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PAGES news

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Paleoceanography

Editors:

Markus Kienast, Jean Lynch-Stieglitz, Louise Newman and Thorsten Kiefer

The Marion Dufresne is a research vessel equipped for the collection of long, large-diameter marine sediment cores. Foraminifera and Coccolithophorids preserved within the sediment are used to reconstruct hydrographical and biogeochemical conditions of the paleo-ocean.

Editorial: Paleoceanography

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The ocean covers 70% of the Earth's surface, contains 55 times more CO_2 than the atmosphere and redistributes heat at a rate comparable to the atmosphere. Understanding the ocean's role in past climate change is thus of fundamental importance for understanding past (and future) global changes.

This PAGES special newsletter section highlights recent advances in paleoceanography. Many of these studies were presented in one form or another at the 9th International Conference on Paleoceanography (ICP9), which took place in September 2007 in Shanghai, China. This meeting was convened as a tribute to Sir Nicholas Shackleton, who was instrumental in developing not only the field of paleoceanography but also the tradition of this triennial meeting and the strong international community it represents. It seems fitting not only to reflect on the contributions of this community over the decades since the first ICP in 1983 but also on the prospects for further influence in the near- and long-term future.

From the outset, paleoceanographers have made fundamental contributions to our understanding of oceanography, climatology and biogeochemistry. The continuous nature of the deep sea record allowed for a better understanding of the history of Quaternary ice-volume changes and their relationship to orbital forcing. Maps of ice age temperatures (CLIMAP) provided the quantitative boundary conditions necessary for the first paleoclimate simulations in general circulation models. Reconstructions of deepwater properties demonstrated that deepwater flow patterns might not have been as stable as previously thought, and were likely involved in glacial-interglacial changes in atmospheric CO_2. Similarly, geochemical and faunal records of algal productivity pointed to time-varying efficiency of the biological sequestration of atmospheric CO_2 into the ocean's interior.

More recently, paleoceanographic studies have been uncovering the mechanisms behind the abrupt changes in climate and greenhouse gas concentrations, as revealed in the ice core records from Greenland and Antarctica. Newly developed and refined proxy methods and targeted coring, much of it coordinated within the IMAGES and IODP programs, are now enabling (semi-)quantitative reconstructions of the cause, nature and extent of rapid changes in ocean circulation (see highlights by Boessenkool, Lynch-Stieglitz, Gherardi, Schmidt) and its linkage with atmospheric circulation patterns (Grimalt, Weldeab, Yamamoto, Kaiser) and deep ocean CO_2 reservoirs (Galbraith) on timescales ranging from millennial to annual. New approaches to reconstructing past changes in sea level challenge the traditional view of very slow ice-sheet growth during the glacial period and rapid loss during the glacial termination (Siddall).

Increasingly, the paleoclimate community is contributing to our understanding of future climate change. Paleoceanographic data and modeling are being used to explore the sensitivity of the ocean/climate/biology systems to increased CO_2. The Late Paleocene-Eocene Thermal Maximum 55 Myr ago (Sluijs) provides a view of the chemical, biological and climatic consequences of adding a large amount of carbon to the ocean-atmosphere system. Pushing our reconstructions of CO_2 beyond the limit of ice core records (Hönisch) will also be crucial to our ability to assess climate sensitivity.

Paleoclimate data are being used to test the models that are used for future climate prediction and provide the context to better understand the magnitude of anthropogenic changes relative to natural variability. We, as data-generating paleoceanographers, are being challenged by modelers and climate dynamicists to make more quantitative reconstructions of ocean and climate variables, and to provide error bars along with these measurements. We are also being asked to do a better job of synthesizing our results in a way that they can be readily used and understood by non-specialists. This will mean some adjustments in the way we have always worked and will also require similar adjustments on the part of our new collaborators outside of the paleo-realm (e.g., explicitly modeling paleoceanographic proxies). We look forward to seeing the advances this will bring to paleoceanography and our understanding of the Earth System in the coming decades.

PAGES Calendar 2008

05 - 07 March 2008 - Boulder, USA
38th Annual International Arctic Workshop
Associated Meeting: 8 March 2008 - PAGES Arctic 2k Workshop
http://instaar.colorado.edu/meetings/AW2008/

20 - 26 April 2008 - Piran, Slovenia
ESF EuroCLIMATE Spring School - "Late Quaternary timescales and chronology"
www.pages-igbp.org/calendar/calendar08.html#AnchorApril

26 - 28 March 2008 - Zürich, Switzerland
"Radiocarbon and Archaeology" 5th International Symposium
www.c14archaeology.ethz.ch/

05 - 09 May 2008 - Cape Town, South Africa
4th IGBP Congress: Sustainable Livelihoods in a Changing Earth System
www.igbp2008.co.za/

26 - 29 May 2008 - Louvain-La Neuve, Belgium
Climate Change: From Geologic Past to Uncertain Future
www.uclouvain.be/en-berger2008.html

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

Inside PAGES

PAGES SSC changes in 2008

2008 sees a major changeover of members on the PAGES Scientific Steering Committee (SSC). After six years of dedicated service, Rick Battarbee (EXCOM), Frank Sirocko and Pinxian Wang (EXCOM; Vice-Chair) have rotated off the committee. While their presence and input at SSC meetings will be missed, they will continue to play key roles in PAGES new scientific structure, thereby guaranteeing their continued involvement.

Joining the SSC this year are four new members. John Dearing (UK) is Professor in Physical Geography at the University of Southampton.

He has a record of years of committed work within PAGES through his leadership of the PAGES Focus on past human-climate-ecosystem interactions. His research expertise is in reconstructing past environmental change through analyses of lake sediments, soils and other archives, and in the integration of climate, human activities and environmental processes. Zhongli Ding (China), a professor at the Institute of Geology and Geophysics, Chinese Academy of Sciences, is specialized in eolian (loess) deposits and eastern Asian paleoclimate of the Quaternary and Neogene. He played a key role in the organization of the 2nd PAGES Open Science Meeting in Beijing in

2005 and is currently involved in setting up a new Working Group on Global Monsoon. Michael Schulz (Germany) is Professor for Geosystem Modeling at Bremen University, coordinator of the PAGES-relevant "Integrated analysis of interglacial climate dynamics" priority program of the German Research Foundation, and PAGES representative to the Oceanography Senate of the German Science Foundation. He specializes in modeling and paleoceanography.

Eric Wolff (UK), a Principal Investigator at the British Antarctic Survey, is a leading ice core scientist, specializing in paleo-atmospheric chemistry studies. He has played a major role in steering large international programs, such as EPICA (European Project for Ice Coring in Antarctica) and IPICS (International Partnerships in Ice Core Sciences).

For more details on PAGES SSC and individual members, see www.pages-igbp.org/people/sscmembers.html.

SSC meeting 2008

This year, the annual meeting of the SSC will be part of a congress convened by PAGES umbrella organization, the International Geosphere-Biosphere Programme (IGBP), to be held 5-9 May in Cape Town, South Africa. A central idea of this Congress is to gather the SSCs of all IGBP projects (see page 6-7 for features of some of them) and associated organizations in one place, and thus create a platform for cross-project interaction and development of collaborations. This meeting will be a good opportunity to propose your ideas for new PAGES activities. Please contact the PAGES IPO or an SSC member with your ideas.

Next issue of *PAGES news*

The second issue of the PAGES newsletter for 2008 will contain a special section on data-model comparisons. It will be guest-edited by Gerrit Lohmann, who spent some weeks as a Guest Scientist at the PAGES IPO in Switzerland. If you are interested in contributing a science highlight to this special section, please contact Gerrit directly (Gerrit.Lohmann@awi.de). You can also contribute a Science Highlight or Program News to the open section of the newsletter. The deadline is 9 February 2008. Guidelines for contributions can be found at www.pages-igbp.org/products/newsletters/instructions.html.

PAGES Sessions at the General Assembly of the European Geosciences Union

13 - 18 April 2008 - Vienna, Austria

We encourage you to submit an abstract to one of the following PAGES co-sponsored and endorsed sessions before the 14 January 2008 deadline:

CL6 - Past atmospheric circulation (co-sponsored)
www.cosis.net/members/meetings/sessions/information.php?p_id=298&s_id=5339
CL7 - Land-Atmosphere-Ocean linkages throughout the Quaternary (co-sponsored)
www.cosis.net/members/meetings/sessions/information.php?p_id=298&s_id=5403
CL32 - Advances in Applied Quaternary Geochronology (co-sponsored)
www.cosis.net/members/meetings/sessions/information.php?p_id=298&s_id=5364
CR4/NH7.4/CL51 - Ever smaller than now? Holocene glacier history with climatic background (endorsed)
www.cosis.net/members/meetings/sessions/information.php?p_id=298&s_id=5369

There are many more PAGES-relevant sessions, particularly under "Climate: Past, Present, Future".
For more information: http://meetings.copernicus.org/egu2008/

The Paleoclimate Reconstruction Challenge

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Detailed understanding of the full range of annual and seasonal climate variability over the past millennium forms an important basis for the interpretation of the observed record, and for gauging the response of the climate system to various forcings. Using different methods and proxy networks, the climate reconstructions available show general similarity in their depiction of large-scale mean-temperature evolution, particularly at the decadal to centennial timescale. There are, however, important differences in reconstructions at the interannual and multi-centennial to millennial scale. It is unclear whether these differences result from the selection of specific proxy networks, the potential inability of the included proxies to resolve information at all timescales, or the algorithms themselves (National Research Council, 2006). The paleoclimate community needs to establish a protocol for reassessing its methods to rebuild confidence in the reconstruction efforts.

The last millennium Paleoclimate Reconstruction (PR) Challenge—run under the auspices of the PAGES-CLIVAR-Intersection and co-sponsored by the Electric Power Research Institute (EPRI)—will allow us to directly address these concerns and to establish objective reconstruction benchmarks. The idea is to use results from state-of-the-art coupled Atmosphere-Ocean-General Circulation Models (AOGCMs) in both open- and blind-test reconstruction exercises. Individual reconstruction groups (and anyone who would like to participate) will be brought together and issued a small set of realistic pseudo-proxy series and calibrated "instrumental data" drawn from the model output. They will be asked to reconstruct the simulated climate evolution to the best of their technique's ability. By comparing reconstructions with the full, "true" model climates, each group can assess their performance in great detail. A key objective of this project is to document how much of the true climate can be described with the combined set of reconstruction results, to determine which aspects of the overall or regional climate are captured well, and whether important elements are being missed.

Beyond the main goal of improved understanding of the performance of climate reconstruction methods, it is hoped that the PR Challenge will improve exchange among the different paleoclimate reconstruction groups and provide a flexible platform for enhanced interaction with the associated disciplines in climate modeling and statistics. The latter might be particularly helpful with regard to a more formal assessment and quantification of uncertainty and regional climate understanding. The results of the PR Challenge will support and steer the community to develop strategies for improving reconstruction methods, so that past climate variations can be better understood.

Paleoclimate Reconstruction (PR) Challenge

Four key components of the PR Challenge:

A Web-Based Open Reconstruction Access Point coordinated with the NOAA World Data Center will serve as the exchange platform for long-term archiving of methods and data.

The Open PR Challenge Intercomparison provides a set of realistic pseudo-proxy series from existing last millennium AOGCM simulations for a standardized validation of individual reconstruction methods, as well as for a cross-method intercomparison. Reconstruction targets are temperature fields, and ideally also moisture and pressure fields, at seasonal resolution if possible.

The Grand PR Challenge is a double-blind reconstruction exercise based on output from a new, coupled simulation with a realistic but unknown forcing history. The challenge is to provide reconstructions of seasonal temperature patterns, as well as moisture and circulation (pressure) changes.

Post-PR Challenge Assessments will coordinate the cross-community (proxy, modeling and statistics) analysis of PR Challenge results in two crucial workshops that aim at:

1) Evaluation: Identifying the current status in reconstructing climate of the last millennium and identification of outstanding critical issues. Formulation of recommendations for future research foci.

2) Climate Model Assessment: Comparison of climate derived from real world proxies with climate reconstructed from simulated pseudo-proxies, to assess the applicability of model frameworks for studying climate variability.

PR Challenge organizers:
Caspar Ammann
National Center for Atmospheric Research
Nicholas Graham
Scripps Institution of Oceanography and Hydrologic Research Center
Rosanne D'Arrigo
Lamont Doherty Earth Observatory
Thorsten Kiefer
PAGES International Project Office

Reference

National Research Council 2006: *Surface Temperature Reconstructions for the Last 2 000 Years*, The National Academies Press, Washington.

BIPOMAC (Bipolar Climate Machinery)

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To facilitate better understanding of the ocean-atmosphere-ice related processes that trigger, amplify and propagate climate change in polar regions, the international and multidisciplinary project "Bipolar Climate Machinery" (BIPOMAC), a study of the interplay of northern and southern polar processes in driving and amplifying global climate variability has been included as a core project in the International Polar Year 2007/08 (IPY; www.ipy.org, Project #130). BIPOMAC has now also been incorporated into PAGES new science program and represents one of the three themes in PAGES Focus 3 "Land/Ocean/Cryosphere/Biosphere Dynamics and Linkages".

Paleoclimatic research and climate models demonstrate that processes and varying conditions in polar regions play a key role in driving and amplifying global climate variability at centennial to millennial timescales. The significance of polar regions in the global climate system is evident from the distinct warming of the polar regions above that of the global average. Important polar processes include the biological cycling and physical circulation in the polar oceans, the formation and distribution of sea ice, the behavior of permafrost areas, atmospheric circulation and transport of water vapor, and the volume and stability of continental ice. Polar and subpolar oceans represent High-Nutrient-Low-Chlorophyll (HNLC) areas and also potentially major CO_2 sinks during glacial conditions, when increased input of micronutrients, like iron, stimulates primary production and enhances the biological pump. Meltwater pulses, which alter surface ocean density gradients, can also induce rapid climate change. The impact of such environmental events in the Arctic Ocean, North Atlantic, North Pacific and Southern Ocean may propagate globally via ocean circulation through the operation of the "bipolar seesaw".

New results from Greenland and Antarctic ice cores have provided details on the methane-linked age relationship of climate variability and its development, particularly over the past 55 kyr (EPICA, 2006). The BIPOMAC network will generate the knowledge necessary to clarify the intertwined roles of bipolar ice, ocean and atmospheric processes in climate evolution and sea level change at different operational modes of the bipolar climate machinery. This knowledge will come from the well-organized collaboration of paleoceanographers, paleolimnologists, geophysicists, glaciologists and modelers, who will study marine and terrestrial records covering the Pliocene to Holocene from both polar regions. This will also include records from areas that have been sparsely investigated to date, if at all (central Arctic Ocean, Arctic Pacific, NE Siberia, Antarctic Pacific, Antarctic ice shelves). Sampling of these areas will benefit from recently developed technologies and encourage further developments at a larger scale (e.g., deep drilling in sea ice covered areas and through ice shelves).

The goals of BIPOMAC

- Decipher the polar mechanisms (ice-permafrost-ocean-atmosphere) and thresholds in triggering rapid (10^2-10^3 yr) climatic changes during warm and cold conditions, and compare the spatial and temporal evolution of such changes in both polar regions and their link with low-latitude climate history.
- Reveal the mechanisms and timing of past bipolar and zonal climate teleconnections.
- Study Pleistocene linkage of climate and biogeochemical cycles on orbital timescales in the 100 kyr and 40 kyr world.
- Document the occurrence and timing of ice, ocean and land conditions of warm early Pliocene in both polar regions.
- Generate networks of polar climate records (ice, ocean, land) to enhance our knowledge of meridional and zonal climate variability during warm and cold climate conditions.

BIPOMAC also includes projects aiming to develop innovative methods for the enhancement of paleoenvironmental reconstructions and increase the accuracy in dating polar records.

Substantial BIPOMAC fieldwork is scheduled or is currently being accomplished for IPY2007/08. Further fieldwork, research and synthesis will extend beyond the IPY, as integration of laboratory results, modeling and datasets remains a key aim of PAGES Focus 3. This research will substantially increase our ability to forecast future climate and sea level change and focus our responses to the environmental challenges that we are, and will be, facing.

Reference

EPICA community members, 2006: One-to-one coupling of glacial climate variability, *Nature*, **444**: doi:10.1038/nature05301

IGBP (International Geosphere-Biosphere Programme): Ocean research programs

Paleoceanographic research requires an understanding of modern oceanic processes and interaction with other components of the Earth System. Thus, it is important for the paleocommunity to be aware of the research being conducted by the wider marine science community. Moreover, in order that the most relevant research questions are addressed, paleoscientists should keep up to date on the scientific focus of their modern-ocean colleagues. Marine science is represented by a number of Core Projects in IGBP that encompass not only the ocean but also the ocean-land and ocean-atmosphere interfaces. Following is an outline of these programs, their aims and current focus.

LOICZ (Land-Ocean Interactions in the Coastal Zone)

www.loicz.org

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Established in 1993, LOICZ is a joint IGBP/IHDP Core Project investigating changes in the biogeochemistry and physics of the coastal zone. In order to address the human dimensions of the coastal zone, LOICZ expanded its areas of research in 2003 to include social, political and economic sciences. Geographically, LOICZ also includes the river catchment scale, in order to encompass land-based processes, where appropriate. *The main goal of LOICZ is to provide the knowledge, understanding and prediction needed to allow coastal communities to assess, anticipate and respond to the interaction of global change and local pressures, which determine coastal change.* Research is being carried out in LOICZ within five Scientific Themes defined in the Science Plan and Integration Strategy (2005):

- Vulnerability of Coastal Systems and Hazards to Society
- Implications of Global Change for Coastal Ecosystems and Sustainable Development
- Human influences on the River Basin Coastal Zone Interactions
- Biogeochemical Cycles in Coastal and Shelf Waters
- Towards Coastal System Sustainability by Managing Land-Ocean Interactions

In order to improve information synthesis, as well as to keep scientific priorities flexible, LOICZ is currently focusing on three Priority Topics (2006-09):

1) Linking Social and Ecological Systems in the Coastal Zone
2) Assessing and Predicting Impact of Environmental Change on Coastal Ecosystems
3) Linking Governance and Science in Coastal Regions

Research explores the role that humans play in the coastal zone, their vulnerability to changing environments, and the options to protect coasts for future generations. In addition, Cross-Cutting Activities (Modeling and Typology; Variability Analyses; Capacity Building) help to better conceptualize, integrate, and generalize knowledge. LOICZ has a geographically widespread organizational structure, with Regional Nodes in Singapore, Sri Lanka, and China. These offices promote and coordinate regional and local contributions to the global research, thus facilitating links and exchanges between international, national and local science and policy.

IMBER (Integrated Marine Biogeochemistry and Ecosystem Research)

www.imber.info

Sylvie Roy

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A newly emerging challenge, dictated by society's need to understand and respond to the impacts of global change, is to determine the inter-relationships between biogeochemical cycles and ecosystems, and to quantify and predict responses of the marine system to natural and anthropogenic perturbations. *The goal of IMBER is to investigate the sensitivity of marine biogeochemical cycles and ecosystems to global change, on timescales ranging from years to decades.*

Five working groups have been formed and are active in the development and implementation of IMBER:

1) The "end-to-end food webs" task team (jointly with GLOBEC) is preparing review papers on the concepts and theories underpinning the end-to-end food web research.
2) The IMBER/SOLAS carbon research group held a workshop on Surface Ocean CO_2 Variability and Vulnerabilities (Paris, April 2007) and is now preparing a special issue for Deep-Sea Research. This group is also leading an international push for the incorporation of oxygen sensors on to the Argo floats.
3) The capacity building task team concentrates on the enhancement of research capabilities in developing countries.
4) The IMBER/LOICZ Continental Margins task team held an Open Science Conference (Shanghai, September 2007), which led to the identification of major research foci on biogeochemistry and ecosystems in the coastal zone that will be developed into a joint science plan and implementation strategy.
5) The Data Management committee met for the first time in June 2007 and developed an innovative strategy for IMBER-related data issues.

Many regional studies and national initiatives are also actively contributing to the implementation of IMBER.

Further information about ongoing activities is available on the IMBER website (www.imber.info).

SOLAS (Surface Ocean - Lower Atmosphere Study)

www.uea.ac.uk/env/solas

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The aim of SOLAS is to quantify the exchange of gases and particles between the ocean and the atmosphere, and to understand the role that these exchanges play in ocean biogeochemistry, atmospheric chemistry and climate.

SOLAS science is organized around three scientific Foci:

1) Biogeochemical Interactions and Feedbacks Between Ocean and Atmosphere
2) Exchange Processes at the Air-Sea Interface and the Role of Transport and Transformation in the Atmospheric and Oceanic Boundary Layers
3) Air-Sea Flux of CO_2 and Other Long-Lived Radiatively-Active Gases. Focus 3 is also home of the joint SOLAS-IMBER Carbon Group.

One of the most significant and discrete scientific recent developments for SOLAS was the synthesis of over a dozen open ocean iron enrichment experiments that have been conducted over the course of the past decade (e.g., Boyd et al., 2007, Science 315).

Another ongoing initiative is on anthropogenic nitrogen impacts on the open ocean. The impact of increased nitrogen loading via atmospheric and riverine inputs is discussed coherently within the scientific community under the coordination of SOLAS, National Oceanic and Atmospheric Administration, the International Nitrogen Initiative (INI), and the European Science Foundation.

SOLAS also leads the development of the Asian Dust and Ocean EcoSystem (ADOES) consortium of scientists who are interested in the response of the ocean surface biogeochemical system on inputs of dust from the Asian plateau.

SOLAS coordinates the Comparison of Oceanic Dimethylsulfide Models (CODiM), where DMS ecosystem models are systematically compared against common data sets to spur improvements and indicate future observations to better constrain the dynamics of DMS systems.

On the capacity building front, SOLAS runs a strong and influential biennial International Summer School. It brings together doctoral students and early-career researchers and lecturers for lectures and practical workshops in disciplines needed to understand the nature of ocean-atmosphere interactions. The last summer school was held in Oct/Nov 2007 in Corsica, the next one is planned for 2009.

GLOBEC (Global Ocean Ecosystem Dynamics)

www.globec.org

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GLOBEC is co-sponsored by the Scientific Committee on Oceanic Research (SCOR) and the Intergovernmental Oceanographic Commission (IOC) of UNESCO. Its implementation plan was approved in 1999, with a mandate to run until December 2009. *GLOBEC's main goal is to understand how global change will affect the abundance, diversity and productivity of marine populations, both globally and regionally*.

In addition to conducting research at a national level (at least 19 countries have GLOBEC research programs) GLOBEC has 10 multi-national and 6 regional programs. The latter include projects that are geographically widespread, such as CLIOTOP (Climate Impacts on Oceanic Top Predators), a program devoted to the worldwide study of the dynamics and management of oceanic top predators, or ESSAS (Ecosystem Studies of Sub-Arctic Seas), which focuses on the impacts of global change on sub-arctic marine ecosystems.

As GLOBEC is in its Integration and Synthesis (I+S) phase, there is particular focus on the development of projects that build on the efforts of the last decade, pushing the multidisciplinary, multiscale approach that permeates most IGBP projects. For example:

QUEST-Fish is a UK-led project investigating how climate change will affect the potential production for global fisheries resources in the future, compared to past and present scenarios, and estimating the additional risks and vulnerabilities of these impacts on human societies (http://web.pml.ac.uk/quest-fish/default.htm).

CLIMECO (Climate driving of marine ecosystem changes) is a GLOBEC, IMBER and CLIVAR training workshop for young marine scientists interested in using climate and climate model outputs for their own ecosystem research. Such training is required if we are to move towards multidisciplinary science. The workshop will take place 21-24 April 2008, in Brest, France (www.imber.info/CLIMECO_home.html).

GLOBEC has been particularly active in developing research in Eastern Boundary Upwelling Systems, where climate and physical forcing play a particularly significant role in structuring and controlling marine ecosystems. We have also been very active in promoting coordinated ecological and socio-economic research. These efforts will culminate in the following two major symposia in 2008:

1) Dynamics of Eastern Boundary Upwelling Ecosystems: Integrative and comparative approaches—Las Palmas, Spain, 2-6 June 2008, www.upwelling-symposium.org/. Sponsored by GLOBEC, IMBER, SOLAS.
2) Coping with global change in marine social-ecological systems—Rome, Italy, 8-11 July 2007, www.peopleandfish.org/. Sponsored by GLOBEC and the Food and Agriculture Organisation (FAO) of the United Nations.

The above are just a few of GLOBEC's activities, which include the use of fish scales in anaerobic sediments off California, Namibia and Peru to estimate centennial- to millennial-dynamics of pelagic fish (see PAGES News 2004, 12:1).

IMAGES (International Marine Past Global Changes Study)

Nicolas Dittert[1] and Ralph Schneider[2]

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www.images-pages.org

IMAGES is an international collaborative science program aimed at the collection and interpretation of high-quality paleoclimate data from the global ocean. It aims to understand the role of marine processes in the Earth's climate system during the past million years at timescales relevant to human life and societal development. To further these aims, IMAGES organizes sea-going missions, thematic and regional working groups, workshops and conferences. IMAGES actively encourages, promotes and supports the participation of early-career scientists in its full range of activities, for example with ship-board opportunities ("University at Sea"), access to infrastructure, integration with research initiatives and participation at workshops.

Working groups form the heart of IMAGES. Organized around a scientific question or theme, a working group allows scientists from around the world to focus their questions and ideas, develop a plan, marshal the needed resources and work together towards success. Past working groups include those leading to coring expeditions, as well as many thematic working groups, such as millennial- to decadal-scale climate variability, and last Glacial and Holocene climate conditions. These have provided new insights into the causes and consequences of past climate change in the ocean and on the continents.

Funding of IMAGES activities has been achieved through a combination of subscriptions/donations from member countries and the collective contributions of participating scientists in cruise campaigns. Currently participating countries include: Australia, Canada, Chile, China, Denmark, France, Germany, Iceland, India, Indonesia, Italy, Japan, Korea, Mexico, Netherlands, New Zealand, Norway, Portugal, Russia, South Africa, Spain, Sweden, Switzerland, Taiwan, Tunisia, UK, USA.

The ability of IMAGES to recover very long "giant" sediment cores is essential for meaningful time-coverage in the targeted high accumulation-rate sediment settings and well-described reconstructions of past climate change. In the mid-90's, IMAGES pioneered the use of a new Calypso Piston Corer; a device capable of routinely collecting undisturbed, continuous sediment sections up to 60 m in length and 12 cm diameter. Paired with other coring systems (e.g., the larger volume CASQ Corer) it provides scientists with a flexible, efficient method of obtaining sufficient amounts of sediment required to execute highest resolution, multi-proxy past climate reconstructions. Previously, such coring systems could be only be provided by the French R/V Marion Dufresne, however, IMAGES expects that more giant piston coring devices or alternative systems will be available on other vessels for future IMAGES needs (e.g., the Norwegian R/V Sars, the US R/V Knorr, or the German MEBO portable submarine drill rig; PAGES News, 2006).

Up to now, in more than a dozen expeditions throughout the world oceans, IMAGES scientists have developed a remarkable archive of sediment cores that can be used for past climate change investigations. Recent cruises comprise the 2005 and 2006 Marco Polo 1 and 2 (MD 147, MD 155) and Pecten (MD 148) cruises, as well as the 2007 Pachiderme (MD 159) cruise. Reports can be requested from the IMAGES office. Coming up in 2008 are the Retro and Amocint cruises to the tropical and the northern Atlantic, respectively. Retro will investigate the response of tropical Atlantic surface and intermediate waters to changes in the Atlantic meridional overturning circulation, whereas Amocint will study the Atlantic meriodional overturning circulation during interglacials.

The scientific outcome of IMAGES cruises and thematic working groups comprises a large number of outstanding publications in high-level international journals, and has contributed to the IPCC reports by providing fundamental and detailed information about past climate changes with nearly global coverage. All IMAGES related information and data are archived at the World Data Centers for Marine Environmental Sciences (WDC-MARE, Bremen, Germany) and for Paleo-climatology (Boulder, USA).

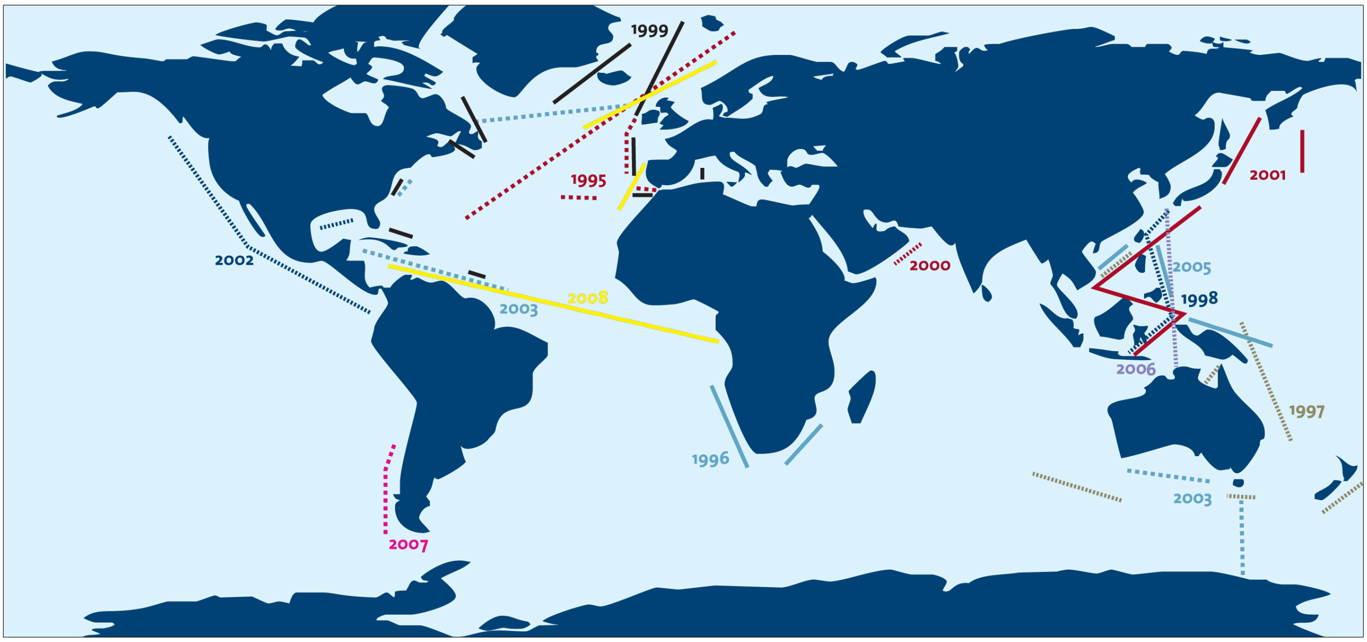

Figure 1: Overview of the regions where IMAGES cruises have taken place. Details of IMAGES cruises can be found at www.images-pages.org/cruises.html

Carbon burp and transient global warming during the Paleocene-Eocene Thermal Maximum

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The Paleocene–Eocene Thermal Maximum (PETM), ~55.5 Myr ago, was a geologically brief (~170 kyr) episode of globally elevated temperatures that occurred superimposed on the long-term late Paleocene and early Eocene warming trend. It was marked by a 5-8°C warming in both low- and high-latitude regions, a perturbation of the hydrological cycle and a major biotic response on land and in the oceans, including radiations, extinctions and migrations (see overviews in Bowen et al., 2006; Sluijs et al., 2007a). In addition, the PETM was associated with a pronounced negative carbon isotope excursion (CIE), recorded as a >2.5‰ decrease in the stable carbon isotope composition ($\delta^{13}C$) of sedimentary components (e.g., Kennett and Stott, 1991; Koch et al., 1992) (Fig. 1). The CIE can only be explained by a carbon "burp"—a massive (at least 1.5×10^{18}g; 1500 Gt) injection of ^{13}C-depleted carbon into the ocean-atmosphere system (Dickens et al., 1995).

Recent work has focused on elucidating the source and injection mechanisms of the carbon that caused the CIE, as well as on addressing the question of whether the ^{13}C-depleted carbon caused the warming or acted as a positive feedback in an already warming world. Other questions of interest include whether the PETM was a unique event in the early Paleogene greenhouse world, and the relevance of the fossil carbon burp to the current carbon burp resulting from fossil fuel burning.

Ocean acidification

Analogous to the modern situation, the injection of a large mass of CO_2 or CH_4 (which would have been oxidized to CO_2 within a century at most; Schmidt and Shindell, 2003) should have increased the acidity of the ocean. As a result, a shallowing of the calcite compensation depth (CCD) and dissolution of deep-sea carbonates should have occurred, thereby buffering the seawater pH change (Dickens et al., 1997). Indeed, the dissolution of deep-sea carbonates has been documented in various deep-ocean basins, based on the occurrence of clay layers as well as biogenic calcite fragmentation (e.g., Zachos et al., 2005) (Fig. 1). The severity of dissolution, however, appears to have been highly variable between various basins (Zeebe and Zachos, 2007), which is as yet unexplained.

Carbon sequestration

The distribution of deep-sea carbonate abundances also points to one mechanism of carbon sequestration. Carbonate accumulation rates at many sites appear to have been very high towards the termination of the PETM—the lysocline (the

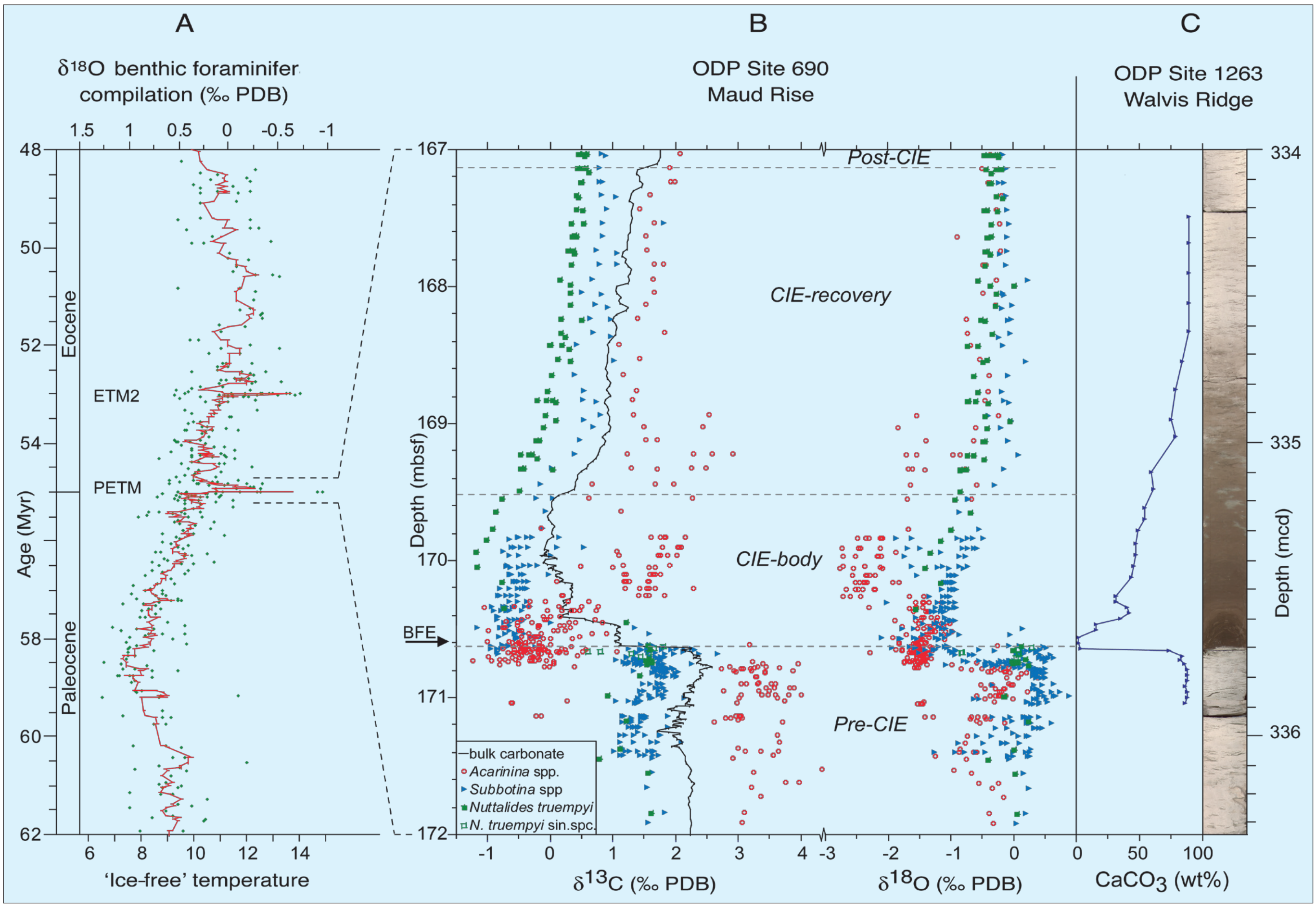

*Figure 1: **A**) Benthic foraminifer $\delta^{18}O$ record from 62-48 Myr (adapted from Zachos et al., 2001; data for ETM2 represent the* Cibicidoides *record from Lourens et al., 2005). $\delta^{18}O$ values represent corrected values (cf. Zachos et al., 2001). An additional correction of -0.25‰ was applied to the ETM2* Cibicidoides *values to synchronize baseline levels between the records. ETM2 = Eocene Thermal Maximum 2 (also referred to as H1 or Elmo), PETM = Paleocene-Eocene Thermal Maximum. **B**) Compilation of $\delta^{13}C$ and $\delta^{18}O$ values across the PETM of planktic foraminifers (surface dweller* Acarinina *and thermocline dweller* Subbotina *spp.; mostly single specimens), benthic foraminifer (*Nuttallides truempyi*) and bulk carbonate from ODP Site 690 from Maud Rise in the Weddell Sea (data compilation and figure modified from Sluijs et al., 2007a). **C**) Carbonate weight % record and core photo of ODP Site 1263 at Walvis Ridge, southeastern Atlantic (adapted from Zachos et al., 2005), showing dissolution and resulting clay layer. BFE refers to the main phase of benthic foraminifer extinction, mbsf = meters below sea floor; mcd = meters composite depth.*

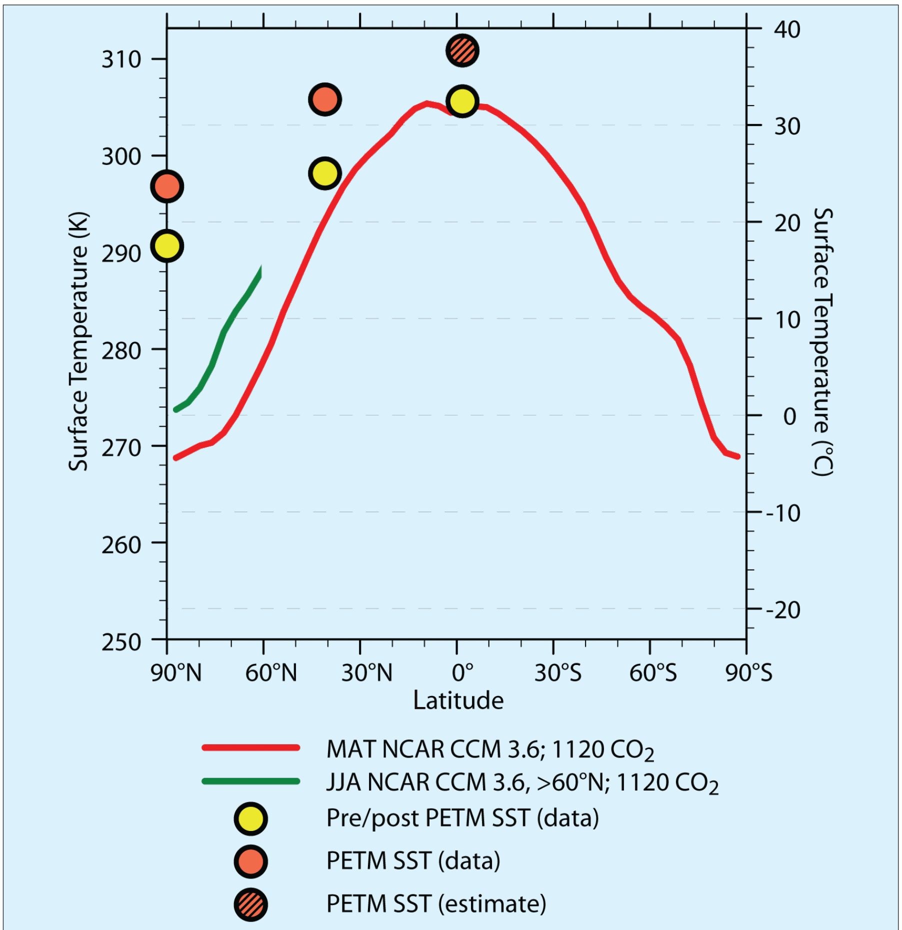

*Figure 2: Data-model comparison of the late Paleocene–early Eocene and PETM meridional temperature gradient. Estimated value for PETM SSTs in the tropics is derived by adding 5°C tropical warming (Zachos et al., 2003) to the background temperatures of Pearson et al. (2007). Mid-latitude data from Zachos et al. (2006) and Arctic data from Sluijs et al. (2006). Model (NCAR's Community Climate System Model 3.6 with Eocene boundary conditions) output (Huber and Nof, 2006) represents mean annual temperature (MAT; **red** line). Arctic proxy estimates may be skewed towards summer temperature and are, therefore, compared to model predictions for June, July, August (JJA) >60°N (**green** line; see text).*

depth in the ocean below which the rate of dissolution of calcite increases dramatically) was located even deeper than prior to the PETM—resulting in sequestration of large amounts of carbon (e.g., Kelly et al., 2005; Zachos et al., 2005). This phenomenon is model-predicted (Dickens et al., 1997) and was probably driven by silicate weathering, which slowly recharged the ocean with carbonate ion and eventually led to carbonate ion over-saturation and extremely good preservation of calcite on the sea floor. In some regions, particularly the Arctic, organic carbon burial increased during the PETM due to increased river runoff, causing more organic production, as well as stratification and bottom water anoxia. Excess burial perhaps comprised in the order of 800 Gt of carbon during the PETM in the Arctic alone (Sluijs et al., 2007b).

Meridional temperature gradients

The application of the organic paleothermometer TEX_{86}, as well as oxygen isotope data (Fig. 1) on well-preserved foraminifers, has recently led to a much better quantification of sea surface temperatures (SSTs) across the PETM. Background late Paleocene and early Eocene were already warm, with SSTs of ~32°C in the tropics (Pearson et al., 2007) and 25°C and 17°C for mid- and high-latitude oceans, respectively (e.g., Sluijs et al., 2006; Zachos et al., 2006). During the PETM, tropical as well as mid-latitude and Arctic SSTs rose by 5-8°C (Zachos et al., 2003, 2006; Sluijs et al., 2006) (Fig. 2). Such temperatures in the high Arctic are supported by biogeographical data, such as the abundant occurrence of subtropical dinoflagellates (Sluijs et al., 2006), and other geochemical information (see e.g., Weijers et al., 2007). Hence, the meridional temperature gradient was only 15°C during both background and PETM conditions, although it remains unclear if the Arctic data represent mean annual or summer temperatures (Sluijs et al., 2006, 2007b). Yet, even if they represent summer temperatures, current generation fully coupled climate models cannot simulate such reduced gradients, even when the model is fed with Eocene geography and high CO_2 concentrations (Huber and Nof, 2006) (Fig. 2). This suggests that higher-than-modern greenhouse gas concentrations must have operated in conjunction with feedback mechanisms that either amplified polar temperatures or cooled the tropics, and that are not incorporated in the models (Sluijs et al., 2006). Potential mechanisms for polar warming and tropical cooling include polar stratospheric clouds (Sloan and Pollard, 1998) and hurricane-induced ocean mixing (Emanuel et al., 2004; Sriver and Huber, 2007), respectively.

Interestingly, the meridional temperature gradient did not further decrease during the PETM. This can be partly explained by the absence of ice-albedo feedbacks, since the Arctic was already ice free prior to the PETM. Additionally, it implies that the mechanism that caused the reduced meridional temperature gradient did not become amplified during the PETM (Sluijs et al., 2006).

Additional early Eocene hyperthermals

Recent work shows that a phase similar to the PETM occurred at ~53.5 Myr (Lourens et al., 2005) (referred to in the literature as H-1, Elmo or Eocene Thermal Maximum 2 (ETM2)), and possible additional related phases at ~53.1 Myr (I-1) and ~52.3 Myr (K or X) (Cramer et al., 2003; Röhl et al., 2005; Nicolo et al., 2007). Although documentation of these phases is, as yet, relatively incomplete, the available information indicates that these additional hyperthermals were also associated with massive injection of ^{13}C-depleted carbon, ocean acidification and perturbations of the hydrological cycle, though less pronounced than during the PETM. Orbital tuning of the complete late Paleocene and early Eocene record at Walvis Ridge (South Atlantic) has indicated a link between the timing of the hyperthermals and eccentricity maxima (Lourens et al., 2005; Westerhold et al., 2007), which would have implications for the mechanisms that caused global change during the hyperthermals.

Leads and lags and mechanisms of carbon input

One prominent example of biotic change associated with the onset of the CIE is recorded along continental margins, where sediment sequences from all latitudes contain high abundances of dinoflagellate cysts belonging to the subtropical genus *Apectodinium* (Crouch et al., 2001; Sluijs et al., 2007a). In part, this must be associated with the PETM warming. However, in stratigraphically expanded marginal marine sections from the New Jersey Shelf and the North Sea, as well as in a section from New Zealand, the onset of the *Apectodinium* acme started some 5 kyr prior to the CIE (Sluijs et al., 2007b). Additionally, the onset of the PETM SST warming at New Jersey led the CIE by several thousands of years (but lagged the onset of the *Apectodinium* acme) (Sluijs et al., 2007b). This indicates that warm SST was not the only environmental control on *Apectodinium* abundances. Moreover, it suggests that the carbon burp that caused the CIE was a result of initial climate change and acted as a positive feedback. This scenario fits the model that CH_4 release from submarine hydrates caused the CIE (Dickens et al., 1995). If this pre-CIE warming was global, it was likely induced by greenhouse forcing, suggesting that the PETM warming and ocean acidification were caused by at least two sources of carbon (Sluijs et al., 2007b).

Concluding remarks

The past years of research on the PETM and the more recently discovered additional hyperthermals have resulted in a clearer picture of these critical phases in Earth's history. Improved drilling techniques (Integrated Ocean Drilling Program) have resulted in the recovery of complete sections, and new analytical techniques have contributed to much better quantitative estimates of SSTs. Moreover, high-resolution studies on expanded marginal marine sequences have identified leads and lags in the interaction between the climate system and the carbon cycle during the onset of the PETM. The new data provide fundamental constraints for modeling global climate and carbon cycling, and are increasingly leading to an improved description and understanding of the state and dynamics of a (in this case the early Paleogene) greenhouse world.

Acknowledgements

I thank the Netherlands Organisation for Scientific Research for funding (VENI grant 863.07.001) and for their continued support of the Integrated Ocean Drilling Program. I also thank all my 'hyperthermal' colleagues, amongst others Stefan Schouten, Jim Zachos, Jerry Dickens, Ursula Röhl, Lucas Lourens, Jaap Sinninghe Damsté, Gert-Jan Reichart, Matt Huber, Gabe Bowen, Mark Pagani, Ellen Thomas, Dick Kroon, Cedric John, Steven Bohaty and Henk Brinkhuis for discussions over the past years.

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Pleistocene records of marine carbonate chemistry

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Ice core records provide the only direct archive for past atmospheric gas composition, and records spanning the past 670 kyr BP reveal a tight correlation between surface temperatures and atmospheric pCO_2 (Petit et al., 1999; Siegenthaler et al., 2005). However, what determines the glacial and interglacial pCO_2 extremes (i.e., 280 vs. 200 ppm), and where the CO_2 was stored is poorly understood, although it is clear that the ocean is the only reservoir that could have absorbed the missing CO_2 from the atmosphere (Broecker, 1982). This uncertainty hampers the prediction of future climate change with continued anthropogenic release of CO_2, and there is a pressing need to better understand the interplay between atmospheric pCO_2 and the much larger oceanic carbon reservoir.

There are several proxies for reconstructing marine carbonate chemistry, all of which have limitations (see Hönisch and Hall, 2007). Although the uncertainties may be large, multiproxy approaches for the late Pleistocene yield an increasingly consistent picture. Paleoreconstructions focus on two approaches: (1) To study the sensitivity of climate to greenhouse gas concentrations beyond the limit of ice coring in Antarctica, reconstructions have focused on the past 60 Myr BP (Pagani et al., 1999, 2005; Pearson and Palmer, 2000; Royer et al., 2001). During this period, oxygen and carbon isotope records from benthic foraminifers indicate large climate fluctuations that coincide with perturbations of the carbon cycle (Zachos et al., 2001). (2) To quantify the potential of the ocean as a sink for CO_2, carbonate chemistry reconstructions focus on benthic foraminifers (Marchitto et al., 2005; Sanyal et al., 1995; Yu and Elderfield, 2007). The glacial deep ocean is thought to be the largest carbon reservoir.

Surface seawater carbonate chemistry

As CO_2 is well mixed in the atmosphere and is exchanged at the air-sea interface, knowledge of past sea surface carbonate chemistry can place constraints on past atmospheric pCO_2. Boron isotopic compositions ($\delta^{11}B$) in marine carbonates record past seawater pH (Hemming and Hanson, 1992; Hönisch et al., 2004; Reynaud et al., 2004; Sanyal et al., 1996, 2000, 2001). Laboratory and sediment validation studies have investigated vital shell size and dissolution effects on $\delta^{11}B$ of planktic foraminifers and corals. Symbiont photosynthesis sequesters CO_2 and thereby increases pH in the calcifying environment of foraminifers (Jørgensen et al., 1985; Rink et al., 1998) and corals (Al-Horani et al., 2003). Respiration has the opposite effect. In planktic foraminifers, these effects have significant consequences for the recorded pH (Hönisch et al., 2003). As symbiont-bearing foraminifers appear to grow larger under higher light levels (Spero and Lea, 1993), higher $\delta^{11}B$ of larger shells of the symbiont-bearing foraminifer *Globigerinoides sacculifer* is interpreted to reflect a shallower growth habitat (Hönisch and Hemming, 2004). The largest shells record surface seawater pH, and because these shells are also the least susceptible to dissolution (typically resulting in offsets to lighter isotopic values), Hönisch and Hemming (2004) recommend using large shells for paleoreconstructions.

A 400-kyr record of $\delta^{11}B$ in large *G. sacculifer* shells from an open ocean sediment core in the equatorial Atlantic shows a ~0.18 unit higher glacial ocean pH compared to interglacials (Hönisch and Hemming, 2005). This is consistent with previous results for Pacific and Atlantic surface seawater pH (Sanyal et al., 1995). Corresponding aqueous PCO_2 estimations showed a remarkable match with the Vostok pCO_2 record (Fig. 1; Hönisch and Hemming, 2005). Hönisch and Hemming are now in the process of extending the surface ocean pH records into the early Pleistocene and eventually throughout the Cenozoic. There are several problems to overcome in this endeavor, including uncertainty of the boron isotopic composition of seawater on time scales longer than 3-5 Myr BP (Lemarchand et al., 2000), unknown species effects, and the need to estimate surface ocean alkalinity or another parameter of the carbon system in addition to pH when estimating PCO_2.

Carbonate chemistry in reef environments changes seasonally with both the productivity of the ecosystem and changes in the currents that carry the open ocean chemistry to the reef. Therefore, since $\delta^{11}B$ in corals reflect local conditions, corals are not suitable archives for approximating global atmospheric pCO_2 (Hönisch et al., 2004; Pelejero et al., 2005).

Foraminiferal B/Ca ratios have been proposed to reconstruct surface seawater pH (Yu et al., 2007). Similar to the boron isotope proxy, B/Ca is based on the equilibrium reaction between boric acid and borate in seawater. Boron isotope studies suggest that borate is the species incorporated into marine carbonates, and the seawater borate concentration increases with pH. A pilot study suggests that B/Ca is strongly dependent on calcification temperature, which could be corrected using Mg/Ca temperature estimates. Application to the paleo-ocean yields a very promising result: pH of the last glacial Southern Ocean was estimated to have been 0.15 units higher and PCO_2 was correspondingly 95 µatm lower than during the Holocene (Yu et al., 2007). This is an exciting new approach that may allow for a much faster sample throughput. However, because carbonate chemistry and temperature in the ocean typically change in unison, culture experiments under controlled conditions in the laboratory are planned to better quantify the effects of pH, temperature, salinity and boron concentration on B/Ca in planktic foraminifers.

Deepwater $[CO_3^{2-}]$

The first boron isotope study to estimate glacial deep-sea pH used mixed benthic foraminifers and suggested a 0.3 units higher glacial pH in the Pacific and Atlantic oceans (Sanyal et al., 1995). This large pH change translates into a 100 µmol kg^{-1} higher deepwater $[CO_3^{2-}]$, which is inconsistent with sediment records of carbonate preservation. More recent geochemical estimates use benthic foraminiferal Zn/Ca and Cd/Ca (Marchitto et al., 2002), and B/Ca ratios (Yu and Elderfield, 2007), which appear to be related to deepwater carbonate saturation state, although the exact mechanism of the respective relationship is not understood. Reconstructions of $[CO_3^{2-}]$ of the glacial Atlantic was 15-30 µmol kg^{-1} higher at intermediate depths, and ~10-20 µmol kg^{-1} lower in waters below the modern lysocline (water depth where the rate of calcite dissolution increases dramatically) (Farrell and Prell, 1989; Marchitto et al., 2002; Yu and Elderfield, 2007). In the Pacific Ocean, a 5 µmol kg^{-1} increase occurred in waters deeper than 3000 m (Anderson and Archer, 2002).

Because of the large discrepancy between mixed benthic $\delta^{11}B$ data and other reconstructions, Hönisch, et al. (in prep.) measured $\delta^{11}B$ in single benthic foraminifer species, which yield corresponding $[CO_3^{2-}]$ data that show a small glacial increase above the modern lysocline and a small decrease below the lysocline. This brings the boron isotope data in line with other reconstructions and strengthens the view that the deep ocean cannot have stored the entire missing CO_2 in dissolved form. Biological mechanisms must have played an important role as well.

Where to next?

Beyond the need for detailed and faithful estimates of surface seawater PCO_2 and atmospheric pCO_2 throughout the Cenozoic (see above), detailed maps of deep sea carbonate parameters are needed to better quantify the past oceanic carbon reservoir. Particularly for deep-sea reconstructions, the mechanisms of the proxy relationships need to be studied and better calibrated, preferably in laboratory culture. Depth profiles from different locations in all ocean basins (particularly the Pacific and Southern Ocean) need to be generated, as well as reconstructions through longer periods of time at single locations. This is a long-term endeavor that needs to be approached by the entire paleoceanographic community and not just by single individuals.

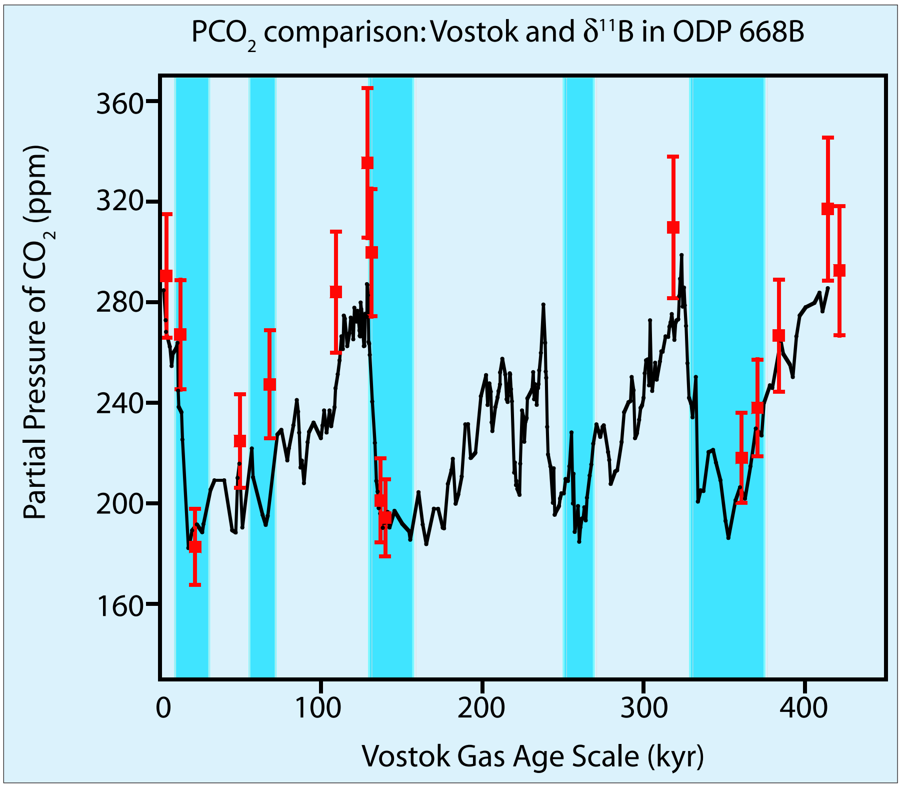

*Figure 1: Estimated aqueous PCO_2 from boron isotopes in planktic foraminifera (**red squares**) closely matches atmospheric pCO_2 from the Vostok ice core record (**black line**), and indicates that atmospheric pCO_2 can be estimated from marine proxy records. **Blue bars** indicate glacial intervals. Modified from Hönisch and Hemming, 2005.*

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An increase in the ventilation of the abyssal North Pacific Ocean at the end of the last ice age

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The rate at which a portion of the ocean interior exchanges gases with the atmosphere is generally described in terms of "ventilation". Ventilation predominantly occurs where dense waters outcrop at high latitudes, pumping radioactive ^{14}C from the atmosphere into the ocean, while simultaneously undoing the work of the 'biological pump'—releasing the CO_2 excess to the atmosphere and replenishing the oxygen shortfall resulting from the decay of organic matter in the ocean interior. As biologically sequestered carbon would be less readily released to the atmosphere if ventilation of the ocean were reduced, some explanations for the low atmospheric pCO_2 of the last ice age have invoked a poorly ventilated deep glacial ocean (Toggweiler, 1999; Stephens and Keeling, 2000; Sigman and Boyle, 2000). However, paleoceanographic evidence to support this has been sparse and often ambiguous, particularly in the Pacific Ocean.

In the modern North Pacific Ocean, the balance between organic matter respiration and the circulation of the ocean interior produces a broad nutrient maximum and oxygen minimum in the upper 1.5 km of the water column (Fig. 1b,c). Upward mixing of the nutrient-rich thermocline waters supplies the fertile North Pacific ecosystem with the ingredients necessary for growth, simultaneously leaking respired CO_2 to the atmosphere. A lid of low-salinity waters impedes local ventilation of deep waters at the subarctic surface, so that abyssal waters are ventilated only at the distant surfaces of the North Atlantic and Southern Ocean. The rapid attenuation of organic matter flux with depth leads to a deep sea that is better oxygenated and contains lower concentrations of remineralized nutrients and carbon, even though exchange with the atmosphere is slower, as indicated by the extremely low $\Delta^{14}C$ (Fig. 1d). Multiproxy records from two sediment cores in the deep subarctic Pacific were developed to investigate how these patterns may have differed during the last ice age. These paleoceanographic records from a little-studied region of the global ocean provide a new perspective on the deep ocean chemistry and surface ocean fertility over the last glacial-interglacial transition (Galbraith et al., 2007).

First, past values of deepwater $\Delta^{14}C$ were estimated by separately measuring the $\Delta^{14}C$ of co-occurring fossil benthic and planktic foraminifers. Using calibrated calendar ages of the planktic foraminifers, the benthic foraminiferal $\Delta^{14}C$ can be decay corrected to the time of growth to give the paleo bottom water $\Delta^{14}C$. These values are shown in Figure 2, calculated in parts per thousand relative to the contemporary atmospheric $\Delta^{14}C'_{cont\text{-}atm}$, as described in Galbraith et al. (2007).

The $\Delta^{14}C$ results clearly show that the deep North Pacific Ocean was more poorly ventilated during the Last Glacial Maximum (LGM) than it is today and that the ^{14}C ventilation improved during deglaciation. This is similar to results from the Panama Basin at 3.2 km depth (Shackleton et al., 1988) but contrasts with measurements previously made at shallower depths in the equatorial Pacific Ocean, which show a scattered range of glacial deep ocean $\Delta^{14}C$ that overlaps with present-day values (Broecker et al., 2004). Although it is difficult to evaluate the cause of this discrepancy, it may reflect a vertical gradient in ventilation, with ventilation similar to today in the upper 2.5 km of the water column, and relatively unventilated water below this. Intriguingly, the sole published glacial-age benthic-planktic pair from the deep South Pacific (Sikes et al., 2000) shows a more ^{14}C-depleted value, suggesting that a lateral gradient also existed across the glacial deep Pacific Ocean at depths of 3-3.5 km, with the most poorly ventilated waters in the south.

Geochemical measurements made on the sediment in which the foraminifers were buried provide additional information on the state of the glacial North Pacific. The analyses of two sedimentary components are shown in Figure 2 (see Galbraith et al., 2007 for more proxy records). The first, opal, suggests decreased diatom export during the LGM, consistent with many previously published records from the subarctic Pacific, which show reduced algal growth during the glacial (Kienast et al., 2004; Jaccard et al, 2005; Brunelle et al., 2007, and references there-

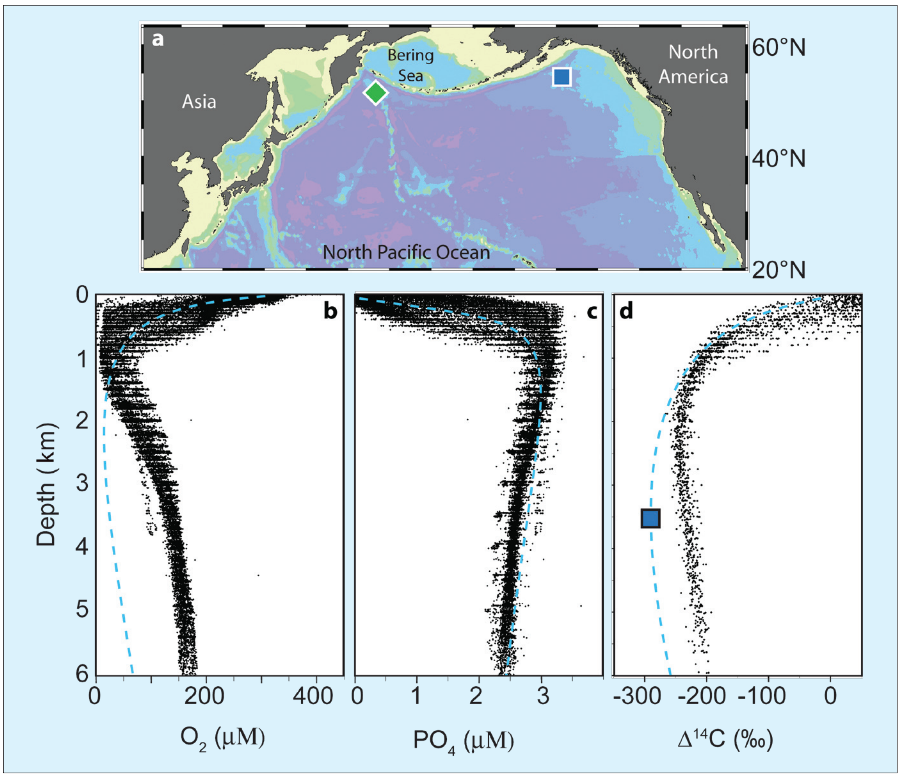

*Figure 1: **a**) Core sites: ODP 882 (50.35°N, 167.58°W, 3244 m; green diamond) and ODP 887 (54.37°N, 148.45°W, 3647 m; blue square); (**b**) Dissolved oxygen, (**c**) phosphate, and (**d**) radiocarbon in the North Pacific. All measurements available in GLODAP north of 20°N in the Pacific Ocean are shown (Key et al., 2004). Reconstructed $\Delta^{14}C'_{cont\text{-}atm}$ of bottom waters at Site 887 during the LGM is shown by the blue square in plot d. Dashed blue lines of b, c and d represent hypothetical North Pacific water-column profiles that appear to be consistent with the available data for the LGM. Note that these are highly speculative sketches based on a small amount of qualitative data.*

in). Studies of the nitrogen isotopic composition of sedimentary organic matter indicate that reduced export production coincided with increased relative nitrate consumption during the glacial (Brunelle et al., 2007; Galbraith et al, in press), suggesting that the upward flux of macronutrients to the surface was reduced. Yet, despite the weakened downward flux of organic matter, the concentration of U in subarctic Pacific sediments—an element typically enriched under low oxygen conditions—was higher during the LGM (Fig. 2). This, therefore, most likely resulted from a significant decrease in bottom water oxygen concentrations—an indirect but robust sign that respired CO_2 concentrations were markedly higher in the deep North Pacific during the LGM.

Together, these proxies indicate that the glacial deep Pacific Ocean was more effectively isolated from the atmosphere, and that the biological pump had succeeded in storing a greater concentration of respired CO_2 in the deep ocean. Although direct causality cannot be proven, this is consistent with models that achieve lower atmospheric pCO_2 by reducing ventilation. Ventilation could theoretically have been impeded in the past by a reduced rate of mixing between surface and deep waters (Toggweiler, 1999), an intensified barrier to ocean-atmosphere exchange (such as expanded sea ice; Stephens and Keeling, 2000), or both. Whatever the case, elevated storage of respired CO_2 within the deep ocean would have enhanced $CaCO_3$ dissolution at the seafloor, elevating the global $CaCO_3$ inventory and thereby contributing to greater CO_2 solubility at the global scale, as hypothesized by Boyle (1988). The evidence for invariant deep Pacific PO_4 concentrations—as inferred by foraminiferal Cd/Ca across the glacial-interglacial transition (Boyle, 1992)—appeared to contradict prior evidence for a buildup of respired carbon in the glacial deep sea. Given our evidence, however, we suggest that increased respired CO_2 arose from a relative decrease in the preformed PO_4 concentration of deep Pacific waters, rather than from an increase of the total PO_4 concentration, alleviating the apparent conflict (Jaccard et al., in prep). The highly schematic water column profiles shown in Figure 1 suggest a possible reconciliation of the available data from the glacial North Pacific.

During the last deglaciation, export production increased dramatically ca. 14.5-15 kyr BP, while the oxygenation of bottom waters increased. The remarkable temporal coincidence of changes in the deep and surface oceans suggests that the arrival of better-oxygenated deep waters was mechanistically linked to an increase in the upward flux of nutrients to the surface. At the same time, intense oxygen depletion developed in the upper water column of the North Pacific, as previously described at multiple sites (e.g., Zheng et al., 2000; Cook et al., 2005), even as oxygen concentrations increased in the abyssal waters below. The close occurrence of this with the start of the Bølling warm period in the North Atlantic hints that a tight physical relationship linked the North Pacific circulation and the reinvigoration of the Atlantic meridional overturning at this time. The observation of increased export production and intensified thermocline oxygen-minimum zones during a period of more vigorous North Atlantic Deep Water formation, are consistent with the model results of Schmittner et al. (2007), which were based on freshwater-forced manipulations of the Atlantic circulation in a global GCM with a prognostic biogeochemical model. However, the apparent rapidity of the transition in the North Pacific is surprising and the relationship to the progression of the overall deglaciation remains to be clarified.

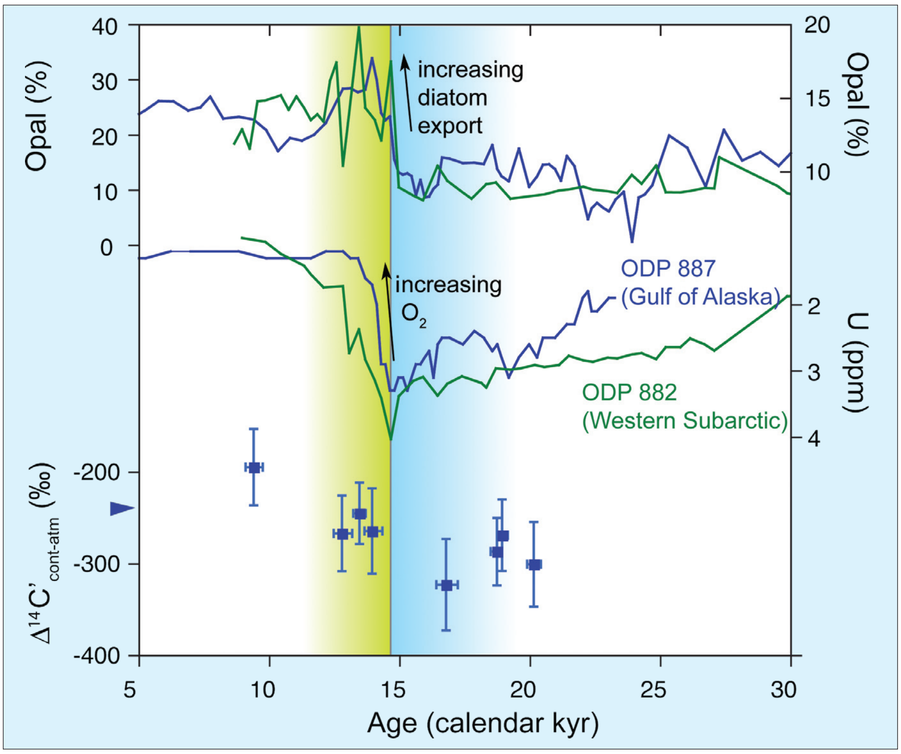

Figure 2: Sedimentary records from the subarctic Pacific, selected from those presented in Galbraith et al., 2007. See Figure 1 for core sites. ***Top****: sedimentary opal concentrations in weight %, measured by spectrophotometry of an alkaline extract.* ***Middle****: U concentrations measured on ODP cores 882 and 887 by ICP-MS and ICP-OES, respectively.* ***Bottom****: $\Delta^{14}C'_{cont-atm}$ of bottom waters at site ODP 887 calculated from benthic-planktic foraminiferal pairs, as described in Galbraith et al., 2007. Blue triangle on axis indicates the present-day $\Delta^{14}C$ of bottom waters near the core site (Key et al., 2004).*

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Convincing evidence for rapid ice sheet growth during the last glacial period

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It is commonly assumed that ice sheet growth over a glacial cycle follows a saw-tooth pattern of very slow ice-sheet growth during the glacial period and rapid loss during the glacial termination (see e.g., Imbrie et al. 1984; Huybers and Wunsch, 2004; Lisiecki and Raymo, 2005). However, this assertion is challenged by observations of sea level derived from Red Sea oxygen isotope records, which clearly and consistently show rates of sea level equivalent ice sheet growth of between 1-2 cm yr^{-1}. Here, we review this evidence and consider the increasing amount of independent data supporting rapid rates of ice-sheet growth during Marine Isotope Stage (MIS) 3, around 60-30 kyr BP.

The Red Sea sea level records

The Red Sea is separated from the open ocean by Hanish Sill, which decreases in passage area by three orders of magnitude during periods of full glacial sea level lowering (Fig.1). This means that (even today) the restricted exchange of waters between the Red Sea and the open ocean is extremely sensitive to sea level variations.

The Red Sea is subject to strong net evaporation. Evaporation strongly enhances oxygen isotope ratios in such marginal basins with limited communication to the open ocean because this enhancement of oxygen isotope ratios in the basin is linked not only to the rate of evaporation but also to the refreshment rate of water in the basin by exchange over the sill (the residence time of water in the basin) (Rohling, 1999). The longer the residence time, the longer the water is exposed to the high evaporation rates, and the heavier the isotope ratio becomes due to preferential evaporation of the lighter ^{16}O isotope.

Evaporative enhancement of oxygen isotope ratios and the great sensitivity to exchange over the sill (Fig. 1) strongly couple Red Sea oxygen isotope ratios with sea level. This is best exemplified by the full glacial-interglacial range of change in stable oxygen isotope ratios in water of 4.5-5‰ (allowing for a 4°C glacial to interglacial temperature range (Arz et al., 2007)), compared to ~1-1.2‰ in the open ocean (Thunell et al., 1988; Hemleben et al., 1996; Rohling et al., 1998; Fenton et al., 2000; Siddall et al., 2003; Arz et al., 2003).

Siddall et al. (2003) used a three-layer hydraulic model to calculate water-mass exchange at the sill (Siddall et al., 2002), coupled to a model of oxygen isotope fractionation in an evaporative basin (Rohling, 1999). By varying sill depth in the model and assuming a 5°C temperature drop at the Last Glacial Maximum (LGM), a relationship was calculated between sea level and oxygen isotope ratios in the central Red Sea (for both water and calcite) (Siddall et al., 2003, 2004). This relationship was then used to calculate sea level fluctuations from Red Sea oxygen isotope records to within ± 12 m (2σ)#.

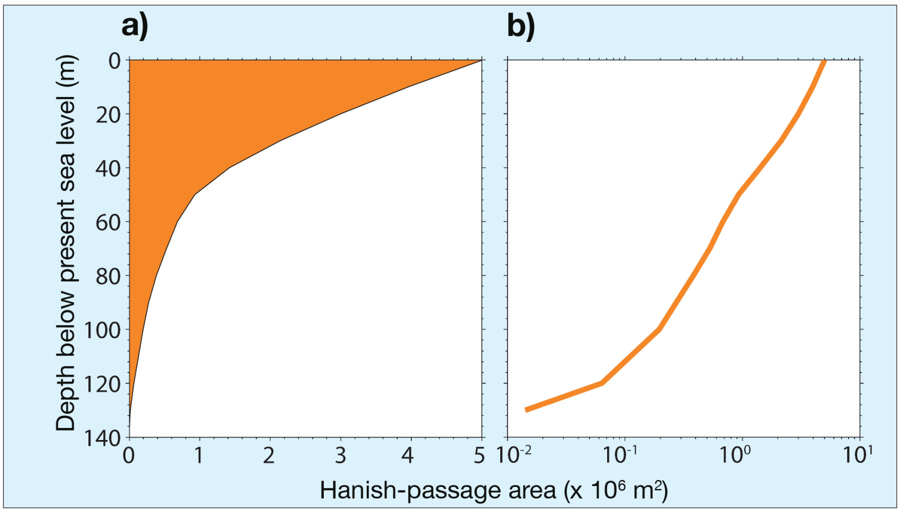

*Figure 1: The Red Sea is separated from the open ocean by Hanish Sill, which is only 137 m deep (Werner and Lange, 1975; Rohling et al., 1998; Fenton et al., 2000; Siddall et al., 2002; 2003; 2004). Bathymetric data show that the sill passage narrows from 110 km to ~6 km at 120 m below modern sea level. Narrowing of the sill passage with depth causes exponential decrease in sill passage area during glacial sea level lowering. Passage area of Hanish Sill with respect to water depth using **a**) linear scale, and **b**) logarithmic scale, emphasizing that passage area changes by 3 orders of magnitude. Note the large change in cross section in 0-120 m range of glacial to interglacial sea level. Due to magnitude of change over this range, the Red Sea is extremely sensitive to sea level change.*

Recently, Arz et al. (2007) used temperature estimates from coccolithophore-based long-chain alkenone unsaturation ratios, in combination with benthic foraminifer-based oxygen isotope records from a core in the northernmost Red Sea, to estimate a seawater oxygen isotope record for MIS 3. This record was then empirically scaled to sea level using coral-based sea level estimates. An additional record was generated using the oxygen isotopes measured on foraminifers, without removing the temperature component. Benthic isotopes in the Red Sea may respond less quickly to varying sea level than those in planktic organisms and may, therefore, smooth out rapid variations in sea level. The Arz et al. (2007) reconstruction was further smoothed using a 5-point running mean.

Comparison

As the underlying mechanism of sea level forcing on Red Sea oxygen isotope ratios is the same for both the approach of Arz et al. (2007) and Siddall et al. (2003) there should be strong similarities between the different reconstructions. To facilitate comparison, Figure 2 plots all three records after transformation to a common (arbitrary) age scale. Despite their different regional origins, the different approaches followed in calibration and the different chronologies, these records show strikingly similar signal amplitudes. All demonstrate higher sea level during the early stages of MIS 3, with subsequently lower sea level during the latter stage (following the trend in summer insolation at 65°N). All include four major sea level cycles within MIS 3, with amplitudes between 20-30 m—this compares well with the variability found from Huon Peninsula coral terraces (Chappell, 2002), and from the compilation of Thompson and Goldstein (2005, 2006). Figure 2 also shows the similarity to scaled open-ocean benthic isotope records (Cutler et al., 2003; Waelbroeck et al., 2002). The high degree of similarity is difficult to explain unless all records contain a strong, common sea level signal.

Additional evidence

Rates of ice-sheet loss reached an average of 1 cm yr^{-1} during the last deglaciation, with peaks of up to 3-5 cm yr^{-1} during so-called meltwater pulses (Fairbanks, 1989; Stanford et al., 2006). It is, therefore, not beyond reason to find evidence for similar rates of ice-sheet loss during preceding sea level cycles within MIS 3. High rates of ice-sheet growth are more controversial, largely because ice-sheet models have struggled to grow ice sheets rapidly (see e.g. Bintanja et al., 2002; Peltier, 2004). However, there is increasing independent evidence that high rates of ice-volume growth/sea level decrease were a reality. In addition to the Red Sea results, coral data indicate such high rates at the MIS 5-4 transition (60 m in 6 kyr: Cutler et al., 2003; Thompson and Goldstein, 2005; 2006), the MIS 5e-5d transition (40 m in 4 kyr: Lambeck et al., 2002; Thompson and Goldstein, 2005; 2006), and during a reversal within the sea level rise of the penultimate deglaciation (40 m in 2 kyr: Esat et al., 1999; Siddall et al., 2006; Thompson and Goldstein, 2005; 2006).

Recently reported data from Barbados also indicates rapid ice sheet growth during the MIS 3-2 transition (30 m in 3 kyr: Peltier and Fairbanks, 2006). Furthermore, the glacio-isostatic ICE5G-V2 model has simulated such a rapid growth rate in the specific context of the growth of the West Keewatin Dome on the North American continent during the MIS 3-2 transition (Peltier and Fairbanks, 2006).

Conclusion

During MIS 3, cold Dansgaard-Oeschger (D-O) stadials lasted 2-3 kyr, and warm D-O interstadials 3-4 kyr. The cycles of warming (2-3 kyr) and cooling (2-3 kyr) in Antarctica lasted around 4-6 kyr. Ice volume is given by the integration of the rate of growth (1-2 cm yr^{-1}) or loss (1-5 cm yr^{-1}) over the duration of growth or loss (2-4 kyr). Regardless of which timing is preferred for the ice-volume fluctuations (following either Antarctic or Greenland climate variability, see Rohling et al., 2004; Arz et al., 2007; Siddall et al., subm.), it is clear that independently observed rates of ice-volume growth, as well as the duration of cold versus warm periods during MIS 3 are more than adequate to give cycles of 30 m sea level equivalent ice sheet growth/loss during MIS 3. We note that Greenland temperatures varied by as much as 75% of their glacial-interglacial amplitudes during MIS 3 (Huber et al., 2006), while Antarctic temperatures varied by 25% of the glacial-interglacial amplitude (EPICA community members, 2006). The suggested magnitude of MIS 3 sea level cycles here is 30 m—25% of the glacial to interglacial amplitude of 120 m.

Finally, we note the intriguing relationship between the relative amplitudes during MIS 3 of the Antarctic temperature signal and the ~30 m of sea level fluctuation suggested here—both being 25% of their glacial-interglacial amplitudes. This fact, combined with the existence of four symmetric cycles during MIS 3 (like Antarctic temperature), and the evidence presented by the phasing of the benthic oxygen isotope record off Portugal (Shackleton et al., 2000), suggests that during MIS 3, ice volume varies on an Antarctic rhythm (Siddall et al., 2003; Rohling et al., 2004). This, however, is a matter of debate (Arz et al., 2007), which will no doubt form the subject of much further research (e.g., Siddall et al., subm.).

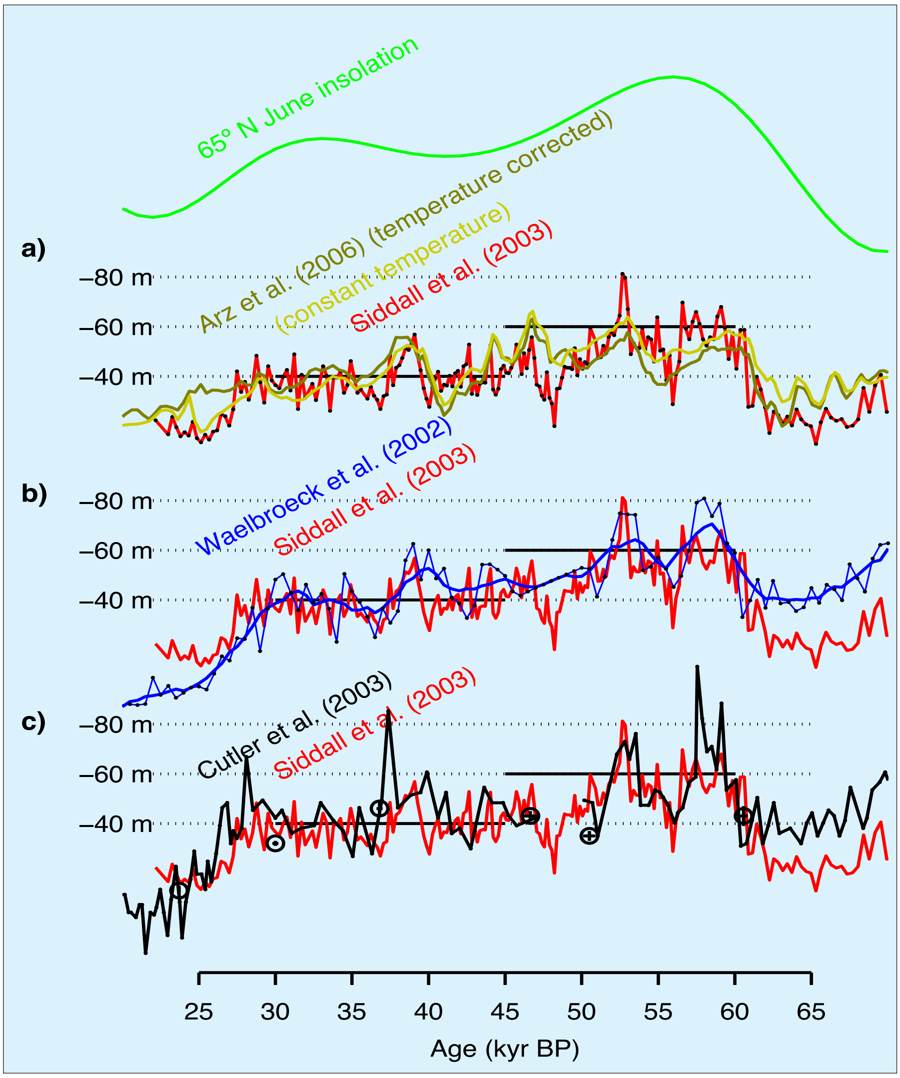

*Figure 2: **a**) Comparison (on an arbitrary timescale) of the Siddall et al. (2003; red line) Red Sea sea level curve (based on central Red Sea planktic oxygen isotopes) with curves of Arz et al. (2007; light and dark brown curves) (based on northern Red Sea benthic oxygen isotopes). **b**) and **c**) Estimates of sea level based on benthic isotopes calibrated to coral indicators of sea level from Waelbroeck et al. (2002; blue line) and Cutler et al. (2003; black line), respectively. Coral sea level indicators used (black circles with crosses to indicate uncertainty) are shown alongside the Cutler et al. (2003) curve. Black lines at -60 m and -80 m indicate 'typical' estimates for early and late periods of MIS 3, respectively. Published sensitivities are: Siddall et al. (2002) ± 12 m, Arz et al. (2007) ± 12 m (without temperature correction) and ± 8 m (with temperature correction), and Waelbroeck et al. (2002) ± 13 m.*

#This uncertainty margin takes meteorological variables into account, by assuming modern maxima and minima as the annual average values, such that a temperature uncertainty is allowed of ± 2°C, while evaporation uncertainties allow a range from 1.4-2.8 m yr^{-1}, and relative humidity varies between 60-80%. All uncertainties were combined into a worst-case scenario to obtain the largest estimate of the sea-level uncertainty (i.e., no natural covariations were taken into account, which—if accounted for—would reduce the actual range of sea level uncertainty reported for the method).

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Control of West African monsoon precipitation: Insights from the past

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The global monsoon system is the key component in determining hydrological cycles in the low latitudes. Irregularities or anomalies in monsoon rainfall severely affect agricultural production of the most densely populated regions on Earth. Understanding monsoon response to, and interactions with, high latitude and tropical climate oscillations is, therefore, crucial for assessing the impact of future climate changes on the low latitude hydrological cycle. Insights into past abrupt climate changes in the low latitudes can provide a showcase to assess the interplay of climate modes and boundary conditions that control monsoon responses.

Here, I will discuss a centennial- to millennial-scale record from the Gulf of Guinea, eastern equatorial Atlantic (EEA) (Weldeab et al., 2007a, Weldeab et al., 2007b). Mg/Ca, Ba/Ca and oxygen isotope composition in shells of shallow-dwelling planktic foraminifers were analyzed, and Ba/Ca was used as an indicator of changes in fresh water input of both the Niger and Sanaga Rivers, which drain large parts of the West African monsoon area (Fig. 1). Ba is enriched in riverine runoff relative to Ba in seawater. Ba uptake into planktic foraminiferal shells is linearly dependent on the Ba concentration of seawater (Lea and Spero, 1994). Thus, temporal variation of planktic foraminiferal Ba/Ca in sediment of core MD03-2707 (Fig. 1) indicates changes in the amount of riverine runoff, which is directly related to changes in West African monsoon precipitation.

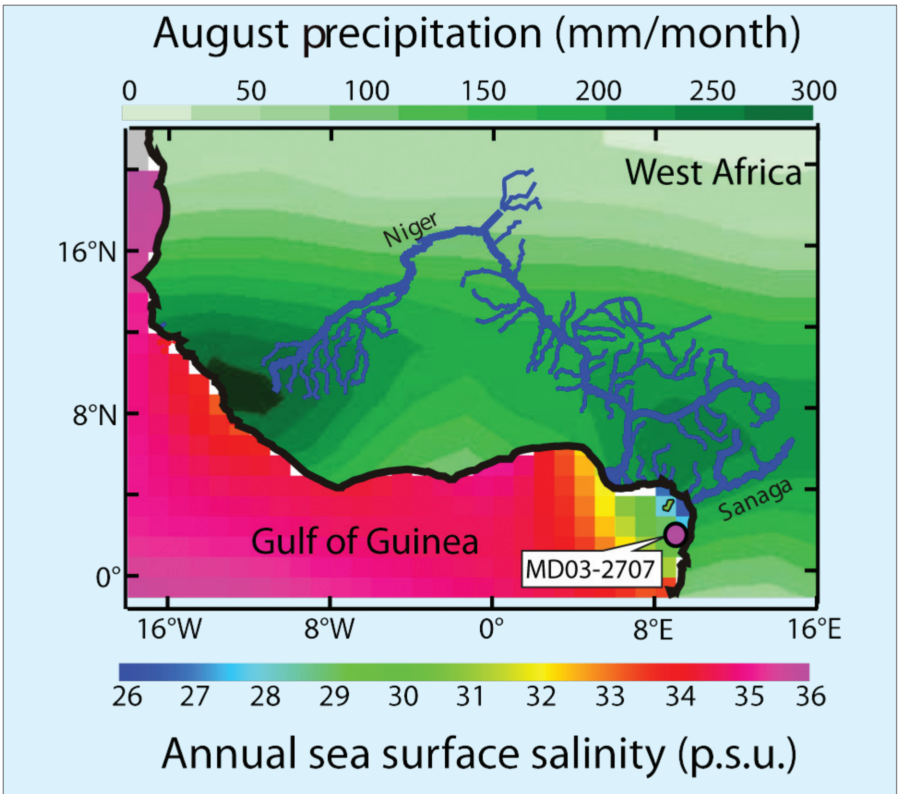

Figure 1: Location of MD03-2707, drainage basin of the Niger and Sanaga Rivers, precipitation in August (the height of West African monsoon precipitation) (Janowiak and Xie, 1999), and annual sea surface salinity in the Gulf of Guinea (Levitus and Boyer, 1994). Note: the drainage basins of the Niger and Sanaga Rivers cover a large part of the West African monsoon, and riverine runoff heavily affects the hydrography over the core site (Weldeab et al., 2007b).

West African monsoon responses to northern high latitude climate

On Milankovitch timescales, the planktic foraminiferal Ba/Ca and oxygen isotope records (Fig. 2) suggest that changes in the West African monsoon precipitation have closely followed the variations in low-latitude insolation and tropical Atlantic sea surface temperature (SST). The Gulf of Guinea records reveal that during interglacials, the West African monsoon was repeatedly punctuated by abrupt centennial- to millennial-scale swings in precipitation that closely correlate with abrupt climate shifts in Greenland (NGRIP members, 2004). Episodes of intensified West African monsoon precipitation coincide with intervals of warm air temperatures over Greenland. Conversely, periods of relatively weak monsoon precipitation during the penultimate interglacial and the last deglaciation tightly correlate with cold events in the Greenland ice core record. Close correspondence between weak monsoon precipitation (Fig. 2b) and early Holocene fresh water discharges into the North Atlantic (Clark et al., 2001) is also evident. These correlations suggest a strong linkage between interglacial West African monsoon conditions and abrupt climate changes in northern high-latitudes. Moreover, because the EEA SST record (see below) does not show fluctuations correlating to the centennial- to millennial-scale changes in West African monsoon precipitation, the West Africa northern high latitude climate linkage appears to have been established via the atmosphere.

Glacial West African monsoon conditions, as reflected by the Ba/Ca and oxygen isotope records, clearly indicate low, stable riverine runoff and do not reveal marked centennial- to millennial-scale oscillations such as those recorded in the Greenland ice cores. This observation suggests that during the last glacial and MIS 3, monsoon precipitation over the Niger and Sanaga drainage basins was fully decoupled from climate fluctuations in the northern high latitudes. We argue that glacial and interglacial boundary conditions and different thermal inertia of the terrestrial and oceanic intertropical convergence zone (ITCZ) have been crucial in determining the response of West African monsoon to climate instabilities in the northern high latitudes. That is, during interglacials, the summer ITCZ lies deep within the African continent and the ITCZ appears to react readily to the abrupt climate changes of the northern high latitudes. During the last glacial, however, the seasonal northward migration of the ITCZ was most likely limited to the region south of the east-west trending West African coast, as suggested by the reconstructed low riverine runoff. I argue that West African monsoon response to glacial millennial-scale northern high latitude climate instabilities was most likely dampened by glacial boundary conditions that kept the ITCZ south of the Niger and Sanaga catchments.

Eastern Equatorial Atlantic SST record

Major changes in eastern equatorial Atlantic SSTs—with increases between 2-3°C—were recorded at glacial-interglacial transitions. The SST record is also in phase with midsummer solar insolation at 15°N, suggesting that the EEA is thermally sensitive to northern hemisphere low-latitude summer radiation, either through a monsoonal feedback or because Mg/Ca-based SST estimates are weighted towards the boreal summer. Major glacial-interglacial SST transitions in the EEA and elsewhere in the tropics are paralleled by large changes in greenhouse gases, as recorded in Antarctic ice cores (Petit et al., 1999). Radiative forcing associated with the increase in greenhouse gases during the glacial-interglacial transition has been estimated to cause an increase of ~2°-3°C in tropical SSTs (Lea, 2004). If this estimate is correct, the EEA SST increase at glacial-interglacial transitions was largely a consequence of radiative forcing corresponding to greenhouse gas increases and orbital insolation changes.

The eastern equatorial Atlantic record does not show SST swings that correlate with millennial-scale ice-sheet instabilities in the northern high latitudes. This observation suggests that the thermal evolution of the eastern equatorial Atlantic over the past 155 kyr was fully decoupled from the Dansgaard Oeschger events, as recorded in Greenland ice cores. This strongly supports the general observation that thermal changes in the tropics primarily reflect greenhouse forcing and orbital insolation changes.

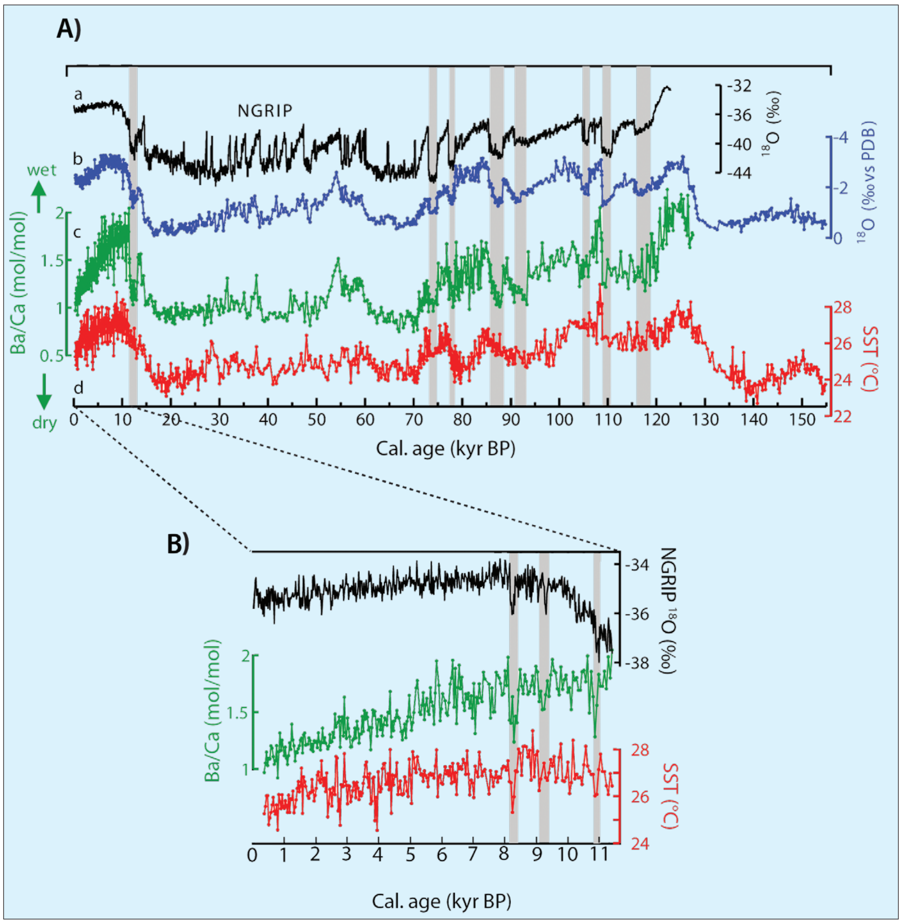

Figure 2: ***A****) Proxy records from shallow-dwelling planktic foraminifers (*Globigerinoides ruber, *pink variety) of core MD03-2707 (b-d) compared (****a****) with isotope composition of Greenland ice core (NGRIP members, 2004). (****b****) oxygen isotope composition, (****c****) Ba/Ca used as indicator of changes in riverine runoff, and (****d****) Mg/Ca-based SST estimate. Gray bars indicate intervals of relatively weak monsoon precipitation that tightly correlate with cold events in the Greenland ice core record (NGRIP).* ***B****) Enlarged section covering the past 11.5 kyr BP. Gray bars indicate periods of low monsoon precipitation that coincide or overlap with cold air temperature over the northern high latitudes and fresh water discharges into the North Atlantic Ocean (e.g., Clark et al., 2001).*

Hydrological and thermal lead-lag relationships

The Gulf of Guinea record shows that the onset of EEA SST increases during the last and penultimate deglaciation occurred ca. 18 and 136 kyr BP, respectively. Intensification of West African monsoon precipitation during the last and penultimate deglaciations started, however, ~14.5 and 129 kyr BP, respectively, lagging behind EEA warming by ~2.5 kyr during the last deglaciation, and by ~7 kyr during the penultimate deglaciation. This observation suggests that a complex role of tropical SST and low-latitude insolation in rising deglacial monsoon precipitation may exist. The lags may be explained by the following possibilities; 1) Tropical Atlantic SST needed to reach a threshold to push the West African monsoon system from dry, stable glacial to wet deglacial and interglacial conditions, or 2) Deglacial ice sheet instabilities and freshwater discharges into the North Atlantic had a dominant control on the timing of the onset of monsoonal precipitation. The author favors the latter explanation because the impact of millennial-scale northern high latitude climate instabilities on the West African monsoon appears to have overridden the trends set by changes in low latitude insolation and tropical Atlantic SST, as clearly evidenced during the penultimate interglacial and the Younger Dryas.

Conclusions

Superimposed on the glacial-interglacial trend, the Gulf of Guinea record reveals that during interglacial periods the West African monsoon was repeatedly interrupted by centennial- to millennial-scale rapidly decreasing precipitation. These declines in monsoon precipitation tightly correlate with the cold events of the Greenland ice core record. In contrast, during the last glacial, climate instabilities did not have a significant impact on the hydrological cycles over the Niger and Sanaga drainage basins. Thus, glacial-interglacial boundary conditions appear to have been crucial in determining if, and how, West African monsoon precipitation responded to millennial-scale climate instabilities in the northern high latitudes. Furthermore, on centennial- to millennial-timescales, eastern equatorial Atlantic SSTs were fully decoupled from swings in West African monsoon precipitation, suggesting that teleconnections between changes in air temperature over the northern high latitudes and atmospheric changes over West Africa are the dominant control of monsoon precipitation.

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East-West seesaw of SST variation in the mid-latitude North Pacific during the last two glacial cycles

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The modern climates of the mid-latitude North Pacific margins are sensitive to the intensity of the summer North Pacific High and winter Aleutian Low, which are linked to the El Niño-Southern Oscillation (ENSO) and the Arctic Oscillation through atmospheric teleconnections. However, our understanding of past changes in the basin-scale climate of the North Pacific is still limited. Therefore, we compare the response of paleotemperature variation to orbital forcing at the Japan and California margins during the last two glacial-interglacial cycles (Yamamoto et al., 2004, 2007).

Japan margin

The Japan margin of the mid-latitude NW Pacific has a subarctic boundary between the subtropical Kuroshio and subarctic Oyashio currents. Core MD01-2421 was taken from a site located in the mixing zone of the Kuroshio Extension and Oyashio currents, and therefore, records past latitudinal displacements of the subarctic boundary (Fig. 1). The latitudinal position of the subarctic boundary, associated with the westerly jet in summer, is principally controlled by the relative intensities of the North Pacific High and the Okhotsk High.

At site MD01-2421, the alkenone $U^{K'}_{37}$-derived sea surface temperature (SST) varied from 13°-23°C during the last 145 kyr (Fig. 2). These SST increases lagged the benthic $\delta^{18}O$-based MIS 1/2 and 5/6 boundaries by ~1 kyr and ~4 kyr, respectively (Fig. 2; Yamamoto et al., 2004; Oba et al., 2006). Additionally, time series sediment-trap studies near the study site demonstrated that the flux-weighted $U^{K'}_{37}$-derived temperature agreed with the summer SST. Examination of diatom, nannofossil and planktic foraminifer assemblages indicates that the alkenone SST was positively correlated with the Kuroshio contribution indices (Kuroshio current indicator species/[Kuroshio current indicator species + Oyashio current indicator species]). These findings suggest a periodic latitudinal displacement of the summer subarctic boundary in the northwestern Pacific.

California margin

The relative intensities of the California Current (CC) and the Southern California Countercurrent (SCC) are controlled by the development of the North Pacific High. The CC is intensified by a strengthened North Pacific High, whereas the SCC is intensified by a weaker North Pacific High.

We obtained $U^{K'}_{37}$-derived SST differences for Ocean Drilling Program Sites 1014 and 1016 ($\Delta SST_{NEPacific} = SST_{ODP1014} - SST_{ODP1016}$; Fig. 1). Site 1014 is influenced by the northward invasion of the SCC into the California Borderland region, whereas Site 1016 is located along the main path of the CC. The ΔSST_{NEP} must therefore, reflect the relative intensities of the CC and the SCC. The ΔSST_{NEP} varied between 0.4° and 6.1°C, with an average of 2.9°C (Fig. 2). A high ΔSST_{NEP} (weaker CC) was observed in late MIS 2 and early MIS 5e, whereas a low ΔSST_{NEP} (stronger CC) was observed in mid-MIS 5e and MIS 1 (Yamamoto et al., 2007).

East-west linkage

Comparisons of the ΔSST_{NEP} and the SST of MD01-2421 at the Japan margin revealed an anti-phase variation (Fig. 2; Yamamoto et al., 2007). Both ΔSST_{NEP} and the SST of MD01-2421 showed variation in 23-kyr and 30-kyr periods and lacked a 41-kyr period. The high ΔSST_{NEP} at the California margin (weakening of the CC) corresponded to low SST at the Japan margin (the southward displacement of the NW Pacific subarctic boundary), and vice versa (Fig. 2). The anti-phase relationship between ΔSST_{NEP} and the SST of MD01-2421 in the precession band suggests that variation in the Kuroshio-Oyashio boundary and in the CC system both responded to changes in the North Pacific High to precessional forcing.

Linkage with tropical Indo-Pacific climates

Today, the North Pacific High is influenced by the modern interannual ENSO through atmospheric teleconnections. In El Niño years, the tropical convection center moves to the central and eastern equatorial Pacific. This process weakens the North Pacific High in summer. In La Niña years, the tropical convection center moves to the western equatorial Pacific, intensifying the summer North Pacific High.

Zebiak-Cane ENSO—a model used in the prediction of modern ENSO—calculations for the past 150 kyr demonstrated that seasonal anomalies in insolation driven by precession could have changed ENSO behaviors (see the calculated NINO3 index—a SST anomaly in the eastern equatorial Pacific used to measure the strength of modern ENSO events—Fig. 2; Clement et al., 1999). At the precession band, the intensity minima of the North Pacific High were in phase with the April perihelion and the maxima of the predicted NINO3 index (Clement et al., 1999; Fig.2). This correspondence suggests that the intensity of the North Pacific High varied in response to precessional forcing and that this response is linked with the changes in tropical ocean-atmosphere interactions. However, the productivity variation in the tropical Indo-Pacific (Beaufort et al., 2001) was out of phase with the ΔSST_{NEP} and the predicted NINO3. This phase discrepancy of long-term ENSO-like variability remains a key uncertainty because little is known about the behavior of tropical ocean-atmosphere interactions at orbital

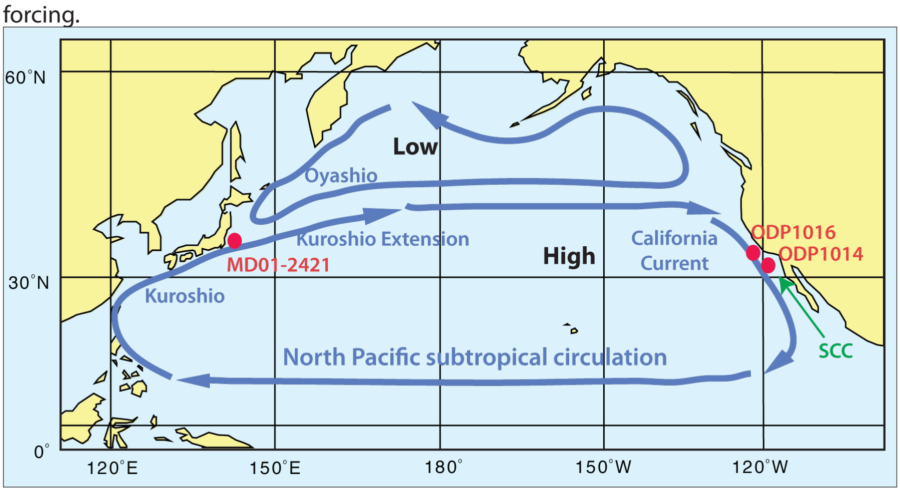

Figure 1: Location of study sites and surface currents in the North Pacific (SCC = Southern California Countercurrent). Local atmospheric cells are also indicated: ***High*** *= North Pacific High,* ***Low*** *= Aleutian Low.*

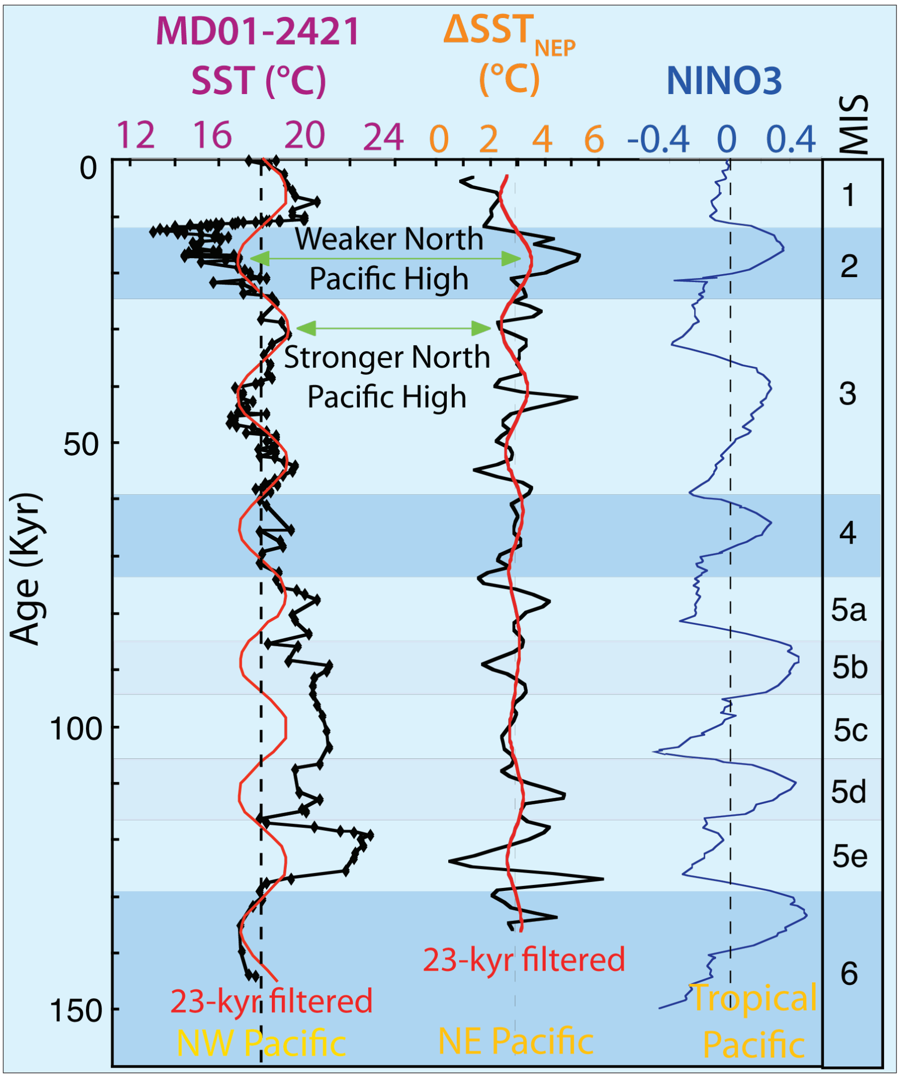

Figure 2: $U^{K'}_{37}$-derived SST at the Japan margin (core MD01-2421; Yamamoto et al., 2004, 2005), lateral temperature gradient ΔSST_{NEP} at the California margin, and the calculated NINO3 index (Clement et al., 1999) during the last 150 kyr. MIS = Marine Isotope Stage

timescales, although some shorter paleorecords in the eastern tropical Pacific and the tropical Andes regions are consistent with the model prediction (e.g., Koutavas et al., 2002; Moy et al., 2002). Long-term ENSO-like variability and wave propagation by teleconnection (Clement et al., 1999; Beaufort et al., 2001; Yamamoto et al., 2004) are potential driving forces of the North Pacific basin-scale climate response. The establishment of the linkage between this basin-scale response and tropical ocean-atmospheric dynamics will be a critical step toward better understanding the role of the Indo-Pacific in global climate change.

In summary, the east-west seesaw-like SST variation in the mid-latitude North Pacific during the last two glacial-interglacial cycles is part of a basin-scale oceanic and atmospheric response to precessional forcing. As this east-west seesaw is also typical of the modern North Pacific on interannual and decadal timescales, common climate-driving processes might exist in the response of the North Pacific to forcing on different timescales.

Note

Data are available from NOAA Paleoclimatology website www.ncdc.noaa.gov/paleo/paleo.html

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Last glacial SST changes in the SE Pacific—a bipolar seesaw perspective

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The SE Pacific is a key region for studying natural variability of globally important atmospheric and oceanic circulation components of the southern hemisphere, from the last glacial and beyond. High resolution paleoceanographic studies have particularly focused on continental margin records off Chile, which were recovered by several international research cruises during the last decade, including Ocean Drilling Program (ODP) Leg 202. The current network of sediment cores along the northern and central Chilean margin have greatly improved our understanding of late Quaternary terrestrial climate change in Chile (e.g., Hebbeln et al., 2007; Lamy et al., 1998, 1999, 2001; Stuut and Lamy, 2004) and the paleoceanography of the adjacent Peru-Chile Current (PCC) system (e.g., Hebbeln et al., 2002; Kim et al., 2002; Mohtadi and Hebbeln, 2004). These findings are summarized in two recent review articles (Marchant et al., 2007; Stuut et al., 2006).

Here, we focus on results based on ODP Site 1233, located at the upper continental slope off southern Chile (41°S) at the northern margin of the Antarctic Circumpolar Current (ACC) and the southern end of the PCC (Fig. 1). This site has received particular attention because the ~70-kyr-old sequence extends over ~135 m composite core depth, resulting in high sedimentation rates, unprecedented in the South Pacific. Site 1233 is ideally located to compare past variations of both surface and deep-ocean water masses with climate records from high southern latitudes (e.g., Antarctic ice-cores). Modern sea sur-

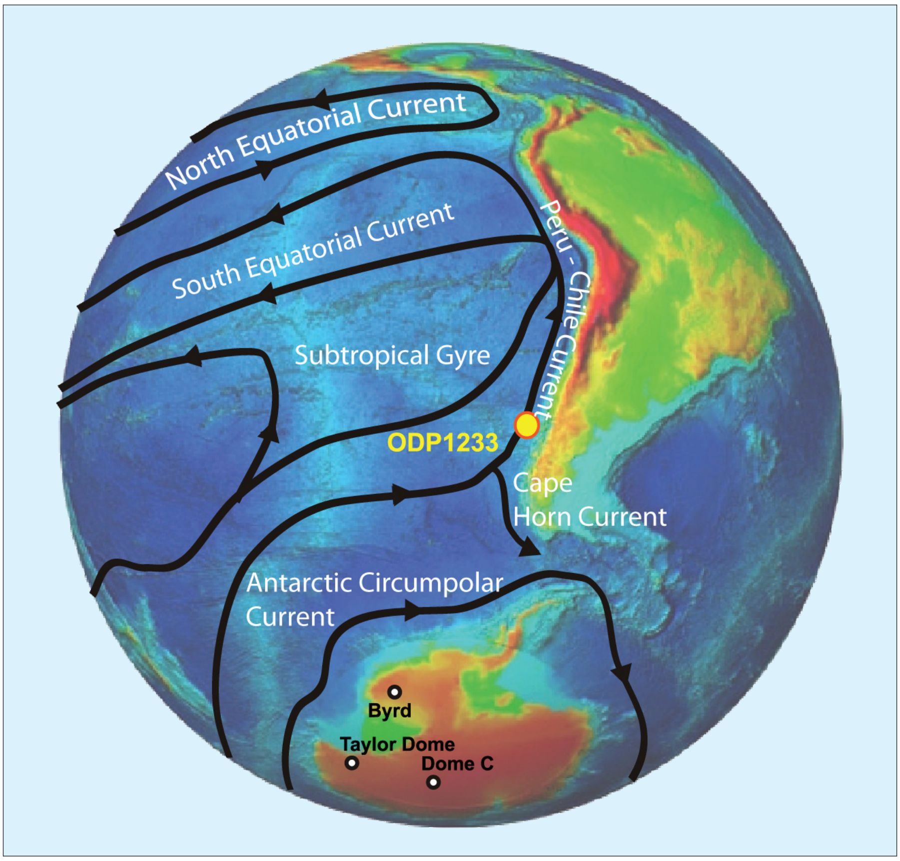

Figure 1: Major surface currents of the South Pacific Ocean and the locations of ODP Site 1233 and Antarctic ice cores discussed in the text.

face temperature (SST) gradients within the northernmost ACC are very large and intimately linked to the northern margin of the southern westerly wind belt (SWW), making this region very sensitive to latitudinal shifts in atmospheric and oceanographic circulation associated with the SWW. Furthermore, Site 1233 is located close to the southern Chilean coast (~40 km) and close to the northwestern margin of the glacial Patagonian Ice Sheet (PIS), which occupied a large area of southernmost South America during the last glacial. This unique location allows a detailed comparison of various continental climate and paleoceanographic proxy records within the same archive and, therefore, avoids problems linked to age model uncertainties. A number of different proxy records from Site 1233 have been published, including alkenone and radiolarian-based SST reconstructions (Kaiser et al., 2005; Lamy et al., 2007, 2004; Pisias et al., 2006), terrestrial sediment input and pollen-based continental climate studies (Heusser et al., 2006; Kaiser et al., 2007; Lamy et al., 2004; Pisias et al., 2006), and nitrogen isotope analyses (Martinez et al., 2006).

"Antarctic timing" of SST changes

The alkenone SST record from Site 1233 shows a clear "Antarctic timing" of millennial-scale temperature changes over the past 70 kyr (Kaiser et al., 2005; Lamy et al., 2004) (Fig. 2). The major Antarctic warm events A1 to A4 (Blunier and Brook, 2001) are characterized by SST increases of up to 3°C. The global Last Glacial Maximum (LGM) is not well defined in the record. Deglacial warming starts at ~18.8 kyr BP, with a ~2-kyr-long increase of nearly 5°C until ~16.7 kyr BP. Thereafter, temperatures remain comparatively stable until the beginning of a second warming step of ~2°C between ~12.7 and ~12.1 kyr BP (Lamy et al., 2007). This pattern is consistent with independent SST estimates based on radiolarian assemblages (Pisias et al., 2006). The first warming step coincides with a major shift in the $\delta^{15}N$ record from Site 1233 that has been explained by a southward shift of fronts in the Southern Ocean (Martinez et al., 2006), and coincides with a major change in pollen assemblages (Heusser et al., 2006).

Millennial-scale temperature changes in Antarctica over the last glacial may be consistently explained by the bipolar seesaw concept, which suggests an out-of-phase millennial-scale climate pattern between the northern and southern hemispheres during the last glacial (Stocker and Johnsen, 2003). Over Termination 1 (T1), detailed radiocarbon dating reveals that the SST in the mid-latitude SE Pacific rose at the same time that the Atlantic meridional overturning circulation (AMOC) decreased (Lamy et al., 2007). Though this timing is largely consistent with Antarctic ice core records, the initial warming in the SE Pacific is more abrupt, suggesting a direct and immediate response to the slowdown of the Atlantic thermohaline circulation through the bipolar seesaw mechanism. This response requires a rapid transfer of the Atlantic signal to the SE Pacific, without involving the thermal inertia of the Southern Ocean that may contribute to the substantially more gradual deglacial temperature rise seen in Antarctic ice cores. The most plausible mechanism is a seesaw-induced change of the coupled ocean-atmosphere system of the ACC and the southern westerly wind belt, as supported by North Atlantic water hosing model experiments (Timmermann et al., 2005). The SST response to a weakening of the AMOC in these and other model simulations (e.g., Knutti et al., 2004; Schmittner et al., 2002) is, however, much smaller than the initial warming observed at Site 1233 (Fig. 2). Apart from the pronounced regional sensitivity of Site 1233 due to strong regional SST gradients, global forcings (such as changes in insolation, CO_2 and atmospheric dust) explain an important fraction of the deglacial SST rise in the SE Pacific (Lamy et al., 2007).

Link to CO_2 changes?

The connection of atmospheric CO_2 content to SST changes in the SE Pacific and the position of the westerlies may be very relevant to our future climate, as some models display significant shifts of the westerlies under future greenhouse scenarios (see e.g., Yin, 2005). Based on a general circulation model, Toggweiler et al. (2006) showed that the equatorward shifted southern hemisphere westerlies during the glacial allowed more respired CO_2 to accumulate in the deep ocean. During glacial terminations, the southward moving westerlies reduced polar stratification and enhanced upwelling of deepwater masses around Antarctica, which would then have released large amounts of the stored CO_2 to the atmosphere. We observe a similar link between SE Pacific SSTs and CO_2 for older intervals. For example, the transition from marine isotope stage (MIS) 4 to MIS 3 (Fig. 2) that did not initiate interglacial conditions, even though insolation changes were similar to those of T1. We suggest that the particular combination of orbital-scale insolation changes and millennial-scale climate variability over T1 (i.e., two major slowdowns of the AMOC (Heinrich Event (HE)1 and Younger Dryas (YD)) over an interval of rising northern hemisphere summer insolation) has been a crucial factor for the shift of the climate system into the present interglacial conditions (for details see Lamy et al., 2007).

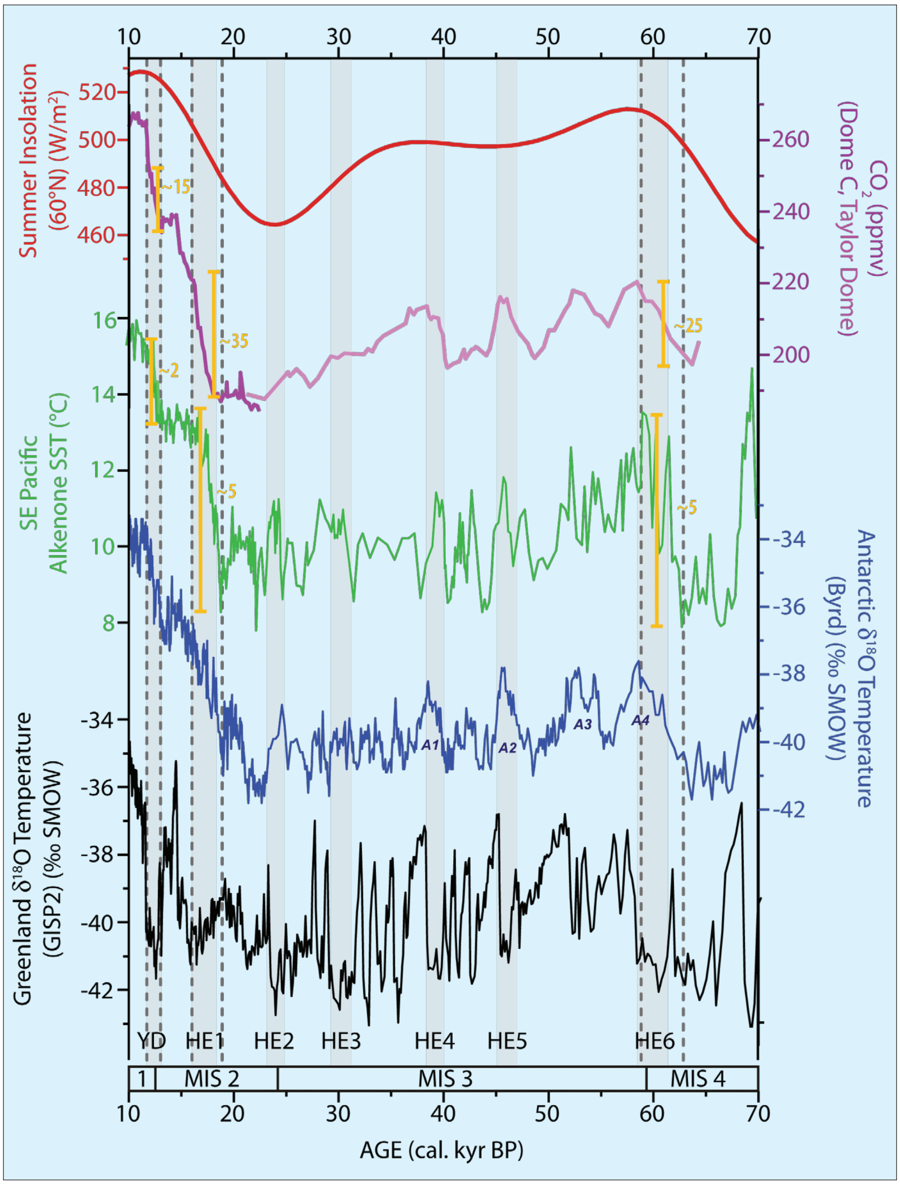

*Figure 2: Comparison of Southeast Pacific SST to Antarctic and Greenland ice core records (atmospheric CO_2 and $\delta^{18}O$ as a temperature proxy) over the past 70 kyr. Summer insolation at 60°N (Berger and Loutre, 1991; **red**). CO_2 record from Dome C (Monnin et al., 2001; **purple**) and Taylor Dome (Indermühle et al., 2000; **pink**) ice cores. (Timescale of the Taylor Dome record has been adapted to the GISP2-synchronized age model of the Byrd ice-core (Blunier and Brook, 2001)). Alkenone SST record from Site 1233 (Kaiser et al., 2005; Lamy et al., 2007; **green**). Oxygen isotope record of the Antarctic Byrd (Blunier and Brook, 2001; **blue**) and Greenland GISP2 (Grootes et al., 1993; **black**) ice cores. HE1-6: Heinrich Events (**gray bars**). YD: Younger Dryas. Dotted lines indicate intervals with substantial increase in SST and CO_2. Yellow numbers show approximate amplitude in ppmv and °C.*

Outlook

A major issue for future research will be to follow the millennial-scale pattern recorded off southern Chile along the Pacific Eastern Boundary Current System (PEBCS) into the tropics. A paleo-SST gradient reconstruction covering the complete latitudinal range of the PEBCS suggests an equatorward displaced subtropical gyre circulation during MIS 2 and 4, with enhanced cold-water advection along the PCC. Conversely, the oceanic circulation in the PEBCS was weakened, and the ACC and associated southern westerly wind belt moved southward during relatively warm periods (early MIS 3 and the Holocene climate optimum) (Kaiser et al., 2005). Furthermore, ultra high-resolution sediment records from the Chilean Fjords and the adjacent continental margin were recovered in February 2007 during the “Marion Dufresne” cruise PACHIDERME. These will provide new Holocene and late glacial records with the potential to look into centennial- or even decadal-scale climate variability.

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North Atlantic salinity oscillations linked to atmospheric and ocean circulation changes over the last glacial cycle

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Evaporation, precipitation and atmospheric water vapor transport play an important role in maintaining North Atlantic Meridional Overturning Circulation (AMOC) through their influence on salinity (Broecker, 1989; Broecker et al., 1990; Zaucker and Broecker, 1992). Net evaporation exceeds precipitation in both the Caribbean and western North Atlantic subtropical gyre, elevating Gulf Stream sea surface salinity (SSS) as waters circulate northward through the subtropics (Broecker et al., 1990; Curry et al., 2003). The excess salt advected to the North Atlantic is critical in maintaining modern AMOC (Broecker, 1991).

It is generally agreed that the abrupt climatic shifts that characterized Dansgaard-Oeschger (D-O) cycles in the Greenland ice cores were triggered by changes in North Atlantic surface water density at the sites of overturning circulation (Boyle, 2000; Oppo and Lehman, 1995; Rasmussen and Thomsen, 2004). While warm interstadials are characterized by a circulation pattern similar to today (Fig. 1), the northward flow of warm, salty surface waters into the sub-polar North Atlantic may have been reduced and/or subducted below a cold, fresh surface layer during stadials. A better understanding of past surface temperature and salinity distributions is needed to determine the role of density-driven changes in ocean circulation.

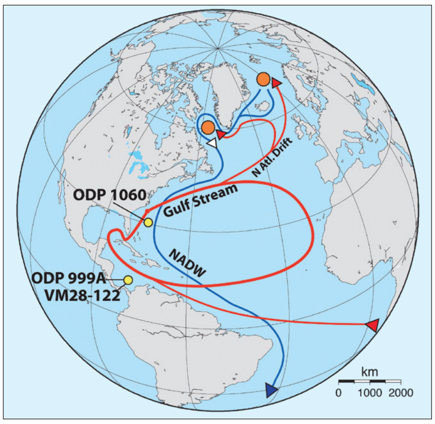

*Figure 1: Modern N. Atlantic surface (**red**) and deep water (**blue**) circulation and location of Caribbean cores ODP 999A (12°45'N, 78°44'W; 2,827 m; 4 cm/kyr sed. rate) and VM28-122 (11.56°N, 78.41°W; 3,623 m; 4-15 cm/kyr sed. rate) and N. Atlantic subtropical gyre core ODP 1060 (30°46'N, 74°28'W; 3480 m; 20-53 cm/kyr sed. rate). Orange circles indicate sites of deepwater formation in N. Atlantic.*

Reconstructing past surface-salinity change

The oxygen isotopic composition of foraminiferal calcite ($\delta^{18}O_c$) is a function of both temperature and the isotopic composition of the seawater ($\delta^{18}O_{sw}$) in which an individual precipitates its shell. Because $\delta^{18}O_{sw}$ covaries linearly with SSS (Charles and Fairbanks, 1990), shell $\delta^{18}O_c$ can be used to estimate past SSS change if $\delta^{18}O_{sw}$ and temperature can be deconvolved. Based on this approach, Schmidt

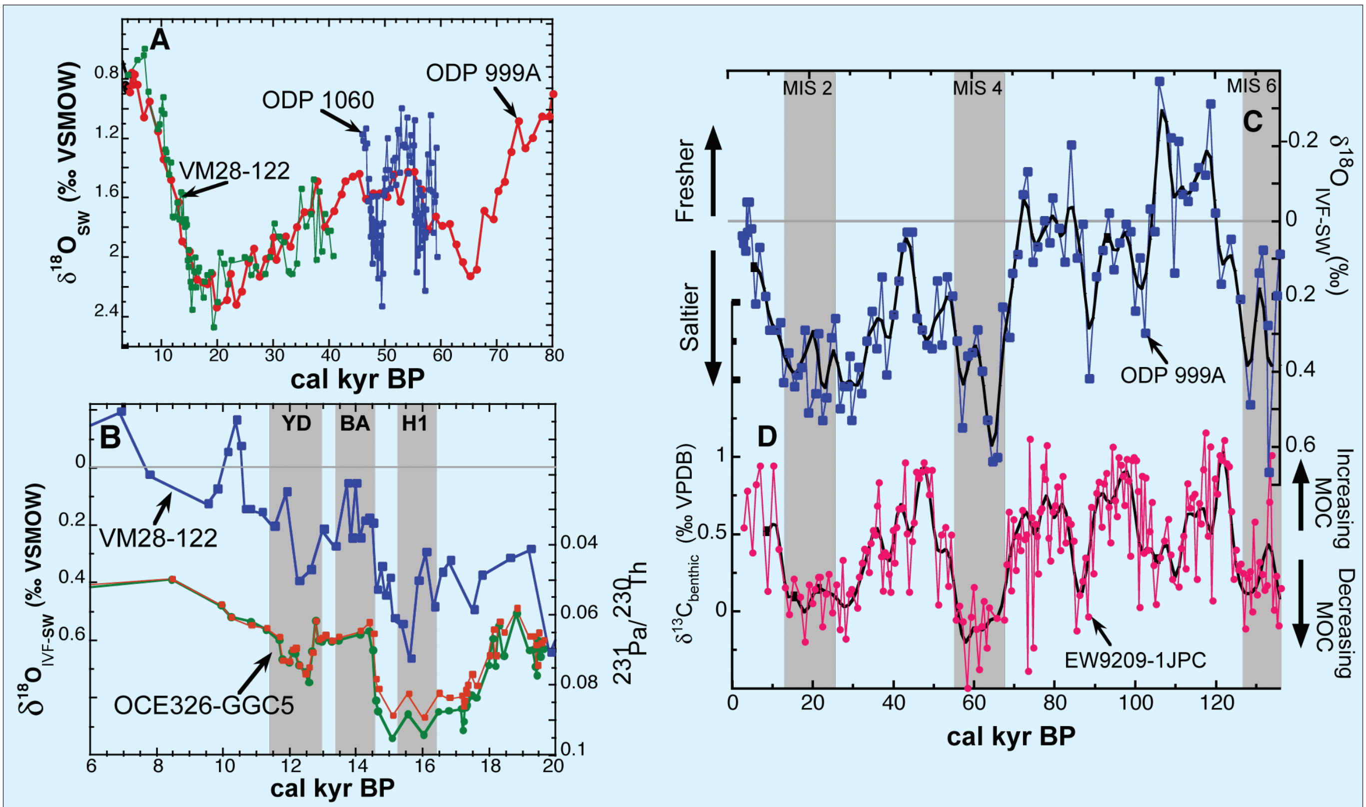

*Figure 2: **A**) Computed $\delta^{18}O_{SW}$ records from the Caribbean at sites ODP 999A (red line) and VM28-122 (green line) and in the North Atlantic gyre at ODP 1060 (blue line) during the last glacial cycle. $\delta^{18}O_{SW}$ values calculated from Mg/Ca-derived SST and $\delta^{18}O_c$ in planktic foraminifer G. ruber. To compare regional $\delta^{18}O_{SW}$ change between Caribbean and gyre site 1060, modern $\delta^{18}O_{SW}$ difference between the two sites (0.3‰) was subtracted from ODP 1060 values to account for additional evaporation that occurs as waters transit between the tropics and subtropics. After removing global $\delta^{18}O_{SW}$ change due to continental ice volume (Waelbroeck et al., 2002), local $\delta^{18}O_{SW}$ records were normalized to modern regional value, resulting in ice volume free $\Delta\delta^{18}O_{IVF\text{-}SW}$ record from VM28-122 (**B;** blue line) and 999A (**C;** blue line) during the last glacial cycle. Note the rapid salinity decrease recorded in the Caribbean at VM28-122 at 14.6 cal kyr BP corresponds to a decrease in $^{231}Pa/^{230}Th$ ratios in Bermuda Rise core OCE 326-GGC5 (**B;** red line) (McManus et al., 2004), indicating a strengthening of AMOC at the beginning of BA. Shaded bars also illustrate Heinrich Event 1 (H1) and Younger Dryas (YD). **C**) $\Delta\delta^{18}O_{IVF\text{-}SW}$ from ODP 999A (black line is a low-pass (5 kyr) filter with 5-point filter weight running through raw data (blue line)). Benthic $\delta^{13}C$ record (**D**) (black line is a low-pass (5 kyr) filter with 10-point filter weight) from Ceara Rise core EW9209-1JPC (5°N, 43°W; 4,056 m; pink line) indicates times of reduced AMOC (lower $\delta^{13}C$)(Curry and Oppo, 1997) when $\Delta\delta^{18}O_{IVF\text{-}SW}$ in ODP 999A are enriched.*

et al. (2004; 2006a, 2006b) combined Mg/Ca-paleothermometry with $\delta^{18}O_c$ measurements on the surface-dwelling foraminifers *Globigerinoides ruber* (white variety) from western Caribbean cores ODP 999A and VM28-122, and from the western North Atlantic gyre site ODP 1060 to reconstruct past variation in tropical/subtropical $\delta^{18}O_{SW}$ (Figs. 1 and 2A).

After removing the influence of continental ice volume on global $\delta^{18}O_{SW}$ (reported as $\Delta\delta^{18}O_{IVF\text{-}SW}$; ice volume free seawater), Schmidt et al. (2004) showed that $\Delta\delta^{18}O_{IVF\text{-}SW}$ values were more positive than modern seawater by ~0.5 to 0.6‰ during glacial marine isotope stages (MIS) 2, 4 and 6 in the western Caribbean (Fig. 2C). Positive values indicate elevated SSS due to the removal of excess $H_2^{16}O$ through evaporation. In contrast, ice volume corrected interglacial $\delta^{18}O_{SW}$ values were indistinguishable from modern values. If the freshwater $\delta^{18}O$ value of Caribbean rainfall during the Last Glacial Maximum (LGM) was similar to the modern value, as some models suggest (Jouzel et al., 2000), the $\delta^{18}O_{SW}$ shifts indicate that Caribbean SSS was ~2.5 psu higher during glacial phases.

Schmidt et al. (2006a) examined the question of whether subtropical North Atlantic SSS varied on millennial timescales using a $\delta^{18}O_{SW}$ record from ODP Site 1060 (Fig. 3A). $\delta^{18}O_{SW}$ showed that abrupt D-O warming events (Fig. 3C) coincided with rapid SSS reductions in the North Atlantic gyre, while gyre salinity increased substantially during cold stadials. Using modern relationships, the average stadial-interstadial $\delta^{18}O_{SW}$ values indicate millennial-scale SSS enrichments of 0.7 to 1.5 psu during stadials. Importantly, absolute reconstructed $\delta^{18}O_{SW}$ from the gyre agree with reconstructed $\delta^{18}O_{SW}$ from Caribbean site 999A during the overlapping MIS 3 time period when the modern $\delta^{18}O_{SW}$ difference between these locations is accounted for (Fig. 2A). This comparison provides internal consistency, indicating that the reconstructed tropical/subtropical salinity shifts are robust. We note that the large amplitude SSS variability observed in the gyre during MIS 3, but absent in the Caribbean, is a result of sedimentation rates that are 8-15 times higher at site 1060 than at 999A.

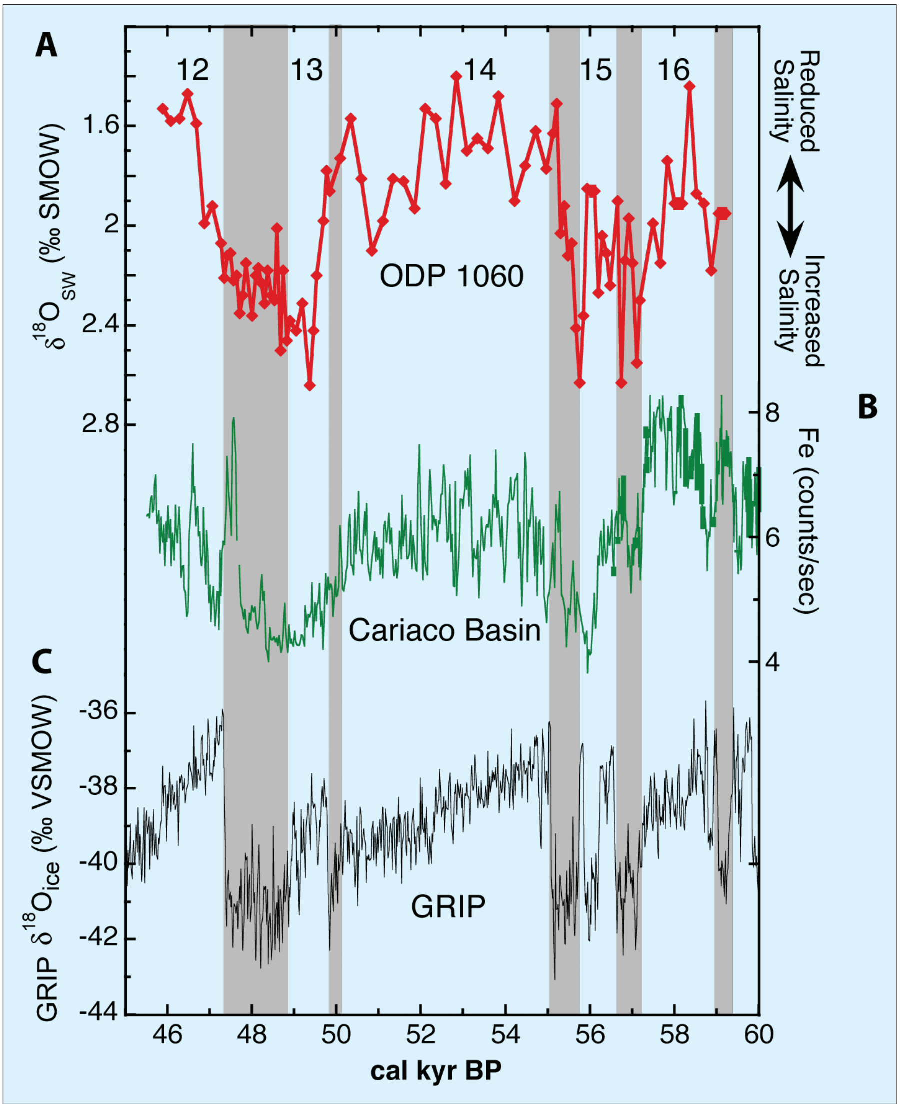

Figure 3: Salinity variation at ODP site 1060 during MIS 3. ***A)*** *Computed $\delta^{18}O_{SW}$ from site 1060;* ***B)*** *Fe content (counts/sec) from Cariaco Basin core ODP 1002 (Peterson et. al., 2000), adjusted to the GRIP age model;* ***C)*** *GRIP $\delta^{18}O_{ICE}$ record (Johnsen et al., 2001). Cold stadials in the GRIP record are marked by more arid conditions in the western tropical Atlantic (lower Fe concentrations) and elevated gyre salinities (increased $\delta^{18}O_{SW}$ values at site 1060). Note the salinity increases (as $\delta^{18}O_{SW}$) associated with the shaded stadial events and the reduced salinities associated with the numbered interstadials 12-16.*

North Atlantic SSS and ocean circulation

It is generally accepted that cold periods in the North Atlantic are associated with reduced AMOC. Benthic foraminiferal $\delta^{13}C$ oscillations from the deep western tropical Atlantic reflect the relative strength of North Atlantic Deep Water (NADW) (high $\delta^{13}C$) and Antarctic Bottom Water (low $\delta^{13}C$) production. $\Delta\delta^{18}O_{IVF\text{-}SW}$ values from ODP 999A show that the positive salinity shifts that characterize cold glacial periods occur when western tropical Atlantic benthic $\delta^{13}C$ is reduced and AMOC is weak (Curry and Oppo, 1997) (Fig. 2D). As AMOC results in the export of cold, salty NADW, reduced AMOC during glacial intervals may contribute to the accumulation of salt in the north Atlantic.

Comparison of VM28-122 $\Delta\delta^{18}O_{IVF\text{-}SW}$ values with the Bermuda rise record of sedimentary $^{231}Pa/^{230}Th$ ratios (a proxy for the strength of AMOC) (McManus et al., 2004) over the last deglacial reveals that Caribbean SSS decreased rapidly at the onset of the Bølling-Allerød (BA), just as the $^{231}Pa/^{230}Th$ record suggests that AMOC resumed (Fig. 2B). During the brief period of BA warmth in the North Atlantic, Caribbean salinity reduced significantly, reaching a minimum between 14.5-13.7 cal kyr BP. Given the saline conditions that existed in the Caribbean during the early deglaciation, it has been proposed that excess salt advecting from the Caribbean at ~14.6 cal kyr BP (Fig. 2B) may have helped offset the low-salinity conditions that existed in the North Atlantic as a result of Heinrich Event 1 (Schmidt et al., 2004).

Tropical atmospheric circulation changes were also a major contributor to shifts in glacial/stadial-interglacial/interstadial SSS. Fe and Ti concentrations in Cariaco Basin core ODP 1002 suggest the Intertropical Convergence Zone (ITCZ) migrated southward during cold stadial and northward during warm interstadial events, resulting in reduced (southward) or elevated (northward) freshwater flux over northern South America and into the North Atlantic (Peterson et al., 2000) (Fig. 3B). Wet/dry oscillations in the ODP 1002 Fe record covary with fresher/saltier conditions at site 1060 (Fig. 3A). Furthermore, general circulation model simulations predict increased northeast Trade Wind strength during periods of high-latitude cooling, associated with an intensification of the subtropical high pressure over the North Atlantic gyre (Lohmann, 2003; Vellinga and Wood, 2002; Vellinga and Wu, 2004). These conditions result in a precipitation deficit in the tropical/subtropical North Atlantic, coupled with a freshening of the tropical/subtropical South Atlantic. Covariation between shifts in the Atlantic ITCZ, as inferred from the Cariaco Basin Fe record, and changes in North Atlantic gyre salinity suggest that a similar oscillation may have operated in the Atlantic during MIS 3 on millennial timescales, resulting in elevated North Atlantic gyre SSS during stadials.

Based on these results, it appears that surface waters in the Caribbean and the subtropical gyre became exceptionally salty during glacial/stadial intervals over the last 136 kyr. Correlations between tropical/subtropical SSS change, inferred AMOC variability and meridional shifts in the ITCZ suggest that changes in ocean circulation and the tropical hydrological cycle combined to alter the glacial/stadial Atlantic salinity budget. Results indicate that as the ITCZ migrated southward during stadials, water vapor supply to the North Atlantic decreased and/or water vapor removal increased (Xie et al., 2007). This lead to the accumulation of salt in the tropical/subtropical North Atlantic, which was not advected out of the basin due to reduced AMOC. Therefore, the hydrological cycle may act as a negative feedback during weak phases of AMOC, increasing North Atlantic surface water density and preconditioning the system for a return to an interstadial mode of strong AMOC. More intriguing is the possibility that these elevated stadial gyre salinities played a critical role in maintaining North Atlantic SSS high enough to allow for the rapid resumption of North AMOC, in spite of increased freshwater input associated with interstadial warming events.

Note

All data are archived at the NOAA Paleoclimatology Database: www.ncdc.noaa.gov/paleo/

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The bipolar seesaw on the Iberian margin stretching over the past 420,000 years

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Continuous cores of ancient ice recovered from Greenland and Antarctica contain unique records of changes related to the air temperature. While several ice age cycles have been recovered for Antarctica (Jouzel et al., 2007), only one climate cycle (i.e., interglacial followed by a glacial period) has been recovered from Greenland (NGRIP members, 2004). This fact presents a challenge if we are to estimate the climate variability at European latitudes, as past temperatures in Antarctica rose and fell gradually, whereas sudden transitions occurred in the Greenland record. A possible explanation for this interhemispheric climate pattern is thresholds and nonlinear hysteresis behavior (i.e., the state of the dynamic system depends on its history) in the climate system (Stocker and Wright, 1991).

The Iberian Margin is a real laboratory for describing hydrological conditions from surface and deepwater masses, from the northern Atlantic and Antarctic regions, respectively. At this location, the surface temperature record very closely resembled the temperature record over Greenland, whereas the deep-temperature estimates were in line with Antarctica, hence providing the opportunity for further testing on the seesaw connection between hemispheres (Blunier and Brook, 2001; Shackleton, 2001; Stocker and Johnsen, 2003).

To contribute to this knowledge of the northern hemisphere climate, a recent study (Martrat et al., 2007) worked on new Iberian sites (Marion Dufresne sediment cores MD01-2443 and MD01-2444). Two questions were posed: Firstly, what were interglacial-to-glacial cycles like, prior to the last one? Secondly, which climatic processes were providing the link between Mediterranean centennial variability and the polar regions? It must be emphasized that conclusions were mainly based on the temporal changes and relative phasing between different indicators measured along each of the two cores. The conclusions were consequently irrespective of the absolute timescale chosen.

In this study at the Iberian Margin, Dansgaard-Oeschger saw-tooth-type variability and associated interhemispheric linkage were both common robust features over the past four climate cycles (420 kyr). Iberian sea surface temperature (SST) variability and stable isotope ratios in ice-water molecules from Greenland had correlation coefficients of up to 0.92 (Martrat et al., 2007). Correlation coefficients for Iberian deep-ocean temperature variability and stable isotope ratios of Antarctic ice-water molecules were similarly high (Martrat et al., 2007). None of the climate cycles studied was an exact reproduction of another (Figs. 1-4). This fact was not surprising, as the governing factors of ice-age dynamics were never identical in the past. One point of interest—both in variable glacials and in the warm, relatively stable preceding periods—was that the SST variability increased while the Pleistocene progressed to the present (annual mean $U^{k'}_{37}$-SST; Figs. 1-4A). Warming stages of limited duration were designated as Iberian Margin Interstadials (IMI) and short-term cooling stages as Iberian Margin Stadials (IMS), with the number of the climate cycle to which they belong always shown immediately before.

Glacial periods were recognized by frequent incursions of extremely cold surface waters traced by the distribution of coccolith-synthesized alkenones, very likely associated with generations of icebergs in the northern Atlantic (increased percentages of $C_{37:4}$; Figs. 1-4B, inverted axis). Eighteen events occurred during the first climate cycle (1IMI and 1IMS events 1-18), nine in the second (2IMI and 2IMS events 1-9), seven oscillations during the third (3IMI and 3IMS events 1-7) and six over the fourth (4IMI and 4IMS events 1-6).

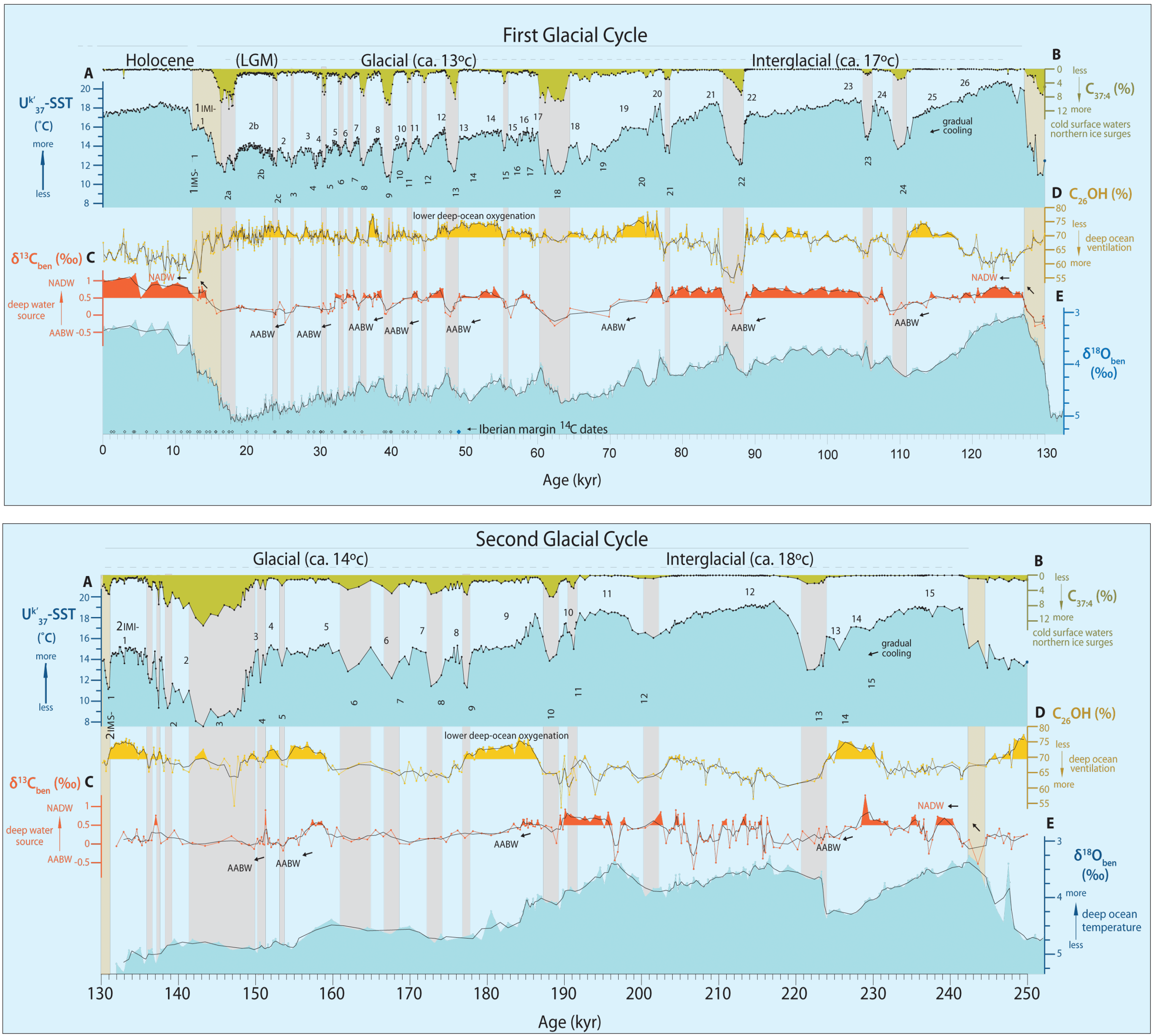
However, as previously observed (Martrat et al., 2004), the magnitude of drops in SST was often more pronounced during interglacials. At least four intense events of this nature interrupted the interglacial of the last climate period (1IMS-21, 1IMS-22, 1IMS-24 and 1IMS-25), three severe oscillations punctuated the second one (2IMS-11, 2IMS-12, 2IMS-13), just two during the third (3IMS-9, 3IMS-10) and none over the fourth climate cycle, until sudden entry into a glacial in a single event (4IMS-7).

This climate variability is specifically relevant at human scale as it encompasses changes in timescales short enough to be noticed in the time frame of a regular human life. The intensity of the changes was in some cases similar to the glacial to interglacial transitions at the onset of every climate cycle and the changes lasted long enough (from 100 to 7400 yr) to constitute long stages from a human perspective.

Different hydrological indicators were considered for the purposes of evaluating the causes of this abrupt climate variability. First, the benthic $\delta^{13}C_{cc}$ record (calcite $\delta^{13}C$) which reflects the influence of deepwater masses from both hemispheres (north Atlantic deep water, NADW, 1.1‰; and Antarctic bottom water, AABW, 0.5‰; Figs. 1-4C). Second, molecular fossil organic compounds originally synthesized by terrestrial flora, which, once accumulated on the sea floor, trace the deep ocean ventilation (decreased percentages of $C_{26}OH$ measure higher oxic transformation of these compounds and thus higher deep-ocean ventilation; Figs. 1-4D). Finally, the benthic $\delta^{18}C_{cc}$ record (calcite $\delta^{18}O$), a proxy for ice volume and deep-sea temperatures, is reminiscent of Antarctica gradual events (Figs. 1-4E).

Particularly for the Holocene, 1IMI-26 and 4IMI-10, decreases in the $C_{26}OH$ ratio and increases in benthic $\delta^{13}C_{cc}$ ratios marked the beginning of every climate cycle, characterized by a deep-sea floor ventilated with powerful arrival of north Atlantic Deepwater (NADW). Harsh drops in SST were preceded by steep decreases in

Figure 1 - 4: The Iberian margin paleoarchive over first to fourth interglacial to glacial cycle. ***A)*** *Changes in SST;* ***B)*** *% of heptatriatetraenone ($C_{37:4}$) to total alkenones, indicating arctic surface water at core location;* ***C)*** *Benthic $\delta^{13}C$ (three point running average) indicating influence of NADW (~ 1‰) and AABW (less than 0.5‰. Arrows indicate increasing flows of NADW or AABW;* ***D)*** *Relative proportion of n-hexacosan-1-ol ($C_{26}OH$) to the sum of n-hexacosan-1-ol ($C_{26}OH$) plus n-nonacosane (C_{29}) providing an oxygenation marker of deep-sea floor (three-point running average);* ***E)*** *Benthic $\delta^{18}O$ (three point average). Numbers over the SST record indicate Iberian Margin Interstadials (IMI), numbers within the blue filling indicate Iberian Margin Stadials (IMS), grey diamonds in First Glacial Cycle represent ^{14}C dates. Gray shaded bars indicate abrupt cooling episodes, yellow shaded bars indicate deglaciation periods. AABW = Antarctic Bottom Water, NADW = North Atlantic Bottom Water, LGM = Last Glacial Maximum.*



both $C_{26}OH$ and benthic $\delta^{13}C_{cc}$ ratios, when the predominance changed from NADW to southern (Antarctic Bottom Water, AABW), a few centuries before the subsequent northern ice surges (Martrat et al., 2007; Figs. 1-4).

Abrupt changes are often defined by observing the effect of climate conditions on the ocean surface and continental land masses. However, this study showed that they occurred simultaneously with reorganization of the deepwater masses in the northern Atlantic Ocean and the arrival of AABW at latitudes such as those of the Iberian peninsula. The important lesson is that due to the non-linear behavior of the ocean-atmosphere-sea ice system in the northern hemisphere, apparent gradual external triggers or slow changes in the deep ocean preceed rapid climate oscillations in the Mediterranean region at surface level. The implications are certainly challenging: A complete bifurcation in the climate conditions of this region will only be preceded by subtle and hardly identifiable changes.

This climate variability responds to the natural climate evolution of the planet. It is not related to human influence but has exerted a huge impact on tree populations around the Mediterranean by exceeding their tolerance limit, leading to population crashes and subsequent predominance of herbaceous, treeless vegetation (Tzedakis et al., 2004).

It has long been known that glacial and interglacial periods are modulated by orderly trends determined by the gradual variation of the Earth's orbital geometry. In contrast, millennial-scale abrupt climate change occurs when the climate system is forced to cross a threshold, triggering the transition into a new climate condition at a rate faster than the cause (Alley et al., 2003).

Acknowledgements

We thank the many people who have contributed to our work; particularly M. Hutterli, T. Stocker and L. de Abreu. We would like to pay a tribute to the late Professor Sir Nicholas J. Shackleton; his presence and his wisdom are greatly missed.

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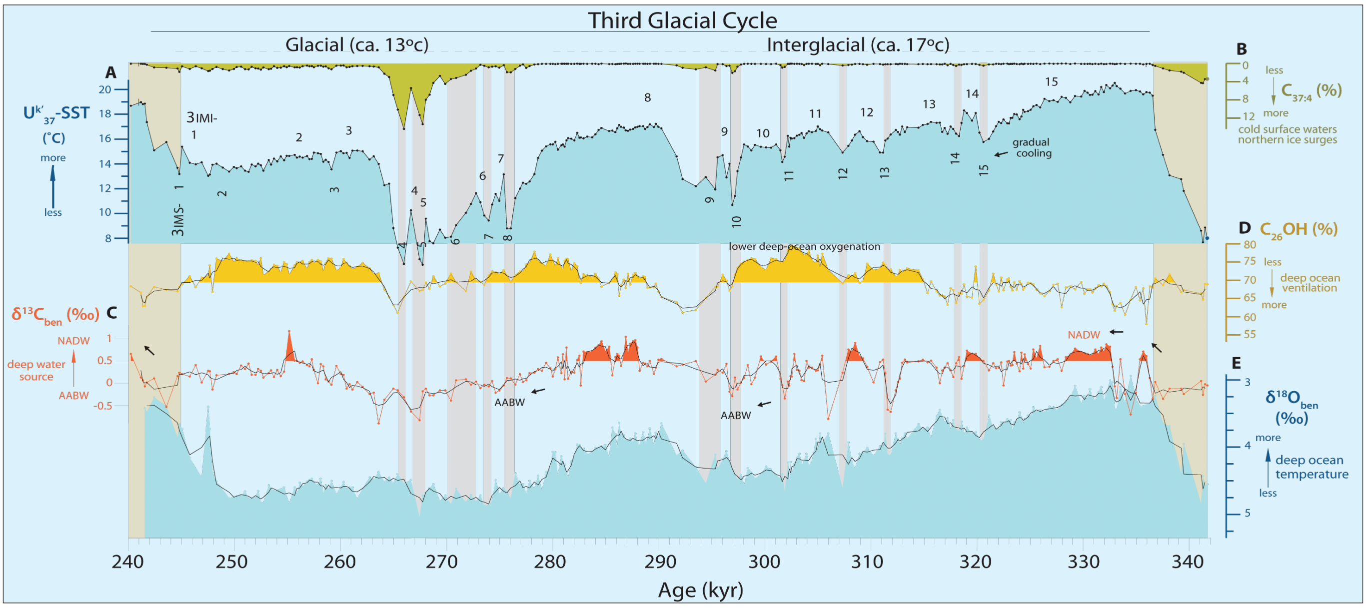

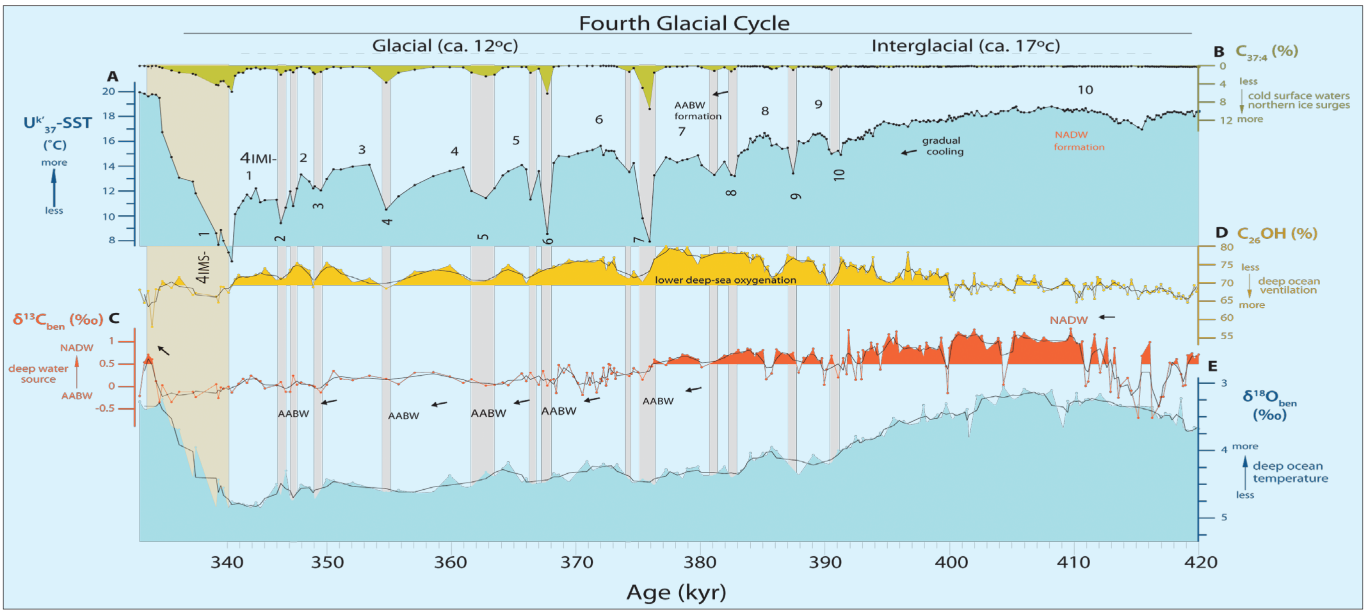

Prospects for reconstructing the Atlantic meridional overturning from cross-basin density estimates

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In much the same way that a sharp contact between warm and cold air masses on a weather map suggests the presence of strong winds, the horizontal differences in seawater density (determined by both temperature and salinity) can tell us about the strength of the ocean currents. Specifically, because large-scale ocean flows are generally in geostrophic and hydrostatic balance, the vertical differences (shear) in horizontal velocities can be determined from the horizontal density gradients. This approach, based on detailed density measurements, has underpinned most of the efforts to quantify elements of the modern ocean circulation over the last century. While closely spaced density measurements are necessary to construct a detailed picture of ocean currents, the meridional circulation integrated zonally across a given basin can be determined from density measurements at the ocean margins (Cunningham et al., 2007; Hirschi and Marotzke, 2007; Marotzke et al., 1999). This has allowed, for example, continuous monitoring of the modern Atlantic Meridional Overturning Circulation (AMOC) at 26°N (Cunningham et al., 2007). Lynch-Stieglitz et al. (1999a; 1999b) showed how the oxygen isotopic composition ($\delta^{18}O$) of benthic foraminifers from sediments could be used to estimate water density#, and hence reconstruct the horizontal flow in the upper ocean for times in the past. They suggested that density estimates at ocean boundaries could be used to reconstruct the shear in the integrated meridional overturning circulation below the wind-driven Ekman layer near the surface (Lynch-Stieglitz, 2001). In a recent paper, Huybers et al. (2007) examined the ability of paleoceanographic tracers to constrain meridional circulation rates in an idealized basin. They found that when data can only be obtained along the seafloor (as is the case for paleoceanographic reconstructions), density provides an important integrative measure of circulation. However, they highlight the need for more accurate paleo-density estimates. Here, we report on recent progress in reconstructing the AMOC from paleo-density estimates. Many of these studies and ideas emerged from the discussions of the Working Group on Past Ocean Circulation, jointly sponsored by IMAGES and SCOR.

LGM South Atlantic water density

In today's South Atlantic, seawater density in the upper 2 km is greater along the eastern margin than along the western (Fig. 1a). This zonal density gradient reflects the shear of the AMOC at these depths, with a northward flow between the surface and 1 km water depth, and a southward flow ("North Atlantic Deepwater") between 1 and 2 km water depth. Lynch-Stieglitz et al. (2006) found that this density gradient is reflected in the higher $\delta^{18}O$ (colder and/or saltier waters) values of foraminifers found in surface sediments on the eastern margin relative to those from the western margin (Fig. 1b). However, they found that foraminifers from sediments corresponding to the LGM showed a reduced gradient, with perhaps slightly higher $\delta^{18}O$ values on the western margin. We do not know the precise relationship between the $\delta^{18}O$ of foraminifers and water density for the LGM in the South Atlantic. However, on both sides of the basin, $\delta^{18}O$ increases with depth, suggesting that like today, higher $\delta^{18}O$ in benthic foraminifers is associated with higher seawater density. This would imply that the shear associated with the AMOC was significantly reduced or even reversed in the South Atlantic at the LGM. This is incompatible with either a strong, deep (similar to modern) AMOC shown by some coupled ocean-atmosphere models for the LGM, or a shallower but still strong overturning cell shown in other models and inferred from sediment-based estimates of nutrient distributions during the LGM.

Gebbie and Huybers (2006) raise the possibility that interpreting glacial foraminiferal $\delta^{18}O$ in terms of water density could be misleading if there were very different water mass properties on either side of the Atlantic Ocean. Given today's relationship between the $\delta^{18}O$ of water

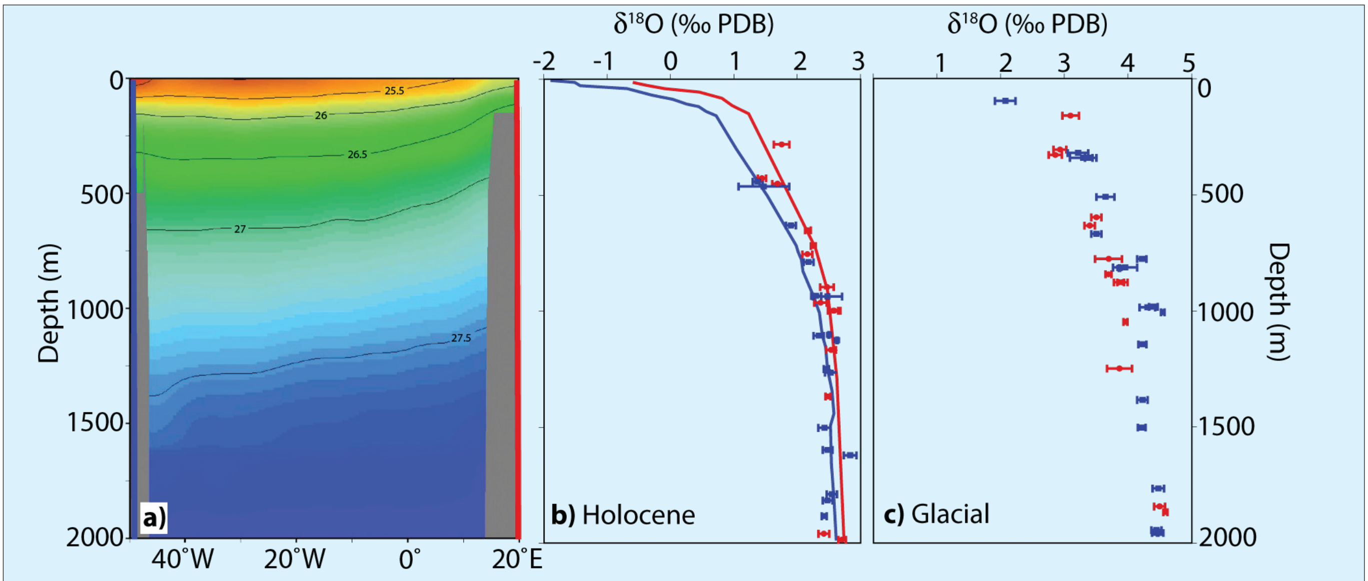

*Figure 1: **a**) Seawater density (σ_θ) along a zonal section at 30°S in the Atlantic (Conkright et al., 2002). The east-west density contrast reflects the shear in the meridional overturning circulation at this latitude; **b**) Oxygen isotopic composition ($\delta^{18}O$) of benthic foraminifers in recent sediments on the eastern (red symbols, mean and standard deviation for each core) and western (blue symbols) sides of the basin reflects the density contrast across the basin. Solid lines are predicted $\delta^{18}O$ based on modern hydrographic data (modified from Lynch-Stieglitz et al., 2006); **c**) Oxygen isotopic composition of benthic foraminifers from the Last Glacial Maximum suggest that the modern density contrast in the upper 2 km was absent or reversed (modified from Lynch-Stieglitz et al., 2006).*

and salinity, they find that waters would need to be 3°C warmer and 0.7‰ saltier on the eastern margin than on the western margin, in order for the benthic $\delta^{18}O$ data to be compatible with a density contrast (and circulation) unchanged from today. Today, the water masses on either side of the South Atlantic have similar temperature and salinity properties, due to the narrow ocean basin, effective mixing along isopycnals in the upper ocean, and the lack of a strong water mass source nearby (Fig. 2a). It would seem unlikely to have such a dramatic change in water mass properties (similar to the impact of the Mediterranean Outflow in the North Atlantic) without a significant change in circulation. However, one cannot easily discount the possibility of more subtle differences in the relationship between $\delta^{18}O$ of water and salinity on the western and eastern sides of the glacial South Atlantic, which could produce a different relationship between benthic $\delta^{18}O$ and water density on either side of the basin. The work of Gebbie and Huybers (2006) clearly points to the necessity to better constrain water mass properties for more accurate density reconstructions.

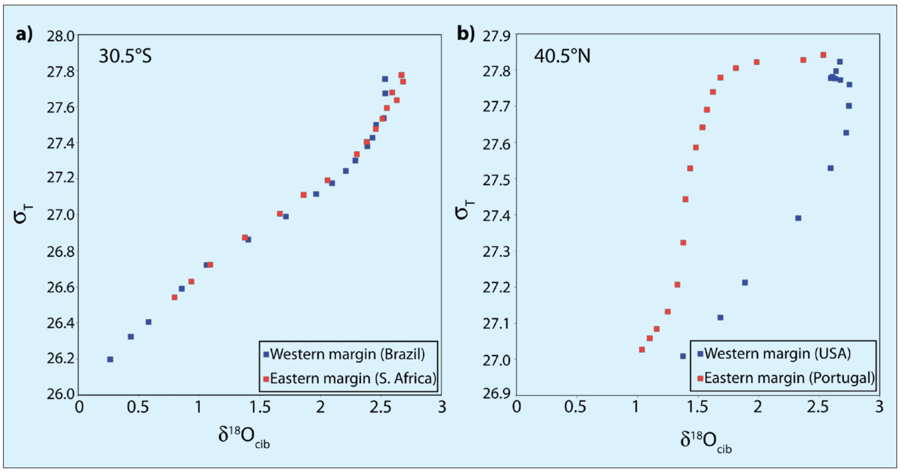

*Figure 2: **a**) Relationship between seawater density (σ_T) and calculated $\delta^{18}O$ of benthic foraminifers calcifying in this water on the eastern and western margins of the South Atlantic between 200-2000 m water depth. Note that water mass properties are relatively similar on either side of the basin; **b**) Relationship between seawater density (σ_T) and $\delta^{18}O$ of benthic foraminifers on eastern and western margins of the North Atlantic between 200 -2000 m water depth. The input of Mediterranean Outflow Water (MOW) just south of this section produces dissimilar water mass properties on either side of the North Atlantic at 40°N. While the impact of the MOW will be less at higher or lower latitudes, the relationship between $\delta^{18}O$ of foraminifers and water density (σ_T) must be determined on each margin using independent reconstructions of temperature and salinity.*

Prospects for improving paleo-density estimates

While the oxygen isotopic composition of benthic foraminifers can be used to estimate water density, it cannot uniquely constrain water density in the geological past. Any uncertainty in regarding the relationship between the $\delta^{18}O$ of foraminiferal calcite and water density will translate into uncertainty in estimates of paleo-density and paleo-flow. Better estimates of paleo-density would require the availability of independent estimates of salinity and temperature. The chlorinity of pore water in deep sea sediments has been used to estimate the salinity of bottom waters during the LGM, and the $\delta^{18}O$ of pore water coupled with the $\delta^{18}O$ of foraminiferal calcite has yielded estimates of LGM bottom water temperatures (Adkins et al., 2002). Although diffusion of pore water properties within the sediments limits the temporal resolution of this approach, such measurements can help provide constraints on the density of bottom waters during the LGM. This information can also help us better interpret the higher time-resolution records obtained from the $\delta^{18}O$ in foraminiferal calcite. However, such an approach would require many more measurements of chlorinity and $\delta^{18}O$ in pore water (e.g., from a wider range of water depths) than currently exist. Independent temperature estimates may be provided by the chemical composition of benthic foraminiferal tests (Mg/Ca or Sr/Ca ratios), although more work is needed to fully understand this emerging proxy (Elderfield et al., 2006; Marchitto et al., 2007). Given accurate temperature estimates, the $\delta^{18}O$ of the water could be determined from the $\delta^{18}O$ measurements on foraminifera. However, independent information on the relationship between $\delta^{18}O$ of water and salinity would be needed to make accurate paleo-density estimates. The lower resolution pore-water data would be able to provide some constraints on this relationship.

High-resolution reconstruction of AMOC

Many of the ideas to explain abrupt climate changes during the last deglacial and glacial periods involve changes in the AMOC. However, we have a limited understanding of how AMOC actually varied in the geological past, in particular on millennial timescales. Reconstructing the shear of the AMOC via estimates of water density at the boundaries in the North Atlantic at millennial timescales would provide a valuable test of these ideas. Hirschi and Lynch-Stieglitz (2006) showed that vertical density profiles on the margins of the Atlantic Ocean at only a few latitudes are necessary to reconstruct the structure and variability of the modern AMOC, provided that density estimates are sufficiently accurate. While the water mass properties on either side of the South Atlantic are relatively similar, there are important zonal differences in temperature, salinity and water $\delta^{18}O$ in the upper 2 km in the North Atlantic, owing to the Mediterranean Outflow Water (MOW) along the eastern margin (Fig. 2).

Thus, the need for independent estimates of temperature, salinity, and/or water $\delta^{18}O$ to address the ambiguity of benthic $\delta^{18}O$ data is even more acute in the North Atlantic than in the South Atlantic. Progress in the interpretation of benthic $\delta^{18}O$ data in terms of water density will likely be based on accurate paleo-temperature estimates from benthic foraminifers and pore water measurements both in the open Atlantic and the Mediterranean. An ocean-margin density-based reconstruction of the AMOC over millennial timescales is a challenge, and would require significant development on both of these fronts. However, if successful, it would be an important advance in our understanding of past variability in the AMOC and its relationship to abrupt climate change.

#Seawater density is controlled by pressure, temperature and salinity. It is the contribution of salinity and temperature to density that can be estimated from the $\delta^{18}O$ of foraminifers. Sediment core depth can be used to estimate pressure and (along with assumptions about the combined effects of temperature, salinity and pressure) the in situ density for calculations.

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Reconstructing changes in the meridional overturning circulation using sedimentary $^{231}Pa/^{230}Th$ ratios

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Reconstructing ocean circulation

The robust evidence from the nutrient-proxies $\delta^{13}C$ (Boyle and Keigwin, 1987; Sarnthein et al., 1994) and Cd/Ca (Marchitto and Broecker, 2006) that the water masses distribution of the ice age Atlantic Ocean was markedly different from modern observations is one of the major contributions of the field of paleoceanography to our understanding of past climate changes. These water masses are related to the Atlantic Meridional Overturning Circulation (AMOC), which plays an important role in oceanic heat transport. One goal for building upon this foundation is to develop a better understanding of past changes in the rate of the AMOC and its potential role in abrupt climate change, using sedimentary proxies that are more directly influenced by circulation dynamics.

$^{231}Pa/^{230}Th$ as a dynamic proxy

We have been developing the $^{231}Pa/^{230}Th$ circulation proxy in order to reconstruct the history of AMOC variability. This method takes advantage of the contrasting chemical behavior of ^{231}Pa and ^{230}Th in the water column. Both nuclides are produced at a constant production ratio of 0.093 from the radioactive decay of dissolved uranium in the ocean (Turekian and Chan, 1971), and are rapidly removed from seawater by adsorption on settling particles. ^{231}Pa is less rapidly removed than ^{230}Th and has a residence time (~100-200 yr) approaching the transit time of deepwater in the Atlantic basin (Broecker, 1979). As a result, ~50% of the ^{231}Pa produced in Atlantic water today is exported with the North Atlantic Deep Water (NADW) into the Southern Ocean instead of being removed into the Atlantic sediments (Yu et al., 1996). On the other hand, ^{230}Th has a shorter residence time (~20-40 yr), limiting redistribution by horizontal transport in the water column. For a given scavenging rate, lower rates of AMOC in the past would result in comparatively less ^{231}Pa export from the Atlantic and in higher sedimentary $^{231}Pa/^{230}Th$, reaching a maximum of 0.093 for a total AMOC cessation. In the Atlantic, the production ratio may also be reached when the water mass residence time equals or exceeds 3 times the ^{231}Pa residence time in the water column (≥ 500-600 yr). This has been calculated as in Yu et al. (1996), using the estimated modern scavenging rate (Fig. 2B). The validity of this tool as a tracer of AMOC rate has recently been supported by modeling experiments (Marchal et al., 2000; Siddall et al., 2007).

Glacial-Deglacial-Holocene reconstructions

Our methods include the production and comparison of detailed time series at different locations and water depths in the North Atlantic basin in order to differentiate the water masses involved in AMOC because sedimentary $^{231}Pa/^{230}Th$ integrates the circulation vigor over the overlying water column. This affords a fuller perspective on changes in AMOC associated with the dramatic climate changes since the Last Glacial Maximum (LGM) 21 kyr BP (± 3 kyrs). Although this is a work in progress, the existing records provide new insights regarding the history of AMOC. So far, five cores have been analyzed at high resolution, providing information on past changes in the rate of AMOC between

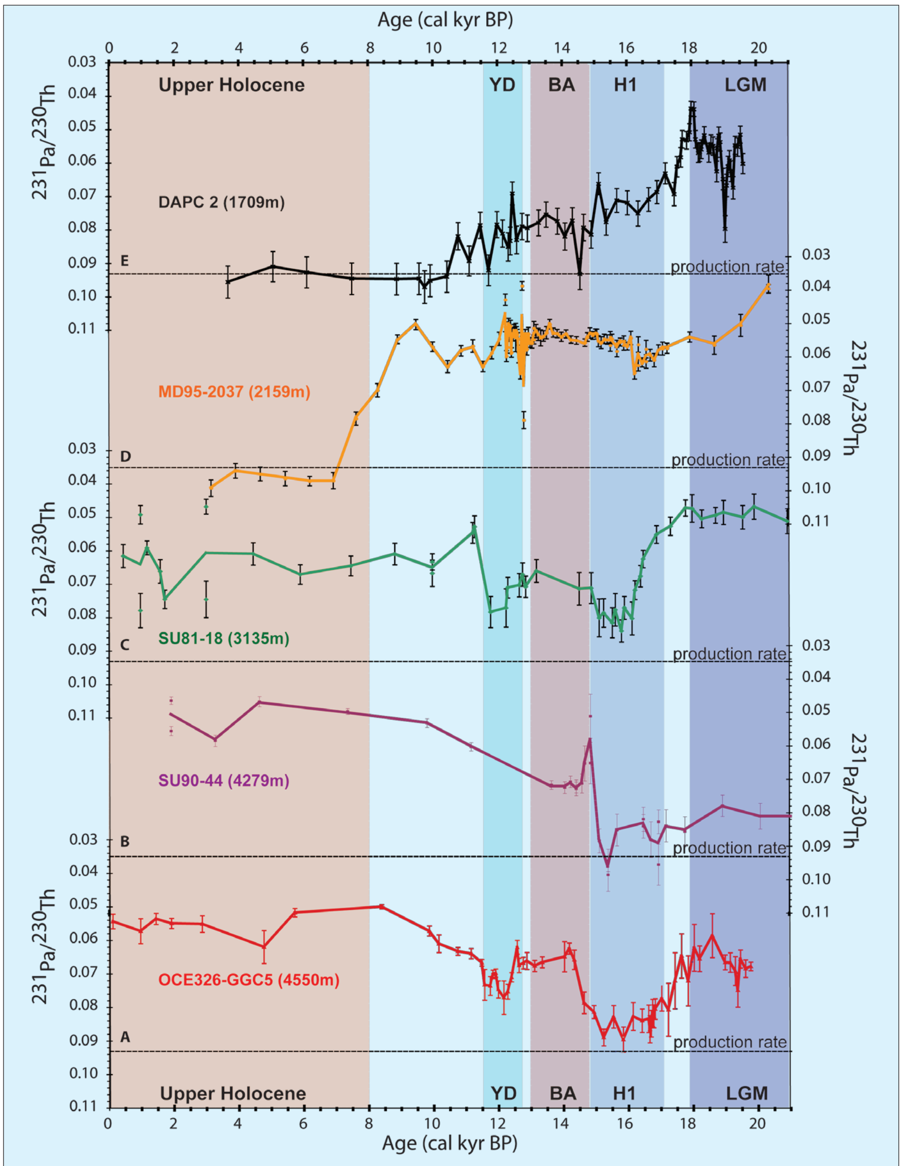

*Figure 1: Sedimentary $^{231}Pa/^{230}Th$ signals; **A**) core GGC5 (red) (McManus et al., 2004); **B**) core SU90-44 (purple) (Gherardi et al., submitted); **C**) core SU81-18 (green) (Gherardi et al., 2005); **D**) core MD95-2037 (orange) (Gherardi et al., submitted); and **E**) core DAPC2 (black) (Hall et al., 2006). The $^{231}Pa/^{230}Th$ scale is inverted. Dashed lines indicate the production ratio (0.093). Standard errors are shown as 2σ. YD = Younger Dryas, BA = Bølling Allerød, H1 = Heinrich event 1, LGM = Last Glacial Maximum.*

1700 m and 4550 m depth (McManus et al., 2004; Gherardi et al., 2005; Hall et al., 2006; Gherardi et al., submitted) (Fig. 1). Since the scavenging rates and fractionation of both isotopes can be altered by particle fluxes and composition changes, it is likely that biogenic opal and productivity are not affecting the $^{231}Pa/^{230}Th$ records and are therefore, not affecting the interpretation, in terms of past circulation changes for all sites. The cores from shallow water depth (DAPC2 and MD95-2037) display trends that present surprising contrasts with the deeper records (Fig. 1E, 1D). In these shallow cores, the glacial $^{231}Pa/^{230}Th$ are the lowest of the past 20 kyr, and $^{231}Pa/^{230}Th$ increases through the deglaciation, reaching the production ratio of 0.093 during the upper Holocene. The gradual deglacial trends are not interrupted in a major way during the abrupt cold events of Heinrich 1 (H1) and Younger Dryas (YD) that are so strongly imprinted in $^{231}Pa/^{230}Th$ records of the deep cores (Fig. 1 A, 1C) (McManus et al., 2004; Gherardi et al., 2005). In all cores, the early Holocene is characterized by active renewal rates at all depths (Fig. 1).

The results are summarized in figure 2A, which shows $^{231}Pa/^{230}Th$ measured in the five cores averaged over five time periods (LGM, H1, BA, YD, late Holocene). While additional cores must be analyzed to better contrast circulation patterns and strength in the eastern and western Atlantic, compilation of the available data already provides a clear picture of the difference in circulation strengths between the Holocene and LGM, and its evolution during deglaciation. These results are consistent with the well-established nutrient proxies (Duplessy et al., 1988; Labeyrie et al., 1992; Curry and Oppo, 2005) but add information on ocean dynamics, which better constrains past changes in the rate of the AMOC.

The Holocene bathymetric profile clearly documents the strength of the AMOC below 3000 m in the modern ocean. Furthermore, the high $^{231}Pa/^{230}Th$ in the two shallowest cores is consistent with the fact that intermediate North Atlantic water has a longer residence time than NADW (Fig. 2A, 2B) (Broecker and Peng, 1982; Campin et al., 1999). In sharp contrast, the LGM profile shows a dramatic acceleration of the overturning circulation above 3500 m and a significant but more modest decrease below. This pattern further demonstrates that Glacial North Atlantic Intermediate Water (GNAIW) was largely compensating the weakened deep-water renewal.

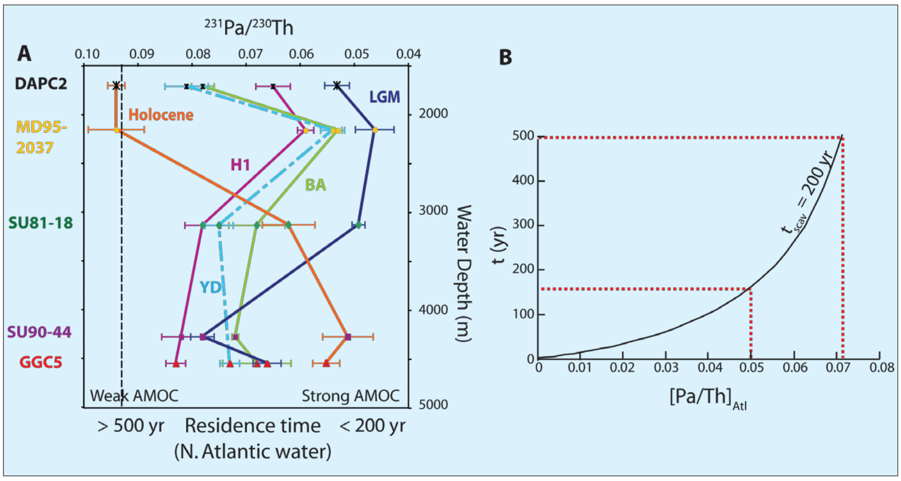

*Figure 2: Summary of $^{231}Pa/^{230}Th$ records presented for different time slices versus water depth. **A**) LGM (dark blue), Holocene (orange), Heinrich event 1 (H1; purple), Bølling-Allerød (BA; green), and Younger Dryas (YD; dashed light blue). Note: $^{231}Pa/^{230}Th$ scale is inverted to show strong MOC on the right hand, and reduced MOC on the left hand side (production ratio represented by the black dash line); **B**) Evaluation of North Atlantic water residence time (t) inferred from sedimentary $^{231}Pa/^{230}Th$ ratio, for an estimated Holocene ^{231}Pa residence time (in response to scavenging) of 200 years (t_{scav}). The red dash lines represent the mean $^{231}Pa/^{230}Th$ ratios used to give an estimation of the residence time in figure 2A (modified from Yu et al., 1996).*

At the beginning of the deglaciation, during H1 (Fig. 2A, purple profile), the GNAIW shoaled and slowed down, but did not totally shut down. Below 4000 m, $^{231}Pa/^{230}Th$ approaches but does not reach, the production ratio. While the rate of AMOC was clearly at its slowest during that time period, there was still an active, shallow overturning, which is also consistent with nutrient proxy data (Labeyrie et al., 2005).

One of the most surprising results of this new data set is the insight that it provides regarding ocean circulation during the Bølling-Allerød (BA) warm period. While it is widely believed that deepwater circulation during BA was similar to modern circulation, $^{231}Pa/^{230}Th$ clearly indicates that it was intermediate between the full LGM and full Holocene circulation pattern (Fig. 2A, green profile). It is characterized by a notable weakened overturning rate above 2000 m and a relatively enhanced overturning rate below, compared to the LGM. Notwithstanding this acceleration, deep water overturning during the BA was clearly slower than today.

The following YD cold period was characterized by a slower rate of overturning at all depths than during BA (Fig. 2A, dashed light blue profile) (not nearly as pronounced as during H1), with the exception of the shallowest of the cores, which suggests that the sharp slow down of the shallow overturning initiated during the BA did not resume and continued to decrease into the Holocene.

Conclusions

These results further highlight the potential of sedimentary $^{231}Pa/^{230}Th$ for reconstructing past changes in ocean circulation, and underscore the need for using multiple records to resolve the lateral and depth structure of the AMOC. By compiling the $^{231}Pa/^{230}Th$ ratios in cores at different depths and latitudes from the two basins of the Atlantic, we will be able to improve our reconstruction of past changes in the rate of formation of different water masses and investigate their role in modulating ocean heat-transport during abrupt climatic changes.

Perspectives

Currently the processes regulating the isotopic equilibration on the settling particles defining the final sedimentary ratio are not fully understood. This work is in progress, as one of the goals of the international research program GEOTRACES. Modeling effort with better representation of particulate processes, is also essential to foster broader application of the proxy.

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For full references please consult:

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Deep-ocean flow-speed changes linked to the NAO through Labrador Sea convection

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The Atlantic Meridional Overturning Circulation (AMOC) is important for the stability of the climate of northwest Europe, with models demonstrating that alterations in its strength and structure can lead to abrupt climate change (Rahmstorf, 2002). The Gulf Stream and its extension, the North Atlantic Current (Fig. 1a), are surface elements of the MOC while North Atlantic Deep Water (NADW) is its main southbound constituent. The densest components of NADW are formed in the Nordic Seas where cold, salty water sinks. Iceland-Scotland Overflow Water (ISOW) and Denmark Strait Overflow Water (DSOW) jointly comprise the cold, dense overflows from the Nordic Seas across the Greenland-Scotland Ridge (GSR). The strength of the GSR overflows seems to be modulated by the North Atlantic Oscillation (NAO) (e.g., Biastoch et al., 2003), which is the dominant mode of atmospheric variability in the North Atlantic sector. As ISOW descends into the deep North Atlantic, its volume nearly triples due to entrainment of salty, warm Atlantic subpolar-mode water (SPMW; Fig. 2) and fresher Labrador Sea Water (LSW; Hansen and Østerhus, 2000). ISOW freshened (Dickson et al., 2002) and the overflow weakened (Hansen et al., 2001) during the last four decades of the 20th century. However, it is not known if these changes fall within the natural variability of the system.

ISOW flow speed changes and the NAO

We reconstructed past changes in the near-bottom flow speed of ISOW using the paleocurrent proxy 'sortable' silt mean grain size ($\overline{SS}$)—the mean grain size of the 10-63 μm terrigenous silt fraction (McCave et al., 1995). The flow of ISOW has built up extensive sediment drifts, such as the Gardar Drift along the eastern slope of Reykjanes Ridge, that are well suited for this method (Bianchi and McCave, 2000). Sediment box core RAPID-21-12B (Fig. 1), recovered from the southern Gardar Drift, was dated using the ^{210}Pb method (Boessenkool et al., 2007). We constructed a continuous $\overline{SS}$ record through the period 1770-2004 AD, where each sample represents an integrated signal of 2.2 ± 0.2 yr. The decadal trends shown in Figure 1b reflect changes in ISOW vigor as it passed over the eastern flank of Reykjanes Ridge ($ISOW_{RR}$; Boessenkool et al., 2007).

The NAO is usually expressed as an index of the normalized sea-level pressure difference between the Azores High and Iceland Low pressure areas. To explore the interrelation between $ISOW_{RR}$ flow speed and the NAO, the winter (December-March) index of the NAO (Jones et al., 1997) was smoothed using a 7-year filter because the ocean's inertia acts as a natural filter for higher-frequency changes occurring in the atmosphere. Statistical analysis (cf. Mudelsee, 2003) revealed a significant, inverse linear correlation between the $\overline{SS}$ record and the NAO index on decadal timescales (Boessenkool et al., 2007), with the strongest correlation (r_{xy}= −0.42) for the period 1885-2004 AD (n=55). It suggests that the flow of $ISOW_{RR}$ has been persistently strongest during low NAO index phases.

Hydrographic timeseries and deep-flow speed

To explain this relation, we first compared flow-speed variations and the NAO index with hydrographic time series of $ISOW_{RR}$. We focused on the period of the pronounced NAO reversal, from an extremely negative index state in the 1960's to dominantly positive values through the 1990's (Fig. 1b), where the $\overline{SS}$ record (Fig. 1c) declines significantly, suggesting a marked slowdown of $ISOW_{RR}$ flow. Parallel patterns in the $\overline{SS}$ record and two ISOW salinity time series (Fig. 1c) suggest that changes in ISOW flow speed and salinity are coordinated. Furthermore, consideration of oceanographic changes between the two NAO extremes showed (1) a density decrease of $ISOW_{RR}$ (Fig. 2), and (2) a ~25% reduction in volume transport of total deep southward flow over the eastern Reykjanes Ridge (Boessenkool et al., 2007), similar to the decrease in ISOW passing through the Charlie-Gibbs Fracture Zone (CGFZ, Fig. 1a; Saunders, 1994). It is likely that variations in $ISOW_{RR}$ vigor are caused by changes in any of its constituents: ISOW proper, SPMW and LSW. Over the four decades spanning the NAO reversal, all three components freshened (Dickson et al., 2002; Curry and Mauritzen, 2005; Lazier et al., 2002). However, while ISOW and SPMW became less dense, LSW not only reached its freshest but also its coldest and densest state ever recorded in 1993/94 (Dickson et al., 1996; Lazier et al., 2002), after a number of high-NAO-index winters (1990-94) led to exceptionally vigorous and deep convection in the Labrador Sea. The unprece-

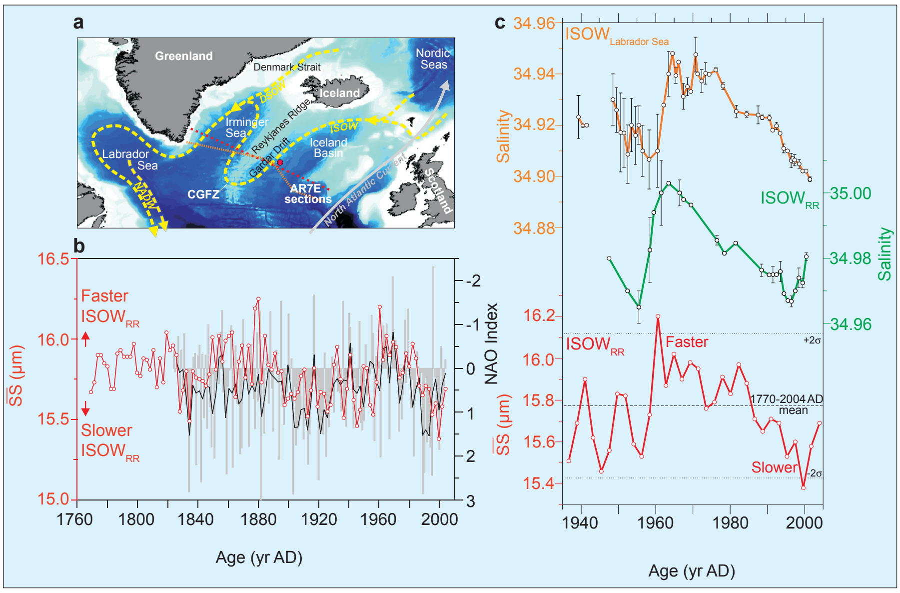

*Figure 1: **a**) Map of North Atlantic Ocean with schematic pathway of ISOW (yellow line), DSOW (yellow line), NADW (yellow line) and the North Atlantic Current (grey line). Location of RAPID-21-12B core indicated (red circle), and hydrographic sections (AR7E section) of Fig. 2 are shown for 1966 (red, dashed) and 1994 (orange, dotted). Location of Charlie Gibbs Fracture Zone (CGFZ) is also indicated; **b**) Evidence of linear relationship between near-bottom flow-speed changes of ISOW on the eastern flank of Reykjanes Ridge ($ISOW_{RR}$) and NAO index: Sortable silt mean grain size ($\overline{SS}$) record of core RAPID-21-12B (red); winter NAO index (grey bars, reverse scale), 7-year smoothed NAO index (black); **c**) Salinity time series of ISOW in Labrador Sea (orange) and eastern Reykjanes Ridge (green), $\overline{SS}$ record of core RAPID-21-12B (red). Figure modified from Boessenkool et al., 2007.*

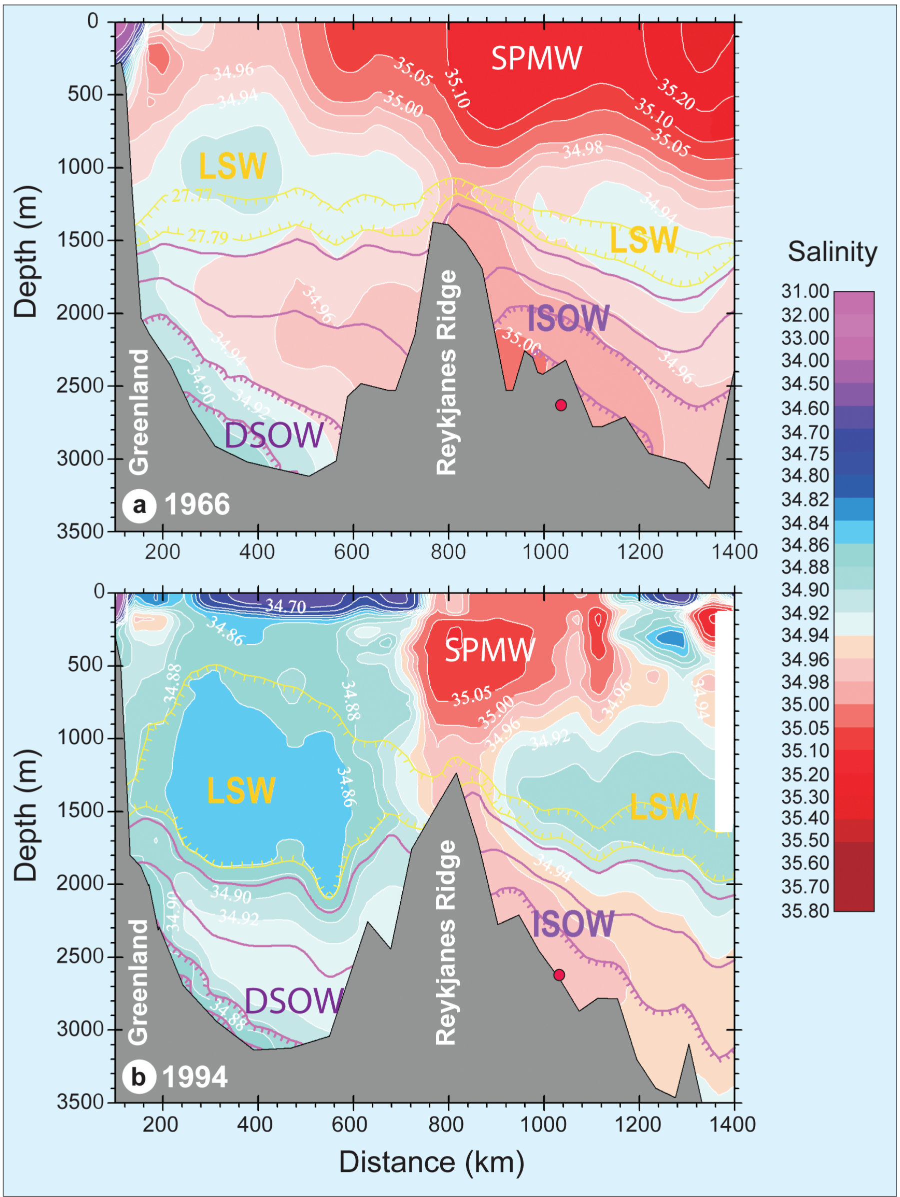

*Figure 2: Salinity and density profiles on trans-Atlantic hydrographic sections (Fig. 1a; section AR7E, World Ocean Circulation Experiment) for **a**) 1966 and **b**) 1994; Red circles indicate (projected) core location. Yellow and magenta contours are isopycnals (kg m^{-3}) indicating characteristic densities of intermediate (yellow, LSW) and deep (magenta, ISOW and DSOW) waters. Figure modified from Boessenkool et al., 2007.*

dented large, dense body of LSW invaded the intermediate depths of the subpolar North Atlantic within 2-5 years (Fig. 2b; Yashayaev et al., 2007). By contrast, LSW production, density and export were greatly reduced during the 1960's (Fig. 2a), after several low-NAO-index winters (Dickson et al., 2002).

Some model studies suggest convective changes in the Labrador Sea may be more important in the production of NADW than variations in the GSR overflows (Cheng and Rhines, 2004; Eden and Jung, 2001); particularly, the modeled overflows weaken when LSW formation intensifies. We suggest that the larger volume of denser and fresher LSW that built up over the NAO transition played a major role in slowing the deep flow of $ISOW_{RR}$. Mechanisms for this slowdown could include: First, a reduction of the density gradient in the Iceland Basin; this would likely diminish transport across the ISR, as has been observed (Hansen et al., 2001). Second, the expansion of denser LSW probably increased its entrainment by ISOW, reducing $ISOW_{RR}$ salinity, density and transport. Third, the density increase of LSW in the Labrador and Irminger Basins likely increased hydrostatic pressure on ISOW, thus decelerating ISOW transport from the Iceland to the Irminger Basin (see Boessenkool et al., 2007). Diminished LSW production and export after 1999 appears to have had the reverse effect on ISOW volume (Curry and Mauritzen, 2005), flow speed and salinity (Fig. 1c).

Implications for monitoring future AMOC stability

Most hydrographic time series started in the 1960's. Although pre-1960's salinity data are sparse, they are again closely mirrored by the $\overline{SS}$ record (Fig. 1c). Only the extreme values for 1961 and 2000 in the $ISOW_{RR}$ flow speed record lie outside the 2σ range of the 230-year record. Thus, most of the recent changes in $ISOW_{RR}$ flow cannot be distinguished from natural variability in the deep flow. Average values for both $ISOW_{RR}$ flow speed and salinity time series were recorded during the mid-1970's, suggesting that this period, coupled with the 1960-2000 range, might provide useful reference levels for future oceanographic changes.

In conclusion, our paleocurrent-speed record suggests that decadal-scale changes in $ISOW_{RR}$ vigor during the past 230 years are significantly, inversely correlated with the NAO index. Property changes of $ISOW_{RR}$ constituents have previously been attributed to NAO forcing. Many of them theoretically work in the same direction, either slowing down or speeding up $ISOW_{RR}$ flow. It is, therefore, difficult to ascribe the observed flow speed changes to a single cause. Nevertheless, our data suggest that the NAO influences deep-ocean current speeds in the North Atlantic, and that LSW could rapidly transfer NAO forcing to the deep ocean.

Note

Data will be available from the NOAA Paleoclimatology website at:
www.ncdc.noaa.gov/paleo/paleo.html

Acknowledgements

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The future ocean: Perspectives from the past — A tribute to Professor Sir Nicholas Shackleton

9th International Conference on Paleoceanography
Shanghai, China, 3-7 September 2007

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Every three years since 1983, the paleoceanographic community has come together at the International Conference on Paleoceanography (ICP) to discuss progress and share new discoveries. The 9th ICP was hosted in China and was attended by more than 500 participants from 31 countries, a third being PhD students. A large number of participants from mainland China and Taiwan also attended, greatly exceeding their representation at previous ICPs.

Thirty speakers in five topical sessions were invited to review the latest progress and highlight the current hot topics in paleoceanography. Three keynote lectures covered the major topics of the conference: Harry Elderfield gave a review of geochemical paleo-proxies and also showed memorial images from Nick Shackleton's life; Jean-Claude Duplessy gave a new insight into the deep ocean circulation over the last climatic cycle; and Christina Ravelo's lecture focused on the permanent El Nino-like conditions in Pliocene, which she named "El Padre". Additionally, 380 scientific posters addressed various aspects of current paleoceanographic research.

The conference was structured into the following five sessions:

Figure 1: The 9th ICP was attended by more than 500 participants from 31 countries

Session 1- Rates and dates: Time constraints on mechanisms for oceanic change

This session provided information on the duration and timing of paleoceanographic events and the speed of change, which can help constrain the mechanisms for changes in the Earth System. The session began with new approaches for extending astronomical time scales to the entire Cenozoic, and ended with addressing synchronization problems between paleoceanographic records from the late Quaternary.

Session 2 - Sea-land interactions and monsoons

This session consisted of two parts: the first emphasized the role of continental shelves in glacial cycles, and the second addressed various aspects of the Asian monsoon archives (e.g., loess, speleothems, deep-sea sediments), and numerical simulation of paleo-monsoon using coupled general circulation atmosphere-ocean-vegetation models.

Session 3 - Inter-ocean exchanges

A broad spectrum of ocean circulation topics was covered in this session, ranging from the meridional circulation to intermediate water, and from the changing Indonesian throughflow to the opening of Drake Passage. A remarkable feature of the session was the use of neodymium isotopes of clay, Fe-Mn leachates and fish teeth in paleo-circulation studies.

Session 4 - Biotic response to perturbations in ocean chemistry

Unlike the other sessions, session 4 discussed pre-Quaternary events to show, for example, how the Cretaceous Oceanic Anoxic Events (OAEs) and Paleocene-Eocene Thermal Maximum (PETM) are related to global carbon cycle perturbations. Pleistocene carbonate and silica chemistry of the ocean was also discussed in the context of glacial cycles.

Session 5 - The Holocene: Baseline for the future

This session reviewed new data and outlined the role of tropical climate processes, sea ice and deep-ocean flow in climate variability. Special attention was paid to interhemispheric gradient and internal forcing of climate changes at the centennial- to millennial-timescales.

Following the tradition of previous ICPs, the Paleomusicology Concert once again showcased the musical talents of paleoceanographers, but this time the concert included traditional Chinese music shows played by Tongji University students. A visit to the State Key Laboratory of Marine Geology, Tongji University, led by Dr. Zhimin Jian and Prof. Pinxian Wang, was also organized. Additionally, over 170 participants attended the two during-conference tours (Zhujiajiao and Zhouzhuang) and three post-conference field excursions (Chongming Wetland Park, Nanjing Visit and Geological Excursion, and Tibetan Plateau and Himalayas).

At the closing session, the Best Student Poster Prizes were granted to thirteen students, and it was announced that the next ICP will be held in San Diego, California, in 2010.

PAGES-IMAGES-NSF Workshop: Intra- and interhemispheric variability of SST and the hydrological cycle over the last 4 Myr

Trins, Austria, 30 May-2 June 2007

Michael Sarnthein[1] and workshop participants
[1]Institute for Geosciences, University of Kiel, Germany; ms@gpi.uni-kiel.de

This lively workshop addressed recent progress in establishing past sea surface temperature (SST) patterns, with new advances in both recording continental humidity changes and modeling past variations of the hydrological cycle. Exciting insights were presented on changes in meridional (L. Stott) and zonal (L. Vidal; L. Peterson) Atlantic moisture gradients and transport on stadial-to-interstadial timescales (Fig. 1). New centennial- to decadal-scale records revealed extreme Holocene variations in the African (S. Weldeab) and Indian (A. Sinha) summer monsoons. These were, in part, coeval with short-term climate changes in Europe, such as temperature-controlled Alpine glacier advances (K. Nicolussi). However, reliable links between marine and continental records will require new standards in age control, with uncertainties better than 300 yr.

During the workshop, participants split into interactive theme groups to develop hypotheses, recommendations and strategies related to the following four major (paleo-) climatic issues:

A) Hadley vs Walker Circulation, Atlantic-Pacific Zonal vs Meridional ITCZ Shifts

Andre Paul and Lowell Stott (Chairs)

This group discussed the role of water-vapor transport, jets and Intertropical Convergence Zone (ITCZ) migrations. Short- and long-term variability of the inter-ocean exchange of water vapor were identified as key objectives, particularly in view of competing ideas on their effect on the oceans' salt balance (including analyses and re-evaluation of meteorological and oceanographic data sets, e.g., from the World Ocean Circulation Experiment (WOCE)).

Data-model comparison is required to test whether:

1) Atmospheric moisture transport across Central America controls the Pacific and Atlantic salinity contrast and modern thermohaline circulation (THC) (Fig. 1).
2) The amplitude of glacial/interglacial and stadial/interstadial changes reconstructed on either side of the Central American Isthmus can be reconciled with changes in zonal moisture transport.
3) Changes in monsoon are related to changes in atmospheric pCO_2.

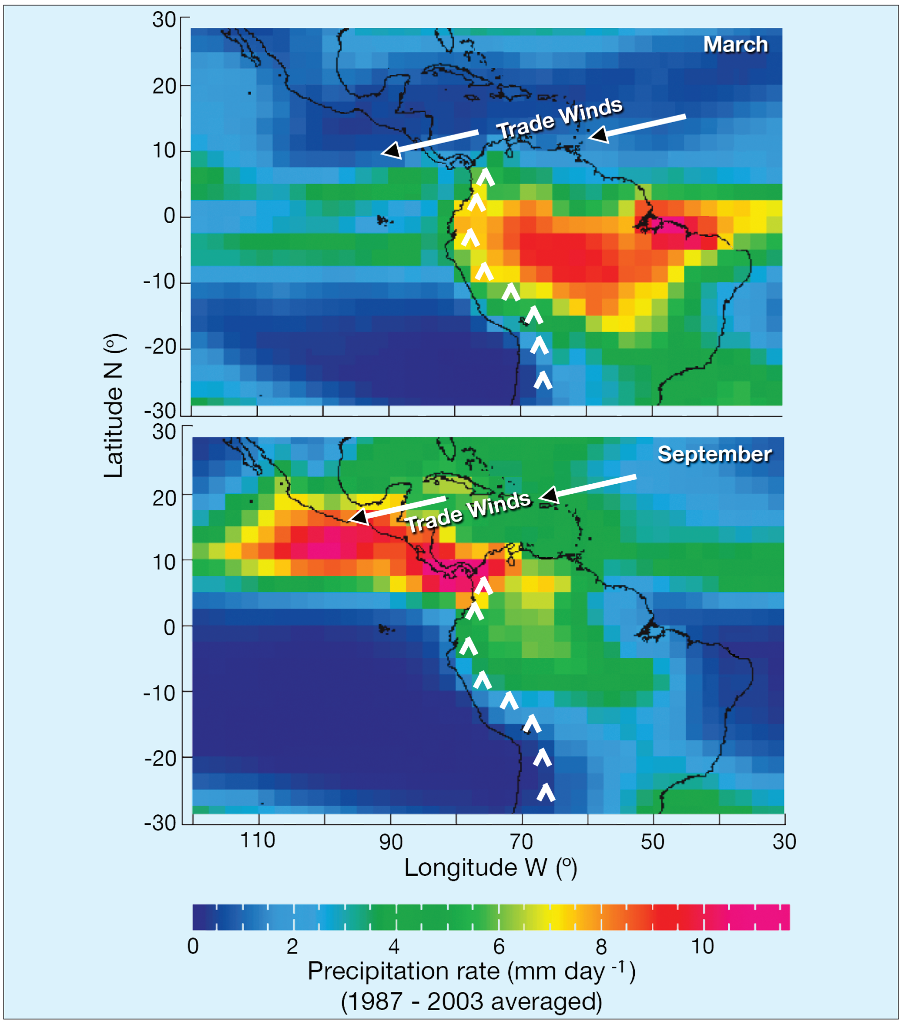

Figure 1: Wind-driven zonal atmospheric water transport, depicted by averaged precipitation rates over Middle and South America for Mar. and Sept. between 1987-2003 AD (modified from Leduc et al., 2007). Enhanced Sept. precipitation in the East Pacific reflects major freshwater export from the equatorial Atlantic that may have strongly varied from interstadial to stadial times, and in turn led to major variations in sea-surface salinity and Atlantic meridional overturning circulation. The Andes (hill symbols) keep freshwater in the Amazon basin during March.

Future studies should focus on target regions that are:

1) Critical for atmospheric dynamics, based on their potential as source (e.g., the tropical ocean), sink, or pathway (e.g., Isthmus of Panama) of atmospheric moisture.
2) Highly sensitive to climate change (producing large and regionally representative signals).
3) Relevant to large human populations.

B) Phasing of Monsoon Precipitation in Africa, India, and East Asia/West Pacific

Dominik Fleitmann and Ralph Schneider (Chairs)

Group B discussed time-transgressive shifts in rainfall and near-shore sea-surface salinities throughout the Early Holocene climate optimum. They also debated the links between precipitation and factors such as tropical Indian SST, the Atlantic Dipole and tropical zonal seesaw. To examine the phasing of such changes, it was felt that chronologies of marine and terrestrial records should be developed separately, to enable reliable and independent comparison of local precipitation and temperature records. Tree rings and speleothems were also considered the superior archives for developing regional master chronologies, as age models deduced from marine records are based on multiple timescales and require initial tuning to Greenland and Antarctic ice-core timescales. Comparison of $\delta^{18}O$ records from fluid inclusions in speleothems with nearby planktic $\delta^{18}O$ records may serve as a novel correlation tool.

Future strategies should include the initiation of new research networks to establish regionally integrated information on monsoon changes, such as tropical ice cores, and include East Pacific regions that are influenced by both monsoon and westerlies.

C) Hemispheric and Interhemispheric Teleconnections

Mark Maslin and Larry Peterson (Chairs)

This group proposed five questions for testing:

1) Do tropical hydrology and ITCZ shifts respond consistently to changing high-latitude temperatures and meridional temperature gradients?
2) Do tropical warm-pool temperatures control the export of water vapor from low to higher latitudes, and what are the climatic feedbacks between these regions?
3) Are methane concentrations in ice cores indicative of methane release in tropical or high-latitude wetlands, and are they an important amplifier of hydrological changes?
4) ENSO as a potential forcing mechanism of past monsoonal intensity has only been recorded in varved sediments off Pakistan. Can a clear ENSO signal also be identified in proxy records from other monsoon regions?
5) High-latitude climate responds to enhanced dust transport due to changes in tropical wetness and aridity, yet what are the actual effects of high dust supply on climate?

D) Human-scale events in the Hydrological Cycle over the last 20 kyr

Ashish Sinha and David Anderson (Chairs)

Group D focused on abrupt climate shifts and magnitudes of change that can be compared to historical records. Periods that appear particularly important include the last 2 kyr and the 8.2 kyr cooling event, implying that the following studies are required:

1) The extent to which climatic changes over the last 2 kyr—termed in Europe the "Little Ice Age", the Medieval and Roman Warm Periods—are connected to large-scale patterns of climate variability. Are these evident in worldwide anomalies of SST, droughts, and floods? To what extent are coeval variations in tropical monsoons connected to other tropical processes such as the Indonesian Throughflow, Walker, and Hadley circulations?
2) The role of tropical SST in driving hydrologic variability throughout the extra-tropics appears evident in model-based studies and instrumental records. Yet, long-term trends in this ocean-climate linkage are poorly known. New proxy records of the last 2 kyr may help to assess the long-term influence of ocean SST patterns on hydrologic changes in remote regions.

This workshop demonstrated the merit of this relatively novel approach in addressing past variations in the hydrological cycle as a result of changes in ocean circulation. The presented results and subsequent discussions suggest that integration of paleoceanography and land paleoclimatology will yield dramatic progress in our understanding of the oceans' role in hydrologic change on many timescales.

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3rd Alexander von Humboldt International Conference: East Asian Monsoon, past, present and future

Beijing, China, 9-11 August 2007

André Berger[1], Z. Ding[2], Z. Guo[2] and P. Fabian[3]

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[2]Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing, China; [3]Technical University of Munich, Germany

The instrumental period of the meteorological record is too short to capture the full variability of the climate system and, in particular, to visualize the type of climate that is predicted to occur over the next decades and centuries. It is therefore, important to reconstruct past climates and understand past climatic variations. Marine deep-sea cores and ice cores have and will continue to contribute to our understanding. Land records also contribute significantly, particularly at the regional scale.

The Third European Geosciences Union (EGU) Alexander von Humboldt International Conference was devoted to the "East Asian Monsoon, Past, Present and Future". Both records of the past and present-day observations and model experiments were reviewed, to better understand the mechanisms driving its behavior and to allow for better predictions of it and its impacts.

60 oral presentations and 26 posters gave an excellent overview of the EAM and its evolution over the last 25 Myr, gathering important records and modeling results. The abstracts of the papers and posters are available in "Program in details" at www.conferencenet.org/conference/3rdAVH/html/whatnew.htm, among them some scientific results to illustrate the EAM behavior at the different timescales covered during the meeting.

J. Guiot presented information on the mechanistic vegetation models that clarify the minimum climatic changes required to produce the vegetation shifts observed in paleodata.

The impact of the uplift of the Tibetan Plateau (TP) and the Rockies (RC) on Asian summer and winter monsoon climate was investigated, using both data and models for the last tens of million of years. Using the Meteorological Research Institue-coupled general circulation model, T. Yasunari

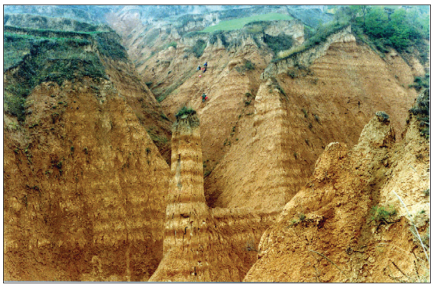

Figure 1: Field photo showing the alternation of loess (yellow layers) and paleosols (red-brown layers) in Miocene loess-soil sequences from the Chinese Loess Plateau, Gansu Province (courtesy of Zhengtang Guo, IGGCAS Beijing).

showed that, the zonal asymmetry of SSTs in the subtropical North Pacific is emphasized by the presence of both TP and RC, and enhancement of the Asian summer monsoon climate is likely to appear as an overall effect of the atmosphere-ocean interactions principally in the Pacific but also secondarily in the North Atlantic.

Z. Guo and Z. An both showed that the climate pattern in Asia experienced major reorganization near the Miocene/Oligocene boundary that was characterized by the onset of a monsoon-dominated regime, replacing the zonal one that dominated during the Paleogene. Since then, eolian dust continues to be deposited in northern China, due to the formation of inland deserts as dust sources and the winter monsoon as a dust carrier, whereas paleosols interbedded in the eolian sequences are indicative of a strong summer monsoon. There were several pulses of TP growth northeastward between 1.3 and 1.0 Myr BP and after 0.6 Myr BP, which were responsible for the stepwise significant intensification of summer monsoons and the aridification of inland Asia.

S. Clemens discussed the phase evolution of Indo-Asian monsoons and global ice volume, suggesting that it requires changes to the marine oxygen isotopic chronostratigraphy (Marine Isotope Stages; MIS) prior to 3 Myr BP to achieve internally consistent and physically plausible responses among summer and winter monsoon circulation, changes in global ice volume, and orbital forcing.

Q. Yin (et al.) demonstrated from modeling experiments that although deep sea and ice core records show a cool MIS 13 interglacial with low greenhouse gas concentrations, the astronomical and ice sheet forcings at ~500 kyr BP are mainly responsible for the exceptionally intense East Asian Summer Monsoon (EASM), in agreement with the proxy record.

A series of papers were also devoted to the climatic optimum of the Holocene. Using a coupled ocean-atmosphere general circulation model, R. Ohgaito and A. Abe-Ouchi found that ocean thermodynamics plays an important role in mitigating the African/Asian monsoon enhancements, whereas ocean dynamics have minor effects. Y. Zhao and S.P. Harrison also discussed oceanic influence on the monsoon 6 kyr BP and showed that ocean feedbacks amplify the astronomically induced increase in eastern Asian monsoon precipitation, but dampen it in northern India. Additionally, C. Marzin and P. Braconnot explained the differences in the behavior of the different monsoon regions throughout the Holocene, through the large scale astronomical heating gradients, the role of the Tibetan Plateau snow cover and teleconnections between the Asian and African monsoon.

Among the papers dealing with the last hundreds of years, T. Yao used the Tibetan ice core record to show that the Tibetan Plateau was warmer during the 20th century than any time during the past 1 kyr, but that the temperature changes on

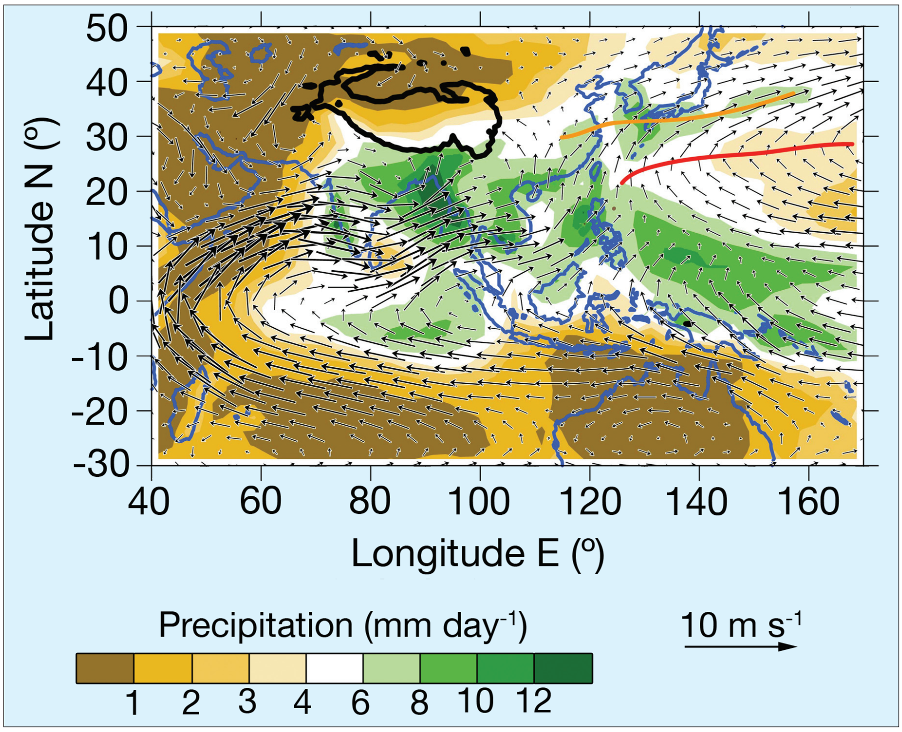

Figure 2: Asian summer (June-July-August) monsoon precipitation and wind field (Courtesy of Bin Wang, University of Hawaii). ***Black line*** *represents 3000 m topographic contour, which outlines the Tibetan Plateau.* ***Red*** *and* ***orange lines*** *represent the subtropical rain band and the ridge of the subtropical high, respectively.*

its northern and southern sides were different, reflecting the influence of the Asian monsoon over that period.

Finally, a few papers dealt with the prediction of climate and East Asian monsoon during the next century. From an ensemble of coupled ocean-atmosphere models used in IPCC, R.H. Kripalani suggested an average increase in precipitation of 8% over the East Asian region.

Analysis of present-day dynamics of the EASM suggests that the mechanisms operating on the annual and interannual timescales are determined, respectively, by external forcing (orbital forcing and land-sea configuration) and internal feedback processes, such as (remote) El Niño/La Niña and monsoon-ocean-land interaction (Bin Wang). The coupling between the East Asia and Australian monsoon is more robust than that between the Indian monsoon and Australian monsoon, at both annual and interannual timescales. The interannual variability of the EASM is primarily attributed to ENSO and local atmosphere-ocean interaction. These conclusions have implications for EAM variability on orbital timescales. While on orbital timescales EASM variability may be attributed primarily to variations in orbital forcing, drastic changes in the Pacific thermal condition may also considerably alter the East Asian-Australian monsoon intensity. An important question is how the EASM variation on orbital timescales is linked to the variation of the Intertropical Convergence Zone (ITCZ). A prevailing notion in the paleoclimate community is that the northward movement of ITCZ would cause an enhanced EASM, while the present-day monsoon dynamics suggest the opposite.

As a side event of the conference, the new PAGES working group "Global Monsoon" was launched with a townhall meeting. The concept and present-day perspective of the global monsoon, and the goals and methods of implementation were discussed. It was concluded that a global view of the monsoon would aid in understanding the behavior of the regional monsoon systems.

This conference was a great promotion of international collaboration on the EAM between China and the communities of scientists related to EGU and PAGES. The invited lectures presented a very successful overview of monsoon studies. Due to our efforts, we expect that meteorologists dealing with present-day monsoon will become more deeply involved in future discussions and reviews. Our meeting was the first step towards cross-disciplinary exchanges in China and international exchanges on monsoon and its impacts on society. It also helped to promote EGU and its journal "Climate of the Past".

Acknowledgements
We thank the sponsors for their support: EGU, Chinese Academy of Sciences (CAS), PAGES, Foreign Affairs Bureau of CAS, and the Institute of Geology and Geophysics of CAS

International Workshop on Methods in Quaternary Paleoecology

La Serena, Chile, 5-8 October 2007

Antonio Maldonado[1] and Claudio Latorre[2]

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[2]CASEB/Departamento de Ecología, Pontificia Universidad Católica de Chile, and Institute of Ecology & Biodiversity, Santiago, Chile

A total of 25 students from six different countries were chosen from over 40 applicants to attend the International Workshop on Methods in Quaternary Paleoecology. The majority of students were from either Argentina or Chile but other countries such as Colombia, Uruguay, France and Germany were also represented.

Students participated in half-day lectures given by eight professors dealing with five major topics: Cathy Whitlock (USA) on charcoal records and analyses; Patricio Moreno (Chile), on high-resolution pollen records; Alan Cooper (Australia) on the extraction and analyses of fossil DNA; Ricardo Villalba (Argentina) on dendrochronology and dendroecology; Christopher Moy (USA) on new methods of radiocarbon and stable isotope analyses; Julio Betancourt (USA), Antonio Maldonado (Chile) and Claudio Latorre (Chile) on methods, analyses and case studies in arid lands paleoecology. The course also involved several laboratory demonstrations involving charcoal analyses, coring equipment, tree rings and rodent middens from the Atacama Desert.

Aside from the lectures, students were also given the opportunity of presenting their work as talks and posters, followed by comments on methods and results from the course professors and attendees. These presentations dealt with a variety of topics on South American paleoclimatology, paleoecology, biogeography, and archeology using a diverse array of methods and proxies. Among these were fossil pollen records, rodent middens, diatoms, chironomids, phytoliths, dendrochronology, glacial geology and modern analogue techniques. Research covered a vast geographic area, ranging from the Bogotá wetlands in Colombia to the southern cone of South America, along the Atlantic coast of Uruguay and Argentina, as well as the Bolivian Altiplano and the coastal Atacama Desert along the Pacific coast down to the Patagonian icefields. This lively round of discussions and the high quality presentations stimulated interactions not only between students and professors, but also kindled possible interactions among students from different countries.

Figure 1: Workshop participants - 25 students from 6 different countries

Exporting training to developing countries

Our motivation for organizing this workshop was owed to the difficulties of developing top researchers in Latin America, as many do not have the resources and training required to carry out the state-of-the-art research performed in developed nations. In most cases, paleoclimatological research is carried out by groups that are inaccessible to Latin American students. One method of tackling this problem was to bring specialists from the different fields of paleoclimatology and paleoecology to South America. This allows students to gain first-hand access to the finest knowledge and expertise.

A better education for future researchers from Latin America will also increase the development of new and better quality geo-historical records, helping to bridge the information gap between nations. The importance of this issue cannot be understated. Interhemispheric comparisons over the last 1000 years are plagued by poor quality records owing to the lack of high-resolution paleoclimate archives.

One important recommendation is that whenever international research efforts are undertaken at sites within a developing nation, the researchers from the developed countries allocate a portion of their time to sharing and teaching their experience to local scientific communities, regardless of whether they are established researchers or potential researchers in the making.

Acknowledgements

The coordinators wish to thank the professors (J. Betancourt, A. Cooper, P. Moreno, C. Moy, R. Villalba and C. Whitlock) and contributors, including PAGES, the Red Latinoamericana de Botanica, Institute of Ecology and Biodiversity (IEB), Center for Advanced Studies in Ecology and Biodiversity (CASEB) and the Center for Advanced Studies in Aridlands (CEAZA), who made this workshop possible.

Fire in the Earth System: The Global Palaeofire Working Group

Totnes, UK, 22 – 26 October 2007

Mitchell J. Power[1], J. Marlon[2], P.J. Bartlein[2] and S.P. Harrison[3]

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Fire is the most ubiquitous disturbance affecting terrestrial ecosystems and has significant impacts on atmospheric chemistry and the global carbon cycle. Even though modern fire regimes are strongly influenced by human activities, the occurrence and magnitude of fires are largely controlled by climate and characteristics of the vegetation cover. The same is true of paleo-fire regimes: humans have used fire as a tool for land clearance and to improve agricultural and grazing land, but the charcoal record shows that on millennial time-scales fire regimes respond to changes in regional climates and climate-induced vegetation changes. However, the interactions between climate, vegetation and human activities are complex and much remains to be done to understand how these factors have influenced fire regimes during the Quaternary. The Global Palaeofire Working Group (GPWG) is providing the tools that will help elucidate these relationships.

The GPWG was formed as part of the IGBP Fast-Track Initiative on Fire and is now part of the IGBP Cross-Project Initiative on Fire. The goals of the GPWG are to collect sedimentary charcoal records and to use these records to analyze the underlying causes of changes in regional fire patterns in the late Quaternary. The GPWG database includes records of charcoal from a variety of sedimentary sequences, including lakes, bogs and soils. The database includes descriptive data about each site (e.g., site type, hydrology), about individual charcoal samples (e.g., sample size, sampling method, size of material counted), and about the chronology of each record. Version 1 of the database (www.bridge.bris.ac.uk/projects/QUEST_IGBP_Global_Palaeofire_WG) contains 405 sites, with representation from every continent (Fig. 1).

The GPWG database has been used to analyze the patterns of changes in fire regimes since the Last Glacial Maximum (LGM) (Power et al., in press; Fig. 1). This analysis shows that there is strong broad-scale coherence in fire activity at the LGM and during the deglaciation, while the Holocene records show greater spatial heterogeneity. Charcoal records from

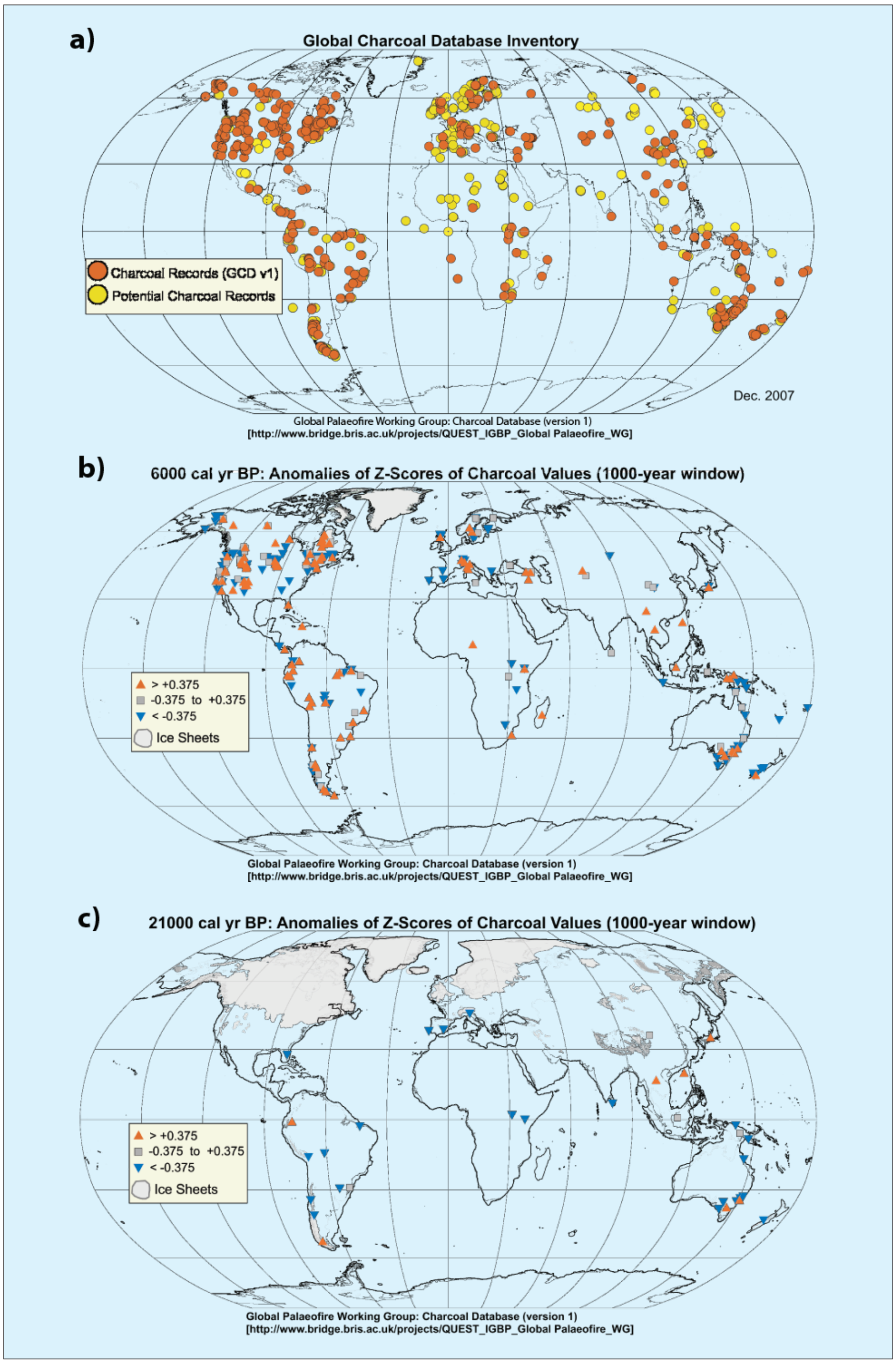

*Figure 1: **a**) global distribution of sites in the charcoal database; **b**) 6 kyr BP minus present (0 kyr) charcoal abundance differences; and **c**) 21 kyr minus present charcoal abundance differences. Distribution of red colored sites (a) represents sites (n = 405) used in first global synthesis (Power et al., in press), gray colored sites are additional records identified since the release of Global Charcoal Database (GCD) version 1. Number of sites shown represents a snapshot of database. Charcoal data used to create the charcoal anomaly maps are heterogeneous, reflecting the range of laboratory and data-analytical methods used to describe charcoal abundance variations over time. Charcoal values contained within the GCD range over 13 orders of magnitude and required a standardization protocol for the recently published global syntheses and subsequent syntheses efforts. Individual records analyzed by: (1) rescaling whole record to range between 0.0-1.0; (2) rescaled values then transformed using Box-Cox transformation to approach normality where possible, where the transformation parameter estimated using maximum likelihood; (3) transformed values were standardized or converted to Z-Scores using mean and standard deviation for each record over the interval from 4000-100 cal yr BP; (4) anomalies were calculated as the difference between the mean of Z-scores for the intervals 6.5-5.5 cal kyr BP (b) or 21.5-20.5 cal kyr BP (c) and those for interval 1000-100 cal yr BP (not shown).*

extratropical regions of North America, Europe and South America indicate reduced fire activity during the deglaciation (21~11 cal kyr BP). The tropical latitudes of South America and Africa show increased fire activity from ~19-17 cal kyr BP, as do most sites from Indochina and Australia between 16-13 cal kyr BP. Many sites indicate increased fire activity during the Holocene, although fire activity was reduced in eastern North America and eastern Asia between 8 and ~3 cal kyr BP, Indonesia and Australia between 11 and 4 cal kyr BP, and in southern South America between 6-3 cal kyr BP.

Comparison of the charcoal-based reconstructions with other paleoclimatic records suggests explanations for the reconstructed changes in fire regimes (see Power et al., in press), but diagnosing the underlying causes of these changes requires modeling of the coupled vegetation-fuel-fire system. The GPWG is currently using LPJ-SPITFIRE—a coupled dynamic global vegetation-fire model (Thonicke et al., subm)—to examine the impact of mid-Holocene (ca. 6 cal kyr BP) and the LGM (ca. 21 cal kyr BP) climates on vegetation and fire. These simulations, driven by climate output from coupled ocean-atmosphere general circulation models from the Palaeoclimate Modelling Intercomparison Project (PMIP2), show surprisingly good matches to the reconstructed fire regimes.

At a workshop in October, sponsored by the UK NERC-sponsored QUEST (Quantifying and Understanding the Earth System) program, iLEAPS and PAGES, members of the GPWG mapped out their future activities. These include: (1) continued expansion of the charcoal database, (2) analysis of the causes and consequences of changes in fire regimes over the last interglacial-glacial-interglacial cycle, (3) development of new interpretive tools, and (4) creation of benchmark model-evaluation data sets for the Fire Model Intercomparison Project (FIREMIP). The GPWG currently has over 90 members worldwide, and welcomes participation by all scientists interested in understanding the role of paleofire in the Earth System.

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Mangrove paleoecology and environmental change

Cairns, Australia, 29 July 2007

Matthew Wooller
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Cairns, Australia was a most appropriate venue for a research session dedicated to mangrove paleoecology. Held at the INQUA 2007 meeting, the session was supported by PAGES and the US NSF. Mangrove ecosystems are productive and important economic resources for people living in tropical coastal areas. They are also highly susceptible to sea level changes and can form protective barriers against wind, flooding, erosion and tsunami damage. Information on past mangroves is imperative in understanding the effects of present and possible future ecological changes. The mangrove paleoecology session brought together researchers studying how mangroves respond to environmental changes. A further objective of the session was to promote the representation of researchers from developing countries, where mangroves are important ecosystems. Towards this goal, PAGES funds supported two researchers (Marcelo Cohen, Brazil and Sauren Das, India) to attend the meeting.

Figure 1: A Rhizophora mangle *(red mangrove) tree off the coast of Belize, Central America. A number of presentations in the session illustrated the abilities of mangroves to track and respond to sea level changes. For instance, stands dominated by* R. mangle *have been able to maintain mangrove habitats off the coast of Belize for at least the last ~8,000 years of sea level changes. (photo: M. Wooller).*

The session, which consisted of four sub-sessions over two days, was co-convened by Matthew Wooller, Hermann Behling, Simon Haberle and Marcelo Cohen and consisted of oral and poster presentations. With study sites included from Brazil, Belize, India, New Zealand, Indonesia and Australia, the session succeeded in its objective to provide a pan-tropical perspective of mangrove paleoecology. The session also succeeded in providing examples of the diverse array of paleoecological techniques needed to understand past mangrove ecological changes.

Patrick Moss began the session with a record from ODP 820 marine core (northeastern Australia) of mangrove paleoecology covering the last million years. James Westgate and Carole Gee followed with faunal and floral ecological reconstructions from the middle Eocene mangroves in Texas. Although these two talks fell outside the Quaternary theme they provided valuable perspectives of mangrove antiquity and the challenges associated with studying these ancient ecosystems. As a temporal contrast, John Cann and Catherine Lovelock presented recent historical data from the northern shores of South Australia and a rapidly-prograding wave-exposed coast in New Zealand. These presentations illustrated the influence of sedimentation in mangrove ecosystem dynamics.

The remaining talks in the session presentd Holocene reconstructions of mangrove environments. Marcelo Cohen and Hermann Behling presented palyological studies of numerous cores from mangrove sites in Brazil during the Holocene, reconstructing vegetation dynamics during relative sea level changes. Natalie Monacci presented pollen-based reconstructions of Holocene mangrove dynamics from Belize. She also showed additional proxies of past environments, including stable isotope analyses (C, N and O) of mangrove leaves preserved in peat cores. Marilyn Fogel followed with details of biomarker analyses of the same cores. Compounds specific to different mangroves and microbial communities were used to complement pollen data to reconstruct past ecosystem composition. Sarah Woodroffe subsequently presented foraminiferal assemblage data derived from mangrove sediments as a proxy of past sea level during the Holocene in tropical north Queensland, Australia. Arghya Hait took a palynological approach to the reconstruction of mangroves of the Chamta and Sudhyanyakhali Islands of the Sundarban Biosphere Reserve, India. Simon Engelhart also focused on a palynological approach but concentrated on a modern calibration set as a method of reconstructing Holocene sea levels and paleoenvironments of southeast Sulawesi, Indonesia. Sauren Das, finished the session by providing a paleoecological reconstruction of the Lower Bengal Basin, Calcutta, India during the Holocene.

The session illustrated the wide range of paleoecological approaches, both traditional and innovative, for reconstructing past mangrove environments. A common finding based on paleoecological inferences from a number of the studies and locations was evidence for significant variability in relative sea level during the Holocene.

International workshop on environmental changes and sustainable development in arid and semi-arid regions

Alashan Left Banner, Inner Mongolia, China, 10-14 September 2007

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The prevailing point of view in many early textbooks was that sand seas experienced an arid climatic optimum in the Holocene, whereas glacial maxima were pluvially active. More recently, an extension of the sand seas during the Last Glacial Maximum (LGM), and a retreat during the Holocene climatic optimum, has been reported. Yet, with considerable improvement in dating techniques (particularly luminescence dating), new data from various deserts of the world suggest a much more complicated picture of desert landscape evolution. The International Workshop on Environmental Changes and Sustainable Development in Arid and Semi-arid Regions was recently held in Inner Mongolia, China. This workshop aimed to compare regional-scale reconstructions of late Quaternary changes in the deserts of various climate zones (monsoon regions, subtropics and westerlies), and to discuss case studies and theories relating to land degradation and sustainable development, geomorphological processes, and interactions between human and natural factors. 83 delegates from 17 countries attended (Fig. 1).

In his opening speech, Jiaqi Liu, Chairman of the Organizing Committee, emphasized the significance of dryland studies in understanding global changes, and for regional developments in China and the rest of the world. Five keynote presentations followed, giving an overview of recent research progress on natural and anthropogenic impacts on arid environments, in addition to land management issues. Andrew Goudie presented sources and trends of desert dust, Ying Wang talked about the origins of the sands in Chinese deserts, Bojie Fu analyzed the problems of land degradation and rehabilitation measurements in China, Arthur Conacher highlighted the future of research in managing land degradation, and Jianguo (Jingle) Wu demonstrated a scientific framework for sustainable development in arid and semiarid regions, with particular reference to the Inner Mongolia grassland. The program that followed included numerous oral presentations and posters.

What became increasingly evident over the course of the workshop was the degree of difference between paleoclimate reconstructions from different regions. New dating indicates that dune sand accumulation in South Australia continued

Figure 1: Workshop participants enjoying the sand dunes on the mid-conference field trip. The workshop also included two optional field trips to active and stable dunes in Inner Mongolia.

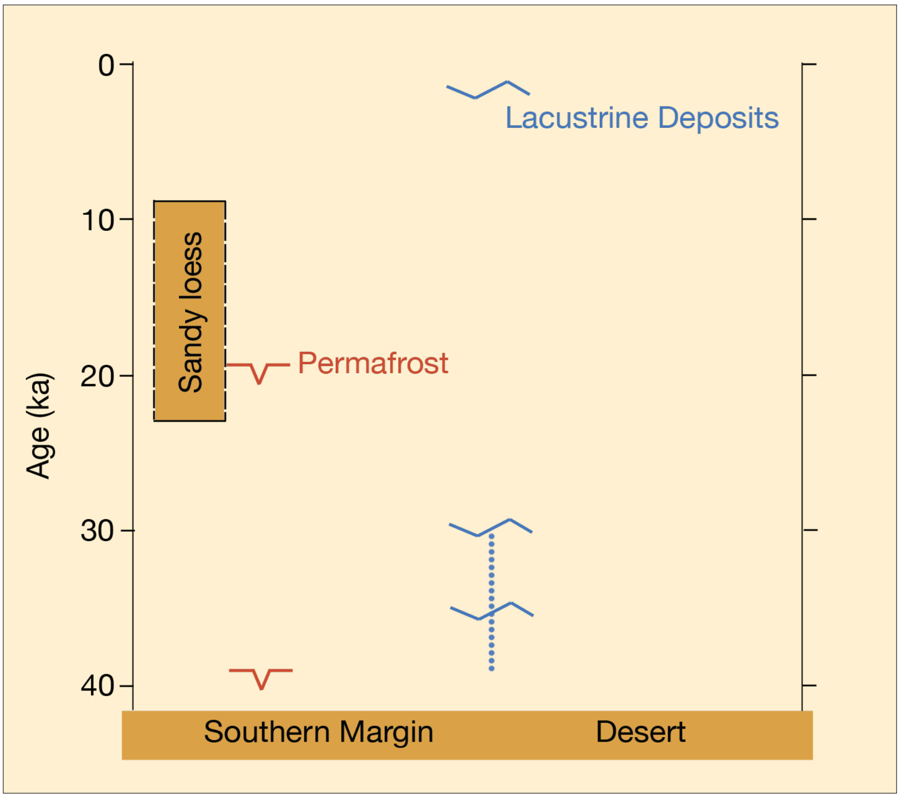

Figure 2: Wetter climate in the Taklamakan Desert of China (recognized from lacustrine processes) and colder times on its south margin (recognized from permafrost processes) (modified from Yang et al., 2006).

throughout the glacials and interglacials of the late Quaternary, with no large-scale hiatus recorded. In contrast, geomorphological and sedimentological records from the Atacama Desert, southern Peru show several phases of drier conditions during the Holocene. Further, sedimentological evidence for the three periods of lake formation during the last 40 kyr in the hyperarid center of the Taklamakan Desert, western China was discussed (Fig. 2). The obvious inconsistencies of paleoclimatic histories between different deserts reconfirm the need for detailed regional desert studies in order to comprehensively understand of paleoclimatic changes in the arid regions of the world.

The workshop also attracted a great deal of attention from the Government of Alashan District, demonstrating the importance of paleoenvironmental studies to society. The local appreciation was shown not only by a welcoming address from a Governor but also by an excellent banquet—with superb Mongolian singing and dancing, and many friendly toasts—provided by the government of the district.

Publications of workshop presentations are currently in preparation. Papers on land degradation and desertification are being considered for a special issue in Geographical Research (March 2009 issue; vol. 47 no. 1), and manuscripts on geomorphology and paleoenvironmental changes for publication in Quaternary Research.

Reference

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First Asian dendrochronology conference and workshop: Environmental change and human activity

Bangkok, Thailand, 9-15 September 2007

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The First Asian Dendrochronlogy Conference and Workshop “Environmental Change and Human Activity” was held in Bangkok, Thailand, in conjunction with a seminar organized by Won-kyu Park, South Korea and Liu Yu, China, and a special one-day course on “Wood anatomy in dendrochronology: concepts, methods, image analysis system and SEM” by Kambiz Pourtahmasi, Iran. The conference allowed researchers in dendrochronology and other disciplines related to climate dynamics and forest science to present their most recent research achievements. It also offered a platform for students and young scientists to present their projects, organize collaborations and arrange tree ring networks in Asia.

The conference and workshop attracted over 80 participants from twenty countries. The first day was focused on opening activities, keynotes and plenary presentations. Three keynote papers were related to issues of climate change, environmental change and human activity in Thailand. The presentations dealt with tree ring research in Thailand, climate data sets and watershed management, and climate change. The keynote session was followed by plenary presentations from several scientists. The first day was wrapped up with a session of 7 oral presentations.

The following days covered a range of topics, such as dendrochronological studies from Himalaya to East Asia, tropical dendrochronology, heavy metal contamination of plants and soil, wood anatomy, forestry and sub-fossil wood in Southeast Asia. For the third day a field trip to Putey National Park, was organized. This is a key study site for pine dendrochronology, particularly in understanding pine forest growth in monsoon climate and external disturbances on growth.

In Thailand, teak tree ring indices have been used for climate reconstruction back to 1640 AD. N. Pumijumnong presented an extended teak chronology from Thailand, which suggests several changes in temperature and precipitation between 1590 and the present. However in general, the climate in Thailand has not changed significantly over the last 300 years. According to the teak index, the climate in Thailand was relatively cool between 1590-1640 and 1800-1890. Furthermore, the precipitation in May-July (beginning of rainy season) has decreased by 0.69 mm, and the temperature in February, March

Figure 1: Workshop participants enjoying Putey National Park.

and April (hot season) has increased by 0.05-0.1°C.

Several groups in tropical regions of south and Southeast Asia have been working to establish a good quality tree ring data network to understand monsoon variability and related global parameters (e.g., ENSO) in the recent past. In this context, teak from Indonesia, Thailand, Myanmar and India have been demonstrated as a potential source for high-resolution reconstruction of monsoon related parameters, such as rainfall, and drought frequencies and intensities.

The way forward

The Asian Dendrochronology Association (ADA) held a panel meeting to discuss future research and the way forward. The following administrative decisions were made:

- Nathsuda Pumijumnong (Thailand) was elected the new ADA president, R.R. Yadav (India) the new treasurer, Osamu Kobayashi (Japan) the new secretary, and a total of 10 representatives from each country in Asia as members. The ADA constitution's term is two years.
- Membership fee for ADA is US$10 per year ($5 for students). There are currently 41 members.
- ADA will establish a website to be launched in December 2007. This website will be available for consultation, linkages and networking among ADA members and research institutions.
- ADA will issue a newsletter three times a year.
- ADA will organize a conference and workshop every two years.
- The next ADA conference will take place in Lucknow, India in 2009.

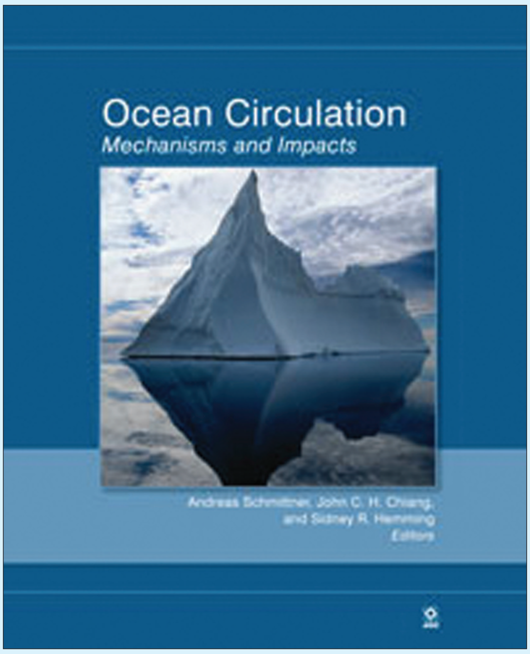
New on the PAGES bookshelf

Ocean Circulation: Mechanisms and Impacts

A publication of the American Geophysical Union
Editors: A. Schmittner, J. Chiang and S. Hemmings

This book covers all aspects of the ocean's large-scale meridional overturning circulation, and is a coherent presentation, from a mechanistic point of view, of our current understanding of paleo, present-day, and future variability and change. It presents the current state of the science by bringing together the world's leading experts in physical, chemical, and biological oceanography, marine geology, geochemistry, paleoceanography, and climate modeling.

Preface: A. Schmittner, J. Chiang and S. Hemming
Section 1. Introduction - The Ocean's Meridional Overturning Circulation
Section 2. Theory and Perspectives
Section 3. Current State and Trend
Section 4. Decadal to Centennial Variability
Section 5. Past States and Millennial Variability
Section 6. Impact on Climate, Ecosystems, and Biogeochemical Cycles
Section 7. Future Projections



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All PAGES newsletters have an open section for general contributions. If you would like to contribute a "Science Highlight", "Workshop Report", "Program News", or an amusing "Tales from the Field" story, please contact Louise Newman (newman@pages.unibe.ch). The next deadline is 9 February 2008.

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