential to correlate paleomagnetic features and transfer ages with an approximate error of less than 200 years is demonstrated by the comparison with paleomagnetic data obtained from the site of Kälksjön (c), which is located in central Sweden and contains uncounted varves. An amalgamated reconstruction of the total field vector (direction and intensity) is the aim of ongoing collaboration. This reconstruction will refine the ages of the regional features and provide a data set that can be used to distinguish solar and geomagnetic influences on rates of atmospheric cosmogenic nuclide production.

of the sediment, when the annual iron cycle is highlighted.

Recent publications report long clastic-biogenic varved sequences in the lakes of Nautajärvi, Alimmainen Savijärvi, Korttajärvi (Ojala & Saarinen, 2002; Ojala et al., in press; Ojala & Tiljander, in press), Kassjön (Pettersson et al., 1999), Sarsjön, Frängsjön (Snowball et al., 2002; Snowball & Sandgren, 2002), Furskogstjärnet, Mötterudstjärnet (Zillén et al., 2002) and Kälksjön (Zillén et al., in press). Counting of the annual laminations indicates that the error estimate of these varve chronologies can be pushed down to  $\pm 1\%$ . Such accurate and precise multiple chronologies form an excellent basis for between-lake comparisons of paleodata and provide a template for assessing the accuracy of correlations made using other techniques, such as paleomagnetic dating and tephrochronology (Ojala and Saarinen 2002, Pilcher et al., this issue, Snowball and Sandgren, 2002, Zillén et al., 2002) (Fig. 2).

**Basis of Climate Reconstruction**  
High- and low-frequency variability of the physical properties of

clastic-biogenic varves (thickness, density, composition and texture) is mainly indicative of the annual influx of mineral matter into the basins, which depends principally on the rate of catchment erosion and the transportation of detritus during the intense spring snowmelt flood. In the boreal vegetation zone,

the intensity of spring discharge is predominately determined by snow storage and the water equivalent of snow in spring (Kuusisto, 1984). Of course, the rate of catchment erosion also depends on the supply of material in the catchment and timing of the most intensive runoff in relation to soil thawing. In contrast to many biological proxies that reflect summer conditions, the physical properties of clastic-organic varves are related to climatic conditions that prevail over the winter months, primarily temperature and the amount of snow that accumulates in the catchments of the individual lakes.

Many of the varved lake sediment sequences under investigation in Finland and Sweden are located in areas that exhibit considerable year-to-year variability of winter temperature and precipitation. One of the phenomena known to regulate winter climate in the North Atlantic-European region is the atmospheric circulation pattern called North Atlantic Oscillation (NAO) (e.g. Hurrell, 1995; Luterbacher et al., 2002). During years of positive NAO, cyclones originating in the Atlantic sweep westwards across Fennoscandia and the Baltic Sea region, causing relatively mild and wet winters. On

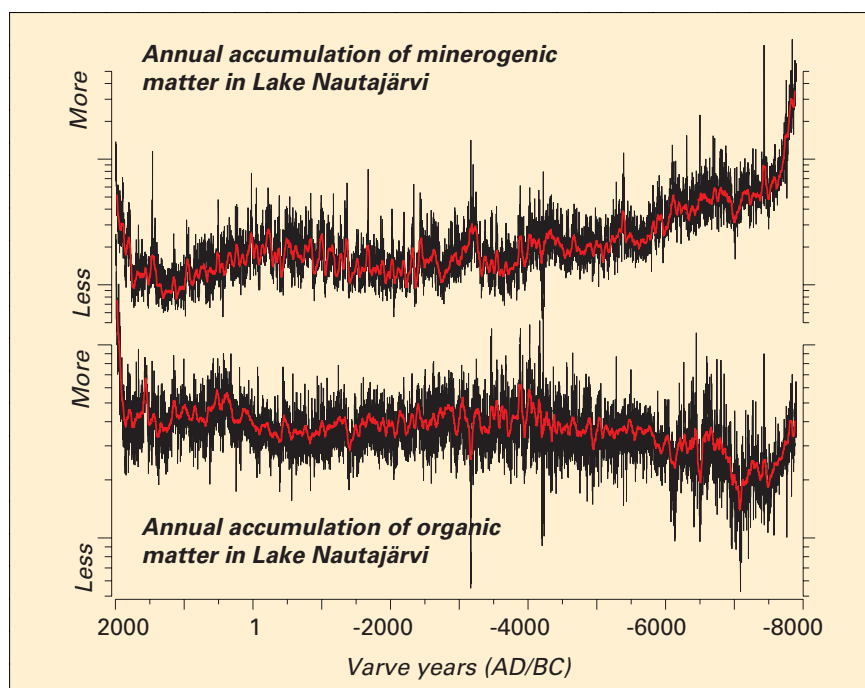


Figure 3: Annual mineral and organic matter accumulation in Lake Nautajärvi central southern Finland since 7902 BC based on studies of relative X-ray density.

the other hand, years of negative NAO are characterized by colder and drier winters. It appears that these lakes are located at a sensitive climatic boundary, where just a few degrees warming during the winter (+NAO) results in a considerably shortened period of snow cover, even to the point where no persistent snow cover forms (Vehviläinen & Lohvansuu, 1991; Vehviläinen & Huttunen, 1997). As a consequence, the peak discharge in spring is severely reduced, catchment erosion is significantly lower and less allochthonous mineral matter is transported and deposited on the lake bottom. One period of weakened spring discharge and erosion has been identified from Finnish varved sediments to have occurred between AD 980-1250 (Saarinen et al., 2001, Tiljander et al., in press). This period coincides with the Medieval Climate Anomaly. Its climate implications are under intensive investigation.

However, due to local system dynamics, it is evident that the relationships between external forcing factors and the annual accumulation of mineral/organic matter are neither linear nor stable over time. Post-isolation catchment stabilization, vegetation succession, human disturbance and extreme events like forest fires exert a considerable influence on catchment erosion and the nature of the varved records. At the end of the day, the properties of clastic-organic varves in Fennoscandia reflect the annual flux of mineral matter to the sedimentary basins via a multitude of interacting factors. The main aim of future work is to use a variety of analytical methods, such as high-resolution digital image analysis (e.g. Tiljander et al., 2002, Ojala & Francus, 2002, Saarinen & Pettersson, 2002), mineral magnetism (Snowball et al., 1999), pollen, and charcoal analysis to discriminate

between the major factors that drive the sedimentation.

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## <sup>14</sup>C as an Indicator of Solar Variability

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### Introduction

The quasi-constant concentration of <sup>14</sup>C on the Earth is maintained by a balance between its radioactive decay and its production from atmospheric nitrogen. This production is possible due to the high-energy protons from cosmic radiation. Atoms of <sup>14</sup>C enter the biogeochemical cycle, where carbon circulates between the atmosphere, terrestrial biosphere and the oceans. Since the characteristic exchange rates between reservoirs and times of circulation within individual reservoirs are significant with respect to the half-life of <sup>14</sup>C, radiocarbon concentration on the Earth is not uniform, being the highest in the atmosphere and distinctly lower in the deep oceans.

Charged particles emitted from the Sun produce a magnetic field in interplanetary space. This field inhibits penetration of low-energy cosmic-ray protons into the center of the solar system. As a rule, an increase in solar activity corre-

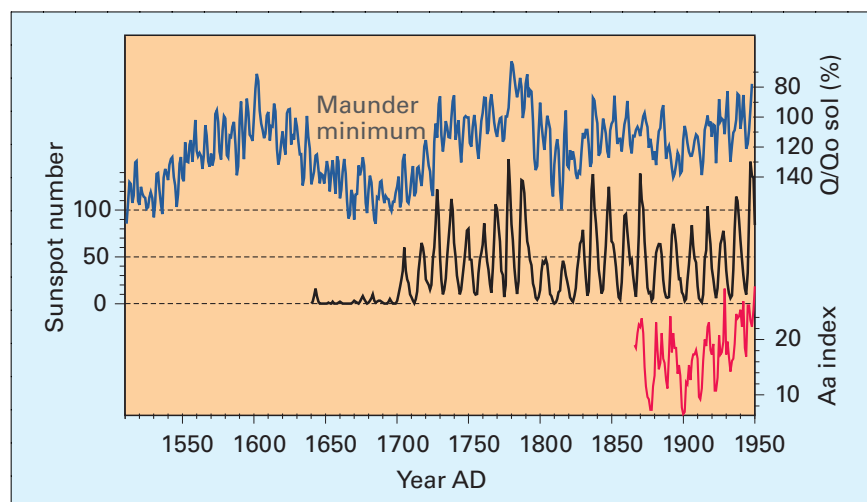


Figure 1: Comparison of radiocarbon production rate ( $Q/Q_0$ ) and records of solar activity in recent centuries.

sponds to a decrease in the flux of galactic cosmic rays impinging on the Earth. The intensity of cosmic radiation in the atmosphere is also modulated by the Earth's magnetic field. To first-order approximation, the globally averaged <sup>14</sup>C production rate is inversely proportional to the square root of the geomagnetic dipole moment (Lal, 1988).

### Reconstruction of Atmospheric <sup>14</sup>C Levels in the Past

Past variations in atmospheric <sup>14</sup>C concentration have been reconstructed as a "by-product" of radiocarbon calibration. During the Holocene period, this calibration is based on <sup>14</sup>C ages of bi-decadal or decadal tree-ring samples, dated absolutely by means of dendro-



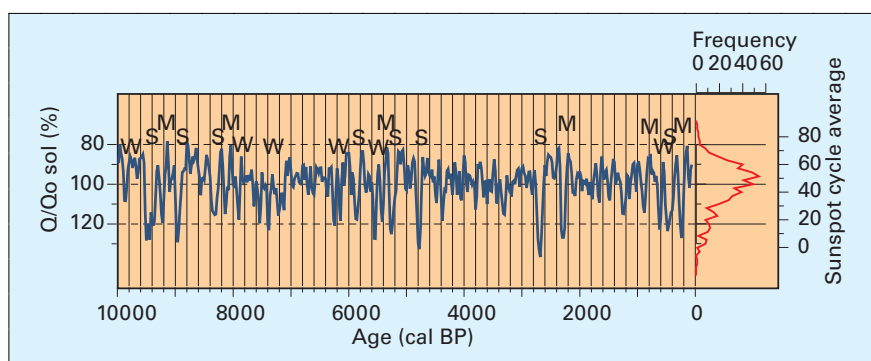


Figure 2: Estimate of Sun-induced fluctuations in  $^{14}\text{C}$  production rate over the last 10,000 years. Right-hand side: Frequency distribution of bidecadal production rate averages. The sunspot number scale is based on the correlation in recent centuries.

chronology (Stuiver et al., 1998). These data document  $\pm 20\%$  fluctuations in atmospheric  $\Delta^{14}\text{C}$ , usually 100-300 years long, superimposed on an almost monotonic downward trend from ca. 120‰ at the beginning of the Holocene to ca. 0‰ at the end of the 19th century.

Over the last few centuries,  $^{14}\text{C}$  concentration has also been measured in single-year tree-ring samples (e.g. Stuiver and Braziunas, 1993). These data reveal quasi-periodic  $\Delta^{14}\text{C}$  fluctuations with an amplitude as low as 2.5‰.

### The Relationship Between $^{14}\text{C}$ Production and Solar Activity in Recent Centuries

As noted above, there is a more direct relationship between solar activity and the rate of  $^{14}\text{C}$  production than  $^{14}\text{C}$  concentration. Fluctuations in  $^{14}\text{C}$  concentration can be caused by changes in  $^{14}\text{C}$  production; this may also reflect solar and/or geomagnetic variability, as well as changes in the global carbon cycle. In general, no single one of these causes can be isolated from the others unless additional information is available. Such information is provided by records of  $^{10}\text{Be}$  in the ice caps of Greenland and Antarctica. Like radiocarbon,  $^{10}\text{Be}$  is produced in the atmosphere by cosmic rays, however it falls out almost immediately, hence its concentration in sediments reflects mostly local cosmogenic production rates. Fine correlation between 100- to 300-year-long features of the  $^{14}\text{C}$  and  $^{10}\text{Be}$  records of the last and earlier millennia indicate that these features are related to Sun-induced changes in production rate

(e.g. Bard et al., 1997). On the other hand, model considerations using archeomagnetic data lead to the conclusion that the long-term decrease in  $\Delta^{14}\text{C}$  results from secular changes in the geomagnetic field (Stuiver et al., 1991).

In historical records, solar activity is quantitatively represented by the number of sunspots (Wolf number). Although correlation between sunspot number and past  $^{14}\text{C}$  changes has been discussed in numerous papers, only a few have directly compared sunspot number with  $^{14}\text{C}$  production rate (e.g. Stuiver and Quay, 1980). This correlation is presented here (Fig. 1).  $^{14}\text{C}$  production rates are calculated from annual values of  $^{14}\text{C}$  concentrations (Stuiver and Braziunas, 1993) with the PANDORA model of the global carbon cycle (used, for example, by Goslar et al., 2001).

The maximum  $^{14}\text{C}$  production rate in the last millennium occurred between AD 1645 and 1715, during the period when sunspots were almost lacking (Maunder Minimum).

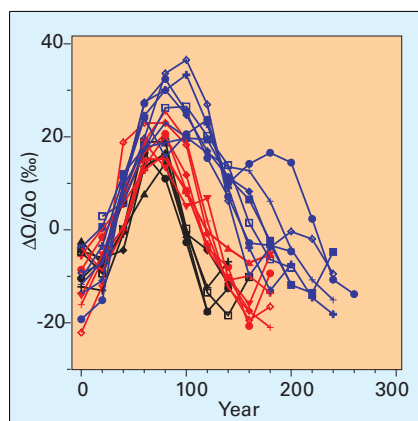


Figure 3: Shapes of Maunder-type (red), Spörer-type (blue) and Wolf-type (black) maxima in  $^{14}\text{C}$  production rate during the Holocene.

Similar maxima, between AD 1290-1390, 1400-1600, and 1800-1860 are known as Wolf, Spörer and Dalton, respectively. Since the nineteenth century, atmospheric radiocarbon concentration has been seriously affected by fossil fuel combustion and nuclear tests. The first effect can be taken into account in the calculations, based on the known history of fossil fuel consumption. The second effect precludes model calculations of  $^{14}\text{C}$  production after 1950.

Production of cosmogenic isotopes depends on both the Earth's and the Sun's magnetic field. It can be expressed as:

$$Q = C * A_{\text{geo}} * A_{\text{sol}}$$

where C denotes the production rate by cosmic rays not attenuated by solar and geomagnetic fields, and  $A_{\text{geo}}$  and  $A_{\text{sol}}$  are the respective attenuation factors. The latter geomagnetic factor has been modeled using a reconstruction of the Earth's magnetic field, as in previous studies (e.g. Goslar, 2001).

There is a striking correlation between mean sunspot number in consecutive sunspot cycles (S) and average values of  $^{14}\text{C}$  production (Q). Although annual values of  $^{14}\text{C}$  production also correlate significantly with annual sunspot number, the single-year Q-S regression coefficient is distinctly lower than that for cycle averages. One reason for this is that annual values of Q are different in different minima of solar activity, despite very similar minimum sunspot numbers (i.e. close to 0). This means that solar activity expressed by the sunspot number is not unequivocally related to  $^{14}\text{C}$  production. Indeed, it has been known for some time that sunspots are not directly tied to the magnetic properties of the solar wind. A more direct measure of solar magnetic field properties is provided by Aa indices, which reflect the magnitude of short-term magnetic activity measured in two antipodal laboratories. Both sunspot number and Aa index reveal an 11-year cycle but, unlike sunspots, the minimum Aa differs for

different cycles and the minimum values appear correlative to the cycle-averages of sunspot numbers (Fig. 1). Nevertheless, since reconstruction of  $\Delta^{14}\text{C}$  in the Holocene relies on bidecadal data, in using it as a proxy of solar activity, the relationship between Q and S cycle-averages still seems applicable.

### Characteristic Features of $^{14}\text{C}$ Production in the Holocene

The  $\Delta^{14}\text{C}$  record in the Holocene allows the  $^{14}\text{C}$  production rate to be calculated provided the parameters of the global carbon cycle are known. In previous studies (e.g. Stuiver and Braziunas, 1988), it has usually been assumed that those parameters were constant and the same as today. The record of past  $^{14}\text{C}$  production rates calculated according to this assumption shows 100- to 300-year-long fluctuations superimposed on a long-term trend. Assuming that this trend re-

flects the changes in geomagnetic field, Sun-induced changes of the  $^{14}\text{C}$  production were calculated (Fig. 2).

The distribution of Q/Q<sub>0</sub> values has no right-hand tail (i.e. almost no value exceeds 130%). This is consistent with equation 1, which requires that the attenuation not be larger than 1 (as it was, for example, during the Maunder Minimum). This consistency provides additional support for the interpretation of the obtained record in terms of past solar activity.

Stuiver and Braziunas (1988) noted distinct similarities between fluctuations in  $^{14}\text{C}$  production, and distinguished nine Maunder-type and eight Spörer-type maxima. Calculations using up-to-date  $^{14}\text{C}$  calibration data (Stuiver et al., 1998) suggest that some maxima, previously qualified as Maunder, are distinctly shorter (Fig. 3). Since this group includes the Wolf maxi-

mum (AD 1290-1390), we propose referring to these shorter events as Wolf-type.

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## Reconstruction of Low- and High-Frequency Summer Temperature Changes From a Tree-Ring Archive of Fennoscandian Forest-Limit Scots Pine

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### Material and its Ecogeographical Setting

Tree-ring samples of Scots pine (*Pinus sylvestris* L.) were collected from living trees, dead standing logs, old buildings, and subfossil wood from peat-bogs and small lakes (Eronen et al., 2002).

The selected dataset containing 1081 tree-ring series. The latter archive is the major source of samples.

The area is situated between 68° and 70° N, 20° and 30° E, in the northern Fennoscandia (Fig. 1). Homogeneity of tree-ring data over the geographical distribution was demonstrated (Lindholm, 1996). Highly consistent tree-ring chronologies may be built from diverse sites as well as from various age-classes of pine trees (Lindholm et al., 2000; Lindholm et al., submitted).



Figure 1: Sampling sites in northernmost Fennoscandia, with national coordinates. Present pine-limit is marked with a broken line.

### Chronology Temporal Ranges

At present, the northern Finnish supra-long pine chronology spans from 5520 BC to AD 2001 (Eronen et al., 2002). As dendrochronological cross-dating yields annual

resolution to tree-ring data, inter-annual-to-decadal scale variability is resolved by most methods of building chronologies. Variation at the multi-centennial time-scale has recently been successfully extracted from the northern data using specified techniques in signal extraction (Helama et al., 2002). Annual accuracy of dendrochronological dating is a prerequisite for several paleoclimate examinations, including quantitative multi-disciplinary comparisons, multi-proxy reconstructions and climate forcing studies (e.g. Ogurtsov et al., 2002). The further extension of this chronology may become possible given that there is a gap between the time of arrival of pine, as indicated by pollen analysis, and the beginning of the earliest tree ring series (Eronen et al., 2002). On the other hand, possibly conditions for

subfossil preservation were not favorable in the early Holocene.

### Reconstruction of Climate Variables

Radial growth (tree-ring width) of northern forest-limit pines is limited by concurrent mean July temperatures over the region under study. This particular relationship becomes weaker with increasing distance from the forest limit (Lindholm et al., 2000). In previous studies, approximately 40 to 50% of independent mid-summer temperature variations were captured by transfer models using a single (ultra-long) tree-ring width chronology. Reconstruction of mid-summer temperatures is elongated over the last 7.5 millennia (Fig. 2). Among climate-related variables, North Atlantic Oscillation (NAO) was reconstructed by Lindholm et al. (2001) using a network of pines mainly from Finland and Northwest Russia.

### Chronology Signal Strength

The confidence of a climate signal is measured as a function of sample replication and inter-correlation. Extraction of signals of low frequency climate variation from a given long chronological sequence requires a greater number of samples than would be needed to obtain the same level of reliability in signals of high frequency variability. The annual sample replication exceeds thirty trees over 36% of the total chronology length. Approximately

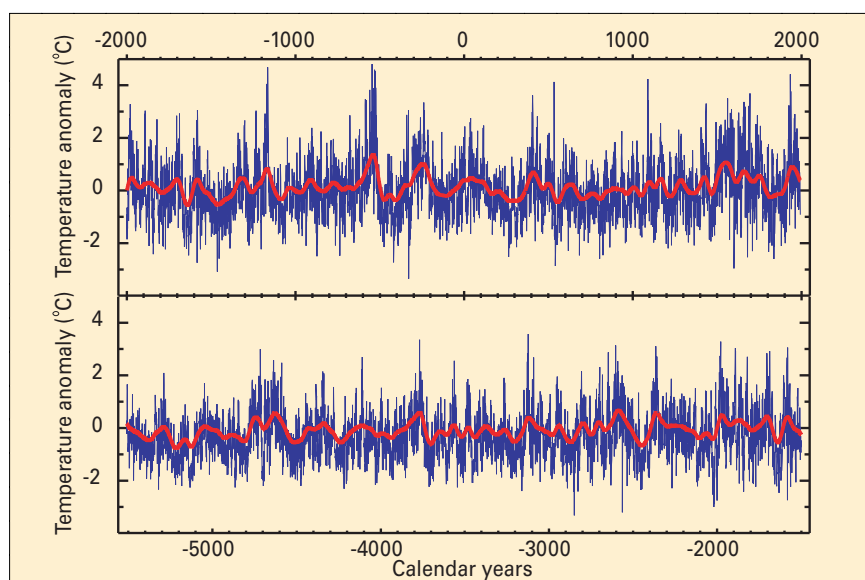


Figure 2: Finnish Lapland pine tree-ring-based mid-summer reconstruction extending back to 5520 BC (data from Eronen et al. 2002; Helama et al. 2002) shown as annual (blue) and centennial (red) anomalies from long-term mean.

13% of the total chronology length is covered by ten or less samples.

### Future Prospects

In addition to increasing sample replication, the intra-annual ring-density record can strengthen the desired temperature signal. The maximum latewood density variable could be used along with ring-width variables in transfer functions. Interestingly, chronology could certainly span over the debated 8.2 k event after an elongation of one millennium.

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## Climate Reconstruction From Peatlands

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Peatlands occur throughout the mid to high latitudes of the northern hemisphere, with huge expanses in low-relief areas of the oceanic and boreal zones. Smaller areas occur in mountainous regions throughout the world, in oceanic temperate zones in the southern hemisphere, and in the tropics. The vast majority of the peat is Holocene in age, often forming

long, continuous sequences from the early to mid Holocene up to the present day. Accumulation rates are highly variable, but 0.5-1 cm per decade is typical for raised bogs in Europe. For example, the long-term average peat accumulation rate for 210 raised bog profiles in Finland is 0.6 cm per decade. The deposits are mainly autochthonous and relatively straightforward to date

with radiocarbon, especially where mosses dominate the peat. Therefore, peatlands potentially provide a widespread source of well-dated paleoenvironmental data, covering most of the Holocene at decadal resolution. Despite this, their use for paleoclimatic reconstructions has still been limited to a relatively small number of studies in a few main locations. Recent innovations





Figure 1: Vegetation and surface patterns (hummocks and hollows) of a raised bog (Kilpisuo) in southern Finland, one of the sites used in studies of carbon accumulation and climate change (Mäkilä, 2001; Mäkilä, et al., 2001).

in techniques applicable to peatlands, better chronological precision of the record, and improvements in our understanding of how peatlands record climate history, mean that the time is now ripe to begin to exploit these deposits more fully. Here, we outline some of the main approaches, current research and ways in which peat records may be developed in the future to meet the needs of Holocene paleoclimate research.

### Approaches to Reconstruct Past Climates Using Peat Deposits:

• *Records of changing surface wetness.* Most techniques aim to reconstruct past surface wetness as a proxy for precipitation-evaporation (PE) balance. These include plant macrofossil analysis, peat humification and testate amoebae analysis. The surface wetness of all peatlands is dependent to some extent on PE but in fact ombrotrophic peatlands (raised bogs or watershed blanket mires) are the only sites where there is no influence of surface runoff or groundwater whatsoever, and precipitation and evapotranspiration are the only components of water balance.

• *Records of temperature change.* Recent work has shown the considerable potential of proxies that record temperature directly. Principal amongst these are species-specific and compound-specific isotopic analysis (e.g. Pendall et al., 2001; Xie

et al., 2000), and mercury analysis (Martinez-Cortizas et al. 1999).

• *Records of changing mass and carbon accumulation rates.* Increased accumulation rates may reflect periods of more positive PE balance (Mäkilä et al., 2001; Mäkilä, 2001) (Fig. 1).

• *The timing and rate of spread of peat initiation.* The most successful of these studies have been in western Canada using large data sets from very wide geographic areas, where peat initiation data have been integrated with other paleoclimatic indices and climate models (Gajewski et al., 2000), and cyclicities similar to those found in ocean and ice core records have been shown (Campbell et al., 2000).

Reconstruction of past surface wetness changes is the basis of many existing records, including some

that use multiple records from several sites in the same climate area to provide composite records (Fig. 2). Many of the records from north-west Europe display cyclicities with periodicities of varying lengths including possible solar-related cycles (Chambers and Blackford, 2001) and links to ocean variability on longer time-scales (Hughes et al. 2000).

One key issue in current research is to resolve how long-term changes in surface wetness relate to seasonal and annual climate variability. Conceptual process models suggest that surface wetness changes reflect some combination of temperature, precipitation, humidity and wind speed. The precise nature of this relationship is unknown and is likely to be different in different climate zones. Variability in surface wetness is probably primarily related to summer climate because peatlands are either saturated or frozen in the winter months. Comparisons with documentary data suggest that both precipitation and temperature may have determined surface wetness in northern England over the past 900 years (Barber et al., 1994) (Fig. 2). Comparisons of high-resolution records with instrumental climate data confirm that summer climate is the main driver of wetness changes but that the relationship with temperature and precipitation probably varies in different locations across Europe (Table 1). Under a prevailing oceanic climate such as that in northern England, summer precipitation may be the main factor reflected in reconstructed water table variability. Under a more continen-

Table 1: Linear correlation coefficients between reconstructed water table records from two European raised bogs (based on testate amoebae analysis) and instrumental climate data. The Butterburn Flow record covers AD 1800-1990 and is based on decadal averages ( $n=20$  for temperature,  $n=17$  for precipitation). The Männikjärve record covers AD 1951-1995 and is based on 5-year averages ( $n=9$ ). \* $p<0.05$ . From Charman et al. (submitted).

Climate variable	Butterburn Flow England	Männikjärve bog Estonia
<b>Temperature</b>		
Summer	-0.046	*-0.698
Growing season	-0.127	-0.176
Mean annual	0.026	-0.060
<b>Precipitation</b>		
Summer	*0.458	0.437
Growing season	0.106	0.377
Mean annual	0.188	*0.585

tal regime such as that in northern Europe, winter precipitation stored as snow can also have an effect on reconstructed water tables. Snow melts rapidly in springtime filling hollows and causing heavy floods. Summer temperature also exerts a much stronger desiccating effect in more continental sites, affecting the moisture balance in surface peats directly. New and improved analytical approaches and better understanding of the peat-climate system now suggest a number of ways forward for maximizing the use of the peat record.

### Key Areas for the Improvement of Climate Reconstructions:

- *Understanding the peatland-climate relationship.* Calibration of records with instrumental data is critical in deriving empirical relationships between changes in proxy data and climate parameters (see above). Development of physical process models from hydrological, biological and meteorological data would lead to greater confidence in empirical relationships and extrapolating calibrated records over pre-instrumental time periods. Comparisons with other independent climate proxies will also help test hypothesized surface wetness-climate links.

- *Further development of new proxy climate techniques.* Isotopic, compound-specific and mercury analyses are now producing exciting results. These approaches need to be explored more extensively.

- *Establishment of additional records from different climatic regimes.* Much existing work has been based in oceanic temperate regions. Additional work on continental, alpine and higher latitude areas is needed to fully exploit the potential peatland archive. Much of this work is already underway, as is reflected in recent results from central Europe (Mitchell et al., 2001), continental North America (Booth, 2002), South America (Pendall, 2001) and New Zealand (e.g. McGlone and Wilmshurst, 1999; Wilmshurst et al., 2002).

- *Improving chronological control.* Existing comparisons between

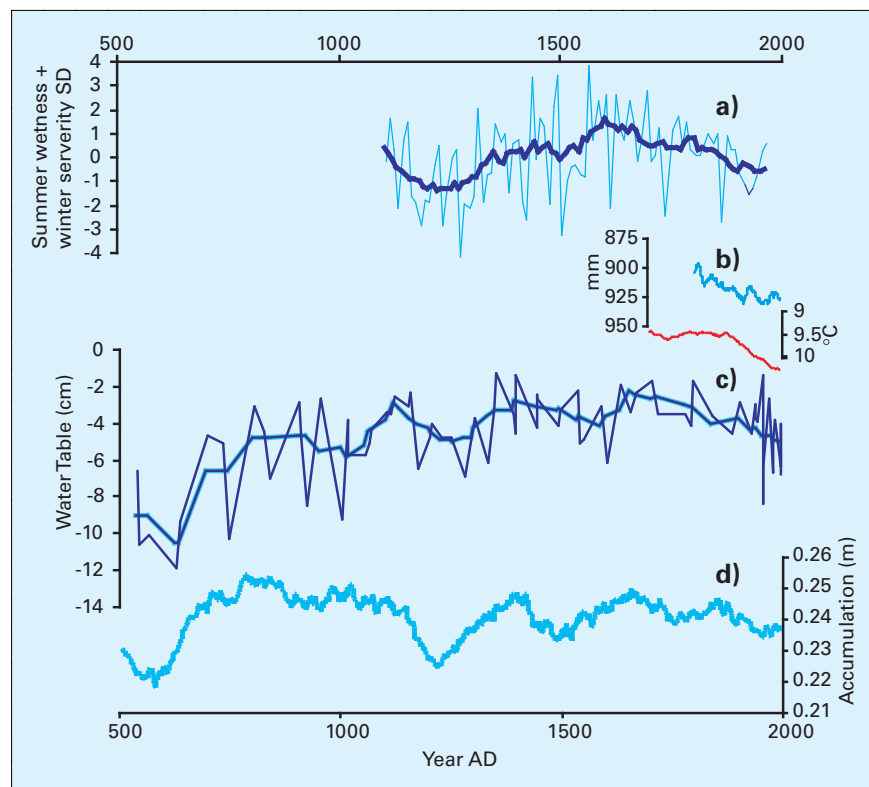


Figure 2: Mean annual water table changes for the last 1500 years, reconstructed from *testate amoebae* analysis of three peat profiles in northern England (c), compared with documentary index of summer wetness and winter severity (a) and ice accumulation record from GISP2 (d). Instrumental records of mean annual temperature and precipitation are also shown (b). All data are 100-year running averages. Raw documentary and water table data are also shown. Fluctuations in the reconstructed water tables, documentary indices and ice accumulation show similar trends over this time period. See Charman and Hendon (2000).

peatland records and other proxies such as speleothem, ice core and ocean records (e.g. Charman and Hendon, 2000; Charman et al., 2001; Pendall et al., 2001) are limited by chronological uncertainty. Calibrated radiocarbon ages still often mean possible  $2\sigma$  errors of  $\pm 200$  years—critical in trying to establish whether climate variability on centennial scales is in or out of phase. Wiggle-matched radiocarbon ages (Mauquoy et al., 2002) and tephrochronology (e.g. Van Den Bogaard and Schmincke, 2002) both have the potential to significantly improve chronologies and the precision of correlations with other records.

### Conclusions:

One of the main HOLIVAR themes is the comparison of different proxy climate records—with all the attendant problems of different chronologies, climate parameters recorded and geographical coverage. With the development of a wider range of techniques and a better understanding of the proxy-climate relationship linked to improved chronologies,

peatland paleoclimate records can now be fully integrated with other Holocene paleoclimate reconstructions.

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## Climate Forcing During the Holocene

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What caused Holocene climate variations? On the very longest, multi-millennial timescales, the main factors affecting Holocene climate change are related to orbital forcing (changes in obliquity, precession and eccentricity). Decadal to century-scale changes may be related to solar forcing (changes in total solar irradiance) and changes on shorter timescales (decadal to inter-annual) are most likely related to volcanic forcing (Bradley, 2003). Not all climatic variability seen in the Holocene can be ascribed to specific external forcings. For example, the ~8200 calendar year BP "event," seen in many paleoclimatic archives, resulted from catastrophic pro-glacial lake drainage at the margins of the Laurentide Ice Sheet (Alley et al., 1997; Barber et al., 1999). This rapid flooding of the North Atlantic with freshwater had a significant regional climate impact, unrelated to any external forcing. Internal modes of climate system variability (e.g. El Niño-Southern Oscillation, North Atlantic Oscillation, Pacific Decadal Oscillation) that probably vary on both long and short timescales—though we know relatively little about their long-term behavior—may also produce significant changes in regional climate. And stochastic resonance in the climate system—by which a weak quasi-periodic forcing signal may be amplified into a non-linear, bi-stable climate signal—may have brought about relatively abrupt changes in the past by pushing the system across critical thresholds (Ruzmaikin, 1999). Thus, the spectrum of Holocene climate variability reflects the combined effects of all of these forcings and feedbacks within the climate system.

Orbital forcing involves a significant redistribution of energy, both seasonally and latitudinally (Fig. 1). In the early Holocene, precessional changes led to perihelion at the time of the northern hemisphere summer solstice (whereas today, it is closer to the winter solstice).

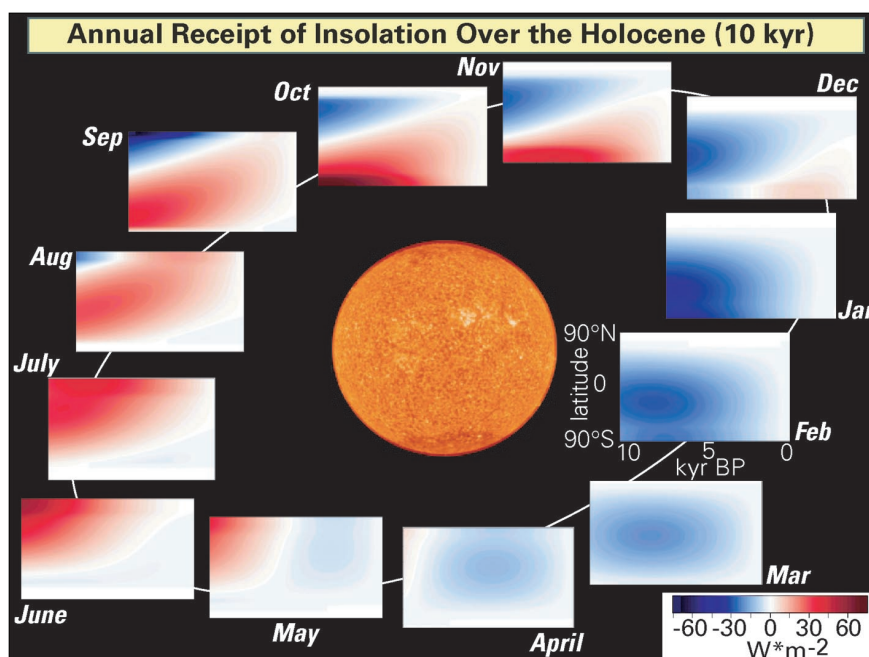


Figure 1: Schematic representation of insolation anomalies at the top of the atmosphere relative to 1950 levels. Anomalies are color-coded in  $\text{W m}^{-2}$ . The x-axis of each monthly panel shows changes from 10,000 calendar years BP (left) to today (right). The y-axis shows latitude from 90°N (top) to 90°S (bottom) (figure prepared by Anne Waple).

This resulted in higher summer insolation in the early Holocene at all latitudes of the northern hemisphere (ranging from ~40  $\text{W m}^{-2}$  higher than today at 60°N to 25  $\text{W m}^{-2}$  higher at the Equator). Thus, July insolation (radiation at the top of, or outside, the atmosphere) has slowly decreased over the last 12,000 years (Fig. 1). Anomalies during southern hemisphere summers were smaller, centered at lower latitudes, and were opposite in sign (that is, insolation increased over the course of the Holocene). For example, January insolation anomalies at 20°S were ~30  $\text{W m}^{-2}$  below current values in the early Holocene.

Changes in solar irradiance (energy emitted by the Sun) might be expected to affect all parts of the Earth equally. However, this is not so because the response to solar irradiance forcing is amplified regionally, as a result of feedbacks and interactions within the atmosphere (Rind, 2002). The record of solar variability in the Holocene is discussed further in the accompanying article by Goslar. Here, I would only note that there are many

Holocene paleoclimatic studies that claim solar forcing has driven observed changes, based largely on comparisons of proxy records with the  $^{14}\text{C}$  anomaly series. It remains to be seen how robust these relationships are, and what plausible mechanism might link solar activity/irradiance variations with climate in widely separated parts of the globe, from the Arabian Sea and Africa, to the North Atlantic and Greenland. One possibility (seen in some model simulations) involves solar variations influencing the Hadley circulation (intensity and/or extent), which then leads to tropical and sub-tropical precipitation anomalies, and to further teleconnections to extra-tropical regions.

It is well known, from studies of instrumental records, that explosive volcanic eruptions can have short-term cooling effects on overall hemispheric or global mean temperatures (Robock, 2000). This results from direct radiative effects, with the volcanic aerosol reducing energy receipts at the surface, plus associated circulation changes that may result from such effects. Most temperature effects are not detect-



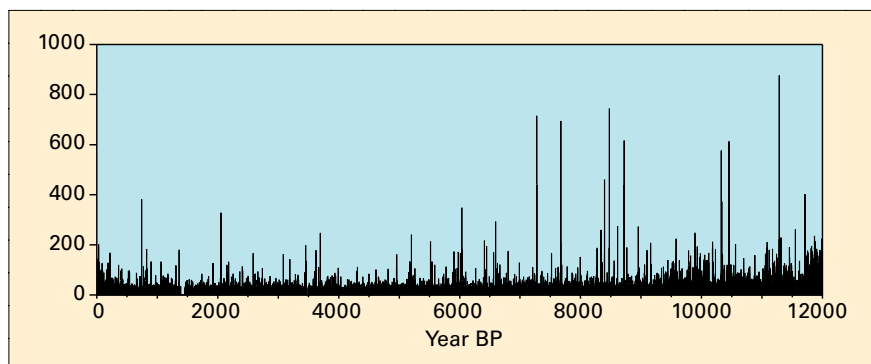


Figure 2: Holocene record of volcanic sulfate (anomalies from background variations) recorded in the GISP2 ice core from Summit, Greenland (Zielinski et al., 1994).

able after a few years, so individual explosive eruptions only contribute short-term variability to the spectrum of Holocene climate. However, if eruptions were more frequent in the past, or if they happened to occur in clusters, it is possible that the cumulative effect of eruptions could have persisted for longer, resulting in decadal- to multi-decadal scale impacts. Such effects would be enhanced if the initial cooling led to feedbacks within the climate system, such as more persistent snow and sea-ice cover, which would raise the surface albedo and possibly alter the atmospheric circulation. Indeed, the non-seasalt sulfate record from the GISP2 ice core does suggest that there were periods of more frequent explosive

eruptions in the past, such as in the period 9500-11500 calendar years BP (Fig. 2) (Zielinski et al., 1994). Furthermore, in the early Holocene there were many large volcanic signals, greater in magnitude than those recorded after the eruption of Tambora (1815), the largest eruption in recent centuries. Of course, a larger sulfate signal might simply mean that the eruption event was closer to the deposition site, so we do not have a definitive long-term record of the magnitude of overall volcanic forcing, or more specifically, of atmospheric optical depth and its distribution latitudinally (cf. Roberston et al., 2001). Energy balance and GCM studies that have parameterized the effects of explosive volcanism and solar forcing over

recent centuries suggest that these two factors can explain most of the variability of temperatures over the last millennium (e.g. Crowley, 2000). It therefore seems likely that they have also played a significant role in overall Holocene forcing on inter-annual to century timescales.

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## Tephra, a Powerful Tool for Precision Dating and Correlation

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### Summary

Icelandic tephra is proving to be a valuable new chronological and stratigraphical tool for the palaeoenvironmentalist in NW Europe. It is particularly useful in the historic period where radiocarbon dating seldom provides adequate precision, and also in situations where sediments are unsuitable for such dating because of variable marine influence.

### Geographical Distribution and Temporal Range

Tephra is the air-fall component of ejecta from a volcano. Tephra can be found embedded in deposits in many areas of the world, in fact

there is probably no part of the globe from which such deposits are absent. The use of Icelandic tephra in stratigraphic studies and as a dating tool is well developed in NW Europe. Tephra particles are usually less than 100 micrometers (commonly 20-60µm in diameter) and are glass (Fig. 1). In all the studies described here, the tephra is invisible in the cores and sections and must be detected microscopically. The ideal medium for detection of minute traces far from the parent volcano is a highly organic matrix such as peat. The tephra can be released by burning sub-samples of the organic material and dissolving the peat ash in dilute acid. The



Figure 1: Tephra (width about 40µm) from the AD1158 eruption of Hekla found in peat from the Lofoten Islands.

clean material can then be mounted in resin and examined under a microscope. This process is described in Pilcher and Hall (1992). Where the matrix has more than about 1% mineral content, separation of the tephra is more difficult. Sieving between mesh sizes of 26 and 75 $\mu$  will retain most of the tephra and will remove sand and clay. If this is not adequate, then a heavy liquid separation has proved successful (Turney, 1999).

### Tephra in Arctic Norway

Last year, a team from the University of Massachusetts, Amherst and

The area has been subject to major relative sea level changes, with many lakes passing through both marine and fresh water episodes. This poses special constraints on the value of radiocarbon dating.

Following the successes of using Icelandic tephra for chronological control in Ireland (Pilcher et al., 1996; Hall and Pilcher, 2002), Scotland (Dugmore et al., 1995), Germany (van den Bogaard and Schminke, 2002) and other areas distant from Iceland, this technique was selected for dating in Lofoten. As there had been no tephra work done in this area before, we select-

to lake basin. Even better, we will also be able to correlate with other work on a whole transect along the Atlantic seaboard of Europe at key dates such as 2310 BC (Hekla 4).

### Chemical Fingerprinting of Tephra

Simple preparation by burning is not suitable when chemical analysis is required, as burning changes the glass chemistry. In this case, the organic matter is dissolved in a chemical oxidizing mixture as described by Dugmore et al. (1995). The tephra recovered from the acid treatment is washed and mounted for electron microprobe analysis.

Volcanic systems vary in their chemistry. The products of individual volcanoes may also differ and in some cases, such as in Iceland, many individual eruptions are geochemically distinct. Because the differences between eruptions are quite subtle, wavelength dispersive microprobe analysis is used rather than the simpler and more commonly available energy dispersive analysis. It is usual to analyze between 10 and 20 individual tephra fragments.

Type material comes from profiles examined in Iceland. Many have been analyzed (e.g. Larsen and Thorarinsson, 1977; Haflidason et al., 2000), many more remain to be examined. Analyses are stored in the TephraBase Data Bank and are available to all researchers at this URL: <http://www.geo.ed.ac.uk/tephra/tbasehom.html>

Not all tephras are chemically distinct. For example, the AD 1947 and AD 1510 tephras from Hekla are very similar, as are those of Hekla 4 (2310 BC) and Hekla 5 (5990 BC). Normally other stratigraphic information allows us to discriminate between these pairs of tephras.

### Tephra for Correlation Between Cores, Sample Sites and Regions

A typical eruption lasts for days or perhaps even months, a very short time in relation to the accumulation of typical terrestrial and

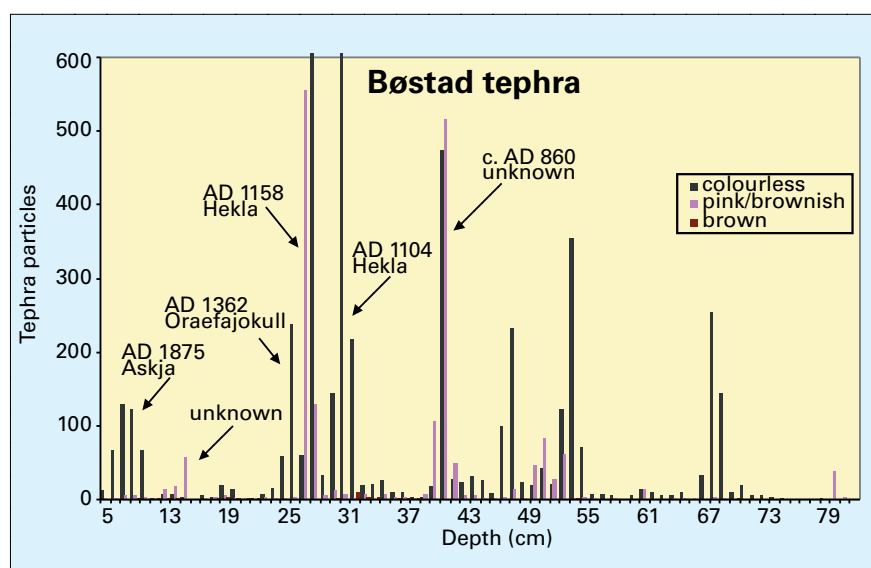


Figure 2: Stratigraphic sequence of tephra analysis from a peat bog at Bøstad in the Lofoten Islands. Marked layers have been identified by matching microprobe-determined major element chemistry of the tephra with that of historically dated layers from Iceland and elsewhere. Not all layers have yet been determined.

Queen's University, Belfast carried out exploratory fieldwork in the Lofoten Islands off the northwest coast of Norway, just inside the Arctic Circle. We hypothesize that the Lofoten islands are sensitive to changes in ocean currents (fluctuations of the North Atlantic Drift) and to circulation shifts associated with different modes of the North Atlantic circulation.

At present, the outer islands are bathed in waters that reach +11°C in summer (+5-6°C in winter) in spite of their high latitude. Changes in the strength and/or position of this warm water tongue will drastically affect the Lofoten environment. The islands have many deep fresh water lakes, fjords and peat bogs with Holocene records.

ed several peat profiles to develop a local tephra stratigraphy before applying this to more complex lake sediments. Two peat profiles have been analyzed and show one of the best historical tephra sequences outside of Iceland itself. A good range of historical tephras has been identified, including among others, tephras from (AD) 1875 (Askja), 1510 (Hekla), 1362 (Oraefajokull), 1158 (Hekla) and 1104 (Hekla) eruptions (Fig. 2) and also the big eruption of Hekla in 2310 BC. The AD 1158 and 2310 BC tephras have already been used to provide chronological control in our pilot cores from lacustrine and brackish water sediments. These layers can be used to correlate core to core and lake basin

marine stratigraphic sequences. Thus, an ash layer forms a tightly defined time-marker.

One of the perennial problems of working in bog and lake deposits is correlation from one core to another. Analyzing tephra can be an ideal technique in these circumstances, since the horizontal layers are so sharply defined.

### Tephra as a Taphonomic Guide

Tephra has so far been under-utilized as a taphonomic guide. As the tephra fall is assumed to occur at least within a single year, we can make a good assessment of post depositional processes by looking at the vertical spread of the tephra in a sediment core. Spreading can also be the result of delayed deposition of particles stored for more or less time in the watershed or the lake basin. As the particle size of the typical tephra layer is of the same order as that of pollen, for example, it can suggest the extent to which pollen and other micro-

fossils may have been moved vertically in the sediment profile. For example, if the tephra were spread over 5 cm, there would be little point in undertaking a pollen study at a resolution of 1 cm.

### Tephra as a Chronology

Tephrochronology consists of knowing when eruptions took place and then of tying a tephra fall to a particular eruption by its chemistry. From about AD 1100, a well-recorded chronology of calendrical accuracy exists for Iceland. Before settlement in Iceland, we are dependent on dating tephra layers by independent means. Radiocarbon dating of a terrestrial peat allows a precise date to be applied to tephra-bearing low-organic lake sediments or marine to brackish water sediment that is unsuitable for precision radiocarbon dating. One of the ongoing projects is to use the calendrical precision of the new NGRIP Greenland ice core to produce dates for the

geochemically typed tephra layers it contains.

### ACKNOWLEDGEMENTS

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## Simulating the Climate of the Last Millennium

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### Introduction

Climatic changes during the last thousand years have received great interest. Uncertainty in climate reconstruction is smaller than in earlier periods and the external forcing factors of the climate system are relatively well known, making comparisons with 20th century climate well suited to assessing the influence of human activities. Numerical modelling complements the efforts to reconstruct past climates from proxy records. The goals of paleoclimate modelling are to reduce uncertainties in climate reconstructions through consistency tests with evidence from proxy data, to validate climate models, to provide hypotheses on the climatic evolution at locations or variables not covered by proxy data, and to improve process understanding. The latter should include distinguishing be-

tween internal variability and the effects of varying external forcings, and understanding feedback mechanisms.

### Types of Climate Models and Simulations

The simplest climate models are zero- or one-dimensional energy balance models (EBMs), which have low computational costs and clear links between simulated processes and climate. At the other end of the spectrum are quasi-realistic, computationally expensive, general circulation models (GCMs), which usually feature sub-models for the atmosphere, the ocean and the sea ice on 3-dimensional grids with typical horizontal spacings of a few hundred kilometers and 15-100 vertical levels. GCM components for the carbon cycle, chemical processes, land ice and vegetation dynamics are currently

under development. In between EBMs and GCMs are a variety of models with varying numbers of dimensions and complexity, for instance, earth system models of intermediate complexity (EMICs), which describe the atmosphere and ocean dynamics in less detail but which place more emphasis on the role of vegetation and chemical processes in the climate system. Climate models are mainly used in two different ways. In equilibrium experiments, the forcing factors for the climate system, such as solar irradiance, the atmospheric composition, or the earth's orbit, are held constant but may vary between different runs. These simulations represent the mean climate and the statistics of internal climate variability. Transient, forced simulations also include the climate response to time-varying forcings using historical estimates.



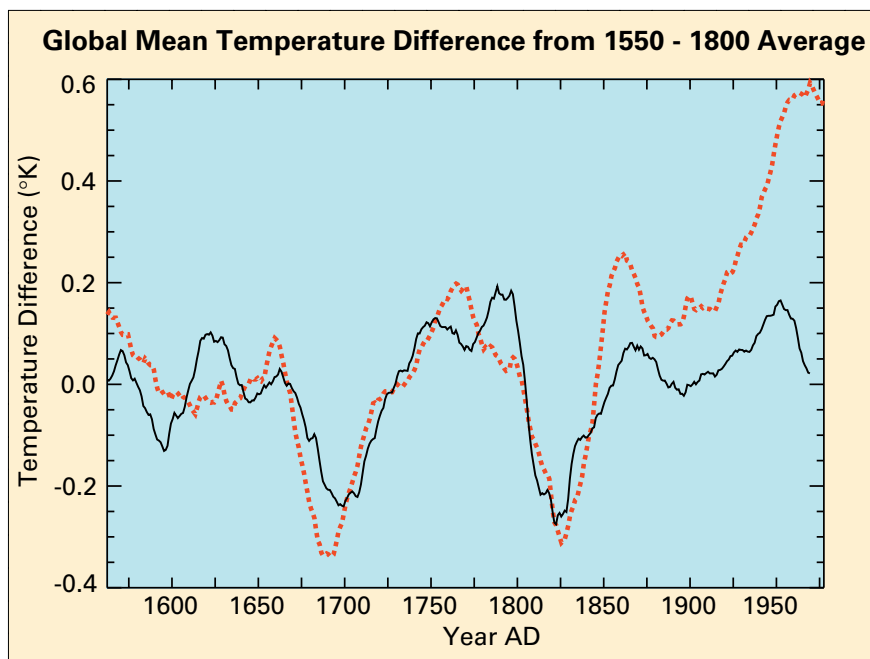


Figure 1: Time series of global-mean temperature. Shown are time series of global-mean temperature from ECHO-G (solid black line) and HadCM3 (dashed red line) simulations. Note that ECHO-G was forced with natural and anthropogenic simulations while HadCM3 was driven only by natural forcings. Both simulations are shown as differences relative to the 1550-1800 average and represent a 25-year running average.

Since the evolution of the climate system is not completely determined by external forcings but also contains a stochastic component, even a perfect model with all forcing mechanisms included will yield only one out of many possible climate realizations consistent with the forcings. This realization will be different from the realization that took place in the real world. Therefore any comparison between model and reconstruction will be probabilistic in nature.

## Results

By the mid-1990s, coupled GCM equilibrium experiments for pre-industrial conditions were typically around 100 years long but the first runs with lengths of about 1000 years became available at some modelling centers (GFDL, MPI and UKMO). These simulations were used, for instance, to clarify the roles of the atmosphere and the ocean in generating internal climate variability (Manabe and Stouffer, 1996), or to estimate natural variability, the basis for detection and attribution of climate change (Hegerl et al., 1996). However, the agreement among models on the spatial structure and magnitude of natural variability

was only moderate and deviations from observations became evident (Barnett, 1999). A very long simulation of 15000 years using the GFDL model with a relatively low resolution suggested that large-scale, multi-decadal temperature anomalies with very strong amplitudes of about 6-10 standard deviations could be generated merely by internal processes (Hall and Stouffer, 2001). Recently, 1000-year-long equilibrium runs with higher resolutions (about 300 km) were conducted at UKMO (Collins et al., 2001) and MPI. Because they are much longer than the instrumental climate record, they are well suited to test paleoclimatic reconstruction methods on decadal to centennial time-scales (Zorita and González-Rouco 2002, Zorita et al. 2003).

Many transient simulations begin in the middle of the 19th century to investigate the climatic effects of anthropogenic greenhouse gases and aerosols (e.g. Stott et al., 2000). The climatic response to changing solar forcing was investigated with a coupled GCM forced by estimates for solar variability from 1700 to the present (Cubasch et al., 1997). The spatial pattern associated with solar forcing was found to be similar but not

identical to the signal of changing greenhouse gas concentrations. The pronounced insolation decrease during the Dalton Minimum (DM) around 1820 caused global cooling. Some of the recent work focuses on the Late Maunder Minimum (LMM). A transient simulation with an EBM forced by solar and volcanic activity, anthropogenic greenhouse gases and aerosols produced a global temperature well correlated with proxy reconstructions (Crowley, 2000); in particular a cooling during the LMM was found. A LMM cooling was also found in a 1000-year-long run with a two-dimensional zonally averaged atmosphere-ocean model (Bertrand et al., 2002). It should be noted, however, that the climate sensitivity to changes in the forcing can be tuned in both models. A 1000-year-long run with an EMIC (Bauer et al., 2003) used similar forcings but also information on deforestation. Northern Hemisphere temperatures correlated well with proxy reconstructions. During the LMM and the DM, pronounced cooling took place due to solar and volcanic forcing. During the last half of the 19th century, deforestation led to cooling.

Shindell et al. (2001) used equilibrium runs of an atmospheric GCM with detailed ozone chemistry coupled to a slab ocean model to model the difference between the LMM and the period around 1780. During the LMM, the surface air temperature over the continents was colder and over some ocean areas warmer than 100 years later. The temperature signal could be shown to be related to a change in the AO (Arctic Oscillation)/NAO (North Atlantic Oscillation), which in turn is driven by variations in the meridional temperature gradient. This temperature pattern appears partly consistent with evidence from proxy data but too many large areas without adequate proxy data remain to draw definite conclusions on the agreement between simulation and observations.

The LMM was also included in 500-year-long transient runs of

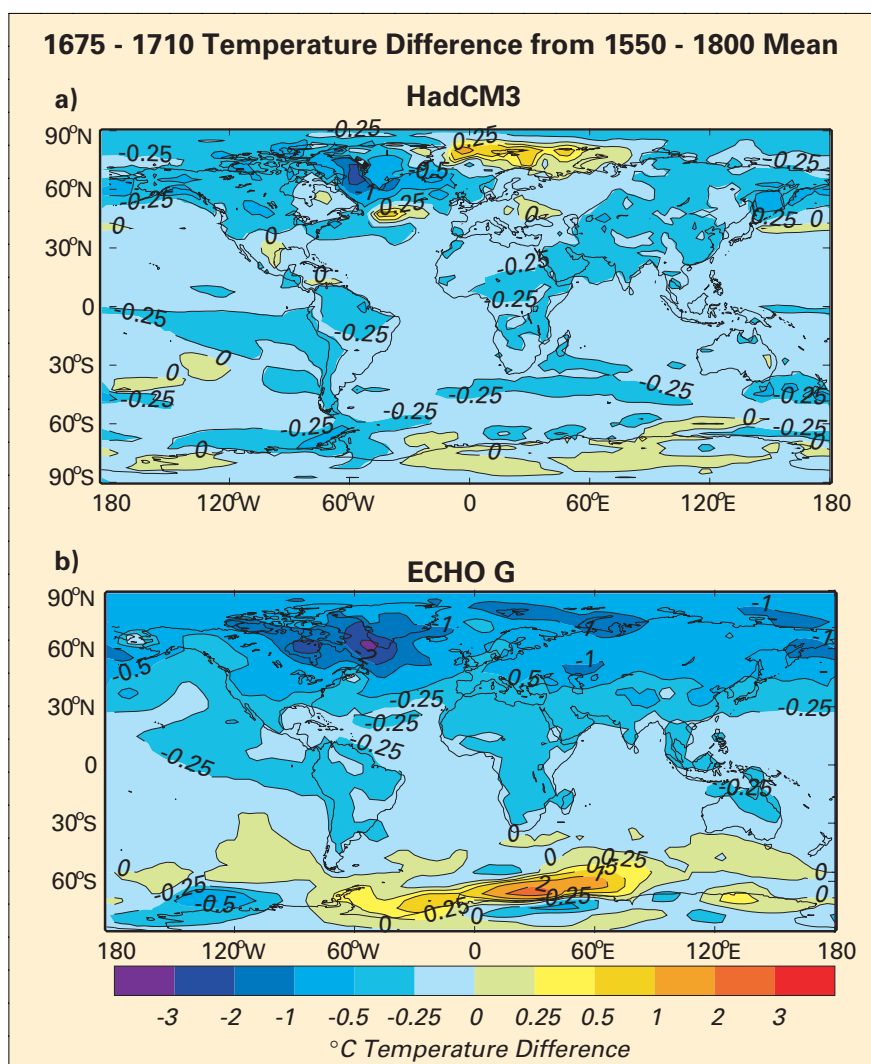


Figure 2: LMM cooling (1675-1710). Shown are changes in near-surface temperature from HadCM3 (a) and ECHO-G (b) for the 1675-1710 period minus the long-term average for 1550-1800. Contours are at  $\pm 3$ , 2, 1, 0.5, 0.25 and 0 K. Global-average values are  $-0.21$  and  $-0.28$  K.

fully coupled atmosphere-ocean GCMs conducted by the GKSS Research Centre in collaboration with the MPI (ECHO-G, Fischer-Bruns et al. 2002, Zorita et al. 2003) and by UKMO (HadCM3). Preliminary results from both models show a clear global-mean cooling during the LMM and the DM (Fig. 1), which is of similar magnitude in both models. The ECHO-G simulation was forced with the major anthropogenic and natural forcings while the HadCM3 was only forced with natural forcings. Both groups are currently carrying out simulations with natural forcings only, and both natural and anthropogenic forcings, respectively. Note the increasing divergence between the two simulations from the mid-19th century as the simulated effect of anthropogenic forcings becomes

more important. The cooling during the LMM has a spatial structure somewhat different from Shindell et al. (2001). Most noticeable is a strong cooling in the North-West Atlantic (Fig. 2), associated with increasing sea-ice extent in both simulations. Also apparent is a smaller cooling over Europe and other regions. In ECHO-G there is widespread cooling over the entire northern hemisphere with peak cooling to the west of Greenland of  $-2$  K. By contrast, HadCM3, while still having a large amount of cooling to the west of Greenland manages to sustain a larger land-sea contrast than that of ECHO-G.

### Summary

In this paper we have introduced the idea of simulating the climate of the last 500 to 1000 years. Pre-

liminary results from two GCM simulations of the last 500 years demonstrate that it is now just about feasible to do this using state-of-the-art GCMs. This then provides a good opportunity to test both climate models and proxy data by comparison with one another and thus to better forecast anthropogenic climate change during this century. It also allows estimates to be made of the relative contribution of natural and anthropogenic climate forcings, and internal climate variability to total climate variability and change. A current European Union funded project called SOAP (<http://www.cru.uea.ac.uk/cru/projects/soap>) aims to do this and bring together scientists working with paleodata with those working with models.

### ACKNOWLEDGEMENTS

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## Late Holocene Paleoclimate and Paleogeography in the Tien Shan-Balkhash Region

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The Tien Shan-Balkhash region (Semirechie) (Fig. 1) is a rich natural archive of paleoclimatic data but is poorly known. Research in this region, performed during Soviet times and resumed in recent years, shows that changes in atmospheric circulation, paleoclimate, and paleo-geographical conditions, including a chronology of basic events in the arid continental regions of Central Asia, can be successfully reconstructed. Research included multiproxy reconstruction from geological-geomorphological, hydrological, paleontological (paleobotanical, palinological), pedological (micro-morphological) and archeological studies, as well as independent dating methods (EPR – Electronic Paramagnetic Resonance;  $^{14}\text{C}$ ).

### Quaternary Climatic Events

Data collected during Soviet times concerning the Quaternary period as a whole, are based on qualitative analyses and relative dating, and provide low temporal resolution. The following results have been reported:

- The formation of the high-mountain range of the Tien Shan began during the Pleistocene, 1.6-1.3 million years BP. The rise of plateaus above 3000 m and the establishment of the first and largest glaciation occurred 1.2-1.1 million yrs BP.

- In the second half of the Pleistocene (0.5 million yrs BP), the increase in mountain height to more than 5000 m blocked the path of the Indian monsoons. This caused a reduction and then total halt of monsoonal influence on West-Central Asia and started the process of aridization that gave the region its modern features.

- With the fading of the monsoonal influence, polar air masses from the Arctic glacial zone (Siberian anticyclone) and eastward branches (along 45°-50° latitude) of the Atlantic anticyclone (Azores High) began to play a major role. In this way, the

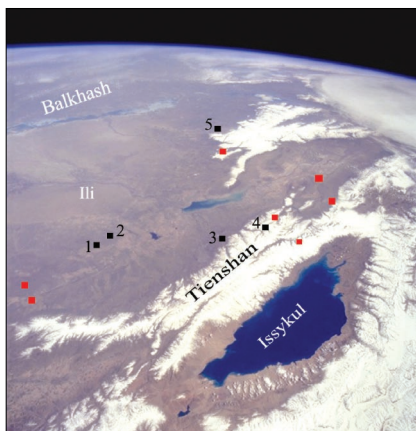


Figure 1: Satellite image STS059-223-042, April 1994. Issyk-kul Lake, Northern Tien Shan and, 400 km north, the Balkhash Lake partly iced. In the upper right, the atmospheric circulation patterns of the Siberian anticyclone are visible. Black dots indicate sites for palinological and geo-archaeological research: 1-Tamgaly (800 m asl) and 2-Serektas (750 m) in semidesert landscape of the Chu-Ili range; 3-Talgar (800 m) in piedmont steppes and 4-Turghen (1800 m) in mountain meadows of Northern Tien Shan; 5-Tasbas (1600 m) in middle mountain steppes on the northern slopes of the Jungarian range. Red dots indicate sites of geo-archaeological research: from left to right Kuljabasi, Oi-Jailau, Assy, Saty, Charyn, Usunbulak, and Koksus.

modern mode of atmospheric circulation was established.

Throughout the Quaternary Period, latitudinal changes in the positioning of the Atlantic anticyclone and its branches exerted a crucial influence on the climate of Kazakhstan and Semirechie. It characterized the switch between glacial and interglacial periods and, during interglacial and Holocene times, between pluvial and arid phases. Changes in the position of the Atlantic anticyclone also affected the water balance of interior reservoirs (Caspian, Aral, Balkhash, Alakol, Zaisan) and the volume of ice deposits in the Tien Shan Mountains. Thus, lakes and mountains provide complementary archives for paleoclimatic reconstruction. In Semirechie during the Holocene period, we reconstruct regular alternation between arid (hot-dry) and pluvial (cold-wet) phases, correlated with high (northerly) and low (southerly) positioning of the Atlantic anticyclone.

### Late Holocene Climate and Human Adaptation

Quantitative evaluation and absolute dating of paleoclimatic changes for the late Holocene have only been attempted in the last 5 years in the context of geo-archaeological research for project INTAS 97-2220. Temperature and precipitation reconstructions are based on palinological data and transfer functions located in three different zones: The semideserts of Southern Pre-Balkhash, the foothills of the Tien Shan and Jungarian ranges, and the high mountains. Sites with average trench depths of 250 cm provided a 3000-3500 year sequence of events. Samples were collected every 7-15 cm to allow 150-year temporal resolution. Dating was based on EPR of carbonates and on correlation with archeological findings from settlements and tombs submitted for  $^{14}\text{C}$  analyses.

It has been established that local climatic fluctuations are well correlated in tendency, time and periodicity with global estimates. But relevant regional anomalies, mainly determined by the continental location of the region, are also observed (phase 3), emphasizing the forcing impact of seasonal anomalies. Also, sub-regional differences exist between plains and mountains because of their different exposure to drought and glacial events and the different (sometimes opposite) reaction of their environments to climatic variations.

In Semirechie, climatic forcing on borders of landscape zones in plains, and of vertical belts in mountains is strong enough to influence human use of large areas. In such cases, one can analyze both the correlation between climatic and palinological events, as well as patterns of human land-use and environmental adaptations such as settlement localization, switches between sedentary and nomadic life or between pastoralist and farming activities, or development of irrigation schemes, etc.



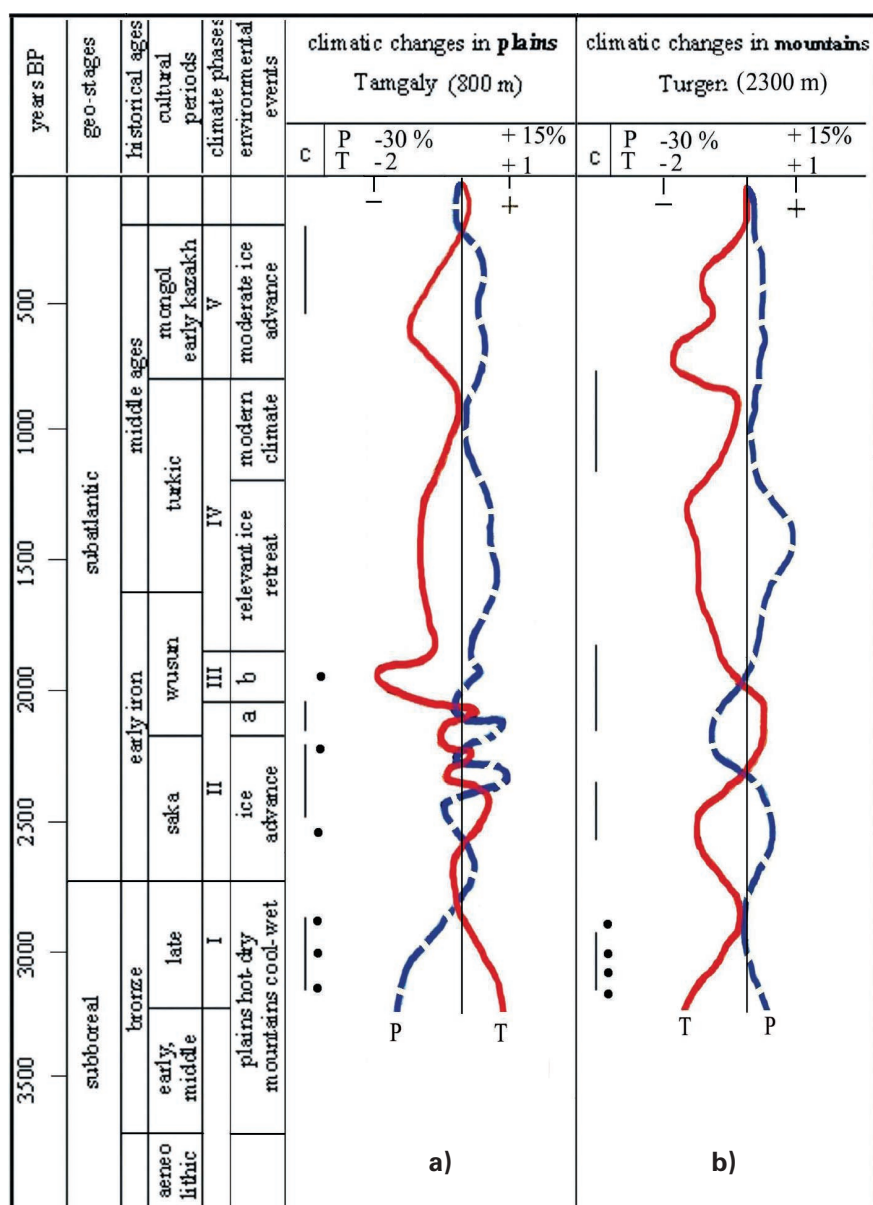


Figure 2: Reconstruction of average temperature and precipitation in Semirechie during the last 3200 yrs (150 yrs temporal resolution; based on palinological analyses). **a)** In plains (Tamgaly, 800 m asl, semidesert landscape); **b)** In mountains of Semirechie (Turghen, 2300 m asl, alpine meadows). Temperature (T) is indicated by red lines, precipitation (P) by blue dashed lines. The absolute chronology is provided by EPR and  $^{14}\text{C}$  analyses (dots) and archaeological correlation (segments).

Modern climatic conditions in Semirechie including the arid continental plains and humid mountains are moderately hot and dry, with an average continentality index of 30. Preliminary reconstruction of paleoclimate and human land-use in plain and mountain zones of Semirechie during the last 3200 years distinguishes 5 main phases, described below (Fig. 2).

Calibration with modern standards suggests that during the whole interval, average temperature range fluctuated between  $+1^{\circ}\text{C}/-2^{\circ}\text{C}$ ; precipitation between  $\pm 20\%$  in plains and  $\pm 30\%$  in mountains, and continentality indexes between 27

and 34. The five main phases are as follows:

#### Late Subboreal: Late-Final Bronze Age (3200-2800 BP)

Plains had arid conditions, slightly warmer and drier than modern; mountains had humid conditions, slightly cooler and wetter than modern. Glaciers on the Northern Tien Shan contracted to less than 2 km in length. Balkhash water level continued to shrink (from 344 m asl at 3800 BP) to less than 342 m asl. From this time on it fluctuated around the 342 m level, due to a complex balancing of synchronic hydrological changes and the melt-

ing of former accumulations of ice. The borders of vegetative cover in all landscape zones and vertical belts remained close to modern. Human communities (Late Bronze culture) practiced pastoralist activities with settled villages in mountain habitats (Assy 2500 m asl, Turghen 2300 m, Tasbas 1600 m, Oi-Jailau 1400) and scattered houses in oases of piedmonts and plains (Tamgaly 800 m).

#### Early Subatlantic; Early Iron Age (2800-2000 BP)

The average climate was pluvial—cooler and wetter than modern, with larger seasonal amplitudes of temperature and humidity. Both plains and mountains had cold-wet conditions, with some differences in periodicity: In plains the peak of cold and humidity fell around 2400 BP; in the mountains around 2200 BP, a difference probably due to prolonged ice accumulation. Glaciers on the Northern Tien Shan grew back to more than 2 km in length. Balkhash water levels reached a minimum of 338 m around 2500 BP and then peaked at a maximum of 343 m in 2200 BP. The borders of vegetal zones in the plains and mountains changed in response to climatic fluctuations. Alpine zones became glacial and were abandoned (at least during the cold season). Semidesert plains were transformed into steppes, consistently increasing the potential areas of human activity and favoring the conversion to nomadic pastoralism with seasonal occupation, new herd composition, horse riding, demographic expansion, and relative decline in stable housing mostly located in the piedmont zone halfway between winter and summer pastures. A major economical and cultural change occurred (Saka and early Wusun cultures).

#### Short Interval 2000-1800 BP

This period must be noted for its peculiarity. There are ubiquitous signs of increased continentality, with very severe cold-dry winters and cold-wet summers. The phenomenon is most pronounced in plains where exceptionally cold temperatures and seasonal contrasts of precipitation caused a botanical catastrophe and

cryolitic formations. Data suggest the establishment of an exceptional blockage of winter atmospheric circulation in Central Asia for almost two centuries, which must correspond to some climatic events of global dimension. Steppes were reduced and human habits become more sedentary, with primitive agricultural practices in the piedmont fans (Wusun culture).

### Middle Subatlantic; Early and Mid Middle Ages (1800-800 BP)

Plains and mountains were characterized by cold-wet conditions until 1000 BP when conditions close to modern were established. Continentality indexes remained high with cold-dry winters. The Northern Tien Shan saw a catastrophic degradation of ice deposits from which they never recovered. Balkhash water levels decreased to a minimum of 339 m around 800 BP. Human geography saw the expansion of agricultural

activities together with the spread of irrigation practices, proto-urbanization along river courses and the blossoming of the northern branch of the Silk Road (late Wusun and Turkic periods).

### Late Subatlantic; Middle and Late Middle Ages (800-200 BP)

Climate became cooler and wetter than either the former period or the modern climate. Moderate advances of ice occurred. The plains reached a minimum temperature around 550 BP, the mountains around 250 BP. Balkhash water levels continued to rise until a peak of 344 m was reached in 1910 AD. A conversion to pastoralist practices and nomadic habits took place. Most likely this was favored by the reestablishment of climatic conditions similar to those of the Early Iron Period but also by political military events and the crisis in the Silk Road trade (Mongol and early Kazakh periods). After 200 BP,

climatic conditions tended progressively towards the warmer and drier conditions of modern times.

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## Holocene Ocean-Climate Variations in the Gulf of California, Mexico

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Despite complexities, the Gulf of California can be considered an ocean-climate system in which primary productivity and sedimentation are largely controlled by seasonal monsoon winds. It offers an ideal model for exploring the ocean-climate variations in which decadal to millennial scale changes can be reconstructed from sediment cores that sample the latest Pleistocene and Holocene.

During winter months, strong NW winds flow down the length of the Gulf, cooling surface waters, and initiating surface mixing and Ekman transport along the eastern margin and the development of a major winter-spring bloom of diatoms. Primary productivity rates in the central Gulf can exceed 4 gC/m<sup>2</sup>/day during the winter season, making the Gulf one of the more productive sites in the global ocean. The winds also transport large quantities of dust, which together with the flux

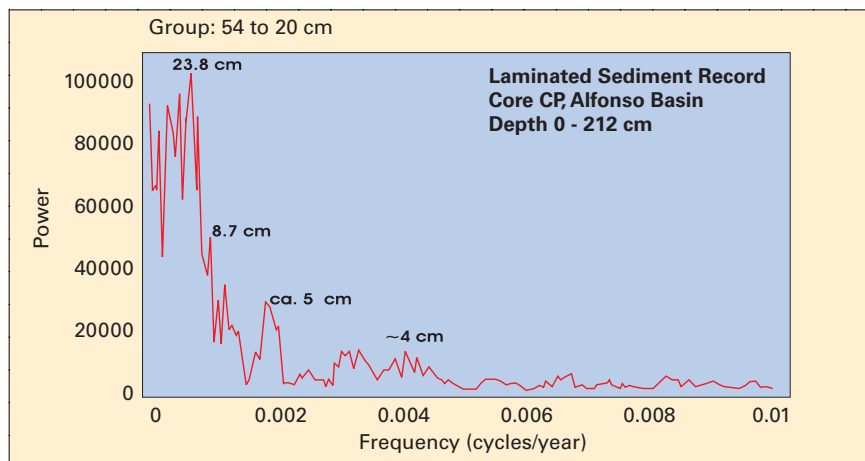


Figure 1: Spectra of peaks of variability found in laminated sediments and carbonate content in core BAP96-CP, Alfonso Basin (MTM method). Major periodicities are given in Table 1.

of biogenic debris contribute to the clayey mud that predominates in slope and basin sediments.

During summer months, winds are from the SE, a strong thermocline develops, which reduces nutrient transfer and there is a decline in primary productivity. The biogenic flux to the seafloor is dominated by pelagic carbonate

and so-called "shade floras," mat-forming and large centric diatoms which grow in the nutricline. The mats are dumped to the seafloor in late autumn or early winter with the onset of the NW winds. In the central and eastern Gulf, these mat-forming diatoms contribute to the formation of sediment laminations. The SE winds bring summer storms

and, except for El Niño years, most of the precipitation in the Gulf falls between July and October.

The deep-water sediment record in the Gulf reflects the monsoon control of biogenic and terrigenous input, especially in the hemipelagic sediments of the slopes. In the Gulf, the Oxygen Minimum Zone (OMZ) typically ranges between about 300 and 1000 m and where it intersects the seafloor, bottom-water dissolved oxygen concentrations are <0.5 ml/l to zero. Laminated varves accumulate in these depositional environments. Preserved within the laminations is a record of the monsoon-induced seasonal variations in production and sedimentation as well as longer-term ocean-climate variations.

Holocene sediments in the Gulf of California are biogenic silica- and organic carbon-rich, generally carbonate poor and within the OMZ, intensely laminated. In contrast, late Pleistocene and Younger Dryas sediments are carbonate-rich, biogenic silica-poor and typically bioturbated.

Recent multi-institutional investigations have emphasized different approaches to producing high-resolution (10-30 years/sample) Holocene records. John Barron and

Table 1: Spectral peaks of variability derived from separate analyses of the laminated sediments and carbonate record in core BAP96-CP in Alfonso Basin (MTM method). Ages estimated using average sedimentation rates derived from AMS  $^{14}\text{C}$  age-depth model.

Laminated Sediment				Carbonate	Periodicities
0-212cm	0-150cm	150-212cm	97-116cm	0-212cm	approx. age
54	42.8			40	1480 $\pm$ 100
23.8	22.6	22.4		27.3	898 $\pm$ 82
16.4	18.7	16.4			615 $\pm$ 44
8.7	5.5	7.6	8.2	7.8	300 $\pm$ 20
5	4.9			5.7	192 $\pm$ 20
4	4		3.7	4.3	144 $\pm$ 18

colleagues of the U.S. Geological Survey (Menlo Park, USA) have focused on the diatom-rich, carbonate-poor sediments in cores DSDP 480 and JPC56 in Guaymas Basin (central area of the Gulf), while our group (listed above) has focused on the sediments microfabrics, stable isotopes and carbonate microfossils in the more carbonate-rich sediments of the western Gulf and Alfonso Basin (mouth of the Gulf). These investigations have produced complementary results and suggest that the shifts in the Holocene Gulf are ultimately the result of an intensification and seasonal shift in the NW monsoon winds that control the patterns of upwelling, and that the changes are paced by climate rhythms that have strong modes of about 200 yr, 300 yr and 1500 yr.

In Guaymas Basin, an increase in the production of biogenic silica and changes in the relative abundance of diatom floras suggest shifts in the seasonal intensity of upwelling, with spring upwelling dominating in the early and late Holocene and winter upwelling dominating in the mid Holocene and today (Barron, et al., 2000; Barron, 2003). After about 6 ka, spring upwelling increased on the mainland side of the Gulf. Coincident with the shift in upwelling, the carbonate content of Guaymas Basin shifted, with more intense dissolution in sediments in the eastern Gulf leading to very low carbonate content, generally beneath the main upwelling centers.

Alfonso Basin is situated near the junction of the Gulf of California and the open Pacific Ocean, which places it in a sensitive location to record the variation in the monsoon-driven climate in the Gulf, as well as the larger-scale climate variations occurring in the Pacific. The basin is silled (depth ca. 250 m), filled with dysoxic-anoxic waters and accumulating laminated sediments on the basin floor. Cores collected from the basin floor have recovered most of the Holocene (7700 yBP) based on AMS radiocarbon dates and varve counts produced from digitally scanned X-radiograph positives. All cores were sampled at 1 cm intervals (approx. 15-35 years/sample).

Spectral analysis of the laminated stratigraphy and carbonate in core BAP96-CP was used to identify millennial and centennial peaks of climate variability (Douglas, et al., 2002) (Fig. 1). For the microfabrics analysis, gray scale images were produced from X-radiograph prints, digitized and converted to pixel number and analyzed using

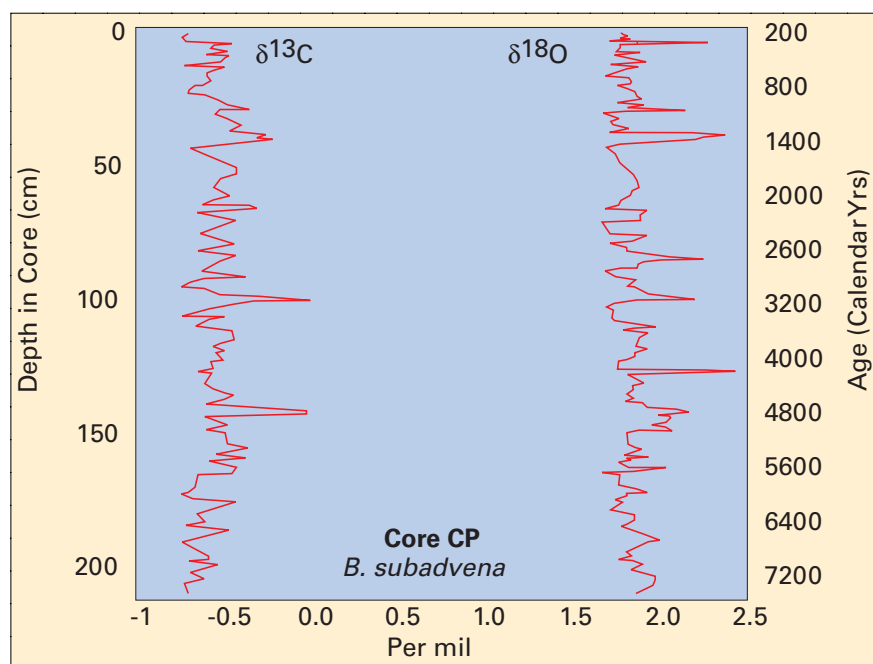


Figure 2: Stable isotope record of *Bolivina subadvena* in a core collected near the center of Alfonso Basin (core BAP96-CP; 1 cm sample interval). Age-depth model based on excess  $^{210}\text{Pb}$  profiles and corrected radiocarbon dates. Based on recently collected multi-cores from the same site, we estimate that about 200 years is missing from the top of core CP.



the multi-tapered Method (MTM). No filters were applied. This produced a continuous, millimeter-scale record. The resulting power spectra frequency peaks were converted to calendar years based on the age-depth model. Because of variations in the microfabric record (density of laminations, microburrows, flood layers), spectral peaks were calculated separately for three cores and for selected intervals within the cores. The results were the same for all cores.

Strong peaks of variability were found with periodicities at about 150 yrs ( $144 \pm 18$  yrs), 200 yrs ( $192 \pm 20$  yrs) and 300 yrs ( $300 \pm 20$  yrs) (Table 1). These are associated with productivity/dissolution cycles in the carbonate record. All these periodicities are present prior to 3200 yBP but the 300-year cycle dominates in the latest Holocene. Similar productivity pulses have been identified by Gladys Bernal-Franco (2001) in the biogenic record in La Paz Basin on a 330-year period. We suspect that the centennial variability is related to variations in solar radiation identified in radiocarbon fluctuations

in tree rings and  $^{10}\text{Be}$  records. Millennial scale variations at 900 yrs ( $898 \pm 82$  yrs) and 1500 yrs ( $1480 \pm 100$  yrs) are strong in both the carbonate and sediment lamination records.

Stable isotopes measured on the benthic foraminifera *Bolivina subadvena* in Alfonso Basin (core BAP96-CP) exhibit small variation through the 7700 yBP record, except in the  $^{18}\text{O}$  record. Beginning about 6ka, the record is punctuated with a series of short-term excursions or events of 0.5 to 0.9‰, the largest of which occurs between 5200 and 1400 yBP (Fig. 2). The events signal a turnover in the water-mass in the basin and replacement by either much colder or higher salinity water. The basin sill is located at ca. 250 m depth, near the present-day lower boundary of Central Gulf Water—a high salinity water-mass produced by evaporation in the northern Gulf of California during winter months—and is advected at shallow depths along the western margin depth of the Gulf towards the mouth. We believe the most likely explanation for the isotopic excursions is basin turnover, when increased production

of Central Gulf Water flooded the basin (Douglas and Staines-Urias, in press). If this interpretation is correct, the isotopic excursions record periods of intensified NW winds in the mid and late Holocene.

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## Climate and the Maya

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The relative stability of Holocene climate, at least when compared to the rapid, large-amplitude climate excursions of the last ice age, has contributed to a view that the road to modern human civilization has been little affected by climate road-bumps. However, significant variations in regional Holocene climate have now been recognized, with some having had clear societal impacts. Here we summarize recently reported new data from the annually laminated sediment record of the anoxic Cariaco Basin off northern Venezuela, a now well-known paleoclimate archive. Using a new method for the measurement of bulk sediment chemistry, we have been able to develop a record of varying river-

derived inputs to Cariaco Basin with roughly bimonthly resolution (50  $\mu\text{m}$  sample spacing) for the period AD 700 to 950 (Haug et al., 2003). Terminal Collapse of the Classic Maya civilization in the lowlands of the Yucatan Peninsula in Mesoamerica occurred during this time, one of the most dramatic events in human history (Fig. 1). Our new record of riverine input to Ocean Drilling Program (ODP) Site 1002 shows in unprecedented detail evidence of a link between regional drought and the demise of the Maya culture.

Paired light-dark laminations preserved in the anoxic, non-bioturbated sediments of Cariaco Basin are the direct result of large regional changes in rainfall and trade wind

strength, driven by seasonal shifts in the position of the Intertropical Convergence Zone (ITCZ; Fig. 1) and its associated convection (Peterson et al., 2000; Haug et al., 2001). Light-colored laminae consist mostly of biogenic components deposited during the dry winter-spring upwelling season when the ITCZ is located at its southernmost position and trade winds along the Venezuelan coast are strong. In contrast, dark laminae are deposited during the summer-fall rainy season when the ITCZ migrates to its most northerly position, nearly above Cariaco Basin. Individual dark laminae are rich in terrigenous grains and contain higher quantities of titanium (Ti) and other lithophilic elements. Our interpretation of bulk

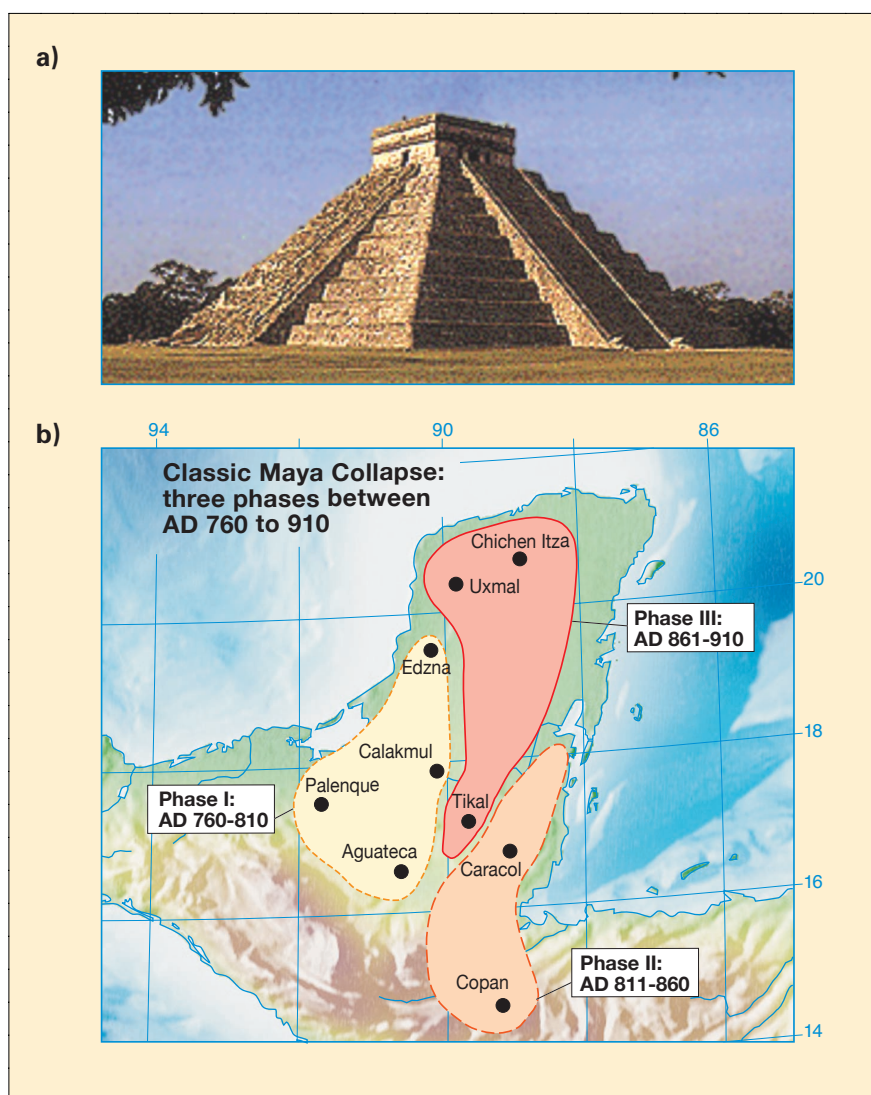


Figure 1: (a) The Pyramid of Chichen Itza in the Yucatan peninsula lowlands. (b) Three phases of Terminal Classic Collapse (~AD 760 to 910). Phase I: Initial abandonment of the western lowlands where rainfall was the primary source of water. Phase II: Abandonment of the southeastern lowlands where freshwater lagoons provided at least some surface water. Phase III: Large-scale abandonment of remaining cities in the central lowlands and the north. (Modified from Gill, 2000).

Ti content as an index of regional hydrologic change, reflecting variations in the mean ITCZ position with time, is supported by comparison of the Holocene Cariaco record with independent paleoclimatic data from the region.

It has been suggested that recurrent patterns of drought played an important role in the complex history of the Maya (Hodell et al., 2001; Gill, 2000). Maya civilization developed in a seasonal desert and was highly dependent on a consistent cycle of rainfall to support agricultural production. Most of the rain available to the Maya fell during the summer, when the ITCZ sits at its northernmost position over the Yucatan. During the winter, the ITCZ is located south of the lowlands and

the climate is dry. Hence, the center of Maya civilization was located in the same climatic regime as Cariaco Basin, with both areas near the northern limit of seasonal ITCZ movement.

In order to inhabit the Yucatan lowlands and to deal with normal seasonal variations in rainfall, the Maya developed elaborate strategies to accumulate and store water. Cities were designed to catch rainfall and quarries were converted into water reservoirs. The Maya also built on topographic highs in order to use the hydraulic gradient to distribute water from canals into complex irrigation systems. Nevertheless, despite its sophistication, the human-engineered system ultimately depended on seasonal rainfall since

natural groundwater resources were restricted over much of the lowlands.

During the Pre-Classic Period prior to about AD 150, Maya culture flourished and the first major cities were built. Between ~AD 150 and 250, the first documented historical crisis hit the lowlands and led to the Pre-Classic Abandonment of major cities (Fig. 2). However, populations recovered, cities were reoccupied and Maya culture blossomed in the following centuries. Around AD 750, at the peak of this Classic Period, the best estimates for the population of the Maya lowlands range from 3 to 13 million inhabitants.

Between about AD 750 and 950, the Maya experienced a demographic disaster as profound as any in human history. During this Terminal Classic Collapse, many of the densely populated urban centers were permanently abandoned and Classic Maya civilization came to an end. What caused this to happen? While the Cariaco Basin record cannot provide a complete explanation, it supports the view that changes in rainfall patterns played a critical role.

Using a Micro-XRF technique not previously applied to sediments, we measured the Ti content (at 50  $\mu$ m spacing) of a slab sample from ODP Hole 1002D taken from the stratigraphic interval known to encompass the period of the Terminal Collapse. Further methodological and chronological details can be found in Haug et al. (2003). Within the Hole 1002D slab sample, we observed distinct Ti minima at depths of ~12 mm, 38 mm, 58 mm and 78 mm (Fig. 2) which we interpret as marking multi-year drought events that began in about AD 910, 860, 810 and 760, respectively. These are superimposed on a period of generally lower Ti content. Not counting the duration of the more severe multi-year droughts, the number of varves between drought events indicates a spacing of ~40 to 47 years ( $\pm 5$ ), a number that agrees remarkably well with the observation of subpeaks at about 50-year intervals in the well-known Lake Chichancanab sediment density record (Hodell et al., 2001).

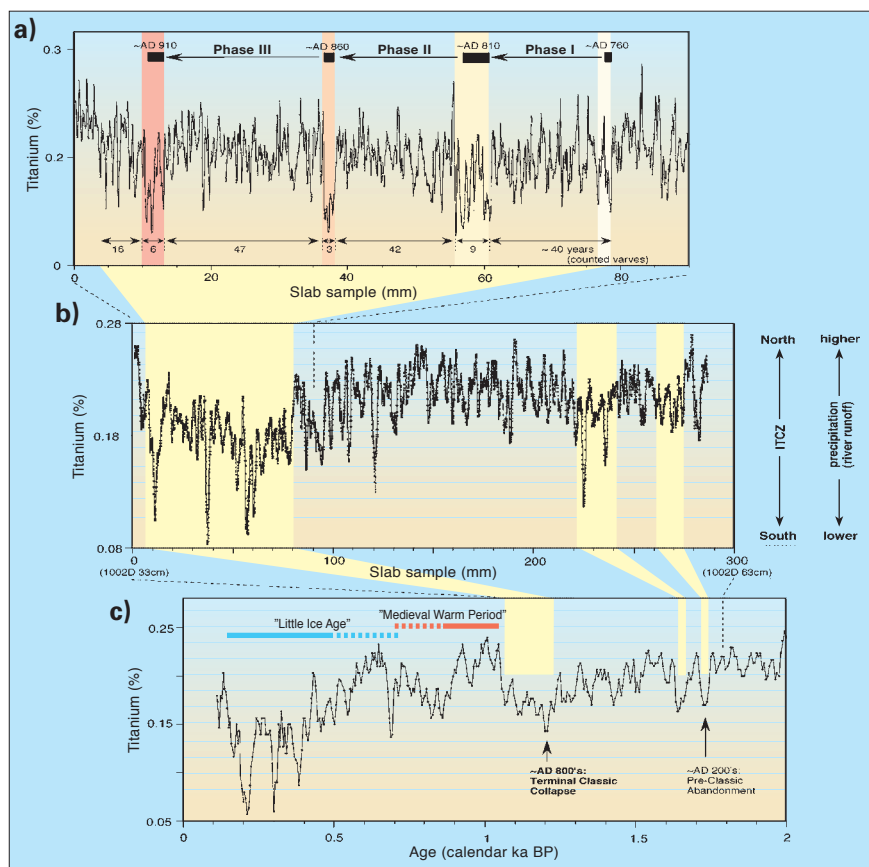


Figure 2: (c) Bulk Ti content (3-point running mean of 2-mm-resolution measurements; Haug et al., 2001) of sediments from ODP Hole 1002C, Cariaco Basin during the last 2000 years. Well-known climate events and major events in Maya civilization history are shown. (b) Bulk Ti content (30-point running mean of 50-μm-resolution analyses) of a 30-cm-long slab sample from companion ODP Hole 1002D in the time interval ~1.8 to 1.0 ka. (a) Bulk Ti content (3-point running mean of 50-μm-resolution analyses) of the slab sample during Terminal Classic Collapse. Gill's three phases of Maya Collapse are shown.

Mayanists generally agree that there is strong evidence in the archeological record for regional variability in the Terminal Classic Collapse. Most would also concur that the collapse occurred first in the southern and central Yucatan lowlands, and that many areas of the northern lowlands underwent similar decline a century or so later. A more controversial tripartite pattern of city abandonment (Fig. 1) was proposed by Gill (2000) based on analysis of the last dates carved into local monuments (stelae). On this basis, Gill argues for three separate phases of collapse that terminated respectively in ~AD 810, 860, and 910. He further speculates that periods of drought triggered the Maya demise. Within the limits of chronological uncertainty, the proposed end dates for each phase of abandonment match the three most severe drought events inferred from the Cariaco Basin record. Considerable variability exists in the distribution and

quality of natural water sources in the Yucatan lowlands, a factor that would clearly come into play during periods of drought. While the northern lowlands have the lowest annual average rainfall, collapsed cenotes (water-filled limestone sinkholes) in this region provide the most direct access to groundwater in the Yucatan. In the central lowlands, some freshwater is available in and around the Petén Lake district. Towards the west and south, access to groundwater is scarce and rainfall was almost certainly the primary source of water for Maya cities. During sustained drought, access to groundwater was likely an important factor in determining which large population centers could survive.

No one archeological model is likely to completely capture a phenomenon as complex as the Maya decline. Nevertheless, the Cariaco Basin sediment record provides support for the hypothesis that regional drought played an important

role in the collapse of Classic Maya civilization, and provides a temporal template for comparison of archeological data.

Drought conditions may also have been responsible for the earlier Pre-Classic abandonment of Maya cities that occurred between ~AD 150 and 250, intervals similarly marked by low sediment Ti. These periods of drought are all most probably the result of climatic conditions that prevented the ITCZ and its associated rainfall from penetrating as far north as usual. A southward displacement of the ITCZ, as indicated by low Ti in Cariaco sediments, would be expected to lead to similar rainfall reductions in the Maya lowlands.

We suggest that the rapid expansion of Maya civilization from AD 550 to 750 during climatically favorable (i.e., relatively wet) times resulted in a population operating at the limits of the environment's carrying capacity, leaving Maya society especially vulnerable to multi-year droughts. Given the perspective of our long, sediment time-series, it would appear that the droughts we have highlighted were the most severe to affect this region in the first millennium AD. The intervals of peak drought were brief, each lasting between ~3 and 9 years. However, they occurred during an extended period of reduced overall precipitation that may have already pushed the Maya system to the verge of collapse.

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## Climate Modeling

ESF/HOLIVAR MEETING. LOUVAIN-LA-NEUVE, BELGIUM, 12-15 JUNE 2002

How could insolation changes, with their modest change in annual mean forcing, cause the drying of the northern subtropical areas—including the full desertification of the Sahara—and the global cooling experienced at high northern latitudes? This question motivated the pioneering general circulation model experiments by Kutzbach and Mitchell in the eighties. They pointed out the importance of the seasonal contrast of insolation in governing the ocean-land temperature gradient. Yet, twenty years later, quantitative understanding of the climate of 6,000 years ago remains a priority and also a prerequisite for confidence in future climate predictions. Modelers have understood the need for considering feedback from the biosphere, the ocean mixed layer and sea-ice, and hence the importance of including these components in state-of-the-art models. While general circulation models have been used to better understand the mean climate features of the Holocene, many new high temporal resolution data have become available, bringing new challenges to climate scientists and modelers. Time series with decadal and annual resolution have shown the need for long transient simulations to reach a better understanding of the mechanisms involved in climate variability and abrupt climate change during the Holocene. Some of the first of these were carried out with models (of intermediate complexity) largely based on a zonally averaged structure with a secondary treatment of the longitudinal resolution. Experiments with CLIMBER-2 (Claussen et al., 1999) suggested that the desertification of Sahara was abrupt because decreasing summer insolation crossed a threshold in Charney's positive monsoon-vegetation feedback. In parallel, Crucifix et al. studied the vegetation-temperature feedback operating at high latitudes, but concluded that this feedback was not strong enough to cause abrupt climate change, at least during the Holocene.

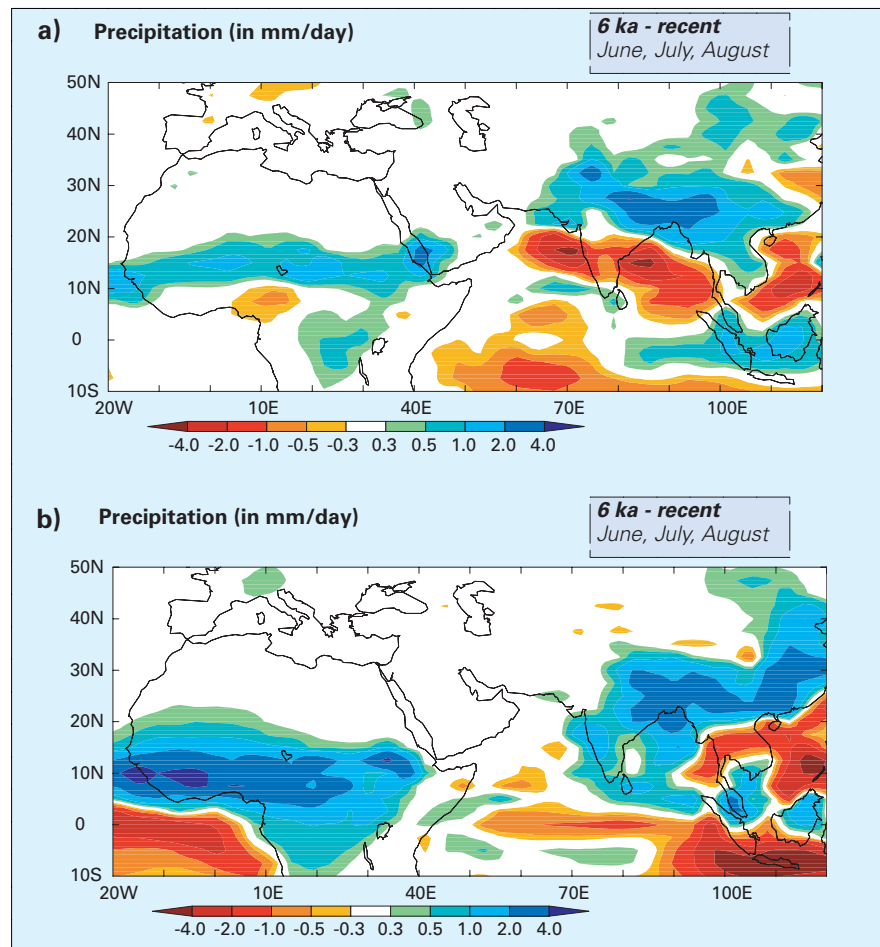


Figure 1: The figure shows the modelled changes in June-July-August mean precipitation for the changes between the mid-Holocene (6000 years ago) and the present day for an example of (a) a PMIP I simulation in which the orbital parameters were changed but the sea surface temperature and vegetation cover were held constant at present day, and (b) a PMIP II style simulation in which changes in vegetation and oceanic circulation were modelled. The monsoons are considerably enhanced when these effects are included. The robustness of these results, and the changes in other regions and interannual variability will be examined in the PMIP II project. The results shown are using version 3 of the Hadley Centre model and all simulations should be considered provisional.

Along with these recently published results, 9,000-year-long time-series computed with 3-D models were presented for the first time. At the cost of increased computing time, the latter models better capture both atmosphere and ocean dynamics, including their natural variability. This sometimes yielded unexpected results. The ECBILT-CLIO model (UCL, Louvain-la-Neuve), for example, exhibits extreme precipitation variability at the century time-scale in the Sahara prior to 5,000 years ago. For the model, insolation is then at such a level that the vegetation-monsoon positive feedback is strongly excited by the internal variability. Even if this result seems unrealistic, it points out the additional complexity brought by

the third dimension, and may be an example of the difficulties that will appear when performing similar experiments with state-of-the-art models.

Currently, state-of-the-art models can only be run for specific time slices (although this is rapidly changing and in the next few years we will start to see the first 9000-year simulations with low resolution versions of state-of-the-art general circulation models). Coupled atmosphere-ocean-vegetation models can be run for simulations up to a millennium in length, and the annual, decadal, and century scale variability can be examined. For instance, changes in ENSO variability during the mid-Holocene can be examined. Such

studies are important to help us understand the controls on climate variability, and to determine whether the current models can successfully reproduce the observed changes. Coupled atmosphere-ocean-vegetation modelling and natural variability will be the major foci of the second phase of the Palaeoclimate Model Intercomparison Project (PMIPII). As well as focusing on the mid-Holocene, the new project will also perform simulations for the early Holocene (see EOS, 1 October 2002, and <http://www-lsee.eea.fr/pmip>).

At such time-scales, it is also crucial to account for solar forcing (i.e., variations in solar activity) and volcanic eruptions. The ECBILT-MOM model, developed at the KNMI, has been used to examine the phase relationships between solar forcing and the extent of glaciers in the Alps. Studies of the last millennium have also highlighted the importance of a good knowledge of the natural variability in forcing mechanisms (e.g. Collins et al., 2002). Model simulations must include this variability if we are to faithfully test the models. Currently, our knowledge of this forcing is generally rather poor.

The increasing importance of gathering more data and modelling expertise on the global carbon

cycle during the Holocene was also stressed. Until recently, most attempts to understand the cause for the CO<sub>2</sub> increase during the Holocene were based on conceptual models. With biogeochemical cycles being implemented in models, a more detailed model-data comparison will be possible. Brovkin et al. (2002) recently illustrated the power of such tools by analyzing the consequences of Holocene climate change and change in ocean alkalinity on the terrestrial and oceanic carbon stocks during the Holocene. They also simulated atmospheric  $\delta^{13}\text{C}$  concentration to compare it with data and test their hypotheses about alkalinity and lysocline depth—even if in this particular case,  $\delta^{13}\text{C}$  data fail to provide sufficient constraint. The alternative approach is to use the model to generate synthetic records. In other words, attempting to reconstruct the raw data seems to be a promising way to better understand how climate worked in the past.

The meeting suggested many future research directions. It also highlighted the importance of studying both past millennium and longer time-scale variability. All of the approaches are valuable for improving our understanding of climate variability and for evaluating climate

models. For this latter problem, it is also essential that we build a new database of the natural variability of climate forcing (especially solar and volcanic), as well as building and maintaining databases of high quality climate proxies for the whole of the Holocene period. The increasing ability of the models and improvements in high-resolution data will ensure that the next few years will be an exciting time.

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## Investigating Holocene Climate Variability: Data-Model Comparisons

ESF/HOLIVAR MEETING. LOUVAIN-LA-NEUVE, BELGIUM, 12-15 JUNE 2002

Comparing model output with information provided by proxy data was discussed in detail. The comparison is challenging because the characteristics of model output and paleodata are very different and many sources of uncertainty exist. Climate is represented at different spatial scales: local in proxy records, several hundred kilometers or more in models. Further, the registered variability in proxies is only partly caused by climatic variations, so that it is necessary to isolate the climatic signal using statistical methods and to represent the non-climatic residuals (perhaps by a suitable stochastic model). Finally, the responses of the proxies to the local or large-scale climate may be non-invertible. A number of model-proxy compari-

son methods were presented at the workshop to address some of these difficulties.

The traditional *inverse* approach is to reconstruct some aspect of climate from proxy data (often including an aggregation to larger spatial scales more suited for comparison with model output) and then compare the reconstruction to simulated climate data. It was demonstrated during the workshop how the non-climatic residuals influence variance, trends and spatial patterns and that appropriate treatment of these residuals can avoid biased comparisons. Examples were given (Collins et al., 2002) of the comparison, at the inter-decadal time-scale, between levels of internally generated variability simulated during a

GCM (coupled ocean-atmosphere general circulation model) control run, and the temperature variability reconstructed from tree-ring density across the Northern Hemisphere. The results were sensitive to the processing of the tree-ring data but indicated an underestimation of the variability by the model. This could be partly accounted for by the influence of natural external forcing changes (solar irradiance or volcanic aerosols). Comparisons of proxy-based temperature reconstructions with EBM (energy balance model) simulations of the response to natural and anthropogenic forcings (updated from Crowley, 2000) were presented, with the reconstructions used to identify the climate sensitivity that provides the best fit between model and data

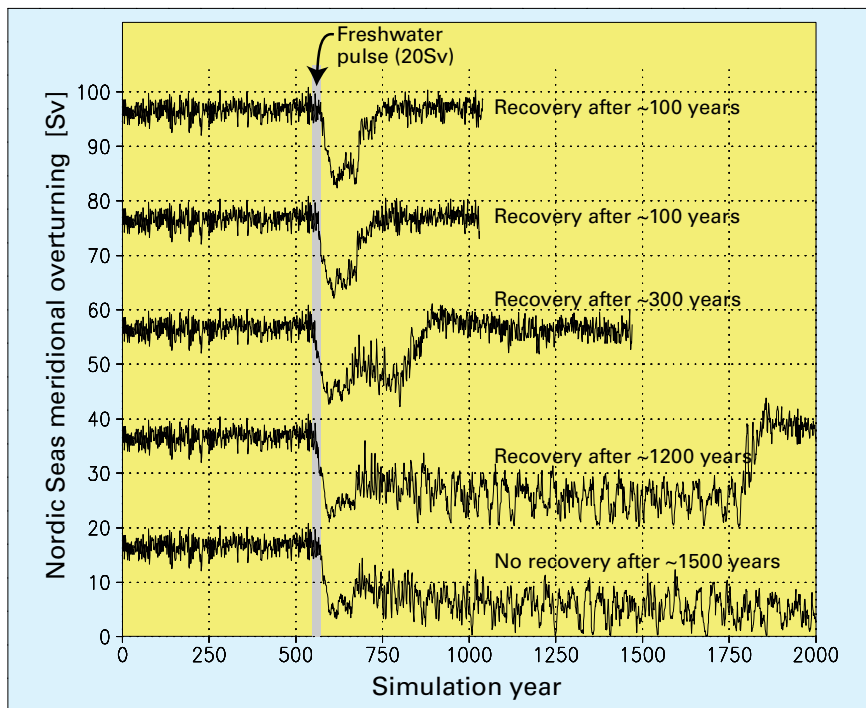


Figure 1: Simulation of the 8.2 ky BP event (Renssen et al., 2002): response of the thermohaline circulation to freshwater pulses of 20 Sv released during simulation years 550-570 in the Labrador Sea, for 5 ensemble members (each offset by 20 Sv for clarity). Other forcings are representative of 8.5 ky BP.

for the past 1000 years. On longer time-scales, both quantitative and qualitative comparisons of proxy data with the climate simulated by GCMs and EMICs (Earth system model of intermediate complexity) were presented, using simulations of time slices, transient simulations of particular events (e.g., Fig. 1 and Renssen et al., 2002) and transient simulations of virtually the whole Holocene (Crucifix et al., 2002; Brovkin et al., 2002).

The workshop participants agreed on the great potential offered by the *forward-modeling* approach, in which appropriate process-based (physical, biological, chemical) or empirical models are driven by climate model output to simulate a proxy value or time series that is then compared with the actual proxy data. This approach can deal explicitly with non-linear and non-invertible proxy response to multiple climate drivers, and can also aid our understanding of the processes responsible for the proxy behavior. Insufficient development, tuning and validation of process-based models for different proxy types and locations has restricted the application of the forward-modeling approach to date but noteworthy progress was reported at the workshop, in-

cluding the simulation of tree rings, ice cores, glacier length and local sea level (e.g., Reichert et al., 2001; Weber and Oerlemans, 2002).

While inverse reconstruction and forward modeling with proxy data allow *comparison* with model output, presentations were also made of possible methods for the *combination* of proxy and model data to provide improved estimates of past climate variations. One technique, named DATUN (Data Assimilation Through Upscaling and Nudging, Jones and Widmann, 2002), 'nudges' the climate towards an atmospheric circulation state that has been reconstructed from a set of paleodata, while remaining nearly consistent with the model's physics and the applied external forcings. A second method was proposed (by Mat Collins), whereby many realizations of each simulation year are generated (again under appropriate external forcing variations) and the closest analog to the available paleodata for that year is selected before proceeding to the next year of the simulation. It was proposed to concentrate efforts on specific periods during the Holocene:

- the classical "Little Ice Age" (16<sup>th</sup> to 19<sup>th</sup> century AD),

- the Sub-Boreal-Sub-Atlantic transition around 850 BC (2750 y BP),
- the termination of the African Humid Period around 6–5 ky BP, and
- the 8.2 ky BP cooling event.

Evidence was presented from proxy data that significant climate change occurred during these periods. The stronger signal-to-noise ratio for these events should make diagnosis of climate behavior more feasible in both data and models. It was noted (Fig. 1) that model studies focusing on these periods should also aim to perform ensemble runs to capture the range of inherent model variability (e.g., Renssen et al., 2002), thereby better allowing the model to encompass the single realization represented by reality (as registered in proxy data).

Discussion made it clear that a hierarchy of modeling studies, including GCMs and EMICs, was considered essential given the uncertain forcings, the need for ensemble simulations, and the complex interactions taking place within and between subsystems of the Earth system. It was proposed that the HOLIVAR program establishes a database of the different model runs covering the Holocene that would be accessible to the scientific community.

Further information is available at <http://www.cru.uea.ac.uk/~timo/holivar/>

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For full references please consult:

[www.pages-igbp.org/products/newsletters/ref2003\\_2.html](http://www.pages-igbp.org/products/newsletters/ref2003_2.html)

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## Environmental Magnetism

INDIAN INSTITUTE OF GEOMAGNETISM, NAVI MUMBAI, INDIA

A one-day workshop on "Environmental Magnetism" was held at the Indian Institute of Geomagnetism (IIG), Navi Mumbai in honor of the donation of equipment from the Alexander von Humboldt Foundation, Germany to IIG's Environmental Magnetism Laboratory (EML). The equipment was formally handed over to IIG's EML group on 15 April 2003 by Ms. Gerda Winkler, Deputy Consul General of Germany - Mumbai. EML was initially set up at the Colaba campus in 1996 albeit only with basic magnetic measurement equipment. The equipment donated by the Humboldt Foundation includes a Spinner Magnetometer and a Thermal Magnetic Susceptibility System for temperature measurement in the range of -200°C to 800°C. Other equipment at EML includes an AF Demagnetizer, Dual-Frequency Magnetic Susceptibility Meter and Pulse Magnetizer. Thus, EML is now a state-of-the-art facility for carrying out sophisticated environmental mineral magnetic experiments on all types of geological materials.

The purpose of the workshop was to announce the availability of EML's high-tech equipment to the Indian scientific community and to highlight the merits of applying mineral magnetism techniques for resolving geophysical, geological and paleoclimatological problems. The scientific program was jointly convened by N. Basavaiah (IIG, Navi Mumbai) and A.S. Khadki-kar (Agharkar Research Institute (ARI), Pune). Participants included scientists from Tata Institute of Fundamental Research, India Institute of Technology-Powai, IIG, Bhabha Atomic Research Centre, ARI, Deccan College, Oil and Natural Gas Corporation and Maharaja Sayajirao University of Baroda.

The workshop consisted of a general and a technical session. The general session, open to all, was devoted to "Space Weather". Prof. G. S. Lakhina (Director, IIG) gave a lecture on the effects of the sun's radiation on Earth's magnetic



Figure 1: Lonar Lake

field and the manifestation of consequences of these interactions in the interplanetary region.

The scientific session was opened with an overview of research using mineral magnetism being carried out in various parts of India. The application of this technique has confirmed the presence of the younger dry cold event recorded in proglacial lake deposits of Garbyang, higher central Himalaya. Other sites being studied across India include Lonar Lake (Fig. 1), Gulf of Kachh and Cambay, east coast deltas and their mangrove deposits, and the Thar Desert lakes. The usefulness of gleaned information from mineral magnetic properties to reconstruct past climates was discussed. The importance and utility of magnetic susceptibility studies in understanding the Deccan trap basalts was also covered in great detail. The practical significance of domain states of Deccan basalt as paleoenvironmental indicators was highlighted. The importance of field studies in deciphering Quaternary climate and geoarchaeological features was delineated by discussing specific examples covering different parts of India, Nepal and Israel. It was shown how field evidence of environmental change and paleomonsoon signatures are reflected through the formation of paleosols, fluvial landforms and desert dunes. The highlight of the meeting was an introduction to the principles and applications of Mössbauer spectroscopy in elucidating magnetic mineralogy. Deciphering the oxidation state of iron in magnetic minerals and its general application to geological problems was discussed.

There is a universal need to have reliable constraints on the timing of any geological formation. Radiometric dating is one such authentic tool, however, the cost factor deters scientists from widely adopting the technique. The workshop highlighted the relatively inexpensive luminescence dating method, which can provide accurate data at a lower price. Chronological results on Aeolian deposits of Western India were presented.

The scientific session also saw discussion on different aspects of climate change and paleoenvironmental reconstruction involving field studies in targeted regions. Results of granulometric and archaeological studies in the Mahi and Sabarmati River basins, the salt lakes of the Thar Desert, and mangroves were presented. The significance of lakes as archives of climate change was emphasized by many participants. The workshop stressed the need to integrate multidisciplinary approaches in the understanding of past climate change through remote sensing and geomorphologic studies.

The workshop concluded with a panel discussion that generated several recommendations. Foremost among them was a proposal to undertake a multilayered and multidisciplinary study to clarify the origins of Lonar Crater Lake in Maharashtra. The calibration of instruments through inter-laboratory and multi-instrument comparisons was also recommended.

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## Changing Perspectives for Changing Times

My love affair with the Holocene began almost 50 years ago. In those days it was called the 'Post glacial', or the 'Flandrian'. At the time, my Cambridge mentors were much beguiled by the Late glacial. For me though, the main excitement came from trying to reconstruct and better understand the peopled landscapes of the past. Despite many deflections from that concern, it has returned consistently, but in so doing, it has not simply been renewed, but rather reinvented. The passage of time has transformed the priorities for Holocene research in ways that could not have been imagined half a century ago. The idea that learning about past climate variability might inform our view of impending future changes would have seemed far-fetched, and the concept of multi-proxy climate reconstructions based on biological remains, quite out of the question.

In the late 1950's, radiocarbon dating was in its infancy and, for most researchers, dates were extremely difficult to obtain. What will be the 'state of the art' and what will our current 'tool kit', look like in fifty years time? Technical innovations are among the most obvious facilitators of future changes in methodology, but for anyone lacking the relevant expertise in instrument design, they are among the least predictable. In my own experience, the interactions between those posing palaeo-environmental questions and those contributing the technology for resolving them, have been rather like a series of dead ends suddenly and unexpectedly opening out into serendipitous partnerships of great delight and excitement. Since the palaeo-scientists' responsibility begins with the questions posed, we should turn to these.

I think there are some safe assumptions – that the underlying 'future-oriented' research agenda for palaeo-science will not be entirely replaced by something quite new and different; the synergy between model and data communities will increase and become central to most advances in the field; computing power will serve this synergy with ever enhanced capabilities; the speed of data acquisition and assimilation will increase at an accelerating rate; the climatic calibration of environmental proxies and associated uncertainties will become increasingly quantitative; and finally, comparisons between past and present climates on a regional, zonal, hemispheric and global basis will become increasingly secure.

Holocene research has strengths arising from the unique opportunities it offers for secure quantitative proxy calibration with minimum extrapolation, for exploring the antecedents of current conditions, whether of climates or ecosystems, for generating multi-archive/multi-proxy reconstructions with high temporal resolution, for elucidating the long term behaviour of current modes of variability, and for providing the longer term historical context for the detection and attribution of future environmental changes. In my view, two of the most intransigent weaknesses are in the areas of chronology and the reconstruction of the long-term dynamics of terrestrial ecosystems. Resolving many of the crucial future research questions will demand increasingly precise and accurate chronologies, and in some key environmental contexts, they remain elusive. My second point may seem harsh or ill-informed, but I make it nonetheless, for it also signals a major opportunity.

If we consider the synergy between PAGES and CLIVAR, it rests in part on a shared exploitation of the continuum between the palaeo-record and the period of direct observations. Palaeo-climatology, within this context, makes a crucial contribution to dynamics rather than 'history'.

As and when the implications of future global change become more clearly and widely apparent, one corollary must surely be a growing interest in the past *response* of ecosystems to a variety of interacting perturbations, on a range of timescales.

What if the hoped-for broader synergy between 'palaeo' and 'present/future' science fails to develop? Certainly, that threat lies implicit in the gap between ecosystem modelling communities using inputs derived from the short period of direct observations, and the terrestrial palaeo-science community that is often seen as dealing with history rather than process. When we compare the situation with that prevailing at the CLIVAR/PAGES interface, the gap is all the more unfortunate: whereas a global network of standardised and verifiable climate records goes back for a century or so, direct observations of ecosystem structure and function are much less systematic and more recent and patchy over most of the world. Closing this gap between 'palaeo' and 'process' in terrestrial ecosystem studies is an immense challenge, but one that must be met if both communities are to benefit and to make the best possible contribution to our understanding of ecosystem responses to global change.

The time interval from which much of the necessary evidence will be drawn is the Holocene. During its life time, HOLIVAR will have helped to strengthen the basis for future research, both by coordinating and publicising what has been achieved so far, and by helping to create a cohort of young researchers whose skills and opportunities will, in due course, outstrip those of their mentors. That is as things should be.

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## CALENDAR 2003 / 2004

**October 27 - 30, 2003, Seattle, USA**  
**First SEARCH Open Science Meeting**

Further information:  
<http://www.arcus.org/search/search.html>

**November 2 - 5, 2003, Seattle, USA**  
**2003 GSA Annual Meeting: Special PAGES Sessions**  
**T96: Lakes and Holocene Environmental Change**  
**T98: Low Latitude Influences on the High Latitude, or the Other Way Around**

Further information:  
<http://geosociety.org/meetings/2003/>

**November 16 - 19, 2003, Trieste, Italy**  
**First International Young Scientists Global Change Conference**

Further Information:  
[http://www.ictp.trieste.it/%7etwas/YS\\_START\\_2003\\_announce.html](http://www.ictp.trieste.it/%7etwas/YS_START_2003_announce.html)

**April 1 - 7, 2004, Berlin, Germany**  
**Paleoclimate Proxy Data for Reconstructing Holocene Environments of West Asia**

Further information:  
[harvey.weiss@yale.edu](mailto:harvey.weiss@yale.edu)

**July 4 - 9, 2004, Granada, Spain**  
**International Palynology Congress (IPC)**  
**Tropical Session**

Further information:  
<http://www.11ipc.org/>  
[http://www.pages.unibe.ch/calendar/2004/topical\\_IPC.html](http://www.pages.unibe.ch/calendar/2004/topical_IPC.html)

**September 1 - 3, 2004, Bergen, Norway**  
**Bjerknes Centenary 2004: Climate Change in High-Latitudes**

Further Information:  
<http://www.bjerknes.uib.no/conference2004/>

<http://www.pages-igbp.org/calendar/calendar.html>

## New Paleofire Database:

The IMPD Advisory Board announces the establishment of an archive of fire history records preserved in natural proxies, called The International Multiproxy Paleofire Database (IMPD). The primary purpose of the IMPD is to provide a permanent repository for high-quality fire-history data from around the world. The IMPD is designed to serve the needs of the fire research community, climate and global change researchers, policy makers, and resource managers. NOAA



and the USDA are sponsoring this effort, and the database will be housed at the World Data Center for Paleoclimatology in Boulder Colorado. The archive will include fire history records based on both tree-ring and sedimentary charcoal data.

We are now soliciting paleofire data for inclusion into the IMPD through online submission forms. The IMPD web site and submission forms are at:

<http://www.ngdc.noaa.gov/paleo/impd/>.

Please take a look at these pages and let us know if you have any questions or suggestions. We can also accommodate bulk contributions, if that is an easier way for you to contribute data. Please contact our database manager, Mike Hartman ([Michael.Hartman@noaa.gov](mailto:Michael.Hartman@noaa.gov)) for information on that.

Thanks in advance for your contributions!

### The IMPD Advisory Board:

*Peter Brown and Andrea Brunelle (Co-chairs)*

*Eric Grimm, Henri Grissino-Mayer, Michael Hartman, Emily Heyerdahl,*

*Thomas Kitzberger, Tom Swetnam, Cathy Whitlock, Connie Woodhouse*