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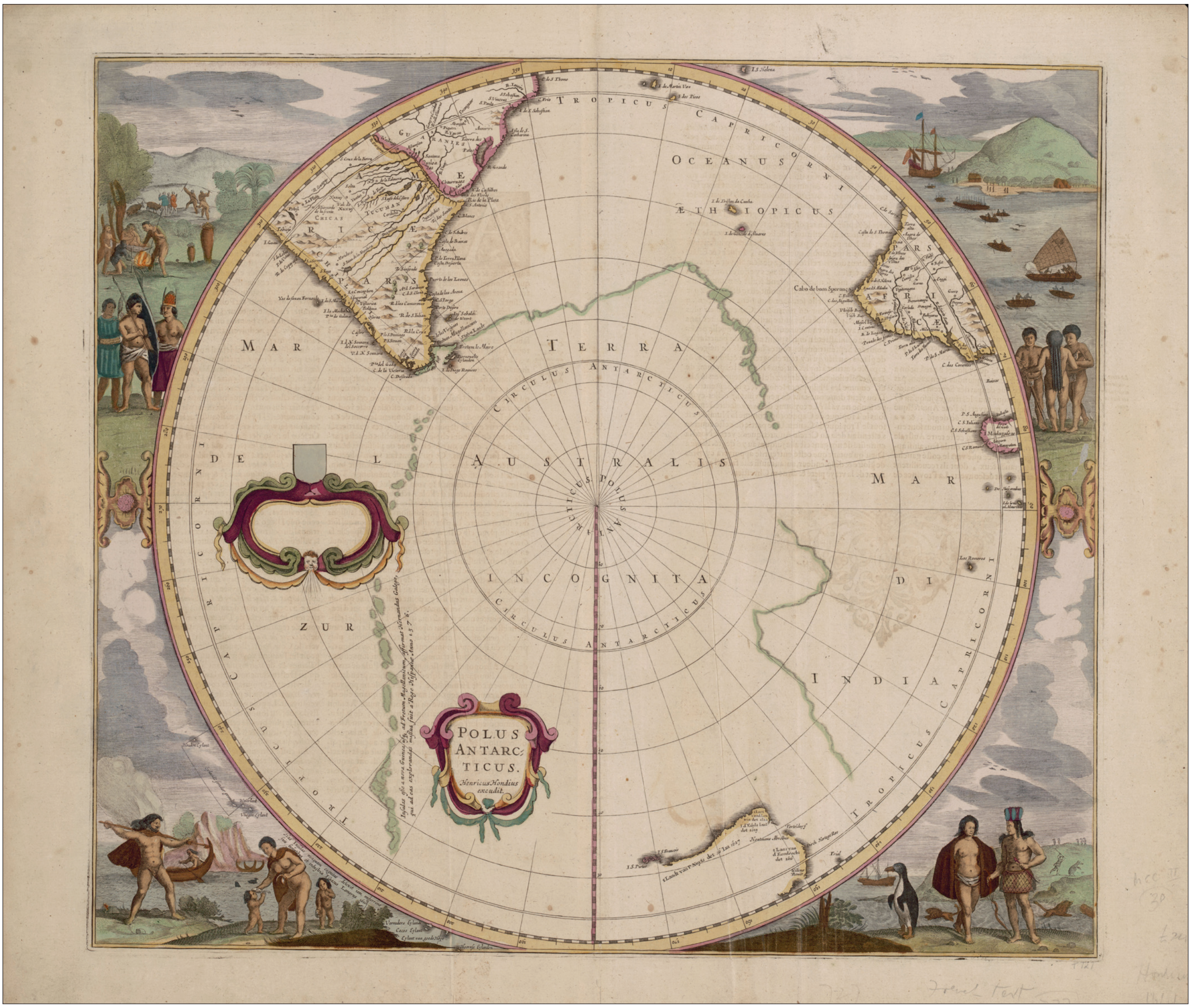
Past Climate Dynamics: A Southern Perspective

Editors:

Peter Kershaw, Jérôme Chappellaz, Louise Newman and Thorsten Kiefer



Polus Antarctica: Terra Australis Incognita
This map, produced in 1642 by Hendrik Hondius, shows the extent of geographical knowledge of the southern hemisphere 365 years ago. Although our geographic knowledge of the region has obviously come a long way since then, the sparsity in the 17th century, shown here, is representative of the current state of our understanding of the paleoclimate of the southern hemisphere. There is much to be done! (Map supplied by the National Library of Australia.)

Editorial: Developments in southern hemisphere paleoclimate research

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The newsletter cover nicely symbolizes the general perception of poor knowledge about the southern hemisphere, which extends into the paleoclimatic realm. Certainly, the tradition of Quaternary research stems from the northern hemisphere and a sustained focus is justified by the dominant role of the North Atlantic region in modulating climate change. The establishment of the PAGES Pole-Equator-Pole (PEP) transects led to a major impetus in the integration of information from southern and northern continents, and further highlighted the geographical separation of southern landmasses. One attempt to provide a southern focus was the INQUA and PAGES inspired 'Paleoclimates of the Southern Hemisphere' (PASH) program, but it succumbed to the tyranny of distance.

The increasing recognition over the last few years of the necessity for a global synthesis in order to refine climate change models—together with an acknowledgement that southern and low-latitude climate mechanisms had a much greater impact on paleoclimate than previously realized (e.g., with the specific presence of a huge ice sheet, surrounded by an ocean playing a key role in redistributing energy and carbon)—has provided a boost to Antipodean project formulation and execution*. But the picture still remains far from the spatial and temporal coverage of its northern counterpart.

This newsletter issue focuses on some science highlights and news articles, which are predominantly linked with these Antipodean projects, and covers all major southern landmasses and the Southern Ocean. Antarctica and its archives have proved a trigger for southern hemisphere research by providing insights into, for example, the polar 'see-saw', the mid-Bruhnes transition—through evidence of a switch to more pronounced interglacials—and the full temporal extent of the current ice-age (the last ca. 35 Myr). Contributions relating to Antarctica in this issue derive from such projects as those within IPICS (International Partnerships in Ice Core Sciences), SCAR (Scientific Committee on Antarctic Research) and ACE (Antarctic Climate Evolution), and extend the main timescale of PAGES interest, in recognition of the need to understand the mechanisms at work, under boundary conditions slightly different to those of today. Several articles relate to the INQUA Paleoclimate Commission (PALCOMM) project on Land-Ocean Correlation of Long Records from the Southern Hemisphere on Orbital and Suborbital Timescales. This is essentially a revamped PASH initiative, with a more integrated structure. In comparison with the oceans, long terrestrial sediment cores have been difficult to recover, however, projects formulated in association with the International Continental Drilling Program, two of which are featured here, are beginning to have a big impact in establishing regional relationships with both high- and low-latitude forcing. Highlighted also are details of the Pleistocene/Holocene transition or Termination I, with the record from Australasia formally incorporated into an Australasian INTIMATE project. This project examines the degree of hemispheric synchroneity between this Pacific region and the North Atlantic, under the parent INTIMATE project. Three contributions herald a new PAGES initiative directed towards the high-resolution reconstruction of past climatic variations and their modeling on a regional basis over the late Holocene, following on from the European LOTRED (Long Term Climate Reconstruction and Dynamics) project. LOTRED-South America was launched at a meeting in Mendoza, Argentina in 2006 and the first outcome, a special issue of *Palaeogeography, Palaeoclimatology, Palaeoecology* will be published in early 2008. Moves have been made to set up an Australasian-LOTRED, and to further expand the network with the group CACHE-PEP, which focuses on the region from southernmost South America to the Antarctic Peninsula.

Overall, we hope that this issue of the PAGES newsletter will increase the awareness that the southern hemisphere must not be underestimated in global change studies, and that long-term efforts are still required to better document its evolution.

* Success of the various projects is dependent on data availability. Contributors are encouraged to lodge their data with the World Data Centre for Paleoclimatology (www.ncdc.noaa.gov/paleo/data.html) or PANGEA (www.wdc-mare.org).

****Acronym Database****

For clarification of acronyms used in this editorial and articles in this newsletter, and links to the websites of the above-mentioned programs, please visit the PAGES-related acronym website: www.pages-igbp.org/about/abbreviations.html

PAGES Calendar 2007/08

14 - 25 January, 2008 - Dichato Concepcion, Chile
Austral Summer Institute VIII
www2.udec.cl/oceanoudec/oceanografia/

26 - 29 May, 2008 - Louvain-la-Neuve, Belgium
Slow dynamics of climate change
www.uclouvain.be/berger2008

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

11 - 14 June, 2008 - Lääne-Virumaa, Estonia
Peatland archives of Holocene climate variability
www.pages-igbp.org/calendar/calendar08.html

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

11 - 13 August - Shanghai, China
Quaternary pollen database of China
www.pages-igbp.org/calendar/calendar08.html

Inside PAGES

SSC Meeting & INQUA Congress

The annual Scientific Steering Committee (SSC) meeting was held 25-27 July 2007, in Atherton, Australia, alongside the XVII INQUA Congress (28 July-3 August in Cairns). In addition to organizational issues (membership, funding, guest scientists, etc.), the SSC meeting focused on PAGES products and ongoing research, supported workshops and initiatives, and on finalizing PAGES Science and Implementation Plan (to be published in 2008). Minutes of the meeting are available at www.pages-igbp.org/people/sscleaders/meetingminutes.html.

The last day of the SSC meeting was dedicated to discussing collaboration with other IGBP core projects (e.g., AIMES and SOLAS), potential liaison with other relevant international organizations (e.g., INQUA, IPICS and ACE), and adoption of new working groups (e.g., past interglacials, and groups on regional climate variability of the last 2000 years). Thirteen invited guests presented ideas and participated in group discussions on possible links and synergies, which PAGES hopes will bear fruit in the coming months and years. In particular, INQUA and PAGES have agreed to consider joint activities and joint support of projects of common interest. Off to a good start, PAGES co-convened three sessions at the INQUA Congress (Land-atmosphere-ocean linkages during past climatic changes; Past 2000 years in the Southern Hemisphere; Human-environment interactions during the Holocene).

AGU Fall Meeting

If you will be at the AGU Fall Meeting in San Francisco (10-14 December 2007), we encourage you to attend one of the following three special sessions that PAGES is co-organizing:

- U04: Quaternary Climate Records from the Continents: Comparisons with Their Marine and Polar Cousins
- PP22: Past Climate Forcings—A New PAGES Focus
- PP25: The Climate of the Monsoon: Proxy Records, Measurements and Models

PAGES Book to Download

All the chapters and figures from "Paleoclimate, Global Change and the Future" are available digitally for free download from PAGES Product Database (www.pages-igbp.org/products/). The book, published in 2003 and now out of print, provides a synthesis of the past decade of research into global changes that occurred in the Earth System in the past.

Next Issue of PAGES News

The next deadline for open manuscript submissions to the PAGES newsletter is 12 November 2007. Guidelines for contributions can be found at www.pages-igbp.org/products/newsletters/instructions.html. This issue will also contain a special section on paleoceanography that will be guest-edited by Jean Lynch-Stieglitz (jean@eas.gatech.edu) and Markus Kienast (markus.kienast@dal.ca). If you are interested in contributing a science highlight to this special section, please contact the guest editors directly.

New on the PAGES bookshelf

Sustainability or Collapse?

An integrated history and future of people on Earth (IHOPE)

Dahlem Workshop Reports
Editors: R. Costanza, L.J. Graumlich and W. Steffen
Dahlem University Press
ISBN-10:0-262-03366-6; ISBN-13: 978-0-262-03366-4

This publication stems from the "Report of the 96th Dahlem Workshop on Integrated History and future Of People on Earth (IHOPE)".
It consists of five main sections:

1) Introduction (3 papers)
2) The Millennial Timescale: Up to 10,000 years ago (6 papers)
3) The Centennial Timescale: Up to 1,000 years ago (5 papers)
4) The Decadal Timescale: up to 100 years ago (4 papers)
5) The Future (4 papers)

Together, these sections present an integrated human and environmental history over millennial, centennial, and decadal timescales and make projections for the future.

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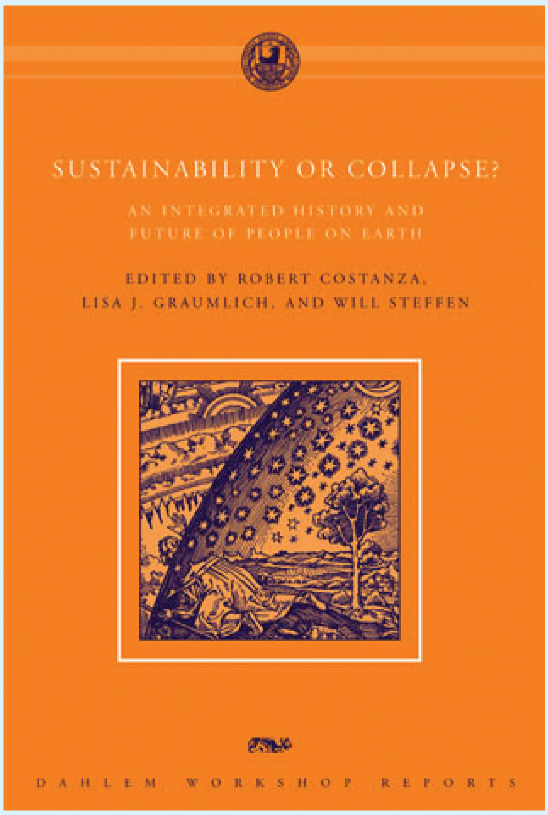

University of Bern's new "Oeschger Centre for Climate Change Research"

Martin Grosjean[1], T. Stocker[2] and H. Wanner[1]

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The University of Bern, Switzerland is pleased to announce the opening of the "Oeschger Centre for Climate Change Research". This Centre aspires to be the leading Swiss institution in research on past global changes and to foster a multidisciplinary approach to the understanding of climate change and its consequences for the environment and society. Rather than having a formal physical location, the Centre is "virtual", gathering together researchers from nine institutes in three faculties, as well as supporting the Graduate School of Climate Sciences.

A special focus on climate science is nothing new for the University of Bern. Already in the 19th century renowned pioneers such as Rudolf Wolf (1816–1893, sunspot numbers), Heinrich Wild (1833–1902, standards for meteorological measurements) and Eduard Brueckner (1862–1927, Ice Age theory) made significant contributions in the fields of meteorology and climatology. Today, different groups work at the forefront of IGBP-PAGES-related research, mainly in climate reconstructions and long-term dynamics. Among others, recent contributions include reconstructions of European temperature variability since AD 1500 (Luterbacher et al., 2004) and the greenhouse gas (GHG) records of the EPICA Antarctic ice core (e.g., Siegenthaler et al., 2005).

The Centre is named after Hans Oeschger (1927–1998), who was a professor of Climate and Environmental Physics at the University of Bern and one of the 'fathers' of PAGES. Among other major achievements, he built the "Oeschger Counter" to measure ^{14}C with very low backgrounds and was the first to date the "age" of Pacific deep water. He pioneered the application of modern physics to investigate the Earth and the global climate system with its interactive components, and was a leader in ice-core research and promoter of the deep-drilling projects in Greenland. Together with colleagues, Oeschger also documented a series of abrupt climate changes in the past, the "Dansgaard-Oeschger events", which became prime symbols for the non-linear nature of climate change.

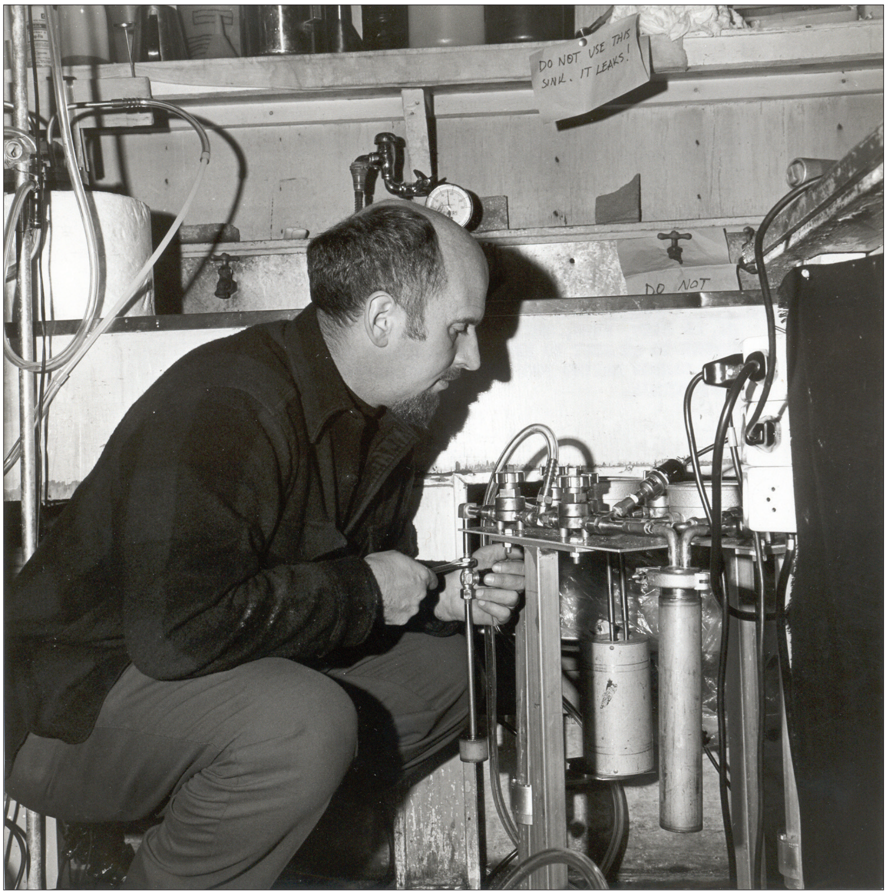

Figure 1: Hans Oeschger at Byrd Station, Antarctica, in 1968 (offical U.S. Navy photograph).

Oeschger's successors at the University of Bern are convinced of the potential of paleoclimatology. A main focus of the new Centre is the study of natural and documentary climate archives and regional multi-proxy climate reconstructions. This includes the investigation of ice cores from polar and alpine areas, sediments from high-elevation lakes, speleothems, tree rings, glacial dynamics, vegetation history and phenology, as well as documentary data (e.g., PAGES News, 2002, 10(3)).

In collaboration with many colleagues from other parts of the World, the different sources of information are integrated into comprehensive high-resolution climate reconstructions for the past 500–1000 years. These studies contribute to the LOTRED (Long-term climate reconstruction and diagnosis) initiatives for Europe and South America (PAGES News, 2006, 14(3): 26), a collaborative study under the umbrella of PAGES.

Among the Oeschger Centre's key activities are also observational and modeling studies of the dynamics of climate, ocean circulation and GHGs (CO_2 and methane) in the past, present and future. In addition, the Centre plays a leading role in the international assessment of climate change and impacts. Finally, the new Centre aims to bridge the gap between the natural sciences and the human dimension of climate change, notably land use and land cover changes and related feedbacks to the atmosphere. This includes impact studies on natural and managed ecosystems, as well as on the relationship between climate and society.

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Working Group on Arctic climate during the last two millennia

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A main conclusion of the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report, 2007 is that the warming of the climate system is unequivocal, as is evident from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice, and rising global mean sea level. Furthermore, most of the observed increase in globally averaged temperatures since the mid-20th century is very likely due to the observed increase in anthropogenic greenhouse gas concentrations. Warming in the Arctic is double that for the globe, both from the 19th to 21st century and from the late 1960's to the present. This amplification in the Arctic is due to a complex interplay between land, ice sheets, ocean and atmosphere, and is not fully understood.

Because climate models disagree on the relative amount of warming to be expected and natural variability adds further uncertainty, the future implications for society of these changes are unclear. The concern, though, is that human-induced climate change is accelerating and that the changes in the Arctic may have global, regional and local effects that challenge human society. The natural climate variability component of the system can be studied indirectly through past climate changes.

Changes in sea ice and tundra surface conditions, and changes in heat fluxes to and from the ocean, contribute to internal feedbacks and multi-year memory in the Arctic climate system. The patterns observed in the second half of the 20th century could be associated with two major atmospheric circulation patterns, the Arctic Oscillation (AO) and Pacific North American (PNA) indices. Large, natural atmospheric variability, as represented in part by the AO and PNA, can result in multi-year persistence of Arctic climate patterns. The long-term history of these regional dynamic patterns can be mapped by paleoclimate proxies.

Figure 1: This photo shows the collection of a number of cores from Kongsfjorden, Svalbard, in connection with the Norwegian-IPY-project "SciencePub". Arctic fjords and continental shelves provide areas of high sediment accumulation rates and give opportunities for collection of high-resolution cores.

About 25% of the Arctic surface air temperature trend from 1979 to 2001 in winter and spring is related to an increase in the amount of net atmospheric northward energy transport across the 60°N latitude circle, with the strongest linkage in the Atlantic sector. What was the long-term influence of mid-latitude atmospheric circulation on Arctic climate, and how did it change during, for example, the Little Ice Age and the Medieval Warm Period? Another question is whether natural climate variability in the Arctic in the past was also generally amplified in comparison with mid-latitudes.

PAGES Working Group on arctic climate during the last two millennia is a new initiative to generate and synthesize high-resolution paleoclimate data to assess and elucidate both the timing and variability of the Arctic climate change during this period. The group will especially work towards contributing to the series of regional reconstructions of the last 2000 years in the new PAGES Focus 2 "Regional climates and modes of variability".

All paleoclimate scientists working in the Arctic with high-resolution data and/or modeling are welcome to join and contribute to this Working Group. Please express your interest through email to Nalan.koc@npolar.no. The first Working Group meeting will be held in connection with the Arctic Workshop in March 2008.

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Extending the Americas paleoclimate transect through the Antarctic Peninsula to the Pole

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If we are to trust models used to predict future climate change, we need to be assured that they can reproduce the spatial and temporal pattern of natural climate variability. PAGES recognized this by setting up the PEP (Pole-Equator-Pole) transects, which aimed to determine the climate, especially throughout the Holocene, along continental transects. However, the PEPs end in mid-latitudes in the southern hemisphere and have not been integrated with the records available from the Antarctic continent. The Antarctic Peninsula (AP) bridges that gap and is particularly important, being one of the three fastest-warming regions on Earth (3.4˚C/century) (Vaughan et al., 2003). The rate of temperature increase is more than five times the global mean (0.6 ± 0.2˚C) during the 20th century, leading to shifts in species distribution, catastrophic disintegration of ice shelves, retreat and accelerated discharge of continental glaciers (Cook et al., 2005; Pritchard and Vaughan, 2007). The British Antarctic Survey (BAS) project “Climate and Chemistry-PEP” (CACHE-PEP) and University of Ghent project “Holocene climate variability and ecosystem change in coastal East and Maritime Antarctica” (HOLANT) are seeking to place the Last Glacial Maximum (LGM) through Holocene variability of AP and Antarctic climate in the context of global variability, as a contribution to understanding the significance of recent changes. It is doing this by extending the PEP-I (Americas) transect through the AP. A program of collaborative fieldwork collecting ice cores, marine and lake sediment core data, is already well underway (Fig. 1).

In 2005, the BAS drilling of a new 948-m-deep ice core to bedrock was completed on Berkner Island at the southern end of the Atlantic conveyor in the Weddell Sea, together with French partners at the Laboratoire de Glaciologie et Géophysique de l'Environnement. Initial results show that the Antarctic ice sheet in the Weddell Sea region was likely to have been thinner at the LGM than ice sheet models suggest, and that it may not have been over-ridden by the main Antarctic ice sheet, calling for a re-think about the volume of the Antarctic ice sheet in this sector of Antarctica during the last glacial period. Preliminary temperature records from the ice core suggest relative stability throughout the Holocene. Building on

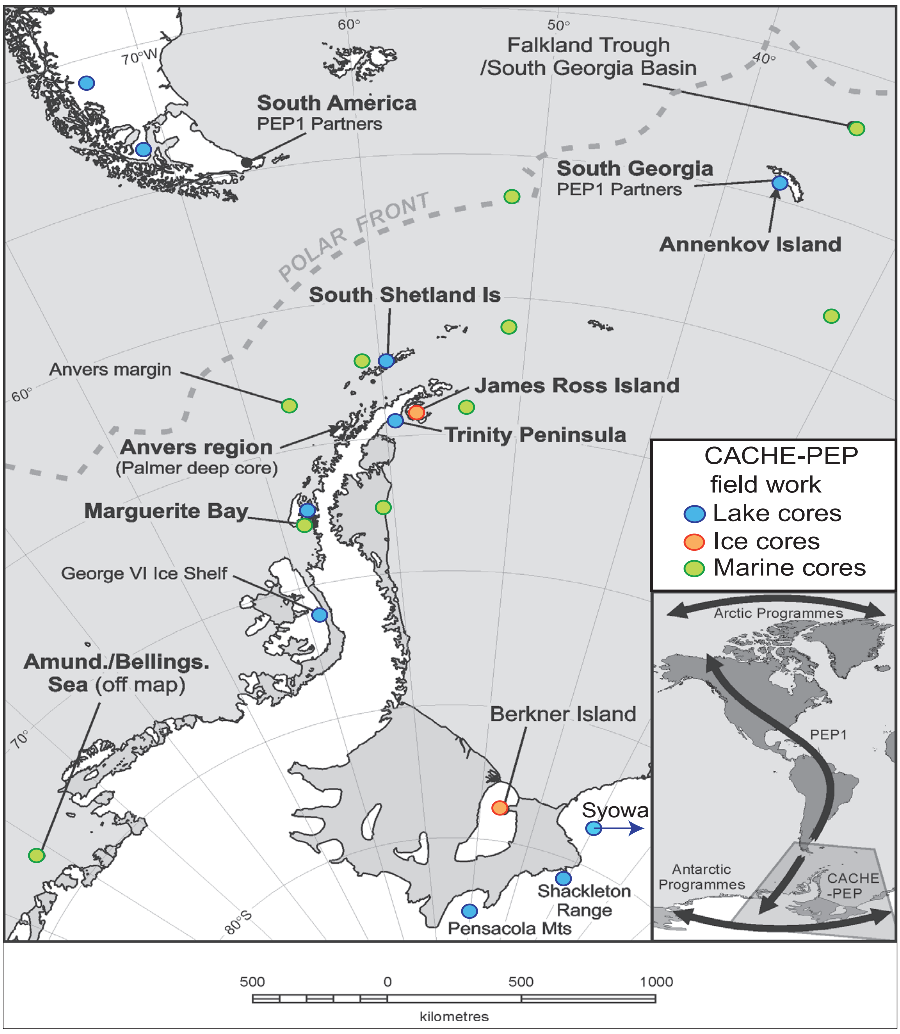

Figure 1: The region of focus, including all core types and locations.

the Berkner Island record, we are now in the advanced stages of logistics planning to drill a further ice core from James Ross Island at the northern end of the Antarctic Peninsula. Radar profiling suggests that this site will contain a 400 m column of ice that is likely to produce the longest Holocene record from the northern AP. Drilling to bedrock on James Ross Island will put the AP ice core records of the past few centuries into the perspective of the full Holocene climate record and allow us to state, in combination with lake records, whether the recent warming is unusual, or is similar to previous trends when the record over centennial timescales is taken into account. The timing of AP warm periods can then, for the first time, be compared with ice-shelf break-up in the same geographical region and with other climate and environmental changes along the extended PEP transect.

Lake and marine sediment records are also being collected to examine how the Holocene record in the ice cores is related to changes in terrestrial and marine environments along the AP transect. Lake sediment cores collected from Tierra del Fuego (with collaborators), South Georgia, the South Shetland Islands, Marguerite Bay, Alexander Island and the Trans-Antarctic Mountains have been selected to span the latitudinal transect. These are being used to provide records of ice-shelf break-up, deglaciation, and temperature-related variables such as changes in primary production and moisture balance. Already, we have shown from ice-dammed lakes that the largest ice shelf on the west of the Antarctic Peninsula, George VI Ice Shelf, retreated in the early Holocene, c. 9.6-7.73 kyr BP. This retreat immediately post-dates the early Holocene climatic optimum recorded in several continental ice cores from Antarctica and coincides with an influx of warmer ocean water onto the western AP shelf at 9 cal kyr BP (Smith et al., 2007). The collapse of a currently extant ice shelf immediately after the early Holocene climatic optimum implies that early Holocene atmospheric and ocean temperatures in the AP region were higher than those measured in recent decades. However, if IPCC predictions of increased atmospheric temperatures in the coming decades continue to apply to the AP we can expect that its ice shelves will continue to retreat (Hodgson et al., 2006).

Marine sediment cores collected from the northeast of South Georgia, the Scotia Sea and down both sides of the AP are also revealing spatial and temporal changes in oceanographic variables along the AP transect. Initial results, focussing on changes in sea-ice extent, suggest an early retreat of summer sea ice across the Scotia Sea, with the average summer sea-ice margin being close to its Holocene position before 21 cal kyr BP. In contrast, the winter sea-ice limit was stable north of the Falkland Trough until at least 19 cal kyr BP (Allen et al., 2005). This is similar to records from the eastern Atlantic and Indian sectors of the Southern Ocean that also document a pre-LGM summer sea-ice maximum and early retreat to a near-modern extent by the LGM (Crosta et al., 1998; Gersonde et al., 2005). This means that the seasonal area of sea-ice growth and decay would have been more than double that of today's Southern Ocean, producing a much larger expanse of seasonally open-water than most models suggest. The associated impacts on Southern Hemisphere albedo and ocean-atmosphere energy transfers would have had a profound influence on feedback-dynamics during the glacial transition and are being further explored.

Our ice, lake and marine records have been selected for their high resolution and to facilitate detailed time-series analyses to determine the timing and phasing of climate events through the Holocene. Our activities also compliment a recent intensification of paleoecological research in southernmost South America and to the new and exciting ice core records from central East Antarctica (produced) and West Antarcica (in progress). Together with records from collaborating groups, these activities should give us a comprehensive view of how the climate system in the AP has behaved, and how it is linked to global climate via CO_2, orbital forcing, major modes of atmospheric circulation, ocean circulation and sea ice.

Further information: www.antarctica.ac.uk/bas_research/current_programmes/cache.php
www.holant.ugent.be/

Selected links:
www-lgge.ujf-grenoble.fr/
www.hamilton.edu/news/exp/antarctica/2004/faculty.html
http://shaldril.rice.edu/
www.salsa.uni-bremen.de/
www.pages-igbp.org/science/initiatives/lotred-sa/

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The Lake Malawi Scientific Drilling Project

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In 2005, an international team of researchers undertook an ambitious plan to drill two sites in Lake Malawi (9°-14°S), in water depths of 592 and 359 m in the central and northern basins of the lake. Lake Malawi is located in the southern end of the western branch of the East African Rift System (Fig. 1, inset). It extends along more than 550 km of the rift valley, and with a depth of 700 m, it is the second-deepest lake in Africa. Along with Lake Tanganyika, Lake Malawi contains one of the longest high-resolution paleoclimate records of the continental tropics.

The primary objective was to obtain a continuous, high-resolution (annual-decadal) record of past climates in the continental tropics, and to then determine if tropical African climate responded to changes in low-latitude precessional insolation (23-19 kyr), or to high-latitude ice volume (100 kyr and 41 kyr) forcing, during the late Pleistocene.

The project initially faced very difficult engineering and logistical challenges. A 160 ft fuel barge was used as the drilling platform, which was stabilized by a portable dynamic positioning system designed to maintain the position of the barge for weeks at a time (Fig. 1). The drilling operation involved 26 personnel aboard the

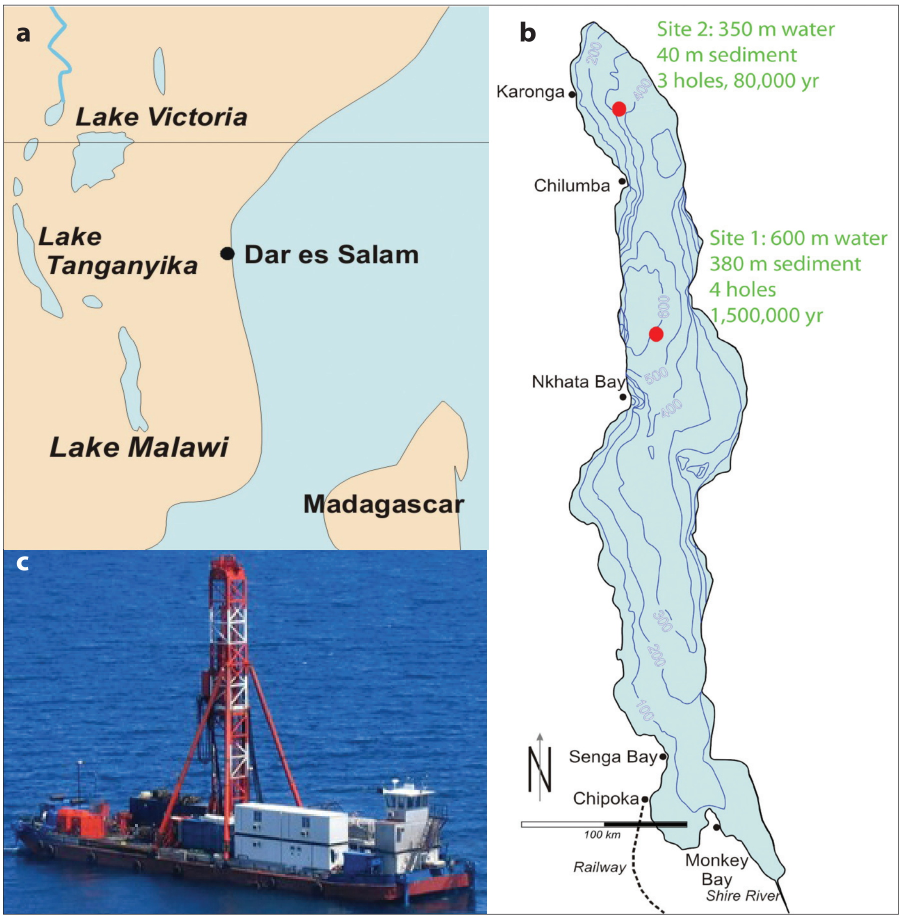

*Figure 1: **a**) Location of Lake Malawi; **b**) Description and location of cores; **c**) The 160 ft drilling barge on Lake Malawi, where 26 members of the drill team, science team and ships crew lived for six weeks in 2005. Image courtesy of I. Castaneda, University of Minnesota.*

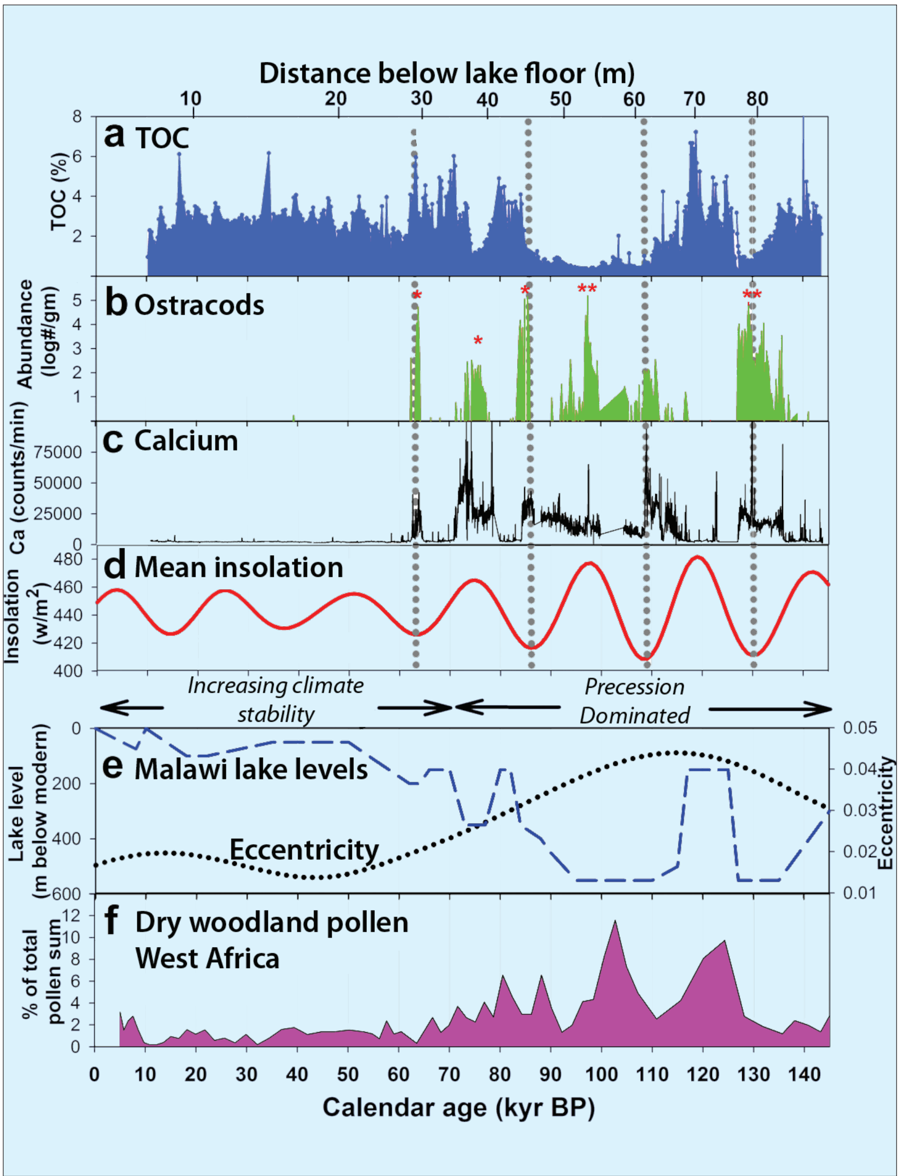

Figure 2: Summary of Lake Malawi lake-level indicators from site 1 cores, with orbital forcing and marine records. ***a****) Total Organic Carbon (TOC) - high values indicate highstand conditions and bottom water anoxia;* ***b****) Ostracod abundance - * core intervals of profundal taxa, ** core intervals of littoral zone taxa and lake shoreline close to drill site. Ostracods are only present when the lake is shallow and bottom waters are oxygenated;* ***c****) Ca abundance - indicates periods of calcium carbonate precipitation (i.e. during severe lowstand, or high salinity events);* ***d****) Local mean insolation (10°S) at the end of the dry season (1 Oct - 1 Dec); Vertical dotted lines signify precession-dominated insolation minima;* ***e****) Malawi lake level vs. eccentricitiy;* ***f****) Dry woodland pollen record from marine core GeoB 1016, West Africa, demonstrating comparable climate signals to those observd in Lake Malawi. (modified from Scholz et al., 2007)*

barge, working continuously in 12-hour shifts and was supported by three supply ships.

More than 623 m of core was recovered from seven holes at two sites. Three cores were collected from the high-resolution site (extending back ~80 kyr), two cores were obtained from the deep site (covering the past ca. 150 kyr) and a single core was collected from the deep site to 380 m, covering as much as a million years or more in age. Sample material recovered included a variety of laminated and homogenous algal-rich mud (dominantly clay) in zones of alternating dry/dense and soft/high-water content material; cemented siltstone; volcanic ash horizons; and fine-grained well-sorted sands at the base of holes at both sites. Laminations from late-Pleistocene and Holocene sediments have been shown to be varves, and thus annual records may be recovered from many discrete intervals over the cored interval.

Prior to drilling, preliminary studies were undertaken including detailed analyses of short cores and extensive seismic reflection datasets (Fig. 2). The earlier studies suggested that the climate system of this southern hemisphere tropical site has linkages to high-latitude climate, but evidence of very high-amplitude lake-level shifts also implied possible orbital control of effective moisture in the lake's vast catchment. The first results from drill core analyses indicate that on two occasions, between 135 and 75 kyr, water levels dropped to more than 550 m below modern levels. Lake level then increased and stabilized after 70 kyr, reaching modern levels sometime after 60 kyr (Scholz et al., 2007). Similar findings are observed in data from Lake Tanganyika and Lake Bosumtwi (West Africa). Surprisingly, the early late-Pleistocene lake-level lowstands and megadroughts were much more severe than the low lake stages observed during the Last Glacial Maximum in all three of these tropical lakes. The termination of the high climate variability interval that included the megadroughts may have played an important role in the final African exodus and population expansion of Early Modern Humans (Scholz et al., 2007).

It appears that in tropical East Africa, the climate forcing underwent a mode switch after ~70 kyr, from eccentricity-modulated precessional control, to one linked to high-latitude climate shifts. Initial results of scanning X-ray fluorescence (XRF) data from the north basin drill site in Lake Malawi suggest that rapid shifts in climate over the past ~55 kyr are related to abrupt warming (Dansgaard-Oeschger) events observed in Greenland (Brown et al., 2006).

Acknowledgements

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Recent advances in understanding Antarctic climate evolution

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Geological evidence shows that the ice sheet and climate in Antarctica has changed considerably since the onset of glaciation around 34 million years ago. By analyzing this evidence, important information concerning processes responsible for ice-sheet growth and decay can be determined, which is vital to appreciating future changes in Antarctica. Here, we document five distinct case studies as examples of recent insights into Antarctic climate evolution.

The extent of the Antarctic ice sheet (AIS) has fluctuated considerably during its ~34 million year existence, and has been a major driver of changes in global sea level and climate throughout the Cenozoic Era. The spatial scale and temporal pattern of these fluctuations has been the subject of considerable debate. Determination of the scale and rapidity of the response of large ice masses and associated sea-ice to climatic forcing is of vital importance. Ice-volume variations lead to both changes in global sea levels—on a scale of tens of meters or more—and in alteration in the capacity of ice sheets and sea-ice as major heat sinks, insulators and reflectors. It is thus important to assess the stability of the cryosphere under a warming climate (IPCC, 2001). Here we assess five areas of activity, which, when combined, provide a means of gauging the variety of activities needed to gain a fuller appreciation of Antarctic glacial history.

CO_2 and ice-sheet inception at the Eocene-Oligocene boundary

While the onset of continental-scale glaciation in the earliest Oligocene (Oi-1 event; ~34 Myr) has long been attributed to the opening of Southern Ocean gateways (Kennett, 1977), recent numerical modeling studies suggest declining atmospheric CO_2 was the most important factor in Antarctic glaciation. As the passages between South America and the Antarctic Peninsula (Drake Passage), and Australia and East Antarctica (Tasmanian Passage) widened and deepened during the late Paleogene and early Neogene, the southern oceans experienced cooling sea surface temperatures by several degrees. Estimates for the opening of Drake Passage range between 40 and 20 Myr, blurring the direct 'cause and effect' relationship between the gateways and earliest glaciation.

To help solve this issue, coupled climate-ice sheet models have simulated the Eocene-Oligocene boundary accounting for decreasing CO_2 concentrations and orbital variability (DeConto and Pollard, 2003). Results from the modeling show that tectonically-forced changes in ocean circulation and heat transport have only a small effect on temperature and glacial mass balance in the Antarctic interior. Considering the sensitivity of polar climate to the range of CO_2 concentrations predicted to have existed over the Paleogene-Neogene, CO_2 likely played a fundamental role in controlling Antarctica's climate. Modeling also revealed that the timing of glaciation in East Antarctica is sensitive to orbital forcing, mountain uplift, and continental vegetation, but only within a very narrow range of atmospheric CO_2 concentrations—around 2.8 times modern levels. Once a CO_2 threshold is approached, astronomical forcing triggers the growth of a continental-scale ice sheet within 100 kyr (Fig. 1).

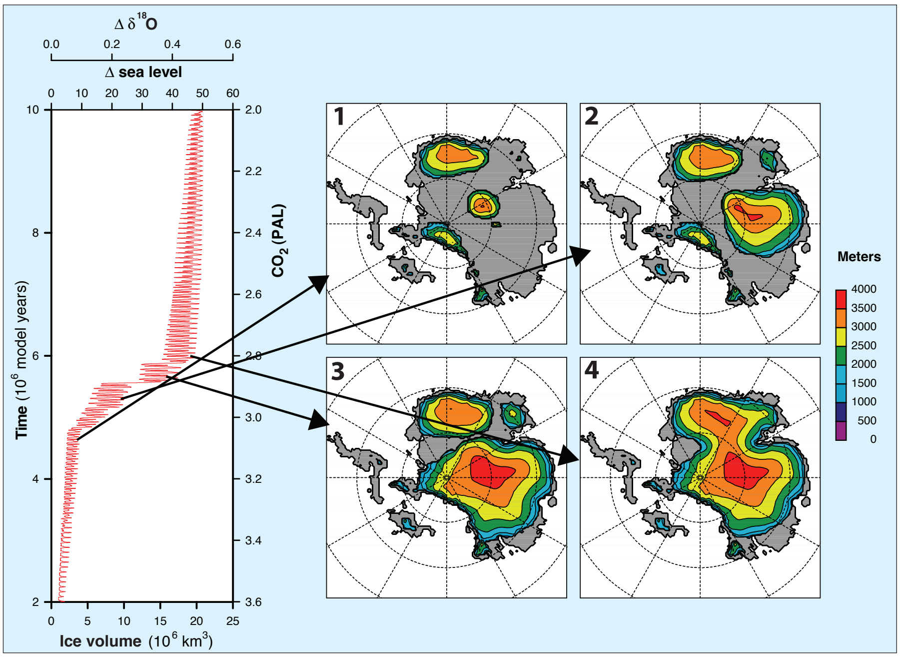

*Figure 1: Ice volume (**left**) and corresponding ice sheet geometries (**right**) simulated by a coupled atmospheric general circulation - ice sheet model, in response to a slow decline in atmospheric CO_2 (modified from DeConto and Pollard, 2003).*

Orbital control on ice-sheet dynamics at the Oligocene-Miocene boundary

Drilling off the Antarctic margin at Cape Roberts has revealed 55 sedimentary cycles recording advance and retreat of the ice margin sea-level changes. Two of the cycles contain volcanic ash whose ages link them with particular Milankovitch cycles 24 and 24.2 Myr in the deep-sea isotope record (Naish et al., 2001). Analysis of deep-sea isotope records indicate sea level variations of 30-60 m from changes in ice sheet volume at this time. The sediments also show that the Antarctic coastal temperature declined progressively through Oligocene and early Miocene time, which is at odds with a major shift of the $\delta^{18}O$ values at ~25 Myr, interpreted previously as a warming of the oceans.

Coring of the Antarctic margin will continue over the next two years in nearby McMurdo Sound, where two 1000-m-deep holes will be cored by ANDRILL, to cover the time interval from the present back to 10 Myr and from 10-20 Myr. Together with the Cape Roberts core, this will provide an unprecedented paleoenvironmental record for this part of the Antarctic margin for the last 34 Myr.

Neogene major expansions and retreats of the EAIS

The Lambert Glacier is the largest fast-flowing outlet glacier in the world, draining ~12% of the East Antarctic Ice Sheet (EAIS) into Prydz Bay. During advances of the Lambert Glacier to the shelf break, glaciogenic material is deposited on nearby mountains. Formations in the Prince Charles Mountains were laid by fast-flowing polythermal tidewater glaciers analogous to those of the modern fjords of East Greenland, with ages ranging from early Miocene (or possibly Oligocene) to Pliocene-Pleistocene. Numerical modeling studies of erosion and sediment supply suggest that, besides climate, continued excavation and overdeepening of the glacial trough during ice advance phases is an important factor controlling the dynamics of the Lambert Glacier (Taylor et al., 2004).

Synchronicity of late deglacial ice retreat in Antarctica

The retreat of Antarctica's ice sheet following the Last Glacial Maximum (LGM) has been studied for more than 30 years, through marine geology and continental glacial geomorphology, yet many questions remain regarding the timing, speed, and style of ice retreat. New coring capabilities, as well as refinements in age-dating methods, are yielding surprising results regarding the timing of last deglacial ice retreat off Antarctica's continental shelf. Long sediment cores have been collected from both sides of the Antarctic Peninsula, the Ross Sea and distant regions of the East Antarctic continental shelf. By dating the biogenic sediments immediately overlying LGM diamict (poorly sorted sediment), it is possible to estimate the timing of ice retreat from outer and mid-shelf regions. The developing view is of rapid and synchronous retreat of ice from widely separated regions of Antarctica's continental shelf beginning at ~11.5 cal kyr BP and lasting for up to 800 years. This apparent synchronicity is unexpected, given previous inferences of large geographic asynchronicity in the timing of maximum glacial advance and subsequent early deglacial history (Anderson et al., 2002).

Subglacial processes and flow dynamics of former Antarctic ice streams

Recent marine geophysical and geological research from the Antarctic continental shelf has significantly advanced our understanding of the extent and dynamics of the Antarctic Ice Sheet (AIS). During the LGM, the AIS was positioned at, or close to, the shelf edge around the Peninsula, the Bellings-hausen Sea and Pine Island Bay. In these areas, large glacial troughs extend

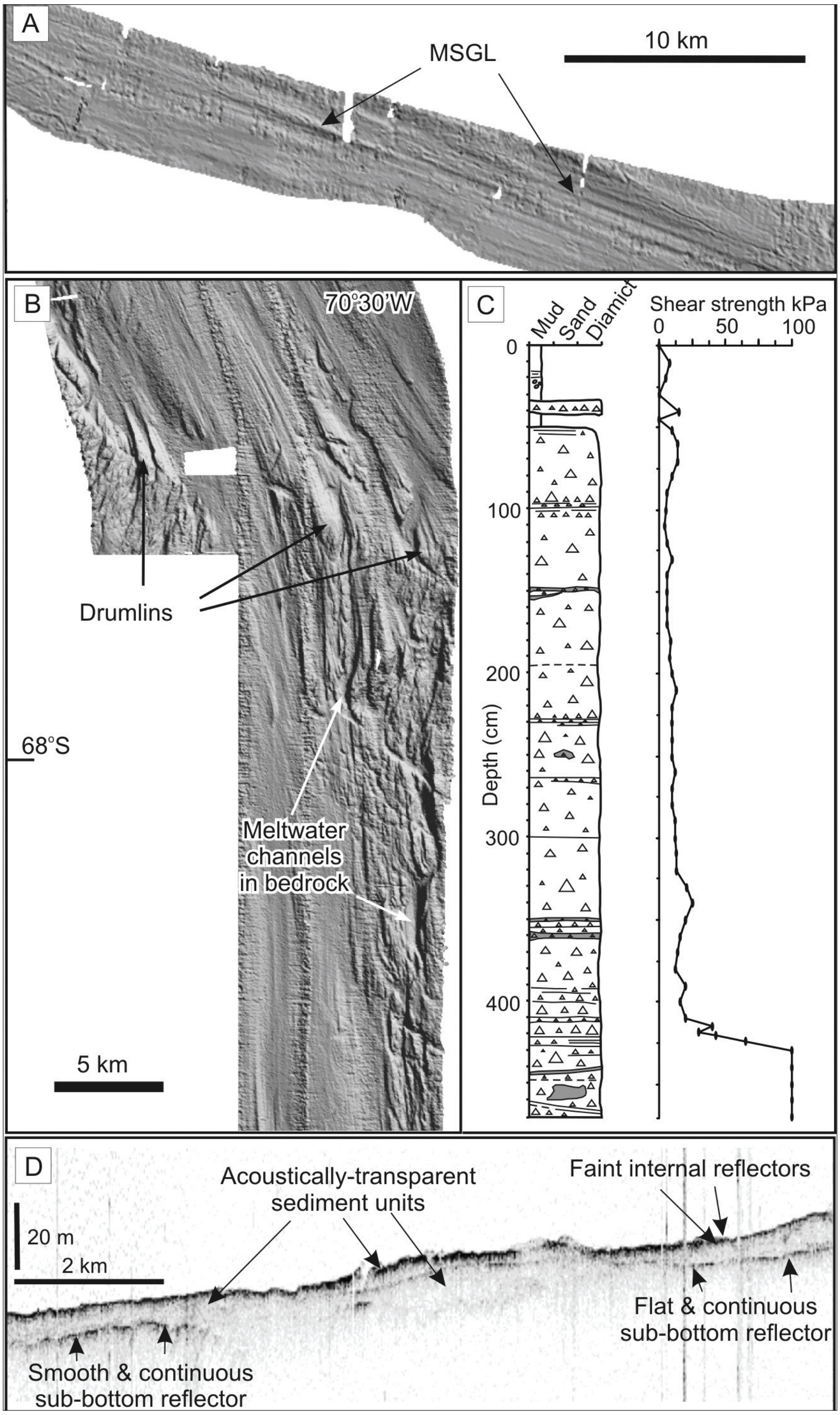

*Figure 2: Geophysical and geological records of paleo ice-stream flow in bathymetric troughs on the Antarctic continental shelf. **A**) Swath bathymetry shaded relief image of mega-scale glacial lineations (MSGL) at the mouth of the Ronne Entrance, Bellingshausen Sea; **B**) Swath bathymetry showing sea-floor morphology as a shaded relief image in middle-outer Marguerite Trough, Antarctic Peninsula; **C**) Core log and shear strength plot of sub-ice stream sediments, Marguerite Trough; **D**) TOPAS sub-bottom profiler record from the Ronne Entrance showing acoustically transparent sediment unit (soft till) sitting above a prominent basal reflector (arrowed).*

across the continental shelf, and sedimentary and geomorphic evidence from these troughs (Fig. 2a,b) indicate that they were occupied by grounded paleo ice streams during, or immediately following, the LGM (Ó Cofaigh et al., 2002). Mega-scale glacial lineations (subglacially produced ridges) can attain lengths of greater than 20 km within the troughs and are characteristically formed in a weak porous and deformable till layer (Fig. 2c,d). Such weak tills have been identified and mapped in all the paleo ice-stream troughs investigated to date. They tend to be confined to the troughs and are not widely observed in the inter-trough areas. The association of this weak porous till layer with highly elongate subglacial bedforms implies that the rapid motion of these ice streams was facilitated, at least in part, by subglacial deformation of the soft bed. Geophysical data also indicate significant transport of subglacial till towards the former ice-stream terminus. The implication that paleo Antarctic ice streams were underlain by weak sediments is indicative of a dynamic, fast-flowing ice sheet at the LGM, much like it is today in West Antarctica, allowing rapid ice-sheet responses to sea level and ocean temperature changes.

Future activities

Although our appreciation of Antarctic history has improved dramatically over the past decade, there is still much to learn. Significant questions exist about the evolution of Antarctic landscape, both above and below the ice cover; its connection with ice-sheet development; past and present large-scale ice-sheet dynamics and stability; the role of sub-glacial water in the ice-sheet system; and the influence of ice-sheet evolution on Antarctic biology. In 2004, the Scientific Committee on Antarctic Research (SCAR) recognised the importance of understanding past changes in Antarctica with the establishment of its Antarctic Climate Evolution (ACE) scientific research program. This program, in conjunction with other SCAR program's (SALE – Subglacial Antarctic Lake Environments; AGCS – Antarctica in the Global Climate System; and EBA – Evolution and Biodiversity in Antarctica), aims to further integrate numerical models with geological data, in order to understand the processes responsible for the growth and decay of large ice sheets and to comprehend the global significance of such changes.

Acknowledgements

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Antarctic ice cores

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Terrestrial and marine paleoclimate records are very sparse in the southern hemisphere, particularly at high latitudes. However, this is where ice cores come into their own. Antarctic ice cores provide a firm and well-resolved anchor for our understanding of how climate has evolved over 800 kyr, and provide climate information for assessing how the Antarctic Ice Sheet may have varied over the same period. They are also the best archive for determining the history of greenhouse gas concentrations and offer unique data on other important forcings, such as volcanic aerosol and solar.

Characteristics of Antarctic ice cores

Almost the whole of the Antarctic ice sheet fulfils the basic requirements for good ice core records, namely that snow is laid down in regular layers without significant loss or percolation by melting. In near coastal areas, relatively high snow accumulation rates allow the collection of records for which annual layer counting is possible. This is the area of choice for well-resolved and precisely dated records of recent centuries. In central regions of the Antarctic plateau, the ice is very thick (~3 km) but the snow accumulation rate may be as low as 2 cm water equivalent. It is in this region that records extending back over hundreds of thousands of years can be found, although the dating is necessarily less precise.

The water isotopes in the ice act as a good proxy of Antarctic temperature and also provide information on conditions over the ocean (the source of the water vapor). Due to the low impurity content of the ice, Antarctic cores are well suited to analysis of trace gases, and the chemical content provides information about environmental conditions in the Southern Ocean and other southern continents.

Recent centuries

As atmospheric measurements of greenhouse gases have only been carried out routinely for, at most, a few decades, ice cores have for some time been relied upon to show how greenhouse gas concentrations increased during the past two centuries, and how they varied in the preceding period. A new study (MacFarling Meure et al., 2006) has extended the period of high-resolution to 2 kyr, expanded the high-resolution work from CO_2 and CH_4 to include N_2O, and filled in gaps in the previous records. Together with the existing data and other data from sites with lower-resolution that confirm most of the details, this work provides a definitive account of greenhouse gas variability and trend; it is indeed

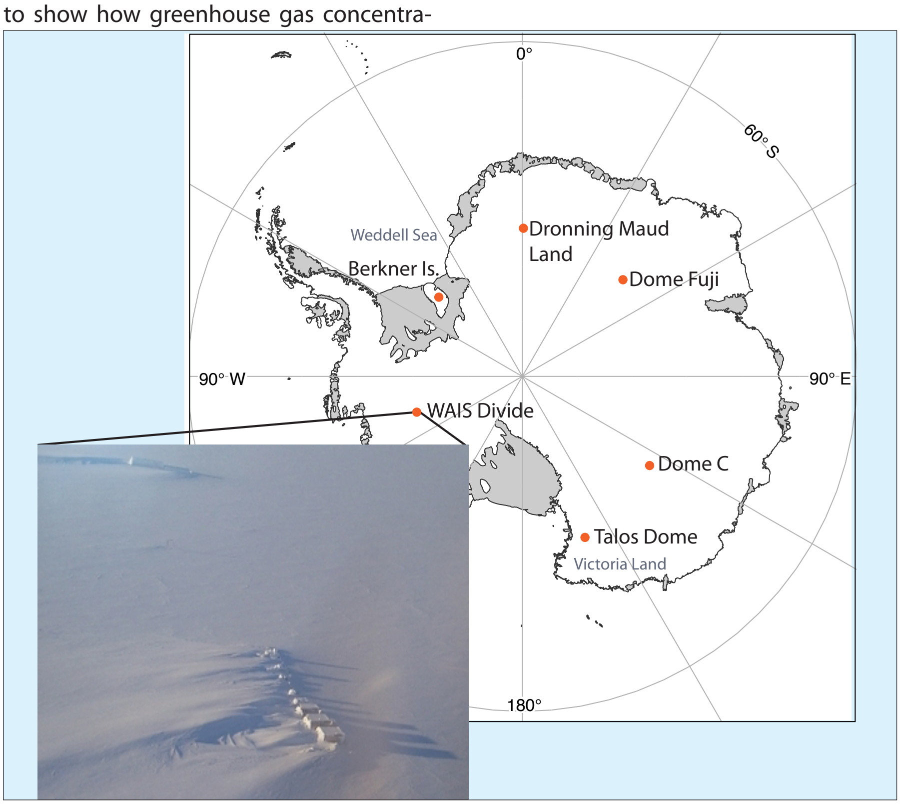

Figure 1: Map of cores and locations mentioned in text. ***Inset****: photo of WAIS Divide site, with camp in center and drilling site top left corner (E. Brook).*

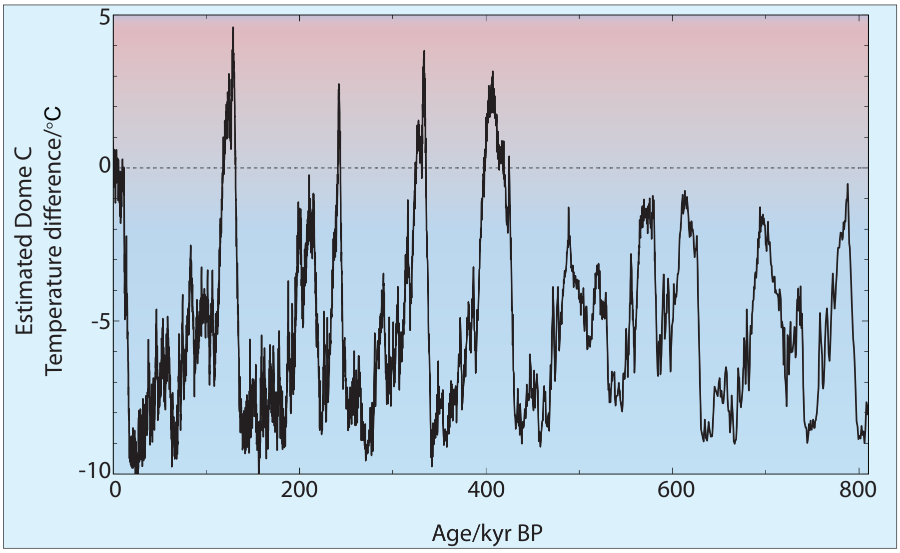

Figure 2: Estimated difference in Dome C temperature, compared to today, over the last 810 kyr, calculated from deuterium data. Figure based on data in Jouzel et al. (2007).

much quoted in the recent IPCC 4th assessment report.

Other studies of the recent past have moved on from interpreting single records and focussed on combining sets of ice core records, in order to establish the reliable common signal and discard the "noise" in the proxy (e.g., Schneider et al., 2006). This kind of work will make ice core data more suitable for inclusion in multi-proxy reconstructions of southern hemisphere climate from different archives. It is now becoming more common to compare data with atmospheric reanalyses to establish relationships and calibrations that might be applied to earlier periods. Both features of the pressure field (for major ionic species) and sea-ice extent (for methanesulfonic acid (Abram et al., 2007)) have been used as targets for reconstruction.

Glacial-interglacial cycles

Probably the biggest excitement in the ice core community in the last few years has come from analyzing the oldest parts of three newly completed deep ice cores: the EPICA cores at Dome C and Dronning Maud Land, and the Dome Fuji core (Fig. 1). Much of the new science coming from these cores has relied on advances in dating the cores. The discovery in the Dome C core of signals (in the ^{10}Be concentration) of the Brunhes-Matuyama magnetic reversal some 780 kyr ago gives a very firm anchor to the deepest part of the record. An entire journal special issue (www.clim-past.net/special_issue7.html) devoted to the dating and synchronization of the two EPICA cores shows that this subject is now being treated very seriously; the new EDC3 age scale for Dome C (Parrenin et al., 2007) is much more compatible with the best marine age scales (Lisiecki and Raymo, 2005), making combined studies much more feasible. Use of N_2/O_2 in the gases in ice (Kawamura et al., 2007), which appears to be related to local insolation, has opened up the possibility of absolute age scales that are accurate enough to allow reliable conclusions to be made regarding the phasing of insolation forcing and climate changes.

The water isotope analysis of the Dome C core has now been completed at high resolution and reveals the temperature history of Antarctica back to just beyond 800 kyr (Fig. 2) (Jouzel et al., 2007), confirming that glacial cycles recurred at 100 kyr intervals throughout but with different styles and amplitudes. It has now been shown that every Dansgaard-Oeschger (DO) event in the northern hemisphere appears to have a subdued counterpart in the south (EPICA Community Members, 2006); further improvements in the definition of the phasing between northern and southern records are still needed but this result is highly suggestive of ocean heat transport as the main player in these changes. The pattern of climate variability seen in each glacial cycle strongly suggests that DO events occurred in earlier glacial periods (Jouzel et al., 2007). Chemical records (Wolff et al., 2006) covering the EPICA Dome C period open up the possibility of assessing the causes of climate change through a range of environmental parameters, since the chemical signals provide information about, for example, South American climate, aerosol concentrations, inputs for iron fertilization, sea-ice extent and marine productivity.

Ongoing projects and future plans

The brief summary above omits numerous interesting data sets, analytical developments and interpretative improvements. Further progress will also come from a number of projects that are currently underway. The US West Antarctic Ice Sheet (WAIS) Divide ice core (Fig. 1) is intended to provide a high-resolution (comparable to Greenland) record of the last glacial cycle in West Antarctica; this should be a particularly good core for assessing the phasing between north and south and between climate and CO_2. The camp construction and pilot hole were completed in 2006/07 and the core should be drilled in the next 3 seasons. Meanwhile, other sites have progressed and contribute to a spatial network of cores covering a similar period. At Berkner Island (Fig. 1), sand was collected from the cold base of the ice sheet in 2005/06 and 948 m of ice is now being processed. This core is revealing both the climate and the ice sheet configuration in the Weddell Sea sector of Antarctica. Meanwhile, drilling is continuing at Talos Dome in Victoria Land, from the depth of 1300 m reached in 2006/07 (Fig. 1).

For the future, IPICS (International Partnerships in Ice Core Sciences; www.pages-igbp.org/science/initiatives/ipics/whitepapers.html) has defined a series of 4 priority science projects and associated technical challenges. Of the 3 projects including Antarctica, one has the ambitious aim of reaching still older ice and assessing the climate and trace gas content during 40 kyr climate cycles that preceded the mid-Pleistocene revolution. Other projects aim to construct a network of cores covering the last 40 kyr, to assess the spatial pattern of change during rapid climate events, and a network of cores representing 2 kyr to contribute Antarctic data to climate reconstructions.

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Late Quaternary Antarctic sea-ice history: Evidence from deep-sea sediment records

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In the Southern Ocean, sea-ice (frozen surface seawater) surrounds the Antarctic continent, covering 4.10^6 km^2 in summer and 20.10^6 km^2 in winter (Gloersen et al., 1992). This pronounced seasonal cycle strongly affects the climate of the Southern Hemisphere through its impacts on the energy and gas budget, atmospheric circulation, hydrological cycle and biological productivity. Sea ice also modulates the climate of more remote regions through its impact on deep and intermediate oceanic circulations.

Sea ice is a very dynamic environment and has varied considerably in its extent through time. Whaling ship records (de la Mare, 1997), satellite measurements (Cavalieri et al., 2003) and ice-core data (Curran et al., 2003) indicate that Antarctic sea-ice underwent a dramatic decrease in maximum extent from the 1950's. Acceleration of this reduction, as a result of future global warming, may have important feedbacks on future climate. However, sea ice is still not well computed in climatic models because of its complicated relationship with climate changes over a large range of timescales. One way to ameliorate our understanding of such relationship is to reconstruct sea-ice extent over long and key time periods for which the global climate is known. These reconstructions, started in the early 1980's, are still very sparse in both number and coverage due to the scarcity of good sediment sequences in the Southern Ocean.

Here, we present three records from the Atlantic and Indian sectors of the Southern Ocean that provide information on sea-ice dynamics over the last two climatic cycles. These records have enabled the development of a map of winter and summer sea-ice extent at the Last Glacial Maximum (LGM), documenting sea-ice distribution in a very different global climatic state.

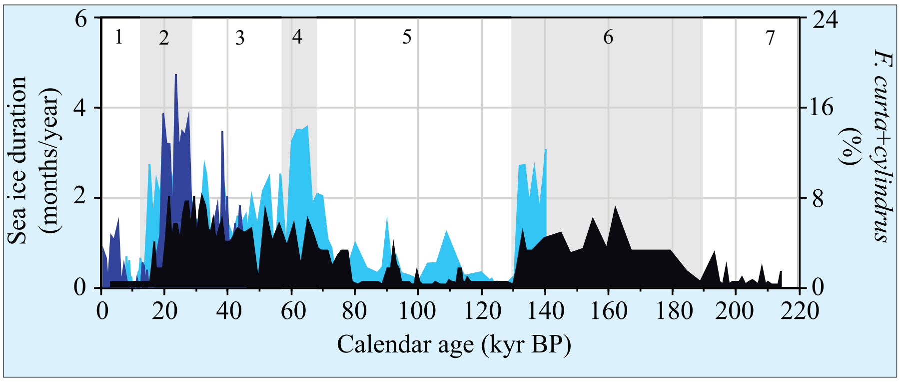

*Figure 1: Sea-ice history over the last 220 kyr BP. Sea-ice duration was estimated by MAT in core SO136-111 from the east Indian sector of the Southern Ocean (**black**) and in core TNO57-13PC4 from the Atlantic Sector of the Southern Ocean (**dark blue**). Sea-ice duration is compared to relative abundances of* F. curta + cylindrus *proxy of sea-ice presence in core PS1768-8 (**light blue**). Core SO136-111 covers the last 220 kyr BP, core TNO57-13PC4 covers the last 40 kyr BP and core PS1768-8 covers the last 140 kyr BP. Odd numbers and white areas represent interglacial stages, while even numbers and shaded areas represent glacial stages.*

Long records

Records of sea-ice extent result almost exclusively from the investigation of fossil diatom assemblages preserved in deep-sea sediments. Some Antarctic species show a strong affinity to sea ice (Horner, 1985) and are, therefore, most useful in estimating paleo sea-ice cover.

Fossil sea-ice diatoms can be used qualitatively to estimate past seasonal sea-ice extent. Abundance of *Fragilariopsis curta* and *F. cylindrus* greater than 3% denotes a recurrent presence of seasonal winter sea ice, while abundance of *F. obliquecostata* greater than 3% denotes the recurrent presence of summer sea ice at the core location (Gersonde and Zielinski, 2000). Increasing abundances of these taxa indicate greater sea-ice cover. Fossil diatoms can also be used quantitatively, based on a statistical treatment of 30 diatom species including sea-ice taxa and open-ocean taxa (Crosta et al., 1998a). The Modern Analogue Technique (MAT) compares the fossil diatom assemblages to a set of core-top diatom assemblages with known modern surface conditions that are subsequently used to attribute the fossil sample with an estimate of sea-ice duration in number of months per year.

Long records of Antarctic sea-ice extent are rare and are to date restricted to the Atlantic and Indian sectors. Three records, one from the east Indian sector (core SO136-111, black curve in Fig. 1), and two from the Atlantic sector (core TNO57-13PC4, dark blue curve in Fig. 1; core PS1768-8, light blue curve in Fig. 1) are presented here. Sea-ice conditions at core locations SO136-111 and TNO57-13PC4 were estimated by MAT (Crosta et al., 2004; Stuut et al., 2004), while winter sea-ice conditions at site PS1768-8 were documented by relative abundances of *F.curta+cylindrus* (Gersonde and Zielinski, 2000).

These three records give a very coherent picture of sea-ice advance and retreat around Antarctica during the Late Quaternary, although the amplitude of sea-ice changes are more important in the Atlantic sector (Fig. 1) in relation to the presence of the Weddell Gyre promoting northward ice transport. The cores are today a few degrees of latitude northward of the winter sea-ice edge (Fig. 2) and were similarly ice-free during other warm periods such as the Marine Isotopic Stages (MIS) 5 and 7. Winter sea-ice extent during these periods was certainly very comparable to today's extent. At interglacial-glacial transitions, sea ice advanced very rapidly to reach its full glacial extent within a few thousand years (Fig. 1). The two longest records (SO136-111 and PS1768-8) indicate that sea-ice conditions were certainly comparable during every glacial stage of the last 220 kyr BP. During glacial-interglacial transitions, sea ice retreated very rapidly—within a few thousand years—to its modern position.

Sea-ice advance and retreat are initiated by variations in atmospheric and oceanic temperature and, due to the very reactive nature of sea ice, reaches full glacial or full interglacial conditions before the completion of the temperature change (Bianchi and Gersonde, 2002; 2004). Conversely, variations in sea-ice cover during full glacial conditions are linked to feedback processes in wind stress and atmospheric temperatures. This finding is also confirmed by investigations of chemical tracers in ice cores (Wolff et al., 2006).

Last Glacial Maximum

In the early 1980's, tremendous effort was applied to reconstruct global conditions of the Earth at the LGM (CLIMAP, 1981). For the Southern Ocean, the effort centered on estimating sea-surface temperatures via a radiolarian-based transfer function, and winter and summer sea-ice limits via a combination of micropaleontological and lithological tracers. According to CLIMAP (1981), the winter sea-ice edge was 5-10° of latitude northward of its modern position, overlying the modern Antarctic Polar Front (Fig. 2), due to colder air and sea-surface temperatures and more intense winds. The winter sea-ice cover at the LGM was, therefore, twice the modern surface. Similarly, the LGM summer sea-ice edge was projected northward of its modern position, overlying the modern winter sea-ice margin (Fig. 2). The summer sea-ice cover was, therefore, 6-7 times greater than modern extent. A huge permanently covered area was estimated, which is likely to have greatly affected the southern hemisphere climate. For example, paleoclimatic models attribute the Southern Ocean with a 70 ppm impact on atmospheric CO_2 out of the 80 ppm drop observed on glacial-interglacial timescale when CLIMAP sea-ice limits are introduced as boundary conditions (Stephens and Keeling, 2000).

The CLIMAP (1981) LGM summer sea-ice extent was quickly found to also represent spring sea-ice extent (Burckle et al., 1982). However, no proxy was calibrated to document summer sea-ice cover until the development of diatom-based transfer function in the late 1990's, which established the relationship between diatoms and surface conditions (Zielinski and Gersonde, 1997; Crosta et al., 1998a). As part of the MARGO initiative (Multiproxy Approach for the Reconstruction of the Glacial Ocean surface), diatom assemblages confirmed a doubling of the winter sea-ice cover at the LGM, mainly due to the progression of the compacted sea ice (Burckle and Mortlock, 1998; Crosta et al., 1998b). The surface covered by sea ice was estimated to be around 43.5 x 10^6 km^2. Conversely, diatom assemblages argue for a more restricted summer sea-ice cover than estimated by CLIMAP (1981), with surfaces around 11 x 10^6 km^2 and 30 x 10^6 km^2 (Fig. 2), respectively. In the Atlantic sector, off the Weddell Sea, the glacial summer sea-ice margin was certainly displaced northward to overlie the modern Antarctic Polar Front (Armand and Leventer, 2003). A similar situation was probably occurring in the western Pacific off the Ross Sea. In the Indian and the eastern Pacific, glacial summer sea-ice cover was certainly comparable to modern conditions prevailing in these sectors. Similar conditions existed in the glacial Northern Hemisphere. LGM winter sea-ice cover was greatly expanded, while summer sea-ice

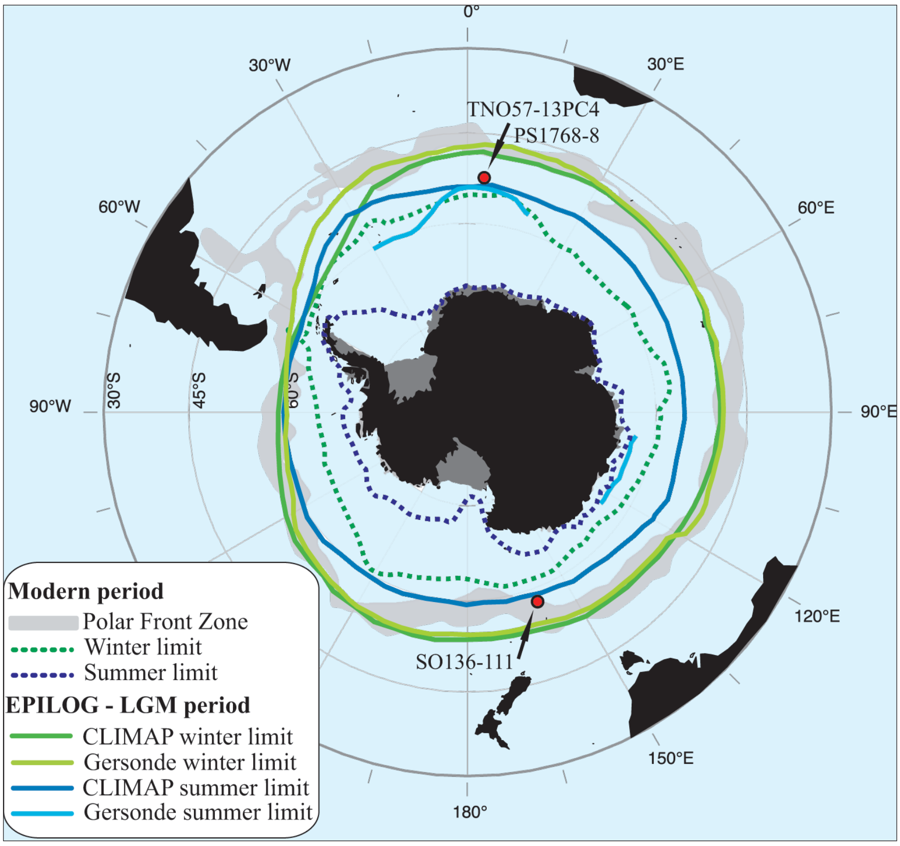

Figure 2: Comparison of LGM winter and summer sea-ice edge reconstructions by CLIMAP (1981) and Gersonde et al. (2005) with modern winter and summer sea-ice edges (Schweitzer, 1995).

cover was comparable to today (de Vernal and Hillaire-Marcel, 2000). Paleoclimatic models estimate a 5-30 ppm impact of Antarctic sea-ice cover on the glacial atmospheric CO_2 drop when diatom-based sea-ice extent and concentration data are used as boundary conditions (Morales-Maqueda and Rahmstorf, 2002; Bopp et al., 2003). Although Antarctic sea ice and, more globally the Southern Ocean, is certainly a key component in regulating atmospheric CO_2 variations and, therefore, climate changes, it cannot alone explain glacial-interglacial changes in pCO_2 that are rather dependant upon the feedback of several components of the internal climatic system.

Conclusion

Despite its importance in global climate changes, Antarctic sea-ice extent during the Late Quaternary has been rarely documented, partly because few proxies are developed to estimate sea-ice past conditions and partly because of the lack of good sediment records. This is particularly true for the Pacific sector of the Southern Ocean. In comparison to the Northern Hemisphere, very few micro-organisms are abundant and well preserved in Southern Ocean sediments. From the oceanic perspective, diatoms are the ultimate reconstructive tool. Chemical tracers preserved in ice cores give additional information from the atmospheric perspective (Wolff et al., 2006). The combination of geological and glacial records will greatly improve our knowledge on paleo sea-ice dynamics, which is of great importance in paleoclimatic models. New geochemical proxies, such as the highly branched isoprenoids (Johns et al., 1999) may emerge in the future. However, this tool is today restricted to coastal Antarctic areas where concentrations in the sediment are sufficiently high.

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Long records of climate in southern Australasia

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Australia, being an arid continent, suffers from a lack of long, well-dated records that can accurately document climate change. Most of our records are fragmentary, like lake shorelines or moraines, or can be difficult to decipher, like pollen records. Our approach has been to turn to the oceans that surround Australia and New Zealand to provide quality records of climate change through time. Marine records are more continuous, easier to date, and temperature change is easier to quantify. Additionally, wind and water transport evidence of changing climates from the continent into the ocean, to be preserved in these deep-sea sediments. The juxtaposition of continental and marine sediments provides a Rosetta Stone from which to interpret undated or ambiguous terrestrial records nearby.

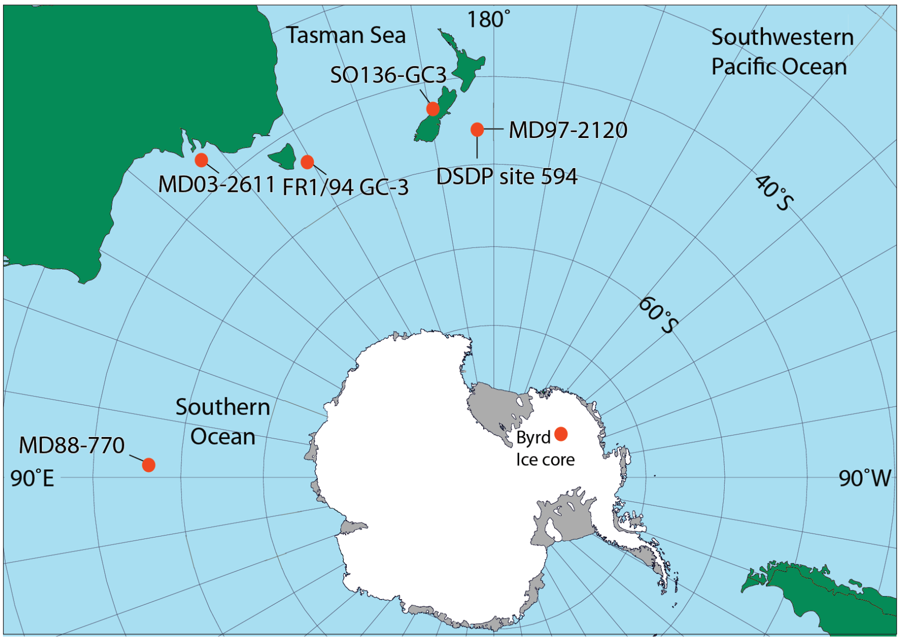

Figure 1: Map showing localities referred to in the text.

In our most recent paper (Barrows et al., 2007), four cores (SO136-GC3, DSDP site 594, MD88-770, MD97-2120) were selected from around the mid-latitude southern margins of Australia and New Zealand (Fig. 1) to benchmark sea-surface temperature (SST) variations over the last 150 kyrs. Published records of terrestrial climate change are available for three of these cores. DSDP site 594 contains a pollen record (Heusser and Van de Geer, 1994) and a clastic record of glaciation from the South Island of New Zealand (Nelson et al., 1993). Both MD88-770 and MD97-2120 contain sediment records from a mixture of sources. To provide an absolute timescale, the oxygen isotope records from each core were matched with North Atlantic Ocean core MD95-2042 on the GISP2 ice core timescale (Shackleton et al., 2004). This permits us to make comparisons between the records and the timing of orbital variations without being constrained by an orbitally tuned chronology.

We gathered SST data for each core for the last glacial cycle. For our new core, SO136-GC3, we counted planktonic foraminifera and estimated SST using three independent approaches with a new core top database (Barrows and Juggins, 2005). We also used this approach to standardize the SST estimates using foraminifera data (Labeyrie et al., 1996; Weaver et al., 1998; Wells and Okada, 1997) from DSDP site 594 and MD88-770. For MD97-2120, existing Mg/Ca SST estimates (Pahnke et al., 2003) were used. Finally, we stacked the two best records from MD88-770 and MD97-2120 to estimate average SST of the Southern Ocean (Fig. 2).

We found that there are obvious similarities between the SST records and the terrestrial records of climate change. Both glaciation on land and changes in vegetation occur in tandem with SST change, signifying a close link between the marine and terrestrial realms. When the timing of SST fluctuations in the SST stack is compared with the timing of changes in midsummer insolation at 65°N, it was found that they agree within error without systematic leads or lags. This supports the idea that the beat of long-term climate change is driven from the northern hemisphere, and that insolation changes in the southern hemisphere are of secondary importance. The matches also occur for the terrestrial records in the cores. The SST records (the lower latitude ones in particular) bear a strong resemblance to ice core carbon dioxide records and have a high correlation with those records. It seems likely then that greenhouse gas changes are the prime candidate for synchronizing southern and northern hemisphere records.

The matches between the proxy climate records and orbital variations are poorest during glacial periods when variations on the suborbital timescale dominate. These variations cannot be explained by orbital theory and are most pronounced in the southern-most cores during periods of high ice volume (Fig. 2). The four most prominent warming peaks in Oxygen Isotope Chronozone 3 occur about 6-7 kyr apart, at almost the same time as the A1-A4 events in the Antarctic Byrd ice core (Blunier and Brook, 2001). Similar features also occur in the terrestrial records, meaning they are widespread phenomena in the Australasian sector of the southern hemisphere. When compared to similar events in Greenland ice (Fig. 2), the warming before these southern hemisphere SST events, and the events themselves, occur shortly before their contemporaries in the northern hemisphere. This lead is what would be expected with a bipolar seesaw operating between the hemispheres (Broecker, 1998).

The other aspect of the millennial timescale climate change is the speed at which it occurs. Warming in the Southern Ocean core (MD88-770) by as much as 5-6°C occurs in less than 200 years. Cooling is only slightly slower than this. The record of glacier extent in DSDP site 594 mirrors these changes, indicating the rapid temperature change is also felt at the same time on land. Similarly, forest expansion according to the pollen record is very rapid at the start of interglacials as the ocean warms up quickly and glaciers retreat. The synchrony over the region indicates a common cause for climate change and close meteorological links between land and sea.

As part of an ongoing effort at the Australian National University, we are looking to other cores to further characterize long-term climate change in the Australasian region, and to better date and quantify terrestrial climate records. In particular, we

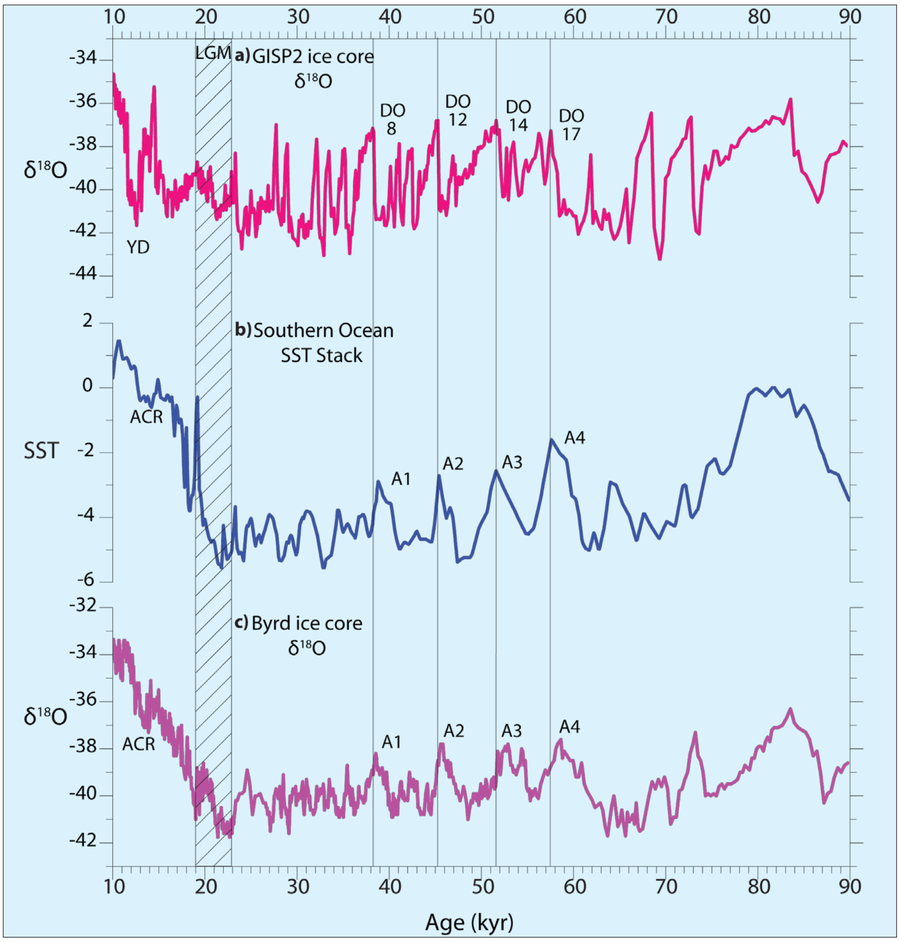

*Figure 2: **a**) Comparison between the GISP 2 oxygen isotope record (Grootes et al., 1993) on the Meese et al. (1997) timescale; **b**) Southern Ocean SST stack; and **c**) Byrd ice core oxygen isotope record (Johnsen et al., 1972) on the Blunier and Brook (2001) GISP2 timescale. Note the similar shape shared by the two southern records compared to the northern one. LGM=last glacial maximum (19 –23 kyr), ACR =Antarctic Cold Reversal, YD= Younger Dryas Chronozone cooling event. From Barrows et al. (2007).*

are studying two cores with high sedimentation rates offshore of the mouth of the Murray River, which drains part of the vast Murray-Darling Basin ($\sim 1.10^6$ km^2). These cores (especially MD03-2611) promise to provide a link between difficult-to-date aeolian deposits on land and aeolian dust deposited offshore (Gingele et al., 2004, 2007). Preliminary results from FR1/94-GC3 offshore from Tasmania—spanning the last 450 kyr—provide an SST record that clearly points to a progressive warming of glacial periods through time (Pelejero et al., 2006). Work is continuing on this core to develop a higher resolution SST record from planktonic foraminifera and to complete a pollen record that will allow us to study vegetation changes in Tasmania over the last half a million years.

Clearly, climate change is more complicated in the southern hemisphere than originally thought. Although we march to the beat of the same drum as the northern hemisphere, over timescales greater than 20 kyr, regional climate in the southern hemisphere has its own melody.

Note

A full list of references to the data referred to above can be found in Barrows et al. (2007). The above research contributes to the PASH2 project. Dates from this paper can be obtained from the World Data Center-A for Paleoclimatology.

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Dynamic Antarctic Ice: Agent for Mid-Pleistocene Transition

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In the record of Plio-Pleistocene climatic evolution, the Antarctic Ice Sheet is generally seen as a passive response to global change, rather than an active agent in its own right. While changes in global relief, particularly the uplift of the Qinghai-Tibet Plateau, are accepted as major drivers into cold, full-glacial 100 kyr cycles (Ruddiman and Kutzbach, 1989; An et al., 2001), the potential influence of change in the Antarctic ice cap has largely escaped attention. The southern Australian coastline, facing the Antarctic continent with some 3000 km of unbroken fetch, is ideally placed to record changes in Southern Ocean dynamics. As the pattern of travelling cyclonic depressions that control the westerly flow across southern Australia reflects steep thermal gradients around the Antarctic margin, the winds and wave regimes impacting southern Australia can be linked to thermal conditions at the Antarctic margin. Changes in one of these systems imply correlative changes in the other. Here, we argue that evidence for dramatic mid-Pleistocene change in Southern Ocean dynamics is present in a remarkable succession of stranded shorelines in the Murray Basin in southeastern Australia, that provides a more-or-less complete record of paleoshorelines deposited over the last 6 Myr (Fig.1a).

The Murray Basin record

Situated in a relatively stable context, the Murray Basin has acted as an epeiric (epicontinental) sea controlled by the Southern Ocean for some 40 Myr. A mid-Miocene regression (12-7 Myr) was followed by an Upper Miocene transgression (6.5-6 Myr) with the maximum late Neogene marine incursion typically extending inland to heights ~60 m above present day sea level (Brown and Stephenson, 1991). Regression from Upper Miocene through Pliocene to present time has left more than 170 shore parallel strandline ridges extending from 500 km inland from the present coast near Naracoorte (Fig. 1b,c). For some 200 km

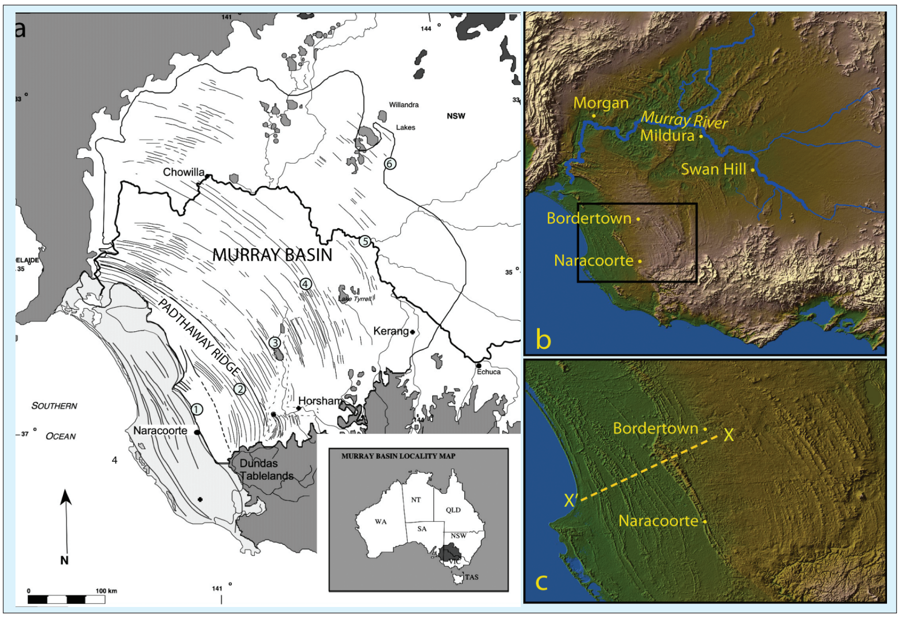

*Figure 1: **a**) Extent of Upper Miocene marine invasion in the Murray Basin, southeastern Australia. Multiple strandline ridges represent legacy of Plio-Pleistocene marine regression falling from near 60 m to present sea level. The Padthaway Ridge controlled early Pleistocene levels on a rising platform with successive interglacial levels separated laterally on uplifted platform (modified from Kotsonis, 1999). Numbers 1 to 6 represent estimated position of coastline 1-6 Ma; **b**) Shaded relief image of the Murray Basin derived from the Shuttle Radar (SRTM) 3 arcsecond topographic data. The green to brown colour transition defines the 60 m contour and corresponds to the former extent of a Plio-Pleistocene lake (Lake Bungunnia) formed by tectonic depression following retreat of the sea; **c**) Detail of the area of transition between inland Parilla siliceous strandlines and the calcarenite beach ridges of Mid-Pleistocene age near Naracoorte. For detail, see Fig. 2.*

inland of Naracoorte, gentle uplift on the NW-SE trending Padthaway Ridge (Fig. 1a), simultaneous with coastal retreat, has separated younger ridges and uplifted older ones (Fig. 1c). At Naracoorte, ridges dated to near the Brunhes-Matuyama boundary (780 kyr) now lie at +70 m, evidencing uplift at ~60 m/Myr (Murray-Wallace et al., 2001).

The ~6 Myr record of retreating coastlines across the Murray Basin strandplain preserves two distinctive sedimentary associations. The older Pliocene sequence of siliceous near-shore sands of the Parilla Formation grade offshore into shallow-water fossiliferous marls of the Bookpurnong Formation (Brown and Stephenson, 1991). The differential elevation between near-shore sands and offshore marls provides a measure of wave-base that rarely exceeds 40-50 m. By contrast, modern storm waves with periodicity in the 12-14 s range are characterized by a wave-base in excess of 100 m depth. The younger Pleistocene sequence of shorelines is reflected in large calcarenite back-beach linear dunes of the Bridgwater Formation, and associated downwind parabolic dune fields, both of which continue to deposit along southwest facing ocean beaches to this day. The changes in shoreline facies, from the lower energy siliceous Parilla Sands to calcarenite ridges of the Bridgewater Formation, occur in the Bordertown-Naracoorte area, and bear witness to a major change in Southern Ocean wind-wave regimes. Intriguingly, the modern interglacial regime is characterized by much higher energy circulation systems than are typical of the Pliocene, and is thus more closely related to those of the Pleistocene windy world. But precisely when and how did that change come about?

The zone between Naracoorte and the present coast preserves some 8 interglacial barriers developed on the rising southern limb of the Padthaway dome, with a clear reflection of 100 kyr cyclicity. Inland, the presence of more than 170 Parilla sand ridges formed within the 6-2 Myr period reflects a strong 20 kyr precessional signal. Between Naracoorte to Bordertown, some 5 younger calcarenite ridges, with spacing intermediate between older ~20 kyr strandlines and younger, more widely separated 100 kyr ridges, plausibly reflects a ~40 kyr obliquity cyclicity. In the isotope curve, the sequence seawards of Naracoorte under chronological control, has been reliably correlated with isotope stages to MIS 25. Inland from Naracoorte East, correlation of younger Bridgewater Formation ridges is based on direct peak-to-peak estimates. The presence of 5 older ridges involves correlation with strong interglacial peaks immediately preceding MIS 25. This would place ages of oldest Bridgewater Formation ridges within the range MIS 43-47 near 1.3-1.4 Myr. This estimate, together with intermediate spacing between ridges, is consistent with dominant 40 kyr controls in both data sets at this time (Fig. 2).

The mid-Pleistocene transition

The onset of Bridgewater facies in the 1.3-1.4 Myr time range poses significant questions for the mid-Pleistocene 100 kyr transition (MPT). The appearance of distinctive calcarenite facies involving an abrupt increase in wave-base with associated shelf abrasion reflects a significant increase in controlling Southern Ocean wind and wave regimes. With Australia's coastal climate so closely tied to high latitude thermal gradients, any major change in controlling Southern Ocean pressure systems points to a change in those controlling regimes; changes that almost certainly involved dynamics of the Antarctic ice cap.

The following interpretation of events is proffered: oscillating patterns on a progressively falling Murray Basin sea level with equivalent isotope reflection defines progressive but oscillatory Pliocene growth of Antarctic ice under warmer and, presumably, wetter conditions than prevail today. After sea level stabilized near present interglacial levels by 2.5 Myr, northern hemisphere ice controlled major changes; Antarctica remained relatively stable in terms of total ice volume. The subsequent transition to a base frozen ice sheet, with development of a sea-ice girdle, leaves virtually no signature in the eustatic record, but enhances surrounding thermal gradients and leads to changes in Southern Ocean dynamics. The increased coastal energy reflected in the transition from Parilla to Bridgewater thereby points directly to amplified cooling in the circum-Antarctic region.

Significantly, this change precedes the MPT by some 300-400 kyr. Once established, such amplified cooling offers two effects. Firstly, it strengthens the control of ~41 kyr obliquity signal by effectively dampening weaker precessional effects. Secondly, by acting in the new role as a global thermostat, the now super-cold ice cap also becomes capable of dampening the power of obliquity insolation to full interglacial levels. This process would effectively favor development of 100 ka cycles, a process anticipated by Ruddiman's (2003) hypothesis for the explanation of the MPT.

The Murray Basin evidence points directly to the role of a highly dynamic ice cap controlling elements of both sea level and climatic evolution, not only in this region of the Southern Ocean but with implications of wider global significance. Far from a simple passive response to global change, it suggests that the Antarctic ice cap has played a much more active role than previously recognized. Improved

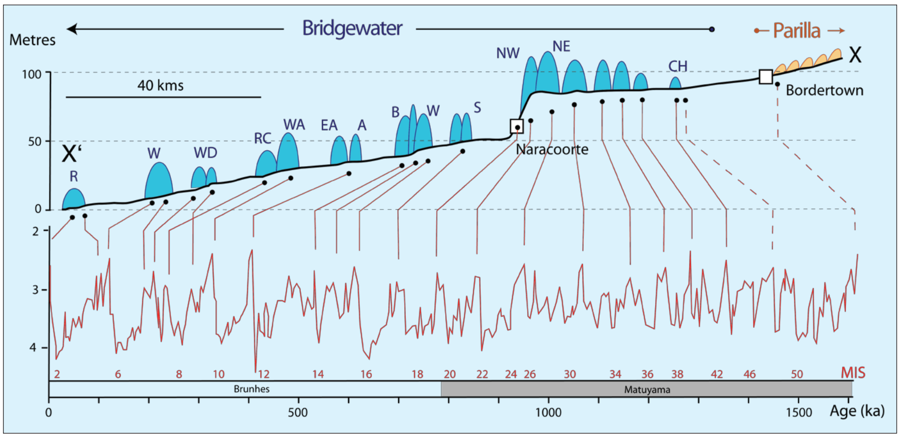

Figure 2: Correlation of the strandline-coastal ridge system (along profile line X'-X in Fig. 1c from near Kingston via Naracoorte to Bordertown) with marine isotopic interglacial peaks based on the chronology of Tian et al., 2002. Ridge sequence and isotope correlation, Naracoorte to coast from Murray-Wallace et al., 2001. The age of the oldest Bridgewater ridge is tentatively correlated with isotope stages 43 or 47, dated to near 1.3-1.4 Myr ago. Beach-ridge names: (CH) Cannonball Hill, (NE) Naracoorte East, (NW) Naracoorte West, (S) Stewart, (W) Woolumbool, (B) Baker, (A) Ardune, (EA) East Avenue, (WA) West Avenue, (RC) Reedy Creek, (WD) West Diary, (W) Woakwine, (R) Robe (Murray-Wallace et al., 2001).

understanding of that role presents new challenges in modeling predictions of future greenhouse responses.

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NZ-Maars: Extracting high resolution paleoclimate records from maar crater lakes, Auckland, New Zealand

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Introduction

An understanding of the mechanics of past climate change is a powerful tool for managing the consequences of present and future climate variability. However, the high-resolution records of climate change needed to determine the forces driving this variability are typically limited to the duration of the instrumental record. The short duration of that record in New Zealand (little more than 100 years) means that we have limited insight into the operation of the climate system under earlier and different climate scenarios, so that we need to use geological data sets to reconstruct past climates (Shulmeister et al., 2006). However, most geological datasets have a resolution of millennia to centuries at best, too coarse for integration with climate systems operating on timescales of months to decades. Hence, the NZ-Maar project was established to exploit the high-resolution paleoclimate records contained in laminated maar lake sediment sequences from Auckland, northern New Zealand (Fig. 1).

The Auckland region has a dense cluster of about 48 basaltic volcanoes, mostly tuff rings and scoriaceous cinder cones, all within Auckland City, New Zealand's largest and most densely populated center (Fig. 1). In addition, there are a number of maar craters, each of which has been a lake some time after its formative eruption, and several of which have been cored to extract records of sedimentation and

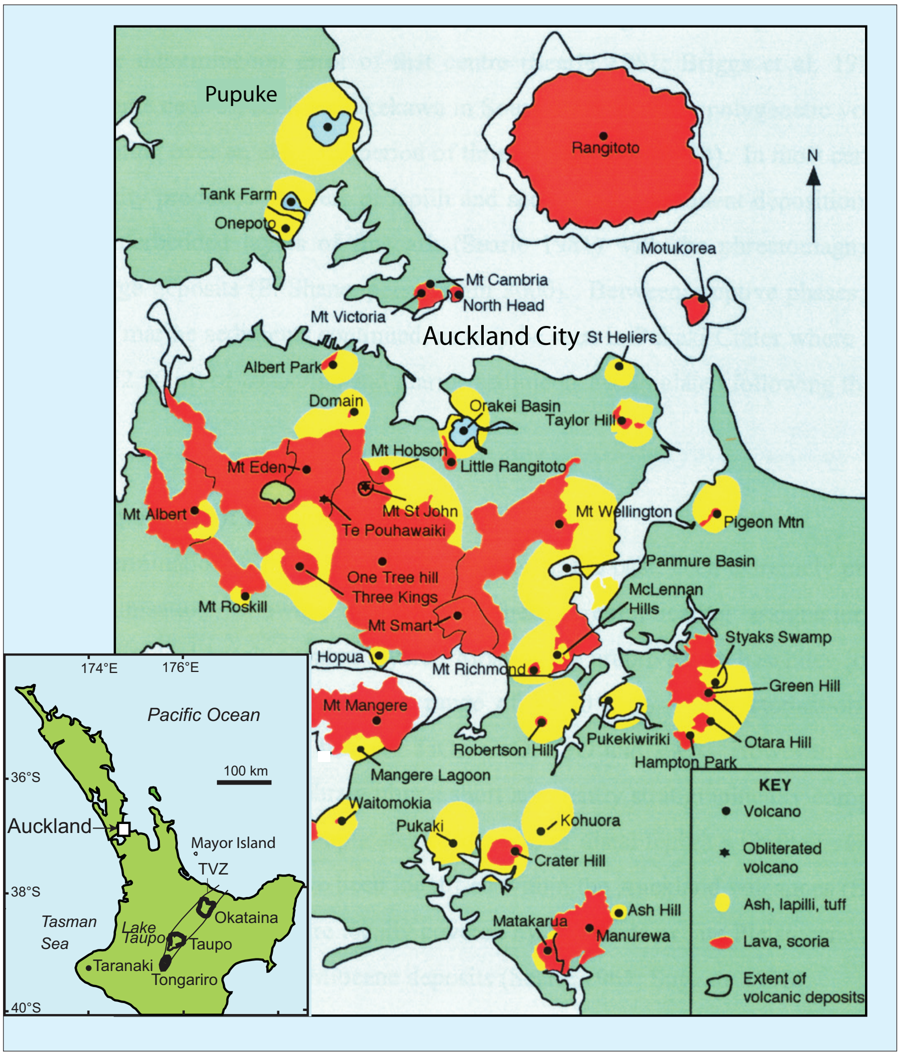

*Figure 1: Location map showing Auckland basaltic cones and maar craters. **Inset** andesitic and rhyolitic tephra sources and volcanic setting of study area (TVZ - Taupo Volcanic Zone) (modified from Alloway et al., 2007).*

paleoenvironments extending back to at least 245 kyr BP. (e.g., Shane and Hoverd, 2002; Horrocks et al., 2005). The Auckland region of northern New Zealand is important in a paleoenvironmental context since it forms an ecological boundary between the far northern North Island and cooler regions to the south.

Aims

The major goal of the NZ-Maar project is to increase our knowledge of the behavior of the New Zealand climate system over the last 50 kyr. This knowledge will be used to contribute to the understanding of climate teleconnections between the northern and southern hemispheres during glaciations, with a focus on abrupt climate change events and long-term variability in global oscillatory climate systems (e.g., El Niño Southern Oscillation: ENSO, and Pacific Decadal Oscillation: PDO). As subsidiary goals, the research is also contributing to the development of paleoclimate proxies and their application to New Zealand data, as well as resolving issues regarding the timing, nature and impacts of volcanic eruptive events in Auckland, the Taupo Volcanic Zone (TVZ) and Mt Taranaki.

Methods

The Auckland maar lake sequences contain numerous chemical and biological markers from which a variety of high-resolution ecological and climatological information is being derived. A multi-proxy approach to reconstructing the past environments is being undertaken using: pollen, diatom and chironomid paleoecology; oxygen isotope analysis of diatom silica and sponge spicules and cellulose extracted from lake sediments; carbon and hydrogen isotope analysis of lipid biomarkers; high-resolution elemental geochemistry, and; laminae thickness and facies analysis. Furthermore, the maar lakes received fallout tephra, many of which are well-dated and chemically distinguishable, providing robust age control for the records of climate change they contain (Shane and Hoverd, 2002). In addition, the Auckland maar lakes sometimes demonstrate annual-to-decadal resolution in their laminae and provide a record that details short-duration climate changes as well as long-term trends (Pepper et al., 2004; Shulmeister et al., 2006). The combination of reliable dating tools and proxies of change gives us the ability to determine the exact timing, duration and nature of all of the major climate events to impact northern New Zealand in the past 50 kyr (the limit of reliable tephra and ^{14}C ages).

Results and discussion

Pupuke (the only crater that contains a lake at present), Onepoto, Pukaki, Hopua and Orakei maar craters (Fig. 1) provide excellent late Quaternary tephra and multi-proxy paleoenvironmental records. The rhyolitic and andesitic marker tephra are sourced from the Taupo Volcanic Zone and Mt Taranaki (Fig. 1) and enable stratigraphic correlation between the maar lake sediment sequences, allowing confident identification of coeval changes in the proxies studied at each site. At the younger end of the Pupuke maar lake sequence, ^{210}Pb dating, combined with known-age chemical markers and first appearance of exotic *Pinus* pollen, have provided a well-dated, high-resolution paleoenvironmental record for the past 200 yr covering the entire period of European settlement on the Auckland Isthmus (Augustinus et al., 2006). We have acquired a complete laminated ca. 50 kyr long record from Lake Pupuke (average sedimentation rate 0.35 mm/yr, increasing to 4.5 mm/yr over the past 190 years), which can be correlated directly using marker tephra to the lower resolution Onepoto maar paleolake record (0.13 mm/yr) that extends from 9 cal kyr BP back to ca. 245 kyr BP (Shane and Hoverd, 2002). We recently analyzed another long lake sediment record extending from 14.7 cal kyr BP to ca. 100 kyr from Orakei maar paleolake at a higher resolution of ca. 1 mm/yr.

The Last Glacial Cold Period (LGCP) to early Holocene sequences from Auckland maar lakes provide probably the highest resolution and best-dated terrestrial paleoenvironmental records spanning this period from New Zealand. Selected features of this record as well as one from Pukaki, are shown in Figure 2. There is a close match between the log lowland podocarp grass pollen ratio (LPG), representative of the degree of forest development, from Onepoto and Pukaki maar lakes. These indicate regional LGCP cooling, which commenced ca. 27.5 cal kyr BP, followed by three cool intervals separated by brief milder intervals. δ^{13}C enrichment in the lake sediment organic matter during the LGCP was largely caused by superimposed changes in atmospheric pCO_2 and climatically-induced water stress. This evidence for drier conditions is supported by coeval increased fire frequency (charcoal peaks) and erosion (clastic sediment inwash). The δ^{13}C depletion, together with the expansion of podocarp forest following the commencement of Termination I at ca. 18 cal kyr BP, reflects climatic amelioration, increased water availability and reduced wind stress. δ^{13}C depletion during the Late Glacial-Interglacial Transition mainly reflects increased algal productivity in Onepoto maar lake during the Early Holocene Warm Period, previously identified in several New Zealand paleoclimate records (Fig. 2; Alloway et al., 2007). The Late Glacial Climate Reversal (Fig. 2; Alloway et al., 2007) may be reflected in a brief period of δ^{13}C depletion at ca. 13 cal kyr BP, although the Auckland maar lake pollen record is equivocal in this regard.

Termination I occurred ca. 18 cal kyr BP in the multi-proxy Auckland maar lake sequences, as well as many other New Zealand and Antarctic ice core proxy records (Fig. 2; Alloway et al., 2007). Furthermore,

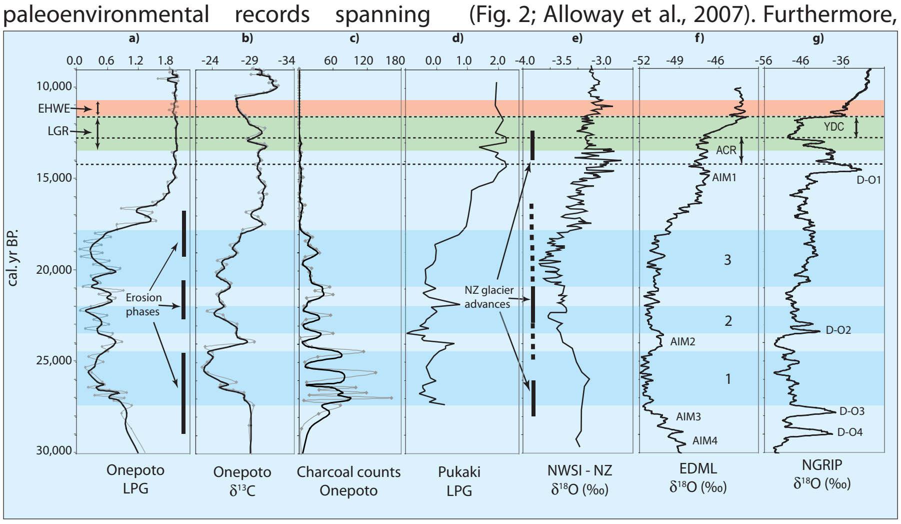

*Figure 2: Comparison of trends in Onepoto maar lake proxies with other proxy paleoclimate data from New Zealand and from Antarctica and Greenland spanning ca. 30 - 9 cal. kyr BP.; **a,b**) Log podocarp/grass pollen ratio (LPG) and organic matter δ^{13}C records from Onepoto maar lake. Erosion phases inferred in the Onepoto maar record from grain size and elemental geochemistry (Augustinus, unpub data); **c**) Charcoal counts from Onepoto maar lake; **d**) LPG record from Pukaki maar lake (Alloway et al., 2007); **e**) New Zealand speleothem composite record from the northwest of the South Island (NWSI) (Alloway et al., 2007); **f**) EPICA Dronning Maud Land δ^{18}O record showing the Antarctic Cold Reversal (ACR) and Antarctic Isotope Maxima (AIM) 1 to 4 (EPICA Community Members, 2006); **g**) NGRIP δ^{18}O record showing the Younger Dryas Chronozone (YDC) and Dansgaard-Oeschger Events (D-O) 1 to 4 (NGRIP Members, 2004). Horizontal blue bars labelled 1 to 3 indicate inferred cool phases during the LGCP. Horizontal green and red bars represent the timing of the Lateglacial Reversal (LGR) and Early Holocene Warm Event (EHWE) respectively in New Zealand (Alloway et al., 2007).*

the apparent phase relationship between the Auckland maar lake and Antarctic Isotope Maxima (AIM) warming intervals during the LGCP and their out-of-phase relationship with Greenland ice core Dansgaard-Oeschger events (Fig. 2) provides further support for interhemispheric asynchrony in rapid climate change.

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Five centuries of ENSO history recorded in *Agathis australis* (kauri) tree rings

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Kauri (*Agathis australis* (D. Don) Lindley) is a canopy-emergent conifer endemic to northern New Zealand (north of latitude 38°S). Mature adults can achieve heights of 30 m and trunk diameters over 2 m are not uncommon. Trees often live for more than 600 years, and ages in excess of 1000 years are known (but rare). This longevity, strategic location in the data-deficient southern hemisphere, and an abundance of source material (living trees, logging relics, colonial-era buildings, sub-fossil wood preserved in swamps; Fig. 1), gives kauri considerable potential for paleoclimate applications. All four sources of material have been successfully exploited and an extensive kauri tree-ring database has been developed. This includes data from 17 modern (living tree) sites, collected in the 1980's, late 1990's and early 2000's (Fowler et al., 2004); 16 colonial-era structures and a logging relic, collected since 2001; and numerous sub-fossil assemblages, collected in the 1980's, late 1990's and early 2000's. The combined tree-ring data provide continuous coverage of the past 3700 years (Boswijk et al., 2006) with "floating" sequences of mid-Holocene date indicating the potential to extend the calendar-dated record back further in time. Large quantities of sub-fossil pre-Holocene wood (Palmer et al., 2006) will also enable paleoclimatic analyses for millennial-length windows over much longer time scales.

In the growing season, Kauri growth is enhanced by cool-dry conditions, yet suppressed by warm-wet conditions, particularly in the austral spring (Sep-Oct–Nov; SON). This relationship to climate is fortuitous in terms of El Niño Southern Oscillation (ENSO) reconstruction potential, because such conditions are associated with El Niño and La Niña events, respectively, in the far north of New Zealand. Moreover, the strongest relationships between kauri growth and climate occur during SON, coincident with the peak strength of the teleconnection between ENSO and New Zealand climate. Recognition of these juxtapositions led to the identification of kauri's potential as an ENSO proxy in the 1990's (Fowler et al., 2000) and has been the primary impetus for research undertaken by the University of Auckland Tree-Ring Laboratory ever since. Fowler et al., (2007) summarized the current understanding, derived from that research. They suggest there is a significant regional-scale forcing signal in the width of kauri tree rings and ENSO is the dominant contributor to that forcing. ENSO's influence on kauri growth is predominantly via the western pole of the Southern Oscillation. Wide kauri tree rings tend to be associated with El Niño events (narrow with La Niña), with similar event registration strength. Strongest statistical relationships are for a five-season window from March, prior to growth initiation (in September), through to the following May. Growing season relationships are stronger when ENSO is most active (e.g., early and late 20th century), but otherwise

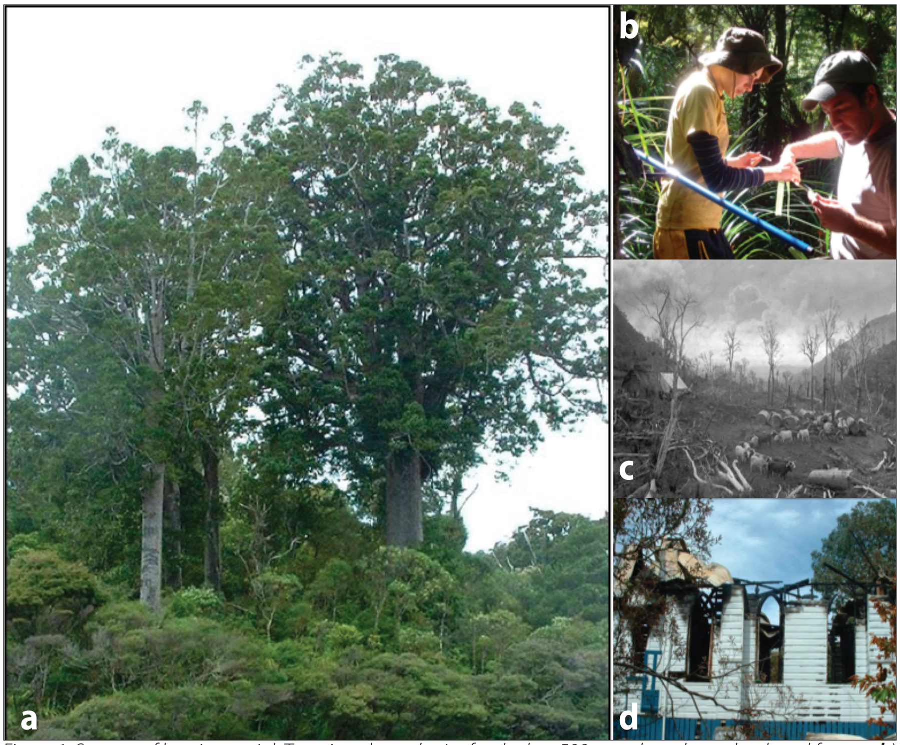

*Figure 1: Sources of kauri material. Tree-ring chronologies for the last 500 years have been developed from: **a,b**) living trees; **c**) a few logging relics (picture courtesy of Auckland Museum Collection); and **d,e**) from colonial-era building timbers.*

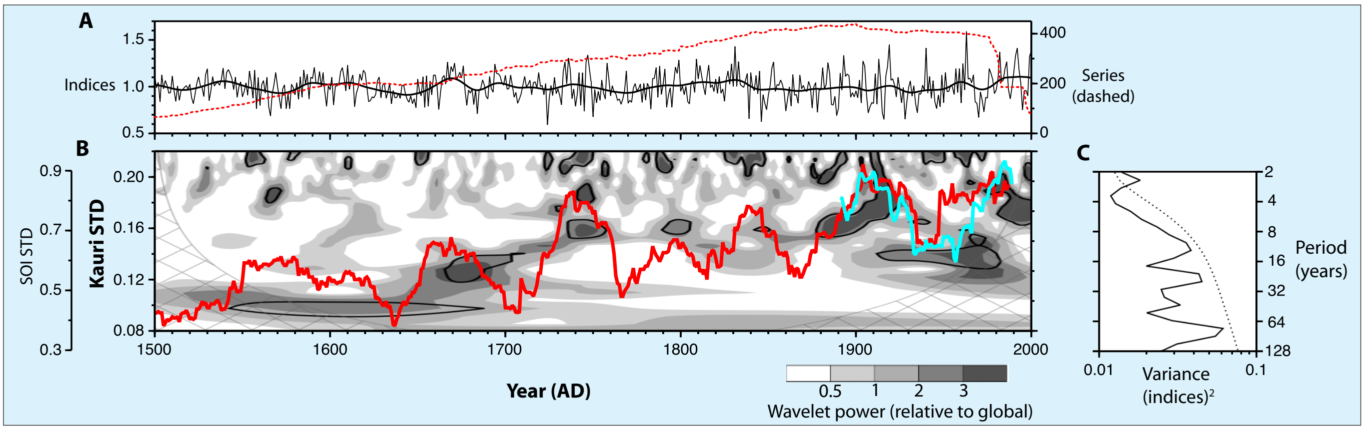

*Figure 2: Kauri master chronology and associated analyses indicating 500 ry of evolving ENSO activity: **A**) Composite kauri master chronology built by combining archeological timbers and samples from living trees. Sample depth (Series, dashed red line) is the number of radii contributing to the master; **B**) Solid red line is running Standard Deviation (STD) (31-year window) for the kauri master. Blue line is the same for the Southern Oscillation Index (SOI) (July-June mean). Shading is the wavelet power spectrum, derived by Morlet wavelet analysis of the kauri master, using zero padding to reduce wrap around effects. Wavelet power is expressed relative to the global wavelet (shown in c), with significant periodicities (far right scale) enclosed by black lines (significance determined at the 10% level using a red-noise background spectrum); **C**) Global wavelet power spectrum (solid line). Dashed line is the significance for the global wavelet spectrum (same significance level and background spectrum as in b). Wavelet analyses were run using the online wavelet toolkit at http://paos.colorado.edu/research/wavelets (Torrence, C. and G. P. Compo, 1998).*

appear to be stationary at the multi-decadal scale. About half of El Niño events are associated with wide kauri tree rings, with very few opposite associations (likewise for narrow rings and La Niña). Finally, kauri carries a multi-decadal signal of the evolving strength of ENSO activity (robustness) within the evolving variance of kauri master chronologies (derived by pooling data from across kauri's growth range).

Fowler (2007) investigated the potential of evolving kauri master chronology standard deviation (STD) as a proxy for ENSO robustness. Results indicated that evolving STD (31-year moving window) of the kauri master chronology is a robust index of the timing of multi-decadal ENSO activity, although the relative magnitude of that activity needs to be interpreted with caution, especially when sample depth (expressed as number of trees) is less than about 20. Based on these results, evolving STD was used to reconstruct ENSO activity back to AD 1580, with supporting evidence inferred from the occurrence of decadal-scale periodicity features (determined from wavelet analysis). Two key findings were: a) the 20th century was the most active ENSO century in at least the last 400 years, and, b) ENSO activity has been characterized by 50-80 year cyclicity in phases of relative robustness.

To extend our ENSO reconstruction prior to AD 1580, a new kauri master chronology was developed by combining archeological data with the living tree data set (Fig. 1). The increase in sample depth markedly improved the statistical quality of the kauri master chronology prior to AD 1700, and particularly prior to AD 1600. Here, we update the Fowler (2007) results, extending the ENSO reconstruction to AD 1500. Our methods essentially duplicate those described in detail in Fowler et al. (2007) and Fowler (2007), including the key pre-processing step of standardizing each series by dividing ring-width values by a fitted low pass filter (spline curve with 50% frequency response at 200 yr). However, because the archeological timbers derive from unknown trees, the master chronology was built by combining individual radii, rather than first producing tree means from same-tree radii and then averaging these.

A notable feature of the kauri master chronology (Fig. 2A) is the trend towards increasing variance from the 16th to 20th centuries. Although this appears to follow the trend in sample depth, we have no reason to believe that this is a sampling artifact—indeed variance would be expected to decrease with increasing sample depth. Monte Carlo resampling of the period of high sample depth in the 19th to mid-20th centuries indicates that this assumption is reasonable and that variance changes associated with a range of 65-439 data series are minor. The 31-year running STD (Fig. 2B) shows the centennial-scale increase in variance over the last 500 kyr, but with a superimposed multidecadal pattern of similar magnitude. Note the similar multi-decadal variance change in the comparable analysis of the Southern Oscillation Index. The underlying wavelet power spectrum shows strong coincidence between kauri STD peaks and periods of relatively strong inter-annual to decadal-scale periodicities. Based on our interpretation of high kauri STD as indicative of robust ENSO (especially when combined with strong periodicities), this suggests that ENSO was relatively quiescent in the 16th and 17th centuries, that there was pronounced ENSO activity centered around 1740, and that the 20th century was the most active in 500 yr.

A number of caveats should be made with the above interpretation. For example, the north of New Zealand is outside the ENSO tropical core zone and subject to other forcing factors. Although ENSO forcing is dominant, other factors must also be influential—so some of the changes in variance in Figure 1 may be un-related to ENSO. Moreover, our interpretation implicitly assumes that the observed 20th century teleconnection is stationary. Finally, ENSO is a highly complex phenomenon and inferring evolving ENSO behavior based on a single proxy is always going to be problematic (especially when that proxy derives from a remote teleconnection region). Multi-proxy research is the obvious next step, at least for the latter half of the millennium, when several other proxy records (e.g., coral, other tree-rings, historical archives) are available. We hope that the kauri data set will be a valuable contribution to such research.

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Linkages between southern hemisphere westerlies and hydrological changes in semi-arid Patagonia during the last 16,000 years

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Sediment cores from the 100-m-deep maar lake Laguna Potrok Aike (52°S, 113 m asl, diameter 3.5 km, Fig. 1) demonstrate that this lake provides a unique record of paleoenvironmental variability. It is located in the dry steppe of southern Patagonia (ca. 200 mm annual precipitation), an area with hitherto scarce paleoenvironmental information. Amongst other proxies, titanium (Ti) and total inorganic carbon (TIC) were identified to reflect hydrological changes (Haberzettl et al., 2005). Precipitating preferentially during lake level recessions and low stands, TIC can be used as an indicator of the evaporation-inflow-ratio and hence as a lake level proxy. Ti is a measure of fluvial input (minerogenic matter) and strongly related to precipitation. Comparing the sedimentary proxy records of Laguna Potrok Aike to radiocarbon-dated lake levels from seismic data demonstrated a close correlation. This is especially evident for the Little Ice Age, the Medieval Climate Anomaly and the Mid-Holocene Optimum (Haberzettl et al., 2005, 2007, in press). Here, we present a new compilation for the long sediment record from the center of the lake (Fig. 1) to demonstrate that west wind variability played a major role in hydrological changes within Patagonia over the last 16 kyr.

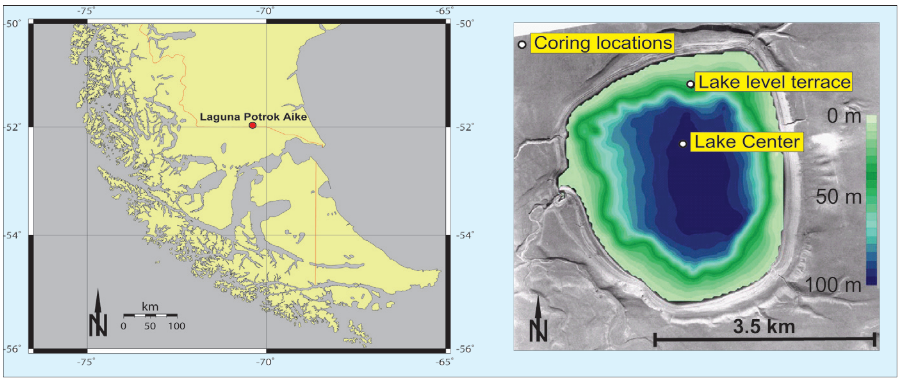

Figure 1: Research area and bathymetry of Laguna Potrok Aike with positions of sediment cores.

Hydrological variations and west wind variability

Interpreting low TIC concentrations during the late glacial as an indication of low ionic concentrations and primary productivity, the lake level of Laguna Potrok Aike was high from 16–13.2 cal kyr BP (Fig. 2). Yet, low values for Ti seem to contradict this proposal of a humid late glacial in this region. However, increased organic matter deposition and preservation (represented by total organic carbon (TOC) Fig. 2) during that period probably diluted the minerogenic sediment fraction. From 13.2–11.4 cal kyr BP the lake level was lower. The occurrence of the green alga *Phacotus lenticularis* between 12.8 and 11.4 cal kyr BP suggests also that surface water temperatures were warmer during this lowstand (Schlegel et al., 2000). The occurrence of *Phacotus* is approximately contemporary to the northern hemisphere Younger Dryas chronozone. Thereafter, TIC-inferred lake levels rose again and remained high until 8.65 cal kyr BP (Fig. 2). At this time drastic hydrological changes occurred at Laguna Potrok Aike. The lake receded to the hitherto lowest known level ca. 30 m below the present surface, creating a lake-level terrace with a seismically detected and radiocarbon-dated unconformity (Haberzettl et al., in press). A sediment core taken from that terrace (Fig. 1) showed undisturbed and continuous sedimentation from 6.75 cal kyr BP onward, manifesting a lake level rise. After 6.75 cal kyr BP, proxies imply that the lake level varied in response to an alternation of humid and dry periods, but never dropped to the former lake level low stand of -30 m. The last humid period, ascribed to the Little Ice Age, appeared to have been the temporally most extended humid period since the early Holocene lake-level highstands prior to 8.65 cal kyr BP (Fig. 2, Haberzettl et al., 2007).

The hydrological variability during the Holocene can at least partially be ascribed to variations in the intensity of the southern hemisphere westerlies (Mayr et al., 2007; Wille et al., 2007). Changes in west wind intensity are documented in the sediment record of Laguna Potrok Aike by variable pollen input of Andean forest taxa (AFT), which consist mainly of pollen from the southern beech (*Nothofagus*). Pollen is transported by westerly winds from the moister Andean forest habitats to the semi-arid steppe region around Laguna Potrok Aike (Wille et al., 2007). Low tree pollen concentrations during the late glacial are probably due to the lack of extensive forests. Hence, the Holocene pollen record (i.e., since ca. 11.6 cal kyr BP, Fig. 2) mainly reflects changes in the intensity of westerly winds, a feature consistent with the interpretation of pollen records further to the west (Mayr et al., 2007). The coincidence of generally higher TIC concentrations, low Ti values and an increased input of AFT to the sediments since 8.65 cal kyr BP (Fig. 2), implies that the regional climate pattern with strong west winds that persists until today was established during the early Holocene.

Outlook

Four seismic surveys at Laguna Potrok Aike indicate ca. 400 m of undisturbed lacustrine sediments. This sediment archive will be drilled in the framework of the ICDP project PASADO (cf., PAGES News 14(2): 39-40) in 2008. The site promises a long continental environmental and climatic record since formation of the maar ca. 770 kyr ago, with decadal-to-centennial resolution. Obtained data and climate–hydrology linkages will serve as a key for a better understanding of late- to mid-Pleistocene climate conditions in southern South America, especially if compared to marine and ice core records. Until now, such long high-resolution terrestrial records are still lacking from the mid- to high latitudes of the southern hemisphere.

Acknowledgments

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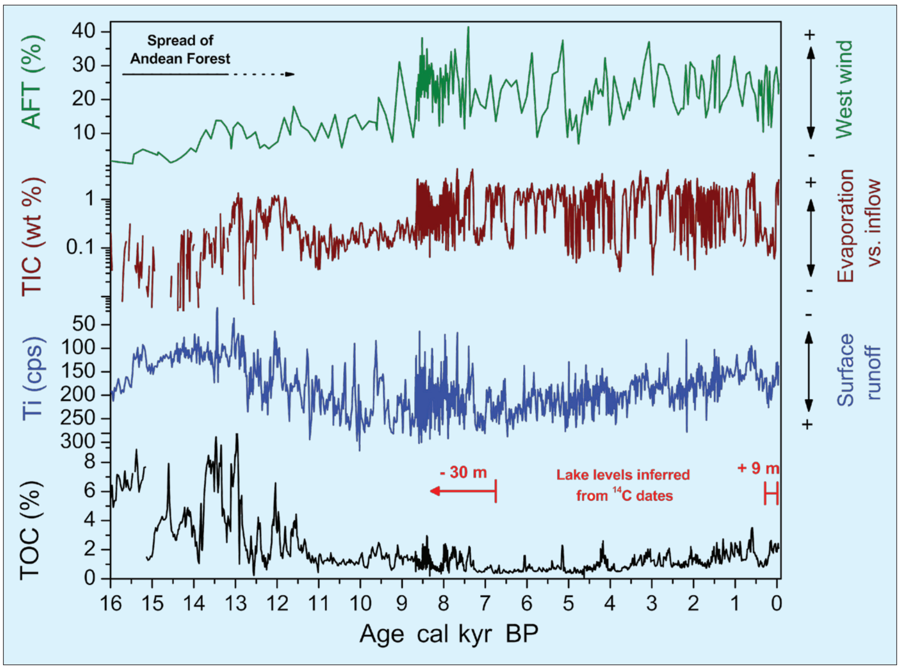

*Figure 2: Climate proxies of the Laguna Potrok Aike sediment archive: Pollen of Andean Forest Taxa (**AFT**) as a measure of west wind variability, total inorganic carbon (**TIC**) as a proxy of the balance between evaporating and inflowing waters, and titanium content (**Ti**; given as counts per second - cps) representing minerogenic sedimentary input mainly by surface runoff. Note that Ti and AFT are influenced by other effects in the late glacial. Radiocarbon-dated lake levels relative to today are given by red bars. Total organic carbon (**TOC**) is plotted to demonstrate that there might be a dilution of Ti by organic matter during the late glacial.*

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Tree-ring evidence for tropical-extratropical influences on climate variability along the Andes in South America

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Instrumental records show that the climate system is characterized by low- and high-latitude modes of variability, which fluctuate at many different temporal scales. The best known is the El Niño-Southern Oscillation (ENSO) phenomenon in the tropical Pacific, which dominates global climate variations on interannual timescales mostly ranging from 3 to 6 years (Diaz and Markgraf, 2000). The Antarctic Oscillation (AAO) is the dominant mode of climate variability at mid- to high latitudes in the southern hemisphere (Thompson and Wallace, 2000). The positive state of this annular mode is associated with intensified subtropical highs and strong polar lows, which drive a strong extratropical circulation. Interannual-to-decadal variability of climate associated with these atmospheric circulation modes exhibits large spatial and temporal variance that remains poorly documented. Continental- and hemispheric-scale networks of instrumental and proxy climate data are needed to document and help understand these changes in the ocean-atmosphere system.

Tree rings represent the most broadly distributed, annually-resolved source of proxy climate data throughout the Andes Cordillera and, thereby, supply the base-

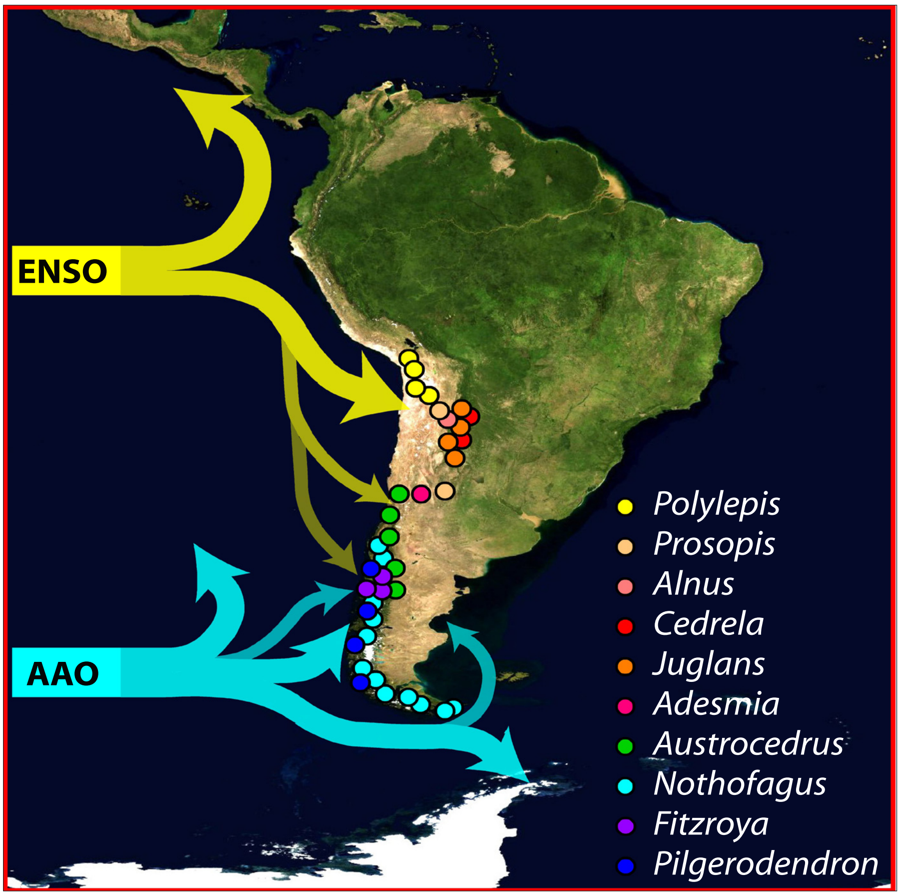

Figure 1: Tree-ring chronologies along the Andes Cordillera in South America. Major tree taxa used for developing the chronologies and their geographical distributions are shown. The geographical domain of the dominant tropical and extratropical forcings of regional climate variability across the Andes, as represented by the El Niño-Southern Oscillation (ENSO) and the Antarctic Oscillation (AAO), respectively, are also indicated.

line data necessary to evaluate natural climate variability on different temporal and spatial scales (Fig. 1). A Collaborative Research Network supported by the Inter-American Institute for Global Change Research (IAI) focused on the development of treeline chronologies from Alaska to Tierra del Fuego (Luckman and Boninsegna, 2001). Using a combination of instrumental and tree ring records, the southern component of this study shows how tropical versus extratropical forcings of climate variability influence regional patterns of temperature and precipitation variations from tropical Bolivia (16°S) to sub-Antarctic, southern South America (55°S).

Tropical-extratropical forcings of regional temperature variations

The continental effects of ENSO in terms of surface air temperature and precipitation vary along the Andes Cordillera. Positive anomalies in summer temperature across the Bolivian Altiplano are associated with increased westerly dry flow on the Altiplano during El Niño events (warm-ENSO phase). As a consequence, the eastern wet influences are reduced over the entire region leading to generally warm-dry summers (Fig. 2c). Conversely, during negative anomalies in the tropical Pacific sea surface temperatures (SSTs) (La Niña events or cold-ENSO phase), this pattern reverses (Vuille et al., 2000; Garreaud et al., 2003).

The radial growth of *Polylepis tarapacana*, a small tree growing between 4000 and 5200 m elevation on the Altiplano, is influenced by changes in summer temperature and precipitation (Argollo et al., 2004). *P. tarapacana* growth is significantly correlated (r = -0.42, n = 138; Fig. 2a) with variations in the Southern Oscillation Index (SOI), from August (previous to the growing season) to February (during the current year of ring formation), encompassing the peak of ENSO (Nov-Feb) when warm and cold events mature in the equatorial Pacific (Christie et al., in press).

At mid-latitudes (39-43°S) in the Patagonian Andes, temperatures during summer (Dec-Mar)—as reconstructed for the past millennium using chronologies from *Fitzroya cupressoides*—are also related to variations in the SOI during the same season (r = -0.36, n = 127; Fig. 2b). There is a significant tendency for the occurrence of relatively warm and dry (cool and wet) conditions along the northwestern part of Patagonia, in Chile and adjacent Argentina during summers coincident with El Niño (La Niña) episodes (Fig. 2c). A larger frequency of anticyclonic circulation anomalies near the southern tip of South America during El Niño episodes contributes to the

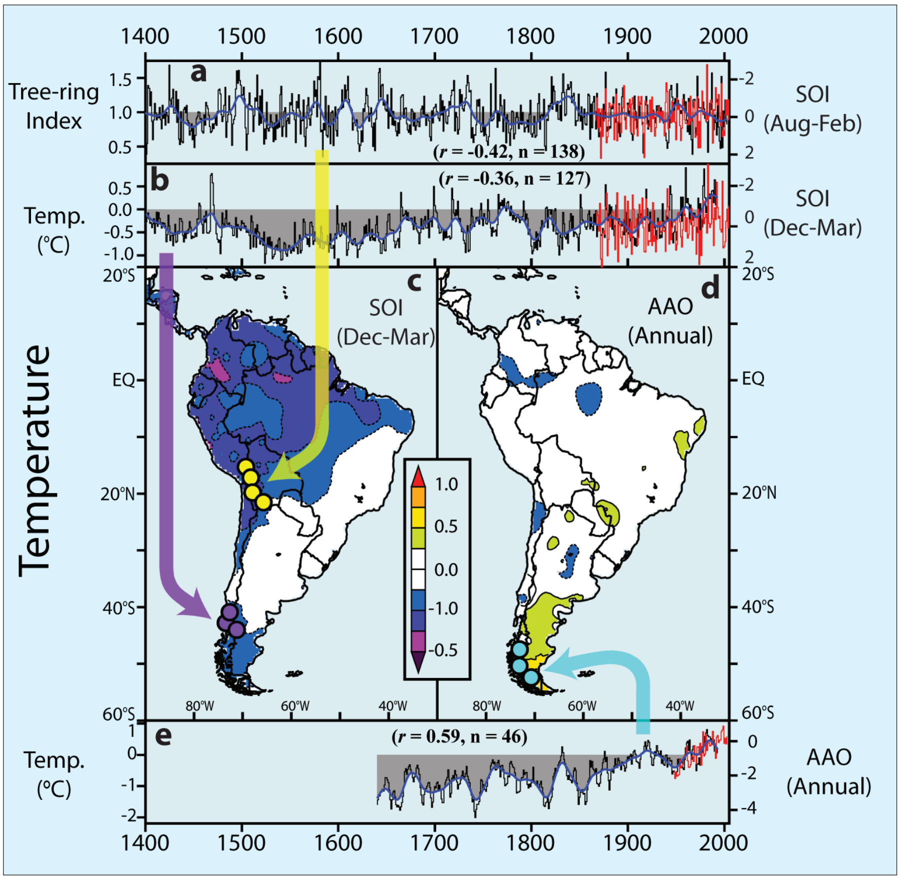

*Figure 2: Temporal and spatial patterns of regional temperature variability along the Andes in South America related to tropical Pacific (Southern Ocillation Index; SOI) and extra-tropical (Antarctic Ocillation; AAO) atmospheric circulation features. SOI-related temperature variability recorded in tree-ring variations from (**a**)* Polylepis tarapacana *in the Bolivian Altiplano and (**b**)* Fitzroya cupresoides *in northwestern Patagonia. Spatial correlation patterns between summer (Dec-Mar) and annual (Aug-Sep) surface temperatures with (**c**) SOI and (**d**) AAO, respectively. Gridded temperature field from University of Delaware (1950-1999). Spatial correlations over ± 0.25 are shown (roughly the threshold of the 95% confidence level). (**e**) AAO-related temperature variability recorded in tree-ring variations from* Nothofagus pumilio *in southern Patagonia.*

strengthening of the southern border of the subtropical Pacific anticyclone, which is located at its southern-most position during summer (Montecinos and Aceituno, 2003).

The positive polarity of the AAO is associated with cold anomalies over most of Antarctica, with the exception of the Antarctic Peninsula and southern South America, where the enhanced Westerlies related to the high AAO polarity increase the advection of relatively warm oceanic air over the land (Thompson and Solomon, 2002; Fig. 2d,e). Annual temperature variations in southern Patagonia, reconstructed from a network of upper-treeline *Nothofagus pumilio* chronologies (Villalba et al., 2003), are significantly correlated with annual variations in the AAO index. Warmer conditions during the 20th century, particularly in the past three decades, are consistent with more positive AAO values in recent times.

A gradual transition from tropical to high-latitude influences in temperature variations from northern (40°S) to southern (>47°S) Patagonia is consistent with temperature anomalies across the Pacific and western South America during ENSO. These anomalies are larger and more spatially consistent in northern than southern Patagonia, resulting in weaker influences of the tropical Pacific at higher latitudes in austral South America.

Tropical-extratropical forcings of regional precipitation variations

Precipitation variations in the Bolivian Altiplano and Central Chile are related to climate in the tropical Pacific (Fig. 3c,e). Interannual variability in summer precipitation, particularly on the western Altiplano, is related to ENSO (Fig. 3c; Vuille et al., 2000; Garreaud et al., 2003). Consistent with these findings, the precipitation-sensitive *P. tarapacana* records from the Altiplano are significantly correlated with the SOI during the 1866-2000 interval used for comparison (r = 0.30; Fig. 3a).

Relationships between SST in the equatorial Pacific and precipitation anomalies in central Chile (30-35°S) have been reported by several authors (Aceituno, 1988; Rutlland and Fuenzalida, 1991; Montecinos and Aceituno, 2003). The steeper gradient in pressure over the southeastern Pacific related to El Niño induces deflections of the low pressure systems, and the associated storms towards the subtropical belt of South America, increasing precipi-

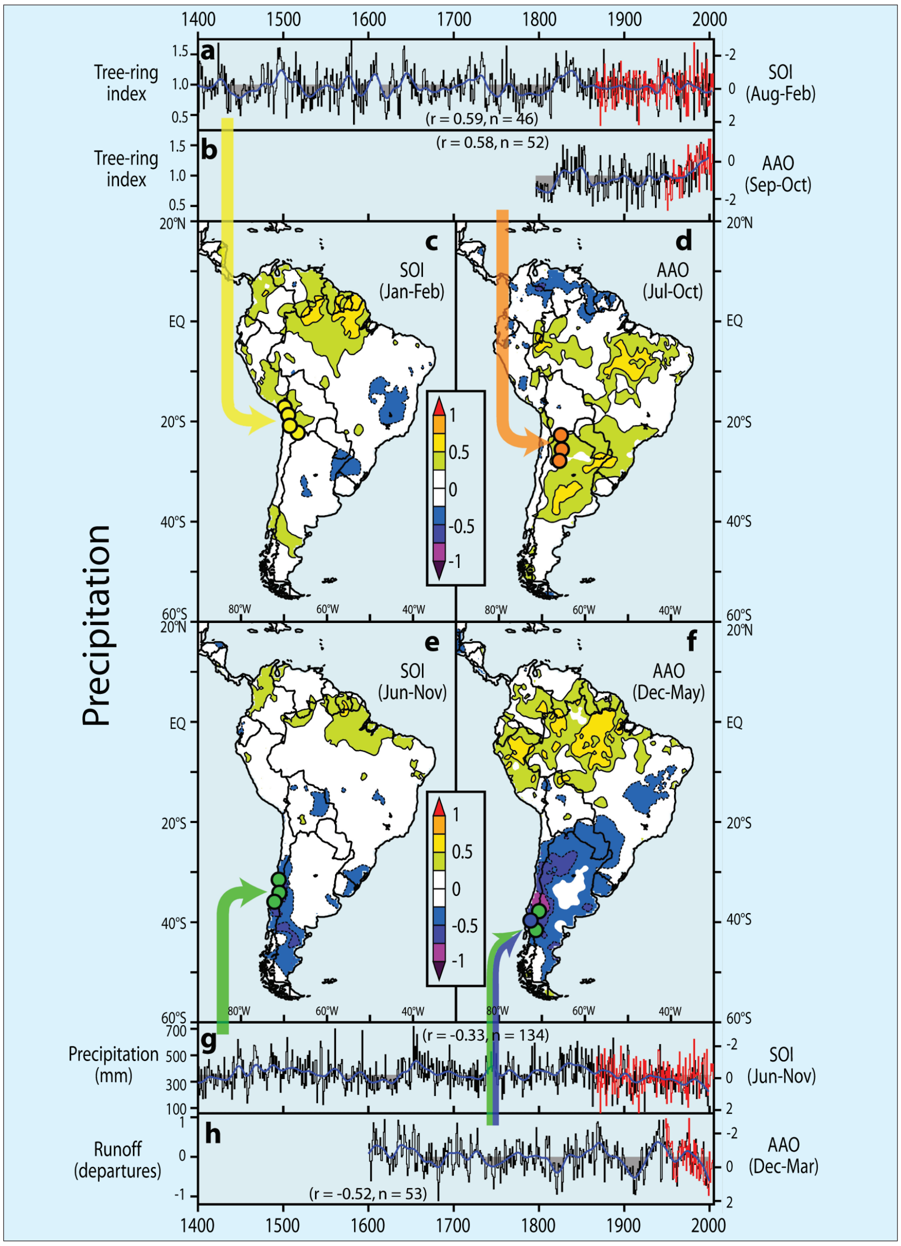

Figure 3: Temporal and spatial patterns of regional precipitation variability along the Andes in South America related to tropical Pacific (Southern Oscillation Index; SOI) and extra-tropical (Antarctic Oscillation; AAO) atmospheric circulation features. SOI-related precipitation variability recorded in tree-ring variations from Polylepis tarapacana *in the Bolivian Altiplano (**a**) and* Austrocedrus chilensis *in central Chile (**g**). AAO-related precipitation variability recorded in tree-ring variations from* Juglans australis *in subtropical northwestern Argentina (**b**) and* Austrocedrus chilensis-Pilgerodendron uviferum *in northwestern Patagonia (**h**). Spatial correlation patterns between summer (Jan-Feb) and winter-spring (Jun-Nov) precipitation and SOI (**c** and **e**, respectively), and between winter (Jul-Oct) and summer-fall (Dec-May) precipitation and AAO (**d** and **f**, respectively). Gridded precipitation field from University of Delaware (1950-1999). Spatial correlations over ± 0.25 are shown (roughly the threshold of the 95% confidence level).*

tation in Central Chile (Fig. 3e). Tree-ring based reconstructions of precipitation derived from *Austrocedrus chilensis* in central Chile (LeQuesne et al., 2006) show a consistent relationship with SOI (Jun-Nov) during the past 140 years (r = -0.33; Fig. 3g).

AAO-related precipitation anomalies have been documented along the subtropical eastern slopes of the Andes (24-30°S) and in northern Patagonia (38-42°S; Gillet et al., 2006). The positive AAO phase in winter-spring (Jul-Oct) is associated with the intensification of upper-level cyclonic activity, the enhancement of the moisture convergence and the increase in precipitation over the subtropics east of the Andes (Fig. 3d; Silvestri and Vera, 2003). The positive trend of tree-growth recorded in the precipitation-sensitive chronologies of *Juglans australis* from the subtropical montane forests in northwestern Argentina may be related to the persistent AAO positive phase during the past three decades (r = 058, n = 52; Fig. 3b).

Negative precipitation anomalies during the positive polarity of the AAO in northern Patagonia are related to a reduction of the zonal flow at mid-latitudes that translate into less frontal and orographic precipitation in the Patagonian Andes (Fig. 3f; Garreaud, in press). Using a combination of *Austrocedrus chilensis* and *Pilgerodendron uviferum* tree ring records from the region, the summer-fall (Dec-May) Puelo River streamflow has recently been reconstructed back to 1599 (Lara et al., 2007). Summer-fall runoff showed a significant negative correlation with the AAO (r =-0.52, n =53; Fig. 3h), reflecting the influences of high-latitude atmospheric circulation on precipitation in northern Patagonia.

Climate fluctuations along the Andes exhibit considerable geographical dependence. Tropical and subtropical regions are mainly influenced by large-scale oscillations rooted in the tropical Pacific ocean, whereas climatic variations in the temperate and sub-Antarctic regions are closely related to mid-and high-latitude phenomena. However, climatic variations simultaneously modulated by tropical-extratropical interactions have also been reported for some regions in South America on the basis of instrumental (Silvestri and Vera, 2003) and proxy records (Villalba et al., in press). The network of climatic-sensitive chronologies across the Andes offers the chance to develop longer data sets that will allow characterization of the full spectrum of regional temperature and precipitation variability, as well as their past interactions with tropical and extra-tropical circulation features. Understanding this variability is key to planning and mitigation of future climatic changes in South America.

Acknowledgments

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Late Quaternary dune development along the western margin of South Africa and its relationship to paleoclimatic changes inferred from the marine record

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Introduction

Lying at the interface of the region's summer and winter rainfall zones, the western margin of South Africa is a transitional area where ca. 400 km of wet winter climates grade northwards to extremely arid conditions with rare summer rains. Throughout glacial–interglacial cycles, hemispheric-scale atmospheric and oceanic circulation variations are likely to have strongly affected environments in this region, with periods of humidity and aridity linked to latitudinal migrations of the westerlies and the frequency and strength of associated frontal systems. Proxies in this belt are, therefore, likely to preserve important information on millennial-scale temperate and subtropical circulation dynamics.

Environmental reconstructions of the west coast of South Africa, however, have been limited by a paucity of terrestrial sedimentary archives. While a series of robust paleoenvironmental records exist for the southern west coast (e.g., Meadows and Baxter, 1999; Parkington et al., 2000), the semi-arid to arid climates of the central and northern regions are not conducive to the preservation of traditional paleoecological proxy data sources (e.g., pollen, charcoal). As a result, such proxy archives are absent from much of the west coast.

The aeolian deposits, which extend along the west coast, have the potential to provide a significant proxy record of paleoenvironmental change in the region (Fig. 1). We sought to explore their potential as indicators of palaeoenvironmental change by applying optically stimulated luminescence (OSL) dating techniques, and identifying phases of aeolian activity and dune development (Chase and Thomas, 2006; 2007).

Aeolian sediment archives

In total, 91 samples from 22 cores were taken from dune deposits along a north–south transect extending up the west coast of South Africa from Elands Bay (32°26'S, 18°14'E) to Kleinsee (29°14'S, 16°59'E) (Fig. 1). OSL ages obtained from these samples allowed for the spatial and temporal dynamics of dune emplacement to be determined.

Recognizing variations in individual dunefield and dune form dynamics, two distinct suites of ages were derived from the OSL data, with accumulating dune forms preserving evidence over different timescales to the region's migrating dune fields. The development of accumulating and migrating dune forms along the west coast is primarily a function of topographic variations in the landscape and the proximity and productivity of potential sediment sources. In sheltered locations, such as the lee of uplands, or in areas of high sediment supply, accumulation is more likely to exceed erosion and allow for the development of thick aeolian deposits, and stacked records of dune development. In more exposed locations, or areas with limited sediment supply, erosion often exceeds accumulation and more migratory dune forms develop. Migratory dunes, identified in this study by their crescentic morphology, are short-lived self-cannibalizing forms that 'roll' across the landscape as sediment is eroded from their windward slopes, transported across the dune, and deposited on the leeward slopes. This constant recycling of the sediment body does not promote the development of long records of aeolian activity, and generally only the termination of the last major phase of activity is preserved.

These variations are illustrated in Figure 2, where ages are rounded to the nearest 1000 years and grouped into 1 kyr intervals, with a five-point moving average calculated for the resulting distribution. The patterning of ages from the accumulating dune forms exhibits five distinct clusters, suggesting phases of activity at 3–5, 16–23.5, 31–33, 43–48.5 and 61–74.5 kyr. Conversely, ages obtained from migrating dune forms exhibit a largely coeval inverse relationship to the ages from the accumulating dunes forms, with periods of activity occurring at 4–8, 11–16 and 21–28 kyr, and single ages at 43.5±2.66 and 82.7±5.88 kyr.

That each major cluster is composed of ages from a range of sites along the coastal transect implies that these phases are not simply episodes of local reworking

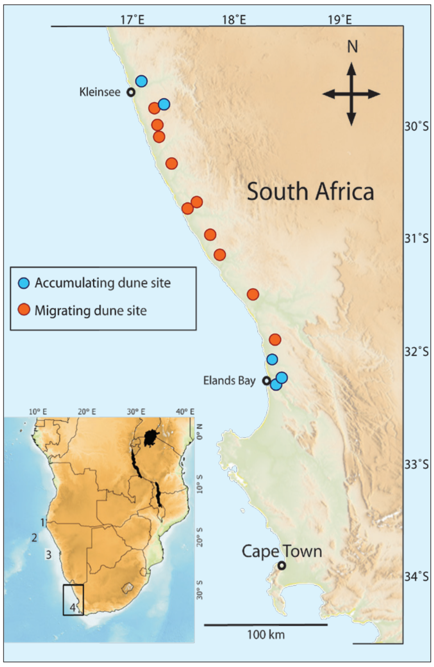

Figure 1: Map of western margin of South Africa indicating dunefield cores sites, sample depths (m) and OSL ages (kyr), with ***inset*** *indicating the study area and sites within the southern African context and the locations of the primary paleoenvironmental sites used for comparison. Sites 1 - 2 indicate the location of the cores displayed in the top 3 panels in Fig 2.*

of sediments, but rather that they are indicative of regional aeolian activity.

Interpretations

Most published studies of the timing and cause of aeolian activity during the late Quaternary equate clusters of luminescence ages with periods of increased aridity (e.g. Stokes et al., 1997; Thomas et al., 1998; Munyikwa, 2005). However, a comparison of the OSL ages from the west coast dunefields with the few well-dated paleoenvironmental records from the region suggests that this interpretation cannot be applied to most of the phases of aeolian activity that have occurred during the last glacial–interglacial cycle in SW Africa.

In general, the findings of Stuut et al. (2002) (Fig. 2) corroborate and refine the interpretations of other paleoenvironmental records (e.g., Parkington et al., 2000; Shi et al., 2001), indicating increased humidity and windiness along the west coast of southern Africa during glacial periods, and increased aridity during interglacial periods. These interpretations are consistent with the conceptual models

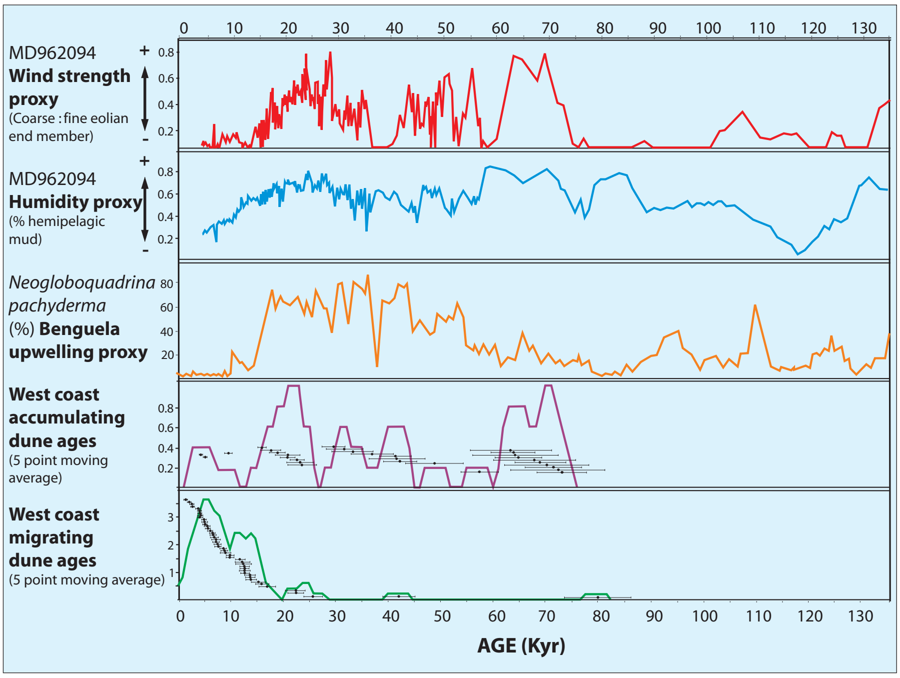

Figure 2: Correlation of Optically Stimulated Luminescence (OSL) age distributions from west coast aeolian sediments with proxies for wind strength and humidity from marine cores off the Namibian coast. Wind strength is indicated by percentages of N. pachyderma *as a proxy for coastal upwelling (Little et al., 1997) and by the ratio of coarse to fine aeolian dust (Stuut et al., 2002), while humidity is inferred from the proportion of aeolian to hemipelagic sediments (Stuut et al., 2002). Dune ages and errors are shown in* ***black***. ***Purple*** *(Chase and Thomas, 2006) and* ***green*** *(Chase and Thomas, 2007) lines indicate five-point moving averages calculated from the ages grouped into 1 kyr bins. The core location for the top three studies can be found in Fig 1 inset.*

that suggest expansions of the Antarctic sea ice would have resulted in an equatorward shift of the westerlies during glacial periods, bringing increased precipitation to SW Africa (e.g., Chase and Meadows, in press; Cockcroft et al., 1987; van Zinderen Bakker, 1976). By exploring correlations between our dune ages and terrestrial and marine records from the region, we have been able to arrive at a more detailed understanding of the dynamics and significance of dune development along the west coast.

Of the phases of aeolian activity preserved in accumulating dune forms, phases from 16–23.5, 31–33, 41–48.5 and 61–74.5 kyr (Fig. 2) are associated with periods of increased windiness and fluvial sediment supply, and correlate with phases of high-latitude cooling, invigorated glacial circulation systems and increased humidity along the west coast (e.g., Little et al., 1997; Parkington et al., 2000; Shi et al., 2001; Stuut et al., 2002). This contrasts sharply with paleoclimatic predictions linking aeolian activity to aridity, and indicates the importance of defining and incorporating the role of wind strength and sediment supply in the interpretation of aeolian proxies.

Rather than indicating phases of increased aeolian activity, ages from migrating dune forms represent a complex history of dune-field development. The oldest ages, between 21–83 kyr, were obtained from the cores of the dunes and, as they were deposited in high wind–high humidity environments, it is likely that they represent localized, fixed aeolian sediments that accumulated around the vegetation that would have been growing in the region. The 11–16 kyr phase of dune development occurred during the still humid, but notably less windy late glacial period (Fig. 2), and aeolian deposits from this phase represent the transition to dormancy of a highly mobile dune field.

The mid-Holocene phase of activity recorded in both accumulating and migrating dune forms occurs during a period of low wind strength and potentially limited sediment supply. It is thus more likely that in this case the widespread reactivation of aeolian deposits occurred as a response to the period of increased aridity that is recorded in the paleoecological proxies from the Elands Bay region (Meadows et al., 1996; Parkington et al., 2000). While human impacts can result in the initiation of aeolian activity through the disturbance of vegetation cover, an occupational hiatus in some of the region's archeological sites from 4–8 kyr (Parkington et al., 1988) does not indicate human agency as a likely driver for this phase of aeolian re-activation.

Conclusions

Compared to other parts of the world where glacial periods were both windier and drier, the increased humidity along the west coast during the last glacial period has allowed for the analysis of the relative importance of wind strength and aridity in the evolution of the region's dune fields. Contrary to the prevailing paradigm of dunes being equated with aridity (e.g., Stokes et al., 1997; Thomas et al., 1998; Munyikwa, 2005), an inverse relationship exists between dune ages and evidence for aridity along the west coast. Instead, phases of dune development correlate most strongly with variations in wind strength; with accumulating dunes recording periods of increased aeolian activity, and ages from migrating dunes marking the threshold in transport capacity below which dunes become dormant.

These results call into question the utility of aeolian sediments as a paleoclimatic proxy. While drier climates can enable aeolian activity, as in the case of the mid-Holocene phase of dune development along the west coast, without evidence of variations in wind and precipitation it is difficult to identify the relative influence of these mechanisms, and thus to clearly attribute phases of dune development to episodes of climatic change.

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Rapid 20th-century increase in coastal upwelling off northwest Africa revealed by high-resolution marine sediment cores

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The climate of the last two millennia has emerged as a crucial baseline period for assessing the present global warming trend. Reconstructions of climate during this period require high resolution (decadal or better) proxies such as ice cores, corals, tree rings and varved lake sediments. Marine sediment-core records, essential for providing information on past oceanic behavior, are generally not considered to be able to provide comparable detail.

Recent programs, however, such as the EU Patterns of Climate Variability in the North Atlantic (PACLIVA) Project (Jansen, 2007), have focused on producing climate records from marine sediment cores of decadal or better resolution. Here, we present two marine sediment core records of alkenone-derived sea surface temperature (SST) that span the last 2500 years, overlap temporally with instrumental data sets for most of the 20th century, and have an exceptional sampling resolution of between 2 and 25 years per sample (McGregor et al., 2007), comparable with other high-resolution proxies. The two cores (gravity core GeoB6008-1 and multi-core GeoB6008-2) were recovered from Cape Ghir off the coast of Morocco (30°50.7'N, 10°05.9'W; 355 m water depth), a location characterized by coastal upwelling, typical for the northwest African margin. The sediment core records allow an unprecedented view of 20th century and late-Holocene coastal upwelling history.

Coastal upwelling, such as that off northwest Africa, occurs along the eastern margins of major ocean basins and develops when predominantly alongshore winds force offshore Ekman transport of surface waters, leading to the rise (or upwelling) of cooler, nutrient-rich water (Tomczak and Godfrey, 2005). Coastal upwelling is of large economic importance and accounts for ~20% of the global fish catch, yet constitutes <1% of the world's oceans by area (Pauly and Christensen, 1995). Coastal upwelling is also of major importance to marine productivity and strongly influences atmosphere-ocean CO_2 exchange, carbon recycling and export to the open ocean. The understanding of potential global warming–related changes in the intensity of coastal upwelling has become increasingly important because of the likelihood of dramatic ecosystem and socioeconomic impacts (IPCC, 2001; Bakun and Weeks, 2004; Goes et al., 2005; Harley et al., 2006). Although there is some evidence that the vigor of coastal upwelling, at least at the decadal scale, has progressively increased as a result of anthropogenic greenhouse gas emissions (Bakun, 1990; Anderson et al., 2002; Goes et al., 2005), most evidence is based only on short instrumental records. Longer temporal records, such as those provided by marine sediment cores, are needed to assess whether upwelling truly has intensified. Thus, using the well-established alkenone unsaturation index ($U_{37}^{K'}$) as a SST proxy, we reconstructed SST and upwelling at Cape Ghir (McGregor et al., 2007).

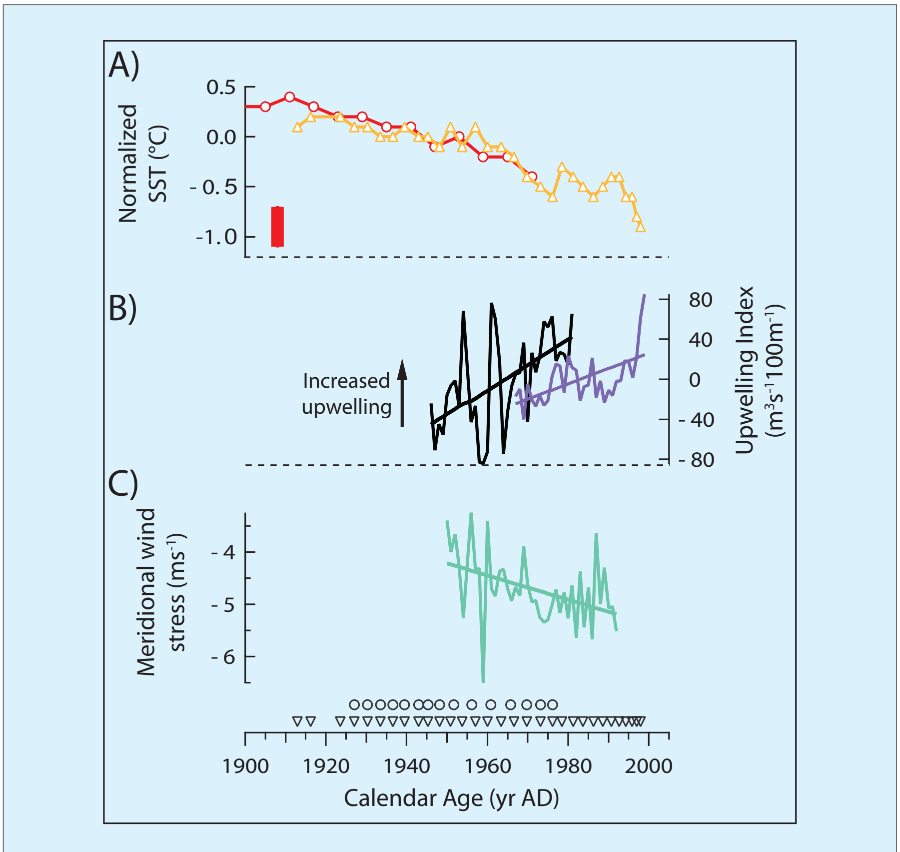

*Figure 1: **A**) Normalized alkenone SST records from cores GeoB6008-1 (**red**) and GeoB6008-2 (**orange**) for the 20th-century (vertical red bar indicates error on estimates) (McGregor et al., 2007); as compared with **B**) the Bakun upwelling index for NW Africa (**black** line) (Bakun, 1990), an upwelling index calculated for Cape Ghir (**purple** line) (www.pfel.noaa.gov, Schwing et al., 1996), and **C**) meridional wind speed data for 31°N, 11°W from 1950–1992 AD (Comprehensive Ocean-Atmosphere Data Set Release 1; Slutz et al., 1985). Alkenone SST records are normalized to the mean for the overlapping period between them (1912-1971 AD) to allow for a ~0.5°C offset. ^{210}Pb dates for GeoB6008-1 (**black circles**) and GeoB6008-2 (**black triangles**) are shown at the base of the graph. Both upwelling indices are presented at annual resolution and as the deviation from the mean of each record. More negative meridional wind speed values indicate more southerly (equatorward), upwelling-favorable winds. Figure from McGregor et al., 2007.*

Alkenone SST records of coastal upwelling

The two alkenone SST reconstructions from Cape Ghir show a steady cooling trend of ~1.2°C for the 20th century, indicating an increase in upwelling intensity (Fig. 1). In addition, the patterns of variability during the ~60-year period where the two cores overlap (1912-1971 AD) are notably similar, which attests to the consistency of the age model (Fig. 1, Fig. 2A) in this part of the core and of the SST signal in each record. The trend to cooler SSTs and increased upwelling through the 20th century is consistent with pronounced upwelling intensification for the latter part of the 20th century, inferred from two calculated upwelling indices for the Canary Current region (Bakun, 1990; Schwing et al., 1996), and with increased upwelling-favorable meridional wind-speed observations for Cape Ghir (Slutz et al., 1985) (Fig. 1).

When looking at the SST anomaly reconstruction for the past 2500 years (core GeoB6008-1; Fig. 2B), the final 100 years of the record clearly show the strongest decrease in SST (corresponding to an increase in upwelling), which is larger and more rapid than any other change in the record. The alkenone SST record of this core also shows pronounced millennial-scale variability during the past 2500 years (Fig. 2B). The reconstructed millennial mode for GeoB6008-1, identified through singular spectrum analysis, highlights this variability and shows local SST extremes that correspond to inferred periods of warming and cooling in the northern hemisphere, the most recent of which being the Medieval Warm Period (MWP) and Little Ice Age (LIA) (Osborn and Briffa, 2006) (Fig. 2B).

20th-century intensification of coastal upwelling

SST records for the 20th century suggests an influence of global warming on the temperature evolution and upwelling intensity at site GeoB6008. The rapid 20th-century cooling at Cape Ghir also coincides with the rise in atmospheric CO_2 (Fig. 2C). This reflects the influence of CO_2 on the land-sea thermal contrast in NW Africa and, in turn, on the alongshore winds driving the upwelling. According to the mechanism proposed by Bakun (1990), increased atmospheric CO_2 concentration could lead to warmer surface air temperatures (SATs) over land relative to those over the ocean, particularly at night time when radiative cooling is suppressed by the blocking of outgoing longwave radiation by CO_2. The increased SAT deepens the thermal low-pressure cell over land, while a higher-pressure center develops over the slower-warming ocean waters. The winds blow clockwise around the high and anticlockwise around the continental low. The coast represents the boundary separating the two centers. Therefore, along the coast, the wind is oriented alongshore and southward (equatorward), which thus drives the upwelling and negative SST anomalies.

Coastal upwelling during the past two millennia

The Cape Ghir SST anomaly record—which includes the rapid temperature changes of the past century and the millennial-scale variability—co-varies with Northern Hemisphere Temperature Anomaly (NHTA) reconstructions (Jones et al., 1999; Mann and Jones, 2003; Moberg et al., 2005), though with the opposite sign; a reverse "hockey stick" pattern (Fig. 2B, 2C). The antiphased behavior is an unexpected result, given the large regional variability captured from different locations by the proxy records used in the NHTA reconstructions as compared to the variability of alkenone SST record, which is a point-recorded time series. The link, however, between NHTA reconstructions and upwelling could come through the land-sea thermal contrast proposed above. The millennial-scale, hemispheric temperature variations could manifest as a greater change in land SAT as compared to SATs over the ocean, which may affect land-sea pressure gradients, alongshore winds, and therefore upwelling.

Conclusions

The sensitivity of upwelling to increases in CO_2 during the 20th century, in addition to our paleo-results of a distinct upwelling response to hemispheric-scale warming and cooling, strongly implies that upwelling may continue to intensify with future increased levels of atmospheric CO_2 and global warming. Upwelling regions, including Cape Ghir, show extremely high levels of biological activity, yet the ecosystem response to upwelling in these regions is dependant on a complex balance of temperature, ocean and circulation, and fishing pressure (Harley et al., 2006). Given the importance of these marine ecosystems, our dependence on these highly valuable

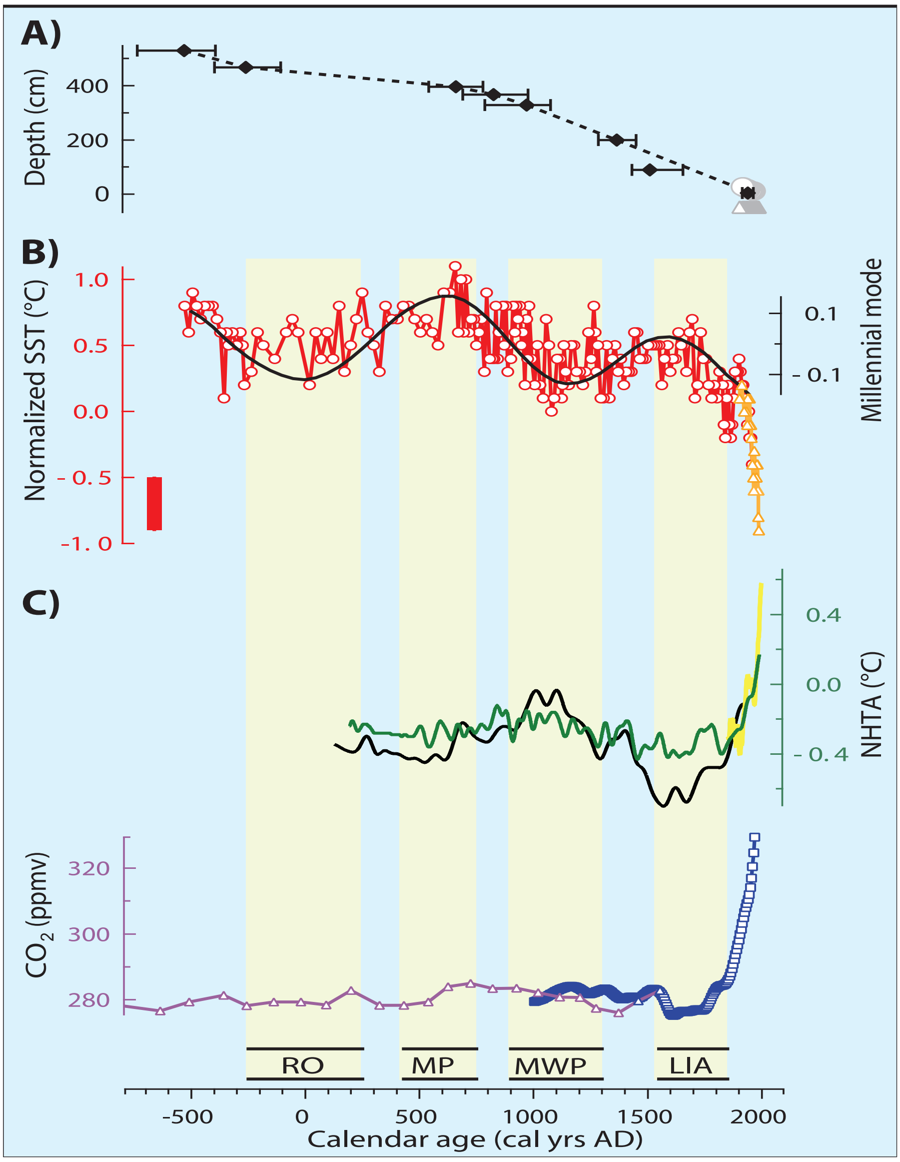

Figure 2: Age/depth relationship, and normalized alkenone SST for the full length of cores GeoB6008-1 and GeoB6008-2, compared with Northern Hemisphere Temperature Anomalies (NHTA) reconstructions and ice-core CO_2 records. Periods highlighted at the base of the figure represent the Little Ice Age (LIA), Medieval Warm Period (MWP), Migration Pessimism (MP), and the Roman Optimum (RO); ***A****) Age model for GeoB6008-1 based on the calibrated AMS ^{14}C ages (****diamonds****; ages are reported as calibrated radiocarbon years AD and error bars represent the 2σ-calibrated age range), ^{210}Pb dates (****gray circles****), and the age model for GeoB6008-2 based on ^{210}Pb dates only (****gray triangles****). ^{210}Pb dates for both cores are shown in more detail in Figure 1.* ***B****) Normalized alkenone SST from GeoB6008-1 (****red circles****) and GeoB6008-2 (****orange triangles****), and the reconstructed millennial mode from the gravity core GeoB6008-1 alkenone SST record (****solid black line****). Vertical red bar indicates the error on alkenone SST estimates;* ***C****) Three NHTA reconstructions: the instrumental record (10-point smoothing;* ***yellow line****) (Jones et al., 1999), ~2000-yr reconstruction based predominantly on terrestrial proxies (****green line****) (Mann and Jones, 2003), and ~2000-yr reconstruction with the use of high- and low-resolution proxy data (****black line****) (Moberg et al., 2005); and from Law Dome (****blue squares****) (Etheridge et al., 1996) and Taylor Dome (****purple triangles****) (Indermühle et al., 1999) atmospheric CO_2 records. Figure from McGregor et al., 2007.*

fisheries, and the potential role of upwelling in the drawdown of atmospheric CO_2, further understanding of climate feedbacks in upwelling regions and the ecological and socioeconomic repercussions is imperative.

This study also demonstrates that marine sediment cores do provide levels of information comparable to more traditional high-resolution proxies. Future studies focused on decadal-resolution marine sediment cores have the very real potential to contribute invaluable data on ocean and climate processes.

Note

The data are archived at the Publishing Network for Geoscientific and Environmental Data public digital library (www.pangaea.de/).

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For full references please consult:
www.pages-igbp.org/products/newsletter/ref2007_2.html

UK IGBP - Paleo and modern perspectives on global change: A personal summary

London, UK, 27 June 2007

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The need to understand the mechanisms and processes of climate and environmental change is a fundamental scientific challenge with profound practical implications. The components of the Earth System respond to perturbations on very different timescales: the atmosphere reacts in hours to years, natural ecosystems over years to centuries, the ocean over centuries to millenia, and the cryosphere over millennia and longer. Thus, it is important to examine climate and environmental changes in the perspective offered by the geological record of the past million years or so, as well as in the recent or historical period, in order to assess (and potentially improve) our ability to quantify anthropogenic effects.

Questions that arise from the paleorecord are modeling foci in several of the IGBP core projects. Explaining the tightly controlled upper and lower limits on atmospheric trace gas concentrations through glacial-interglacial cycles as shown by the ice core record is a focus in IGAC, iLEAPS and SOLAS. Understanding how ecosystem structure and function are affected by changes in atmospheric composition, biogeochemical cycles and climate is a focus in GLP and IMBER. However, paleodata gathering and analysis activities (necessary to compare with modeling results) fall within the domain of PAGES. This structure, combined with the generally limited communication between modelers and observationalists and between scientists working on modern and paleo timescales, may limit progress towards an integrated understanding of global change.

It was with these concerns in mind that the UK IGBP Committee organized a one-day meeting at the Royal Society in June this year to explore commonalities between modern and paleo-perspectives on global change. Speakers from each of the core projects, and members of the PAGES community, were invited to address the common themes of: biodiversity, ecosystem structure and functioning; the regulation of ocean productivity; ocean fertilization and the biological pump; fluxes to the coastal ocean—changing land-surface conditions and human interactions; and natural regulation of atmospheric oxidizing capacity.

One theme that emerged is the scarcity of high-quality data on key processes. In the ocean, for example, there are large uncertainties in estimates of primary production and vanishingly few measurements of respiration outside the Atlantic. Estimates of iron solubility in the ocean range over several orders of magnitude; different measures of export production sometimes yield opposite signals of change between glacial and interglacial states. On land, assessments of contemporary rates of biodiversity loss are heavily biased by sampling of charismatic species, while natural migration rates are poorly constrained. There are few experiments quantifying CO_2 fertilization outside the temperate forest zone; there is very limited understanding of the differential resilience of plants, insects and mammals to environmental change. However, the lack of data to address key questions may sometimes be more apparent than real: a major limitation is the availability of data in appropriate formats and centralized facilities. Networking and synthesis activities sponsored by PAGES and the Paleoclimate Modeling Intercomparison Project (PMIP) have shown that there are many hundreds more individual paleo records than are generally known to the paleo-modeling community. Similarly, GLOPNET (Wright et al., 2004) and the IGBP Fast-Track Initiative on Plant Functional Classification are demonstrating that there is an untapped wealth of measurements that could be used to analyze plant and ecosystem processes when brought together in a global database.

A second emerging theme was that multiple data sources can offer valuable complementary perspectives but that this synergy is often not exploited. The existence of multiple paleo proxies for a given process or variable has often been interpreted as increased "uncertainty" in paleoclimate reconstructions, largely because of the focus on statistical rather than process-based interpretation of the records. Paleo-observations can challenge our understanding of modern processes in surprising ways: the record of past changes in vegetation patterns, for example, indicates that migration rates can be fast, and that plant species have been extremely resilient in the face of large and rapid climate changes such as occurred in the North Atlantic region during the deglaciation. Sedimentary records from estuarine environments indicate much larger variability in water and sediment fluxes to the coastal oceans than revealed by the limited observations available from monitored rivers. The challenge is to use long-term observations to inform analyses of potential future changes and to help define the questions worth asking.

A third emerging theme was the need for a more sophisticated approach to modeling. Models are necessarily simplifications of the real world; they can lead to erroneous conclusions. For example, to the extent that ocean biology depends on ocean circulation, conclusions about the role of changes in the biological pump for glacial-interglacial CO_2 changes are hampered by limitations in ocean general circulation models. However, the creation of ever more complex models incorporating a multiplicity of feedbacks creates its own problems—e.g., the diagnosis of the causes of simulated changes—and is not a panacea. One implication is that the paleocommunity should move away from the concept of using their data for model evaluation towards the idea that models and data should be used together to explore hypotheses concerning the causes of phenomena. This should be achieved by collaboration involving people fully informed about the strengths and weaknesses of both models and data sets.

A clear overall message from the meeting was the need for a sustained dialog between the modeling and observational communities, and a dialog that bridges the divide between modern and paleo timescales. A sustained dialog cannot be achieved entirely through ad hoc meetings. Efforts such as ELME (European Lifestyles and Marine Ecosystems) and LOIS (NERC Land-Ocean Interactions Study) suggest that integration within a project framework is a potentially effective solution. Similarly, a closer integration between PAGES and the other IGBP projects in the planning and implementation of activities would be highly desirable. This could be assisted through Fast-Track Initiatives, and/or explicit cross-project activities. A second message is that while we need to continue efforts to monitor the Earth System and to make new measurements of key processes, we also need to exploit the full potential of existing observations through global syntheses and analyses. Organizing, archiving and disseminating these syntheses and analyses appropriately will require a clearer definition of intellectual property rights in the research framework.

Finally, it was generally accepted that process-based modeling is the key to making sense of observations. One aspect of this is developing the tools that will enable us to take the "proxy" out of paleo records, i.e., models that explicitly simulate the relative abundance of different groups of organisms or isotopic tracers. "Taking the models to the data" is not a new idea, but now, with the rapid development of process-based models for land and marine ecosystems and for many isotopic tracers, the tools are at hand to make it a practical reality.

Paleo-databases: Their role in modeling, reconstructing paleoclimate and understanding paleoenvironments

Arbois, Aix-en-Provence, France, 7-12 May 2007

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Aims

The European Pollen Database (EPD) began with a flourish in 1992 as a world leader and quickly grew in size and scientific value. Funding, however, has been sporadic during recent years and the addition of new sites has slowed to a trickle. A workshop was held to highlight the value of paleo-databases and to revitalize the EPD with a new generation of European palynologists. The fresh impetus follows the appointment of Michelle Leydet as database engineer (funded by the French CNRS), new financial support from the European Science Foundation through the EuroCLIMATE program (coordinated by Daniela Turk, www.esf.org/euroclimate), and the EU through the EVOLTREE Network of Excellence. 78 scientists (mostly early in their pollen careers) gathered in Arbois for lectures, posters, a field excursion and four training workshops.

Activities

Highlights from the invited talks included the varied applications of the North American Pollen Database to climate research (Jack Williams, Madison) and the use of a fossil mammal database to track long-term developments in species diversity (Tony Barnosky, Berkeley). The three key functions of paleo-databases were identified as:

1) Data preservation (as information is quickly lost - Fig. 1)
2) Inter-site comparisons
3) Regional-continental syntheses.

Simon Brewer (Cerege) and Thomas Giesecke (Liverpool) gave examples of data-model comparisons using pollen data to verify climate and dynamic vegetation models and generate paleoclimatic reconstructions by inverse modeling. The use of pollen databases in development of the modern genetic structure of European forests was reviewed (Jacques-Louis de Beaulieu, Marseilles), as was the reconstruction of changing European land-cover (Marie-Jose Gaillard, Kalmar), which has important feedbacks to the climate system. 31 poster presentations supported the lecture themes.

Most of the participants took part in a one-day excursion to the Champsaur basin, where the Holocene vegetational development and the origin of the present landscape were presented, based on paleoecological records from several sedimentary basins (Fig. 2). The meeting concluded after the field trip with the following four training workshops:

1. Multivariate methods (Bent Odgaard, Aarhus)
2. Data-model comparison (Simon Brewer, Cerege)
3. Pollen-land surface calibration (Jane Bunting, Hull)
4. Age-depth modeling (Maarten Blaauw, Belfast)

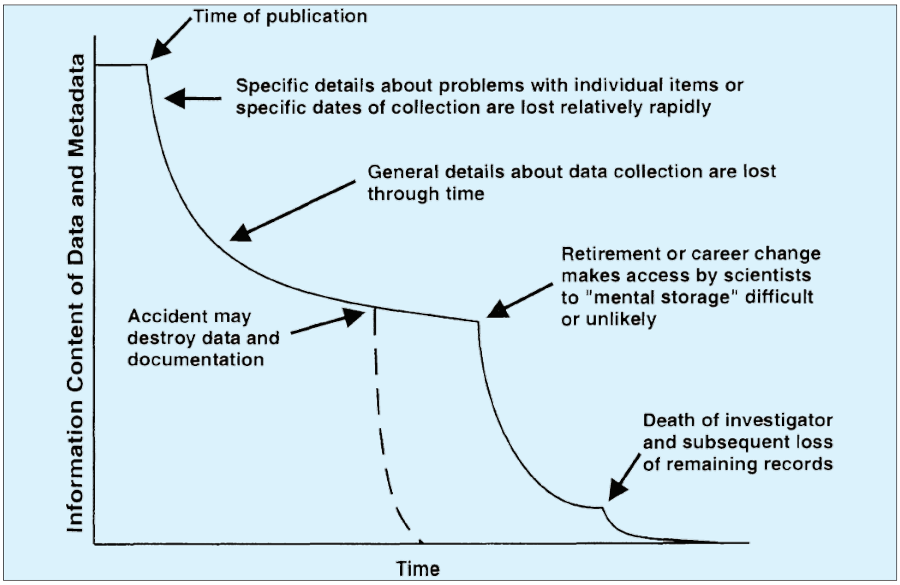

Fig. 1. A typical trajectory of information loss following publication of data (after Michener et al. 1997: Nongeospatial metadata for the ecological sciences, Ecological Applications, ***7****: 330-342.)*

Outcomes

The main outcomes of the workshop included a plan to re-launch the EPD, to involve a larger section of the research community than before, and to take advantage of the many online and informatics tools that have developed over the last 15 years.

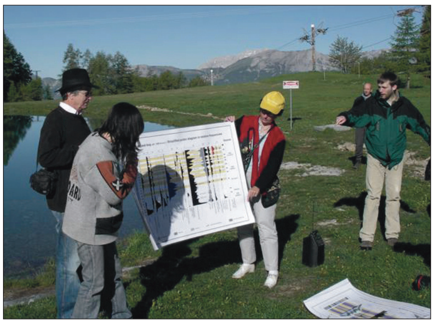

Fig. 2. The French team interpret a pollen diagram in the field.

A commitment was made to make data accessible as quickly as possible, once the backlog of work from the unfunded years has been added.

Three breakout groups also reported on the desired uses of the paleo-database, administrative structure and database structure. Conclusions of these discussions can be found at www.europeanpollendatabase.net. Finally, eight support groups were established to assist Michelle Leydet with database maintenance (taxonomy, database structure, age-depth chronologies, finance, community outreach, national contact points, mapping and data accuracy, intellectual property and protocol).

Getting involved

If you wish to join one of the aforementioned support groups, please add your name to the EPD wiki on the website. All are now encouraged to add or download data and provide ideas for improvement on the wiki. Authors contributing new data can choose to submit a 2-page standardized description of their site for publication in *Grana* to gain extra academic merit. The support groups are co-ordinated by Richard Bradshaw (Liverpool) and Valerie Andrieu (Marseilles) until the next EPD open meeting that is to be held at the International Palynological Congress in Bonn September 2008.

ESF-EuroClimate: Radiocarbon and ice-core chronologies during glacial and deglacial times

Heidelberg, Germany, 5-7 March 2007

Bernd Kromer[1], Barbara Wohlfarth[2] and Daniela Turk[3]

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EuroCLIMATE is a European Collaborative Research Programme (EUROCORES) that coordinates and promotes research on climate variability and the past, present and future dynamics of the carbon cycle (www.esf.org/euroclimate). A key component of the program is an accurate time scale of climate archives to infer spatial patterns and rate of climate change. EuroClimate projects provide, and profit from, advances in dating techniques for the glacial and deglacial interval, as discussed at this workshop co-sponsored by PAGES.

M. Friedrich, F. Kaiser and F. Guibal/C. Mirramont presented late glacial tree-ring chronologies. Beyond the absolutely dated part, starting at 12,593 BP, several floating pine chronologies were constructed, and are currently being cross-matched into a Bølling/Allerød sequence, covering the ^{14}C age range of 12.5 to 10.6 ^{14}C kyr BP. S. Talamo and B. Kromer presented the ^{14}C sequences obtained from the floating sections and compared them to the marine based ^{14}C calibration data set IntCal04. The tree-ring based data set can be matched to IntCal04 for most of the Allerød interval but clear discrepancies are apparent for three centuries around the onset of the Younger Dryas (YD). One explanation involves an increased marine reservoir age in the ^{14}C data set from Cariaco Basin. R. Muscheler suggested an alternative solution, based on a link of ^{10}Be in Greenland ice cores to ^{14}C anomalies in the tree ring sequence, which would imply timescale differences between IntCal04 and the tree ring/ice core scales around the onset of the Younger Dryas. A. Hogg and C. Turney presented fascinating prospects for tree ring based ^{14}C sequences from millennia-long Kauri sections, ^{14}C dated between 25 and 45 ^{14}C kyr BP.

L. Edwards demonstrated recent improvements in U/Th dating and new high-resolution ^{18}O series from Dongge and Hulu cave stalagmites. K. Hughen presented the revision of the Cariaco ^{14}C calibration data set, now anchored to the U/Th-dated Hulu cave record, back to 50 cal kyr BP. Consistent ^{14}C calibration back to at least 45 cal kyr BP, based on the revised data set and new coral data, now appears feasible. ^{14}C calibration procedures

Figure 1: Participants of the EuroClimate workshop

and the importance of high-resolution sequences were demonstrated by M. Blaaw, using sections of the RESOLuTION project (PAGES News 2007, 1)—a EuroCLIMATE project presented by B. Wohlfarth, M. F. Sánchez-Goñi and J.A.A. Boos. The new Greenland ice core timescale GICC05, shown to have profited greatly from the progress in multi-tracer, continuous flow analysis, was presented by A. Svensson and S. Johnsen. F. Preusser demonstrated the state of the art on OSL dating of lacustrine sediments, using two cores from Les Echets, France.

J. Beer addressed the question of common, production-induced signals in the fluctuations of ^{14}C and ^{10}Be records—as opposed to climate and carbon system effects—and presented new evidence for a dominant production signal. I. Hajdas discussed ^{14}C anomalies in several data sets during Heinrich event 4. C. Spötl and A. Mangini presented complex response patterns of ^{18}O in speleothems in the Austrian Alps, as compared to northern hemisphere climate proxies. A. Brauer and U. von Grafenstein presented new advances in chronology and stratigraphy of sediment records from five European lakes, based on detailed micro-facies and $\delta^{18}O$ analyses. D. Verschuren showed first results of the CHALLACEA project, which aims to reconstruct climate variability, from pre-LGM to present, in equatorial East Africa using a finely laminated sediment record from Lake Challa, Mt. Kilimanjaro.

Participants noted the strong synergies offered by the ESF EuroCores concept—and exemplified during the workshop— resulting from collaboration between 'producers' and 'users' of chronologies. Tree-ring based ^{14}C calibration of terrestrial sequences was agreed to be of prime importance. The Europe-wide aim to locate glacial and late glacial subfossil wood and the initiative to extend the Kauri database was, therefore, considered essential. The current update of the radiocarbon calibration data set IntCal04 was welcomed. New climate proxy records, especially from well-dated speleothems, will be an important addition to the coverage of climate records, and will fill gaps at low latitudes.

The Eastern African Quaternary Research Association (EAQUA) inaugural workshop

Kampala, Uganda, 7-8 June 2007

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The first PAGES/Eastern African Quaternary Research Association (EAQUA) workshop was held in Kampala, Uganda, from 7-8 June 2007. The workshop was jointly organized by Mbarara University of Science and Technology, Makerere University, and National Museum of Kenya, and was sponsored by PAGES, INQUA, PAST and BIEA. The EAQUA inaugural workshop was officially launched by Dr. Margaret Avery, the Vice President of the INQUA Commission for Paleoecology and Human Evolution.

This two-day workshop aimed to enhance the growth of the Quaternary science community in eastern and central Africa, through training, promotion of regional collaborative research, and information exchange on Quaternary science research issues. A scientific conference was also held, under the theme *"Understanding human-environment interrelationships in the Great Lakes region of central Africa during the late Quaternary"*, with the aim of understanding the history of human and environment interdependencies in eastern and central Africa, and how environmental variability relates to the cultural and socio-economic changes in the region during the late Quaternary.

The workshop also aimed at fostering dialog among young and senior research scientists from eastern and central Africa, with scholars from developed countries engaged in diverse Quaternary research disciplines. The primary objective of this was to build academic partnerships and enhance Quaternary research capacity in the region.

Figure 1: Workshop participants in front of Ridar Hotel

Workshop participants and paper presentations

The workshop attracted over 40 participants from ten different countries in eastern and southern Africa, as well as participants from Australia, the UK, Belgium and Sweden. The first day focused on the opening activities, keynote and plenary presentations. Four keynote papers relating to issues of paleoclimate and paleoenvironment in central Africa were presented. The presentations stressed the value of Africa's archives, which range from marine to continental, and lowland to mountain summits, and span millennial to decadal and inter-annual scales. Issues of non-orbital abrupt changes that have dramatic societal effects, such as El Niño related drought and flood events, were also highlighted.

The Holocene environmental history of this region was discussed. Multi-proxy analyses of sedimentary records, together with historical and archeological data, reported significant changes in environmental conditions in the inter-lacustrine region of central Africa during this time. It was noted that population and land-use change was perfectly correlated, and that as the population continued to grow the arable land size became scarce. Human impact on shallow, fluctuating African lakes has exacerbated the situation. For example, pollution on Lake Victoria has resulted in low water quality as O_2 is depleted in the deeper waters.

The keynote session was followed by plenary presentations from scientific organizations (PAST, BIEA, START and WAYS-Africa), who presented brief program backgrounds. The first day was wrapped up with a session of 8 oral and 3 poster paper presentations that addressed paleoclimate and paleoenvironment of central Africa.

The second day focused on the history, archeology and paleontology of the great lakes region, with a total of 7 oral papers and 2 poster presentations. This session discussed issues pertaining to the evolution of anatomically modern humans in eastern Africa and the African continent at large, including the timing and formation of social complexity and technological transformations in the Great Lakes region.

Workshop synthesis and way forward

The workshop concluded with panel discussions on future research and the way forward. It was agreed that:

- Consultations, linkages and networking among EAQUA members and research institutions on EAQUA activities would be encouraged.
- EAQUA should be strengthened and maintained by making use of local institutional facilities to minimize expenses.
- An EAQUA secretariat and website should be set up for easy circulation of information amongst members and other partners (donors/researchers).
- EAQUA information should be posted on the PAGES and INQUA websites.
- An interim committee will be set up to run EAQUA activities for the next two years before general election (Dr. Julius Lejju and Dr. Mohammed Umer were nominated as Chair and Vice Chair, respectively).
- EAQUA draft constitution will be rectified in the next meeting when membership has been realized.
- The next PAGES/EAQUA workshop should be held in Addis Ababa Ethiopia in 2009.

Morocco

PAGES
PAST GLOBAL CHANGES

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Abdelmalek Essaadi University; b_damnati@yahoo.fr

Morocco is the eastern-most country in the Mediterranean basin, extending from 28°N to 36°N latitude and from 2°W to 12°W longitude. Located in the very northwest of Africa, Morocco is bordered to the north by the Strait of Gibraltar and the Mediterranean Sea, to the south by Mauritania, to the east by Algeria and to the west by the Atlantic Ocean. Climatically, the country lies between the Mediterranean climatic belt and the Saharan subtropical desert, with high mountain ranges introducing an altitudinal climatic gradient that overlies the latitudinal gradient. Recent paleoclimatic reconstructions in Morocco are based on studies of the regional prehistory, of dunes and paleodunes, of paleosoils and other Quaternary deposits, and of the marine sediments cored along the Moroccan coast.

National Science Highlight:

Changes in climate and vegetation in Morocco during the Holocene are well documented through studies of diatoms, sedimentology, geochemistry and pollen analysis (Lamb et al., 1995, 1999). Quantitative climate reconstructions from the pollen record of Lake Ifrah indicate that winter temperatures during the Last Glacial Maximum were lower than present by ~10-12°C. The annual rainfall during the same period did not exceed 400 mm/yr compared to modern values of ~800 - 900 mm/yr. Sediment cores from Lake Tigalmamine (Fig. 1) provided a 10,000 year old record, which indicated that very wet climatic conditions existed in this region between 9600 and 8000 yr BP. Conversely, relatively dry conditions occurred between 2500 and the present day (Fig. 2).

Cheddadi, R., et al., 2004: Climate changes since the last glacial maximum in Morocco and predicted impact on the Mediterranean ecosystems. In: Leroy S. and Costa P. (Eds) *Environmental catastrophes in Mauritania, the desert and the coast*, Atar, Mauritania, 39-43.
Lamb, H., et al., 1995 : Relation between century-scale Holocene arid intervals in tropical and temperate zones, *Nature*, **373**: 134-137.
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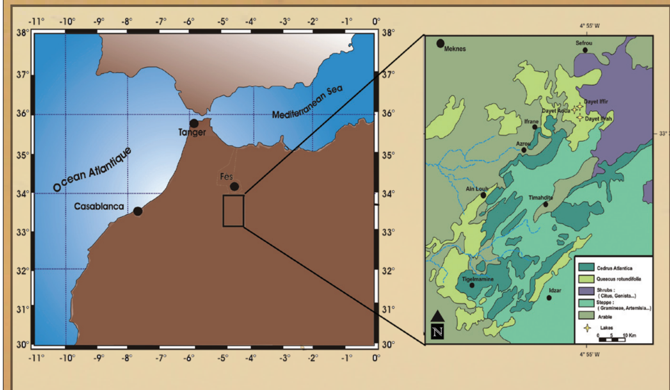

Figure 1: Location of lake core sites.

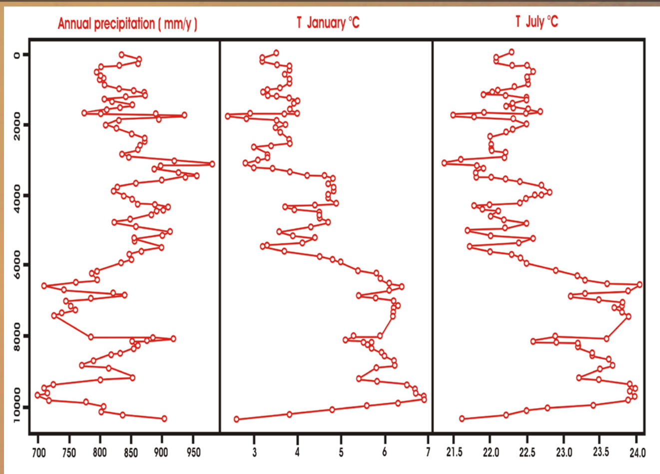

Figure 2: Climate reconstruction from Lake Tigalmamine

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Call for contributions to the PAGES newsletter

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 for the upcoming December 2007 issue of PAGES News, please contact Louise Newman (newman@pages.unibe.ch).

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